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James B. Glattfelder

INFORMATION–CONSCIOUSNESS–REALITY

How a New Understanding of the Universe Can Help Answer Age-Old Questions of Existence

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In loving memory of my father
and father-in-law

Preface

Through our eyes, the universe is perceiving itself. Through our ears, the universe is listening to its harmonies. We are the witnesses through which the universe becomes conscious of its glory, of its magnificence.

Alan Watts, quoted in *The Best Alan Watts Quotes*, David Crombie and Catriona Jardine, Crombie Jardine, 2016.

We are a way for the cosmos to know itself.

Carl Sagan, quote taken from *Cosmos: A Personal Voyage—Episode 1*, Carl Sagan, Ann Druyan, and Steven Soter, PBS, 1990.

The manuscript, which would eventually evolve into this book, has been accompanying me for many years. And even before I officially embarked on this creative journey in 2013, the ideas spanning the book's narrative arc started to form years prior. I cannot pinpoint the exact moment this started. As a child, I was often curious about the workings of the world, eager to catch a glimpse of the cosmic order. This desire to understand would later lead me to study theoretical physics. After graduating, I was, however, left with more questions than answers. Then, sometime while backpacking around the world in 2000 and 2001, my mind started to wonder about a bigger contextual picture of the world and myself in it. One of the earliest structuring influences came in the form of John L. Casti's book, titled *Alternate Realities: Mathematical Models of Nature and Man*, in late 2001. Perhaps, the first conscious thoughts, ultimately leading to this current writing effort, formed while I was lying in a hammock, on Havelock Island in 2006, reading Robert M. Pirsig's *Zen and the Art of Motorcycle Maintenance*. Then, in 2008, another pivotal moment occurred. At the time, I found myself back at university, in the middle of a dissertation on complex systems, years after my master's graduation. Each semester, Ph.D. students were required to attend a lecture, some of which needed to be on a topic outside their field of research. I chose an introductory course on the philosophy of science. Consolidating these inputs and subsequent ideas led to the first rough draft of this book,[1] appearing as an appendix in the thesis in 2010. Further condensation of ideas resulted in an Ignite Talk in Zurich in 2011.[2] Then, in 2014 I could present an outline of this book at TEDxSalford.[3] Finally, in 2016 I was fortunate enough to be able to contribute my story, as a two-page science essay, to Lucy and Stephen Hawking's children's book series, in the cosmic adventure called *George and the Blue Moon*.

Long before I had a clear vision of the structure of this book, the slowly emerging categorization of ideas endowed me with a contextual field, acting as a fine mesh able to capture and order many conceptual fragments ever since. Having said this, most of the information presented here is not original—compiled form close to 1800 sources, of which nearly 600 are books. Overall, more than 920 original quotes enter the book. My contributions can be found in the concepts related to the history of science, offered in Chap. 5; the insights stemming from my academic and professional work which can be found in Sects. 6.4.3.4, 7.3.2.1, and 7.4.3; and the synthesis of ideas presented in Chap. 15, specifically the entelechy of existence and the rhizome of reality.

This book is an amalgamation of existing thought—my best effort at connecting the dots. It is an attempt to grapple with existence, highlighting the existential challenges that keep mocking us. For instance, our continued collective failure to answer three age-old questions: What am I? What is reality? What can I know? In essence, the dissonance between our subjective streams of perception and the supposed objective reality they describe. This yearning to know and experience is echoed in the quotes found at the beginning of this preface. Compounding the enigma, and contrasting this ignorance, is humanity's unimaginable success in decoding reality and engineering it at will.

At a superficial level, it appears that we can indeed offer answers to these questions. However, under closer inspection the answers become vacuous, and the dilemmas only deepen. Here this book provides a remedy. We are invited to rethink our most basic assumptions and cherished beliefs about existence. It is an appeal to consider that there may be something we don't yet know about ourselves and the universe we inhabit, the knowledge of which could change everything.[4]

[1] Next to various blog posts, summarized in http://j-node.blogspot.ch/2015/07/the-consciousness-of-reality-illusion.html.
[2] See https://www.youtube.com/watch?v=1XKAe4ypn_k.
[3] See https://www.youtube.com/watch?v=zMckdYX0fTU.
[4] Adapted from Neale D. Walsch.

Once upon a time, I, Zhuang Zhu, dreamt I was a butterfly, fluttering hither and thither, to all intents and purposes a butterfly. I was conscious only of my happiness as a butterfly, unaware that I was Zhu. Soon I awaked, and there I was, veritably myself again. Now I do not know whether I was then a man dreaming I was a butterfly, or whether I am now a butterfly, dreaming I am a man.

Zhuang Zhu, 3rd Century B.C.E.

Zürich, Switzerland
September 2018

James B. Glattfelder

Acknowledgements

The realization of this book is a result of many interactions happening over many years. Beginning in chronological order, I would like to start by repeating some parts of the acknowledgments I wrote for *Decoding Complexity: Uncovering Patterns in Economic Networks*, *Springer Theses*, 2013. The following words also apply to this context:

> I would like to thank my mother and late father, Caroline and Tazi Glattfelder, who, from an early age on, fostered my budding interest in science. My special gratitude goes out to Peter Henley-Smith from Forest School, London, who coincidentally and spontaneously offered to introduce me to chemistry and physics at the age of 15 and awakened my dormant passion for science.
>
> I thank my employer, Richard B. Olsen of Olsen Ltd, Zurich, who, from the very beginning on, was highly supportive of my endeavor to complete a Ph.D. and arranged for me to continue working at the company on a part-time basis. I am very grateful to Frank Schweitzer, who was willing to embark on the adventure of advising an older than average and only part-time employed Ph.D. student. I also thank him for his scientific guidance and support.

For this book, I am moreover indebted to my former and current employers, who enabled me to pursue this undertaking and who also supported me: namely, Stefano Battiston from the Department of Banking and Finance at the University of Zurich and Anton Golub from Flov Technologies AG. I thank Angela Lahee from Springer for her invaluable coaching and her stoic patience—initially, in 2013, I believed I would finish the book by the end of 2014.

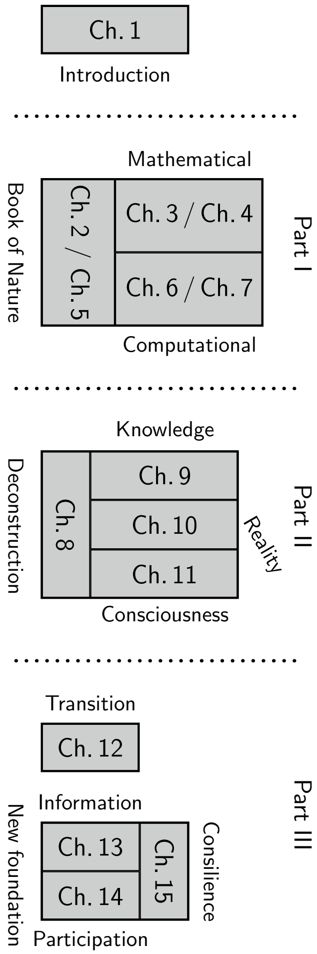
Furthermore, I thank Franz Vollenweider and Lukas Eppler for challenging and helping expand my reality bubble. I could profit from discussions with Matthias Brändle, Martin Schlatter, Gian Klainguti, Marco Pfister, Jan Arpe, Curdin Parli, Alexeja Pozzoni, Sarah Shephard, David Müller, Dominic Rau, Pascal Fischer, Thomas Bisig, Gabriele Visentin, Ralf Gautschi, Christopher Lim, Claus von Bohlen, Nicolas Perony, James Gien Varney-Wong, and the organizers of TEDxSalford. Some of these interactions go back to the early 1990s. I would also like to thank Vladimir Petrov for being the first brave person to ever read the manuscript and comment on it. I am also indebted to Lucy Hawking and Tsatrul Rinpoche.

Perhaps more unorthodoxly, but still sincerely, I would like to thank the following institutions and content providers. Today, we are lucky to find ourselves fully immersed in knowledge—much of it freely and instantaneously accessible. Without these possibilities, this book would have been impossible within the scope it finally reached. Specifically, I utilized Wikipedia, TEDTalks, Google Scholar, Google Books, Amazon's book scanning service, the Stanford Encyclopedia of Philosophy, and the YouTube content providers PBS Space Time, Kurzgesagt, Vsauce, CrashCourse, and Veritasium. The idea of freely accessible knowledge prompted me to publish this book as an open-access contribution to the SpringerOpen portfolio.

I am very grateful to the people who helped this project financially, aiding the free dissemination of knowledge: namely, Jürg Conzett of the *Sunflower Foundation* in Zurich and my brother-in-law Adrian Plattner.

Finally, I am also grateful to all my friends who helped and supported me throughout this journey. Last but not least, I am sincerely thankful to my wonderful wife Ladina Glattfelder for continuing to be a constant source of joy.

Schematic Outline



User Manual

In order to make the content of this book more accessible, seven different ways of reading are recommended. Lacking the time to engage in the 650-page-plus journey from cover to cover, the hurried reader is offered the following options:

1. The introductory parts of the first and last chapter (i.e., Chap. 15) are written in a different tone compared to the rest of the monograph's more technical appeal. They are conceived to be more accessible and should set the stage and capture the essence of the journey.
2. The most condensed and high-level version of the voyage is found in Sect. 1.1.
3. Extending the scope, each chapter—except the first and the last, i.e., from Chaps. 2 to 14—begins with an *Abstract* section and ends with a *Conclusion* section. By only reading these, the reader can fast-forward through the narrative.
4. Uncovering more detail, Sect. 1.2 recounts the entire story in a nutshell.
5. Section 1.3 provides a "content map," summarizing each chapter, section by section.
6. The main thesis is presented in:
    - Chapter 13: the information-theoretic ontology.
    - Chapter 14: the participatory ontology.
7. The most efficient mode of reading is to directly move to Chap. 15. As much of the book is cross-referenced, the interested reader can then backtrack from there and reconstruct the narrative. However, without having been introduced into the context of the new information-theoretic and participatory ontology, it is rather information dense and perhaps somewhat hard to grasp at first.

The book is comprised of three distinct parts:

1. Part I: The island of knowledge.
2. Part II: Its boundaries of ignorance.
3. Part III: New frontiers on the horizon.

In essence, it tries to grapple with the age-old questions: What am I? What is reality? What can I know? To be more precise, this book is about:

- Science and philosophy.
- A historical perspective.
- Our first-person subjective perspective and objective physical reality.
- Knowledge and the nature of reality and consciousness.
- Our place in the cosmos and possible meaning.

The book is idiosyncratic in the sense that it encompasses different levels of formalism. Chapters 3 and 4 in Part I are very technical, as is witnessed by the appearance of 197 equations (out of 243 in total). This is in stark contrast to Parts II and III which do not rely too much on mathematical formalism. In summary, Part II is more philosophy and general science oriented while Part III entertains more speculative notions, related to the human mind and the nature of reality. However, to makes all parts as accessible as possible, some precautions have been taken. First of all, many quotes are woven into the story line to give the reader a flavor of the original context in which the ideas appeared. Then, the narration, especially in Part I, is infused with historical and biographical anecdotes in an attempt to add vibrancy to the story. Accompanying this effort is the decision to clearly demarcate and encapsulate all the heavy mathematical machinery. To this aim, special attributed tags are utilized, denoted by $\{\oiint \ldots \oiint\}$, which signal that the following formal part can be safely skipped, without losing track of the story line. As an example, the text is interrupted here to include an encapsulated equation.

$\Bigg\{ \oiint \; |\mathit{1\text{-}example} >$

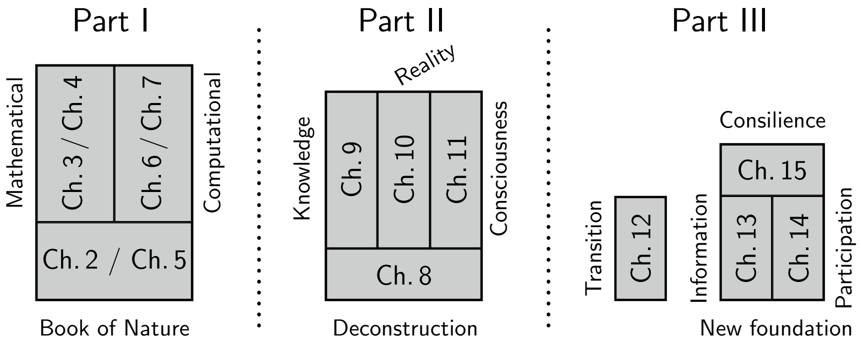
Contained within the tags, the following example equation is presented

$$\zeta := W\mathcal{D}(\mathbb{1} - W)^{-1}v.$$

$< \mathit{1\text{-}example}| \; \oiint \Bigg\}$

In any case, Part I can be fully omitted without jeopardizing the understanding of the content of Part II and the conclusions presented in Part III. However, although all three parts are designed to be independent and self-sufficient, it is perhaps worthwhile to embark on as much of the journey as possible to fully appreciate the depth, subtlety, and evolution of the thoughts leading to the concluding concepts. Without proper context and framing, the final ideas could appear uncompelling, ad hoc, and even alien.

A schematic overview of the contents of this book is found in the following figure:



In a nutshell, Chaps. 2 and 5 introduce an overview and classification of formal knowledge generation. As mentioned, Chaps. 3 and 4 discuss theoretical physics. Then, Chap. 6 introduces the nascent understanding of complexity and Chap. 7 relates this to finance and economics. Both of these chapters of Part I are stand-alone. Chapter 8 outlines the age-old questions of existence and introduces Part II. In addition, Chap. 9 details the philosophical aspects and challenges of science. Then, Chap. 10, necessarily scientific again, outlines the crisis of the modern scientific edifice and its inability to grasp the fundamental nature of reality, while Chap. 11 grapples with the enigma of consciousness. Moving to Part III, Chap. 12 looks at the current state of the world. Chapters 13 and 14 present the main thesis: namely, the emerging information-theoretic paradigm in physics and computer science, next to the information-theoretic nature of consciousness appearing in the philosophy of mind and neuroscience. Finally, Chap. 15 offers a synthesis of this novel information-based ontology and its implications for existence.

Hopefully, these attempts at making the narrative easier to access help more content to be extracted and allow for a more enjoyable experience, while minimizing the risks of getting lost in a conceptual jungle. Without further ado, the reader is invited to jump into Chap. 1.

Contents

Chapter 1
Introduction

THIS is a story about you.

IN this very moment, you are consciously reading this sentence in your mind. You are aware of your body and the world surrounding you. Your breath is flowing through your body.

EVERY day you wake up. Instantly, the memories of who you are enter your mind. You start to sense yourself and the external world you woke up to. Then you open your eyes. Everything appears familiar and unspectacular.

But how can you trust this emergence of a world? Can you be certain of the accuracy of the perceptions you are experiencing and the faithfulness of the memories in your mind? Are you perhaps just a brain kept alive in a vat in a dark room, receiving fabricated electrical impulses, stimulating it into perceive a fictitious world? Or did you never actually wake up? Are you experiencing an episode of false awakening, the phenomenon of dreaming that you woke up, where the vividness and crispness of the conscious experience trick you into believing its authenticity? Or could you be inhabiting a simulated reality, designed to emulate "true" reality? Or are you currently incarcerated in a psychiatric institution and your mind is hallucinating an entire world of fiction in order to not have to face its own pathology? The array of conceivable alternative explanations for your experience of a reality can be frightening.

IMAGINE, for a moment, that you are a member of an isolated society. You were never exposed to the collection of human ideas shaping the world today. As a child, your inquisitive mind, exploring your inner and outer reality, was never influenced by human thought traditions, spanning several millennia. You were never told any tale sourced from the competing brands of theology we today find distributed around the globe. You never felt the existential angst that can be triggered by contemplating philosophical problems related to existence, knowledge, reality, and the human mind. You never felt exalted and overwhelmed by the vastness of understanding contained within the edifice of science.

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
https://doi.org/10.1007/978-3-030-03633-1_1

How would you then explain your existence? How would you go about answering the questions “What is reality?”, “What can I know?”, and “Who am I?” Assuming a robust skeptical demeanor, you would probably arrive at a fundamental philosophical insight (Descartes 1637):

> I think, therefore I am.

The only thing you can truly be sure of is the reality of your own subjective experiences at this very moment. Everything else is questionable. Moreover, musings about the meaning of life would perhaps, in the final analysis, gravitate towards another fundamental philosophical observation, encapsulating the mystery of existence (Leibniz 1714):

> Why is there something rather than nothing? For nothing is simpler and easier than something. Furthermore, assuming that things must exist, we must be able to give a reason for why they must exist in this way, and not otherwise.

How can you ever be certain about anything? Gazing at the night sky, you would be filled with a deep longing for knowledge.

FOR centuries, people hoped that science, the abstract mathematical understanding of the physical world, would shed light on the true nature of reality. Indeed, the explanatory power of science has exploded and with it humanity’s capacity to manipulate reality. The emergence of science is a story of how the human mind gained intimate knowledge of the workings of the universe and how this expertise gave us one of the greatest gifts: the fruits of technology.

However, in an act of cosmic irony, this expanding continent of knowledge found itself surrounded by ever longer shores of ignorance. We have been able to probe the unseen subatomic world, only to discover quantum weirdness at its heart. Subatomic particles that display two contradictory properties, depending on if and how they are observed (wave-particle duality). We encountered an insurmountable fundamental physical limit on how much we can ever know about a particle (uncertainty principle). At the quantum level of reality, any certainty is lost and measurements can only be expressed as probabilities (wave function). For instance, the location of an elementary particle is probabilistic, meaning that it could be observed anywhere in the universe with a sufficiently low probability. As a result, a subatomic particle can appear at places which should be impossible (quantum tunneling). The discovery of a zoo of elementary particles and the mirror-world of antimatter revealed a far greater structure to reality anyone had dared to dream of. Empty space (the quantum vacuum) was found to be permeated with energy and nothingness became something (zero-point energy, Casimir effect). Dramatically, the very act of measuring a quantum system changes its properties, appearing to give the observer a special status (measurement problem). Indeed, some experiments suggest that the choice of an observer in this moment can alter the past (delayed choice experiments). To this day, we are baffled by the marriage of quantum entities that allows them to stay connected and be both instantaneously influenced (non-locality, violation of local realism), regardless of the spatial separation between them (entanglement).

Indeed, we are truly surrounded by perplexing enigmas. There exists an upper limit to how fast information can travel in the universe (the constant speed of light) which results in the surprising malleability of space and time (special relativity), where the passage of time can vary for each observer. Even time itself emerged as a problem child—a notion so central to our experience of reality but also so far from our intellectual grasp, as it appears to be an emergent property. At the core of reality we find no foundation. Even matter itself eludes the grasp of our minds—neither the notions of fields nor particles suffice to capture its essence. Exasperatingly, causality cannot be upheld in time alone. The question whether *A* caused *B* to happen, or vice versa, is futile. However, causality reemerges in the mystifying weaving of space and time into the fabric called space-time, an inconceivable four-dimensional atemporal reality where the borders of space and time are blurred. Now the force of gravity turns out to be an illusion, created solely by the unseen curvature of space-time (general relativity). The discovery that our universe is forever expanding at an accelerated rate (dark energy) may mark one of humanity's greatest cosmological achievements, but it is a profoundly unsettling fact. Furthermore, 95% of the contents of the universe is, embarrassingly, not accounted for in our theories of the cosmos (dark matter and energy). Then, modern theoretical (high-energy) physics has reached a dead-end, after string theory was hailed as the light-bringing savior decades ago. The list of paradoxes we are faced with goes on and on. It appears as though every explanation creates more new problems—the closer you look, the more you see. Most humblingly, the success of science rests on two miraculous circumstances. One is "the unreasonable effectiveness of mathematics in the natural sciences" and the other is the fact that simplicity lies at the heart of complexity. These are the two pillars our whole human knowledge generation rests upon. To this day, we can only shrug in the face of this cosmic design and be grateful that we do not find ourselves inhabiting a universe that is fundamentally incomprehensible to our minds.

Of all the failings of science, perhaps the most pressing is its inability to comprehend life and consciousness, going to the very core of our being. The most complex structure we ever encountered in the universe is our brain. Through it, we experience and perceive the physical world and ourselves. We are minds incarnated in flesh, able to discover and create science, enabling us to manipulate and engineer reality at will. How can that which is closest to us be so elusive? Why don't we understand the nature of consciousness? How does life encode such breathtaking complexity in a zygote which triggers self-organizing biological structure formation (embryogenesis)?

Even more troubling, there have been a multitude of cosmic coincidences happening, in order for the universe to have reached this exact point in its 13.8 billion year history, where you now happen to be reading this sentence. For instance, the perfect fine-tuning of physical constants allowing a complexly structured universe to emerge from the primordial cosmic energy soup (Big Bang); the unseen universal force driving the cosmos to ever greater structure and complexity (self-organization and emergence); the forging of heavy elements in exploding suns (supernovae), like carbon and oxygen; the special properties of water and carbon—a necessary prerequisite for life; the exact positioning of Earth in our solar system; the accumulation of (liquid!) water on Earth; the emergence of the first biological replicators on Earth; the appearance of cyanobacteria, the first organisms able to harness the energy emanating from the Sun by unlocking the secret of photosynthesis, an event marking the beginning of the terraforming of an oxygen-filled atmosphere; the self-organized engineering of complex life forms from (Eukaryotic) cells; the Cambrian explosion, an evolutionary burst 540 million years ago, filling the seas with an unprecedented diversity of organisms; the emergence of insects displaying social behaviors; at least a dozen extinction events, some resulting in the eradication of nearly all of the biodiversity on Earth, rendering the evolutionary process chaotic, highly path-dependent, and extremely unique; the extinction of dinosaurs allowing mammals to exit their niche and start world domination; and the demise of all other human species leaving one lineage as the sole conqueror of the solar system, due to the emergence of consciousness and the capacity for abstract thought—igniting language and culture—in the brain of Homo sapiens. This stunning tale of cosmic evolution, fraught with chance, has attracted very different explanations:

E1 It is all just one big coincidence and happened by pure chance. We know the fundamental laws of nature and that is all there is to say. [Materialism, scientific realism]

E2 A God created the universe in this fashion. Perhaps 13.8 billion years ago or perhaps 6,000 years ago with fictitious properties making the universe appear older (or even 5 seconds ago, with false memories implanted in all human minds). [Creationism in Abrahamic religion]

E3 Reality is a vast and impermanent illusion (*anicca*) comprised of endless distractions and suffering. The quest of the mind is to cultivate a state of awareness, allowing the illusion to be seen for what it is. Then the enlightened mind can withdraw from the physical realm and enter a state of pure bliss. [Buddhism]

E4 Only the Self exists. Life is the endless play of the Self (*lila*) losing itself only to find itself again in a constant game of hide-and-seek. [Hinduism]

E5 Only pure consciousness exists. In endless cycles, it manifests itself as separate physical embodiments, allowing for an experiential context, only to merge in unity again and start afresh. [Spirituality, panpsychism]

E6 We are dreaming this life and will some day “wake up” to a richer reality which is unimaginably more lucid and coherent. Physical death marks the transition of consciousness from the dreaming state to a higher-dimensional reality or maybe a reality entirely outside the realm of space and time. [Esotericism variation]

E7 We live in the multiverse, the infinite set of all possible universes. As a consequence, we naturally find ourselves in that corner of it which allows for intelligent and sentient life. [String/M-theory, cosmology, many-worlds interpretation of quantum mechanics]

E8 Our physical three-dimensional universe is a hologram that is isomorphic to the quantum information encoded on the surface of its boundary. [Holographic principle, AdS/CFT duality]

E9 We inhabit a simulation that has these features programmed. [Simulation hypothesis]

Every justification has its proponents, be they spiritual, religious, philosophical, or scientific. Especially explanations $E7$ to $E9$ are espoused by people who have been greatly exposed to the mathematical underbelly of reality in the form of theoretical physics or quantum computation. Of course, every angel of attack has its drawbacks. For instance:

E1 This reasoning is simply an assertion without any explanatory power.
E2 Which God (or gods)? What is the nature of God (or gods)? What causes God (or gods)?
E3 How does one experience this and how does one reach enlightenment?
E4 Who or what is choreographing this grand play?
E5 Where does this pure essence of consciousness reside and how does it invoke the physical?
E6 Who is dreaming and what is the nature of the waking reality?
E7 An unimaginably rich and transcendental structure is invoked to explain our reality.
E8 Is M-theory correct?
E9 What is the nature of the simulation and in what computational entity is it running?

As ever, certainty appears like a futile quest.

To add insult to injury, the understanding we have managed to gain about the mechanisms and processes in our brains paints a gloomy picture. Neuroscience has uncovered that our normal perception of reality is a hallucination guided only by a little external input. The conscious mind's role is to narrate and justify, in hindsight, the decisions reached by the many subconscious subroutines in the brain. Tweaking the neurochemical balance in the brain can lead to the firsthand, immersive experience of realities, radically different to the default mode of sober consciousness. These are realities that defy and transcend any conceptualization attempts and which can only be subjectively experienced—through altered states of consciousness. Many experiments have shown that the simple expectation of a particular experience changes how we perceive it, from pleasure to pain. We now also know that memories are distorted and can be false, as they are actively constructed in the very moment of remembering, rather than being retrieved from a storage archive in the brain, cataloging all past events. Other experiments have uncovered how we continuously, and embarrassingly, behave in irrational manners, while at the same time taking pride in the belief of our rational capabilities. Perhaps most troubling, and explaining a lot about the state of the post-truth world we live in today, is the following observation: Grossly incompetent people lack the skill to identify their own lack of skill, leading to an inflated and distorted self-perception, while highly competent people are troubled by doubt and indecision, resulting in a self-conscious and distorted perception of themselves (Dunning-Kruger effect).

THIS story is also a tale of our possible role in the universe, offering a novel approach to all the enigmas we are faced with—all the existential challenges that keep mocking us. It hinges on the question "Could there be something we don't yet know about ourselves and the universe, the knowledge of which could change everything?" Are we harboring erroneous concepts in the contemporary scientific worldview? Can we rectify this by exploring new ideas? For instance, the notion that the foundation of reality is based on information. Or the radical possibility that consciousness also plays a fundamental role in the universe. Can information, consciousness, and reality be braided into a unified fabric of existence?

Plato was the most famous student of Socrates, the Greek philosopher who is considered to be the father of Western philosophy. He proposed the following thought experiment, captured in an analogy called the Allegory of the Cave. It appeared in his Socratic dialogue called *The Republic*, around 380 B.C.E. In a nutshell[1]:

> The story is a description of a group of people who have lived chained to the wall of a cave all of their lives, facing a blank wall. The people watch shadows projected on the wall from objects passing in front of a fire behind them, and give names to these shadows. The shadows are the prisoners' reality. It is explained how the philosopher is like a prisoner who is freed from the cave and comes to understand that the shadows on the wall are not reality at all, for he can perceive the true form of reality rather than the manufactured reality that is the shadows seen by the prisoners. The inmates of this place do not even desire to leave their prison, for they know no better life.
>
> Like the fire that cast light on the walls of the cave, the human condition is forever bound to the impressions that are received through the senses. We cannot free ourselves from the phenomenal state just as the prisoners could not free themselves from their chains. If, however, we were to miraculously escape our bondage, we would find a different world. In other words, we would encounter another "realm," a place that is the source of a higher reality than the one we have always known.

What if you were the fortunate convict able to escape your prison of perception and discover a higher reality behind the mundane one? What if your mind could suddenly merge with a universal cosmic consciousness? What if you unexpectedly started to understand the unknowable, the ineffable, the thing-in-itself, the noumenon? Or, what if you started to receive knowledge directly from sources outside of space and time? What if God (or the gods) began to engage you in a dialogue? Even more dramatic, what if you discovered the spark of God (or the gods) within yourself? Being absolutely certain, with every single fiber of your being, of the authenticity of such truths, how would you communicate this transcendent knowledge to your ignorant fellow human beings? How would you handle the crippling solitude of being the only person bestowed with such divine insights? How then, would you continue to lead your life? Would you commit yourself to a psychiatric institution with a self-diagnosed manic psychotic break? Or, would you start to source the knowledge through yourself and try to inspire others? Perhaps some inspiration can be found in the spoken words of Alan Watts, a philosopher, psychonaut, mystic, and interpreter of Eastern philosophy[2]:

> Some people get a glimpse that we are no longer this poor little stranger and afraid in a world it never made—but that you are this universe. And you are creating it at every moment.
>
> And you see, if you know that the I—in the sense of the person, the front, the ego—it really doesn't exist, then it won't go to your head too badly if you wake up and discover that you're god.

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[1] Adapted from https://en.wikipedia.org/wiki/Allegory_of_the_Cave, retrieved December 2, 2017.

[2] See http://www.alanwatts.com/ or https://soundcloud.com/gutzeit-945453634/elias-dore_gutzeit_1#t=12s, retrieved December 6, 2017.

1.1 At a Glance

There are various options of how one can proceed with reading this book. The *User Manual*, beginning on page xv, summarizes them. In the following, Sect. 1.1.1 gives a very brief outline of the entire content and Sect. 1.1.2 a compact chapter overview. Then, Sect. 1.2 provides a more detailed summary of each chapter. Finally, Sect. 1.3 offers a content map, giving an even more detailed overview of the covered terrain, by chapter and section.

1.1.1 A Very Short Outline of the Journey

The voyage you are about to embark upon is broken down into three separate legs:

1. Part I: Climbing to the summit of the island of knowledge.
2. Part II: The downfall and the boundaries of ignorance.
3. Part III: New frontiers on the horizon.

The story evolves around human knowledge generation and ignorance, the struggle to find an island of certainty in a fierce sea of uncertainty. In a nutshell, it is the adventure of the human mind's search to understand itself and the world it is inhabiting. In other words, the age-old questions "What is reality?", "What can I know?", and "Who am I?" are tackled once again. It is a long journey building on all the achievements and failures of the human mind. In essence, it is an adventure of science and philosophy.

After reading Part I, one should be greatly awed and humbled by our mind's profound ability to make sense of a world it woke up to one day. The relentless dedication, decisiveness, and perseverance of the humans pursuing the quest for knowledge should be a source of true inspiration to us. However, after finishing Part II this exhilaration should have turned into despair. The world has stopped making sense, and cracks appeared in the foundations of reality. The very notion of certainty is in jeopardy. In the words of Albert Einstein (Einstein 1949, p. 45):

> It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere upon which one could have built.

Reality, and its material source, fractures. Time and causality lose their meaning. Our own identity is demystified. The self is a hallucination and free will an illusion. The inner world we experience is precariously detached from the outer world. The darkness of existential angst momentarily settles upon the human psyche.

Here is where Part III provides comfort and shines a novel light onto the world. A new horizon emerges, offering a new kind of knowledge—a novel understanding of ourselves and the world, that potentially can disentangle some of the mystery of being. However, in order to accept this new chapter in the history of human knowledge, a lot of conceptual baggage needs to be thrown overboard. The reader is invited to entertain notions which might feel alien and heretical—invited to rethink the most basic assumptions and most cherished beliefs about existence. The new gospel is simple: Information is the essence of reality—the substrate of existence. It has an inner aspect giving rise to subjective experience (consciousness) and an outer aspect from which the tapestry of reality is woven. The implications and conclusions of this new paradigm are truly outlandish. Here the inquisitive reader can directly proceed to the last chapter, summarizing the journey and the new insights.

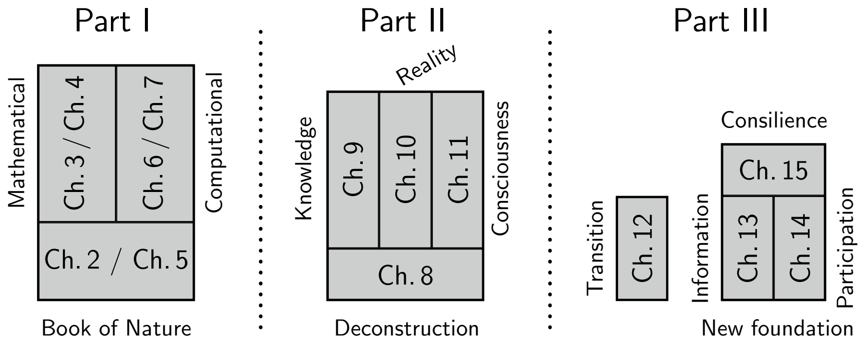
1.1.2 Chapter Overview

The adventure begins with the understanding that the Book of Nature is written in the language of mathematics. It is uncovered, how an act of translation enables the human mind to generate knowledge of the world (Chap. 2). This mechanism is elucidated by the notion of symmetry, allowing a large chunk of theoretical physics to be discovered (Chaps. 3 and 4). Analyzing the structure of knowledge uncovers a classification scheme, which orders human knowledge generation—from the understanding of fundamental processes of the universe to the complexity surrounding us (Chap. 5). A detailed description of the study of complex systems is given (Chap. 6) and its applications to finance and economics (Chap. 7).

Up to now, Part I has chronicled the success story of the human mind scaling the mountain of knowledge. Despite coming close to the summit, the apparently inevitable downfall is encountered in Part II. All the challenges vexing the human mind are outlined in Chap. 8, setting the stage for a detailed analysis in the following chapters. Chapter 9 asks, "What can I know?" Any attempts at answering this question touch upon the philosophy of science, the crisis of modern science, and the limitations of mathematics. "What is reality?" uncovers our vast ignorance of the nature our universe. Our theories fall apart, revealing a fragmented and incoherent landscape of knowledge. We are unaware of a majority of the content of reality. Moreover, under close inspection, time and matter loose their tangibility (Chap. 10). Finally, "What am I?" exposes the greatest enigma. How can a brain create subjective experiences and why? Our brains are forever locked in a dark and silent skull, constructing virtual reality simulations. The conscious mind is only a tiny island in the large archipelago of subconscious processes. Memories are also unreliable fabrications of the mind. Even the notion of an identity and free will is an illusion (Chap. 11). Part II exposes the futility and incomprehensibility of existence—the universe appears pointless, callous, cruel, and cynical. This has ramifications for society as a whole (Chap. 12).

Finally, Part III offers a novel understanding of the nature of consciousness and reality. A new paradigm emerges, built upon an information-theoretic ontology (Chap. 13). Moreover, this knowledge uncovers an even deeper reality: a participatory universe, where there exists a kinship between the mind and the cosmos (Chap. 14). In effect, the prevailing materialistic and reductionistic scientific worldview has been replaced by a novel understanding of existence, incorporating the human mind at its very core. In conclusion, Chap. 15 summarizes the entire journey and catches a glimpse of the new horizon.

A schematic overview of the content of this book is provided in the following illustration:



- Part I: The gift of knowledge. A story of how the human mind was able to unlock the workings of the universe in order to manipulate physical reality, creating technology.
  - Chapter 2: Mathematics is the language of the universe. Human knowledge generation hinges on an act of translation.
  - Chapter 3: How the notion of symmetry is one of the most powerful concepts in physics.
  - Chapter 4: Symmetry allows physics to be unified.
  - Chapter 5: A classification of knowledge. Understanding the universe with equations is only the beginning. Complexity can be tamed with algorithms running in computers.
  - Chapter 6: The new science of complexity.
  - Chapter 7: Applied complexity. Finance and economics in a new light.
- Part II: Ignorance and the limits to knowledge. The self-critique of the modern mind. The growing cracks in the edifice of the current materialistic and reductionistic scientific worldview.
  - Chapter 8: The problem of certainty. Age-old questions of existence.
  - Chapter 9: The crisis of modern science, or “What can I Know?”
  - Chapter 10: The true and uncanny nature of reality.
  - Chapter 11: The reality of subjective consciousness, or “What am I?”

- Part III: New horizons. "Could there be something we don't yet know about ourselves and the universe, the knowledge of which could change everything?"
  - Chapter 12: We live in the age of post truth, where "my ignorance is as good as your knowledge." A glimmer appears on the horizon.
  - Chapter 13: An information ontology is discovered, where information is physical and the foundation of reality.
  - Chapter 14: A participatory ontology is outlined, where the human mind and the cosmos share a kinship.
  - Chapter 15: The final summary and conclusion, glimpsing a new horizon.
- Epilogue.

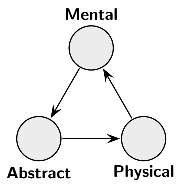
1.2 The Story in a Nutshell

1.2.1 Part I: Climbing to the Summit

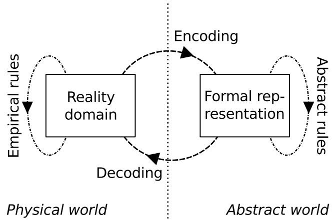
Chapter 2: In Search of the Book of Nature

The history and hallmarks of human knowledge generation are discussed. An old metaphor describing the intelligibility of the world was found in the idea of the Book of Nature, where the universe can be read for knowledge and understanding. It was realized a long time ago that the Book of Nature is written in the language of mathematics.

Philosophers and scientists have argued that this metaphor encapsulates the interplay of three distinct worlds: the abstract Platonic realm of mathematics, external physical reality, and the human mind harboring mental states. This is shown in Fig. 2.2 on Page 58:



In effect, the Book of Nature can now be rephrased with modern concepts. Quintessentially, knowledge generation is an act of translation in the human mind. Aspects of the physical world are encoded as formal representations, like mathematical equations. These abstractions inhabit an abstract world of their own and follow their own rules of consistency. The human mind can access and manipulate the formal representations in the abstract world and decode them. This happens by predicting behaviors of the physical world, from abstract insights, which then can be empirically tested. This knowledge generation process is illustrated in Fig. 2.1 on Page 45:



Modern examples of this mechanism are discussed, starting with Isaac Newton's prototypical physical theory of classical mechanics. The interplay between mathematics and physics is examined and some aspects of mathematics analyzed. Several biographies are presented.

Philosophers and insightful scientists realized that this intimate interplay of the human mind with the workings of the universe poses mystifying challenges. In essence, three worlds are interacting: the physical, the mental, and the abstract. More sober scientists have declared "Shut up and calculate!" and circumvent such philosophical artifacts by focusing on the formalism.

On a technical note, the contents of this and the two following chapters are necessarily laden with mathematical symbolism. In order for the non-mathematical reader to still be able to follow the narrative, a precaution is taken. All of the more involved equations are clearly delimited, allowing the reader to avoid these abstract pitfalls. To this aim, special attributed tags are introduced, denoted by $\{\oiint \ldots \oiint\}$, which encapsulate the mathematical formalism. See also the *User Manual* on Page xv.

Chapter 3: The Semantics of Symmetry, Invariance, and Structure

A case study of how the notion of symmetry underpins modern physics. The intuitive idea of symmetry is formalized as a mathematical concept (group theory). Now it becomes an ideal vessel for encoding aspects of the physical world in abstract terms, illustrating the act of knowledge generation via translation.

Symmetry can be intuitive and elusive at the same time. Obvious and straightforward notions related to it can result in deep mathematical structures being uncovered, which mirror the workings of the universe. Namely, invariance, the concept that the manipulations of a system leave it unchanged. For instance, rotating an unmarked cube by 90° along any of its three axes leaves it indistinguishable from its original orientation. The cube is invariant under such transformations. Requiring that the outcome of a physical experiment should not depend on the time and location it is performed at can be expressed mathematically as invariance. In detail, the invariance of physical theories under changes in space and time result in conservation laws, specifically the conservation of momentum and energy in the universe. This theme goes to the heart of theoretical physics (Emmy Noether's theorem). The fundamental symmetries of space-time are encoded as a mathematical group and give rise to fundamental laws of nature. Moreover, physical particles, so elusive to our senses and intuition, transform according to yet another symmetry group, giving us an analytical lever to manipulate them. Finally, the very relation of space and time, encoded in a transformation, results in a maximum speed of causality, which is confined to be the speed of light by invariance.

In order to understand the importance of group theory in physics, the mathematics of geometry are introduced. Classical mechanics is rediscovered in the generalized formalism of the Euler–Lagrange equation. Also, elements from quantum theory, quantum field theory, philosophy, and history are discussed throughout the chapter.

The notion of conserved quantities has an ancient history in Greek philosophy (Parmenides, Heraclitus, Anaximander, Leucippus, and Democritus). It is related to the concept that nothing can come from nothing and that reality is composed of indivisible, indestructible, and eternal atoms. A similar concept of atoms is found in the Indian religion of Jainism, a radically non-violent tradition which shares in its cosmology many of the elements of pre-Socratic Greek philosophies.

Chapter 4: The Unification Power of Symmetry

Inspired by the success of Albert Einstein's general relativity, Hermann Weyl introduced a new kind of symmetry in 1918. It was called gauge symmetry and the corresponding notion of gauge invariance lead to the discovery of gauge theory, a pivotal achievement in theoretical physics. This would then revolutionize the understanding of all three non-gravitational forces in the universe. In essence, the discovery of a novel local type of symmetry would allow the standard model of particle physics to be formulated, decades later. Going beyond this edifice, modern unification efforts in physics extend those notions of symmetry in what is know as superstring theory.

The principle of covariance was one of Einstein's main ingredients for the theory of general relativity. It rests on a benign assumption of symmetry: the contents of a physical theory should not depend on the choice of coordinates required to express and compute the theory. In other words, physical laws are invariant under coordinate transformations. This commonsensical requirement is one of the two cornerstones of general relativity. The second one being the principle of equivalence: it is impossible to distinguish the force of gravity from the effects of acceleration.

The history of gauge theory was a meandering story that led to the uncovering of a new layer of reality below the phenomena of electromagnetism (electromagnetic potential, Aharonov–Bohm effect). Theories were formulated, which lay dormant for years, and nearly forgotten, before they came to prominence and paved the way to a new understanding of the universe (Yang-Mills theory). Indeed, many theoretical hurdles had to be overcome before a successful marriage of gauge theory and quantum field theory culminated in the standard model of particle physics. For instance, the Higgs mechanism, a mathematical machinery designed to generate mass terms in the theory via spontaneous symmetry breaking.

However, the standard model marks only the beginning of a unified theory. The Holy Grail of physics is seen as the unification of the standard model with gravity, in a overarching theory of quantum gravity. Physicists attempts to reconcile their fragmented theories has led to many esoteric postulations about the nature of reality. For instance, the existence of unseen extra spatial dimensions, rendering our universe a higher-dimensional behemoth. An idea first introduced by Theodor Kaluza and Oskar Klein, it saw its coming of age in ten-dimensional and 26-dimensional variants of superstring theory. Moreover, the adjective "super" in superstring theory refers to yet another novel symmetry attached to nature, relating bosons (the force-carrying particles) to fermions (the matter particles: quarks and leptons).

Whole new branches of mathematics (algebra, topology, geometry, and group theory) were forged in order to reconcile the splintered landscape of theoretical physics in a unified theory. The resulting attempts culminated in M-theory, the eleven-dimensional unification of the five existing ten-dimensional superstring theories, approximated by the theory of supergravity at low energies.

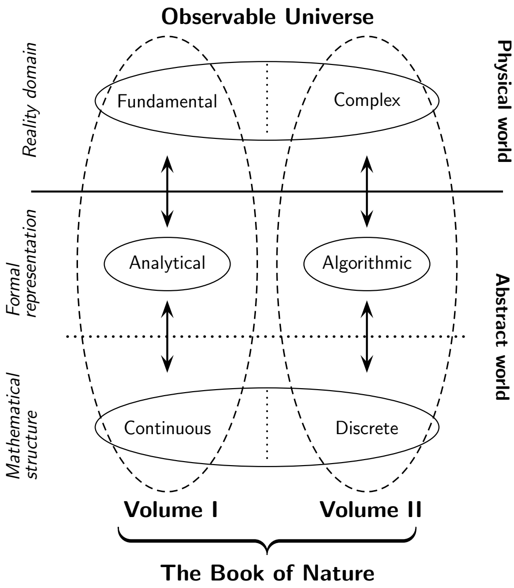
Despite the enormous experimental success of the standard model, string/M-theory has to this day produced no (falsifiable) predictions. Indeed, Einstein already failed at formulating a unified field theory in his final years. Being arguably the most influential physicist (the Nobel Prize-winning photoelectric effect, special and general relativity), he struggled with the reality and implications of quantum mechanics and spent the years from 1928 to his death in 1955 grappling with his unified field theory.

A brief detour through the history of quantum mechanics and quantum information is included.

Chapter 5: The Two Volumes of the Book of Nature

The age-old dream that mathematics represents the blueprint for reality has become fulfilled: the Book of Nature is intelligible to the human mind. Consider the notion of symmetry. Expressed mathematically, it is foundational to physics and runs through its fabric as a common thread. This is an example of how knowledge generation is the result of an act of translation: the human mind encodes reality domains into formal representations and is able to make predictions about the workings of the universe (decoding).

As it happens, this way of categorizing knowledge is only the beginning. In other words, what has been called the Book of Nature is in fact only Volume I in a greater series. Chapter 5 attempts to outline this Weltanschauung. The resulting picture is captured in Fig. 5.8 on Page 171:



It rests on three classifications which are introduced and elucidated in detail:

1. The distinct reality domains: fundamental/complex.
2. The nature of the formal representation: analytical/algorithmic.
3. The structure of mathematics: continuous/discrete.

From this, two dichotomies of understanding emerge:

1. The *fundamental-analytical*, found in Volume I of the Book of Nature.
2. The *complex-algorithmic*, describing the recently discovered second volume.

In a nutshell:

VOLUME I The *fundamental* reality domains (mostly pertaining to the quantum and cosmological levels of reality) are made accessible to the mind via *analytical* formal representations (equations). This relates to physical science.

VOLUME II Real-world *complexity* (from inanimate self-organizing structure formation to emergent phenomena like life and consciousness) is encoded via *algorithmic* formalizations (algorithms and simulations running in computers, they themselves being a gift found in Volume I). This relates to complexity science.

Following this categorization of human knowledge, the success, paradigms, and limitations of fundamental processes and complex systems are outlined. Most crucially, both volumes of the Book of Nature rely on two specific miraculous circumstance for their success:

VOLUME I The power of human formal thought systems: "The unreasonable effectiveness of mathematics in the natural sciences" (Eugene Wigner). See Sect. 9.2.1.

VOLUME II Complexity arises from simplicity: "Some of the very simplest programs that I looked at had behavior that was as complex as anything I had ever seen. It took me more than a decade to come to terms with this result, and to realize just how fundamental and far-reaching its consequences are" (Stephen Wolfram). See Sect. 5.2.2.

In this context, chaos theory, fractals, agent-based simulations, and complex networks are discussed.

Relating to historical circumstances, this part of the journey takes the reader to the new science of networks, starting with sociological experiments ("the strength of weak ties", "six degrees of separation") and culminating in the discovery of small-world and scale-free networks, appearing everywhere in nature and human affairs, at the turn of the millennium.

Contemplating the two dichotomies of fundamental-analytical and complex-algorithmic knowledge generation, the following question arises. What about the two other possible modes of understanding? Namely, the fundamental-algorithmic and complex-analytical categorizations. It is discussed how these two play a minor role in the Book of Nature.

Finally, the deepest layer in Fig. 5.8 is discussed, relating to the structure of the mathematics underlying the two dichotomies (i.e., Volume I and II). In this sense, mathematics is the ultimate unifying theme of all human knowledge of the universe. Specifically, mathematics can be delimited into two subject matters: the continuous and the discrete. This schism has its philosophical roots in ancient Greece and is also related to the conflicting notions of the finite and infinite. The history of continuous mathematics is recalled, starting in Greece, moving through the Protestant Reformation and the Middle Ages, and ending today. In essence, the multifaceted mathematical tool of the derivative, a cornerstone of continuous mathematics, appears in all of physics.

Discrete mathematics, the antipode of the continuous, also has an ancient history. However, the concept only really came to prominence in the context of information theory and computation. One specific area of discrete mathematics emerged as the cornerstone for the description of complex systems: graph theory (developed by Leonard Euler, one of the most prolific mathematicians of all times). Similar to the derivative playing a prominent role in Volume I of the Book of Nature, the graph is an essential formal concept, encoding complex systems in Volume II.

Chapter 6: Volume II: The Simplicity of Complexity

So, what is written in Volume II of the Book of Nature? What exactly is complexity science? And how does the science of simple rules work?

Complexity theory is not a single discipline, but an amalgamation of different fields of study. It has a long history, starting in the 1960s with cybernetics. Other influences came from systems theory, artificial intelligence research, non-linear dynamics, fractal geometry, and chaos theory. Today, a major discipline of complexity science is complex systems theory. A complex system is comprised of many interacting elements. Here the relevance of simple rules of interactions becomes visible. Moreover, a complex system can be formally represented as a complex network.

From a philosophical perspective, structural realism argues that, in fact, only relations are relevant. In other words, the network of interactions is key. This has, however, been contested by some philosophers of complexity, who favor poststructuralism, a variant of postmodernism. In a nutshell, complexity science invites a systemic and holistic paradigm, abandoning the prevalent, and thus far successful, reductionist thinking. It is characterized by decentralization and a bottom-up approach to the understanding of reality.

Complex networks are ubiquitous and found in many different domains, from the living to the non-living. The research on complex networks has exploded in the last decades. This development happened hand in hand with the emergence of data science, providing the empirical foundations. Complex network analysis can be applied at different levels of resolution and detail.

A scaling law describes a simple functional relationship. A change in input results in a proportional change in output. Albeit being an elementary mathematical expression, scaling laws describe a vast amount of natural phenomena. In effect, scaling laws can be understood as laws of nature describing complex systems. There exist four types of scaling laws. Allometric scaling laws describe how the properties of living organisms change with size. For instance, heavier animals live longer and have slower heart-rates than lighter ones. However, the actual number of heart-beats per lifetime is constant across mammals. Then, scaling-law distributions characterize many phenomena, in contrast to a normal distribution. In essence, most members of a population are irrelevant in scaling-law distributions, whereas a select few are disproportionately important. There is no preferred scale, resulting in scale-invariant behavior. A myriad of phenomena obey such a distribution. Furthermore, scale-free networks incorporate scaling laws in their topology. Again, many such networks can be found in nature. Finally, cumulative scaling-law relations describe how properties appearing in time-series are related. Especially, in financial data. Historically, scaling laws are associated with the Pareto principle, Zipf's law, and Benford's law.

Chapter 7: Applied Complexity: Finance and Economics in a New Light

In the past 500 years, humanity has created a single world order based on the interplay of science and technology, industry and economics, and military interests. In essence, our species has merged into one global network of human activity. The understanding of the structure and functioning of this super-system is perhaps the single most important goal to ensure equitable future prosperity, in economic and ecological terms.

The mathematization of finance began in the year 1900 and involved some eminent physicists. It was centered around the concept of a stochastic process. 97 years—and many equations—later, the Nobel Memorial Prize in economic sciences was awarded for the Black-Scholes model, leading to a financial crisis and bank bailouts. At the center of this mathematical evolution stood (and stands) the quantitative analyst, often recruited from physics.

Perhaps the single most influential ideological influence came from the Chicago School, promoting the neoclassical brand of economic thought, giving birth to the doctrine of neoliberalism around 1980. Today, neoliberalism is the world's dominant economic paradigm, favoring decentralization and privatization. Many economists have criticized this concoction of mathematical opacity, laissez-faire economics, belief in efficient markets and human rationality, lack of empirical foundation, and missing governmental oversight as the root cause of the housing bubble, which turned into a global financial crisis, and eventually a sovereign debt crisis.

In contrast, complexity science offers a new paradigm to understand financial and economic systems. Yet again, networks of interaction are the the heart of the solution. Complex dynamic systems, based on empirical observations, including feedback loops and non-linear behavior, replace idealized and arcane mathematical wizardry, based on very stringent assumptions. One specific approach employs agent-based models to decode financial markets. Another one utilizes centrality measures in the global ownership network to estimate corporate power.

The history of finance and economics is closely tied to the rise of European imperialism. Capitalism is based on the trust in the future, allowing for progress. One vision of this, advocated by neoliberalism, sees unapologetic and unrestrained human self-interest at the core of the engine generating collective wealth. However, greed and fraud are very seductive. They promise short-term enrichment but threaten the long-term formation of an equitable and sustainable society, living in ecological balance with the biosphere supporting life on Earth. Indeed, the banking sector has a notoriously bad reputation when it comes to financial scandals. Greed and fraud appear to be a systemic affliction of the profession. Buddhism, at its core, identifies insatiable greed as one of the main causes of human suffering. Happiness economics appears to agree. Moreover, confronted with one's own death, a life spent with meaning and social interactions appears to outmatch a life solely filled with material wealth.[3] In stark contrast, evolutionary (and mathematical) biologists see cooperation and altruism as the successful templates and driving forces of sustainable collective well-being, outperforming selfishness and egoism.

Today, eminent economists identify the accelerated increase in global inequality as one of the greatest threats to future prosperity—economic and ecological. Even some billionaires agree that they profit from a system which is not sustainable. Looking into the future, a paradigm change could be underway, with the potential to disrupt all financial and economic interactions. It is initiated by a change in the architecture of our man-made systems. A new blueprint, favoring decentralization, is beginning to replace the predominant design pattern: the tribal pyramid of power. Motivated by insights from complexity science, these new systems have the potential to exhibit self-correcting, sustainable, and resilient behavior. In detail, the emergence of a distributed, fail-proof, and tamper-proof public ledger, enforcing transparency, security, and auditability by design, is driving the revolution. Distributed ledger technology is the great innovation at the heart of the nascent rise of Bitcoin.

[3]Based on statements of US citizens requiring palliative care.

1.2.2 *Part II: The Downfall*

Chapter 8: A Brief Story of Success: The Manifestation of Knowledge and the Hydra of Ignorance

The quest to comprehend the world we live in has taken the human mind on a true odyssey—it is a spectacularly successful story of knowledge generation. Ignorance is dispelled and the unveiling of knowledge is driving the acceleration of modern technological advances. All seems comprehended and we are tempted to close the Book of Nature with satisfaction. However, in an astonishing, unexpected, and momentous plot twist, the anticipated ending of this narrative opens up Pandora's box of existential dilemmas, ontological paradoxes, and epistemic uncertainty. Ominous clouds appear on the horizon.

First of all, uncertainty viciously raises its head—again. Throughout the history of thought, uncertainty could never be banished. The most developed theory of ignorance in modern philosophy is that of Immanuel Kant. His epochal classic *Critique of Pure Reason* argues that we can only ever know things as they appear to us and never the things as they are in themselves. Furthermore, the question of "Why is there something rather than nothing?" truly represent one of the hardest enigmas of existence. Finally, all the cosmic coincidences which had to occur in the evolution of the universe for this exact moment in time to transpire raises more mind-numbing challenges. We are confronted with issues relating to teleology, entelechy, creationism, and the notion of a simulated reality.

In summary, the core enigmas of existence can be phrased as three questions:

1. What can I know? (Chap. 9)
2. What is reality? (Chap. 10)
3. What is consciousness? (Chap. 11)

And so the grand narrative of the world continues to unfold, albeit in a very unexpected direction.

Chapter 9: Philosophy and Science: What Can I Know?

The spectacular display of human technological prowess seen today is a testimony to the success of the human mind in deciphering the workings of the universe. Science works! But how exactly and why? The philosophy of science outlines the failure of the attempts to explain, structure, and justify science. Beginning with logical empiricism and critical rationalism, the efforts to systematize the scientific method based on common sense failed. Inductive and deductive reasoning suffer from conceptual problems. Thomas Kuhn influentially argued that science progresses by virtue of sudden, unforeseeable disruptions, called paradigm shifts. Science is not a linear accumulation of knowledge and it is greatly influenced by socio-cultural aspects and the idiosyncratic preferences of scientists. Abandoning the hope for a single universal truth, postmodernism focuses on ambiguity and diversity. Indeed, modern theoretical physics appears to have reached a threshold, where meaning, clarity, and understanding are in jeopardy. Then, constructivism argues, once more, that social and cultural conditions shape knowledge. Finally, relativism appears to undermine any structured knowledge of the world. The influential and controversial philosopher of science, Paul Feyerabend, continually challenged the scientific establishment. He was dubbed “the worst enemy of science.” Perhaps Feyerabend was profoundly misunderstood, as he wholeheartedly embraced science but rejected the claims of its rational and structured nature.

Looking at the evolution of science, the emergence of modern science marks the begin of a deep crisis, beginning in 1901. Nearly every postulate of classical science was overthrown by the new physics and replaced with bizarre new concepts, from the elusive quantum fluctuations to the fabric of space-time. The aftershocks of this fundamental transformation still echo to this day. Quantum theory represents one of the greatest conceptual enigmas ever to have challenged the human mind. Perhaps even more pressing is then the question relating to the comprehensibility of the universe. Why can the mind unlock the secrets of reality? This question continues to baffle many great scientists and philosophers. Finally, is the end of science in sight? Is science being undermined by the all-too-human nature of scientists? Is scientific progress grinding to a halt? Paradoxically, as each question about the workings of the universe gets answered, new and harder questions emerges. An observation many scientists agree upon. In effect, ever more knowledge is uncovered, but it only represent an infinitesimal progress in understanding. If asked, some scientists will admit to these shortcomings: uncertainty and ignorance are inherent and ubiquitous.

Finally, even mathematics, allegedly the pristine body of knowledge containing aesthetic and timeless truths, turns out to be severely limited. Not only is mathematics incomplete (Kurt Gödel’s famous theorems) but it is fundamentally plagued by randomness. The mathematician proving this statement, thus continuing Gödel’s haunting legacy, radically compared mathematics to zoology. Indeed, hyper-abstract modern mathematics also suffers from the loss of meaning, clarity, and understanding. Such insights do not bolster the confidence in any enterprise relying on mathematics.

In the final analysis, it seems as though the edifice of human knowledge is a shifting, ad hoc, and fragmented structure, lacking any clear foundation and overarching and unifying context. Mathematics and science appear to be true by accident.

Chapter 10: Ontological Enigmas: What is the True Nature of Reality?

Physics has reached a dead end. All the successful theories describing the intimate workings of reality turn out to be incomplete and incompatible fragments of knowledge floating in the void of the unknown. Under closer inspection, the impressive theories of the universe unravel. The whole monumental structure of knowledge falls apart like a house of cards. We are left with a frustratingly long list of unsolved mysteries—from the bizarre quantum level of reality to the vast cosmos, of which 95% of its content is still unknown to the human observer. Moreover, the most accurate theories fail miserably at the borders of their domain of comfort. Even worse, it turns out that the human mind has cultivated the wrong intuitions about reality. But perhaps the hardest blow comes from quantum physics. The realm of the very small displays behaviors which transcend our conceptions of reality—even after over a century of grappling with its interpretation. So too does the cosmic fabric. Space, time, and matter are found to be ineffable qualities of a formerly comprehensible universe. Determinism, causality, materialism, the past and the future, definiteness, and an objective and a mind-independent world seem like the dreams of an unattainable paradise. Ironically, the mind is allowed to transform the knowledge fragments it is given into powerful technology, but it is not permitted to peak behind the curtains of reality. The ontology of reality is not comprehensible to the human mind. Our best efforts at extending our knowledge—in the guise of a theory of quantum gravity—have all been unsuccessful. The Book of Nature turns out to be an incomplete translation. The original appears to be written in an alien language, unintelligible to us, hiding vastly greater knowledge from the our mind. It is then perhaps no wonder that some great physicists became enticed by mysticism and spirituality at the end of their lives.

Chapter 11: Subjective Consciousness: What am I?

Philosophers have been debating consciousness since the birth of philosophy. Until recently, the very notion of consciousness was excluded from any scientific investigation. Today, philosophers of the mind, neuroscientists, and cognitive scientist agree that consciousness is one of the biggest enigmas. On the one hand it is so intimately familiar to us. Indeed, we all appear to be self-determined consciousness—a self with free will. On the other hand, linking the ethereal mind to tangible physical processes in the brain is a hard problem. Solutions come form an outright denial of the reality of consciousness to viewing reality as goal-driven and caused by a transcendent agent. Something has to give. The inner world we experience is precariously detached from the outer world.

Insights from neuroscience speak of the limited capabilities of the conscious mind. Consciousness appears to be a narrator reacting in hindsight to decisions made in the vast subconscious mind. The perception of the outer world is based on a constructed simulation, rather than reflecting objective truths. The sense of self is also an intricate construct of the mind which can be damaged. Memories are not archived but are constructed on the fly. Beliefs, morals, and ethics have a biochemical component and also depend on the biologically evolved "hardwiring" in the brain. Human behavior is demonstrably irrational and we are blind to a huge number of cognitive biases. We can be easily be manipulated without ever knowing. Then, our brains and minds can fall apart. A dramatic number of psychopathological disorders have been documented. Sometimes a brain trauma unlocks genius traits. Split-brain patients experience their unified self divide into two separate streams of independent consciousnesses.

The notion of free will appears highly problematic. From quantum mechanics we get two radically opposing options: either there is no free will in the universe or everything, including elementary particles, has free will. Neuroscientific experiments demonstrate the lag between the time a subconscious decision is made and the time the conscious narrator is informed about the decision.

These are today's challenges arising at the borders of knowledge, enigmas that are mostly swept under the carpet in a pragmatic attempt to conduct business as usual.

We face a gloomy dichotomy: the emergence of an astonishing body of knowledge—accurately decoding the workings of the physical world and fostering technological progress at breathtaking speed—is eclipsed by paradoxes, ambiguity, and incoherence. The true nature of reality is as elusive and mysterious as ever, we are missing the foundations and cohesion of science, and the problem of subjective experience dramatically exposes our profound ignorance. Is this a world doomed by uncertainty? Do we really live in a cynical universe, which reveals itself to the human mind just as far as to awaken the false hope in its comprehensibility and then leaves us forever in a state of epistemic and ontic nihilism? Was the Book of Nature simply a grand and elaborate farce?

Perhaps things are not what they appear to be. Maybe there is something we don't yet know about ourselves and the universe, the knowledge of which could change everything.

1.2.3 Part III: A New Horizon

Chapter 12: The Age of Post-Truth

The human mind lost all guidance form science and philosophy. An existential threat emerged, relating to the fundamentally incomprehensible nature of reality and consciousness. We are left with amazing technology, which we unfortunately and astonishingly keep utilizing to destroy the entire biosphere sustaining all life on Earth. Untethered, ignorance and anti-intellectualism abounds. Conspiracy theories are popular across a wide demographic. Conflicting beliefs result in a gridlock that is paralyzing our world on at every level. Sociopolitical, cultural, theological, philosophical, and scientific wars are waged.

But perhaps things are not as bad as they appear. We are slowly seeing the emergence of a new age. We have the first blueprints for decentralized economic interactions with the potential for collective intelligence—adaptability, resilience, and sustainability. Overall, the universe appears to be guided by an invisible force driving it to ever higher levels of self-organized complexity.

The voices presented in this book are intended to help this malaise. Motivated by scientific utilitarianism and radical open-mindedness, we are invited to rethink all our assumptions about reality and consciousness. A new horizon emerges, offering a firm foundation for existence. In the following chapters, the notions of information, consciousness, and reality will be braided into a novel unified fabric of existence. This is the final quest of the human mind: facing its own existence.

Chapter 13: A Universe Built of Information

We are currently witnessing a paradigm shift—perhaps the profoundest one to ever occur. The human mind is invited to sacrifice one of the most successful conceptions of understanding: the materialistic and reductionistic scientific worldview. This commonsensical idea, that at the core of reality lies a tangible essence from which the universe is constructed, no longer seems adequate. Guided by a small anomaly that was discovered in the 1970s, many branches of theoretical physics—including quantum gravity variants—and theoretical computer science are converging to uncover a novel unified picture. Information is physical. In other words, the seemingly intangible notion of information has clear physical consequences. For instance, information cannot be erased without the universe taking note (by registering an increase in entropy). Information theory, giving birth to the bit and our current digital computational revolution, is the first theory quantizing information.

Two great physicists and pioneers of modern theoretical physics—John Wheeler and Carl Friedrich von Weizsäcker—suspected that information was the ultimate nature of reality. "It from bit" popularizes this view. Indeed, the intractable conceptual issues related to the interpretations of quantum mechanics reemerge in a new light, once framed in a quantum-computational framework. Digital physics is a contemporary movement advocating this information-centric worldview. In essence, it argues that reality is inherently finite. Only in our formal mathematical theories do we encounter infinity. There is a fundamental limit—one bit per Planck area—to how much information can be stored anywhere in the universe.

Perhaps the most persuading hints come from the study of black holes. In 1974, Stephen Hawking discovered a property which challenged the laws of quantum mechanics. The crux was related to information loss. Today, this topic is still relevant and passionately debated. A key insight from string/M-theory entered the picture. As a result, all the cutting-edge theories speak of a holographic universe. Our familiar three-dimensional reality appears to be fictitious, emerging from the information encoded on a two-dimensional area. Moreover, space and time seem to be emergent properties arising from pure quantum entanglement. The final faction joining the struggle is theoretical computer science. Now it is as though computational complexity is driving the evolution of this information-theoretic reality. Given the potential of such an outlandish information-theoretic ontology, it comes as no surprise that some scholars have taken the next bold step. They suspect reality itself being a vast simulation.

The metaphor of the Book of Nature was a misguided thought. It seems that at the core of reality we find a computational engine which needs to be fed with information. The "Book of Nature" should be closer to a computational device in which the algorithms of reality are encoded. The static physical "pages" are replaced with a dynamic and fluid "display."

Chapter 14: The Consciousness of Reality

Information lies not only at the heart of objective reality, it is also intimately connected to subjective consciousness. In a final radical step, the information-theoretic paradigm shift unearths a participatory ontology. Consciousness is seen as primal and universal—a fundamental building block of the cosmos. A series of taboos is being broken and blind spots exposed, all inherently contained within the current materialistic and reductionistic scientific worldview. The question "Could there be something we don't yet know about ourselves and the universe, the knowledge of which could change everything?" is beginning to be answered. From subjectivity, spirituality, Eastern contemplative wisdom, shamanic traditions, psychedelics, and paranormal and psychic phenomena, the human mind is invited to reframe and reassess such notions. Such disruptive thinking within the Western mind goes back to Immanuel Kant. Contemporary scholars, like John Wheeler and Richard Tarnas, agree: we inhabit a participatory universe.

Hints are found in the emergence of non-localized and non-sentient intelligence, peer-reviewed studies in physics journals, and reports from psychonauts. In essence, many pioneers of quantum mechanics had always argued for such a participatory ontology. However, blinded by the current paradigm, which—confidently and with great certainty—deems what is heresy and not, certain elusive phenomena could have escaped our collective attention. While, for instance, infinite parallel universes, higher-dimensional space-time, and the denial of the existence of consciousness lie within the orthodoxy, the notion of a mind-matter link is off-limits—seemingly only espoused by the deluded, the fraudulent, or the incompetent. However, guided by the first formal approach to consciousness, based on information, new terrain is being charted. By welcoming the participatory ontology, reality and consciousness appear in a new light, offering novel understanding to help answer age-old questions of existence.

Chapter 15: Consilience

This is the last chapter in the human mind's quest for understanding. As it is itself a summary of the entire journey, the reader is invited to directly continue there. Final thoughts and outlooks are provided.

1.3 Chapter/Section Content Map

Part I: Climbing to the Summit

Chapter 2: In Search of the Book of Nature

The Book of Nature is an ancient metaphor describing humanities quest to understand the universe it inhabits. The philosophical notion is that nature is a book to be read for knowledge and understanding. Beginning with the scientific revolution over 300 years ago, it became apparent that the language of the Book of Nature is mathematics. Thus science can be understood as the challenge to capture the processes of nature within formal mathematical representations. This "unreasonable effectiveness of mathematics in the natural sciences" raises philosophical questions.

At the heart of this knowledge generation process lies an act of translation. Aspects of the physical world are encoded as formal representations. Once such abstract renderings are found, they can be manipulated by the human mind. Finally, new insights are decoded back into the physical world and their predictions can be experimentally tested.

– Section 2.1: A Modern Edition of the Book of Nature

Examples in the Book of Nature are presented: Newton's classical mechanics and electrodynamics, next to mathematical physics and new mathematics from physics.

– Section 2.2: Seeking Meaning

Philosophical implications are discussed. For instance, the existence of a Platonic realm of abstractions. This is placed within the context of the philosophy of mathematics. Bertrand Russel's paradox and Kurt Gödel's two incompleteness theorems, disrupting the foundations of mathematics, are encountered, next to some biographical elements from the lives of Srinivasa Ramanujan and Paul Erdős.
In essence, there exist three worlds : the physical world, accommodating the mental world of the human mind, which discovers or creates the abstract world of formal thought systems. The success of human knowledge generation rests on the peculiar fact that the abstract world mirrors the structures of the physical world. The questions of scientific realism and structural realism are touched.
Many scientists are, at best, uncomfortable when confronted with philosophical challenges. This sentiment finds its expression in the physicists rallying cry "Shut up and calculate!"

Chapter 3: The Semantics of Symmetry, Invariance, and Structure

The notion of symmetry , formally encoded as a principle of invariance, is singly one of the most powerful mathematical tools in unearthing novel and deep insights into the structure of the universe. Symmetry, expressed as invariance, essentially means that certain manipulations of a system leave it unchanged. This property can be encoded mathematically in the language of group theory. The tragic story of Évariste Galois is told, the founder of the theory.

– Section 3.1: Symmetry in Action: Conservation Laws

Another example in the Book of Nature is presented: conservation laws. Theses have an ancient history and a deep meaning in physics. In a nutshell, if a system possesses symmetry properties, then there exist quantities that are conserved in time. This profound theorem was proved by Emmy Noether. For instance, the invariance in time of a theory's symmetry (in plain words, the outcome of a physical experiment should not depend on the time it is performed at) results in the conservation of energy in the system it describes.
In order for this property to emerge, more mathematical abstractions are needed, in the guise of geometry. It is seen that classical mechanics can be rephrased in a geometric language introduced by Leonard Euler and Joseph-Louis Lagrange. A new quantity emerges in physics: the Lagrangian. It appears in many branches of theoretical physics (electromagnetism, the standard model of particle physics, and general relativity).
Returning to the notion of symmetry, Sophus Lie revolutionized its understanding, by introducing Lie groups and algebras. This allowed the purely mathematical concept of symmetry to enter physics, as groups can be represented by matrices that act as operators on quantum systems. Finally, some elements of quantum mechanics and quantum field theory are discussed and linked to representation theory.

– Section 3.2: Symmetry Manifested

Some concrete examples of the successful application of symmetry are described. By expecting the universe to be consistent and make sense to all observers, space and time have to be mixed. The resulting transformation, introduced by Hendrik Lorentz, encodes this peculiar behavior. Invariance under this symmetry results in the constant speed of light being the maximal speed for causality to propagate in the universe. Lorentz set the foundation for Albert Einstein to develop the theory of special relativity. This lead to the introduction of four-dimensional space-time, formally described by a Minkowski space.
The Lorentz transformation can be further formalized, yielding the Lorentz group. It encodes the fundamental symmetries of space and time. As a result, the behaviors of electromagnetism, special relativity, and all quantum fields are encoded via this formal representation. Finally, the Poincaré group extends the Lorentz group. All known physical particle states are described by this abstract mathematical framework, built from the notion of symmetry.

Chapter 4: The Unification Power of Symmetry

All the previously encountered instances of symmetry are expressions of global symmetry principles. In other words, these types of symmetry do not change at different locations in space-time. In 1918, a new local symmetry was introduced, leading to the development of gauge theory, a pivotal achievement in theoretical physics. This new type of symmetry would allow the standard model of particle physics to be formulated, decades later.

– Section 4.1: Back to Geometry: The Principle of Covariance

Einstein's theory of general relativity , describing gravity, rests on two assumptions. The principle of equivalence states that it is impossible to distinguish the force of gravity from the effects of acceleration. Einstein called this the "happiest thought of his life." The principle of covariance is the second ingredient. At first sight, it appears rather dull. The choice of the coordinates, required to make the elements of the theory computable, should not influence the content of the theory. In other words, physical laws are invariant under coordinate transformations. Unexpectedly, this leads to a deep mathematical formalism known as covariance. Specifically, the covariant derivative and Christoffel symbols.

– Section 4.2: The History of Gauge Theory

Inspired by the success of Einstein's general relativity, Hermann Weyl introduced a new kind of local symmetry in 1918. It was called gauge symmetry and the corresponding notion of invariance was introduced via the gauge-invariant derivative. Originally, Weyl applied his theory to electromagnetism. This attempt failed. However, with the developments of quantum mechanics, he successfully re-applied the ideas, leading to the formulation of gauge theory. Later on, this would lead to the development of Yang-Mills gauge theory.
Initially, quantum field theory and gauge theory were plagued by major problems. This "Dark Age" of theoretical physics was ended by the development of novel mathematical tools, collectively called renormalization.
A final hurdle in the formulation of the standard model of particle physics, a Yang-Mills gauge (quantum field) theory, was the problem of mass. The symmetries of the theory are only upheld if it describes massless particles. The final ingredient solving this issue is the Higgs mechanism of spontaneous symmetry breaking.

– Section 4.3: The Road to Unification

Unification is the Holy Grail of physics. It is the attempt to consolidate all physical theories in one single overarching framework. The "theory of everything" is the immodest name given to the postulated unified quantum field theory describing all known forces in the universe (the three non-gravitational ones unified in the standard model plus gravity). To this day, it is still an elusive dream.

An early successful attempt at unifying electromagnetism with gravity was found in Kaluza-Klein theory. This was achieved by moving to a five-dimensional space-time. A mechanism called compactification describes how our four-dimensional reality reemerges from the higher-dimensional theory.

A next attempt was string theory, an accidental discovery. It was originally formulated in a very different context unrelated to unification. At its core, the theory postulates that elementary particles and force carrying particles are not point-like (i.e., 1-dimensional) but extended 2-dimensional entities, akin to strings. For string theory to be mathematically consistent, it requires esoteric postulations about the nature of reality. For instance, the existence of unseen extra spatial dimensions, rendering our universe an eleven-dimensional structure. Moreover, a totally novel symmetry is proclaimed: supersymmetry. Now bosons (the force carrying particles) and fermions (the matter particles: quarks and leptons) are the two sides of the same coin. "String theory" is an abbreviation of superstring theory.

Historically, around 1980, string theory lay dormant. The candidate for a theory of everything was a higher-dimensional (quantum field) theory called supergravity. Physicists then believed that by the end of the century this would reveal the sought-for unified theory. After it was realized that supergravity could not fulfill its claims, string theory came to prominence in 1984. After this "first superstring revolution," five consistent string theories had been formulated in ten-dimensional space-time. The goal of unification appeared to move closer. Then, in 1995, Edward Witten showed that behind the five string theories lurked a unified eleven-dimensional theory, called M-theory, igniting the "second superstring revolution." Specifically, he showed that by moving to eleven dimensions, the physics described by this new theory corresponded to the five ten-dimensional string theories in limiting cases. Moreover, eleven-dimensional supergravity emerged as the low-energy limit of M-Theory.

Finally, the narrative returns to Einstein. After the spectacular success of his early years, he spent the last thirty years of his life chasing chimera. One futile endeavor he pursued to his deathbed was the failed development of a unified field theory. Einstein was also skeptical of the validity of quantum theory, despite his vital role in initiating the theory (his Nobel Prize-winning discovery of the photoelectric effect). He famously quipped that "the old one" (God) does not play dice, expressing his doubt of the probabilistic and indeterministic nature of quantum theory. A brief history of quantum mechanics and quantum information is presented: Max Planck's introduction of quanta in an act of despair and entanglement. To this day quantum theory remains undisputed.

– Section 4.4: Unification—The Holy Grail of Physics

This section concludes the current and previous chapters, which described the long journey from symmetry principles to the standard model of particle physics. Although a theory of everything—the unified theory of quantum gravity—appears as unattainable as ever, the standard model and general relativity, both based on symmetry principles, mark perhaps the greatest achievements of theoretical physics. Both theories have been tested to an extraordinary precision.

Chapter 5: The Two Volumes of the Book of Nature

It appears as though the Book of Nature has been found and deciphered. The universe has become intelligible to the human mind—from he subatomic world to vast cosmic scales. In essence, this understanding comes from translating reality domains into formal representations (encoding) and deriving predictions about the workings of the universe from them (decoding). However, this should only mark the beginning.

What has been called the Book of Nature up to now was a very specific translation: The *fundamental* reality domain (encapsulating the quantum and cosmological levels of reality) was encoded as an *analytical* formal representation (equations). A few decades ago, another translational process was discovered: *Complex* phenomena (from inanimate self-organizing structure formation to emergent phenomena like life and consciousness) are encoded via *algorithmic* formalizations (algorithms and simulations running in computers). In essence, the human mind has uncovered two volumes in a larger Book of Nature Series. For each volume a dichotomy has been unearthed, allowing the human mind to probe reality: the *fundamental-analytical* and the *complex-algorithmic*.

– Section 5.1: Volume I: Analytical Tools and Physical Science

Volume I of the Book of Nature is discussed. The success (seen in Chaps. 2–4), paradigms (symmetry and invariance), and limitations (from condensed matter physics to n-body problems and systems of interacting agents) of this approach are outlined. First hints of non-linearity and chaos theory emerge.

– Section 5.2: Volume II: Algorithmic Tools and Complex Systems

Volume II of the Book of Nature is introduced, allowing the human mind to tame complexity. This feat hinges on two novel paradigms. Complex systems are formalized as a set of agents and a set of interactions between the agents (P_1^c). Moreover, complexity is the result of simple rules of interaction (P_2^c).

(P_2^c) sets the stage for the new science of simple rules. This fact is as wondersome as Eugene Wigner's comments on the "reasonable effectiveness of mathematics in the natural sciences." One of the first scientists to glimpse the simplicity at the heart of complexity was Stephen Wolfram, a physicist, computer scientist, and entrepreneur. He set out to redefine all of science in *A New Kind of Science*. Chaos theory and fractals are discussed.

(P_1^c) spawned a new science of networks. Having its roots in sociology ("the strength of weak ties" and "six degrees of separation"), this research field exploded around the turn of the millennium. Driving the success was the discovery of two types of complex networks, found to be ubiquitous in nature (small-world and scale-free). This unlocked the understanding of complex systems found in socio-economical, biological, and physio-chemical domains. A new awareness of nature emerged, moving beyond reductionistic problem-solving and embracing a systems-based and holistic outlook.

– Section 5.3: The Profound Unifying Powers of Mathematics

The two classification schemes (reality domain vs. formal representation type) are extended by another level, relating to the structure of mathematics itself. From a bird's-eye perspective, mathematics splits into two subject matters: the continuous and the discrete.

The history of continuous mathematics is recounted. It begins in ancient Greece (Pythagoreans, Zeno, and Archimedes) and touches on the Protestant Reformation and the Jesuits, the persecution of Galileo Galilei, and the independent discovery of calculus by Isaac Newton and Gottfried Wilhelm Leibniz. Some of the philosophically relevant concepts include: the finite vs. the infinite, synechism, atomism, and monadism. A cornerstone of continuous mathematics is the derivative. This formal tool lies at the heart of the analytical machinery that is employed to represent fundamental aspects of the physical world. In essence, it drives all physical theories.
Although discrete mathematics is as old as humankind, it plays a minor role in today's mathematics curriculum. However, discrete mathematics is relevant for information theory and computation. Boolean algebra was a landmark development in logic. Claude Shannon implemented this for the first time using electronic components. He also introduced the notion of a bit—a binary digit—to represent digital information as 0 or 1. This is the basis of information theory, ultimately leading to the computer.
One specific area of discrete mathematics emerged as the cornerstone for the description of complex systems: graph theory. This was developed by Leonard Euler, one of the most prolific mathematicians, while he was thinking of how a walk through the city of Königsberg could be devised, that would cross each of the seven bridges only once.
Just as the derivative of continuous mathematics plays a crucial role in the *fundamental-complex* dichotomy (Volume I), graph theory from discrete mathematics allows complex systems, represented by networks, to be formalized as graphs, a cornerstone of the *complex-algorithmic* dichotomy (Volume II). In this sense, mathematics is the ultimate unifying theme of all human knowledge generation.

– Section 5.4: The Book of Nature Reopened

The dichotomies of *fundamental-analytical* and *complex-algorithmic* knowledge generation are only two possibilities out of four. It is discussed how the two other options—the fundamental-algorithmic and complex-analytical categorizations—play a minor role in the Book of Nature Series.

Chapter 6: Volume II: The Simplicity of Complexity

Finally, Volume II of the Book of Nature gives the mind insights into the workings of complexity. After decoding many aspects of the universe using equations, we now have the tools to tackle the complexity surrounding us and contained within us.

– Section 6.1: Reviewing the Book of Nature

A short reiteration of the concepts and ideas relating to the two volumes of the Book of Nature is given. Now, the simplicity of complexity is at the center of attention.

– Section 6.2: A Brief History of Complexity Thinking

The historical roots include cybernetics (1940s and 1950s), systems theory (1950s and 1960s), early artificial intelligence research (1950s and 1960s), and non-linear dynamics, fractal geometry and chaos theory (1960s to 1980s). One specific domain of complexity science is complex systems theory. A complex system is comprised of many interacting elements where a natural formal representation is found in a network. From a philosophical point of view, structural realism is pitted against post-structuralism.

– Section 6.3: Complex Network Theory

The core formal concept related to complex systems is discussed. Complex networks are ubiquitous in nature. Complex network analysis can be performed at different levels of resolution.

– Section 6.4: Laws of Nature in Complex Systems

Scaling laws can be understood as laws of nature describing complex systems. A scaling law is a basic polynomial functional relationship, where a relative change in input results in a proportional relative change in output, independent of the initial size of input. Scaling laws are scale-invariant and scaling-law relations characterize an immense number of natural processes. There exist four types: (1) allometric scaling laws (in biology), (2) scaling-law distributions (in contrast to a normal distribution), (3) scale-free networks (a scaling law found in the topology), and (4) cumulative relations of stochastic processes (relating to time series, especially financial ones). Historically, scaling laws go back to Galileo Galilei. The economist and sociologist Vilfredo Pareto found a scaling laws in the distribution of wealth in 1896, coining the Pareto principle (or 80-20 rule). Modern measures capturing inequality are the Lorenz curve and the Gini coefficient. Analyzing language, the linguist and philologist George Kingsley Zipf discovered a scaling law in the frequency of words. Finally, Benford's law describes a peculiar pattern found in random data.

Chapter 7: Applied Complexity: Finance and Economics in a New Light

Finance and economics are arguably the most important academic disciplines, as they have the greatest impact on all of life on Earth. Moreover, they are the fuel of progress, financing science and technology. Ironically, financial and economic systems are still badly understood and are affected by ideological entrenchment and dogma.

– Section 7.1: Terra Cognita

Adam Smith is the founder of modern economic thought. In 1776, he presented *An Inquiry into the Nature and Causes of the Wealth of Nations*. The mathematization of finance began in the year 1900, when Louis Bachelier introduced the notion of a stochastic process. This formalization of randomness was intertwined with the physics of the time and Max Planck and Albert Einstein played an important role. More mathematization included the Langevin and Fokker-Planck equations, next to Itô stochastic calculus and Benoît Mandelbrot's discovery of the fractal geometry of nature. In 1973, the Black-Scholes equation represented the pinnacle of this evolution and was rewarded with the Nobel Memorial Prize in economic sciences. The academics went on to found a hedge fund, which, after initial success, collapsed and resulted in bank bailouts. When physicists were faced with a dire academic job market in the early 1990s, they migrated to Wall Street. The quant, or quantitative analyst, came of age.

The global financial crisis was interpreted by many as exposing the failures of the predominant brand of economic thinking. Exponents from the "Chicago School" (going back to Milton Friedman and the Chilean free-market experiment), and neoclassical economics per se, were seen as accountable. However, the accused refused to accept the blame and saw others as responsible. One criticism addressed the mathematics, namely, the heavy, opaque, and archaic mathematical formalism utilized by neoclassical economics—not only due to its lack of empirical foundation, but also due to very stringent and unrealistic assumptions about human behavior and market dynamics. One example is the Gaussian copula, making the pricing of, formerly too complex, investments possible. For instance, the collateralized debt obligation (CDO) which, with credit default swaps (CDSs), fueled the subprime housing bubble which would ultimately trigger the financial crisis and in its wake, the sovereign debt crisis.

– Section 7.2: A Call to Arms

  Many pundits blaming neoclassical economic theory see complexity theory as a potential savior. Pioneers of econophysics, like Jean-Philippe Bouchaud and Didier Sornette, have shown, with empirical evidence, that the complex dynamic behavior of markets defies the neoclassical paradigm. Moreover, complexity researchers have urged that the structure and dynamics of economic networks should be better understood and analyzed in-depth. Indeed, the global financial and economic networks are characterized by extreme interdependencies, where feedback loops and non-linear behavior are very relevant. Financial supervisors, regulators, and policymakers felt betrayed by the prevailing orthodoxy during the finical crisis and are looking for inputs from complexity science. Proposed reforms center around data-driven, interdisciplinary research, embracing complex networks, allowing for heterodox economics.

– Section 7.3: Complexity Finance and Economics

  In detail, approaching economics and finance from a complexity perspective entails an empirical focus and the deployment of computer simulations. One specific algorithm-driven methodology is that of agent-based models. Agent-based simulations have revealed structures and mechanisms underlying the dynamics of real-world markets. In this paradigm, heterogeneous agents interact with each other, giving rise to emergent complexity. This is the polar opposite of the framework of representative agents in neoclassical economics, maximizing some utility. By employing network theory, the global ownership network can be analyzed in order to uncover the architecture of power. A network centrality measure is reinterpreted as corporate influence, linking the formal network to its domain of application.

– Section 7.4: The Past, Present, and Future of Economic Interactions

  The cross-pollination of science and technology , industry and economics, and military interests led to the rise of European imperialism. The quest for profit and knowledge allowed Europe to establish a new global hegemony. When the Italian maritime explorer and navigator Christopher Columbus set sail, the Chinese, Muslims, and Indian domination soon faltered. Limited liability joint-stock companies, traded on stock exchanges, generated the profits for conquering the world.

However, there is a dark side associated with all this progress. Capitalism takes a heavy toll on the individual human psyche and the global ecosystem. Since the days of Adam Smith, it has been argued that, in fact, egoism is altruism. Self-interest is seen as a virtue. In contrast, evolutionary and mathematical biologists have long suspected cooperation and altruism to be the recipe for sustainable collective well-being. In Buddhism, greed is seen as one of the root causes of suffering—an insatiable hunger leaving one perpetually unsatisfied. Indeed, when humans are facing death, the accumulation of material wealth appears fruitless and hollow. Moreover, many people in Europe and the US experience their work life as a treadmill, devoid of meaning and gratification. Happiness economics analyzes how and when humans can gain spiritual satisfaction from material wealth. Fraud, next to greed, is another detrimental temptation. The banking industry has a long history of financial scandals, where markets were systematically manipulated for personal gain.

Keynesian economics, characterized by government spending during economic crisis, was a dominant economic ideology at the beginning of the 20th Century. In 1947, a small group of thinkers founded what later became to be knows as neoliberalism. Today, neoliberalism is the world's dominant economic paradigm, favoring deregulation and privatization. It is associated with unrestrained self-interest and laissez-faire economics and has influenced many different political movements. Neoliberalism has been spectacularly successful for a select few. Despite the spoils, insiders have reported on the unsavory culture which often prevails in places having the easiest access to wealth-accumulation. On a systemic level, the accelerating increase of global inequality is seen by many—economists and billionaires—as the key challenge facing humanity and threatening economic and ecological sustainability.

The design of most human systems is governed by a very specific architecture: the pyramid of power. This is a simple tribal hierarchy of concentrated influence. In contrast, the design patterns of nature, and hence complexity, are characterized by decentralization. The nascent rise of the crypto-currency Bitcoin has initiated a paradigm change in finance and economics by introducing the first decentralized blueprint of interaction. The innovation fueling crypto-currencies is the underlying data structure, called the blockchain. A blockchain is a decentralized, fail-proof, and tamper-proof public ledger, enforcing transparency, security, and auditability by design. The future of distributed ledger technology lies in its potential as a global "decentralized public compute utility," executing code representing any conceivable financial and economic interaction. Many expect a global disruption, similar to the introduction of the Internet.

Part II: The Downfall

Chapter 8: A Brief Story of Success: The Manifestation of Knowledge and the Hydra of Ignorance

The human mind's quest to comprehend the world is compared to the journey of the archetypal hero who ventures from the common world into a region of supernatural wonder and returns, bestowed with new powers. The discovery of the two volumes of the Book of Nature is reiterated. This manifestation of knowledge is driving the acceleration of technological advances and is having an unprecedented impact on how human societies organize themselves and interact with their environment. Indeed, we appear increasingly accustomed to this ongoing success.

– Section 8.1: Clouds on the Horizon

Regrettably, age-old questions, relating to existential dilemmas, ontological paradoxes, and epistemic uncertainty, continue to vex the human mind. Why does anything exist at all? Let alone life and consciousness? What can I learn, know, and understand about reality? Why can't uncertainty and ignorance be banished from the edifice of knowledge? In retrospect, looking at the 13.772-billion-year history of the universe, a plethora of cosmic coincidences conspired, bringing the universe's chaotic path-dependent evolution to this very moment in time.

– Section 8.2: The Core Enigmas of Existence

What can I know about the world (Chap. 9)? What is reality's fundamental nature (Chap. 10)? What is the true nature of consciousness (Chap. 11)?

Chapter 9: Philosophy and Science: What Can I Know?

Despite the spectacular success of the human mind in decoding reality and crafting technology, questions relating to the nature and structure of knowledge and science remain elusive.

– Section 9.1: The Philosophy of Science

This journey begins with history's first scientist in Greece. Two millennia later, the modern scientific method began to emerge, establishing experiments as the cornerstone of physical sciences. Logical empiricists and critical rationalists failed to found science on common sense notions—inductive and deductive reasoning suffer from conceptual problems.

Later, science was understood to undergo abrupt and unforeseeable paradigm changes in its evolution. The philosophies of postmodernism, constructivism, and relativism tried to come to terms with a reality which is ambiguous and tainted by every observer's belief system and socio-cultural context. Two examples are discussed, where postmodernism and theoretical physics have lost their meaning.

– Section 9.2: The Evolution of Science

At the same time as the human mind was extending its knowledge, the constricting limits of this knowledge became apparent. The discovery of quantum mechanics, special, and general relativity rocked the foundations of science. The classical notion of a comprehensible clockwork universe, independent of observers, was uprooted. The unsettling effects of this fundamental transformation are still felt today. The question of why the universe is comprehensible at all, emerges. Finally, some observers diagnosed the end of science. For every question science answers, new and harder questions emerge. In effect, while science produces ever more increments of knowledge, the understanding of the universe does not progress. Moreover, like every social human endeavor, academia can be plagued by blind obedience to authority, groupthink, corruption, and fraud. Scientists are put under relentless pressure to "publish or perish."

– Section 9.3: The Practitioners of Science

Usually, scientists aren't very vocal about their personal experiences of practicing science. The problem with knowing what beliefs scientists hold dear is that, by definition, this information is non-scientific. However, if asked, some sympathetic scientists will admit to the shortcomings discussed in this chapter—specifically, challenging notions of objectivity, truth, knowledge, and certainty relating to laws of nature, reality, and science. Uncertainty and ignorance are understood as being inherent and ubiquitous in the human condition.

– Section 9.4: The Limits of Mathematics

In a final blow, the limits of mathematics were exposed by Kurt Gödel and Gregory Chaitin. Building on the theorems of incompleteness, mathematicians discovered fundamental randomness at the heart of mathematics. All hopes of a consistent edifice of mathematics, built on a clear foundation, are lost. Mathematics is demoted from its status of absolute and timeless beauty and becomes a "quasi-empirical" endeavor. Formal axiomatic systems fail and meaning is lost in the mist of formal hyper-abstraction, only penetrable by a handful of minds. Bad news for the epistemic status of science.

Chapter 10: Ontological Enigmas: What is the True Nature of Reality?

The discovery of the Higgs boson closes a successful chapter of physics—and leaves us in the dark. The list of unsolved problems in physics is extensive and no empirical tether can guide the mind anymore. Moreover, the nature of reality is very puzzling. Why do three spatial dimensions exists? Why does our universe appear fine-tuned?

– Section 10.1: The Worst Prediction in Physics

Quantum filed theory is spectacularly accurate in describing the interactions of particles. However, it makes a fantastically absurd prediction when confronted with the zero-point energy of particles and the observable energy density of the vacuum.
The discovery of the accelerated expansion of the universe reopens an old chapter of cosmology. Einstein had tweaked the equations of general relativity to prevent an expanding universe. Ironically, this trick also can account for the energy density of the vacuum, driving the expansion of the universe.

– Section 10.2: Quantum Gravity: The Cutting-Edge of Theoretical Physics

The theory of quantum gravity, merging quantum mechanics with general relativity, is the holy grail of theoretical physics. Decades of work have resulted in an elaborate mathematical framework, called string/M-theory. Indeed, the development of this physical theory has resulted in the discovery of new fields of mathematics. Unfortunately, there is no empirical prediction anywhere in sight. Moreover, M-theory speaks of an eleven-dimensional space-time, containing supersymmetric particles. It was long hailed as the "only game in town." While string theory starts with quantum field theory and adds gravity, loop quantum gravity—the underdog of quantum gravity—takes general relativity and adds quantum properties. In this framework, space itself is quantized. The theory also allows older attempts at quantum gravity to reemerge. Overall, quantum gravity has been a hot battleground for physicists.

– Section 10.3: The Large and the Small

Analyzing the nature of reality at the largest and smallest scales reveals many enigmas. For one, both the positioning of the Earth in the entire universe, and the current time we are living in, appear special. Then, 95.14% of all that exists is unknown to us. We are surrounded by ghostly dark matter and energy.
At the quantum level of the universe, reality seems outlandish. The interpretation of quantum mechanics is—after over a century—as elusive and controversial as ever. Waves behave like particles and vice versa. Quantum sates are strange superpositions of clearly defined states: The 0/1 dichotomy of binary logic is transcended, as there exists a superposition of zero and one. Measuring quantum phenomena seemingly influences their properties. Reality is reduced to clouds of probability. Perhaps the strangest of all quantum qualities is entanglement. This acts like a structural glue connecting particles independently of their spatial distance—instantaneously. It is a feature at the core of quantum encryption. The story of its discovery opens a colorful chapter in the history of physics, involving hippies, psychedelics, and superstition. Countless quantum experiments verify that local realism cannot be true. Indeed, the "now" appears to alter the past. Explanations have invoked the existence of infinitely many parallel universes or the quantized nature of space itself. Other thinkers believe we should move to a wholly new informational foundation of reality, in order to make sense of our world. The materialistic and reductionistic scientific worldview is fading.

– Section 10.4: The Nature of Reality

The ontology of reality seems unknowable to the human mind. The true nature of things appears to transcend any and all human conceptions. Many physicists and philosophers answer the question "Does matter exist?" with a clear "No!" Perhaps even more troubling, they answer the question "Is time an illusion?" with a definitive "Yes!" Some see the problems related to consciousness itself.

Chapter 11: *Subjective Consciousness: What am I?*

What is consciousness? Remarkably, this innocuous question is one of the hardest the human mind has ever asked itself. It represents the last enigma in the journey of the mind to understand the universe and itself within it.

– Section 11.1: The History and Philosophy of Our Minds

In 1994, the hard problem of consciousness was stated. The "easy problem" of consciousness relates to explaining the brain's dynamics in terms of the functional or computational organization of the brain. The hard problem of consciousness is the challenge of explaining how and why we have phenomenal experiences? Why do we perceive colors, tastes, and pain? Why are we not "zombies?" How do the laws of nature give rise to first-person conscious experience?

– Section 11.2: Modern Neuroscience

Neuroscience has progressed remarkably in the last decades. Brain imaging technology allows researchers to track thoughts in the brain and read them. The brain is understood as a vast decentralized network of processes and modules interacting with each other. However, neuroscience also tells us that our perception of reality is a hallucination. Our brains construct a virtual reality simulation of the outer world based on best guesses. We can never know what the true nature of reality is. This view is similar to Kant's noumenon. As a result, we are blind to much of the activity going on in the world. Indeed, expectations and context can alter the way we perceive the world—from pleasure to pain. Flase awakenings and out-of-body experiences can shatter many intuitions about reality.

– Section 11.3: Impressionable Consciousness

Perhaps the most humiliating discovery relating to the human mind is its innate irrationality. We constantly fall prey to faulty reasoning and self-deceit, while proudly claiming rationality. The list of cognitive biases is frighteningly long. Our minds can be influenced by microorganisms, parasites, and genes. Or it can be purposefully manipulated. Even false memories can be implanted. By magnetic stimulation of the brain supernatural belief can be momentarily suspended while empathy for immigrants increased. Indeed, political affiliation is correlated with fear mechanisms. Behavioral economists have uncovered a trove of embarrassing findings exposing innate and ubiquitous human irrationality. Sometimes, even animals can outperform humans. It turns out that pigeons have a better intuition of probability than physics Nobel laureates.
Finally, the mind can break. This is documented by the many psychopathological disorders, from compulsive swearing to the firm belief that one doesn't exists. Split-brain patients can experience alien hand syndrome, where one hand becomes an adversary. Acquired savants display genius traits after brain trauma. Some case studies document normally functioning humans lacking vast parts of their brains. Neurolaw questions the culpability of certain criminals. Are we really free to choose if we have a brain tumor affecting vital emotional processing areas of the brain?

– Section 11.4: The Mind-Body Problem

The placebo and nocebo effects hint at an intriguing connection between the mind and the body. The mind can will the body into healing or harming itself. Then, free will is a thorny issue in physics as well as neuroscience. This may sound astounding, then how can free will be contestable? I choose to be reading this sentence in this moment. If there is no free will, then who or what is deciding and why? Quantum mechanics first discovered the problem of an observer in physics. Apparently, consciousness is able to manipulate physical reality. The status of free will in quantum mechanics is still far from being understood. It appears that we have to choose. Either there is no free will or everything in the universe is imbued with it. In neuroscience the situation is clearer. Many experiments have demonstrated how a decision is made in the subconscious mind which is then, seconds later, relayed to the conscious narrator. Of course, the conscious mind insists that it was the cause of the decision. Overall, consciousness seems to be an ironic anomaly which cannot be integrated into the scientific worldview it created itself.

Chapter 12: The Age of Post-Truth

The situation is dire. We have lost the guidance from science and philosophy and ignorance is rampant. Trench wars are fought along social, political, and religious delimitations. Hostility and misanthropy permeate the very fabric of society. We are lost in an existential vacuum, where we ultimately use the gift of technology to destroy the biosphere which provides the bases of all life.

– Section 12.1: The Cult of Ignorance

Today, anti-intellectualism is socially acceptable. "My ignorance is just as good as your knowledge." Experts and scientists are perceived as villains who are deceiving the people—either for self-enrichment or by adhering to a sinister hidden agenda.

– Section 12.2: The Age of Conspiracy

Conspiracy theories are surprisingly popular. From creationism, motivated by religious beliefs, to denying climate change, motivated by political beliefs, to the astonishing claim that the Earth is flat. Some conspiracies have been peddled for self-enrichment, like the false claims that vaccines cause autism. The most popular and widespread conspiracy is creationism, disseminated by Evangelical Christians mostly in the United States.

– Section 12.3: What About This Book?

A superficial understanding of this book up to now could lead to the false belief that it can be instrumentalized for anti-intellectualism. The failure of science and philosophy to explain the world can be seen as an invitation for arbitrary beliefs about existence. Indeed, nothing is as it seems. Once this truth is admitted, the human mind can reconsolidate and search for new horizons. We are invited to reassess all our assumptions and be open-minded towards even seemingly "crazy" ideas. We should not be blinded by the illusion of knowledge. In being skeptical and honest, false ideas about existence can be eradicated, regardless of their origin. A new foundation is now possible.

– Section 12.4: The Dawning of a New Age

Perhaps things are not as bad as they seem. We are seeing signs of an emerging new age. Perhaps we will soon be able to translate our amazing powers of individual intelligence into collective intelligent behavior. Maybe soon we can construct an economy that is adaptive, resilient, and sustainable. After all, the universe has an intrinsic propensity to forge complexity. Self-organization appears like a fundamental force guiding cosmic evolution.

Pragmatically, we can assess human thought systems and check their level of scientific utilitarianism. Conspiracy theories, for instance, require many arbitrary and ad hoc explanations to account for simple facts. Most importantly, radical and empathetic open-mindedness can help us reevaluate all our beliefs. There is no idea which should be excluded based on our current materialistic and reductionistic scientific worldview. "The universe is queerer than we can suppose" and perhaps also our own minds.

Chapter 13: A Universe Built of Information

Paradigm shifts are hard to discern from within. However, slowly the evidence is mounting that humanity is currently witnessing a profound recontextualization of its belief systems. Specifically, the materialistic and reductionistic scientific worldview appears to have reached its limit—not only in terms of knowledge generation but also in its capacity to probe the ultimate nature of reality.

– Section 13.1: The Many Faces of Information

Information is hard to grasp. It appears ethereal and intangible, somehow detached from the physical. Its definition is a challenge in the philosophy of information. However, information is remarkably physical. Claude Shannon's information theory introduces the notion of quantized information: the bit. This unit is the building block for our modern digital computational world, established by Alan Turing. It was discovered that irreversible computational steps, for instance, erasing information, increases the entropy of the universe. Information cannot be destroyed—it is physical.

– Section 13.2: It from Bit

In a more radical assertion, two pioneers of modern theoretical physics believed that information is fundamental. "It from bit" popularizes the view that from an information-theoretic bedrock our reality emerges. Such views are shared by contemporary scholars of quantum information and computing. Indeed, the bizarre nature of quantum mechanics can be overcome by framing it in an informational context. At the core is the qubit, a quantum representation of a classical bit utilizing the multilayered nature of the quantum realm. Humanity is, however, only at the threshold of unleashing the powers of quantum computers. Historically, Charles Babbage and Ada Lovelace were the first to implement a mechanical computer.

– Section 13.3: Digital Physics

A group of contemporary scientists is advocating the idea of digital physics as an overarching concept. One postulate is that reality is inherently finite. Infinities are only encountered in the formal mathematical systems the human mind accesses.

– Section 13.4: An Information Ontology

Albeit tantalizing, up to now the human mind only caught a glimpse of this novel information ontology. However, there should exist more evidence to substantiate the claim. Indeed, by studying black holes many different theories converge and point in the same information-theoretic direction. General relativity uncovered the existence of black holes. Applying information theory and thermodynamics in their study resulted in more understanding. However, including quantum mechanics unearthed a paradox. In detail, it appeared as if information is lost in black holes violating the principles of quantum physics. Further research uncovered that there is a fundamental limit to how much information—how many bits—can be stored in any region of space.

Perhaps the most powerful tool coming from string/M-theory is the so-called AdS/CFT duality. In the context of black holes, it can be re-expressed as the holographic principle. Our three-dimensional world is in fact the manifestation of information encoded on a two-dimensional area. Moreover, space and time appear to be emergent properties arising from pure quantum entanglement. Finally, theoretical computer science is currently aiding the understanding of this new line of research. Specifically, computational complexity seems to be a likely candidate fueling the computational engine of the universe. In a last step, some scholars have expressed their suspicion that the entire universe is a simulation.

Chapter 14: *The Consciousness of Reality*

The connection between subjective consciousness and objective reality has been debated for ages. René Descartes and John Locke introduced primary and secondary qualities for objects appearing in the mind. Bishop Berkeley argued that all qualities reside in the mind. David Hume and Immanuel Kant rejected the empirical nature of knowledge. More recently, Hilary Putnam pondered the idea of brains in a vat.

– Section 14.1: Formalizing Consciousness: Integrated Information Theory

  Integrated information theory (IIT) is the first formal attempt at grappling with consciousness. Next to information's observational and extrinsic nature, described by Claude Shannon, IIT deals with its compositional and qualitative nature. An inner view of information is presented, giving rise to subjective experience.

– Section 14.2: The Cosmic Nature of Consciousness

  The recalcitrant nature of consciousness , stubbornly refusing to yield to a materialistic and reductionistic scientific worldview, has led scholars to debate seemingly outlandish ideas. A consequence of IIT is that consciousness is a universal—perhaps also fundamental—property of reality. Such concepts are dangerously close to notions of spirituality. Subjectivity was a taboo not too long ago, as is spirituality now. The emergence of intelligence in animals and plants, next to primitive organisms and even innate matter and pure software, appears to challenge the human mind's dominance—and intelligence's tangibility. Indeed, collective intelligence is a decentralized emergent property untethered from any individual localized cognitive capability.

– Section 14.3: Enhanced Consciousness: The Psychedelic Renaissance

  For a long time, the scientific and societal verdict was clear: psychedelic substances have no potential benefits and lead the mind astray. In the current psychedelic renaissance, the remarkable therapeutic potential of these substances has been uncovered. Intriguingly, the human brain synthesizes the strongest psychedelic substance known: DMT. Influenced by this chemical compound, human consciousness appears to be "teleported" into realms of existence transcending space, time, and matter. These universes, experienced as being just as real—or even more real—as the reality perceived by sober waking consciousness, are populated with other alien conscious entities. Especially in shamanic traditions, the "plant spirits" give insights into healing. It is tempting to disregard such experiences as hallucinations, but how to discern, with certainty, what is true and what is false about our perception is very challenging. Particularly, as sober waking consciousness is also a hallucination induced by the brain utilizing some sensory input—rendering a tiny subspace within a much richer "reality topology" available to the brain.

– Section 14.4: A Participatory Ontology

John Wheeler was one of the pioneers to introduce the notion of an information-theoretic ontology into physics. Thinking this idea to its radical conclusion, he introduced the concept of a participatory ontology. This insight had also not escaped Immanuel Kant and Richard Tarnas. In the long and colorful history of quantum physics, many scholars believed the encountered enigmas and paradoxes originated from a fundamental misconception: the separation of mind and matter.
In a final act of heresy, the prevailing materialistic and reductionistic scientific world-view is denounced. All the associated taboos and blind spots are exposed. In the peer-reviewed scientific literature one finds hints of paranormal and psychic—or psi—phenomena. Reproduced double-slit quantum experiments demonstrating the human mind's role as quantum observer and manipulator. Indeed, other outlandish psi phenomena have been reproduced by skeptics, however, only to be dismissed.

Chapter 15: Consilience

This is the last chapter in the human mind's quest for understanding. As it is itself a summary of the entire journey, the reader is invited to directly continue there. Final thoughts and outlooks are provided.

– Section 15.1: The Inner and Outer Aspects of Information
– Section 15.2: The Rhizome of Reality and the Entelechy of Existence
– Section 15.3: A New Horizon

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Part I
Climbing to the Summit

Wherein the edifice of science is constructed.

Chapter 2
In Search of the Book of Nature

Abstract The Book of Nature is an ancient metaphor for knowledge, where the universe can be read like a book for understanding. It is written in the language of mathematics, giving birth to science. A modern interpretation is that human knowledge generation rests on an act of translation. Aspects of the physical world are translated into abstract, formal notions. These can be manipulated by the mind to gain insights into the workings of the world. This raises many philosophical questions, as it posits the existence and interaction of three worlds: the physical (space, time, and energy), the mental (consciousness), and the abstract (Platonism).
Level of mathematical formality: medium.

One of the main wellsprings of modern thought can be traced back to an obscure and secretive religious cult flourishing around 500 B.C.E. The Pythagoreans were a very unlikely origin of ideas that would influence the progress of human understanding of the world. They can be seen to have initiated a transformation in knowledge seeking, away from myth and superstition towards abstract truths which can be uncovered and grasped by the human mind.

Pythagoras, of whom very little is known, founded a religion of which the main principles were the transmigration of souls and the sinfulness of eating beans (see Russell 2004, for a list of other bizarre rules of the Pythagorean order). Nonetheless, a crucial element in their thinking was the realization that a mathematical reality underpins the physical. This is reflected in their motto "All is number" (Boyer 1968, p. 49). Thought to have coined the term "mathematics" (Heath 1981, p. 11), the Pythagoreans begin with the study of the subject for its own sake. Indeed, Aristotle would later credit the Pythagoreans for being the first to take up and advance mathematics, next to understanding the principles of mathematics "as being the principles of all things" (Kirk and Raven 1957, p. 236f.). Furthermore, they were associated with the analysis of the four sciences, which will later be known as the *quadrivium*: arithmetic, geometry, music, and astronomy. Although Pythagoras himself is often seen as a founder of mathematics and physics still today, it is unclear if such accomplishments should actually be credited only to him personally (Huffman 2011).

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
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Moreover, the Pythagoreans also had a great influence on philosophy, as their ideas molded Plato's thinking, and through him, reached out to all of Western philosophy: "[…] what appears as Platonism is, when analyzed, found to be in essence Pythagoreanism" (Russell 2004, p. 45). The conception of an abstract, eternal world, revealed to the intellect but not to the senses, finds a new expression in Plato's notion of a perfect realm of ideas and forms. His vision of these abstract entities yields both an ontology and an epistemology: Platonic Ideas are not constructs of the human mind and the belief in their objective nature implies the existence of a domain of reality harboring them, a third realm next to the physical world perceived by the senses, and the inner thought world of consciousness. True knowledge is only attainable because of the mind's ability to access this otherworldly sphere, and thus any empirical evidence must always be prone to fallibility.

The emergence of this worldview, where the regularities in the physical world are explicable through the structures in the abstract world, finds its metaphorical incarnation as the Book of Nature. The mind of God, the master-mathematician, is revealed to humans in this way. This conviction, that the coherence of the universe is explained by equations and can hence be comprehended by the human mind, echoes over the ages: "Mathematics is the door and key to the sciences" (Roger Bacon in 1267); "This book [the universe] is written in the mathematical language […]" (Galileo Galilei in 1623); "Mathematical and mechanical principles are the alphabet in which God wrote the world" (Robert Boyle in 1744); "In every specific natural science there can be found only so much science proper as there is mathematics present in it" (Immanuel Kant in 1900); "Mathematics is the foundation of all exact knowledge of natural phenomena" (David Hilbert in 1900). (All quotes are taken from Hanson 2010, p. 193, except the first and last ones, which are found in Wolfram 2002, p. 859.)

Nonetheless, the rigorous and systematic description of physical processes aided by the use of analytical tools—the true mathematization of nature—can be seen to have started to emerge roughly four centuries ago. By introducing the idea of elliptical orbits into celestial motion, Johannes Kepler was able to solved the ancient mystery of planetary behavior. He thus demonstrated "mathematics' genuine physical relevance to the heavens—its capacity to disclose the actual nature of the physical motions. Mathematics was now established not just as an instrument for astronomical prediction, but as an intrinsic element of astronomical reality" (Tarnas 1991, p. 257). Synthesizing Kepler's laws of planetary motion, Galileo Galilei's laws of dynamics, and René Descartes's laws of motion and mechanistic philosophy, Isaac Newton was able to construct a single comprehensive mathematical framework, describing the general motion of matter under the action of forces. It is seamlessly able to describe terrestrial and celestial phenomena, explaining everything known about motion with a handful of mathematical equations. This body of work, which is seen by some as the beginning of modern physics (Russell 2004; Tarnas 1991), laid the foundations for what has come to be know in physics today as classical mechanics. Since this turning point in history, the understanding of the world has forever been transformed. Science is now seen as the effort to capture the processes of nature in formal mathematical representations.

But what is it exactly that bestows mathematics with such power? Why is it the blueprint for reality? And how topical are the musings about a Platonic world of mathematical forms?

2.1 A Modern Edition of the Book of Nature

The cornerstone of the scientific knowledge-generating process called science can be understood as an act of translation: quantifiable aspects of reality are transformed into formal, abstract representations which are hosted in the mind. Thus parts of reality become intelligible and the formal encodings foster novel insights. This enterprise can be understood as the quest of the natural sciences. In Fig. 2.1 a rough sketch of this idea is presented. Guided by observation, measurement, and reflection, a natural system of a given reality domain is encoded into a formal representation. Aided by the rules pertaining to the chosen abstract model, for instance, logical consistency or symmetrical regularities, novel insights about the behavior or characteristics of the natural system can be found, allowing predictions to be made. This newly decoded information can then be compared with experimental outcomes, lending validity to the formal representation as a model of the natural system. These ideas are reflected in the words of Paul A. M. Dirac (quoted in Goenner 2004, p. 6):

> The successful development of science requires a proper balance between the method of building up from observations and the method of deducing by pure reasoning from speculative assumptions […].

Still today, this interplay of the physical with the abstract is emphasized by scientists, for instance, as observed in Davies (2014, p. 83):

> The history of physics is one of successive abstractions from daily experience and common sense, into a counterintuitive realm of mathematical forms and relationships, with a link to the stark sense data of human observation that is long and often tortuous.

Nonetheless, for many scientists this cycle of translation is implicit and the focus is placed heavily on the details of the abstract realm. Albert Einstein remarked (as quoted in Schweber 2008, p. 97):

> I am convinced that we can discover by means of pure mathematical constructions the concepts and the laws connecting them with each other, which furnish the key to the understanding of natural phenomena. Experience may suggest the appropriate mathematical concepts, but they most certainly cannot be deduced from it. Experience remains, of course, the sole criterion of the physical utility of a mathematical construction. But the creative principle resides in mathematics. In a certain sense, therefore I hold it true that pure thought can grasp reality, as the ancients dreamed.

To illustrate how effective this act of translation has become, in the following, some examples of physical theories are presented. The mathematical formalism is kept brief for the moment. Only later on will examples of full-blown analytical machineries be unveiled.

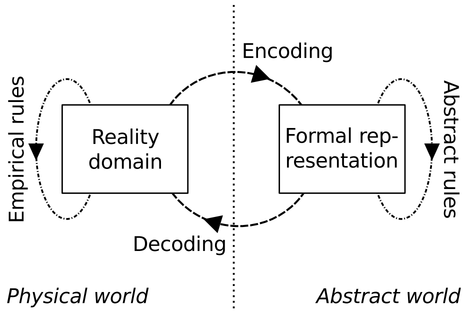

Fig. 2.1 Schematic illustration of the interplay between the physical and the abstract realms, each adhering to their own sets of rules, where knowledge can be generated by mapping aspects of the real world into formal representations and back again (encoding/decoding). Adapted from Casti (1989)

2.1.1 Classical Mechanics

A simple example of this recipe, described in Fig. 2.1, can be found when applied to Newtonian mechanics. The reality domain is restricted to be comprised of a system of n (unit) point masses in three-dimensional Euclidean space $\mathbb{R}^3$, described by their locations and velocities. These observables can exist in physically distinct states and are represented by two sets of $N = 3n$ numbers. Conceptually, the encoding of the observables is accomplished by mapping the abstract states into the points of the space $\mathbb{R}^{2N} = \mathbb{R}^N \times \mathbb{R}^N$, also referred to as state- or phase-space. In detail, each particle's location is formally captured by a differentiable mapping, called a motion, $\mathbf{x}_i : I \to \mathbb{R}^3$, $i = 1, \ldots, n$, where $I \subset \mathbb{R}$ is a time interval. Thus any configuration of the positions of a mechanical system of n points is captured by the motion $\mathbf{X} : \mathbb{R} \to \mathbb{R}^N$, where $\mathbf{X}$ is the vector constructed from all $\mathbf{x}_i$. Taking the derivative of $\mathbf{X}$ with respect to time yields the velocity vector $\dot{\mathbf{X}}$. The derivative's abstract capacity to measure how a function changes as a result of changes in its input, encodes the physical notion of displacement with respect to time. Newton's equation is a function $\mathbf{F} : \mathbb{R}^N \times \mathbb{R}^N \times \mathbb{R} \to \mathbb{R}^N$ such that

$$\ddot{\mathbf{X}} = \mathbf{F}(\mathbf{X}, \dot{\mathbf{X}}, t), \tag{2.1}$$

and it is the basis for his mechanics. Once the initial conditions are specified, i.e., $\mathbf{X}(t_0)$ and $\dot{\mathbf{X}}(t_0)$, a theorem relating to ordinary differential equations guarantees the existence and uniqueness of the solution of (2.1), see, for instance Blanchard et al. (2011). Decoding this equation reveals that the initial positions and velocities alone determine the acceleration forces emerging in the system. This is the predictive power of the formal representation, captured by a system of ordinary differential equations: the specification of the evolution of the physical system in time. The abstract rules relating to the mathematics of the infinitesimal are a concrete example of what the arrow on the far right-hand side in Fig. 2.1 is alluding to. What is today known as calculus, was first formally spelled out by Newton and, independently, Gottfried Wilhelm Leibniz.[1] A general reference introducing classical mechanics is Arnold (1989).

2.1.2 Classical Electrodynamics

The formal rules relating to derivatives also have the capacity to breathe life into another fundamental set of equations. Taking the reality domain to encompass interactions between electric charges and currents, an extension of the classical Newtonian model results in a unified theory describing all electromagnetic phenomena with great precision. On the side of the abstract formulation, the notion of derivatives is extended to apply to vectors fields, which is the subject of vector calculus. Both the electric and magnetic fields, **E** and **B**, respectively, find a formal encoding as functions $\mathbf{f} : \mathbb{R}^3 \times \mathbb{R} \to \mathbb{R}^3$. The main mathematical actor is a vector differential operator, referred to as *nabla*.

$$\nabla := \sum_{i=1}^{3} \hat{\mathbf{e}}_{\mathbf{i}} \frac{\partial}{\partial x_i}. \tag{2.2}$$

The $\hat{\mathbf{e}}_{\mathbf{i}}$ are a standard basis in $\mathbb{R}^3$ and the partial derivative, $\partial/\partial x_i$, denotes differentiation with respect to the variable x_i. The symbol ":=" identifies the expression on the left-hand side as a novel term defined by the quantities on the right-hand side.

What are today known as Maxwell's equations, a particular set of partial differential equations, is perhaps one of the most important aggregations of empirical facts in the history of physics. James Clerk Maxwell built on the experimental observations and insights gained, among others, by André-Marie Ampère, Jean-Baptiste Biot, Charles-Augustin de Coulomb, Michael Faraday, Carl Friedrich Gauss, Hermann von Helmholtz, Hans Christian Ørsted, Siméon Denis Poisson, and Félix Savart, next to contributing his own (Panat 2003). An early form of Maxwell's equations was published between 1861 and 1862, but only two decades later Oliver Heaviside provided the mathematical tools to elegantly group the four equations together into the distinct set still used today.[2] The modern form of the four equations are based on the following expressions, building variations on the theme of the derivative

$$\dot{\mathbf{E}},\ \dot{\mathbf{B}},\ \nabla \cdot \mathbf{E},\ \nabla \cdot \mathbf{B},\ \nabla \times \mathbf{E},\ \text{and } \nabla \times \mathbf{B}. \tag{2.3}$$

[1]Historically, the question of who discovered calculus first caused a major intellectual controversy at the time.

[2]Heaviside was not the only scientist grappling with these problems. Heinrich Hertz was doing similar work, and the reformulated Maxwell equations became known for some years as the "Hertz-Heaviside equations." The young Einstein referred to them as "Maxwell–Hertz equations," and, today, the legacy of Heaviside and Hertz has been lost to history (Nahin 2002, p. 111f.). In addition, Heaviside and Josiah Willard Gibbs both developed vector calculus independently of each other during the same period.

The resulting equations are an explicit example of an encoding scheme illustrated in Fig. 2.1. All observable electromagnetic phenomena find their formal representation in four simple equations[3]

$$\nabla \cdot \mathbf{E} = \rho \tag{2.4a}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{2.4b}$$

$$\nabla \times \mathbf{E} = -\dot{\mathbf{B}} \tag{2.4c}$$

$$\nabla \times \mathbf{B} = \mathbf{J} + \dot{\mathbf{E}} \tag{2.4d}$$

Decoding these abstract expressions enables the physical manipulation of all electromagnetic manifestations and fosters technological innovation. Indeed, simply by the power of mathematical consistency, a new feature of reality is uncovered: decoding Maxwell's equations also reveals that the electric and magnetic forces are in fact expressions of a single overarching electromagnetic force. Moreover, a further application of the operator $\nabla\times$, called *curl*, on (2.4c) and (2.4d), yields novel wave equations describing the propagation of electromagnetic waves traveling at the speed of light in a vacuum. Maxwell, understanding the connection between electromagnetic waves and light, thus unified the theories of electromagnetism and optics. For a general reference see Jackson (1998).

2.1.3 Mathematical Physics

Today, it is hardly possible for a layperson to distinguish modern physics from pure mathematics. The merger of mathematics and physics has reached an unprecedented level. Even if by looking back at history this development seems natural, indeed inevitable, there were times when people disagreed. Johann Wolfgang von Goethe saw the necessity of keeping physics and mathematics independent. Physics should strive to understand the divine forces of nature, unaffected by the characteristics of mathematics. In reverse, mathematics should not be restricted or tainted by the outer world, as it is an immaculate tune of the spirit (Schottenloher 1995). An influential proponent of the idea that physics is not in need of mathematics to be a successful endeavor was Faraday. He developed a field theory describing electrical and magnetic forces without the aid of mathematics (Schottenloher 1995). Notwithstanding, the mathematization of physics marched on, culminating in today's level of integration. This can be witnessed, for example, in mathematical textbooks aimed at introducing physicists to the mathematical methods. For instance, seen in the 1200 pages of Arfken et al. (2012). Or in a book written by the mathematical physicists Roger Penrose. It is an ambitious and comprehensive account of the physics describing the universe—a thousand page tour de force—focusing essentially on the underlying mathematical theories, giving a good impression of how far this enterprise has come,

[3]The charge and current densities are captured by ρ and $\mathbf{J}$, respectively. Constants relating to the choice of electromagnetic units are ignored and set to one.

and how complete the Book of Nature has become (Penrose 2004). The following is a selection from the table of contents, highlighting the mathematical context[4]:

The Pythagorean theorem; Euclid's postulates; Hyperbolic geometry: conformal picture; Solving equations with complex numbers; Convergence of power series; Caspar Wessel's complex plane; How to construct the Mandelbrot set; Geometry of complex algebra; The idea of the complex logarithm; Multiple valuedness, natural logarithms; Complex powers; Higher derivatives, C1-smooth functions; The rules of differentiation; Integration; Complex smoothness, holomorphic functions; Contour integration; Power series from complex smoothness; Analytic continuation; Conformal mappings; The Riemann sphere; The genus of a compact Riemann surface; The Riemann mapping theorem; Fourier series; Functions on a circle; Frequency splitting on the Riemann sphere; The Fourier transform; Frequency splitting from the Fourier transform; Hyperfunctions; Complex dimensions and real dimensions; Smoothness, partial derivatives; Vector Fields and 1-forms; The Cauchy-Riemann equations; The algebra of quaternions; Geometry of quaternions; Clifford algebras; Grassmann algebras; Manifolds and coordinate patches; Scalars, vectors, and covectors; Grassmann products; Integrals of forms; Exterior derivative; Tensors; Complex manifolds; Groups of transformations; Subgroups and simple groups; Linear transformations and matrices; Determinants and traces; Eigenvalues and eigenvectors; Representation theory and Lie algebras; Tensor representation spaces, reducibility; Orthogonal groups; Unitary groups; Symplectic groups; Parallel transport; Covariant derivative; Curvature and torsion; Geodesics, parallelograms, and curvature; Lie derivative; Symplectic manifolds; Some physical motivations for fibre bundles; The mathematical idea of a bundle; Cross-sections of bundles; The Clifford bundle; Complex vector bundles, (co)tangent bundles; Projective spaces; Non-triviality in a bundle connection; Bundle curvature; Finite fields; Different sizes of infinity; Cantor's diagonal slash; Puzzles in the foundations of mathematics; Turing machines and Gödel's theorem; Euclidean and Minkowskian 4-space; The symmetry groups of Minkowski space; Hyperbolic geometry in Minkowski space; Non-commuting variables; Unitary structure, Hilbert space, Dirac notation; Spin and spinors; Higher spin: Majorana picture; Infinite-dimensional algebras; The Weyl curvature hypothesis; Killing vectors, energy flow—and time travel!; The algebra and geometry of supersymmetry; Higher-dimensional space-time; The magical Calabi-Yau spaces, M-theory; The chiral input to Ashtekar's variables; Loop variables; The mathematics of knots and links; Spin networks; Theories where geometry has discrete elements; Conformal group, compactified Minkowski space; Twistors as higher-dimensional spinors; Twistor sheaf cohomology.

[4]Indeed, Penrose has contributed to many of these topics, as can be see, for instance, in the book summarizing his work (Huggett et al. 1998).

Penrose also acknowledges an intimate relationship of the two realms seen in Fig. 2.1 (Penrose 2004, p. 1014):

> The interplay between mathematical ideas and physical behavior has been a constant theme in this book ["The Road to Reality"]. Throughout the history of physical science, progress has been made through finding the correct balance between, on the one hand, the strictures, temptations, and revelations of mathematical theory and, on the other, precise observation of the actions of the physical world, usually through carefully controlled experiments.

It is an interesting observation, that the most fruitful branch of mathematics appears to be geometry (Schottenloher 1995; Huggett et al. 1998; Barndorff-Nielsen and Jensen 1999; Frankel 1999; Gray 1999; Nakahara 2003; Atiyah et al. 2010). Indeed, the mathematician Marcel Grossmann introduced Einstein into the field of differential geometry, which would turn out to be the mathematical foundation of general relativity (Goenner 2005). Moreover, "[o]ne of the remarkable developments of the last decade is the penetration of topological concepts into theoretical physics" (Tom W.B. Kibble quoted in Nash and Sen 1983, back cover).

2.1.4 Mathematics from Physics

In the last decades, the pursuit of new physical theories has also spawned and nurtured new results in mathematics, namely topology, a field of study developed from geometry analyzing concepts of space and transformation. This is a remarkable cross-fertilization. Not only does the formal encoding of aspects of the natural world necessitate structures in the abstract realm which lead to the discovery of novel (decoded) features back in the physical world, now, crucially, these encoded remnants act as a guiding principle by which new structures in the abstract world are uncovered.

In 1994, the physicists Nathan Seiberg and Edward Witten introduced an equation within the context of quantum field theory[5] (in detail, supersymmetric[6] Yang-Mills theory,[7] Seiberg and Witten 1994a, b), that had a great impact on the mathematical field of topology, namely the research of four-dimensional manifolds. This prompted the mathematician and Fields Medalist Simon Kirwan Donaldson to remark (Donaldson 1996):

> In the last three months of 1994 a remarkable thing happened: this research [in 4-manifold topology] was turned on its head by the introduction of a new kind of differential-geometric equation by Seiberg and Witten: the space of a few weeks long-standing problems were solved, new and unexpected results were found, along with simpler new proofs of existing ones, and new vistas for research opened up.

A few years earlier, Witten's work on topological quantum field theory provided new insights for the mathematical field of knot theory (Witten 1989). He showed

[5] See Sects. 3.1.4, 3.2.2.1, 4.2, and 10.1.1.

[6] Discussed in Sect. 4.3.2.

[7] The topic of Sect. 4.2.

how the invariant of an oriented knot, the Jones polynomial, can be obtained by considering geometric insights of Chern–Simons theory.[8] Indeed, Witten, who had graduated with a degree in history, was the first physicist to be awarded the Fields Medal in 1994, a prestigious award for outstanding discoveries in mathematics. The mathematician Michael Atiyah commented on Witten's dual impact on physics and mathematics (Atiyah 1991, p. 31):

> Although he is definitely a physicist (as his list of publications clearly shows) his command of mathematics is rivaled by few mathematicians, and his ability to interpret physical ideas in mathematical form is quite unique. Time and again he has surprised the mathematical community by his brilliant application of physical insight leading to new and deep mathematical theorems.

More on the history and details of the entwinement of physics and topology can be found in Nash (1999).

Another example of theoretical physics pollinating mathematics is monstrous moonshine. Next to being a rather peculiar name for a mathematical theory, it ties up some very exotic mathematical concepts with the help of string theory.[9] The mathematical structure called monster group[10] was independently postulated in 1973 by the two mathematicians Bernd Fischer and Robert L. Griess. It is a structure with

$$\begin{aligned} M_s = & 808017424794512875 \\ & 886459904961710757 \\ & 005754368000000000, \end{aligned} \tag{2.5}$$

elements in it. However, only in 1982 its existence was proved (Griess 1982). Bare-handed, without the aid of a computer, Griess constructed the monster group by associating it with a 196,883-dimensional vector space. It was known, that if the group should exist, it would only become manifest at certain specific numbers of dimensions M_{d_i} (see, for instance Conway and Norton 1979): $M_{d_1} = 196,883$, $M_{d_2} = 21,296,876$, $M_{d_3} = 8,426,093,265,\ldots$ A true oddity at the fringes of mathematics.

Unrelated, in another corner of mathematics, number theorists were analyzing a mysterious object, also inspired by string theory, called the modular function. Variants of this function would later turn out to be the unexpected key to solving Fermat's Last

[8] A quantum field theory theory built around the concept of the Chern–Simons form, an integrable geometric object on a manifold (Chern and Simons 1974). James Simons left academia in 1978 to set up Renaissance Technologies, a multi-billion quantitative hedge fund management company, heavily staffed with employees with non-financial backgrounds but with detailed scientific knowledge. They recruited researchers from the fields of cryptoanalysis and computerized speech recognition. For decades, Renaissance Technologies operated one of the most successful, albeit highly secretive, funds in the business, and the wealth that Simons has amassed also finances his many philanthropic pursuits. See Patterson (2010).

[9] String theory will be introduced in Sect. 4.3.2.

[10] Groups are discussed in detail at the beginning of Chap. 3 and in Sect. 3.1.2.

Theorem,[11] a famous conjecture which had remained unproven since 1637 (Wiles 1995). Back in the late 1970s, a strange coincidence was noticed. The modular function introduced by Felix Klein, called the j-function, was known to be expressible as a Fouries series (Rankin 1977). John H. Conway and Simon Norton discovered an unexpected connection between the monster group and the j-function: the Fourier coefficients could be expressed as linear combinations of the dimension numbers M_{d_i}. This conjectured relationship was called monstrous moonshine (Conway and Norton 1979), at a time the existence of the monster group was still unproven.

As if this intimate connection between two very separate fields in mathematics was not puzzling enough, the techniques used to prove this kinship would come from an even more unexpected source: modern theoretical physics. Richard Borcherds proved the conjecture (Borcherds 1992), an achievement that would later also win him a Fields Medal. Using a theorem from the mathematical framework of string theory, he catapulted exotic topics from mathematics into the limelight, intriguing mathematicians and physicists alike. Indeed, before his discovery he would lament about the "new and esoteric algebraic structure" he introduced in 1986, called a vertex operator algebra (Du Sautoy 2008, p. 347):

> I was pretty pleased with it at the time but after a few years I got a bit disillusioned, because it was obvious that nobody else was really interested in it. There is no point in having an idea that is so complicated that nobody can understand it. I remember I used to give talks on vertex algebras, and usually nobody turned up. Then there was this one time when I got a really big audience. But there had been a misprint, and the title read "vortex algebras," not "vertex algebras." The audience was made up of fluid physicists, and when they realized it was a misprint, they weren't interested either in what I had to say.

This quote[12] can be found along with a gripping account of the history and the events that conspired, leading to Borcherds' proof in Du Sautoy (2008). Fascinatingly, the cross-pollination of mathematics and physics continued. Indeed, the initial notion of vertex operators originated in string theory, inspiring a proper mathematical formalization yielding the concept of Borcherds' vertex algebra, which, in turn, could help to underpin some major ideas in modern physics and string theory (Gebert 1993).

But next to the success of mathematics in the sciences, and the mysterious connections between mathematic and physics, what does this all really mean? What is revealed about the nature of reality and the nature of mathematics?

2.2 Seeking Meaning

Albeit simple, clear-cut, and seemingly straightforward, the conceptual categorization sketched in Fig. 2.1 already suffices to open Pandora's Box of epistemic and ontic puzzles. The power of mathematics can be understood in its capacity to mirror the

[11] No three positive integers a, b, and c can satisfy the equation $a^n + b^n = c^n$ for any integer value of n greater than two.

[12] Seen on p. 347.

structure of reality. As a consequence, two main themes emerge. First, questions about the reality status of the abstract Platonic world of ideas re-emerge. Then, crucially, an intermediary between the physical and the abstract worlds is required: a translating entity, responsible for the encoding and decoding. Such a vessel for abstract thought conjures up a third world, bringing consciousness to the center stage. Now, nested in the physical reality, a mental world, containing the mind's reality content, appears. A schism, making it necessary to delimit between inner and outer worlds, an objective and subjective reality. In summary, the implicit assumptions underlying Fig. 2.1 are:

- The existence of a physical reality governed by regularities.
- The emergence of living structures inside this concrete world.
- The formation of a mind within these beings, i.e., a set of cognitive faculties, harboring an inner, mental world.
- The existence of a Platonic realm of abstractions.

This all culminates in knowledge about physical reality spontaneously becoming manifest in the mind: the workings of the natural world are wondrously uncovered when quantifiable subsets thereof are mapped into formal descriptions and are subjected to the constraints governing the abstract reality. The mind's ability to access the Platonic world, meaning the emergence of abstract ideas within the mind's reality, is in effect a conduit for the Platonic realm to enter the physical world.[13]

This discussion can be framed in the broader context given by the philosophy of mathematics, as one of the main tenets deals with mathematical realism. Regarding the ontological status of mathematics, mathematical anti-realists would deny that mathematical entities exist independently of the human mind. In other words, they posit that humans do not discover mathematical truths, but invent them. The three main schools of thought in the philosophy of mathematics, existing around the end of the nineteenth and the beginning of the 20th Century, were all anti-realist, and thus anti-Platonist, reflecting the general philosophical and scientific outlook of the time which tended toward the empirical. Logicism (Frege 1884) is the program aimed at reducing mathematics to logic, an idea dating back to Leibniz. Formalism understands mathematics as a formal game in which symbols are manipulated according to fixed rules and axioms (associated with David Hilbert). Finally, intuitionism assumes that mathematics is a creation of the human mind—it is essentially an activity of mental construction—with implications for logic, set theory and elementary arithmetic (the first piece of intuitionistic mathematics in a widely read international journal is Brouwer 1919, but the idea originates from his 1907 dissertation). Brouwer's mathematical philosophy of intuitionism can be seen as a challenge to the then-prevailing formalism of Hilbert. Indeed, the intuitionistic critique of classical mathematics required a revisionist stance toward the existing body of mathematical knowledge (Horsten 2012). In contrast, Hilbert's program was aimed at a formalization of all of mathematics in axiomatic form, together with a proof that this axiomatization of mathematics is consistent (Hilbert 1922, although the ideas can be traced back at least to Hilbert 1899). A, at times bitter, foundational controversy ensued between

[13] More on the interaction of these three worlds can be found in Chapter 1 of Penrose (2004).

Brouwer and Hilbert, and in 1921, Hilbert's favorite student, the mathematician and physicist Hermann Weyl, would side with Brouwer (Weyl 1921).

However, in the years before the Second World War serious objections had been raised against each of the three anti-Platonist programs in the philosophy of mathematics. Regarding logicism, Bertrand Russell, a mathematician and philosopher like Frege, had discovered a contradiction in one of Frege's basic laws, demonstrating that the axioms he was employing to formalize his logic were inconsistent. This challenged the foundations of set theory and is known as Russell's paradox (Russell 1902). Let R be the set of all sets which are not members of themselves. If R is a member of itself, then by definition it must not be a member of itself. Similarly, if R is not a member of itself, then by definition it must be a member of itself. Symbolically

$$R = \{x; x \notin x\}, \text{then } R \in R \iff R \notin R. \tag{2.6}$$

Frege abandoned his logicist program, but Russell continued with Alfred North Whitehead. Together they wrote the monumental three-volume *Principia Mathematica* (Whitehead and Russell 1910, 1912, 1913), hoping to achieve what Frege had been unable to do. By devising new abstractions (a hierarchy of "types" of sets), they tried to banish the paradoxes of naive set theory. Although the *Principia* was, and still is, a hugely influential book, the questions of whether mathematics can be reduced to logic, or whether it can only be reduced to set theory, remain open (Irvine 2010). In any case, Russell and Whitehead's program would soon receive the final blow, shattering their dreams of a paradox-free foundation of mathematics. This same fate would also befall Hilbert's program. With the failure of formalism and logicism, the face of mathematics would forever be changed. This upheaval was achieved single-handedly by Kurt Gödel, yet another mathematician and philosopher (a colorful account of his momentous work can be found in Hofstadter 1999, 2007).

Both the logicists and formalists, like most mathematicians, placed their faith in the precept that the edifice of mathematics is built on a rock-solid foundation. Mathematics must posses two qualities:

- Consistency: a statement is true because there is a proof of the statement.
- Completeness: if a statement is true there is a proof of the statement.

Gödel's shocking revelations were centered around an act of translation. He devised a mechanism which assigns natural numbers to terms and formulas of a formal theory (Gödel 1931). Relying on the unique representation of natural numbers as products of powers of primes, Gödel was able to encode the whole *Principia Mathematica* into numbers. In essence, any pattern of symbols representing abstract formulas in a formal theory can be assigned a unique integer number. Vice versa, any number can be decoded to reveal the sequence of symbols it corresponds to. These Gödel numbers—"arithmetizations" of strings of symbols—translate elaborate manipulations of abstract symbols, as found in the *Principia*, into simple number-crunching. Now, starting from a set of axioms of a theory, the undertaking of finding a series of formulas leading to a proof has a number-theoretic counterpart. The trouble comes in the guise of self-referentiality. Consider a formula expressed within the *Prin-*

cipia, stating: "The integer g does not correspond to a formula provable within the *Principia*." This statement, denoted as $\mathcal{S}$, is innocuous and unsurprising, as there is no reason to believe that every integer can be decoded into a meaningful, let alone provable, formula. However, the consequences are disastrous when g is taken to correspond to $\mathcal{S}$. This self-references amounts to the statement $\mathcal{G}$: "This statement is unprovable." Gödel's first incompleteness theorem (Gödel 1931) spelled doom for the logicist program, showing that the *Principia* could not be both consistent and complete. If $\mathcal{G}$ is provable, then it is false, and if $\mathcal{G}$ is not provable, then it is true. The act of translation has, again, the capacity to teleport a given domain into a new realm where powerful novel possibilities can be unlocked, both desirable and undesirable.

The first incompleteness theorem can be restated as follows: all consistent axiomatic formulations of number theory include undecidable propositions. This did not bode well for Hilbert, who set out to prove the consistency of, for instance, the set of axioms of mathematical analysis in classical arithmetic, going back to Giuseppe Peano. A possible loophole of regaining consistency by the use of higher mathematics was also closed by Gödel's second incompleteness theorem (Gödel 1931): no formal system extending basic arithmetic can be used to prove its own consistency. In other words, if number theory is consistent, then a proof of this fact does not exist using the methods of first-order logic, as axiomatized by Peano arithmetic. Hilbert's program fails: higher mathematics cannot be interpreted in a purely instrumental way.

Finally, the last anti-Platonist program, intuitionism, simply faded out of fashion. The initial enthusiasm for the intuitionistic critique of classical mathematics and the alternative that it propose was dampened, as it became clear what this approach entailed for higher mathematics. Namely, a drastically unfamiliar and complicated theory. Thus room was created for a renewed interest in the prospects of Platonistic views about the nature of mathematics. Notably, Frege, Gödel, and Russell were advocates of this idea. In the words of Gödel (quoted in Kennedy 2012):

> I am under the impression that after sufficient clarification of the concepts in question it will be possible to conduct these discussions with mathematical rigor and that the result will then be […] that the Platonistic view is the only one tenable.

The influential mathematician Godfrey H. Hardy expressed a similar conviction (Hardy 1967, p. 123):

> I believe that mathematical reality lies outside us, that our function is to discover or observe it, and that the theorems which we prove, and which we describe grandiloquently as our "creations," are simply the notes of our observations.

Other notable and prolific mathematicians have espoused similar views. On the 16th of January 1913, Hardy received a letter (Selin 2008, p. 1868) from "an unknown Hindu clerk" (Hardy 1937, p. 144). Srinivasa Ramanujan, twenty-six at the time, had sent him a list of mathematical theorems out of the blue. One equation read (Hardy 1937, p. 143):

$$\frac{1}{1+\cfrac{\exp(-2\pi\sqrt{5})}{1+\cfrac{\exp(-4\pi\sqrt{5})}{1+\cdots}}} = \left[\frac{\sqrt{5}}{1+\sqrt[5]{5^{\frac{3}{4}}\left(\frac{\sqrt{5}-1}{2}\right)^{\frac{5}{2}}-1}} - \frac{\sqrt{5}+1}{2}\right]^{\exp\frac{2\pi}{\sqrt{5}}} . \tag{2.7}$$

Hardy was taken by surprise (Hardy 1937, p. 144):

> I had never seen anything in the least like them [the three formulas in the form of (2.7)] before. A single look at them is enough to show that they could only be written down by a mathematician of the highest class. They must be true because, if they were not true, no one would have had the imagination to invent them.

The quote also echoes his Platonist conviction, namely that true mathematics is discovered by the human mind. Hardy became Ramanujan's mentor and brought him to England the next year. After having achieved word-wide fame, Ramanujan would die six years later due to an array of ailments, like tuberculosis and vitamin deficiency (Selin 2008, p. 1868). Ramanujan was a unique mathematician. He was an autodidact with no formal tuition, unaware of most of existing Western mathematics. These circumstances resulted in him unwittingly discovering, i.e., rediscovering, a wealth of known mathematics. In Hardy's words (Hardy 1937, p. 145):

> It was inevitable that a very large part of Ramanujan's work should prove on examination to have been anticipated. He had been carrying an impossible handicap, a poor and solitary Hindu pitting his brains against the accumulated wisdom of Europe. […] I should estimate that about two-thirds of Ramanujan's best Indian work was rediscovery […]

Ramanujan was also an idiosyncratic mathematician. For one, he had an intimate relationship with numbers. A famous anecdote is given by Hardy (1937, p. 147):

> I remember going to see him once when he was lying ill in Putney. I had ridden in taxi-cab No. 1729, and remarked that the number seemed to me rather a dull one, and that I hoped that it was not an unfavorable omen. "No," he replied, "it is a very interesting number; it is the smallest number expressible as a sum of two cubes in two different ways."[14]

Moreover, only in his later years was he introduced to the idea of proof in mathematics. He mostly mixed reasoning with intuition to reach his insights (Hardy 1937, p. 147). Ramanujan was also a Platonist and believed in the divine nature and reality of mathematics (Hardy 1937, p. 139):

> Ramanujan used to say that the goddess of Namakkal inspired him with the formulae in dreams.

The goddess, also known as Namagiri of Namakkal, is just one divine manifestation in the vast and rich Hindu pantheon of deities. Another quote attributed to Ramanujan reads (Pickover 2005, p. 1):

> An equation means nothing to me unless it expresses a thought of God.

[14] $1729 = 12^3 + 1^3 = 10^3 + 9^3$.

Hardy would compare Ramanujan to mathematical geniuses like Leonhard Euler and Carl Gustav Jacob Jacobi (Hardy 1937, p. 149). Indeed, he saw his own role as mathematician only in the context given by Ramanujan (Kanigel 1992, p. 358):

> Paul Erdős has recorded that when Hardy was asked about his greatest contribution to mathematics, he unhesitatingly replied, "The discovery of Ramanujan."

Hardy was very fond of Ramanujan. He described his collaboration with him as "the one romantic incident in [his] life" (Hardy 1937, p. 138). It is hard to imagine what mathematical knowledge could have been discovered by Ramanujan, had he been formally educated in mathematics and spared from the redundant task of rediscovering known theorems.

Paul Erdős was another influential and idiosyncratic mathematician holding Platonist views (Aigner and Ziegler 2010, preface):

> Paul Erdős liked to talk about The Book, in which God maintains the perfect proofs for mathematical theorems, following the dictum of G. H. Hardy that there is no permanent place for ugly mathematics. Erdős said that you need not believe in God but, as a mathematician, you should believe in The Book.

He led a peculiar life (Dunham 1994, p. 9f.):

> [Erdős was] the 20th Century's most prolific, and perhaps most eccentric, mathematician. Even in a profession in which unusual behavior is accepted as something of the norm, Erdős is legendary. For instance, so sheltered was this young scholar that only at the age of 21 [...] did he first butter his own bread. [...] Equally unusual is that Erdős has no permanent residence. Instead, he travels around the globe from one mathematical research center to another, living out of a suitcase and trusting that at each stop someone will put him up for the night. As a result of his incessant wanderings, this vagabond mathematician has collaborated with more colleagues, and published more joint papers, than anyone in history.

Due to his prolific output, friends created the Erdős number as a humorous tribute to him (Goffman 1969). Defined as zero for Erdős himself, every collaborator with a joint paper gets assigned the Erdős number 1. Likewise, an Erdős number 2 denotes an author who published a mathematical paper with a person having Erdős number 1. Due to the occasional blurring of clear boundaries between scientific fields, some researchers in physics, chemistry, and medicine also have low Erdős numbers. For instance, Einstein has Erdős number 2. In general, this number is a reflection of the tight-kit nature of the collaboration network in academia, an example of the small world phenomenon, summed up as "six degrees of separation" (discussed in Sect. 5.2.3). Another small-world network is that of movie actors, where the Bacon number is an application of the Erdős number concept to actors, centered around Kevin Bacon. Finally, the Bacon–Erdős number is the sum of a person's Erdős and Bacon numbers. As an example, the mathematician Steven Strogatz, co-author of a seminal paper on small-world networks, has a Bacon–Erdős number of 4, as he appeared as himself in a documentary about "six degrees of separation" featuring Bacon.

To conclude this section, all proposed mathematical anti-realist programs faced serious problems, leaving Platonism as a sound, albeit philosophically challenging, option. As discussed, many of the greatest mathematical minds subscribed to Platonism.

2.2.1 *Shut Up and Calculate!*

At this point the discussion threatens to be come intractable. For one, there are many conceptions of what Platonism is really supposed to mean. Perhaps the most extreme view comes in the guise of mathematical monism. A view espoused by Max Tegmark, a cosmologist, in his mathematical universe hypothesis. This radical Platonist view states (Tegmark 2008, 2014): Our external physical reality[15] is in actual fact a mathematical structure. In effect, not only mathematical anti-realists would disagree with ideas espoused as Platonism, but also the various Platonists factions among themselves. Furthermore, one key criticism is the following. Platonic realism posits the existence of mathematical objects that are independent of the mind and language, which bear no spatiotemporal relations to anything. In contrast, flesh and blood mathematicians are physically localized in space and time. The so-called epistemological argument against Platonism is the question how human beings can attain knowledge of abstract objects. Is the human mind capable of penetrating the border between the physical and an eternal realm of existence? This puzzle is captured in the directed link labeled M_1 in the schematic illustration seen in Fig. 2.2, where the interplay between these various modes of reality is summarized. There have been many responses by Platonists to this challenge, followed by more arguments against Platonism. The problem now is manifold. Why should anyone be convinced by either view, if not based on pure belief or intuition? Is an argument outlining a problem sufficient to prove an idea false? And, what then, is a tenable alternative? A general reference relating to Platonism and the philosophy of mathematics is Linnebo (2013).

Even if one chooses to ignore discussions relating to the ontological status of mathematics and epistemological inquiries about how the human mind can access mathematical structures, another problem emerges. The urgent question is why mathematics plays such a crucial and essential role for science? Perhaps since Galileo our best theories from the natural sciences are expressed with true mathematical rigor. This enigma obviously blurs the clear demarcation line between philosophy and science, making it difficult to retreat to the safety of objective inquiry. What is the ontic and epistemic status of the connection between mathematics and the workings of nature, captured by the relationship M_2 in Fig. 2.2? One possible interpretation is in terms of the concept of entelechy,[16] where the physical world is an actualization or

[15] "I use the word [reality] to mean the ultimate nature of the outside physical world that we're part of […]" (Tegmark 2014, p. 14).

[16] The term was coined by Aristotle to describe the dichotomy between potentiality and actuality. Leibniz adapted the concept in a way that gave rise to the notion of energy used today in physics. See also Sect. 15.2.

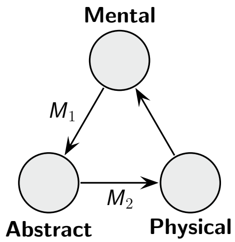

Fig. 2.2 The three worlds: the abstract Platonic realm of mathematics, external physical reality, and the human mind harboring mental states. The arrows allude to the mysteries M_1 and M_2 relating to the connections of the worlds. See also Penrose (2004)

manifestation of the potential abstractions residing in the Platonic realm. The mental agent acts as a bridge from the physical back into the abstract, denoted as M_1.

In a nutshell, the assumptions underlying Fig. 2.1, detailed in the list given on p. 53, can be restated as follows, given a structured external reality and ignoring the lack of knowledge related to the emergence and nature of the human mind:

1. There exists an abstract realm of objects transcending physical reality (ontology).
2. The human mind possesses a quality that allows it to access this world and acquire information (epistemology).
3. The structures in the abstract world map the structures in the physical (structural realism, see Sect. 6.2.2).

The idea of structural realism holds that the physical domain of a true theory corresponds to a mathematical structure. Or stated more cautiously, it is a "belief in the existence of structures in the world to which the laws of mathematical physics may approximately correspond" (Falkenburg 2007, p. 2). The term universal structural realism has been used for the hypothesis that the physical universe is isomorphic to a mathematical structure (Tegmark 2008), leading to Tegmark's mathematical universe hypothesis. This would be one explanation for the puzzle in Fig. 2.2, referred to by M_2: the abstract and the physical worlds are the two sides of the same coin. However, such lofty radical ideas can be hard to stomach, making other, more modest and benign mysteries appear more tempting. For instance, why is there a correspondence or kinship between the realms to being with?

Many scientist abhor the idea of a reality existing beyond space and time. Being pragmatic, such ideas are viewed as ultimately futile and unnecessary baggage in any theory of the world. Specifically, the claim is "that purely philosophical considerations on ontology are fruitlessly speculative and ill-founded and have no value in the light of 'real scientific findings"' (Kuhlmann 2010, p. 186). The power then, of mathematics in the natural sciences lies in the simple fact that it works. "Shut up and calculate!" is the rallying cry.[17] Such an inclination reflects an instrumentalist

[17] Originally this maxim goes back to the physicist Nathaniel David Mermin (Mermin 1990, p. 199), as a response to the persistent philosophical challenges posed by quantum theory.

outlook. Theories are seen as mere conceptual tools for predicting, categorizing, and classifying observable phenomena. Assigning a reality to unobservables has no merit. Moreover, the genuine content of science is not to be found at the level of theories (Duhem 1991).

Essentially, these are debates relating to the old question of scientific realism, a belief in the content of theories and models, regarding both observable and unobservable aspects of the world as described by science. In detail, it is a commitment metaphysically "to the mind-independent existence of the world investigated by the sciences," semantically to "a literal interpretation of scientific claims about the world," and epistemologically "to the idea that theoretical claims [...] constitute knowledge of the world" (Chakravartty 2013). In this sense, instrumentalist epistemologies of science can also be understood as being anti-realist. Historically, in the first half of the 20th Century, empiricism came predominantly in the form of variations of instrumentalism. Vocal advocates of this idea were the logical empiricists (or logical positivists), philosophers often associated with the notorious *Vienna Circle*. However, facing opposition from influential scholars, some even from within the Circle—the likes of Norwood Hanson, Thomas Kuhn, Karl Popper, Hilary Putnam, and Willard Van Orman Quine—the demise of logical empiricism was inevitable.[18] In 1967 the philosopher John Passmore reported that: "Logical positivism, then, is dead, or as dead as a philosophical movement ever becomes" (as quoted in Creath 2013). This was followed by the resurrection of realism. However, as always, the demarcation lines are anything but clear. Instrumentalists can be non-realist, i.e., taking an agnostic stance as to whether parts of a physical theory have a correlate in reality. Moreover, structural realism is a very specific and restrictive type of realism: the real nature of things can never be known, only the way things are related to one another has true meaning. Indeed, in the ontic version of structural realism, relations are all that exist, without assuming the existence of individual things (French and Ladyman 2003). So the world is made up solely of structures, a network of relations without relata. See Sects. 6.2.2 and 10.4.1.

Be that as it may, "Shut up and calculate!" can help one avoid becoming stuck in philosophical mires. In the case at hand, it can be understood as encouraging the inquiry into the specifics of mathematics that makes this formalism such a powerful tool for science—abandoning musings about meaning and implications. And indeed, there is one primary mathematical ingredient that distinguishes itself among others:

> The notion of symmetry, formally encoded as a principle of invariance, is singly one of the most powerful tools in unearthing novel and deep insights into the structure of the universe.

[18] See Sect. 9.1.1 for more details.

Conclusion

The Book of Nature has been found: The human mind can access the world of abstractions, which mirror the structures of the physical world. Consciousness is the translator. One archetypical example of these conceptualizations—representing a narrative arc in the Book of Nature—is found in the notion of symmetry, a fundamental cornerstone of physics. Symmetry will be the accompanying theme of the next two chapters. “Shut Up and Calculate!” allows the philosophical analysis to be postponed—for the moment.

The reader not wishing to dive into the particularities of the mathematics relating to symmetry and the corresponding physical concepts describing, for instance,

- conservation laws (Sect. 3.1),
- the speed of causality (Sect. 3.2.1),
- the classification of elementary particles (Sect. 3.2.2),
- unification schemes, ranging from the standard model of particle physics to string/M-theory (Chap. 4),

next to the historical embedding of some core ideas (Sects. 4.2 and 4.3), can jump to one of the following locations:

- Chapter 5: Unearthing the second volume in the Book of Nature Series, related to the algorithmic understanding of complexity, allowing for a further classification of human knowledge generation.
- Chapter 6: The new understanding of complexity, i.e., the science of simple rules.
- Chapter 7: Applying complexity thinking to finance and economics, concluding Part I and representing the highest point on the mountain of knowledge—reached before the downfall.
- Chapter 8: The beginning of Part II, glimpsing the first signs of uncertainty and confusion.
- Chapter 12: The start of Part III, transitioning to new horizons.
- Chapter 15: The final analysis.

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Chapter 3
The Semantics of Symmetry, Invariance, and Structure

Abstract Symmetry carries the connotation of beauty. Mathematized, it is a deep and reoccurring theme in the Book of Nature. Many unexpected properties of reality are uncovered by it. A key concept related to symmetry is invariance, the simple property of a system to remaining unchanged under manipulations. Invariance has the power to unlock fundamental knowledge.
Level of mathematical formality: high (however, the mathematically involved parts are encapsulated and demarcated by the tags {∯ . . . ∯}, hence easily bypassed).

The notion of symmetry carries with it the connotation of beauty, harmony and unity. In the words of Hermann Weyl (1952, p. 5):

> Symmetry, as wide or narrow as you may define its meaning, is one idea by which man through the ages has tried to comprehend and create order, beauty, and perfection.

The history of symmetry begins with the Greeks, coining the term *summetria*, derived from the words *sun* (meaning "with," "together" or "by association") and *metron* ("measure"). In a modern, scientific context, symmetry is recast in terms of invariance: under certain manipulations, namely transformations, specific features of a physical system remain unchanged. Symmetry is thus mathematized as an operator acting on an object, where the defining feature is that the object remains unaltered. Expressed in other words, the object is invariant under the symmetry transformation.

The mathematical structure that underlies the study of symmetry and invariance is known as group theory. Here now is a concrete example of Fig. 2.1: the real-world notion of symmetry is encoded as the mathematical concept of invariance. In order to gain new insights into the workings of the physical world, one needs to burrow deeper into the abstract world. The first gem that can be discovered is group theory, which, as will be discussed, is intimately related to geometry. From the formal rules pertaining to these areas of mathematics encapsulated in the abstract world, three applications can be derived: a universal law of conserved quantities, a tangible grip on elementary particles, and a merger of fragmented forces in nature.

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
https://doi.org/10.1007/978-3-030-03633-1_3

$\Big\{ \oiint \; |3\text{-}\mathit{groups} >$

A group G is defined as a set together with an operation that combines any two group elements, satisfying the axioms of closure, associativity, the existence of inverse elements, and containing an identity element. A group action on a set X is defined as a function $\Phi : G \times X \to X$, obeying the axioms of compatibility[1] and the existence of an identity function. This defines a bijective map $\Phi_g : X \to X$, where $\Phi_g(x) := \Phi(g, x)$. G is a symmetry group if its group action Φ preserves the structure on X. In other words, if Φ_g leaves X invariant. The set X can be equipped with algebraic, topological, geometric, or analytical structures. See, for instance Schottenloher (1995).

$< 3\text{-}\mathit{groups}| \; \oiint \Big\}$

Although the history of group theory has many sources and its evolution unfolded in various parallel threads, listing many famous contributors—the likes of Joseph-Louis Lagrange, Carl Friedrich Gauss, and Augustin-Louis Cauchy—Évariste Galois formalized the abstract notion of a group and is generally considered to have been the first to develop group theory (Kleiner 1986). Galois' life was tragic. His budding mathematical influence started at the age of seventeen, only to be stifled by his early death three years later. He died in a duel in 1832. The manuscripts he had submitted to Cauchy, and later, Jean-Baptiste Fourier, would both be lost, never to reappear. Galois was incarcerated for nine months for political reasons and was shunned by the French mathematical establishment, which he fought against with vitriol and anger. Only posthumously he was awarded the recognition for his important contributions to mathematics. See, for instance Du Sautoy (2008).

This simple idea, that the symmetry transformations of an object with a predefined structure constitute a group, allowing the concept of symmetry to be formalized in terms of group theory, has proven to be very powerful. Indeed, the more symmetries an object has, the larger its symmetry group. As an example, the monster group was constructed by Robert L. Griess as a group of rotations in 196,883-dimensional space. It is a symmetry group that belongs to a structure with the mind-bogglingly large number of symmetries given by M_s, as specified in (2.5).

Although the groups studied by group theory are algebraic structures, it was recognized that they also play a fundamental role in geometry. Felix Klein initiated a research program in 1872 which aimed at classifying and characterizing geometries, utilizing group theory. It was a manifesto for a new kind of mathematics which thought to capture the essence of geometry not in terms of points and lines, but in the group of symmetries that permuted those objects. This effort became known as the *Erlanger Program* (Hawkins 1984). The notions of geometry and symmetry, and crucially their deep relationship, are perhaps one of the most fruitful and far reaching

[1] $\Phi(g, \Phi(h, x)) = \Phi(gh, x)$.

themes in physics. If the Book of Nature is written in the alphabet of geometric symbols, then symmetry furnishes its syntax.

3.1 Symmetry in Action: Conservation Laws

In classical physics, a conservation law states that some aspect of a dynamical system remains constant throughout the system's evolution. In a first mathematical formalization this means that some quantity X exists, a dynamical variable capturing the system's evolution over time. In other words, X obeys some equation of motion encoded in (2.1) or (3.1). As X is conserved, i.e., $\dot{X} = 0$, it remains constant along its flow in phase space—it is an invariant. Conserved quantities are often called constants of motion. In effect, this imposes a constraint on the physical system under investigation. Albeit a constraint originating in the abstract world: a natural consequence of the equations of motions, driven by the mechanics of derivatives, rather than a physical restriction which would be a manifestation of some force.

The notion of conserved quantities and the general idea of persistence, with the antonyms related to perpetual flux, form the basis of very dissimilar philosophies. The pre-Socratic Greek philosopher Parmenides in the early 5th Century B.C.E. resisted the teachings of Heraclitus, who maintained that everything is change. Parmenides initiated the search "for something not subject to the empire of Time" (Russell 2004, p. 54). He asserted the principle that "nothing comes from nothing," ex nihilo, nihil fit. In the social network of Greek philosophers, Parmenides was influenced by Pythagoras and, in turn, would leave an impression on Plato's thinking. His principle, which can also be traced back to the Milesian philosophers (Roecklein 2010), argues that existence is eternal and not the result of a divine act of creation. A related idea, which can be seen to prevail throughout time, is called principle of sufficient reason. From Anaximander, Baruch Spinoza, notably Gottfried Wilhelm Leibniz, and to Arthur Schopenhauer, the tenet, that nothing happens without reason, is echoed. Formally, for every fact F, there must be an explanation why F is the case. It is a powerful and controversial philosophical principle and entails bold assertions regarding metaphysics and epistemology. See Melamed and Lin (2013).

The notion, that nothing can come from nothing, is also entailed in the natural philosophy of atomism proposed by Leucippus and his pupil Democritus. They believed that everything is composed of indivisible, indestructible, and eternal atoms. Around the same time, in India, a similar concept of atoms, called *aṇu* or *paramāṇu*, appeared perhaps for the first time in Jain scriptures. Jainism, a radically non-violent Indian religion, shares in its cosmology many of the elements of pre-Socratic Greek philosophies, stating that the universe and its constituents are without beginning or end, and nothing can be destroyed or created. The Jain philosophy contains categories that have a distinct scientific flavor, even today. The part of reality that is "non-spirit," i.e., not related to consciousness is divided into time, space, the principles of motion and stability, and matter (Nakamura 1998). Also in Buddhism, although originally harboring a qualitative, Aristotelian-style atomic theory, would later in the 7th Century develop notions, reminiscent of today's Weltanschauung, considering atoms as point-sized, eternal units of energy (Singh 2010). A general reference discussing naturalism in Indian philosophy is Chatterjee (2012).

However, a lot of time would pass, before the philosophical notions of immutable, eternal entities could be put on a firm footing and recast in the language of conserved quantities in nature. In 1644, René Descartes published an influential book, called *Principles of Philosophy*. Not only did he describe laws of physics, which would later be incorporated into Newton's first law of motion (Whiteside 1991), he also introduced a conserved quantity, which he indiscriminately referred to as "motion" or "quantity of motion." For the first time, an attempt was made to identify an invariant or unchanging feature of mechanical interactions. Moreover, Descartes envisioned the conservation of motion as one of the fundamental governing principles of the cosmos. Indeed, his law falls just short of the modern law for the conservation of momentum. See Slowik (2013).

While it took many scientists over time to tediously formulate and prove the conservation laws for mass and energy, the insights of one person lead to the uncovering of an overarching framework and the deep understanding of the specifics relating to conservation laws. In her 1918 publication, the mathematician Emmy Noether spelled this out in a theorem, wrapping up a deep physical truth with the mathematics of symmetry (Noether 1918). In plain words (Thompson 2004, p. 5):

> If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

To understand what this really means, expressed in the language of mathematics, one needs to embark on a journey starting with some notions from geometry.

3.1.1 From Geometry . . .

In the centuries following the introduction of Newton's dynamical laws of classical mechanics, a restatement and further development of the formalism yielded powerful new tools to investigate mechanical systems. The key concepts were unsurprisingly related to geometry. The encoding of the observables leading to (2.1) can be cast in a new light, uncovering the powerful formalisms of Lagrangian and Hamiltonian mechanics.

Each spatial arrangement of a system of particles, or a rigid body, is captured by a single point in a multidimensional space $M \in \mathbb{R}^n$, called the configuration space. Each point in M is described by a generalized coordinate $q = (q^1, \ldots, q^n)$, where n reflects the degrees of freedom of the classical system. In effect, a curve in the configuration space represents the evolution of the physical system in time. Technically, M has the structure of a (differentiable) manifold, a generalization of the notions of curves, surfaces, and volumes to arbitrary dimensional objects. From the coordinates, the generalized velocities can be derived as $\dot{q}^i = \mathrm{d}q^i/\mathrm{d}t$, defining the phase-space $P = M \times \mathbb{R}^n$ with elements $(q^i, \dot{q}^i)$.

$\Big\{ \oiint \; |3.1.1\text{-}euler-lagrange-hamilton >$

Because the velocities are tangential vectors by construction, the set of these vectors at any point $x \in M$ form a vector space TM_x, called the tangent space to M at x. The union of the tangent spaces to M at all points is the so-called tangent bundle, $TM = \cup_{x \in M} TM_x$. Hence P can be understood as the tangent bundle TM of the configuration space M. In Lagrange mechanics, a function on the tangent bundle $L : TM \to \mathbb{R}$ encodes the structure of the physical system it represents. The equations of motion are given by the Euler–Lagrange equation

$$\frac{\partial L(q^i, \dot{q}^i, t)}{\partial q^i} = \frac{\mathrm{d}}{\mathrm{d}t} \left(\frac{\partial L(q^i, \dot{q}^i, t)}{\partial \dot{q}^i} \right), \tag{3.1}$$

equivalent to Newton's laws of motion.

By introducing the concept of generalized momentum

$$p^i = \frac{\partial L}{\partial \dot{q}^i}, \tag{3.2}$$

Hamiltonian mechanics can be formulated, where the elements (q^i, p^i) define the (momentum) phase-space. The equations of motion in this point of view are given by

$$\dot{q}^i = \frac{\partial H}{\partial p^i}, \quad p^i = \frac{\partial H}{\partial \dot{q}^i}, \tag{3.3}$$

where the function H is obtained via a special transformation of L. Although Lagrangian mechanics is contained in Hamiltonian mechanics as a special case, "the Hamiltonian point of view allows us to solve completely a series of mechanical problems which do not yield solutions by other means" (Arnold 1989, p. 161). In geometric terms, the momentum phase-space has the structure of a cotangent bundle T^*M. Technically, it is the dual vector space of TM, defined for each $x \in M$ as

$$T^*M_x := (TM_x)^* := \{\eta : TM_x \to \mathbb{R}; \quad \eta \text{ linear}\}. \tag{3.4}$$

Hence the η are linear functionals or 1-forms. This recasts Hamiltonian mechanics as geometry in phase-space, $H : T^*M \to \mathbb{R}$. General references are Arnold (1989), Frankel (1999), Nakahara (2003).

$< 3.1.1\text{-}euler-lagrange-hamilton| \; \oiint \Big\}$

The geometric language of the Lagrangian or Hamiltonian approach finds its successful application in various domains of physics, fueled by the key concept of what is known as the Lagrangian density. In the following detour, these ideas will be explored.

Both Lagrangian and Hamiltonian mechanics have played highly influential roles in modern physics, as the formalisms can be naturally extended to fields. Especially Lagrangian field theory has become a cornerstone in many physical theories. Here the Lagrangian functionals L are replaced by their field-theoretic counterparts, called Lagrangian densities[2] $\mathcal{L}$. In general, the following discrete point-particle expressions are extended to fields with an infinite degree of freedom:

$$\begin{aligned} q^i &\longrightarrow \psi^j(x^\nu), \\ \dot{q}^i &\longrightarrow \partial_\mu \psi^j(x^\nu), \\ L(q^i, \dot{q}^i, t) &\longrightarrow \mathcal{L}(\psi^i, \partial_\mu \psi^j, t), \end{aligned} \tag{3.5}$$

where $x^\nu := (t, \mathbf{x})$ is a point in four-dimensional space-time and the components $\psi^j, j = 1, 2, \ldots$, describe a quantum field. The corresponding derivative is $\partial_\mu := \partial/\partial x^\mu$, or, alternatively, $\partial_\mu = (\partial_{x^0}, \ldots, \partial_{x^3}) = (\partial_t, \partial_x, \partial_y, \partial_z)$. Now the Euler–Lagrange equations also take on a field-theoretic form

$$\frac{\partial \mathcal{L}}{\partial \psi^j} = \partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \psi^j)} \right). \tag{3.6}$$

As an example, Maxwell's theory of electromagnetism, encoded as (2.4), can be concisely recast as a field theory in four-dimensional space-time[3] building on the field-strength tensor $F_{\mu\nu}$. The components of $F_{\mu\nu}$ are derived from the components of the electric and magnetic field vectors $\mathbf{E}$ and $\mathbf{B}$, respectively. The Lagrangian of electromagnetism takes on the form

$$\mathcal{L}_{\text{EM}} \sim F_{\mu\nu} F^{\mu\nu}, \tag{3.7}$$

where the Einstein summation convention is assumed and the expression "$\sim$" implies equality up to a constant factor. The Euler–Lagrange equations can elegantly[4] retrieve Maxwell's equations, seen in (2.4), by substituting (3.7) in (3.6). See Jackson (1998), Collins et al. (1989) for more details.

Another, more abstract, example is the Lagrangian of the standard model of particle physics. It is a very accurate theory describing the interactions of matter particles

[2]When there is no danger of ambiguity, the Lagrangian densities are also simply referred to as Lagrangians.

[3]This means that the equations are now compatible with the theory of special relativity, yielding a variation called the covariant formulation of electromagnetism.

[4]Two details are ignored here. $F_{\mu\nu}$ is constructed from the 4-vector potential A^μ described below and the true Lagrangian, given in (4.15), has an additional term $J_\mu A^\mu$, with the 4-vector current density $J_\mu = (\rho, \mathbf{J})$, recalling the note related to (2.4).

via the electromagnetic, weak, and strong forces. In other words, it covers all know forces excluding gravity. The force carrying particles are called gauge bosons (seen in Sect. 4.2). In detail, there exist four boson fields associated with the electroweak force, a unification of electromagnetism and the weak force (discussed in Sect. 4.2.1), and the gluon boson field which propagates the strong force. Gauge bosons represent one of two categories classifying particles according to the value of the spin they carry. The notion of spin can be understood as an intrinsic form of angular momentum of elementary particles (described in Sect. 3.2.2.2), and gauge bosons carry an integer spin value. Particles with half-integer spins are called fermions, the second category of existing particles. All matter is composed of fermions, with a sub-categorization distinguishing leptons and quarks. See Fig. 4.1 on p. 109 for an overview of bosons and fermions. Gauge bosons are formally represented as vector potential A^μ, discussed in (4.12), with corresponding field tensors $F^{\mu\nu}$, constructed in (4.14) or (4.41a). Fermions find their formalization as spinor fields ψ, entities which, unlike vectors, require 720° to complete a full rotation (as explained in Sect. 3.2.2.1). The last ingredient is a scalar Higgs boson ϕ, required for the generation of mass terms for the bosons and fermions, which are missing in the Lagrangian. The mathematical trick necessary for this feat is called the Higgs mechanism (introduced in Sect. 4.2.1). Returning to the standard model Lagrangian, in a nutshell, one finds

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{force}} + \mathcal{L}_{\mathrm{matter}} + \mathcal{L}_{\mathrm{Higgs}} + \mathcal{L}_{\mathrm{coupling}}, \tag{3.8}$$

where

$$\mathcal{L}_{\mathrm{force}} \sim A_{\mu\nu} A^{\mu\nu}, \tag{3.9}$$

describes the vector bosons,

$$\mathcal{L}_{\mathrm{matter}} \sim i\bar{\psi} \not{D} \psi, \tag{3.10}$$

encodes the fermionic matter fields, where D_μ is a special derivative operator, expressed using Feynman's slash notation, encoding the interactions with the bosons. The bar denotes the Hermitian conjugate which is associated with antiparticles. The next term is related to the Higgs field

$$\mathcal{L}_{\mathrm{Higgs}} = \left| D_\mu \phi \right|^2 - \mathcal{V}(\phi), \tag{3.11}$$

with $\mathcal{V}$ describing the potential energy of the scalar field. Finally, the fermions couple to the Higgs scalars as specified by what is known as the Yukawa coupling

$$\mathcal{L}_{\mathrm{coupling}} \sim (\bar{\psi}\phi)\psi. \tag{3.12}$$

These quantities are responsible for generating the mass terms in the Higgs mechanism. This shorthand notation of the standard model Lagrangian goes back to the physicist John Ellis and has been featured on T-shirts and mugs. However, accounting for every detail, the full-blown standard model Lagrangian is comprised of a myriad of terms, filling a whole page. See, for instance, Appendix E in Veltman (1994). General information on the standard model can be found in textbooks on quantum field theory (Kaku 1993; Peskin and Schroeder 1995; Ryder 1996), general theoretical physics (Collins et al. 1989; Lawrie 2013), and particle physics and symmetry (Cheng and Li 1996; Mohapatra 2003).

A final example of an important Lagrangian is related to Einstein's theory of general relativity, the only successful theory to accurately describe gravitational forces. Here matter, radiation, and non-gravitational force fields are expressed through the four-dimensional stress-energy tensor $T^{\mu\nu}$, which becomes the source of the gravitational field. The physical effect of gravitational pull is translated into the abstract notion of the curvature of space-time.[5] The tools for quantifying such perturbations are found in the mathematics of differential geometry, rendering general relativity a geometric theory. The metric tensor $g_{\mu\nu}$, formally a bilinear form defined on a manifold, captures the geometric structure of space-time. Note that $g^{\mu\nu}g_{\nu\rho} = g_{\rho\nu}g^{\nu\mu} = \delta^{\mu}_{\ \rho}$, where the Kronecker delta represents the identity matrix, and $A_{\mu\nu} = g_{\mu\rho}g_{\nu\sigma}A^{\rho\sigma}$. The curvature of space-time can be measured in a series of higher degrees of abstractions, starting with the metric tensor. In detail

$$g_{\mu\nu} \rightarrow \Gamma^{\lambda}{}_{\mu\nu} \rightarrow R^{\rho}{}_{\sigma\mu\nu} \rightarrow R_{\mu\nu}, R \rightarrow G_{\mu\nu}. \tag{3.13}$$

Labeling the terms form right to left: the Einstein tensor is constructed from the curvature scalar and the Ricci tensor, which are contracted from the Riemann tensor, which depends on the Christoffel symbols, defined via the metric. Encoding all this information uncovers Einstein's elegant field equations

$$G_{\mu\nu} \sim T_{\mu\nu}. \tag{3.14}$$

An in-depth account can be found in Sects. 4.1, 4.3.1, and 10.1.2. Again, this shorthand notation does not convey the level of detail and technicality going on behind the scenes. Even simple gravitational problems can be very arduous to solve. Interestingly, it was not Einstein who derived the corresponding Lagrangian which yields the gravitational field equations by virtue of the Euler–Lagrange equations. On the 25th of November 1915, after a series of false starts and detours, Einstein presented the final version of his geometrodynamic law, in the form in which it is still used today (Einstein 1915). Five days earlier, David Hilbert had independently discovered the Lagrangian, respectively the Hamiltonian approach from which Einstein's theory can be derived (Hilbert 1915). The Lagrangian reads

$$\mathcal{L}_{\mathrm{GR}} \sim \sqrt{-\det(g_{\mu\nu})}R. \tag{3.15}$$

As a mathematician, Hilbert believed in the axiomatic foundations of physics. Indeed, he stated this as the sixth problem in his famous list of 23 mathematical problems

[5]Regarding the reality status of space-time genuinely being curved, see the discussion in Chapter 11 of Thorne (1995).

(Hilbert 1900). This intuition allowed him to find such an elegant path to the field equations of gravity, in contrast to Einstein's struggles. Hilbert tersely remarked (Sauer and Majer 2009, p. 403, translation mine):

> If Einstein ends up with the same result [equation of motion] after his colossal detour [...], this can be viewed as a nice consistency check.

According to Kip Thorne, an expert on general relativity, the reason for Einstein's priority over the geometrodynamic field equations, detailing how matter warps space-time, is the following (Thorne 1995, p. 117f.):

> Quite naturally, and in accord with Hilbert's view of things, the resulting law of warpage was quickly given the name the Einstein field equation rather than being named after Hilbert. Hilbert had carried out the last few mathematical steps to its discovery independently and almost simultaneously with Einstein, but Einstein was responsible for essentially everything that preceded those steps.

Thus ends the excursion sketching the prominence of the Lagrangian formalism in various fields of physics. General references for general relativity are Misner et al. (1973), Collins et al. (1989), Lawrie (2013) next to the specific challenges of formulating quantum field theories in curved space (Birrell and Davies 1994).

Returning to the geometric reformulations of Lagrangian and Hamiltonian mechanics, perhaps the most important aspect of this approach is that it allows the ideas of symmetry to be naturally incorporated. By extending the formal representation of an existing theory to incorporate new abstractions, novel and powerful insights into the fundamental workings of the physical world can be uncovered.

3.1.2 ... To Symmetry

The mathematician Sophus Lie revolutionized the understanding of symmetry and greatly extend its scope of influence with his work on continuous symmetries, with the idea that such transformations should be understood as motions. In contrast, discrete symmetries are always associated with non-continuous changes in the system. For instance, permutations, reflections, or a square's discreet rotational symmetry, always being multiples of 90°. Lie's notable achievement was the realization that continuous transformation groups, today known as Lie groups, could be best understood by "linearizing" them. In detail, he realized that it suffices to study the group elements in the local neighborhood of the identity element to understand the group's global structure. In effect, Lie repeated for symmetries what Galois had achieved for algebraic structures: to classify them in terms of group theory. Indeed, initially Lie worked with Klein on the *Erlanger Program*. Years later, after Lie had suffered from a mental breakdown and became increasingly paranoid, fearing people would steal his ideas, the friendship between him and Klein would turn sour. See Du Sautoy (2008).

$\left\{ \oiint \right.$ $|3.1.2\text{-}\textit{lie-group}>$

Technically, a Lie group G is a differentiable manifold endowed with a group structure such that multiplication and the inverse transformation are differentiable maps. The tangential space TG_e of a Lie group at the identity element $e \in G$ is a very special and useful mathematical structure called a Lie algebra. In the terminology of abstract algebra, a vector space over a field[6] $\mathbb{F}$ is a set V together with a bilinear operation for adding the elements of V (called vectors, $u, v \in V \Rightarrow u + v \in V$), and one linking the scalars, or the elements of $\mathbb{F}$, with vectors, referred to as scalar multiplication ($a \in \mathbb{F}, v \in V \Rightarrow a \cdot v \in V$). Eight axioms specify the properties of a vector space. Generalizing this notion, an algebra $\mathfrak{a}$ over a field $\mathbb{F}$ is a vector space over $\mathbb{F}$ equipped with an additional bilinear operation for multiplying elements in $\mathfrak{a}$. For many Lie algebras $\mathfrak{g}$, this operation, denoted by Lie brackets, is given by a skew-symmetric product. An example is given by the commutator

$$(X, Y) \in \mathfrak{g} \times \mathfrak{g} \to [X, Y] := XY - YX \in \mathfrak{g}. \tag{3.16}$$

Although, generically, the Lie brackets must obey an equation known as the Jacobi identity.

The relationship between Lie algebras and Lie groups is captured by a map

$$\exp : \mathfrak{g} \to G. \tag{3.17}$$

It is a homomorphism, or a structure preserving map, taking addition to multiplication. For the many Lie groups that are comprised of matrices, the exponential map takes its usual form for any matrix A: $\exp(A) := \sum_i \frac{1}{i!} A^i$. The existence of this map is one of the primary justifications for the study of Lie groups at the level of Lie algebras. In the general case, a continuous symmetry $S(t) \in G$, parametrized by $t \in \mathbb{R}$, can now be described as

$$S(t) = \exp(tX^a), \tag{3.18}$$

where the vector $X^a \in \mathfrak{g}$ is called a generator. The set of such generators, equipped with a Lie bracket, defines the Lie algebra. Given a basis $X^a \in \mathfrak{g}$, (3.16) generalizes to

$$[X^a, X^b] = f_c^{ab} X^c, \tag{3.19}$$

where all the information is coded into the f^{abc}, the structure constants. Note the usage of Einstein's summation convention.

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[6] A field is defined as a commutative ring with an identity element and contains a multiplicative inverse for every nonzero element. Such algebraic structures contain the notions of addition, subtraction, multiplication, and division. Examples of fields are rational numbers $\mathbb{Q}$, real numbers $\mathbb{R}$, and complex numbers $\mathbb{C}$.

$< 3.1.2\text{-}\textit{lie-group}| \oiint \}$

To summarize, the knowledge of the structure constants, defining the Lie brackets of a Lie algebra, is sufficient to determine the local nature of the Lie group near the identity element. In effect, the Lie brackets can be understood as a linearized version of the group law, a powerful insight provided by Lie.

3.1.3 ... And Back

The formal mathematical framework detailed above can be linked to the dynamics of physical systems. Again, the continued encoding of natural systems into formal representations yields novel insights into the structure of the physical world. Specifically, it is the richness of the abstract world, allowing formal structures to be viewed from seemingly unrelated points of view, that allows for the discovery of similarities between concepts not obvious from the outset.

$\{ \oiint |3.1.3\text{-}\textit{one-parameter-subgroup} >$

As mentioned, every Lie group can also be understood as a manifold. It is special in the sense that it always has a family of diffeomorphisms, i.e., invertible functions between differentiable manifolds, such that: $L_g : G \to G$, where $L_g(h) = gh$, with $g, h \in G$. This means that L_g acts as a translation.[7] For any (differentiable) map on a manifold, $f : G \to G$, the naturally corresponding differential map f_* can be defined as

$$f_* : TG_p \to TG_{f(p)}, \tag{3.20}$$

meaning that a tangent vector X to G at the point $p \in G$ is transformed into a tangent vector f_*X at $f(p)$. The notion is that of a directional derivative along a curve $c(t)$, with $c(0) = p$. In the case of Lie groups, given a tangent vector X_e at the identity, the translation L_g of group elements has the derivative L_{g*} which maps the vector to any point in G, as $X_g := L_{g*}X_e$. Finally, a vector field X on G is said to be (left) invariant if it is invariant under all (left) translations, that is $L_{g*}X_h = X_{gh}$. In this new terminology, a Lie algebra $\mathfrak{g}$ of G is the space of all (left) invariant vector fields on G. Moreover, the Lie bracket of two left-invariant vector fields is also left invariant.

There is still one piece of the puzzle missing, in order for the formal machinery to spit out novel insight into the workings of physical systems. This missing element is called a one-parameter subgroup of G. In general, it is a differentiable

[7] Technically, it is a left translation, and a second family of diffeomorphisms defines the right translation $R_g(h) = hg$.

homomorphism[8] $\varphi : \mathbb{R} \to G$. It describes a path $\varphi(t)$ in G and satisfies the condition $\phi(t+s) = \phi(t)\phi(s)$. For any Lie group G the one-parameter subgroup, whose generator at the identity e is the tangent vector X, is given by

$$\varphi(t) = \exp(tX). \tag{3.21}$$

< 3.1.3-*one-parameter-subgroup*| $\oiint$ }

In other words, any continuous symmetry $S(t)$ is equivalent to a one-parameter subgroup $\varphi(t)$, and there exists an associated left invariant vector field $X \in \mathfrak{g}$. This links the formal framework of one-parameter subgroups to the notion of symmetry, namely Lie groups and algebras. In a next step, the abstract ideas relating to such one-parameter subgroups can be re-expressed in terms of tangible physical concepts. If M is the phase-space of a physical process, then $x \in M$ describes the state of the system at some initial time t_0. A mapping $g_t : M \to M$ takes this state to the state at the later instant t, $g_t x$. These transformations g_t are also called the phase flow, as the phase space can be thought of as filled with a fluid, where a particle located at x flows to the point $g_t x$ during the time t. It is required that the particular order in which states are transformed is irrelevant. So $x \mapsto g_{t+s}x$ and $x \mapsto g_t x \mapsto g_s g_t x$ are identical. This condition, that $g_{t+s} = g_s g_t$, reveals the phase flow to be a one-parameter subgroup of M, $g_t = \exp(tX)$.

In a nutshell, each flow g_t, or curve in phase space, can be associated with a velocity vector field in the tangent space. The converse result is "perhaps the most important theorem relating calculus to science" (Frankel 1999, p. 31): roughly speaking, to each vector field corresponds a flow which has this particular vector field as velocity field. Moreover, the exact form of the flow can be found by solving a system of ordinary differential equations associated with the dynamics of the system, similar to (2.1).

At this point it is not yet obvious what the gained benefit of this lengthy formal derivation is. Indeed, it could appear that one is going round in circles. General references to the above discussed topics are Frankel (1999), Nakahara (2003), Arnold (1989).

3.1.4 Noether's Theorem: Digging Deeper

In more formal detail, Noether's theorem states that whenever a system (described by a Lagrangians L or $\mathcal{L}$ and obeying the Euler–Lagrange equations (3.1) and (3.6)) admits a one-parameter subgroup of diffeomorphisms (the Lagrangian is invariant under a the action of a continuous symmetry group) there is a conserved quantity. For instance, if the Lagrangian is invariant under time translations, spacial translations

[8] A structure preserving map.

or the angular rotation about some axis, then the energy, momentum or angular momentum, respectively, is conserved in the system.

Crucially, continuous symmetries are the cornerstone in Noether's theorem, unveiling the deep connection between the conservation of physical quantities and the formal language of symmetries. However, the truly universal importance of these symmetries in understanding natural phenomena only really started to become apparent with the further developments of quantum theory. Weyl, influenced by the work of Lie, was instrumental in helping foster the understanding of the symmetry structure of quantum mechanics, namely its group-theoretic basis (Weyl 1928, translated into English as Weyl 1950).

In a nutshell, the formal machinery related to symmetries is applied to Lagrangian densities describing quantum fields.[9] Digging deeper, by adding more analytical formalism to the mix, the insights gained in the abstract realm can be decoded back into the physical world, allowing for novel conserved quantities to emerge. Starting with a Lagrangian $\mathcal{L}$ describing an arbitrary vector field ψ^i $(i = 1, \dots, N)$, the invariance under a symmetry group G is expressed as

$$\mathcal{L}(\psi^i) = \mathcal{L}(\psi'^i), \tag{3.22}$$

where ψ'^i is the transformed field under the group action. The missing link required to specify how, in detail, a group element $g \in G$ acts as an operator on ψ^i, is called representation theory, a sub-field of group theory.

$\left\{ \oiint \right.$ |3.1.4-*representation-theory* >

In this framework, the abstract mathematical operators of a group are represented as linear transformations of a vector space V (over a field $\mathbb{F}$). This implies that a group element $g \in G$ is transformed as $g \to U(g)$, where now $U(g) : V \to V$ is a linear mapping. In other words, U is an element of $GL(V)$, the set of all linear transformations on V, called the general linear group. The advantage of this formal translation is gained from an important result of linear algebra. The structure of the transformation U can be encoded in a matrix[10] as

$$U(g)[v] = \mathrm{U}(v), \tag{3.23}$$

for $v \in V$. As a result, $GL(V)$ is isomorphic to $GL(n, \mathbb{F})$, the set of all $n \times n$ matrices U over the field $\mathbb{F}$. In effect, by mapping g via U to U, representation theory allows one to manipulate ever more concrete and tangible objects. The abstract quantity g reemerges as a matrix representation U with concrete physical connotation. Formally,

[9] See Sect. 10.1.1.

[10] In the scheme of things, a scalars s denotes a single real or complex number, a vector v^i is comprised of a row or column of scalars, a matrix M^{ij} contains a rectangular array of scalars, and a tensor $T^{i_1 \dots i_n}$ represents the most complex arrangement of scalars in a multidimensional array.

$$\begin{tikzcd}
\mathfrak{g} \arrow[r, "\mathfrak{U}"] \arrow[d, "\exp"'] & \mathfrak{gl}(V) \arrow[d, "\exp"] & \\
G \arrow[r, "U"] & GL(V) \arrow[r, "\rho"] & GL(n, \mathbb{F}) \\
g & U(g) & \rho[U(g)] = \mathrm{U}
\end{tikzcd}$$

Fig. 3.1 A commutative diagram showing the Lie algebra $\mathfrak{g}$, the exponential mapping to its corresponding Lie group G—described in (3.17) and (3.21)—the representation of $g \in G$ as an element of $U(g) \in GL(V)$, the Lie algebra of $GL(V)$, called $\mathfrak{gl}(V)$, with the representational mapping $\mathfrak{U}$ from $\mathfrak{g}$, and, finally, the matrix representation given by the mapping ρ yielding the matrix U

U can be expanded via the basis vectors of V as $\mathrm{U}^{ij} \in \mathbb{F}$. Recalling that the group G is associated with a corresponding Lie algebra $\mathfrak{g}$, Fig. 3.1 shows a diagrammatic representation of how all these concepts fit together.

< 3.1.4-*representation-theory*| $\oiint$ }

Before it is possible to explain how representation theory transitions from pure mathematics to physics, a detour into a special aspect of the framework of quantum mechanics is required. To specify the effect of the group action g on the vector field ψ^i, i.e., to uncover the form of ψ'^i, a powerful procedure from quantum field theory is invoked, called second quantization. In quantum mechanics, the properties of a physical system are encoded into a state vector $|\psi\rangle$, employing a notation introduced by Paul A. M. Dirac (1939), referred to as bra-ket notation (see, for instance also Sakurai 1994). $|\psi\rangle$ is a vector in an infinitely dimensional complex Hilbert space, an abstract vector space, generalizing the notion of Euclidean space, equipped with specific structures. Physical measurements are associated with linear operators on this space of quantum state vectors, called observables. From $|\psi\rangle$ the wave function $\psi(t, \mathbf{x})$ can be derived, which is interpreted as a probability amplitude, assigning $|\psi(t, \mathbf{x})|^2$ the role of a probability density for locating the particle at $\mathbf{x}$ at time t. This interpretation goes back to Max Born (Born 1926), winning him a Nobel Prize in 1954. The time evolution of the wave function is described by the Schrödinger equation (Schrödinger 1926a, b, c, d)

$$i\hbar\partial_t \psi(t, \mathbf{x}) = H\psi(t, \mathbf{x}), \tag{3.24}$$

where H is the Hamiltonian operator, characterizing the energy of the system, awarding Erwin Schrödinger a Nobel Prize in 1933. General textbooks on quantum mechanics are, for instance Feynman et al. (1965), Sakurai (1994), Messiah (2000), Schwabl (2007). In essence, a particle located at $(t, \mathbf{x})$ is described by the wave function $\psi(t, \mathbf{x})$. This idea is referred to as first quantization. To extend this notion of quantization from objects with three degrees of (spatial) freedom to quantum fields with infinite degrees of freedom, a procedure called second quantization is called for. Essentially, the wave function is promoted from a vector to an operator in a Hilbert space, see, for instance Schwabl (2008). There exist, however, various types quantization schemes that have been proposed over the decades, each coming with their own merits and drawbacks (Kaku 1993). A prominent example is Feynman's path integral formulation (Feynman 1942, 1948), see Sect. 9.1.

After this detour, in the context of second quantization, ψ^i is now understood as being on par with the transformation operator $U(g)$, and the effect of the group action g can be stated as

$$\psi'^i = U(g)\psi^i U^{-1}(g). \tag{3.25}$$

By virtue of this equation, it has become possible to link quantum fields with group theory. So not only is quantum field theory quantum mechanics extended to infinite degrees of freedom, it is, roughly speaking, also the merger of quantum theory with group theory. Namely in the sense that abstract group transformations are represented and thus realized as linear transformations on the vector spaces of quantum physics.

$\{\oiint$ |3.1.4-*representation-theory-continued* >

It should be noted that (3.25) can be understood in the terms of linear algebra as a similarity transformation of matrices, where ψ^i and ψ'^i represent the same operator under two different bases. Using the power of representation theory (Tung 1993; Cornwell 1997), the effect of the transformation can be explicitly formulated[11] as

$$U(g)\psi^i U^{-1}(g) = \mathrm{U}^i_j \psi^j, \tag{3.26}$$

employing Einstein's summation convention. In a final step, the effect of the group action on the vector field can now be solely derived from the knowledge of the Lie algebra. As the Lie group G is a continuous transformation group, its elements can be naturally parametrized, for instance, by the set of scalars θ_k, as $g = g(\theta_1, \dots, \theta_n)$, with $n = \dim(G)$. These variables carry over into the matrix $\mathrm{U} = \mathrm{U}(\theta_1, \dots, \theta_n)$.

By virtue of (3.21), U can be associated with a one-parameter subgroup of G. Alternatively, via (3.18), U is understood as a continuous symmetry. In the end, the generators $X^a \in \mathfrak{g}$ encode the information for the group action

$$\mathrm{U}(\theta_1, \dots, \theta_n) = \exp(\theta_k \mathrm{X}^k), \tag{3.27}$$

where the matrices X^k are a matrix representation of the Lie algebra generators X^k, implying that they satisfy the commutation relations (3.19). In other words, the Lie brackets of the matrix representations must obey the Jacobi identity. As the structure

[11]Two technicalities are glossed over here. For one, $\psi^i = \psi^i(x^\mu)$ and x^μ is also affected by the transformation. In addition, there is the issue of passive and active transformations, see, for instance Schwabl (2008).

constants f^{kij} satisfy a similar relation, the elements of the matrix representations can be defined as

$$[\mathrm{X}^k]^{ij} := f^{kij}. \tag{3.28}$$

By construction, this simple definition of the matrices X^k captures all the features of the Lie algebra, satisfying (3.19), and is called the adjoint representation.[12] All these manipulations culminate in the following equation, reducing the effect of the symmetry group action on the vector filed to the structure constants of the Lie algebra. Expanding (3.25)–(3.27) in a Taylor series yields

$$\begin{aligned} \psi'^i &= \exp\left(\theta_k [\mathrm{X}^k]^i{}_j\right) \psi^j = \exp\left(\theta_k f_j^{ki}\right) \psi^j \\ &= \psi^i + \theta_k f_j^{ki} \psi^j + \mathcal{O}(\theta^2), \end{aligned} \tag{3.29}$$

for generators close to the identity element. The symbol $\mathcal{O}$, also known as big-O notation, generally describes the asymptotic behavior of a function, or, in this case, encapsulates higher order terms. In a more compact notation, the Lagrangian of a vector field is invariant under a symmetry group G, transforming $\psi^i \to \psi'^i$, if (3.22) holds. Then, for infinitesimal transformations

$$\psi'^i = \psi^i + \theta_k f_j^{ki} \psi^j = \psi^i + \delta\psi^i. \tag{3.30}$$

Building on this procedure, Noether's theorem can now easily be proved. The change in the quantum field ψ^i, induced by the symmetry transformation and encoded as $\delta\psi^i$, causes a corresponding perturbation in the Lagrangian

$$\delta\mathcal{L} = \frac{\delta\mathcal{L}}{\delta\psi^i}\delta\psi^i + \frac{\delta\mathcal{L}}{\delta(\partial_\mu\psi^i)}\delta(\partial_\mu\psi^i). \tag{3.31}$$

Utilizing the Euler–Lagrange equations for Lagrange densities, the field-theoretic version of (3.1), yields

$$\delta\mathcal{L} = \theta_k \partial_\mu \left[\frac{\delta\mathcal{L}}{\delta(\partial_\mu\psi^i)} f_j^{ki} \psi^j\right] =: \theta_k \partial_\mu \mathcal{J}^{\mu k}. \tag{3.32}$$

The invariance requirement $\delta\mathcal{L} = 0$ leads to a conserved quantity $\mathcal{J}$. See, for instance Cheng and Li (1996).

< 3.1.4-*representation-theory-continued* | $\oiint$ $\}$.

[12] Adding a symbol for this element to the empty top right-hand corner of Fig. 3.1 would complete the diagram.

3.2 Symmetry Manifested

Symmetry is perhaps the profoundest concept ever to be discovered in theoretical physics, uncovering deep truths about the workings of reality. It lies at the heart of special relativity and quantum theory, as will be demonstrated in the following sections.

3.2.1 Causality and the Relation of Space and Time

The experimental discovery that light propagates at a constant speed c, regardless of the speed of any observer, posed a great challenge to physicists. The resolution would transform physics as it was known and reveal deep connections between different laws of physics.

In April and July of the year 1887, Albert A. Michelson and Edward Morley set up an experiment to verify the existence of the aether, a postulated substance that permeated all of space and acted as the medium for light to propagate in. The result was negative. Not only was there no aether to be detected, but more puzzlingly, velocities could not be simply added up linearly, as Galileo Galilei had envisioned in his theory of relativity.

One year after the Michelson–Morley experiment, George FitzGerald proposed the revolutionary idea that the Galilean transformation should be replaced with a transformation that mixes space and time coordinates in inertial frames (Faraoni 2013). This was the first postulation hinting at the malleability of space and time. Hendrik Lorentz, soon after, introduced a fully-fledged transformation rule, today named after him. Consider an inertial frame described by the space and time coordinates $\{t, x, y, z\}$. An additional inertial frame $\{t', x', y', z'\}$ is moving with relative velocity v in direction of the x-axis. The following transformation rule describes the mathematics behind moving from $\{t, x, y, z\}$ to $\{t', x', y', z'\}$, called a Lorentz boost

$$\begin{aligned} t \to t' &= \frac{x - vt}{\sqrt{1 - \frac{v^2}{c^2}}}, \\ x \to x' &= y, \\ y \to y' &= z, \\ z \to z' &= \frac{t - \frac{vx}{c^2}}{\sqrt{1 - \frac{v^2}{c^2}}}. \end{aligned} \tag{3.33}$$

Historically, Lorentz derived his transformation rule employing the newly discovered invariance of the speed of light, the fact that all observers measure the same value for c in their reference frames. Consider a spherical pulse of electromagnetic radiation emitted at the origin of each inertial system at $t = 0$. It propagates along the x and x'-axis as follows

$$\begin{aligned} x &= ct, \\ x' &= ct'. \end{aligned} \tag{3.34}$$

From this consistency requirement, the Lorentz transformation in (3.33) can be derived (Faraoni 2013).

However, the Lorentz transformation reveals a far deeper truth. The constant c appearing in (3.33) denotes a fundamental velocity, which is a priori unrelated to the speed of light in a vacuum. Let us call it c_{sc}, representing a space-time structure constant. If one postulates that reality should make sense, then the Lorentz transformation is the only possible solution. In other words, in a comprehensible universe, the laws of physics are unchanged in reference frames and are independent of position, orientation, and velocity. This consistency assumption translates into the following commonsensical requirements that:

(1) There exist no preferred reference frames.
(2) It is possible to transform between observers in reference frames.

Only by adhering to these postulates, the Lorentz transformation can be derived, without any reference to c, the invariant speed of light (von Ignatowsky 1911; Pelissetto and Testa 2015). Now, the constant velocity c_{sc} appearing in (3.33) is interpreted as the speed of causality, the theoretical maximal velocity of information transmission in the universe (Landau and Lifshitz 1951). To understand this, the theory of special relativity, building on Lorentz' insights, had to be formulated.

Einstein interpreted the meaning of the Lorentz transformation in his theory of special relativity, yielding the theory's prominent predictions: time dilation, length contraction, and the equivalence of mass and energy $E = mc^2$. He original introduced special relativity in 1905 based on two postulates of symmetry (Einstein 1905):

(1) The laws of physics are invariant in all inertial systems (i.e., non-accelerating frames of reference)
(2) The speed of light in a vacuum is the same for all observers (regardless of the motion of the light source).

Enforcing Lorentz invariance for Postulate (2) results in the mixing of space and time. As a result, observers disagree on the chronological order of events—someone's past is in someone else's future. This dramatic turn of events threatened to render time and causality meaningless. Luckily, the universe conspires in a way to uphold a more general notion of causality than the temporal one we naively assumed to exist. If causality is expressed as a space-time interval, then it becomes a universal property all observers agree on. In mathematical terms

$$(\Delta s)^2 := (c\Delta t)^2 - (\Delta x)^2 - (\Delta y)^2 - (\Delta z)^2. \tag{3.35}$$

The space-time interval $(\Delta s)^2$ encodes the separation of events in space-time and it holds that

$$(\Delta s)^2 = (\Delta s')^2, \tag{3.36}$$

for all reference frames. Due to the minus sign, $(\Delta s)^2$ can be positive, zero, or negative. This means that the space-time interval between two distinct events can result in the events being separated by more time than space, or vice versa. In other words, the space-time interval between events A and B says something about if and how A can influence B. This is a description of causality, which is invariant and universally agreed upon by all observers. Having lost causality in time, we rediscover it in space-time. Mathematically, this is described by a Minkowski space, a four-dimensional reality that contains all past, present, and future events (see Sect. 3.2.2.1 below for a more formal definition). The notion of space-time invokes the analogy of a block universe, where the passage of time is an illusion. All observers in space-time move through the block and experience slices of it as their present. In this sense, the entire unchanging time-line of an observer represents their reality. So, why do our brains make us perceive space-time so vividly as a distinctly spatial entity evolving in time? No one knows, but this apparent atemporal reality underlying our illusion of the passage of time can be consoling. During Einstein's early years, he worked in obscurity in the patent office in Bern with Michele Besso. When Besso died in 1955, Einstein wrote to the widow (Wuppuluri and Ghirardi 2017, p. 469):

> Now he has departed from this strange world a little ahead of me. That signifies nothing. For those of us who believe in physics, the distinction between past, present and future is only a stubbornly persistent illusion.

Two weeks later, Einstein would also die.

The question remains how the speed of causality c_{sc} in the Lorentz transformation, derived solely from the relation between space and time, is related to the speed of light. Yet again, invariance gives the answer. Maxwell's equations (2.4), encoding everything there is to know about electromagnetism, are only invariant under Lorentz transformations for a very specific value of c_{sc}. The fundamental speed limit of causality and the contents of Maxwell's equations have to interrelate, in order for invariance to be upheld.

It was known that a wave equation, describing the propagation of electromagnetic radiation, can be easily derived from Maxwell's equations (Jackson 1998). The speed of these waves is derived from the two fundamental constants appearing in the equations: the permittivity (ε_0) and the permeability (μ_0) of the vacuum. They combine to yield a theoretical definition of the velocity of electromagnetic radiation—in other words, the speed of light. It is found that

$$c := \sqrt{\frac{1}{\varepsilon_0 \mu_0}}. \tag{3.37}$$

This is the only speed massless particles can travel at and particles with mass can never reach this speed. Equipped with this knowledge, the final piece of the puzzle is found, where $c_{sc} = c$.

> The Lorentz transformation is a manifestation of a deep symmetry in nature. Requiring physical theories to be Lorentz invariant results in the speed of causality being the constant speed of light. Moreover, the Lorentz transformation reveals the intimate interplay of space and time, setting the stage for special relativity.

3.2.2 Elementary Particles

Continuing with the story, another surprising and deep link between symmetry and the nature of elementary particles becomes apparent. This insight would also be awarded with a Nobel Prize.

3.2.2.1 The Lorentz Group

A prominent example of a Lie group G is the Lorentz group $\mathscr{L}$. As a group of transformations it encodes fundamental symmetries of space-time. In detail, $\mathscr{L}$ is the group of the isometries of space-time, i.e., distance-preserving maps between spaces endowed with a metric, which leave the origin fixed.

Formally, the merger of space and time is accomplished by the means of Minkowski space, a four-dimensional manifold. A vector in this space is comprised of $x^\mu = (t, \mathbf{x})$, where natural units[13] are assumed. This is the abstract setting in which Einstein's theory of special relativity is formulated. The metric tensor associated with flat Minkowski space-time is simply a diagonal matrix $g^{\mu\nu} = \mathrm{diag}(-1, 1, 1, 1) = -g_{\mu\nu}$. Hence $x_\mu = g_{\mu\nu} x^\nu = (t, -\mathbf{x})$. Sometimes the notation $\eta^{\mu\nu}$ is used for flat space-time, reserving $g^{\mu\nu}$ for the curved case. The Lorentz group can be represented as the generalized orthogonal group $O(1, 3)$, the matrix Lie group which preserves the quadratic form $ds^2 = g_{\mu\nu} dx^\mu dx^\nu = dt^2 - dx^2 - dy^2 - dz^2$. Recall (3.35) defining the space-time interval.

As Maxwell's field equations in the theory of electrodynamics, seen in (2.4), the Dirac equation,[14] and the kinematic laws of special relativity, given in (4.56), are all invariant under Lorentz transformations, the corresponding Lorentz group is understood as encoding the symmetries of fundamental laws of nature.

$\Big\{ \oiint$ |3.2.2.1-*lorentz-transformation* >

In detail, a general group element $\varLambda \in \mathscr{L}$ induces the transformation

[13] In the context of physics this means, for instance, $c = \hbar = 1$.

[14] A relativistic wave equation describing electrons and quarks, described below in (3.41) and (3.42).

$$x^{\mu} \to x'^{\mu} = \Lambda^{\mu}_{\ \nu} x^{\nu}. \tag{3.38}$$

A concrete example of Λ is the Lorentz boost seen in (3.33). In analogy to (3.26), the effect of $\mathscr{L}$ on a generic quantum field ψ^{ρ} is captured by the following expression

$$U(\Lambda)\psi^{\rho}(x^{\mu})U(\Lambda^{-1}) = [\mathrm{U}(\Lambda^{-1})]^{\rho}_{\ \sigma}\psi^{\sigma}(\Lambda x^{\mu}), \tag{3.39}$$

where U is the operator representing Λ on the Hilbert space where ψ^{ρ} is defined, with the corresponding matrix representation on the right-hand side.

< 3.2.2.1-*lorentz-transformation*| $\oiint$ }

Fields transforming as (3.39) are called spinors. These objects, requiring 720° to complete a full rotation, reflect the true rotational symmetry of space. As mentioned earlier, spinors represent mass particles, i.e., leptons and quarks, and are generally categorized as fermions, particles carrying half-integer spin. It is an interesting piece of history, that it took a long time for physicists to understand these strange quantities existing in Minkowski space. Paul Ehrenfest, coining the term spinor, remarked in 1932 (adapted from a translated quote seen in Tomonaga 1997, p. 130):

> By all measures, it is truly strange that absolutely no one, until the work of Pauli [...] and Dirac, which is twenty years after special relativity [...], suggested this eerie proposition, that a mysterious tribe by the name of the spinor family inhabits isotropic [three-dimensional] space or the Einstein-Minkowski world.

Until the full connection between the transformation properties of spinors and the Lorentz group were uncovered, spinors had raised their heads at various points in time. In their most general mathematical form they were discovery by Éli Cartan in 1913 (Cartan 1913, 1938, 1966), a mathematician who was involved in fundamental work on the theory of Lie groups and also their geometric applications. Then, due to efforts aiming at incorporating the notion of spin into the framework of quantum mechanics, in other words, by constructing a quantum theory of the electron, Wolfgang Pauli and Dirac found equations describing the behavior of spinors (Pauli 1927; Dirac 1928). As these entities were comprised of two respectively four elements, they were simply referred to as two-component or four-component quantities. In 1928, Dirac started to investigate how the Schrödinger equation (3.24), could be made consistent with the principles of special relativity, in effect marrying quantum mechanics and relativity. Formally, he was searching for a Lorentz invariant quantum wave equation, incorporating spinor fields $\psi(x^{\nu})$ with mass, describing electrons and quarks. This straightforward task would lead him deeper into the abstract world, as this feat could only be accomplished by introducing novel mathematical quantities. In order to sculpture yet another variation of the theme of derivatives, Dirac introduced a set of specific matrices γ^{μ}, $\mu = 0, \dots, 3$. Today, they are known as Dirac matrices and the new derivative takes the from

$$\not{\partial} := \gamma^{\mu}\partial_{\mu}, \tag{3.40}$$

introducing Feynman's slash notation. The Dirac equation for a free spin-1/2 particle with mass m reads

$$(i\not{\partial} - m)\psi = 0. \tag{3.41}$$

In the presence of an electromagnetic field, encoded in the 4-vector potential A_{μ} of (4.12), the equation takes on the form

$$(i\not{\partial} - e\not{A} - m)\psi = 0, \tag{3.42}$$

where e is the elementary charge. The Dirac Lagrangian reads

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}\gamma^{0}(i\not{\partial} - m)\psi, \tag{3.43}$$

with the Hermitian conjugate $\bar{\psi}$. As usual, the equations of motion, in this case the Dirac equation (3.41), can be derived from the Lagrangian utilizing the Euler–Lagrange equations (3.6). Dirac's insights opened up a whole new section in the Book of Nature, see Collins et al. (1989), Kaku (1993), Peskin and Schroeder (1995), Ryder (1996). More on the history of spin can be found in the book of the Nobel laureate Sin-itiro Tomonaga (Tomonaga 1997).

$\left\{ \oiint \right.$ |3.2.2.1-*lorentz-group-representation* >

The generators $M^{\mu\nu}$ of the Lie algebra $\mathfrak{o}(1,3)$ of the Lorentz group satisfy the specific commutation relations

$$\left[M^{\mu\nu}, M^{\rho\sigma}\right] = i\left(g^{\nu\rho}M^{\mu\sigma} - g^{\mu\rho}M^{\nu\sigma} - g^{\nu\sigma}M^{\mu\rho} + g^{\mu\sigma}M^{\nu\rho}\right), \tag{3.44}$$

encoding the properties of $\mathrm{U}(\Lambda) \in O(1,3)$. An explicit matrix representation is found to be

$$[\mathrm{M}^{\mu\nu}]^{\rho}{}_{\sigma} = i(g^{\mu\rho}\delta^{\nu}{}_{\sigma} - g^{\nu\rho}\delta^{\mu}{}_{\sigma}), \tag{3.45}$$

employing Kronecker's delta. Parameterizing $\Lambda = \Lambda(\omega)$, the operators, following (3.27), can be defined via these generators in the Lie algebra

$$\mathrm{U}(\Lambda) = \exp(i\omega_{\mu\nu}\mathrm{M}^{\mu\nu}). \tag{3.46}$$

A Lorentz transformation is now explicitly implemented on a 4-vector field V^{ρ}, similarly to the generic case seen in, as (3.39)

$$V'^{\rho}(x^{\mu}) = V^{\rho}(\Lambda x^{\mu}) + i\omega_{\mu\nu}[\mathrm{M}^{\mu\nu}]^{\rho}{}_{\sigma}V^{\sigma}(\Lambda x^{\mu}). \tag{3.47}$$

Compare with (3.29). In summary, the representation of the Lorentz group given by $M^{\mu\nu}$ yields the transformation rules for Lorentz vectors V^ρ. There is, however, another important representation to be uncovered, which is related to spinor fields $\psi^\alpha(x^\nu)$. The representation matrices are

$$\Sigma^{\mu\nu} := \frac{i}{4}[\gamma^\mu, \gamma^\nu], \tag{3.48}$$

defined via the Dirac matrices. By replacing $V^\rho \to \psi^\alpha$ and $[\mathrm{M}^{\mu\nu}]^\rho_{\ \sigma} \to [\Sigma^{\mu\nu}]^\alpha_{\ \beta}$ in (3.47), the transformation property of 4-component spinors under Lorentz transformations is discovered. The matrices $\Sigma^{\mu\nu}$ are the generators of the spinor representation of the Lorentz group, derived solely from the Dirac matrices. For more details, see, for instance, Peskin and Schroeder (1995). In Sect. 4.3.2, starting from (4.61), more layers of abstraction will be uncovered.

< 3.2.2.1-*lorentz-group-representation*| $\oiint \Big\}$

In summary, quantum fields[15] can be understood by virtue of their transformation properties specified by representations of the Lorentz group. This feat does not only apply to spinors but can generally be extended to bosons: scalar spin-0 fields, vector spin-1 fields, and tensor spin-2 fields can all be characterized by specific representations of $\mathscr{L}$. General references are Tung (1993), Schwabl (2008).

> The Lorentz group encodes the symmetries of fundamental laws of nature: electromagnetism, special relativity, and the quantum behavior of the electron (via the Dirac equation), as all quantum fields transform as representations of the Lorentz group.

3.2.2.2 The Poincaré Group

The Poincaré group $\mathscr{P}$ extends the Lorentz group by an additional transformation

$$x^\mu \to x'^\mu = x^\mu + a^\mu. \tag{3.49}$$

This is simply a translation in space-time along the vector a^μ.

$\Big\{ \oiint$ |3.2.2.2-*poincare-group* >

[15] See also Sect. 10.1.1.

In essence, $\mathscr{P}$ represents all isometries of Minkowski space by combining Lorentz transformations with translations:

$$x^{\mu} \to x'^{\mu} = \Lambda^{\mu}_{\ \nu} x^{\nu} + a^{\mu}, \tag{3.50}$$

The Poincaré group is generated by the Lorentz group generators $M^{\mu\nu}$, recalling (3.46), and the additional generators P^{μ}, obeying specific commutation relations. It can be shown that $P^{\mu} = i\partial^{\mu}$ (Ryder 1996). This is in analogy with ordinary quantum mechanics, where classical quantities are replaced by operators. For instance, energy and momentum:

$$E \to i\partial_t, \quad \mathbf{p} \to \nabla / i, \tag{3.51}$$

see, for instance Schwabl (2007). In effect, a state in the Hilbert space representing a massive particle with 4-momentum $p^{\mu} = (m, \mathbf{p})$, written in bra-ket notation (Sakurai 1994) as $|p^{\mu}\rangle$, satisfies the eigenvalue equation $P^{\mu}|p^{\mu}\rangle = p^{\mu}|p^{\mu}\rangle$.

The full commutation relations defining the Poincaré algebra are

$$\begin{aligned} \left[P^{\mu}, P^{\nu}\right] &= 0, \\ \left[P^{\mu}, M^{\nu\rho}\right] &= i\left(g^{\mu\nu}P^{\rho} - g^{\mu\rho}P^{\nu}\right), \\ \left[M^{\mu\nu}, M^{\rho\sigma}\right] &= i\left(g^{\nu\rho}M^{\mu\sigma} - g^{\mu\rho}M^{\nu\sigma} - g^{\nu\sigma}M^{\mu\rho} + g^{\mu\sigma}M^{\nu\rho}\right), \end{aligned} \tag{3.52}$$

where $g^{\mu\nu} = \mathrm{diag}(1, -1, -1, -1)$ represents the flat space-time metric as in the case of the Lorentz group.

Lie algebras contain special elements called Casimir operators. By definition, they commute with all generators in the Lie algebra. The representations of the group can always be labeled by the eigenvalues of the Casimir operators (Tung 1993; O'Raifeartaigh 1988). The Poincaré group has two Casimir operators, $C_1 = P_{\mu}P^{\mu}$ and $C_2 = W_{\mu}W^{\mu}$, where W^{μ}, called the Pauli–Lubanski tensor, is a function of P^{ν} and $M^{\rho\sigma}$.

< 3.2.2.2-*poincare-group*| ∯ }

Using this mathematical machinery, Eugene Wigner could demonstrate the following remarkable fact (Wigner 1939):

> All known physical particle states transform as representations of the Poincaré group.

These insights would win him the Nobel Prize in 1963.

{ ∯ |3.2.2.2-*casimir-operator* >

In detail, the eigenvalues[16] of the Casimir operators are

$$C_1 = m^2, \quad C_2 = m^2 s(s+1), \tag{3.53}$$

where m represents the particle's mass and s its spin. The resulting representations are associated with the following particle states

$$\begin{aligned} &|m, s\rangle; \quad s = \frac{1}{2}, 1, \frac{3}{2}, \ldots \\ &|h\rangle; \quad h = \pm s, \end{aligned} \tag{3.54}$$

where h is the generalization of spin to mass-less states called helicity and $|m, s\rangle$ labels particle state distinguished by their mass and spin.

< 3.2.2.2-*casimir-operator*| $\oiint$ }

Wigner's work also sheds light on the question why particles have quantized spin and establishes that spin is indeed associated with the group of rotations, justifying and formalizing the vague notion of understanding spin as an intrinsic quantum form of angular momentum. General references are Tung (1993), Kaku (1993), Ryder (1996).

It should, however, also be noted, that other states associated with further possible representations have not been observed in nature. As an example, Wigner's classification also yields tachyons. These are particles with $m^2 < 0$, implying imaginary mass. Using the equation for the total relativistic energy of a particle with rest mass m (Einstein 1956), and switching to the SI system of units

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}, \tag{3.55}$$

the condition $v > c$, implying a speed faster than light, results in $E = m'c^2/ib$, for some real number b. As E is a real number by definition, this requires $m' = im$, establishing tachyons, defined by imaginary mass, as being superluminal particles.

{ $\oiint$ |3.2.2.1-*quantum-fields-and-particle-states* >

Finally, the groups $\mathscr{L}$ and $\mathscr{P}$, with their representations describing the transformation properties of quantum fields and physical particle states, respectively, are related as follows. Recalling that in bra-ket notation, an arbitrary state is described

[16] For an operator A acting on a vector v, the eigenvalue equation reads $Av = \lambda v$, with the eigenvalue λ.

by $|\psi\rangle$, the wave function associated with this state is found to be $\psi(x^\mu) = \langle x^\mu|\psi\rangle$. In momentum-space, this wave function can be re-expressed as $\Psi(p^\mu) = \langle p^\mu|\psi\rangle$, where the relationship between ψ and Ψ is established by a Fourier transformation (Sakurai 1994). Both fields transform identically under Lorentz transformations. A wave equation for Ψ, for instance the Schrödinger or Dirac equation, allows the quantity to be expanded in terms of coefficients which transform as representations of the Poincaré group, i.e., identically to the particle states (Tung 1993, Section 10.5.3).

< 3.2.2.1-*quantum-fields-and-particle-states* **|** $\oiint \Big\}$

Conclusion

Symmetry, unexpectedly, emerged as an abstract notion running like a golden thread through the Book of Nature, intimately mirroring the structure of the tapestry of reality. This chapter only disclosed the beginning of the power of symmetry. In the next chapter, the concept of symmetry allows dramatically different physical theories to be unified in a single unified description of the universe. In other words, symmetry is a Rosetta Stone able to decipher the different hieroglyphic scripts of physics into a unified language.

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Chapter 4
The Unification Power of Symmetry

Abstract The introduction of a new kind of symmetry ushered in a golden era for theoretical physics. The marriage of this novel gauge theory with quantum field theory culminated in the standard model of particle physics. This is the unified description of all three non-gravitational forces in the universe, a momentous milestone in human knowledge generation. Inspired by this success, physicists hoped for a "theory of everything," uniting the standard model with general relativity, the theory of gravity. These attempts uncovered five ten-dimensional superstring theories, unified within an overarching eleven-dimensional framework called M-Theory. To this day, the theory of everything remains an elusive dream. Albert Einstein, arguably the most insightful physicists, played a rather tragic role in the history of unification and quantum theory.
Level of mathematical formality: high (however, the mathematically involved parts are encapsulated and demarcated by the tags $\{\oiint \ldots \oiint\}$, hence easily bypassed).

All the previous accounts of symmetry have one thing in common: they are all instances of global symmetry principles. This means that these symmetries are unchanged for all points in space-time. The introduction of a new kind of twist on the idea of symmetry in 1918 unlocked even greater powers of this abstract formalism in its propensity to probe reality, paving the way for a novel type of field theory to flourish. Today, the tremendous success of the mathematical framework underlying the standard model, providing a unified and overarching theory of all non-gravitational forces, can be understood to rest on the insights gained from what is known as gauge theory. The idea fueling this novel approach is related to a new kind of symmetry, called gauge symmetry. It is a local symmetry, meaning that its properties are now a function of the space-time coordinates x^μ. This principle was first fully formulated, independently, by Hermann Weyl and Emmy Noether in the same year (Brading 2002). However, the course of the history of gauge theory, and in parallel the road to unification, would take meandering paths.

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4.1 Back to Geometry: The Principle of Covariance

Einstein's theory of general relativity, sketched in (3.14), is an extremely elegant and aesthetic physical theory. It is based on two very subtle principles, a physical and a mathematical requirement.

The physical principle is known as the equivalence principle. Sometimes, seemingly innocuous observations have the power to help uncover deep truths about the workings of nature. Say, a ball rolling in a toy wagon or a spinning bucket. To quote from Matthews (1994):

> As a child, the Nobel Prize-winning physicist Richard Feynman asked his father why a ball in his toy wagon moved backward whenever he pulled the wagon forward. His father said that the answer lay in the tendency of moving things to keep moving, and of stationary things to stay put. "This tendency is called inertia," said Feynman senior. Then, with uncommon wisdom, he added: "But nobody knows why it is true."

Inertia, the measure of a body's resistance to acceleration, is encoded in Newton's second law describing the resulting force F due to the acceleration $a = \ddot{x}$ reads $F = m_{\mathrm{i}}a$. The mass term m_i appearing in this equation is called inertial mass. This is to distinguish it from the mass term appearing in Newton's law of universal gravitation,[1] called gravitational mass m_{g}. A simple experiment, going back to Newton, is the following. A bucket partly filled with water is hung from a long cord and rotated so many times until the cord becomes strongly twisted. By releasing the bucket, after ensuring the water is at rest, it will rotate in the other direction due to the cord untwisting. Slowly the water begins to rotate with the bucket and as it does so the water moves to the sides of the bucket. In effect, the surface of the water becomes concave. This effect is not due to the water spinning relative to the bucket, as, at some point, the bucket and the water are spinning at the same rate while the surface stays concave. Again, the question of inertia emerges. Why should the surface of the water bulge? What is the origin of this effect? One explanation was proposed by the philosopher and physicist Ernst Mach. He attributed the source of inertia to the whole matter content of the universe, an idea today referred to as Mach's principle (Misner et al. 1973). This principle guided Einstein in his formulation of general relativity (Penrose 2004, p. 753). In his equivalence principle, Einstein asserted that the gravitational mass m_{g} is equivalent to the inertial mass m_{i}. In other words, the acceleration a body experiences due to its mass being exposed to the pull of the gravitational force, is independent of the nature of the body. The insight leading to the postulation of this principle, Einstein would later call "the happiest thought of my life" (Thorne 1995, p. 97). This thought was the following, quoting Einstein in Thorne (1995, p. 96f.):

> I was sitting in a chair in the patent office at Bern, when all of a sudden a thought occurred to me: "If a person falls freely, he will not feel his own weight."

In effect, the principle of equivalence states that there is no local way of knowing if one is feeling the effect of gravitational pull or the force due to acceleration. So a

[1] Seen in (4.55).

free falling observer will not detect any traces of gravity in her local reference frame, and only the laws of special relativity apply. Einstein soon derived two testable consequences of the equivalence principle, namely that gravity bends light, and that the frequency of radiation varies with the strength of gravity (Torretti 1999, p. 290). Unfortunately, it was later shown that Mach's principle is not actually incorporated in general relativity (Penrose 2004, p. 753), and still today the origins of inertia are puzzling (Matthews 1994). Thus, seemingly obvious and uncontroversial aspects of reality can have very deep and mysterious connotations.

Leaving the physical world and returning to the realm of mathematical abstractions, Einstein required another principle to base general relativity on. This mathematical requirement is intimately interwoven with the ideas of invariance, related to symmetry and is called the principle of (general) covariance. In a nutshell, it states that the contents of physical theories should be independent of the choice of coordinates needed to make explicit calculations. In accordance with the insights gained from analyzing symmetry transformation, the equations of general relativity are invariant under general (differentiable) coordinate transformations: they are covariant. Lorentz transformations, seen in (3.38), can also be understood as coordinate transformations. This means that they do not infer a change in the physical system anymore, but now relate to the choice of the coordinate system used for labeling and measuring abstract vectors and tensors. As an example, some manipulations on the vector $\boldsymbol{a} \in \mathbb{R}^3$ only become possible once a coordinate system is chosen, relative to which the vector components a_1, a_2, and a_3 can be assigned numbers. For instance, if $\boldsymbol{a} = (1, 1, 1)$ is one manifestation then a 45° rotation around the x_3-axis of the coordinate system reveals $\boldsymbol{a}' = (\sqrt{2}, 0, 1)$. As this is still the same abstract entity, its properties, such as the length,[2] must stay unchanged: $|\boldsymbol{a}| = \sqrt{3} = |\boldsymbol{a}'|$. Covariance may not appear like a particularly profound insight into the workings of nature, as one could argue that theses are common sense requirements for a physical theory. However, the ramifications are far-reaching and profound.

$\left\{ \oiint \right.$ $|4.1\text{-}\mathit{covariant\text{-}derivative}>$

Formally, general coordinate transformations in four-dimensional space-time are defined as follows

$$x^\mu \rightarrow x'^\mu = x^\mu + \xi^\mu(x^\mu), \tag{4.1}$$

where ξ^μ is some smooth function of the coordinates. This can be rephrased infinitesimally[3] in general terms for a vector $\mathrm{d}x^\mu$ as

[2] This is also called the norm of a vector: $|\mathbf{X}| := \sqrt{x_1^2 + x_2^2 + x_3^2}$.

[3] Infinitesimal quantities are the cornerstone of the notion of derivatives in calculus. The idea being, that, for instance, a small displacement along the x-axis, Δx, is infinitesimally set to the approach zero, yielding $\mathrm{d}x$, an abstract non-zero quantity.

$$\mathrm{d}x^{\mu} \to \mathrm{d}x'^{\mu} = \frac{\partial x'^{\mu}}{\partial x^{\nu}} \mathrm{d}x^{\nu}, \tag{4.2}$$

where the new set of general coordinates are denoted by the prime symbol, and $x'^{\mu} = x'^{\mu}(x^{\nu})$ describe the same point in space-time as x^{ν}. These transformations are represented by elements of $GL(4, \mathbb{R})$, i.e., real 4×4 matrices:

$$\Delta^{\mu'}_{\ \nu} := \frac{\partial x'^{\mu}}{\partial x^{\nu}}. \tag{4.3}$$

It should be noted that

$$\Delta^{\mu'}_{\ \nu} \Delta^{\nu}_{\ \lambda'} = \delta^{\mu'}_{\ \lambda'} = \delta^{\mu}_{\ \lambda} = \Delta^{\mu}_{\ \nu'} \Delta^{\nu'}_{\ \lambda}, \tag{4.4}$$

employing Kronecker's delta. These transformation matrices can be used to define vectors and tensors. In other words, the details of how an object transforms covariantly under general coordinate transformations renders it a vector or a tensor. As an example, for a second-rank tensor transforms as

$$T'^{\nu}_{\ \mu} = \Delta^{\nu'}_{\ \sigma} \Delta^{\rho}_{\ \mu'} T^{\sigma}_{\ \rho}. \tag{4.5}$$

Although the placement of the indices in the subscript or superscript is related to the details of the transformation properties,[4] these technicalities are irrelevant for this discussion. It suffices to recall that the metric tensor can be utilized to lower or raise indices, e.g., $A_{\mu} = g_{\mu\nu} A^{\nu}$. The metric also transforms as a second-rank tensor:

$$g'_{\mu\nu} = \Delta^{\sigma}_{\ \mu'} \Delta^{\rho}_{\ \nu'} g_{\sigma\rho}. \tag{4.6}$$

Looking at the transformation properties of a derivative of a vector $\partial_{\nu} A^{\mu}$, with $\partial_{\nu} := \partial / \partial x^{\nu}$, one finds

$$\begin{aligned} \partial'_{\mu} A'^{\nu} &= \left(\Delta^{\sigma}_{\ \mu'} \partial_{\sigma}\right) \left(\Delta^{\nu'}_{\ \rho} A^{\rho}\right) \\ &= \Delta^{\sigma}_{\ \mu'} \left(\partial_{\sigma} \Delta^{\nu'}_{\ \rho}\right) A^{\rho} + \Delta^{\sigma}_{\ \mu'} \Delta^{\nu'}_{\ \rho} \left(\partial_{\sigma} A^{\rho}\right), \end{aligned} \tag{4.7}$$

using the product rule. The first term in the second line of the equation breaks the transformation law for a second-rank tensor. In order to restore covariance, a new kind of derivative is introduced, called the covariant derivative

$$\nabla_{\mu} A^{\nu} := \partial_{\mu} A^{\nu} - \Gamma^{\nu}_{\ \mu\lambda} A^{\lambda}, \tag{4.8}$$

where $\Gamma^{\nu}_{\ \mu\lambda}$ are the Christoffel symbols seen in (3.13), which have the following special transformation properties

[4] Called covariant and contravariant behavior.

$$\Gamma'^{\nu}{}_{\mu\lambda} = \Delta^{\alpha}{}_{\mu'}\Delta^{\beta}{}_{\lambda'}\Delta^{\nu'}{}_{\gamma}\Gamma^{\gamma}{}_{\alpha\beta} + \Delta^{\alpha}{}_{\mu'}\Delta^{\beta}{}_{\lambda'}\left(\partial_\alpha \Delta^{\nu'}{}_{\beta}\right). \tag{4.9}$$

Now the covariant derivative can be seen to transform correctly under general coordinate transformations

$$(\nabla_\mu A^\nu)' = \nabla'_\mu A'^\nu = \Delta^{\sigma}{}_{\mu'}\Delta^{\nu'}{}_{\rho}\left(\nabla_\sigma A^\rho\right), \tag{4.10}$$

where the second term in the transformed Christoffel symbols is responsible for the cancellation of the undesired expression in (4.7). Note that (4.4) was employed for the calculation. See Misner et al. (1973), Peebles (1993), Lawrie (2013).

$< 4.1\text{-}\mathit{covariant\text{-}derivative}| \oiint \}$

In summary, the innocent requirement that geometric entities, like vectors and tensors, should be independent of their coordinate representation conjures up a novel mathematical machinery. Yet again, the basic operation of taking the derivative is recast in a more general form, bringing with it powerful new properties and relationships. Indeed, it is interesting to note that the Christoffel symbols are associated not only with the curvature of space-time, see (3.13), and the covariant derivatives of (4.8), but also the differential geometric notions of parallel transport and geodesics, a generalization of the idea of a straight line to curved space-time. Additional equations relating to general relativity are (4.47) and (4.56).

Guided by the principles of equivalence and covariance, Einstein was able to formulate the famous geometrodynamic field equations, one of the most aesthetic and accurate physical theories. One experiment confirmed the effect of gravity, as predicted by general relativity, on clocks up to an accuracy of 10^{-16} hertz (Chou et al. 2010). Another experiment measured the "twisting" of space-time, called frame-dragging, due to the rotation of Earth to be 37.2 ± 7.2 milliarcseconds. The theoretical value was calculated to be 39.2 milliarcseconds (Everitt et al. 2011). This amazing accuracy between experiment and theory is only rivaled by the relativistic quantum field theory of electrodynamics, know as quantum electrodynamics, winning Tomonaga, Julian Schwinger, and Feynman a Nobel Prize in 1965. In this theory, the magnetic moment of the electron can be computed. The experimental measurement can be performed with an impressive precision of fourteen digits, in exact correspondence with the theoretical value (Hanneke et al. 2008). For more details on the field equations of general relativity, see Sect. 10.1.2.

4.2 The History of Gauge Theory

A key feature of general relativity is that it is a local theory. Only local coordinate systems are meaningful. Christoffel symbols describe the effects of transporting geometrical information along curves in a manifold, allowing coordinate systems to be related to each other. In detail, the value of $\Gamma^{\nu}{}_{\mu\lambda}$, defined via the metric tensor at each point in space-time, depends on the properties of the gravitational field, allowing the relative "orientation" of local coordinate systems to be compared. Weyl took this idea to the next level (Moriyasu 1983). He wondered if the effects of other forces of nature could be associated with a corresponding mathematical quantity similar to $\Gamma^{\nu}{}_{\mu\lambda}$. Weyl was specifically thinking about electromagnetism.

He embarked on a quest that would eventually reveal "one of the most significant and far-reaching developments of physics in this [20th] century" (Moriyasu 1983, p. 1) in 1918, when he was attempting to derive a unified theory of electromagnetism and gravitation (Weyl 1918). The same year Noether published her famous theorems relating symmetry to conserved quantities, Weyl was independently attempting to explain the conservation of the electric charge with a novel local symmetry. He called the invariance related to this new symmetry *Eichinvarianz*. Although the notion was originally related to invariances due to changes in scale, the English translations of Weyl's work referred to gauge invariance and gauge symmetry. It would, however, require nearly 50 years for gauge invariance to be rediscovered and reformulated as the powerful theory known today. Indeed, the idea of local gauge symmetry was premature in 1918, where the only known elementary particles were electrons and protons.

In more detail, Weyl proposed that the norm of a physical vector should not be a constant, but depend on the location in space-time. Associated with this, a new quantity, similar to the Christoffel symbols is required, in order to relate the lengths of vectors at different positions.

$\Big\{ \oiint$ |4.2-*gauge-invariance* >

Formally, invariance is restored again, if, in analogy to (4.8), the derivative is replaced with a new kind of derivative, resulting in the cancellation the unwanted terms

$$D_\mu := \partial_\mu - c_1 \Lambda_\mu. \tag{4.11}$$

D_μ is called the gauge-invariant derivative and $c_1 > 0$ is some constant. Note that $\Lambda_\mu(x^\nu)$ is a new vector field, referred to as the gauge field. Weyl's great insight was his idea to decode these abstract notions and connect them with electromagnetism.

The equations of electromagnetism can be recast in Minkowski space by introducing the so-called 4-vector potential, defined as

$$A_\mu := (\Phi, \boldsymbol{A}). \tag{4.12}$$

The scalar potential Φ and the vector potential $\boldsymbol{A}$ can be derived from the charge density ρ and the current density $\boldsymbol{J}$, respectively. Recall that ρ and $\boldsymbol{J}$ appear in (2.4). Similarly to A_μ, they can be understood as the components of the 4-vector current density, or 4-current $J_\mu = (\rho, \boldsymbol{J})$. Moreover, both the electric and magnetic fields can be derived from the scalar and vector potentials as

$$\boldsymbol{B} = \nabla \times \boldsymbol{A}, \quad \boldsymbol{E} = -\partial_t \boldsymbol{A} - \nabla\Phi, \tag{4.13}$$

where ∇ is defined in (2.2). From the new quantity of (4.12), the Maxwell field-strength tensor, hinted at in (3.7), can be explicitly constructed as

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \tag{4.14}$$

Now Maxwell's equations can be recovered in two different ways. Either by inserting the true electromagnetic Lagrangian

$$\mathcal{L}_{\text{EM}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - J_\mu A^\mu, \tag{4.15}$$

into the Euler-Lagrange equations (3.6). Alternatively, Maxwell's equations can be computed directly from $F_{\mu\nu}$. The inhomogeneous Maxwell equations (2.4a) and (2.4d) are retrieved by virtue of

$$\partial_\mu F^{\mu\nu} = \Box A^\nu - \partial^\nu(\partial_\nu A^\mu) = J^\nu. \tag{4.16}$$

The new type of derivative, called the d'Alembertian operator, is defined as

$$\Box := \partial_\mu \partial^\mu = \partial^2/\partial t^2 - \nabla^2. \tag{4.17}$$

The homogeneous equations (2.4b) and (2.4c) can be derived from

$$\partial_\mu \hat{F}^{\mu\nu} = 0, \tag{4.18}$$

where $\hat{F}^{\mu\nu}$ is obtained from $F^{\mu\nu}$ by substituting $\boldsymbol{E} \to \boldsymbol{B}$ and $\boldsymbol{B} \to -\boldsymbol{E}$. For more details, see Jackson (1998), Collins et al. (1989).

It turns out that the formulation of electrodynamics in this guise leads to a large redundancy associated with the theory. All the equations related to A_μ, importantly Maxwell's equations, are invariant under the following transformation

$$A'_\mu = A_\mu + c_2 \partial_\mu \chi, \tag{4.19}$$

where χ is an unspecified scalar function of x^ν and c_2 is a constant.

$< 4.2\text{-}gauge\text{-}invariance| \oiint \}$

Weyl realized, that (4.19) could be understood as a local gauge transformation, associated with the covariant derivative D_μ. In effect, he identified the potential A_μ

to be the gauge field or gauge boson Λ_μ appearing in (4.11). Technically, for the equations to work, the constants are required to be $c_1 = ie$ and $c_2 = 1$, where e denotes the elementary charge. See, for instance de Wit and Smith (2014), Peskin and Schroeder (1995). Unfortunately, it was shown by Einstein and others that Weyl's gauge theory based on changes in scale had failed—it lead to conflicts with known physical facts (Vizgin 1994; Moriyasu 1983 and Penrose 2004, Section 19.4). The mathematical observation that Maxwell's equations are gauge invariant was simply seen as an accident, as there was no deeper interpretation of the phenomena able to shed some light on the issue. The potential A_μ was just a ghost in the theory.

However, with the development of quantum mechanics, Weyl could re-apply the idea of gauge invariance in a new context. This gave his gauge theory a new meaning. Note that the wave function, as any plane wave, can be expressed as

$$\psi(t, \boldsymbol{x}) = C \exp\left(i(\boldsymbol{k} \cdot \boldsymbol{x} - \omega t)\right), \tag{4.20}$$

where C is the amplitude, $\boldsymbol{k}$ the wave vector, and ω represents the wave's angular frequency. For details, see, for instance Schwabl (2007). A change of the phase of a wave by the amount λ is related to the transformation $\exp(i\lambda)$. In quantum mechanics, for the wave function of an electron, this is realized by the transformation

$$\psi' = \exp(ie\lambda)\,\psi, \tag{4.21}$$

where e is the elementary charge. Weyl's essential idea was to interpret the phase of the wave function as the new local variable. In other words, the value λ is promoted to $\lambda(x^\nu)$ in (4.21). Instead of changes in scale, this new local gauge transformations is now interpreted as changes in the phase of $\psi(t, \boldsymbol{x})$, encoded via λ at various points in space-time (Weyl 1929). From the explicit form of the gauge transformation (4.21), the covariant derivative and the transformation properties of the gauge fields can easily be derived.

$\Big\{ \oiint$ |4.2-*quantum-mechanics-and-gauge-theory* >

The transformation of the derivative of the field is given by

$$\left(\partial_\mu \psi\right)' = \partial_\mu \psi' = \exp(ie\lambda)\left(\partial_\mu \psi + ie\partial_\mu \lambda \psi\right), \tag{4.22}$$

utilizing the chain rule for the derivative of the exponential function. The term $ie\partial_\mu\lambda$ due to the local parameter breaks the covariance. Introducing the gauge fields in the covariant derivative as $D_\mu = \partial_\mu - ieA_\mu$, similarly to (4.11), one finds

$$\left(D_\mu \psi\right)' = \left(\partial_\mu \psi\right)' - ie\left(A_\mu \psi\right)'. \tag{4.23}$$

By inserting (4.22) into this equation, and noting that $(A_\mu \psi)' = A'_\mu \psi'$, it can be shown that the additional term in the covariant derivative cancels the quantity destroying the covariance. However, this is only true if the gauge field transforms as follows

$$A'_\mu = A_\mu + \partial_\mu \lambda. \tag{4.24}$$

$$< 4.2\text{-}quantum\text{-}mechanics\text{-}and\text{-}gauge\text{-}theory| \oiint \Big\}$$

These calculations finally offered new insights for the interpretation of (4.19). The Schrödinger equation, seen in (3.24), is left unchanged after the two gauge transformations (4.21) and (4.24), with $\lambda = \lambda(x^\nu)$. Despite offering a clear meaning for the new local variables λ, it was still believed that the potential A_μ had no physically measurable effects. It took nearly thirty years before a simple but ingenious idea uncovered a possible observable effect due to the potential (Aharonov and Bohm 1959), promoting A_μ to a physical field in its own right. In a sense, it is more fundamental than the electric or magnetic fields. A year later an experimental verification of the Aharonov-Bohm effect was carried out (Chambers 1960). Looking back at these developments, Feynman would remark (quoted in Moriyasu 1983, p. 21):

> It is interesting that something like this can be around for thirty years but, because of certain prejudices of what is and is not significant, continues to be ignored.

To summarize, the electromagnetic interactions of charged particles can be understood as a local gauge theory, embedded in the deeper framework of quantum mechanics. Just as the $\Gamma^\nu{}_{\mu\lambda}$ describe how coordinate systems are related to each other in general relativity, the connection between phase values of the wave function at different points is given by A_μ, just as Weyl had originally envisioned. The link to the global symmetry transformations discussed previously is given by the following. Recalling that (3.29) describes the transformation properties of a quantum field under a group action, the formula given in (4.21) can be understood as a special case thereof. If the variable λ, parameterizing the symmetry transformations, would be a constant, (4.21) reveals the transformation property of the field ψ under a global $U(1)$ symmetry.[5] The simple mathematical trick of letting the parameter λ become space-time dependent is responsible for the transition between the global and the local symmetry. In other words, and in the general case where the parameters of the symmetry group are not restricted do being scalars as seen in (3.27), the notion of "gauging the symmetry" is the straightforward substitution

$$\theta_k \to \theta_k(x^\nu). \tag{4.25}$$

Adding this small degree of freedom to the mathematical machinery has profound consequences.

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[5] $U(1)$ is also called the unitary group.

$\left\{ \oiint \right.$ |4.2-*gauge-theory* >

Re-expressing (3.29) as the transformation properties related to a local symmetry yields

$$\psi' = \exp\left(\theta_k(x^\nu)\mathrm{X}^k\right)\psi =: \mathrm{U}(x^\nu, \theta_i)\psi, \tag{4.26}$$

In plain words, the matrix U is an element of a local symmetry group G, with the group generators represented as matrices X^k which satisfy commutation relations (3.19), and the parameters θ_k are now gauged. Note that (4.21) is a special case of (4.26).

Again, this subtle change of letting the parameter θ_k be a function of x^ν results in an additional term in the transformation rules, as now $\partial_\mu\theta_k \neq 0$. This new term is responsible for breaking the covariance. As discussed above, and in the case of general relativity, in order to restore gauge invariance, a gauge field $A^k_\mu(x^\nu)$ is required.[6] The covariant derivative is constructed from these fields. Similarly to (4.11) and (4.8)

$$D_\mu := \partial_\mu - A^k_\mu \mathrm{X}_k =: \partial_\mu - B_\mu, \tag{4.27}$$

where B^μ is a matrix constructed from the gauge fields. By replacing ∂_μ with D_μ gauge invariance is restored. The transformation properties of B_μ can be calculated as follows. The requirement of covariance also applies to the transformed covariant derivative. So, utilizing the gauge transformation laws specified in (4.26)

$$(D_\mu\psi)' = D'_\mu\psi' = \mathrm{U}\left(D_\mu\psi\right). \tag{4.28}$$

Inserting (4.27) yields

$$\left(\partial_\mu - B'_\mu\right)\mathrm{U}\psi = \mathrm{U}\left(\partial_\mu - B_\mu\right)\psi. \tag{4.29}$$

Noting the product rule for derivatives, and rearranging some terms, the following expression can be found, describing the transformation property associated with the gauge fields

$$B'_\mu = \mathrm{U}B_\mu\mathrm{U}^{-1} + \left(\partial_\mu\mathrm{U}\right)\mathrm{U}^{-1}. \tag{4.30}$$

Infinitesimally, i.e., for small parameter values $\theta_k(x^\nu) \ll 1$, the gauge transformation can be expressed as

$$\begin{aligned} \mathrm{U} &= 1 + \theta_k\mathrm{X}^k + \mathcal{O}(\theta^2), \\ \mathrm{U}^{-1} &= 1 - \theta_k\mathrm{X}^k + \mathcal{O}(\theta^2). \end{aligned} \tag{4.31}$$

From this, an expression for the components of the wave function can be derived, similar to (3.29)

$$\psi'^i = \psi^i + \theta_k f^{ki}{}_j\psi^j. \tag{4.32}$$

[6] Note that for every matrix generator X^k there is now an associated vector A^k_μ.

Recall that the adjoint representation (3.28) employs the structure constants f^{ijk}, which encode the generator matrices X^k. Switching to the gauge fields, one finds that

$$A'^k_\mu = A^k_\mu + f^k{}_{ij}\theta^i A^j_\mu + \partial_\mu \theta^k. \tag{4.33}$$

The details of how the commutation relations for the generators X^k and the associated structure constants enter the picture can, for instance, be seen in Cheng and Li (1996, p. 232), de Wit and Smith (2014, p. 408f). Again, the expression (4.24) is found as a special case of (4.33).

< 4.2.1-*gauge-theory*| $\oiint$ }

In order to link the abstract equations of gauge theory with concrete physically relevant quantities, one introduces a free parameter g into the theory[7]. The local parameter and the gauge fields are rescaled with this value

$$\theta_k \to g\theta_k, \quad A^k_\mu \to gA^k_\mu. \tag{4.34}$$

The resulting effect of this trivial exercise is that the values g appear in the Lagrangian and can be interpreted as the physical coupling strength (de Wit and Smith 2014). This is a number that determines the strength of the interaction associated with the gauge fields. As was seen for the case of electromagnetism, $g = e$. Essentially, the abstract concepts of the formal representation are enriched by encoding additional measurable aspects of the physical reality domain.

After a long journey through symmetry and geometry, all that remains, due to the requirement of gauge invariance, are transformation properties of the wave function and the gauge field determined solely by the structure constants and the parameter of the local symmetry. Today, such theories are called Yang-Mills gauge theories. Originally proposed by Chen Ning Yang and Robert Mills in 1954, as a gauge theory describing the strong nuclear interaction (Yang and Mills 1954). They postulated that the local gauge group was $SU(2)$. However, this specific theory for the strong force failed. It was known from experiments, that the nuclear force only acted on short ranges. Yang and Mills' theory, however, predicted that the carrier of the force, the gauge field, would be, like the photon in electromagnetism, long-range. This is because there is no way to incorporate gauge invariant mass terms for the gauge field into the Lagrangian (Moriyasu 1983). Nevertheless, this specific kind of gauge theory laid the foundation for modern gauge theory, culminating in the standard model of particle physics. Unfortunately, the potential power inherent in the formal machinery of gauge theories was not anticipated at the time. Indeed, Freeman Dyson would, eleven years after the introduction of Yang-Mills theory, gloomily remark (quoted in Moriyasu 1983, p. 73):

[7] Some authors choose $-ig$, which changes some technical aspects of the equations, for instance, $c_2 = -1/g$.

> It is easy to imagine that in a few years the concepts of field theory will drop totally out of the vocabulary of day-to-day work in high energy physics.

Quantum field theory (Sect. 10.1.1) and gauge theory were each plagued, individually, by major problems. While the issue of quantum field theory was related to a mathematical nightmare, the gauge theory problem was related to symmetry. It was found that any gauge invariant Lagrangian cannot contain mass terms, as they necessarily break covariance. So how can a physical system with mass be described by a gauge theory and still have properties which violate gauge invariance? The mathematical problem was, in detail, related to infinities appearing in the framework. Quantum field theory is based on perturbation theory, the idea of taking the solution to an easier problem and then adding corrections to approximate the real problem. Unfortunately, the perturbation series are divergent, assigning infinite values to measurable quantities.

> It is obvious that, in order for a field theory to be at all sensible or believable, the problems raised by the divergences must be satisfactorily resolved.

Quote from Ryder (1996, p. 308). It is ironic, that at a time when experimental physics had entered a golden era, theoretical efforts, after so many promising findings, would dwindle and "the practice of quantum field theory entered a kind of 'Dark Age'" (Moriyasu 1983, p. 85). However, due to new technological advances—epitomized by the high-energy particle accelerator—more and more particles were discovered. Simply organizing these was a challenge. As an example, Murray Gell-Mann and others introduced new fermions, they called quarks (Gell-Mann and Ne'eman 1964). Now it was possible to categorize many of the observed particles as being composed of quarks. The quarks themselves are representations of the global symmetry group $SU(3)$. Gell-Mann called this classification scheme the Eightfold Way. Although alluding to the Noble Eightfold Path of Buddhism, the reference is "clearly intended to be ironic or humorous" (Kaiser 2011, p. 161).

Bearing witness to the tremendous success of deciphering the workings of reality in mathematical terms, the mathematical obstacles were overcome. The theory of renormalization, first developed for quantum electrodynamics, is a collection of techniques for dealing with the infinities of perturbative quantum field theory. The divergent parts of the theory can be tamed: the infinities are viewed as rescaling factors which can be ignored. In more detail, the mathematical manipulations related to these scale transformations can be understood in terms of what is called the renormalization group. Wrapping it all up (Peskin and Schroeder 1995, p. 466):

> The qualitative behavior of a quantum field theory is determined not by the fundamental Lagrangian, but rather by the nature of the renormalization group flow and its fixed points. These, in turn, depend only on the basic symmetries that are imposed on the family of Lagrangians that flow into one another. This conclusion signals, at the deepest level, the importance of symmetry principles in determining the fundamental laws of physics.

General references are Peskin and Schroeder (1995), Ryder (1996), Cheng and Li (1996).

The solution to the problem of incorporating mass terms into a gauge-invariant theory is discussed in the following section. The details require a journey deep into the undergrowth of the abstract world.

4.2.1 *The Higgs Mechanism*

The Higgs mechanism is the mathematical machinery that allows massless gauge invariant Lagrangians to collect mass terms for their quantum fields via the notion of spontaneous symmetry breaking. It is an elaborate mathematical trick used in the standard model to regain the physical mass terms in the most "natural" way possible.

$\Big\{ \oiint \; |4.2.1\text{-}higgs\text{-}mechanism >$

It is a formalism related to a scalar field ϕ described by $\mathcal{L}_{\text{Higgs}}$, seen in (3.11). The mass parameter m_H implicit in the scalar potential $\mathcal{V}$, which, taking the most general $SU(2)$ invariant form, is derived to be

$$\mathcal{V}(\phi) = m_H^2 \bar{\phi}\phi + \lambda_H (\bar{\phi}\phi)^2, \tag{4.35}$$

with a dimensionless coupling λ_H and $\bar{\phi}$ denoting the Hermitian conjugate. In perturbation theory, ϕ is expanded around the minimum of $\mathcal{V}$, i.e.,

$$\left. \frac{\partial \mathcal{V}}{\partial \phi} \right|_{\langle \phi \rangle} = 0, \tag{4.36}$$

where the vacuum expectation value of the field is defined as $\langle \phi \rangle := \langle 0 | \phi | 0 \rangle$. This specifies the vacuum state of the theory. The mass parameter m_H^2 in (4.35) is related to spontaneous symmetry breaking. If $m_H^2 > 0$, i.e., the parameter is real, this simply would describe the mass of a scalar spin-0 field. Moreover, the shape of the potential is such, that there is a single global minimum at $\phi = 0$. However, by taking m_H^2 to be negative,[8] the minimum of $\mathcal{V}$ is shifted. Now there is a local maxima at $\phi = 0$ and an infinite number of minima appear at

$$\bar{\phi}\phi = |\phi|^2 = -\frac{m_H^2}{2\lambda_H} = \frac{\mu^2}{2\lambda_H} =: v^2, \tag{4.37}$$

where $m_H = i\mu$ is the imaginary mass. In summary, the infinite minima are located at $|\phi| = v$ and the original symmetry is spontaneously broken. This is also associated with a non-zero vacuum expectation value of $\langle \phi \rangle = v$. Now a new field can be

[8]Recall that this corresponds to superluminal tachyons, as seen in (3.55).

introduced, called the Higgs field. Technically, there exists a non-zero component[9] of the scalar field ϕ, such that $\langle\phi_i\rangle = v$. The new Higgs fields, associated with a Higgs boson, is defined as

$$h(x^\nu) = \phi_i(x^\nu) - v. \tag{4.38}$$

This can be interpreted as follows. In perturbative field theory, a scalar field ϕ is expanded about some minimum of the associated potential $\mathcal{V}(\phi)$. If the minimum of the non-zero vacuum expectation value is chosen, the physical Higgs particle is now interpreted as quantum fluctuations of ϕ_i about the value v. In essence, the Higgs field "plays the role of a new type of vacuum in gauge theory" (Moriyasu 1983, p. 120). Formally, replacing ϕ_i in the appropriate places in the Lagrangian with $h + v$, yields the much awaited mass terms appearing due to the value v entering the mathematical machinery.

The Higgs scalar ϕ appears the standard model Lagrangian via the (Yukawa) coupling to the fermions, seen in (3.13). The covariant derivative D_μ, seen in (3.11), defines the kinetic quantities and takes the following form

$$\mathcal{D}_\mu := \partial_\mu + igW^i_\mu\tau_i + ig'B_\mu Y. \tag{4.39}$$

Here g and g' are the coupling constants introduced in (4.34). The terms τ^i and Y are the generators of the symmetry groups $SU(2)$ and $U(1)$, respectively. Finally, W^i_μ and B_μ are the gauge fields associated with the corresponding symmetry groups, and $i = 1, 2, 3$. The gauge-invariant Lagrangian, containing the field-strength tensors, reads

$$\mathcal{L} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W_i^{\mu\nu}, \tag{4.40}$$

It can be constructed from the gauge bosons as follows

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \tag{4.41a}$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\varepsilon_{ijk}W^j_\mu W^k_\nu, \tag{4.41b}$$

where ε_{ijk} is the Levi-Civita symbol in three dimensions.[10] Note that (4.41a) and (4.14) are identical expressions. In the next step, the physical boson fields are constructed from the quantities W^1_μ, W^2_μ, W^3_μ, B_μ. This yields the $W^\pm$ bosons ($W^\pm_\mu$), the Z boson (Z_μ), and the photon field (A_μ). These gauge bosons are the carriers of the electroweak force. As anticipated, these quantum fields receive mass terms, if ϕ is substituted with $h + v$ from (4.38) in the Lagrangian $\mathcal{L}_{\text{Higgs}}$, described in (3.11) and (4.35). This is the process of spontaneous symmetry breaking and results in

[9] It should be noted, that although ϕ is a scalar and hence has only one component by definition, gauge invariance requires it to transform as a complex doublet representation of $SU(2)$, in effect assigning it four components.

[10] It has the value 1 if (i, j, k) is an even permutation of $(1, 2, 3)$, or -1 if it is an odd permutation, and 0 if any index is repeated.

$$m_{W^\pm} = \frac{1}{2} v g, \quad m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}, \quad m_\gamma = 0, \tag{4.42}$$

without violating the gauge-invariance of the theory. Similarly, the fermions get their mass terms using the same substitution, i.e., also via spontaneous symmetry breaking. But now the part of the Lagrangian describing the coupling of fermions to the Higgs field is employed, seen in (3.13). The result is

$$m_{\text{leptons}} = \frac{v\lambda_l}{\sqrt{2}}, \quad m_{\text{quarks}} = \frac{v\lambda_q}{\sqrt{2}}, \tag{4.43}$$

where λ_l and λ_q are arbitrary coupling constants. For more details see Collins et al. (1989).

< 4.2.1-*higgs-mechanism*| $\oiint$ }

Although the theoretical contraptions, described in (4.35)–(4.43), are today associated with Peter Higgs, there were many contributors. The first discovery of the ideas of symmetry breaking was made in condensed matter physics, namely in the theory of superconductivity, formalized by John Bardeen, Leon Cooper, and Robert Schrieffer. Using quantum field theory techniques (Bardeen et al. 1957), symmetry breaking properties of superconductors were uncovered. This theory of superconductivity would win the authors a Nobel Prize in 1972. Important mathematical details were also gleaned from an earlier phenomenological theory of superconductivity (Ginzburg and Landau 1950). Here, the explicit shape of the scalar potential, seen in (4.35), was introduced, and its critical dependence on the sign of the mass term noted. In 1962, Schwinger discussed gauge invariance and mass (Schwinger 1963). He suggested the following (quoted in Anderson 1963, p. 439):

> [...] associating a gauge transformation with a local conservation law does not necessarily require the existence of a zero-mass vector boson.

Building on the works of Schwinger, Philip Warren Anderson spelled out the first accounts of what would later become known as the Higgs mechanism (Anderson 1963). He also incorporated the insights gained from superconductivity. There, in the theory of Bardeen et al. (1957), it was realized that the mechanism of breaking the symmetry was associated with the appearance of a new boson (Nambu 1960). These ideas could be systematically generalized within the context of quantum field theory (Goldstone et al. 1962). Anderson grappled with the technicalities related to the Goldstone theorem, which was a final hurdle in the mass generating mechanism. The term "spontaneous symmetry breaking" was introduced in Baker and Glashow (1962), to account for the fact that the mechanism does not require any explicit mass terms in the Lagrangian to violate gauge invariance. The full model was developed in the same year by three independent groups:[11] Englert and Brout (1964), Higgs

[11] Ordered by publication date.

(1964), Guralnik et al. (1964). However, the names Higgs mechanism and Higgs boson stuck. Indeed, the Nobel Committee, allowed to nominate a maximum of three people, only awarded François Englert and Higgs, with a Nobel Prize in 2013, after the 2012 discovery at CERN's LHC (CERN 2013):

> [...] today, the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analyzed two and a half times more data than was available for the discovery announcement in July [2012], they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

A general reference is Gunion et al. (2000). Here the parenthesis closes.

4.2.2 Tying Up Some Loose Ends

Incidentally, Yang-Mills theory also uncovered a new type geometry for physics. This understanding only became apparent in the 1970s, and helped in popularizing gauge theories. Interestingly, this new concept in physics of uniting space-time with an "internal" symmetry space had been proposed by mathematicians at nearly the same time. See, for instance Moriyasu (1983, p. 32), Schottenloher (1995, p. 8). In detail, gauge theories have the topology of a fiber bundle. This means, that at every point in space-time a Lie group G is attached; there is an internal symmetry space existing at every space-time coordinate. The group G associated with a point x^ν is called a fiber. As a particle moves through space-time, it also follows a path through the internal spaces at each point. The gauge transformations describe how the internal spaces at different points can be transformed into each other. The tangent bundle TM, described in Sect. 3.1.1, is a specific example of a fiber bundle. More details can be found in Drechsler and Mayer (1977), Nash and Sen (1983), Coquereaux and Jadczyk (1988).

Finally, there is one peculiar historical confusion related to Noether and Weyl. It is a good reminder that the devil, as always, is in the details. Many textbooks and review articles on quantum field theory gloss over the fact, that Noether actually published two theorems in 1918. The first one, famously deals with global symmetries and conserved quantities. However, she also proved a second theorem relating to local symmetry, which, prima facie, has nothing to do with conservation laws. Brading (2002) observes that there is either no, or no detailed, discussion of the second theorem in the literature, for instance O'Raifeartaigh (1997), Vizgin (1994), Kastrup (1984), Moriyasu (1982). Notable exception are Utiyama (1959), Byers (1999), Rowe (1999). As mentioned, Weyl, working on his unified field theory of electromagnetism and gravity in 1918, independently was trying to explain the conservation of the electric charge with the notion of a local symmetry. His results, in effect, can be understood as an application of Noether's second theorem. The confusion arises, because "the standard textbook presentation of the connection between conservation of electric charge and gauge symmetry in relativistic field theory involves Noether's first theorem" (Brading 2002, p. 9). Although these books discuss both local and global symmetries, they do not mention her second theorem. Despite the fact that both ways of deriving the conservation of electric charge, employing local or global symmetries, are correct, the text book approach via global symmetry is somewhat misleading. There it is implied that the conservation of charge depends on the Euler-Lagrange equations of motion being fulfilled. Noether's second theorem, and Weyl's derivation, yields the conservation law based on local symmetry only, without the necessity of the additional constraint due the equations of motion. See Brading (2002).

The mathematical methods of renormalizing quantum field theories and the spontaneous symmetry breaking mechanism for gauge theories would help pave the way to unification, ultimately unearthing a powerful formalism describing all non-gravitational forces and matter: the standard model of particle physics.

4.3 The Road to Unification

The road to unification has been a rocky one. Unification is the epitome of human understanding of reality. What appear as independent phenomena, described by frag-

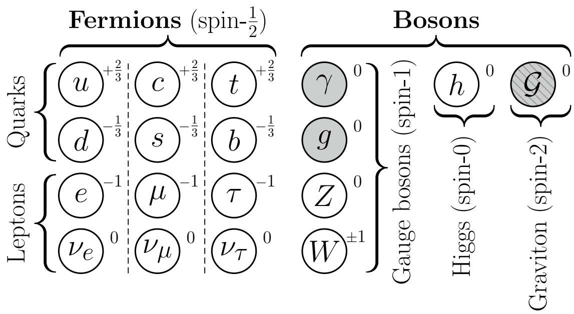

Fig. 4.1 The contents of the physical universe. Matter particles, called fermions due to their half-integer spin, are classified either as quarks or leptons and come in three generations. The six types of quarks are labeled according to their flavor, up (u), down (d), charm (c), strange (s), top (t), and bottom (b) and are the constituents of composite particles (such as protons and neutrons). The muon (μ) and tau (τ) can be understood as heavier versions of the electron (e), each coming with an associated neutrino (ν). The three non-gravitational forces are associated with spin-1 gauge bosons, where the photon (γ) mediates the electromagnetic force, gluons (g) the strong nuclear force, and the Z and $W^{\pm}$ bosons the weak force. The Higgs particle (h), a scalar spin-0 boson, is associated with the phenomena of mass. The graviton ($\mathcal{G}$) is the hypothetical quantum particle associated with gravity which, up-to-date, has not been detected. The elementary particlues represented by gray circles are massless, and each particle comes with an electric charge, given by the number associated with it on the upper right side. Next to these particles there also exists an elusive mirror world of antiparticles, or antimatter, with identical properties but opposite charge

mented theories, suddenly become united in a unified framework. It is the ultimate act of translation seen in Fig. 2.1: superficially separate properties of the natural world are encoded and merged into a single formal description. In essence, from the multifarious complexity of nature the formal essence is distilled, a unified theory of phenomena. Such an over-aching structure of knowledge has the power to unlock new and unexpected understanding of the workings of nature. This is why, in physics, the ultimate unified field theory describing all fundamental forces and elementary particles is, grandiosely, known as "the theory of everything." It should be noted, however, that here the context of "everything" excludes emergent complexity, discussed in Chap. 6, and the fact that a conscious entity, the physicist, is doing the inquiring, covered in Chaps. 11 and 14. Nevertheless, this version of the theory of everything tries to explain all observable phenomena related to the fundamental workings of reality. In detail, it should explain all four known forces and describe the behavior of all elementary particles and antiparticles. What this all amounts to can be seen in Fig. 4.1.

In the history of physics there were a few instances where different abstract formalisms representing unrelated aspects of the world could be fused into a single conceptual formalism. For instance, Maxwell's insight that light was an electromagnetic wave, unifying the fields of optics and electromagnetism. Or the fusion of thermodynamics with statistical mechanics (Gibbs 1884, 1902). In a sense, special relativity can be understood as the merger of electromagnetism with the laws of classical mechanics (Einstein 1905b), and general relativity as the synthesis of inertial and gravitational forces (Einstein 1915).

4.3.1 Jumping to Higher Dimensions

However, the first unification success regarding the forces of nature goes back to Maxwell. The theory of electromagnetism is a classical unified field theory. As is inherent in its name, the two separate phenomena of electricity and magnetism can be understood as a new single force. Formally, the introduction of the 4-vector potential A_μ of (4.12) is enough to derive the following quantities:

1. The electric and magnetic fields: (4.13).
2. The corresponding field-strength tensor: (4.14) and (4.41a).
3. Maxwell's equations: (2.4).

Although Weyl, as discussed, was successful in spawning the idea of gauge theory, his unification scheme marrying electromagnetism with gravity ultimately failed (Weyl 1918, 1929). However, this approach would eventually lead to the unification of all known forces. Moreover, gauge theory also naturally incorporates matter particles next to particles mediating the interaction. In detail, matter is represented as operator-valued spin one-half fermion quantum fields (spinors) in the Lagrangian, as seen in (3.8), and the force carrying bosonic quantum fields appear by virtue of the gauge-invariant derivative, described in (4.39). This dichotomy between matter and forces was a major problem at the time, as the attempts to unify gravity and the electromagnetic force focused on incorporating matter as classical fields obeying the Schrödinger equation (3.24) or the Dirac equation (3.41) or (3.42). An additional problem was that up to "the 1940s the only known fundamental interactions were the electromagnetic and the gravitational, plus, tentatively, something like the 'mesonic' or 'nuclear' interaction" (Goenner 2005, p. 303). In effect, lacking the correct quantum field formalism and missing crucial experimental observations, people embarked on the futile quest of unification. To make matters worse, general relativity substitutes the notion of a gravitational field with an elaborate geometry of space-time. To summarize, general relativity is formulated in a (pseudo) Riemannian space-time, with zero torsion and non-vanishing curvature. Torsion and curvature are two natural defining properties of differentiable manifolds, where torsion is related to the twisting of space-time.

$\Big\{ \oiint$ $|4.3.1\text{-}torsion\text{-}curvature >$

Formally, torsion is defined as a tensor

$$T(X, Y) = \nabla_X Y - \nabla_Y X - [X, Y], \tag{4.44}$$

where X, Y are two vector fields on the manifold and ∇_X, related to (4.8), computes the covariant derivative of a vector field in the direction of X. The Lie brackets, introduced in (3.19), are now also functions of vector fields. For a basis $\boldsymbol{e}_i$ one finds

$$\nabla_{\boldsymbol{e}_i} \boldsymbol{e}_j = \Gamma^k{}_{ij} \boldsymbol{e}_k, \tag{4.45}$$

with the Christoffel symbols seen in (4.9). Thus the components of the torsion tensor are

$$T^k{}_{ij} = \Gamma^k{}_{ij} - \Gamma^k{}_{ji} - f^k{}_{ij}, \tag{4.46}$$

for non-vanishing structure constants $f^k{}_{ij}$. For more details, see Nomizu and Sasaki (1994). Similarly, the Riemann curvature tensor is found to be

$$R(X, Y) = [\nabla_X, \nabla_Y] - \nabla_{[X,Y]}. \tag{4.47}$$

This can also be expressed componentwise as $R^\rho{}_{\sigma\mu\nu}$, the quantity appearing in (3.13), by utilizing the $\Gamma^k{}_{\sigma\mu}$ and their derivatives. See, for instance Misner et al. (1973, p. 224).

$< 4.3.1\text{-}torsion\text{-}curvature|$ $\oiint \Big\}$

The equations defining torsion and curvature nicely illustrate how the concepts of group theory, namely the Lie brackets, enter into the language of geometry. In a general sense, general relativity is only one manifestation of possible space-time structures, with $T = 0$, $R \neq 0$. Varying these parameters categorizes different space-times and gravitational theories. The case $T \neq 0$, $R \neq 0$ yields the Riemann-Cartan space-time, which can be associated with a gauge theory of gravity à la Yang-Mills theory, for instance, the gauging of the Lorentz group (Utiyama 1956). This was later extended to a gauged version of the Poincaré group[12] (Kibble 1961; Sciama 1962, 1964). Setting the curvature to zero in the Riemann-Cartan space-time, uncovers Weitzenböck space-time with $T \neq 0$, $R = 0$, a variant Einstein would later work on, as detailed in Sect. 4.3.3. More details are found in Gronwald and Hehl (1996). Generalizing the idea of geometrization was the main avenue for unification at the time. A wealth of details on the history of unified field theories, including an extensive bibliography, can be found in Goenner (2004). A shorter version is Goenner (2005).

Until 1928, Einstein only reacted to the new ideas advanced by others. One notable and bold idea was proposed by the mathematician Theodor Kaluza. He picked up on an obscure theory aimed at unifying gravity with electromagnetism (Nordström 1914). The concept is simple as it is mysterious: space-time is assumed to be five-dimensional, i.e., comprised of four spacial and one temporal dimension. Kaluza communicated these new ideas to Einstein in 1919, who was initially very supportive. “At first glance I like your idea enormously;” and “The formal unity of your theory is startling” (Goenner 2004, p. 44). Kaluza had achieved to show that electromagnetism is a consequence of general relativity in five dimensions. The metric tensor $g_{\mu\nu}$, from which the curvature of space-time is derived by virtue of (3.13) and (4.47), is extended by one dimension as follows

$$g_{MN} := \left(\begin{array}{c|c} g_{\mu\nu} & cA_\mu \\ \hline cA_\nu & \phi \end{array} \right), \tag{4.48}$$

where the indices M and N run from 1 to 5, and A_μ is the vector potential of (4.12), incorporated with a proportionality factor c. The component $g_{55} = \phi$ is a new scalar gravitational potential. While promising, this extra-dimensional framework was plagued by inconsistencies. Moreover, could there really be any physical reality at the heart of this idea transcending human perception? Although Kaluza published his work in 1921 (Kaluza 1921), Einstein would remain silent on these matters until 1926. In that year, the physicist Oskar Klein[13] reawakened the interest in Kaluza’s ideas (Klein 1926). He not only linked quantum mechanics to the machinery of general relativity in five dimensions, crucially, he was able to give a physical interpretation of the extra dimension. This idea is today known as compactification, or dimensional reduction. If the extra dimension is “curled up” tight enough it becomes undetectable from our familiar slice of reality. Only at sufficiently large

[12] This theory is sometimes called Einstein-Cartan gravity, due to Cartan’s early work on the subject (Cartan 1922).

[13] Not to be confused with Felix Klein of the *Erlanger Program*.

energies, the three-dimensional world unveils its richer structure due to the additional compactified dimensions. Today, modern versions of Kaluza-Klein theories can go up to 26 dimensions.[14]

Back in 1926, Klein had only to grapple with one additional compactified dimension. He imposed a simple topology on the higher-dimensional space-time structure. Instead of simply using a five-dimensional Minkowski space M^5, he assumed a product space $M^4 \times S^1$, i.e., the product of a four-dimensional Minkowski space and a circle. If the radius of the circle is small enough, our reality appears four dimensional. A lucid discussion of how this idea might be possible can be found in Einstein and Bergmann (1938). The special topology Kaluza chose means that Kaluza-Klein theories have a similar geometric structure to gauge theories. Recalling that in gauge theory an internal symmetry space is attached at each point in space-time giving it the structure of a fiber bundle, now, in Kaluza and Klein's version, a multi-dimensional compactified space, consisting of the "curled up" dimensions, resides at each point of physical reality.

$\Big\{ \oiint \; |4.3.1\text{-}compactification >$

To illustrate, a quantum field $\psi(x^M)$, with $x^M := (x^\mu, y)$, where x^μ is the usual space-time coordinate, is constrained as follows

$$\psi(x^\mu, y) = \psi(x^\mu, y + 2\pi r), \tag{4.49}$$

where the scale parameter r gives the "radius" of the fifth dimension. Expanding ψ in a Fourier series yields

$$\psi(x^\mu, y) = \sum_{n=-\infty}^{\infty} \psi_n(x^\mu) e^{iny/r}. \tag{4.50}$$

In the context of quantum mechanics, one can now identify the y-component of a state with given n as being associated with the momentum $p = |n|/r$. Thus, for a sufficiently small r, only the $n = 0$ state will appear in the low-energy world we live in. As a result, all observed states will be independent of y

$$\frac{\partial \psi}{\partial y} \approx 0. \tag{4.51}$$

$< 4.3.1\text{-}compactification| \; \oiint \Big\}$

If the radius of compactification r is of the order of the Planck length $l_p \approx 1.6 \times 10^{-35}$ m, the masses associated with the higher modes ($n \neq 0$) would be of the order

[14] Disguised as bosonic string theory, see Sect. 4.3.2.

of the Planck mass $m_p \approx 2.2 \times 10^{-8}$ kg (Collins et al. 1989, p. 295), removing the effects of the higher-dimensional space-time structure from current technological possibilities. What is today known as Kaluza-Klein theory is in fact an amalgamation of different contributions by both scientists. A detailed account of their various contributions can be found in Goenner and Wünsch (2003).

$\Big\{ \oiint \ |4.3.1\text{-}kaluza\text{-}klein >$

A modern version of Kaluza-Klein theory can, for instance, be found in Kaku (1993), Collins et al. (1989). Now

$$g_{MN}(x^\mu, y) = \sum_n g^{(n)}_{MN}(x^\mu) e^{iny/r}, \tag{4.52}$$

with

$$g^{(0)}_{MN} = \phi^{-1/3} \left(\begin{array}{c|c} g_{\mu\nu} + \phi A_\mu A_\nu & \phi A_\mu \\ \hline \phi A_\nu & \phi \end{array} \right). \tag{4.53}$$

$< 4.3.1\text{-}kaluza\text{-}klein| \ \oiint \Big\}$

The scalar field ϕ appearing in the theory is known as a dilaton or a radion. So the five-dimensional metric g_{MN} can be decomposed in four space-time dimensions as the metric tensor of gravity $g_{\mu\nu}$, a massless spin-1 photon A_μ, and a predicted massless scalar ϕ. However, interpreting ϕ as a physical particle was very radical at the time and most researchers tried to eliminate it. "[…] this prediction seems to have embarrassed the early writers; predicting a new particle […] was not so accepted in those days" (Green et al. 2012a, p. 15). Finally, inserting (4.53) into the five-dimensional version of (3.13), yields the five-dimensional Lagrangian $\mathcal{L}^{(5)}_{\text{GR}}$, which can be simplified as

$$\mathcal{L}_{\text{KK}} \sim \sqrt{-\det(g_{\mu\nu})} \left(R + \frac{1}{4} \phi F_{\mu\nu} F^{\mu\nu} + \mathcal{F}(\phi) \right). \tag{4.54}$$

In essence, the Kaluza-Klein Lagrangian unifies general relativity, expressed as $\mathcal{L}_{\text{GR}}$ in (3.13) and Maxwell's theory of electromagnetism encoded as $\mathcal{L}_{\text{EM}}$ in (3.7). The equation for the scalar field is encapsulated in the function $\mathcal{F}$.

Some authors did, however, take the prediction of Kaluza-Klein theory seriously and accepted the reality of the scalar field ϕ. In their eyes, five-dimensional general relativity is reduced to a scalar-tensor theory of gravity. Such an extension of general relativity was proposed in Brans and Dicke (1961). In the version of Brans-Dicke, the metric tensor $g_{\mu\nu}$ is paired with a scalar dilaton field ϕ. The physical justification for such a theory came from the desire to make Einstein gravity more Machian. This was achieved by promoting the gravitational constant G to become a dynamical variable.

This constant appears in Newton's law of universal gravitation

$$F = G\frac{m_1 m_2}{r^2}, \tag{4.55}$$

describing the force F between two masses, m_1 and m_2, separated at a distance r. It is also featured in Einstein's field equations of general relativity, sketched at in (3.14)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \tag{4.56}$$

where c denotes the speed of light in a vacuum. Hence, in Brans-Dicke gravity, the following substitution is made

$$G \to \phi(x^\nu), \tag{4.57}$$

where the dynamical field ϕ is dependent on the position in space-time (Peacock 1999), yielding a theory closer to the ideas of Mach.

4.3.2 The Advent of String Theory

The study of string theory has become one of the main focuses within theoretical physics. Its proponents hail it the only viable candidate for a "theory of everything." While Einstein and others had hoped to achieve such a feat by staying faithful to the paradigm of geometrodynamics, modern attempts at unification propose that gravity should also undergo the treatment of quantization, forging a theory of quantum gravity. However,

> Quantum gravity has always been a theorist's puzzle *par excellence*.

> Experiment offers little guidance except for the bare fact that both quantum mechanics and gravity do play a role in natural law.

> The real hope for testing quantum gravity has always been that in the course of learning how to make a consistent theory of quantum gravity one might learn how gravity must be unified with other forces.

All three quotes from Green et al. (2012a, p. 14). In this respect, string theory has a lot to offer and, indeed, ties together some of the ideas emerging from the early attempts in constructing a unified field theory (Green et al. 2012a, p. 14):

> The earliest idea and one of the best ideas ever advanced about unifying general relativity with matter was Kaluza's suggestion in 1921 that gravity could be unified with electromagnetism by formulating general relativity not in four dimensions but in five dimensions.

Nonetheless, string theory was in fact discovered by accident. Edward Witten, arguably the most important contributor to the enterprise, once remarked (quoted in Penrose 2004, p. 888):

> It is said that string theory is part of twenty-first-century physics that fell by chance into the twentieth century.

The evolution of this theory also had many twists and turns. Originally, string theory models were proposed to describe the strong nuclear force in the late 1960s, known as dual resonance models. These developments started with (Veneziano 1968). In 1970, it was independently realized by Yoichiro Nambu, Leonard Susskind, and Holger Bech Nielsen, that the equations of this theory should, in fact, be understood as describing one-dimensional extended objects, or strings (Schwarz 2000). The first manifestation of these ideas is known as bosonic string theory, living in 26-dimensional space-time. See, for instance Polchinski (2005a). One year later, a string theory model for fermions was proposed (Ramond 1971; Neveu and Schwarz 1971). However, these theories, aimed at describing hadrons, i.e., composite particles comprised of quarks held together by the strong force, were competing with another theory which was rapidly gaining popularity. By 1973, quantum chromodynamics had become an established and successful theory describing hadrons. It was formulated as a Yang-Mills gauge theory with a $SU(3)$ symmetry group, capturing the interaction between quarks and gluons, the gauge bosons in the theory. A special property, called asymptotic freedom (Politzer 1973; Gross and Wilczek 1973), was instrumental in developing the theory, winning a Nobel prize in 2004. Unsurprisingly, in the wake of quantum chromodynamics, the string model became an oddity within theoretical physics.

Strings and Gravity

In 1974, things changed for string theory. It was known that the theory contained a massless spin-2 particle. "This had been an embarrassment with the original 'hadronic' version of string theory, since there is no hadronic particle of this nature" (Penrose 2004, p. 891). Instead of trying to eliminate this unwanted particle, a simple acceptance lead to profound consequences: it was identified as the graviton, the elusive quantum particle of gravity (Yoneya 1974). Although general relativity does not admit a force carrying particle for the propagation of gravitational interactions—missing a quantum gauge boson of gravity—due to the fact that the space-time curvature per se encodes the gravitational dynamics, a straightforward quantization scheme of gravity is the following. The metric can be expanded as

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \tag{4.58}$$

where $\eta_{\mu\nu}$ is the metric of flat Minkowski space and $h_{\mu\nu}$ represents the excitation of the gravitational quanta. By inserting this new quantity into Einstein's field equations, a wave equation can be derived that corresponds to the propagation of a massless spin-2 particle, identifying $h_{\mu\nu}$ as the graviton (Collins et al. 1989). This made the next step in the evolution of string theory obvious and its original purpose, as theory of hadrons, was abandoned. "The possibility of describing particles other than hadrons (leptons, photons, gauge bosons, gravitons, etc.) by a dual model is explored" (Scherk and Schwarz 1974, abstract).

Unexpectedly, string theory had suddenly become an exciting candidate for a "theory of everything," as it had "[…] the remarkable property of *predicting gravity*" (Witten 2001, p. 130). Indeed, as up to then the merger of gravity with quantum physics proved to be such an intractable and elusive puzzle, this was big news:

> […] the fact that gravity is a consequence of string theory is one of the greatest theoretical insights ever.

Again, Witten quoted in Penrose (2004, p. 896). Unfortunately, at the time not many physicists took the idea seriously. It would take another ten years before string theory would experience the next advancement in its evolution: an event that would propel it into the limelight of theoretical physics. After 1984, string theory was transformed into one of the most active areas of theoretical physics. See, for instance Bradlyn (2009), for a chart of the number of string theory papers published per year from 1973 onward, as cataloged by the ISI Web of Science. Or Google's Ngram Viewer,[15] which "charts the yearly count of selected *n*-grams (letter combinations) or words and phrases, as found in over 5.2 million books digitized by Google Inc (up to 2008)".[16] It is also interesting to graph comma-separated phrases in comparison: "string theory, loop quantum gravity." This clearly illustrates the predominance of string theory over other proposed "theories of everything," like loop quantum gravity. While string theory is a theory of quantum gravity originating in the paradigm of quantum field theory, loop quantum gravity has its foundation in general relativity. See, for instance, Smolin (2001) for a popular account of the various paths to quantum gravity, and (Giulini et al. 2003) for a technical one. For a general discussion of loop quantum gravity, consult Sect. 10.2.3.

Supersymmetry

In the early 1980s it was realized, that by introducing a crucial novel element into the string theory formalism, some pressing problems could be solved. Inadvertently, a powerful new level of descriptive power would emerge. This missing element was associated with a novel symmetry property, called supersymmetry. Historically, it was originally developed as a symmetry between hadrons, namely a symmetry relating mesons (a composition of a quark and an anti-quark) to baryons (made up of three quarks, like the neutron and proton) (Miyazawa 1966). "Unfortunately, this important work was largely ignored by the physics community" (Kaku 1993, p. 663). Only in 1971, a refined version of supersymmetry was independently discovered from two distinct approaches. In the early version of fermionic string theory (Ramond 1971; Neveu and Schwarz 1971) a new gauge symmetry was discovered, from which supersymmetry was derived (Gervais and Sakita 1971). The second approach was based on the idea of extending the Poincaré algebra described in (3.52), resulting in the super-Poincaré algebra (Gol'fand and Likhtman 1971). Then, in 1974, the first four-dimensional supersymmetric quantum field theory was developed (Wess and Zumino 1974). Even ten years before it would have a fertilizing

[15]Found at https://books.google.com/ngrams.

[16]See http://en.wikipedia.org/wiki/Google_Ngram_Viewer.

effect on string theory, supersymmetry was understood as a remarkable symmetry structure in and of itself, fueling advancements in theoretical physics. In essence, it is a symmetry eliminating the distinction between bosons and fermions. Now matter particles—fermions described by spinors with 720° rotational-invariance—and force mediating particles—the gauge bosons emerging from the covariant derivatives in the Lagrangian, with 360° rotational-invariance—lose their independent existence in the light of supersymmetry. It also turns out that supersymmetry is the only known way to unify internal gauge symmetries with external space-time symmetries, a marriage otherwise complicated by the Coleman-Mandula theorem (Coleman and Mandula 1967). There is, however, a heavy phenomenological price to pay for the mathematical elegance of supersymmetry. The number of existing particles has to be doubled, as each matter fermion and gauge boson must have a supersymmetric partner, conjuring up a mirror world of Fig. 4.1.

Formally, there exists an operator Q, which converts bosonic states into fermionic ones, and vice versa. Symbolically, $Q|B\rangle = |F\rangle$.

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Infinitesimally, supersymmetric transformations Q can be expressed in group theoretic terms described in (3.30), similarly to the example given for the Lorentz group in (3.30)

$$\delta^{\mathrm{SUSY}}\Phi = i\varepsilon Q\Phi, \tag{4.59}$$

where the super-multiplet Φ contains all the matter and gauge fields and spans a representation of the supersymmetric algebra associated with Q and ε is the usual parametrization parameter. From the Poincaré algebra the super-Poincaré algebra can be constructed by adding Q to the old (bosonic) commutation relations seen in (3.52). The new (fermionic) sector of the algebra is now given by anticommutation relations for the Q, similar to (3.16), which are defined as

$$\{X, Y\} = XY + YX. \tag{4.60}$$

In mathematical terms, the basic tools to construct supersymmetric extensions of the Poincaré algebra are called Clifford algebras (Varadarajan 2004). These are algebras defined via specific anticommutation relations. The operator Q transform themselves as a 2-component Weyl spinor under Lorentz transformations. This means that the usual four-dimensional theory is broken down to two dimensions via the Pauli matrices σ^i, $i = 1, 2, 3$. Mathematically, the Pauli matrices are related to the Dirac matrices γ^μ, introduced in Sect. 3.2.2.1, (given in the Weyl representation) as follows

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix}, \tag{4.61}$$

with $\sigma^\mu := (\mathbb{1}_2, \boldsymbol{\sigma})$ and $\bar{\sigma}^\mu := (\mathbb{1}_2, -\boldsymbol{\sigma})$, where $\mathbb{1}_2$ is the two dimensional identity matrix. Note that the bar is just a notational convention and does not denote the Hermitian conjugate of a matrix, as the previous usage of the symbol could imply. Dirac and Pauli matrices are defined by the virtue of anticommutators

$$\begin{aligned}\{\sigma^i, \sigma^j\} &= 2\delta^{ij}\, \mathbb{1}_2; \quad i, j = 1, 2, 3,\\ \{\gamma^\mu, \gamma^\nu\} &= 2g^{\mu\nu}\, \mathbb{1}_4; \quad \mu, \nu = 0, \ldots, 3,\end{aligned} \tag{4.62}$$

with the flat Minkowski metric $g^{\mu\nu}$ and the Kronecker delta. For more details, see, for instance Peskin and Schroeder (1995). Just as the γ^μ are associated with a 4-component spinor representation of the Lorentz group generators via (3.48), the Pauli matrices give a 2-component (Weyl) spinor representation. Now each point x^μ in space-time is associated with a matrix X by virtue of the Pauli matrices

$$x^\mu \leftrightarrow X := \sigma_\mu x^\mu. \tag{4.63}$$

The action of the Lorentz group on a Weyl spinors is captured by the following

$$x'^\mu = \Lambda^\mu_\nu x^\nu \leftrightarrow X' := \mathcal{M} X \mathcal{M}^*, \tag{4.64}$$

where $\mathcal{M}^*$ denotes the Hermitian conjugate.[17] It should be noted that $\mathcal{M} \in SL(2, \mathbb{C})$, establishing a relationship between the Lorentz group and $SL(2,\mathbb{C})$. See, for instance Sternberg (1999). A Weyl spinors transforms under this representation as

$$\psi_\alpha \to \psi'_\alpha = \mathcal{M}_\alpha{}^\beta \psi_\beta, \quad \bar{\psi}_{\dot{\alpha}} \to \bar{\psi}'_{\dot{\alpha}} = \mathcal{M}^*_{\dot{\alpha}}{}^{\dot{\beta}} \bar{\psi}_{\dot{\beta}}. \tag{4.65}$$

In other words, there are two Weyl spinors associated with the two possible representations of the Lorentz group, $\mathcal{M}$ and $\mathcal{M}^*$. They are either labeled with the indices $\alpha, \beta, \ldots$, or the dotted indices $\dot{\alpha}, \dot{\beta}, \ldots$, which run from one to two. Again, the bar is simply a notational convention associated with quantities carrying dotted indices and does not denote the Hermitian conjugate of a 2-component spinor ψ_α. These computations imply that for supersymmetry there also exist two operators: Q_α and $\bar{Q}_{\dot{\alpha}}$. Now the novel fermionic sector of the super-Poincaré algebra can be defined via the following anticommutators which are added to the set of equations seen in (3.52)

$$\{Q_\alpha, \bar{Q}_{\dot{\beta}}\} = 2[\sigma^\mu]_{\alpha\dot{\beta}} P_\mu. \tag{4.66}$$

Note that $[\sigma^\mu]_{\alpha\dot{\beta}} := (\mathbb{1}_2, -\sigma_i)_{\alpha\dot{\beta}}$. All other combinations of Q_α and $\bar{Q}_{\dot{\alpha}}$ are trivial. Finally, the combination of the fermionic and bosonic sector needs to be specified. The only non-zero relations are

[17] For a complex matrix A_{ij}, $A^*_{ij} := \bar{A}^t_{ij}$, where the operator t transposes the matrix and $\bar{A}_{ij}$ is the complex conjugate of the complex matrix element A_{ij}.

$$[M^{\mu\nu}, Q_\alpha] = i[\sigma^{\mu\nu}]_\alpha{}^\beta Q_\beta,$$
$$[M^{\mu\nu}, \bar{Q}^{\dot{\alpha}}] = i[\bar{\sigma}^{\mu\nu}]^{\dot{\alpha}}{}_{\dot{\beta}} \bar{Q}^{\dot{\beta}}. \tag{4.67}$$

See Wess and Bagger (1992) for more details. The matrices $\sigma^{\mu\nu}$ and $\bar{\sigma}^{\mu\nu}$ are the generators of the Lorentz transformations for Weyl spinors. They can be expressed using the Pauli matrices σ^μ. It holds that

$$[\sigma^{\mu\nu}]_\alpha{}^\beta = \frac{1}{4}\left([\sigma^\mu]_{\alpha\dot{\gamma}}[\bar{\sigma}^\nu]^{\dot{\gamma}\beta} - [\sigma^\nu]_{\alpha\dot{\gamma}}[\bar{\sigma}^\mu]^{\dot{\gamma}\beta}\right),$$
$$[\bar{\sigma}^{\mu\nu}]^{\dot{\alpha}}{}_{\dot{\beta}} = \frac{1}{4}\left([\bar{\sigma}^\mu]^{\dot{\alpha}\gamma}[\sigma^\nu]_{\gamma\dot{\beta}} - [\bar{\sigma}^\nu]^{\dot{\alpha}\gamma}[\sigma^\mu]_{\gamma\dot{\beta}}\right), \tag{4.68}$$

where $[\bar{\sigma}^\mu]^{\dot{\alpha}\beta} = (\mathbb{1}_2, +\sigma_i)^{\dot{\alpha}\beta}$. The spinor representation, whose matrices are derived from the Dirac matrices in (3.48), is related to the Pauli matrices as follows

$$\Sigma^{\mu\nu} = \frac{i}{4}\begin{pmatrix} \sigma^\mu\bar{\sigma}^\nu - \sigma^\nu\bar{\sigma}^\mu & 0 \\ 0 & \bar{\sigma}^\mu\sigma^\nu - \bar{\sigma}^\nu\sigma^\mu \end{pmatrix}. \tag{4.69}$$

More details can be found in Bilal (2001). Finally, extended supersymmetry algebras are possible, with Q^A_α and $\bar{Q}^B_{\dot{\beta}}$, where $A, B = 2, \ldots, N$, see Wess and Bagger (1992).

< 4.3.2-*supersymmetry-algebra*| $\oiint$ $\}$

Supersymmetry can exist in various space-time dimensions. However, eleven is the maximal number of dimensions in which a consistent supersymmetric theory can be formulated in Nahm (1978).

Supergravity

From the mid-1970s to the mid-1980s string theory lay dormant amongst the exciting developments related to supersymmetry, and only a handful of dedicated people kept it alive. Gell-Mann, shortly before his 80th birthday, reflected on this as follows in an interview (Siegfried 2009):

> I didn't work on string theory itself, although I did play a role in the prehistory of string theory. I was a sort of patron of string theory—as a conservationist I set up a nature reserve for endangered superstring theorists at Caltech, and from 1972 to 1984 a lot of the work in string theory was done there. John Schwarz and Pierre Ramond, both of them contributed to the original idea of superstrings, and many other brilliant physicists like Joel Sherk and Michael Green, they all worked with John Schwarz and produced all sorts of very important ideas.

However, at the same time, the idea of supersymmetry was uncovering important novel insights. "Perhaps one of the most remarkable aspects of supersymmetry is that it yields field theories that are finite to all orders in perturbation theory" (Kaku 1993, p. 664). This makes the heavy machinery of renormalization redundant. And, as many times before in the history of physics, tinkering with the mathematical formalism would uncovered new ideas and powerful tools that had the power to unlock new and unexpected knowledge. In the early years, supersymmetry was understood as a global symmetry. Taking the promising step of gauging supersymmetry, that is, by reconstructing it as a local gauge symmetry, a new type of gauge theory emerged. This new theory, called supergravity, is a supersymmetric theory inevitably accommodating gravity (Freedman et al. 1976). Only two years after string theory was given a new twist as "theory of everything," another viable candidate for quantum gravity had been discovered, fascinating the community of theoretical physicists. Not long after the discovery of the elven-dimensional limit to supersymmetry (Nahm 1978), it was realized in Cremmer et al. (1978) "that supergravity not only permits up to seven extra dimensions but in fact takes its simplest and most elegant form when written in its full eleven-dimensional glory" (Duff 1999, p. 1). Supergravity would provide the impetus for a revival of Kaluza-Klein theory. This allowed $D = 11$, $N = 1$ supergravity to be compactified to a $D = 4$, $N = 8$ theory (Cremmer and Julia 1979), where $N > 1$ describes the extended supersymmetry algebra and D denotes the dimensions of space-time. In an influential paper, Witten proved that the structure of the associated four-dimensional gauge-group is actually determined by the structure of the isometry group—the set of all distance-preserving maps—of the compact seven-dimensional manifold $\mathcal{K}$ (Witten 1981). He showed, "what to this day seems to be merely a gigantic coincidence, that seven is not only the maximum dimension of $\mathcal{K}$ permitted by supersymmetry but the minimum needed for the isometry group to coincide with the standard model gauge group $SU(3) \times SU(2) \times U(1)$" (Duff 1999, p. 2). The next steps were the development of $N = 8$ supergravity with $SO(8)$ gauge symmetry in $D = 4$ anti-de Sitter space[18] or AdS_4 (De Wit and Nicolai 1982), and its extension to eleven dimensions, compactified on a seven dimensional sphere S^7 which admits an $SO(8)$ isometry (Duff and Pope 1983). Indeed, the compactification from eleven-dimensional space-time to $AdS_4 \times S^7$ could be shown to be the result of spontaneous compactification (Cremmer and Scherk 1977). These were certainly very promising developments. Indeed, so much so, that a then 38-year-old Stephen Hawking was tempted in 1980, in his inaugural lecture as Lucasian professor of mathematics at the University of Cambridge, England (Hawking 1980), to divine that $N = 8$ supergravity was the definite "theory of everything" (Ferguson 2011). Indeed (as quoted in Ferguson 2011, p. 5):

> He [Hawking] said he thought there was a good chance the so-called Theory of Everything would be found before the close of the twentieth century, leaving little for theoretical physicists like himself to do.

The First Superstring Revolution

Alas, things turned out quite differently and supergravity did not fulfill its promising claims. "We therefore conclude that, despite the initial optimism, $N = 8$ supergravity theory is not theoretically or phenomenologically satisfactory" (Collins et al. 1989). Perhaps the most damning problem was the reappearance of non-renormalizability.

[18] A specific symmetric manifold with a curvature.

The infinities meticulously removed from quantum field theory returned to render the theory of supergravity useless. Indeed, all known quantum theories of spin-2 particles, meaning the elusive gravitons, are now known to be non-renormalizable. Yet again, gravity and quantum physics refuse to cooperate. That is, as quantum theories of point particles. This opened up a loophole for string theory, as its theoretical machinery never touched the notion of particles and rested on extended one-dimensional, vibrating strings. Some general references are Wess and Bagger (1992), Buchbinder and Kuzenko (1998), Duff (1999).

Unsurprisingly, the pendulum of interest slowly swung back to string theory in the beginning of the 1980s. A major driving force was the introduction of the newly discovered idea of supersymmetry to the framework, unleashing superstring theory.[19] An earlier modification to the original Ramond and Neveu-Schwarz models was conjectured to harbor supersymmetry (Gliozzi et al. 1977), which was proved by Green and Schwarz (1981). Unfortunately, these superstring theories appeared to be inconsistent (Alvarez-Gaume and Witten 1984), plagued by anomalies. Then, later in 1984, an avalanche was triggered by some notable developments. For one, a method was found to cancel the anomalies by assigning the gauge group of the theory to be $SO(32)$ or $E_8 \times E_8$ (Green and Schwarz 1984). Moreover, a new superstring theory was introduced, called heterotic string theory (Gross et al. 1985). The "first superstring revolution" was ignited. In the words of Witten (2001, p. 130):

> Since 1984, when generalized methods of "anomaly" cancellation were discovered and the heterotic string was introduced, one has known how to derive from string theory uncannily simple and qualitatively correct models of the strong, weak, electromagnetic, and gravitational interactions.

Also Hawking realized the potential, aligning his prophecy (Ferguson 2011, p. 213f.):

> In June 1990, ten years after his inaugural lecture as Lucasian Professor, I asked him [Hawking] how he would change his Lucasian lecture, were he to write it over again. *Is* the end in sight for theoretical physics? Yes, he said. But not by the end of the century. The most promising candidate to unify the forces and particles was no longer the $N = 8$ supergravity he'd spoken of then. It was superstrings, the theory that was explaining the fundamental objects of the universe as tiny, vibrating strings, and proposing that what we had been thinking of as particles are, instead, different ways a fundamental loop of string can vibrate. Give it twenty or twenty-five years, he said.

To summarize, five consistent string theories have been developed, living in ten-dimensional space-time. In the low-energy limit, they reduce to $N = 1, 2$, $D = 10$ supergravity of point particles. String theory is a bizarre contraption. It alludes to outlandish realms of reality, like ten-dimensional space-time and a mirror world of supersymmetric particles laying latent in the undiscovered weaves of the fabric of reality. It is built up of an extraordinarily vast and abstract formal machinery, blurring the borders between mathematics and physics, as was discussed in Sect. 2.1.4. Yet, at its heart, it has a surprisingly simple and colorful intuition attached to it (Greene 2013, p. 146):

[19]Nowadays, when people refer to string theory they implicitly mean superstring theory.

> What appear to be different elementary particles are actually different "notes" on a fundamental string. The universe—being composed of an enormous number of these vibrating strings—is akin to a cosmic symphony.

String theory has the potential to unify all known forces within a single framework. The theory could support a marriage between gravity and quantum mechanics, by offering a theory of quantum gravity which is not plagued by unwanted infinities. Finally, it can accommodate the symmetries of the standard model. The six extra spacial dimensions are compactified on special geometries, called Calabi-Yau manifolds (Candelas et al. 1985). They are shapes, wrapping the additional dimensions into tiny packages located at each point in four-dimensional space-time, which reside at length scales not accessible to current experimental probes. Basically, Calabi-Yau manifolds are similar to fiber bundles. Moreover, as the strings still vibrate in all ten dimension after compactification, "the precise size and shape of the extra dimensions has a profound impact on string vibrational patterns and hence on particle properties" (Greene 2004, p. 372). As an example, if the Calabi-Yau spaces have a topology with three holes, as a result, there will be three families of elementary particles (fermions), as seen in Fig. 4.1. Technically, the number of particle generations is one half of the Euler characteristic of the chosen Calabi-Yau manifold (Candelas et al. 1985).

In all string theories, also already in the early bosonic versions (Scherk and Schwarz 1974), a scalar ϕ with a gravitational-strength coupling to matter is found. This scalar field has a very special property in the theory. Its expectation value

$$\exp(\langle\phi\rangle), \tag{4.70}$$

controls the string coupling constant, determining the strength of the string interaction. If the coupling constant gets too large, perturbation theory breaks down. This scalar ϕ can also be identified with the dilaton, the scalar field appearing in Kaluza-Klein theory, linking back to the scalar-tensor theory of Brans-Dicke gravity (Brans and Dicke 1961). Indeed, there are proposed theories of superstring cosmology, for instance Lidsey et al. (2000).

General references for string theory are, for instance (Hatfield 1992), (Polchinski 2005a, b), (Green et al. 2012a, b), (Rickles 2014). Examples of non-technical references are Greene (2004, 2013), Randall (2006), Susskind (2006).

After over a decade of intense study, in 1995, the next remarkable step towards a "theory of everything" was achieved. Initiated by a single person, the "second superstring revolution" took place. In that year, Witten published a paper which would changed the face of string theory for ever (Witten 1995). By moving to elven-dimensional space-time, and allowing for membranes in the theory, i.e., the higher-dimensional equivalents to vibrating two-dimensional strings, he realized that all five superstring theories could be united within one overarching theory. So the previous embarrassment of having five "theories of everything" was finally explained.

> Witten put forward a convincing case that this distinction is just an artifact of perturbation theory and that non-perturbatively these five theories are, in fact, just corners of a deeper theory. [...] Moreover, this deeper theory, subsequently dubbed *M-theory*, has $D = 11$ supergravity

> as its low energy limit! Thus the five string theories and $D = 11$ supergravity represent six different special points in the moduli space of M-theory.

Quote from Duff (1999, p. 326). Technical references on M-theory theory are, for instance Duff (1999), Kaku (2000), Rickles (2014). More details on the issues plaguing string theory—and quantum gravity in general—can be found in Sect. 10.2.2. For the notion of AdS/CFT duality, see Sect. 13.4.1.2.

4.3.3 *Einstein's Unified Field Theory*

Returning back to 1926, Klein's twist on Kaluza's original proposal ignited new interest in five-dimensional gravity as a unified field theory incorporating electromagnetism. Einstein remarked in 1927 (Goenner 2004, p. 65):

> It appears that the union of gravitation and Maxwell's theory is achieved in a completely satisfactory way by the five-dimensional theory.

In the following years, many physicists and mathematicians started to study the implications and finer details of Kaluza-Klein theory. See Goenner (2004, Section 7.2.4). Albeit promising, the theory ultimately failed. In 1929, the physicists Vladimir A. Fock summarized the situation as follows (Goenner 2004, p. 105):

> Up to now, quantum mechanics has not found its place in this geometric picture [of general relativity]; attempts in this direction (Klein, [...]) were unsuccessful.

Also the reality status and the meaning of the extra dimensions was seen as problematic. Indeed, a little more than a year after his initial publication on the matter, Klein conceded (Goenner 2004, p. 112):

> Particularly, I no longer think it to be possible to do justice to the deviations from the classical description of space and time necessitated by quantum theory through the introduction of a fifth dimension.

In 1928, Einstein himself took a leading role in the conceptual development of a unified field theory. A new wave of research ensued. Einstein was tinkering with the equations of general relativity and set out to extend the formalism. On the 10th of June of that year, he introduced the idea of teleparallelism, originally called *Fernparallelismus*, which allowed the comparison of the direction of a tangent vector at various points in space-time (Einstein 1928a). Technically, the underlying space-time is a Weitzenböck space-time[20] (Gronwald and Hehl 1996). Four days later, Einstein published his first attempt of constructing a unified theory of gravitation and electromagnetism (Einstein 1928b).

> [Since the publication of the 10th of June] I discovered that this theory—at least to a first approximation—yields the field laws for gravitation and electromagnetism easily and naturally. It is thus conceivable, that this theory will supersede the original version of general relativity.

[20] A space-time with zero curvature but non-vanishing torsion, see (4.44) and (4.47).

Quote from Einstein (1928b, p. 224, translation mine). With this, Einstein would embark on a more than two-decade long scavenger hunt, chasing this elusive goal. At the time, he was probably quite upbeat about the project's future. His intuition as a physicists had been validated by two very unexpected and profound theories of relativity. An additional motivational factor was perhaps also given by the fact that he had disproved Weyl's attempts at a unified field theory. On the 10th of January 1929, Einstein published an update (Einstein 1929a, p. 1, translation mine):

> Indeed, it was possible to assign the same coherent interpretation to the gravitational and the electromagnetic field. However, the derivation of the field equation from Hamilton's principle did not lead to a straightforward and unambiguous path. These difficulties intensified under further reflection. Since then, I was however successful in finding a satisfactory derivation of the field equations, which I will present in the following.

Unfortunately, there would be more clouds on the horizon. Others doubted the validity of the field equations Einstein presented in Einstein (1929a). To such criticism, on the 21st of March 1929, he responded as follows (Einstein 1929b, p. 156, translation mine):

> In the meantime, I have discovered a possibility to solve this problem in a satisfactory manner, founded on Hamilton's principle.

Then, on the 9th of January 1930 (Einstein 1930, p. 18, translation mine):

> A couple of months ago I published an article [...] summarizing the mathematical foundation of the unified field theory. Here I want to recapitulate the essential ideas and also explain how some remarks appearing in previous works can be improved.

Undeterred, Einstein continued with his quest. He was assisted by Walther Mayer, a mathematician specialized in topology and differential geometry. New technical publications followed (Einstein and Mayer 1930, 1931a, b). Einstein knew that his attempts had opened a Pandora's box of challenges. Indeed, the very notion of teleparallelism, the original seeding insight, had to be abandoned. On the 21st of March 1932, in a letter to Élie Cartan, he observed (as quoted in Goenner 2004, p. 85):

> [...] in any case, I have now completely given up the method of distant parallelism. It seems that this structure has nothing to do with the true character of space [...].

By 1932, Einstein had become increasingly isolated in his research. Most physicists considered his attempts to be ultimately futile. Indeed, from 1928 to 1932 Einstein had been faced with criticism by notable scholars, like Hans Reichenbach, a logical positivist philosopher of science, and Weyl (Goenner 2004). But Wolfgang Pauli was most vocal in his criticism. Already on the 29th of September 1929, in a letter to a fellow physicists, Pauli confessed (Goenner 2004, p. 89):

> By the way, I now no longer believe one syllable of teleparallelism; Einstein seems to have been abandoned by the dear Lord.

Then, on the 19th of December 1929, Pauli wrote a direct and blunt letter to Einstein (quoted in Goenner 2004, p. 87):

> I thank you so much for letting be sent to me your new paper […], which gives such a comfortable and beautiful review of the mathematical properties of a continuum with Riemannian metric and distant parallelism […]. Unlike what I told you in spring, from the point of view of quantum theory, now an argument in favor of distant parallelism can no longer be put forward [...]. It just remains […] to congratulate you (or should I rather say condole you?) that you have passed over to the mathematicians. Also, I am not so naive as to believe that you would change your opinion because of whatever criticism. But I would bet with you that, at the latest after one year, you will have given up the entire distant parallelism in the same way as you have given up the affine theory earlier. And, I do not wish to provoke you to contradict me by continuing this letter, because I do not want to delay the approach of this natural end of the theory of distant parallelism.

Einstein answered on 24th of December 1929 as follows (Goenner 2004, p. 88):

> Your letter is quite amusing, but your statement seems rather superficial to me. Only someone who is certain of seeing through the unity of natural forces in the right way ought to write in this way. Before the mathematical consequences have not been thought through properly, it is not at all justified to make a negative judgment.

In 1931, a collaborator of Einstein published a review article on teleparallelism (Lanczos 1931). It appeared in a journal whose name can be literally translated as "Results in the Exact Sciences." Pauli, when reviewing the article, sarcastically remarked (Goenner 2004, p. 89):

> It is indeed a courageous deed of the editors to accept an essay on a new field theory of Einstein for the "*Results* in the Exact Sciences."

A summary of Einstein's work between 1914 and 1932, appearing in the *Preußischen Akademie der Wissenschaften*, can be found in Simon (2006).

4.3.4 A Brief History of Quantum Mechanics

After 1932, things became quiet around Einstein's unified field theory. He spent the remaining years up to his death in 1955 publishing articles on the philosophy of science, the history of physics, and special and general relativity. He was also concerned with quantum mechanics, a subject he continued to be displeased with. Ironically, Einstein himself was instrumental in the creation of the theory.

Quanta

In Einstein (1905a) he proposed that the experimental data relating to the photoelectric effect should be interpreted as the result of light being made up of discrete quantized packets, called *Lichtquanten*. These light quanta, known as photons today, each come with the energy

$$E = h\nu, \tag{4.71}$$

i.e., an energy proportional to the frequency ν of the light, where the proportionality constant is given by Planck's constant h. Max Planck had proposed this relationship to explain the observed frequency spectrum of black-body radiation (Planck 1901), for which he would receive a Nobel prize in 1918. With the radical and revolutionary assumption that radiation is not emitted continuously but in discreet amounts, Planck was able to solve a puzzle, which had baffled physicists at the time: all previous theoretical calculations of black-body radiation resulted in nonsensical, infinite results. "It is a remarkable fact that so simple a hypothesis [$E = h\nu$], even if incomprehensible at first sight, leads to a perfect agreement with everything we can observe and measure" (Omnès 1999, p. 138).

For Planck, postulating quanta was an act of despair: "I was ready to sacrifice any of my previous convictions about physics" (quoted in Longair 2003, p. 339). Indeed, he originally believed that the notion of quanta was "a purely formal assumption and [he] really did not give it much though [...]" (Longair 2003, p. 339). Einstein understood the quantum hypothesis literally to explain the photoelectric effect. This work, and not his groundbreaking publications on special and general relativity, would win him a Nobel prize in 1921. Planck and Einstein's discoveries led to the quantum revolution.

In another notable publication, Einstein proposed the possibility of stimulated emission, the physical process making lasers possible (Einstein 1917). Despite his vital role in the initiating developments of quantum theory, Einstein always stayed skeptical. In a letter he wrote to Max Born in 1926, he lamented (quoted in Schweber 2008, p. 34):

> Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not bring us closer to the secret of the "old one." I, at any rate, am convinced that He is not playing with dice.

Einstein's reservations explicitly dealt with the probabilistic and indeterministic nature of quantum theory. For instance, Born's interpretation of the wave function as a probability amplitude (Born 1926) or, later, Heisenberg's uncertainty principle (Heisenberg 1927). Einstein still believed that his unified field theory would shed light on these issues, and "that the quantum mechanical properties of particles would follow as a fringe benefit from [the field theory]" (Goenner 2004, p. 8). In the end, his skepticism stemmed from certain philosophical considerations relating to the nature of reality, of which there is an abundance. For instance, the philosopher Charles S. Peirce proposed the theory of *tychism*, where he argued that chance and indeterminism are indeed ruling principles in the universe (Peirce 1892)—a direct antithesis to Einstein's opinion.

Entanglement

In what would end as an ironic turn of events, Einstein set out to disprove the bizarre consequences of quantum theory with collaborators. The now infamous EPR paradox, an acronym containing the last initials of the authors, was a clever thought experiment designed to show that quantum mechanics must be incomplete (Einstein et al. 1935). In a nutshell, the experiment showed that quantum mechanics allows for non-local effects: under certain conditions, a measurement conducted on a particle A would instantaneously change the properties of a particle B, regardless of the distance of separation between the two. Einstein felt victorious, as he did not believe such "spooky actions at a distance" (Kaiser 2011, p. 30) could be possible. But alas, things turned out differently. John Stewart Bell was able to furnish a theorem out of the EPR paradox. He proved that non-locality was indeed endemic to quantum mechanics (Bell 1964). The experimental validation was given years later in Freedman and Clauser (1972) and notably by Aspect et al. (1981, 1982a, b). In trying to expose the outlandish nature of quantum physics, Einstein helped to distill one of reality's most mind-boggling properties: entanglement, a term introduced by Schrödinger in (1935) to account for the "spooky action at a distance." Although it seems to imply that in some bizarre way reality is simultaneously interconnected with itself, entanglement does not allow actual information to propagate faster than the speed of light. Hence special relativity is not violated and there are no tenable objections form physics against entanglement. Quite to the contrary, today entanglement plays a central role in the emerging fields of quantum computation, quantum information, and quantum cryptography, the cutting-edge of current technological advancements. Indeed (Nielsen and Chuang 2007, pp. 11f.):

> Entanglement is a uniquely quantum mechanical *resource* that plays a key role in many of the most interesting applications of quantum computation and quantum information; entanglement is iron to the classical world's bronze age. In recent years there has been a tremendous effort trying to better understand the properties of entanglement considered as a fundamental resource of Nature, of comparable importance to energy, information, entropy, or any other fundamental resource.

Key to this surge in research was a theorem proved in 1982. It goes by the name of the no-cloning theorem (Wootters and Zurek 1982). In a nutshell (Kaiser 2011, p. xxv):

> [...] the no-cloning theorem stipulates that it is impossible to produce perfect copies (or "clones") of an unknown arbitrary quantum state. Efforts to copy the fragile quantum state necessarily alter it.

This property thwarts any attempts to intercept the communication of information, allowing for a 100% secure transmission channel: quantum encrypted communications cannot, by the laws of nature, be tapped without the signal being affected. This promise of perfect security would be the gold standard in an age of information processing and global computer networks. Experiments have demonstrated the proof-of-concept, for instance Poppe et al. (2004). And real-world applications followed (Hensler et al. 2007):

> On Thursday, October 11 [2007], the State of Geneva announced its intention to use quantum cryptography to secure the network linking its ballot data entry center to the government repository where the votes are stored. The main goal of this initiative, a world first, is to guarantee the integrity of the data as they are processed.

For more details on entanglement and the no-cloning theorem, see Sect. 10.3.2.1.

In the ebb and flow of history one can sometimes lose track of the peculiarities and coincidences leading to a major advancement in science. The popularization of entanglement and the development of the no-cloning theorem are prominent examples of how a very unlikely group of people can end up being responsible for such revolutionary feats: a loose collaboration of physicists, dabbling in psychedelics, Eastern mysticism, parapsychology, and other esoteric concepts. Indeed, it is often hard to appreciate how drastically geopolitics has influence the development of science and how crucial mindsets and culture can be for setting research agendas. See Kaiser (2011).

Some technical aspects of quantum mechanics can be found in the paragraphs encapsulating the following equations: (3.24) on p. 78, (3.51) on p. 88, and (4.20) on p. 100.

4.3.5 *Einstein's Final Years*

Regarding Einstein's post-1932 research, in 1945 a publication surfaced where he once gain engaged in the quest of formulating a unified field theory. He would call his new conception the generalized theory of gravity (Einstein 1945). More publications followed in 1948, 1950, 1953, 1954, and 1955. In December 1954, in a note for the fifth edition of Einstein (1956), his passion was still burning:

> For the present edition I have completely revised the "Generalization of Gravitation Theory" [Appendix II] under the title "Relativistic Theory of the Non-Symmetric Field." For I have succeeded—in part in collaboration with my assistant B. Kaufman—in simplifying the derivations as well as the form of the field equations. The whole theory becomes thereby more transparent, without changing its contents.

Einstein, well aware of the pressing conflicts in his approach, was confident that no one else could claim any certainty on the matter either (Einstein 1956, p. 165f.):

> Is it conceivable that a field theory permits one to understand the atomistic and quantum structure of reality? Almost everybody will answer this question with "no." But I believe that at the present time nobody knows anything reliable about it. [...] One can give good reasons why reality cannot at all be represented by a continuous field. From the quantum phenomena it appears to follow with certainty that a finite system of finite energy can be completely described by a finite set of numbers (quantum numbers). This does not seem to be in accordance with a continuum theory, and must lead to an attempt to find a purely algebraic theory for the description of reality. But nobody knows how to obtain the basis of such a theory.

For a detailed account of all of Einstein's works, see Schilpp (1970).

Although being isolated from most of the physics community, and not up-to-date with modern advancements in quantum field theory, Einstein's work still managed to catch the attention and fascination of the media. For instance, a newspaper article, appearing on the day of Einstein's death, hailed (Associated Press 1955, p. 17):

> In 1950, after 30 years of intensive study, Einstein expounded a new theory that, if proved, might be the key to the universe.

In the end, Einstein's efforts at a unified field theory are reduced to a footnote in history. What has stayed, is Weyl's idea of local gauge symmetry, Kaluza's venture into extra dimensions, and Klein's compactification scheme. Gauge symmetry would reveal itself as the unifying principle behind the standard model of particle physics, as is discussed in the next section. Additional spatial dimensions, the novel symmetry principle called supersymmetry, and compactification are the fundamental building blocks of string theory to this day.

4.4 Unification—The Holy Grail of Physics

Chapter 3 set out to establish the power of a simple abstract notion, called symmetry, in decoding the workings of the universe. The notion of symmetry fulfills a dream of physicists. The hope that nature is ultimately not only comprehensible to the human mind, but also in a way that is pleasing and satisfying. In the words of Nobel laureate Steven Weinberg (Weinberg 1992, p. 165):

> We believe that, if we ask why the world is the way it is and then ask why that answer is the way it is, at the end of this chain of explanations we shall find a few simple principles of compelling beauty.

This was witnessed in the insights gained from invariance: the emergence of conservation laws, presented in Sect. 3.1, and the fundamental physical classification of matter states and particle fields, discussed in Sect. 3.2. Perhaps the epitome of Weinberg's dream comes in the guise of unification, the theme with which this chapter began. Indeed, Weinberg was himself instrumental in showing how symmetry principles are instrumental tools for crafting a unified theory of all known forces excluding gravity, leading to the standard model of particle physics. Weinberg in (1992, p. 142):

> Symmetry principles have moved to a new level of importance in this [twentieth] century […]: there are symmetry principles that dictate the very existence of all the known forces of nature.

However, before these groundbreaking insights could be uncovered, some obstacles still needed to be removed for quantum field theory and gauge theory to emerge from the "Dark Age." The single most damning problem was that the mathematics was still plagued by infinities, the demon of non-renormalizability. Almost simultaneously, Weinberg (1967) and Abdus Salam (Salam 1968) "boldly ignored the problem of the 'non-renormalizable' infinities and instead proposed a far more ambitious unified gauge theory of the electromagnetic and weak interactions" (Moriyasu 1983, p. 102). They built on the work by Schwinger (1957) and Sheldon Glashow (Glashow 1961) and developed a spontaneously broken gauge theory by incorporating the Higgs mechanism, discussed in Sect. 4.2.1. Nearly a century after Maxwell's merger of electricity and magnetism, the next step in unifying the forces of nature was in sight: the electroweak interaction. It is based on the gauge group $SU(2) \times U(1)$. Salam, Glashow, and Weinberg were awarded the Nobel Prize in Physics in 1979 for this achievement.

The final piece of the puzzle was found by Gerard 't Hooft. He proved that spontaneously broken gauge theories are renormalizable ('t Hooft 1971). This crucial theorem was all that was holding back the inevitable step to unification (Moriyasu 1983, p. 113):

> However, [renormalizability] could not be proved at the time and the general response of the community of physicists to the Weinberg-Salam theory was best described some years later by Sidney Coleman: "Rarely has so great an accomplishment been so widely ignored."

The strong nuclear force, responsible for the stability of matter, confining the quarks into hadron, was successfully described as a gauge theory of a new quantum charge, called color (Han and Nambu 1965; Greenberg and Nelson 1977). These are new quantum properties carried by the quarks, just like electric charge is a property of some fermions and bosons, recall Fig. 4.1. Hence the term quantum chromodynamics is used to describe this theory. The gauge potential fields are called gluons and mediate the strong interaction between the color charged quarks. The gauge group is $SU(3)$ and some mathematical tools can be borrowed from the $SU(3)$ classification in the old quark model provided by Gell-Mann and Ne'eman (1964). However, "it is important to keep in mind that neither the theoretical predictions nor the experimental tests of chromodynamics have yet achieved the level of either quantum electrodynamics or the Weinberg-Salam theory" (Moriyasu 1983, p. 122).

Although, basically, the standard model was created by splicing the electroweak theory and the theory of quantum chromodynamics, it ranks as "one of the great successes of the gauge revolution" (Kaku 1993, p. 363). Technically, the standard model is a spontaneously broken quantum Yang-Mills theory describing all known particles and all three non-gravitational forces.

The standard model Lagrangian, seen in (3.8), is invariant under the unified symmetry group

$$G_{\mathrm{SM}} = SU(3) \times SU(2) \times U(1). \tag{4.72}$$

Fermionic matter is described by spinors which interact via gauge bosons that enter the Lagrangian through the gauge-invariant derivative

$$\mathcal{D}_\mu = \partial_\mu + i\hat{g}\sum_{\alpha=1}^{8} G_\mu^\alpha \lambda^\alpha + ig\sum_{i=1}^{3} W_\mu^i \tau^i + ig' B_\mu Y, \tag{4.73}$$

where the $SU(3)$ generators λ^α, with the corresponding coupling constant $\hat{g}$ and gluon gauge fields G_μ^α, are added to (4.39). The scalar Higgs field is responsible for generating the mass terms without violating covariance, as described in Sect. 4.2.1.

General references are Moriyasu (1982, 1983), Collins et al. (1989), Kaku (1993), Peskin and Schroeder (1995), Cheng and Li (1996), Ryder (1996), O'Raifeartaigh (1997).

Conclusion

This now closes a comprehensive chapter in the Book of Nature, representing a long voyage through the muddy waters of theoretical physics, guided solely by the notion of symmetry. Very distinct phenomena could be melded into a single abstract structure. Despite this momentous success of the human mind in decoding the workings of reality, the keen reader may notice a crucial omission. Up to now, the narrative has been preoccupied with fundamental aspects of the universe: from subatomic to cosmic scales. However, what about all the real-world complexity surrounding us? What about the emergence of life and consciousness? To continue with the metaphor of the Book of Nature, a major extension is required. What has bee discussed up to now is only Volume I in a greater series. In the next chapter, Volume II will be introduced, a recent addition to the Book of Nature Series. While Volume I dealt with the analytical (i.e., equation-based) understanding of fundamental processes, Volume II uncovers the algorithmic (i.e., computer-aided) understanding of complex systems. Whereas the following chapter is concerned with the bird's-eye classification of knowledge, the actual content of Volume II is only fully disclosed in Chap. 6 and its application to finance and economics is discussed in Chap. 7.

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Chapter 5
The Two Volumes of the Book of Nature

Abstract The Book of Nature has been found. The mathematical description of the universe gives the human mind the power to manipulate reality and technology becomes possible. However, this miraculous knowledge generation has been very specific: fundamental aspects of reality (from the quantum realm to cosmic scales) are encoded analytically, i.e., as equations. This appears to exclude real-world complexity, for instance, the emergent property of consciousness appearing in a self-organizing biological neural network. A fluke of reality allows the human mind to also conquer this domain. What appears as complexity, turns out to be the result of simple rules. Only very recently have the fruits of technology given humans a new level of abstraction: the magic of computation. Now, complex systems can be encoded algorithmically, i.e., by utilizing algorithms and simulations running in computers. As a result, complexity can be tamed and comprehended. This new knowledge generation is understood as Volume II of the Book of Nature, whereas physical science represents Volume I. Underlying the analytical and algorithmic formal representations are two fundamental structures of mathematics: the continuous and the discrete. In this sense, all human knowledge generation is unified mathematically. *Level of mathematical formality*: medium to low.

The age-old dream that mathematics represents the blueprint for reality has started to become fulfilled: the Book of Nature is intelligible to the human mind and deep truths about the workings of the world have been decoded. In other words, the human mind has begun to venture into realms in the abstract world which interrelate with the workings of the physical world—from the quantum foam comprising reality to the awe-inspiring vastness of the cosmic fabric. This main theme is encapsulated in Fig. 2.1, which is reproduced below.

However, this translation of aspects of reality into abstract representations has been very specific. For instance, the considered reality domains interestingly omit the very cornerstone of the whole enterprise of knowledge seeking: the human brain. And with it, a whole branch of reality is ignored, relating to self-organization, structure formation, and emergent complexity in general. Curiously, the Book of Nature does not speak much about the everyday structures and systems surrounding us humans.

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
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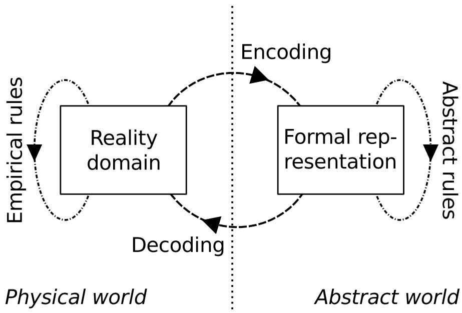

Fig. 5.1 A copy of Fig. 2.1 on Page 46, illustrating the human mind's journey into the abstract world, retrieving knowledge about the physical world

The complexity of life is mostly excluded. Furthermore, the focus of the abstract representation has been on a scheme of mathematization first introduced by Isaac Newton and Gottfried Wilhelm Leibniz (see also Sect. 2.1.1). In a nutshell, this approach can be labeled as equation-driven.

These observations allow the Book of Nature to be classified as follows. Its reality domain, while excluding complex phenomena like life and consciousness, focuses on *fundamental* aspects of the physical world. For instance, describing how subatomic particles interact via a unification of three of the four fundamental forces (Sect. 4.4) and how the force of gravity, replaced by the dynamics of space-time geometry (Sects. 4.1 and 10.1.2), sculptures the cosmos. The formal representation is equation-based, in other words, it is *analytical*. This *fundamental-analytical* dichotomy is the paradigm of the Book of Nature.

Only recently, with the advent of information processing,[1] Fig. 5.1 could be applied in a whole new context. By extending the validity domain of the formal representation to encompass computational aspects, a novel reality domain becomes intelligible that is much closer to human experience than, for instance, the elusive entities comprising matter and transmitting forces. Now, the focus shifts away from an equation-driven effort and embraces computational and simulational tools. This formal approach can essentially be denoted as *algorithmic*. Slowly, the everyday complexity surrounding us can be tackled. This reality domain, in contrast to the fundamental, will be called *complex* in the following. Miraculously, the human mind

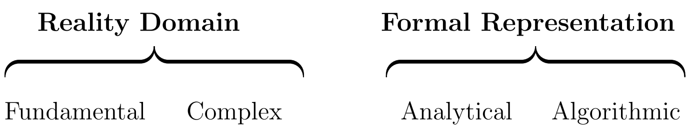

Fig. 5.2 The dichotomies of reality and understanding. (*Left*) partitioning the world into the two domains labeled fundamental and complex. (*Right*) the two main modes of formal representation of reality relating to analytical and algorithmic descriptions

[1] Which, in itself, is a prime example of the enormous effectiveness of this scientific knowledge-generating process.

has suddenly stumbled upon an extension of the Book of Nature. A new dichotomy emerges, relating to the *complex-algorithmic* classification, uncovering the next volume of the Book of Nature. In Fig. 5.2 a conceptual demarcation of these concepts is shown.

The Pythagoreans' dream of the mathematization of nature (Chap. 2) turns out to be only the beginning of a profound knowledge generation process. Building on the tools enabled by the *fundamental-analytical* dichotomy, new abstract worlds become accessible by the aid of computation and the *complex-algorithmic* paradigm is uncovered. In summary, the Book of Nature has been greatly expanded and is now comprised of:

VOLUME I The *fundamental* reality domain made accessible to the mind via *analytical* formal representations.
VOLUME II Real-world *complexity* encoded via *algorithmic* formalizations.

In the following, essential features of Volume I and II of the Book of Nature will be independently summarized and analyzed (Sects. 5.1 and 5.2), before a unifying theme is unveiled (Sect. 5.3). Finally, the entire landscape spanned by the *fundamental-complex* and *analytical-algorithmic* classifications is examined (Sect. 5.4). Elements are taken or adapted from Glattfelder et al. (2010) and Appendix A in Glattfelder (2013). Note that the contents of Volume II, relating to complex systems, is presented in detail in Chaps. 6 and 7.

5.1 Volume I: Analytical Tools and Physical Science

The tremendous success of the first volume of the Book of Nature is summarized in the next section and some cornerstones of its analytical powers highlighted. Then the limitations are exposed.

5.1.1 The Success

Staying faithful to the credo "Shut up and calculate!" (Sect. 2.2.1) has allowed a lot of ground to be covered. By not being consumed by philosophical questions relating to the nature of the abstract world, the human mind's capacity to host or access it, and the correspondence between the physical and the abstract (the topics addressed in Fig. 2.2), progress can be made. Although, as mentioned, the reality domain is restricted to exclude complex systems, it still covers most of physical science. In effect, laws of nature can be understood as regularities and structures in a highly complicated universe. They critically depend on only a small set of conditions and are independent of many other conditions which could also possibly have an effect. Science can be understood as the quest to capture fundamental processes of nature within formal mathematical representations, i.e., in an analytical framework. To understand more about the nature of the physical system under investigation, experiments are performed yielding new insights. Historically, Robert Boyle was instrumental in establishing experiments as the cornerstone of physical sciences around 1660 (insights later published as Boyle (1682). Approximately at the same time, the philosopher Francis Bacon introduced modifications to Aristotle's nearly two thousand year old ideas, introducing what came to be known as the scientific method, where inductive reasoning plays an important role (Bacon 2000). This paved the way for a modern understanding of scientific inquiry. From this initial thrust our modern knowledge of the world emerged, laying the fertile groundwork on which technology would flourish. All our current technologicontinuouscal advances, and the increasing speed at which progress is made, trace back to this initial spark.

A powerful example within the *fundamental-analytical* dichotomy, highlighting the success of the interplay between the abstract and physical worlds, is the notion of symmetry. This simple idea found its formal expression in the concept of invariance (Chap. 3). This is a prime example illustrating the translation process described in Fig. 5.1: a tangible idea is encoded as a mathematical abstraction. Digging deeper in the abstract world further unearthed group theory and its ties to geometry (Sects. 3.1.1 and 4.1). Mathematical invariance was then seen to flow into various themes. For instance, universal conservation laws (Sect. 3.1), the causal relation of space and time (Sect. 3.2.1) elementary particles being categorized by the groups describing space-time symmetries (Sect. 3.2.2), and the unification of the non-gravitational forces (Chap. 4). Weaving a tapestry out of these threads made from symmetry necessarily integrates a wide array of topics seen in physics. From

- classical mechanics (Sects. 2.1.1 and 3.1.1) to quantum mechanics (Sects. 4.3.4 and 10.3.2);
- special relativity (Sect. 3.2.1) to general relativity (Sects. 4.1 and 10.1.2);
- quantum field theory (Sects. 3.1.4, 3.2.2.1, 4.2, and 10.1.1) to the standard model of particle physics (Sects. 4.2, 4.3, and 4.4);
- unified field theories (Sect. 4.3.3) to higher dimensional unification schemes (Sect. 4.3.1).

And, last but not least, electromagnetism (Sect. 2.1.2 and Eq. (4.18)).

5.1.2 The Paradigms of Fundamental Processes

From the fundamental and universal importance of symmetry, three paradigms applicable to physics can be derived:

> **Mathematical models of the physical world are either:**
>
> P_1^f: **independent of the choice of representation in a coordinate system;**

P_2^f: unchanged by symmetry transformations;
P_3^f: constrained to transform according to a symmetry group.

To illustrate P_1^f, imagine an arrow located in space. It has a length and an orientation. In the mathematical world, this can be represented by a vector, labeled a. By choosing a coordinate system, the abstract entity a can be given physical meaning $a = (a_1, a_2, a_3)$. For each axis direction x_1, x_2, x_3, the a_i describe the number of increments along the axis the vector is projected on. For instance $a = (3, 5, 1)$. The problem is, however, that depending on the choice of the coordinate system, which is arbitrary, the same vector is described very differently: $a = (3, 5, 1) = (0, 23.34, -17)$. The paradigm above states that the physical content of the mathematical model should be independent of the decision of how one chooses to represents the mathematical model.

The first two requirements P_1^f and P_2^f, seemingly innocuous, straightforward and commonsensical, are conceptualized as the powerful ideas of general covariance and invariance. The notion that vectors and tensors should be independent of the choice of coordinates used to express and compute these quantities, leads to one of the two main ingredients in the theory of general relativity, describing gravity (Sect. 4.1 and 10.1.2). Moreover, expecting the outcome of an experiment to be independent of the exact time and location the experiment was conducted at, results, via Noether's theorem, in the conservation of energy and momentum in the universe (Sect. 3.1.4). Alternatively, imposing a theory to be invariant under gauge transformations (Sect. 4.2) yields a unifying theme on the basis of which the standard model of particle physics is constructed (Sect. 4.4). In Fig. 5.3 a schematic overview is given, of how P_1^f leads to the theory of general relativity and P_2^f to the standard model. While the former utilizes the external symmetry of space-time, the latter relies on internal gauge symmetry. It is indeed amazing, how the adoption of such simple paradigms leads to such effective and complete physical theories. P_3^f is more subtle, as it describes a link between the quantum world and the structure of the symmetry groups of space-time: the mathematical representation of the groups encode the transformation properties of quantum fields and particle states (Sects. 3.2.2.1 and 3.2.2.2). This gives rise to a mathematical lever with which the unseen quantum entities can be manipulated.

5.1.3 The Limitations

In the last chapters, it was unveiled how mathematics underlies physics. From classical mechanics, electromagnetism, the non-gravitational forces unified in the standard model of particle physics to gravitational forces. In spite of this tremendous success there is still one omission, relating to many-body problem. This is a large category

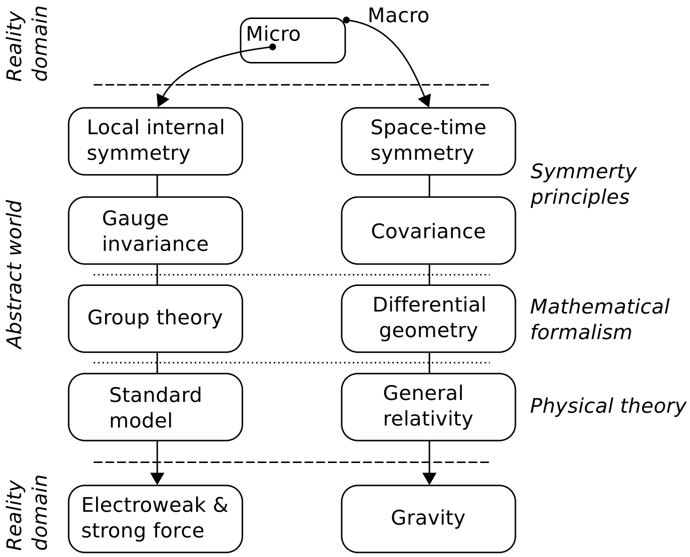

Fig. 5.3 Conceptual overview of the structure of the two main physical theories describing all known forces in the universe: the standard model and general relativity. Focusing on specific reality domains (the quantum world or the arena of space-time) and guided by symmetry principles, it is possible to translate the physical essence into an abstract structure. Once encoded, this information is subjected to the dictum of mathematical theories, yielding the physical theories. Finally, decoding these formal representations allows the effects of the fundamental physical forces to be calculated. Adapted from Glattfelder (2013)

of physical problems pertaining to the properties of microscopic systems that are comprised of a large number of interacting entities.

Condensed matter physics attempts to explain the macroscopic behavior of matter based on microscopic properties and quantum effects (Ashcroft and Mermin 1976). It is one of physics first ventures into many-body problems in quantum theory. Although the employed notions of symmetry do not act at such a fundamental level as in the above mentioned theories, they are a cornerstone of the theory. Namely, the complexity of the problems can be reduced using symmetry in order for analytical solutions to be found. Technically, the symmetry groups are boundary conditions of the Schrödinger equation. This leads to the theoretical framework describing, for example, semiconductors. In the super-conducting phase (Schilling et al. 1993), the wave function becomes symmetric.

Another macroscopic characteristic of matter based on microscopic properties are quasicrystals (Mackay 1982). A quasicrystalline pattern can fill an entire space, but lacks translational symmetry. In short, quasicrystals are structures which are ordered but not periodic. They have fractal properties (Sect. 5.2.1). Until Dan Shechtman received the 2011 Nobel Prize for the discovery of quasicrystals, the topic was controversial. Eminent chemist and two-time Nobel laureate[2] Linus Pauling exclaimed that “there are no quasi-crystals, just quasi-scientists” (quoted in The Guardian 2013). Shechtman faced disdain from his peers and his research was rejected as erroneous. Lesley Yellowlees, president of the Royal Society of Chemistry, summarized the ordeal (quoted in The Guardian 2013):

> Dan Shechtman’s Nobel prize celebrated not only a fascinating and beautiful discovery, but also dogged determination against the closed-minded ridicule of his peers, including leading scientists of the day. His prize didn’t just reward a difficult but worthy career in science; it put the huge importance and value of funding basic scientific research in the spotlight.

Overall, many-body problems in physics represent a vast category of challenges which are notoriously hard to tackle. Determining the precise physical behavior of systems composed of many entities is, in general, hard, as the number of possible combinations of states increases exponentially with the number of entities to be considered. This intricacy drains the *analytical* formal representation’s power, as calculations become intractable. In contrast, the understanding of many-body problems often relies on approximations specific to the problem being analyzed and result in computationally intensive calculations. The *algorithmic* approach to decoding such *complexity*, defining a new dichotomy, emerges.

As an example, in classical mechanics the n-body problem describes the challenge of predicting the motions of n celestial bodies interacting with each other via Newton’s law of universal gravity. Already 3-body problems—for instance, describing a Sun-Earth-Moon system given their initial positions, masses, and velocities—yield equations with no closed form solutions. As a result, numerical methods or computer simulations need to be invoked in order to solve such seemingly simple problems (Valtonen and Karttunen 2006).

A further challenge related to the understanding of systems of many interacting agents, rendering equations mute but emphasizing the power of *algorithmic* tools, is the discovery of chaos theory (Mandelbrot 1982; Gleick 1987). For instance, the behavior of water molecules in a dripping faucet becomes unpredictable, when the system enters the chaotic state (Shaw 1984). One critical aspect of chaotic systems in nature is their dependence on initial conditions. The Butterfly Effect describes this sensitivity metaphorically: The flapping of the wings of a butterfly creates tiny perturbations in the atmosphere which set the stage for the occurrence of a tornado weeks later. More precisely, the exact values of the initial conditions determine how the system evolves in time. However, as these initial conditions can never be set with infinite accuracy in the real world, the system’s evolution shows a path-dependence. In other words, two dynamical systems with nearly identical initial conditions can end up in two vastly different end states. More on chaos theory is presented in Sect. 5.2.1.

The Butterfly Effect was coined by Edward Lorenz, a mathematician, meteorologist, and a pioneer of chaos theory. Meteorology is a prime example of how inquiries into the workings of a complex system are stifled by chaotic behavior. In theory, if

[2] He was awarded the Nobel Prize in chemistry and the Nobel Peace Prize. Marie Curie was the first person to ever be honored twice, with a Nobel Prize in physics and chemistry. To this day, the illustrious group of people to have received two Nobel Prizes is comprised of four people.

there existed an infinitely small grid of atmospheric measurements stations scattered all over the world, weather predictions would be accurate. Facing such impossibility, scientists have devised simulational methods able to tackle the uncertainty. As an example, the Monte Carlo method utilizes computational simulations which are repeated many times over with random sampling to obtain numerical results. The key insight is to use the statistical properties of seeming randomness to solve problems that might be deterministic in principle. The *algorithmic* Monte Carlo methods are mostly employed, and often useful, when it is difficult or even impossible to use other approaches, like *analytical* tools.

Another key limiting factor for the equation-based understanding of the workings of the world comes in the guise of non-linearity, a cornerstone of chaos theory. For linear systems the change of the output is proportional to the change of the input. Expressed mathematically

$$f(x) \sim x. \tag{5.1}$$

Already the square of a variable is non-linear, i.e., $f(x) = x^2$. Here we see an emerging conflict between the *fundamental-analytical* and the *complex-algorithmic* dichotomies. Linear algebra is the branch of mathematics describing vector spaces and, crucially, linear mappings between such spaces. The linear mappings are expressed as matrices. This mathematical language, relying on linear systems, has been extremely fruitful in describing quantum mechanics. However, most physical systems in nature are inherently non-linear (Mandelbrot 1982; Strogatz 1994). Moreover, this non-linear (and chaotic) behavior is, again, analytically hard to tackle. To conclude, a final limitation in physics comes from dissipative effects, like friction or turbulence, where the system loses energy (or matter) over time and exhibits non-linear dynamics. Hence calculations in physics often rely on idealizations. For instance, Newton's classical mechanics can easily describe a game of pool, i.e., collisions between billiard balls, if friction is ignored, the balls are assumed to be perfectly spherical, and the collisions taken to be elastic (i.e., the kinetic is energy conserved).

In essence, while physics has had an amazing success in describing most of the observable universe in the last 300 years, it appears as thought its powerful mathematical formalism is ill-suited to address the real-world complexity surrounding and including us. Namely, situations where many agents are interacting with each other. For instance, ranging from particles, chemical compounds, cells, biological organisms to celestial bodies, and systems thereof. In order to approach real-life complex phenomena, one needs to adopt a more systems oriented focus.

5.2 Volume II: Algorithmic Tools and Complex Systems

For centuries, the *fundamental-analytical* dichotomy of understanding the universe has prevailed. A vast array of knowledge has been accumulated. However, only recently our focus has shifted to the intricate realities of systems of interacting agents surrounding us, contained within us, and comprising us. A new dichotomy relating to the *complex-algorithmic* classification emerged. Equipped with new computational and simulational tools we started to probe a new reality domain encompassing complex systems. A true paradigm shift occurred in our understanding, away from a reductionist philosophy prevailing in science towards a holistic, networked, and systems-based outlook.

Complex systems theory is the topic of Chap. 6. Here, in a nutshell, we introduce complex systems and networks, describe the paradigms of the *complex-algorithmic* dichotomy, and outline the success of this endeavor.

5.2.1 The Paradigms of Complex Systems

A complex system is usually understood as being comprised of many interacting or interconnected parts (or agents). A characteristic feature of such systems is that the whole often exhibits properties not obvious from the properties of the individual parts. This is called emergence. In other words, a key issue is how the macro behavior emerges from the interactions of the system's elements at the micro level. Moreover, complex systems also exhibit a high level of adaptability and self-organization. The domains complex systems originate from are mostly socio-economical, biological, or physio-chemical (Chaps. 6 and 7).

The study of complex systems appears complicated, as it implies an approach very different from the reductionistic thinking of established science. Now, breaking down, identifying, and analyzing the behavior of a single constituent of a system does not reveal anything about the dynamics of the system as a whole. A quote from Anderson (1972), an influential article succinctly titled "More is Different", illustrates this fact:

> At each stage [of complexity] entirely new laws, concepts, and generalizations are necessary [. . .]. Psychology is not applied biology, nor is biology applied chemistry.

In the same vein, it is far from clear how to get from a description of quarks and leptons, via DNA, to an understanding of the human brain and consciousness. It appears as though these hierarchical levels of order defeat any reductionistic attempts of understanding by their very design.

As discussed, complex systems are usually very reluctant to be cast into closed-form analytical expressions. This means that it is generally hard to derive mathematical quantities describing the properties and dynamics of the system under study. If the paradigms of fundamental processes described on Page 143 fail, what is needed to replace them? Indeed, can we even hope to find such succinct guiding principles a second time? Remarkably and, again, unexpectedly, the answer is yes. The paradigms of complex systems are, once again, very concise:

> **P_1^c: Every complex system is reduced to a set of objects and a set of functions between the objects.**
> **P_2^c: Macroscopic complexity is the result of simple rules of interaction at the micro level.**

P_1^c is reminiscent of the natural problem solving philosophy of object-oriented programming, where the objects are implementations of classes (code templates) interacting via functions (public methods). A programming problem is analyzed in terms of objects and the nature of communication between them. When a program is executed, objects interact with each other by sending messages. The whole system obeys specific rules (encapsulation, inheritance, polymorphism, etc.). See, for instance Gamma et al. (1995).

Similarly, in the mathematical field of category theory a category is defined as the most basic structure: a set of objects and a set of morphisms (maps between the sets) (Hillman 2001). Special types of mappings, called functors, map categories into each other. Category theory was understood as the "unification of mathematics" in the 1940s. A natural incarnation of a category is given by a graph or a network, where the nodes represent the objects and the links describe their relationship or interactions. Now the structure of the network (i.e., the topology) determines the function of the network. This new science of networks, emerging from the study of complex systems and building on the formal representation of P_1^c as a graph, is presented in the Sect. 5.2.3.

Paradigm P_2^c, the topic of the following section, describes how order emerges out of chaos, driven by a set of simple rules describing the interaction of the parts making up a complex system. Together, these two paradigms represent a shift away from mathematical models of reality towards algorithmic models, computing and simulating reality. In other words, a change in modus operandi from the *fundamental-analytical* to the *complex-algorithmic* dichotomy has occurred. Now, the analytical description of complex systems can be abandoned in favor of the algorithms describing the interaction of the objects, i.e., agents, in a system, according to specified rules of local interaction. This is the fundamental distinguishing characteristic outlined on the right-hand side of Fig. 5.2. Instead of encoding certain aspects of reality into mathematical equations, now computers are programmed with step-by-step recipes which are conjured up to tackle problems. Only by letting the algorithm run new knowledge is generated and the design of algorithms and the existence of algorithmic solutions become relevant.

This prominent approach is called agent-based modeling. One key realization is that the structure and complexity of each agent can be ignored when one focuses on their interactional structure. Hence the neurons in a brain, the chemicals interacting in metabolic systems, the ants foraging, the animals in swarms, the humans in a market, etc., can all be understood as being comprised of featureless interacting agents and modeled within this paradigm. By encapsulating the algorithms into a system of agents, complex behavior can be simulated. Some successful agent-based models are Axelrod (1997), Lux and Marchesi (2000), Schweitzer (2003), Andersen and Sornette (2005), Miller et al. (2008), Šalamon (2011), Helbing (2012).

5.2.2 *The Science of Simple Rules*

Paradigm P_2^c of complex systems, stating that complexity emerges from simplicity, is unexpected and very surprising. It is perhaps as puzzling as Eugene Wigner's comments on the "unreasonable effectiveness of mathematics in the natural sciences" (Sect. 9.2.1). Prompted by the tremendous success of Volume I of the Book of Nature in decoding the workings of the universe by utilizing equations, scientists expressed their bafflement. For instance, also Albert Einstein (quoted in Isaacson 2007, p. 462):

> The eternal mystery of the world is its comprehensibility. The fact that it is comprehensible is a miracle.

Now compounding the enigma is the discovery of Volume II. What appeared as intractable complexity from afar is uncovered to be the result of simple rules of interaction closeup. First, the universe speaks a mathematical language the human mind can discover or create. Then, what appeared as hopeless complicatedness is in fact derived from pure simplicity.

A New Kind of Science

Although the simplicity of complexity (Chap. 6) has attracted less philosophical interest than the "unreasonable effectiveness of mathematics", some scientists have expressed their total bewilderment at the realization. For instance, Stephen Wolfram, a physicist, computer scientist, and entrepreneur. Wolfram started his academic career as a child prodigy, publishing his first peer-reviewed and single-author paper in particle physics at the age of sixteen (Wolfram 1975). Three years later, a publication appeared which is still relevant and referenced today, forty years later (Fox and Wolfram 1978). In 1981, he won the MacArthur Fellows Program,[3] colloquially know as the "Genius Grant", a prize awarded annually to researchers who have shown "extraordinary originality and dedication in their creative pursuits and a marked capacity for self-direction". In parallel, Wolfram led the development of the computer algebra system called SMP (Symbolic Manipulation Program) in the Caltech physics department during 1979–1981. A dispute with the administration over the intellectual property rights regarding SMP eventually caused him to hand in his resignation. Continuing on this computational journey, Wolfram began the development of Mathematica in 1986. This was a mathematical symbolic computation program and would become an invaluable tool used in many scientific, engineering, mathematical, and computing fields. In 1987, the private company Wolfram Research Inc. was founded, releasing Mathematica Version 1.0 in 1988. By 1990, Wolfram

[3] See https://www.macfound.org/programs/fellows/strategy.

Research reached $10 million in annual revenue.[4] Today, Mathematica (Version 11.2.0) remains highly influential and most of its code is written in the Wolfram Language. This is a general multi-paradigm programming language developed by Wolfram Research.

However, Wolfram's biggest fascination lies with complexity. It started with his work on cellular automata in 1981. These are discrete models studied in computability theory, mathematics, physics, complexity science, theoretical biology, and microstructure modeling. A cellular automaton consists of a regular grid of cells, each in one of a finite number of states. A famous cellular automaton was devised by the mathematician John Conway in 1970, called the Game of Life (Gardner 1970). It is an infinite two-dimensional orthogonal grid of square cells, which can be in two sates (dead or alive). The game evolves according to four simple rules and the whole dynamics are solely determined by the choice of the initial state. The Game of Life attracted a lot of attention due to the complex patterns that could emerge from the interaction of the game's simple rules. In essence, an early computational implementation demonstrating emergence and self-organization. In 1987, Wolfram founded the journal Complex Systems,[5] "devoted to the science, mathematics and engineering of systems with simple components but complex overall behavior". This fascination with complexity had life-changing consequences for him.

In 2002, Wolfram wrote (Wolfram 2002, p. ix):

> Just over twenty years ago I made what at first seemed like a small discovery[6]: a computer experiment of mine showed something I did not expect. But the more I investigated, the more I realized that what I had seen was the beginning of a crack in the very foundations of existing science, and a first clue towards a whole new kind of science.

Developing this new science would become his passion. In 1991, Wolfram set out to realize this vision, resulting in the 2002 book, *A New Kind of Science*, a one-thousand-two-hundred-page tour de force (Wolfram 2002). During the time of writing, Wolfram became nocturnal and reclusive, totally devoted to his project. Indeed, when he realized that there was no publisher who could print the book with the quality he envisioned for the diagrams, he simply founded Wolfram Media Inc. to do the job. See (Levy 2002) for more anecdotes. The book begins by setting the stage with the demarcation described in Fig. 5.2 (Wolfram 2002, p. 1):

> Three centuries ago science was transformed by the dramatic new idea that rules based on mathematical equations could be used to describe the natural world. My purpose in this book is to initiate another such transformation, and to introduce a new kind of science that is based on the much more general types of rules that can be embodied in simple computer programs.

In other words, Wolfram describes the two opposing formal representations we humans can access: analytical vs. algorithmic. In essence "the big idea is that the

[4]See http://www.stephenwolfram.com/scrapbook/timeline.

[5]See http://www.complex-systems.com.

[6]Wolfram is referring to a cellular automaton rule he introduced in 1983, called Rule 30, out of 256 possible rules. Rule 30 produces complex, seemingly random patterns from the simple, well-defined rules of interaction.

algorithm is mightier than the equation" (Levy 2002). Wolfram claims to have re-expressed all of science utilizing the formal language of cellular automata, in essence, simple programs. Indeed, looking at the table of contents reveals the great scope in the topics that are covered:

1 The Foundations for a New Kind of Science
2 The Crucial Experiment
3 The World of Simple Programs
4 Systems Based on Numbers
5 Two Dimensions and Beyond
6 Starting from Randomness
7 Mechanisms in Programs and Nature
8 Implications for Everyday Systems
9 Fundamental Physics
10 Processes of Perception and Analysis
11 The Notion of Computation
12 The Principle of Computational Equivalence

From mathematics and its foundation, complex systems found in nature, physics and its foundation, to the nature of computation, a vast array of subject matter is covered diligently in great detail. Wolfram acknowledges the tremendous success of the mathematical approach to science, but stresses that many central issues remain unresolved, where the simple-programs paradigm could possibly shed new light on the challenges (Wolfram 2002, p. 21):

> The typical issue was that there was some core problem that traditional methods or intuition had never successfully been able to address—and which the field had somehow grown to avoid. Yet over and over again, I was excited to find that with my new kind of science I could suddenly begin to make great progress—even on problems that in some cases had remained unanswered for centuries.

A New Kind of Science was received with skepticism and ignited controversy. However, regardless of how one views Wolfram and his claims, one epiphany remains. Namely, the counterintuitive realization that simplicity unlocks complexity (Wolfram 2002, p. 2):

> Indeed, even some of the very simplest programs that I looked at had behavior that was as complex as anything I had ever seen.
>
> It took me more than a decade to come to terms with this result, and to realize just how fundamental and far-reaching its consequences are.

Furthermore (Wolfram 2002, p. 19):

> And I realized, that I had seen a sign of a quite remarkable and unexpected phenomenon: that even from very simple programs behavior of great complexity could emerge.

Until this phenomenon was reliably demonstrated and studied by Wolfram, people expected simple rules of interactions to lead to mostly simple outcomes. Discovering simplicity to be the spawning seed of complex behavior was truly unexpected. But perhaps the boldest claim in the book relates to the computational nature of the universe. Wolfram invokes a radical new level of reality, where beneath the laws of physics there lies a computational core. This theme will reappear in Chap. 13.

Quadratic and Logistic Maps

Another archetypal theme describing how simplicity encodes complexity comes from chaos theory. This time the notion is nested deep within mathematics itself and comes in the guise of fractal sets. Fractals are very particular abstract mathematical objects. The term was coined by the mathematician Benoît Mandelbrot (Mandelbrot 1975). Fractals came to prominence in the 1980s with the advent of chaos theory, as the graphs of most chaotic processes display fractal properties (Mandelbrot 1982)—that is, foremost, self-similarity. This is a feature of an object to contain, exactly or approximately, similar parts of itself. For instance, a coastline is self-similar: parts of it show the same statistical properties at many scales (Mandelbrot 1967). Such a characteristic is also called scale invariance, a topic discussed in Sect. 6.4 in the context of scaling laws. Indeed, many naturally occurring objects display fractal properties. So much so, that Mandelbrot chose the title of his seminal and hugely influential work on fractals and chaos theory to read: *The Fractal Geometry of Nature* (Mandelbrot 1982).

The most prototypical fractal, also entering pop culture, is the Mandelbrot set (Douady et al. 1984). Due to the rise of computational power, graphical images started to become more detailed around the 1980s, slowly unveiling the set's aesthetic appeal. But most stunning was the self-similar property of the Mandelbrot set, where the original iconic shape would reemerge over and over again, at all resolutions accessible within the current computational limits. See Fig. 5.4 for an illustration. The Mandelbrot set is defined as the set of values c for which the iterations of the quadratic map

$$z_{n+1} = z_n^2 + c, \tag{5.2}$$

remain bounded, where $z_0 = 0$. In other words, a chosen c belongs to the set if the series $z_1 = c$, $z_2 = z_1^2 + c = c^2 + c$, … does not go to infinity for $n \to \infty$. As c is a complex number, i.e., $c \in \mathbb{C}$, it can be represented as

$$c = a + i \cdot b, \tag{5.3}$$

with $a, b \in \mathbb{R}$ and $i := \sqrt{-1}$. Hence one can display c graphically as a point in the (complex) plane with the coordinates $c = (a, b)$, explaining the two-dimensional nature of fractals. Variants of the Mandelbrot set are easily conceived of, by altering the nature of the map. For instance

$$\hat{z}_{n+1} = \hat{z}_n^4 + c, \tag{5.4}$$

yields the fractal set seen in the middle and right-hand panels of Fig. 5.4. Generically

$$\tilde{z}_{n+1} = f(\tilde{z}_n) + g(c), \tag{5.5}$$

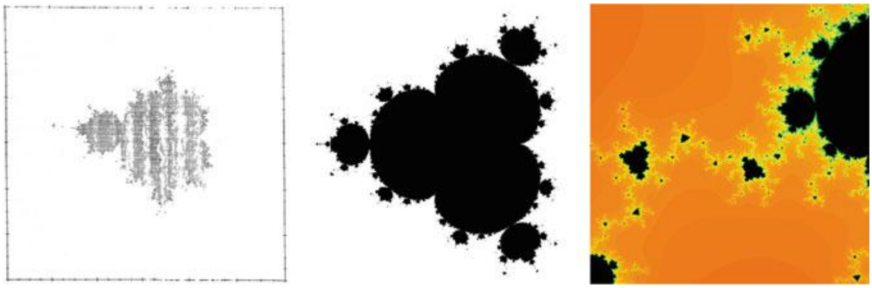

Fig. 5.4 The evolution of fractals. (*Left*) the first glimpse of the Mandelbrot set defined in Eq. (5.2), reproduced from Gleick (1987), (p. 225). (*Middle*) a fractal variant defined by Eq. (5.4). (*Right*) zooming into the middle fractal, revealing its self-similar nature. The colors indicate how quickly c diverges (the lighter the slower the divergence) while black shows the converging points defining the set. Note that these are original images produced by myself in the mid-1990s, explaining the pixelation seen somewhat skewing the self-similar patterns

with two defining functions f and g. These iterative equations are also known as difference equations, a hallmark of discrete mathematics, discussed in Sect. 5.3.

Another simple equation describing a chaotic system is know as the logistic map

$$x_{n+1} = r x_n (1 - x_n), \tag{5.6}$$

where the value of the term following the nth one is again determined by the values of the nth term itself, the initial value x_0, and a constant r. It has the same structure as Eq. (5.2) defining the Mandelbrot set. The logistic map was introduced in a seminal paper by the biologist Robert May (May 1976). It is another archetypal example of how complex, chaotic behavior can arise from very simple non-linear dynamical equations. The equation describes the evolution of populations due to reproduction and starvation and is famous for its bifurcation diagram (Feigenbaum 1978), showing how the system descends into chaos.

Before Mandelbrot and others[7] first saw the intricate shape of the fractal set named after him in the late-1970s, no one could have imagined that such a simple equation, $z_{n+1} = z_n^2 + c$, had the power to encode such a wealth of structure. In essence, the simple rule of the iterative map contains an infinitude of complexity. Anywhere on the boundary of the Mandelbrot set, one can zoom in, theoretically indefinitely, and keep on rediscovering new delicate structures and patterns of stunning complexity. This is another prime example of P_2^c: A seductively simple procedure results in one of the most complex objects in mathematics.

[7]There exists a dispute about the discovery of the Mandelbrot set (Horgan (2009)).

5.2.3 *The New Science of Networks*

While the second paradigm of complex systems uncovers that simple rules drive complex behavior, Paradigm P_1^c states that complex systems should be broken down into individual agents and their interactions. As a result, networks are an ideal abstraction for theses systems. The agents are represented by featureless nodes and the interactions are given by the links connecting the nodes. This thinking gave rise to a new interaction-base worldview and the crucial realization that networks are able to mirror the organizational properties of real-world complex systems. A new science of networks was ignited (Dorogovtsev and Mendes 2003, p. 1):

> In the late 1990s the study of the evolution and structure of networks became a new field in physics.

The formal mathematical structures describing networks are graphs. The nearly three hundred year history of graph theory is briefly discussed in Sect. 5.3.2, where the notion of a random graph takes center stage around 1960. This fruitful marriage of probability theory and graph theory resulted in much successful scholarly work. So what is there to add in terms of a new science of networks? Indeed (quoted in Newman et al. 2006, p. 4):

> If graph theory is such a powerful and general language and if so much beautiful and elegant work has already been done, what room is there for a new science of networks?

The authors then offer the following answers (quoted in Newman et al. 2006, p. 4):

> We argue that the science of networks that has been taking shape over the last few years is distinguished from preceding work on networks in three important ways: (1) by focusing on the properties of real-world networks, it is concerned with empirical as well as theoretical questions; (2) it frequently takes the view that networks are not static, but evolve in time according to various dynamical rules; and (3) it aims, ultimately at least, to understand networks not just as topological objects, but also as the framework upon which distributed dynamical systems are built.

The first glimpse of this new science of networks came from sociology in the late 1960s. A milestone being the work of Mark Granovetter on the spread of information in social networks (Granovetter 1973). He realized that more novel information flows to individuals through weak rather than strong social ties, coining the term "the strength of weak ties." Since our close friends move in similar circles to us, the information they have access to overlaps significantly with what we already know. Acquaintances, in contrast, know people we do not know and hence have access to novel information sources. Another topic of interest was the interconnectivity of individuals in social networks. Stated simply, how many other people does each individual in a network know? Stanley Milgram devised an ingenious, albeit simple, experiment in 1969. The unexpected results propelled a novel concept into the public consciousness: the notion of the small world phenomenon, colloquialized as "six degrees of separation" (Milgram 1967; Travers and Milgram 1969) In a nutshell (Newman et al. 2006, p. 16):

> Milgram's experiments started by selecting a target individual and a group of starting individuals. A package was mailed to each of the starters containing a small booklet or "passport" in which participants were asked to record some information about themselves. Then the participants were to try and get their passport to the specified target person by passing it on to someone they knew on a first-name basis who they believed either would know the target, or might know somebody who did. These acquaintances were then asked to do the same, repeating the process until, with luck, the passport reached the designated target. At each step participants were also asked to send a postcard to Travers and Milgram, allowing the researchers to reconstruct the path taken by the passport, should it get lost before it reached the target.

The researchers recruited 296 starting individuals from Omaha, Nebraska and Boston, and targeted a stockbroker living in a small town outside Boston. 64 out of the 296 chains reached the target, with the median number of acquaintances from source to target being 5,2. In other words, a median of six steps along the chain were required. A surprisingly short distance and an unexpected result considering the potential size of the analyzed network. As a modern example, researchers set up an experiment where over 60,000 e-mail users tried to reach one out of 18 target persons in 13 countries by forwarding messages to acquaintances. They also found that the average chain length was roughly six (Dodds et al. 2003). In an other experiment, the microblogging service Twitter was analyzed in 2009. Then it was comprised of 41,7 million user profiles and 1,47 billion social relations and had an average path length found to be 4, 12 (Kwak et al. 2010).

In 1998, Duncan Watts and Steven Strogatz introduced the small-world network model to replicate this small-world property found in more and more real-world networks (Watts and Strogatz 1998). They identified two independent structural features according to which graphs could be classified. The clustering coefficient is a measure of the degree to which nodes in a graph tend to cluster together, derived from the number of triangles present in the network. The second classification measure is the average shortest path length, the key parameter of small-world networks. Applying these quantities to random graphs, constructed according to the prototypical Erdős-Rényi model,[8] reveal a small average path length (usually varying as the logarithm of the number of nodes) along with a small clustering coefficient. In contrast, small-world networks are characterized by a high clustering coefficient and a small average path length. The algorithm introduced in the Watts-Strogatz model considers regular ring lattices, or graphs with n nodes each connected to k neighbors, and imposes a probability for the rewiring of links (excluding self-loops). These models also turned out to be receptive to a variety of techniques from statistical physics, attracting "a good deal of attention in the physics community and elsewhere" (Newman et al. 2006, p. 286).

Finally, after the random graph and small-world network models had been introduced, an additional type of real-world network was discovered by Albert-László Barabási and Réka Albert. This seminal finding ultimately ushered in the new field of complex networks, indeed ignited "a revolution in network science" (Dorogovtsev and Mendes 2003, p. 1). In summary, the hallmark of this new network class

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[8]See Eq. (5.11) on Page 168.

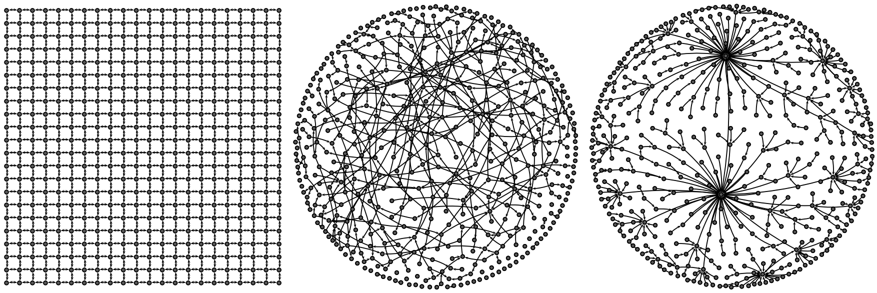

Fig. 5.5 Examples of common network topologies. (*Left*) a regular two-dimensional lattice. (*Middle*) a random network with an average degree of one. (*Right*) a scale-free network with an average degree of one showing two hubs. Reproduced with kind permission from Geipel (2010)

is that its degree distribution follows a power law.[9] As power-law distributions are discussed in detail in Sect. 6.4, it suffices to mention here that such distributions are characterized as follows: while there are a few nodes, called hubs, which have very high connectivity, most nodes, however, have medium to low degree. In Barabási and Albert (1999) the authors proposed that the power-law degree distribution they observed in the WWW is a generic property of many real-world networks. In addition, they offered a specific model of a growing network that generates power-law degree distributions similar to those seen in the WWW and other networks. This growth mechanism is know as preferential attachment: with a certain probability new nodes are added to the network and these preferentially form links with existing nodes of high degree. The influence of Barabási and Albert on this new budding network science is reflected in the number of citations of their publications. Alone Barabási and Albert (1999) and Albert and Barabási (2002) jointly garnered over 18,000 citations.[10]

Note that although scale-free networks are also small-world networks, the opposite is not always true. However, many real-world complex networks show both scale-free and small-world characteristics. In Fig. 5.5 examples of networks with various levels of structure are shown. The feature of complex networks in general to capture and encode the organizational architecture of complex systems is what ushered in the new science of complexity, explained in Chap. 6.

5.2.4 The Success

It is remarkable that a multitude of simple interactions can result in overall complex behavior that exhibits properties like emergence, adaptivity, resilience, and sustain-

[9] See Eq. (5.17) on Page 168.

[10] 10,641 plus 7,646, respectively, retrieved in February 2015 from the Web of Knowledge, an academic citation indexing service provided by Thomson Reuters.

ability. Moreover, the fact that order and structure can arise from local interactions between parts of an initially disordered system is astonishing. Indeed, the universe has always been governed by this structure formation mechanism, self-organizing itself into ever more complex manifestations. From an initial singularity with no structure the universe appears to, at least in our vicinity, be spontaneously evolving towards ever more order. Albeit with no external agency and despite the second law of thermodynamics forcing the entropy—the level of disorder—of the universe to increases over time.[11] Mysterious as these processes may appear, the study of complex systems gives us insights into the mechanisms governing complexity. Moreover, should there exist an unseen fundamental force in the universe, driving it to ever more complexity, then the emergence of first life and later consciousness is perhaps less wondrous.

In essence, complexity does not stem from the number of participating agents in the system but from the number of interactions among them. For instance, there are about 20,000–25,000 genes in a human (International Human Genome Sequencing Consortium 2004). In contrast, bread wheat has nearly 100,000 genes (Brenchley et al. 2012). Thus the complexity of humans is evidently not a result of the size of our genome. It is crucial how the genes express themselves, meaning how the information encoded in a gene is used in the synthesis of functional gene products, such as proteins. The gene regulatory network is a collection of molecular regulators that interact with each other to govern the gene expression levels (Brazhnik et al. 2002).

This novel interaction-based outlook also highlights the departure from a top-down to a bottom-up approach to understanding complexity. A top-down philosophy is associated with clear centralized control or organization. In contrast, bottom-up approaches are akin to decentralized decision-making. The control or organization is spread out over a network. For instance, it once was thought that the brain would, like a computer, have a CPU—a central processing unit responsible for top-down decision-making (Whitworth 2008). Today, we know that the information processing in our brains is massively parallel (Alexander and Crutcher 1990), decentralized into a neural network, giving rise to highly complex, modular, and overlapping neural activity (Berman et al. 2006).

Philosophically, the step towards bottom-up approaches can be understood as a departure from reductionist problem-solving methods and an embracing of a systems-based and holistic outlook. It marks the acceptance of the fact, that we should stop looking for a master-mind behind the scenes, an elusive puppet-master orchestrating the occurrence of events, following devilishly cunning plans.[12] Mapping interactions onto networks or simulating them in agent-based models allows the complex system

[11]This is possible because the second law of thermodynamics only applies to isolated systems. Systems far from the thermodynamic equilibrium (non-equilibrium thermodynamics) are candidates for self-organizing behavior. Overall, the entropy always increases in the universe. See Nicolis and Prigogine (1977).

[12]This philosophical realignment as potential political and societal ramifications. For instance, with respect to the surprising popularity and pervasiveness of conspiracy theories in the 21st Century, see Sect. 12.2.

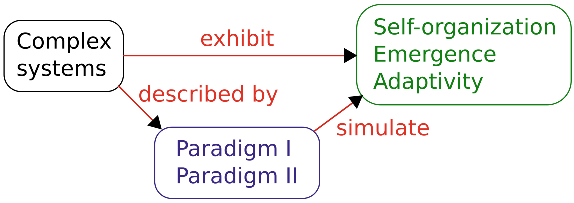

Fig. 5.6 The properties of complex systems and the paradigms leading to an agent-based simulation describing them. Reproduced from Glattfelder et al. (2010)

they describe to be formally analyzed. In Fig. 5.6 an illustrated overview of an agent-based simulation is given: In a computer program agents are interacting according to simple local rules and give rise to global patterns and behaviors seen in real-world complex systems.

By adopting a bottom-up philosophy, novel problems become tractable which before resisted a top-down attack. For instance, modeling the flocking behavior of birds. This swarming behavior has all the hallmarks of complexity (Bonabeau et al. 1999). It is an adaptive and self-organizing phenomenon. So how is it possible to program a simulation of such intricate behavior? Again, adhering to the paradigm of simple rules, a bottom-up approach turns out to offer an easy solution. In 1986 an artificial life program called *Boids* was developed,[13] reproducing the emergent swarming properties. The following three simple rules tell each agent how to interact locally in the simulation:

1. Separation: steer to avoid a crowding of agents.
2. Alignment: steer towards the average heading of local agents.
3. Cohesion: steer to move toward the average position of local agents.

Many hitherto hard (or impossible) to tackle problems suddenly become accessible and tractable with the application of the paradigms of complex systems. In detail, the organizing principles and the evolution of dissipative, real-world complex systems, which are inherently unpredictable, stochastic in nature, and plagued by non-linear dynamics, can now be understood. This, by analyzing the architecture of the underlying network topology or by computer simulations. Hence more patterns and regularities in the natural world are uncovered. For instance, earthquake correlations (Sornette and Sornette 1989), crowd dynamics (Helbing et al. 2000), traffic dynamics (Treiber et al. 2000), pedestrian dynamics (Moussaïd et al. 2010), population dynamics (Turchin 2003), urban dynamics (Bettencourt et al. 2008), social cooperation (Helbing and Yu 2009), and market dynamics (see Sect. 7.3). Recall the mentioned selection of effective agent-based models (Axelrod 1997; Lux and Marchesi 2000; Schweitzer 2003; Andersen and Sornette 2005; Miller et al. 2008; Šalamon 2011; Helbing 2012). Chapter 6 is exclusively devoted to the successful treatment of complex systems and Chap. 7 discusses finance and economics.

[13] See http://www.red3d.com/cwr/boids/.

5.3 The Profound Unifying Powers of Mathematics

The two volumes of the Book of Nature appear to speak two different formal dialects. While Volume I is written in an equation-based mathematical language, Volume II utilizes an algorithmic formal representation, intelligible to computers. In this section it will be uncovered how a mathematical idiom also underpins the algorithmic abstraction. In essence, the entirety of mathematics incorporates both formal strands and hence unifies all human knowledge generation in one consolidated formal representation. The journey leading to this realization begins in pre-Socratic Greece and touches on the Protestant Reformation, the Jesuits, Newton, Galileo Galilei, the bridges of Königsberg, and digital information (bits). Before embarking on this voyage, the edifice of mathematics requires a closer inspection.

There is one general demarcation line one can find in mathematics, splitting the subject matter into *continuous* and *discrete* renderings. Most non-mathematicians only come into contact with the continuous implementation of mathematics,[14] for instance, by being exposed to calculus, geometry, algebra, or topology. While the branch of discrete mathematics deals with objects that can assume only distinct, separated values, continuous mathematics considers only objects that can vary smoothly.[15]

Philosophically, the schism between continuity and discreteness originated in ancient Greece with Parmenides, who asserts that the ever-changing nature of reality is an illusion obscuring its true essence: an immutable and eternal continuum. Still in modern times this intellectual battle between viewing the nature of reality as fundamentally continuous or discreet is been fought. Charles Pierce proposed the term *synechism* to describe the continuous nature of space, time and law (Peirce 1892). A related mystery is the question if reality is infinite or not. Immanuel Kant, for instance, came to the startling conclusion that the world is "neither finite nor infinite" (Bell 2014). In contrast, the triumph of "atomism," i.e., the atomic theory developed in physics and chemistry, only applies to matter and forces, conjuring up the following image: the discrete entities making up the contents of the universe act in the arena of continuous space-time. This view goes to the heart of Leibniz' philosophical system, called *monadism*, in which space and time are continua, but real objects are discreet, comprised of simple units he called *monads* (Furth 1967).

There are, however, also modern efforts to discretize space and time as well, in effect bringing the quantum revolution to an even deeper level. This proposition goes to the very heart of one of theoretical physics' most pressing problems: the incompatibility of quantum field theory (Sects. 3.2.2.1 and 3.1.4), describing all particles and their (non-gravitational) interactions, and general relativity decoding gravity (Sects. 4.1 and 10.1.2). Quantum theory, by its very name, deals with discrete entities while general relativity describes a continuous phenomenon. For decades,

[14]Next to basic arithmetic, which is, of course, part of discrete mathematics.

[15]Technically, this means that between any two numbers there must lie an infinite set of numbers, as is the case for real numbers.

string/M-theory was hailed as the savior, however to no avail (Sect. 4.3.2). These issues are discussed in Sect. 10.2.

Despite the clear top-level separation of mathematics into these two proposed themes, there also exist overarching concepts linking the continuous and the discrete. Indeed, many ideas in mathematics can be expressed in either language and often there are discrete companions to continuous notions to be found[16] and vice versa. Specifically, the discrete counterpart of a differential equation[17] is called a recurrence relation, or difference equation. Examples of such equations were given in Sect. 5.2.1, discussing chaos theory.[18] Then, what is known as time-scale calculus is a unification of the theory of difference equations with that of differential equations. In detail, dynamic equations on time scales are a way of unifying and extending continuous and discrete analysis (Bohner and Peterson 2003). One powerful mathematical theory, spanning both worlds, is group theory. It was encountered in its continuous expression in Chap. 3, specifically the continuous symmetries described by Lie groups (Sect. 3.1.2), arguably the most fruitful concept in theoretical physics (Chaps. 3 and 4). In its discrete version, group theory underlies modern-day cryptography, utilizing discrete logarithms, giving rise to the modern decentralized economy fueled by blockchain technology (Sect. 7.4.3). But perhaps the most interesting mathematical chimera is the fractal. It is defined by the discrete difference equation (5.2) but its intricate border (seen in Fig. 5.4) is continuous and hence infinite in detail, allowing one to indefinitely zoom into it and witness its mesmerizing self-similar nature.

5.3.1 The Continuous—A History

The process of finding the derivative, i.e., the mechanism of differentiation, not only lies at the heart of contemporary mathematics but also marks the birth of modern physics. It builds on a hallmark abstract notion that first appeared in pre-Socratic Greece and can be seen in the calculations performed by Democritus (Boyer 1968), the proponent of physical atomism (see Sect. 3.1), in the 5th Century B.C.E. Since then, this novel idea entered and left the collective human consciousness at various times in history. The concept in question is the abstract idea of infinitesimals. As an example, a continuous line is thought to be composed of infinitely many distinct but infinitely small parts. In general, the concept of infinitesimals is closely related to the notion of the continuum, a unified entity with no discernible parts which is infinitely divisible. In this sense, a global perspective yields the continuum, while an idealized local point of view uncovers its ethereal constituents, the infinitesimals (Bell 2014). The idea of infinitesimals is a deceptively benign proposition, but nonetheless problematic and even dangerous.

[16]For instance, discrete versions of calculus, geometry, algebra, and topology have been defined, although they are less commonly used.

[17]Like Newton's or Maxwell's equations, i.e., Eqs. (2.1) and (2.4), respectively.

[18]Recall Eqs. (5.2) and (5.6).

Ancient Greece

One account has it that the Pythagoreans expelled one of their own philosophers, Hippasus, from their order and possibly even killed him, as he had discovered "incommensurable magnitudes" (Boyer 1968). Hippasus understood that it was impossible to compare, for instance, the diagonal of a square with its side, no matter how small a unit of measure is chosen. In essence, this is a consequence of the existence of irrational numbers. These are real numbers that cannot be expressed as a ratio of integers. In other words, irrational numbers cannot be represented with terminating or repeating decimals. Looking at a square of unit length, its diameter is given, ironically, by the Pythagorean theorem $a^2 + b^2 = c^2$ which yields $c = \sqrt{2} = 1.4142\ldots$ This is a number with infinitely many digits. Other famous irrational numbers, magically appearing everywhere in mathematics and physics, are $\pi = 3.1415\ldots$ and $\exp(1) = 2.7182\ldots$ Currently, the record computation of π has revealed 1.21×10^{13} digits (Yee and Kondo 2013). Irrational numbers posed a great threat to the fundamental tenet of Pythagoreanism, which asserted that the essence of all things is related to whole numbers, igniting the conflict with Hippasus.

This early budding of the notion of the infinitesimal would soon be stifled by associated paradoxes uncovered by the philosopher Zeno. The notorious Zeno's paradoxes show how infinitesimals lead to logical contradictions. One conundrum argues that before a moving object can travel a certain distance, it must first travel half this distance. But before it can even cover this, the object must travel the first quarter of the distance, and so on. This results in an infinite number of subdivisions and the beginning of the motion is impossible because there is no finite instance at which it can start. "The arguments of Zeno seem to have had a profound influence on the development of Greek mathematics [...]" (Boyer 1968, p. 76). "Thereafter infinitesimals are shunned by ancient mathematicians" (Alexander 2014, p. 303), with the exception of Archimedes. Still today there are discussions on whether Zeno's paradoxes have been resolved—touching issues regarding the nature of change and infinity (Salmon 2001). It would take another two thousand years, before the dormant idea of infinitesimals would reemerge. If only to be faced with more antagonism. This time, the threat emanated from the Catholic Church, which saw its hegemony in Western Europe threatened by the power-struggles initiated by the Reformation. In the wake of these events, Galileo would be sentenced to house arrest in 1633 by the Inquisition for the last nine years of his life.

Middle Ages: The Protestant Reformation

In 1517, the Catholic priest Martin Luther launched the Reformation by nailing a treatise comprised of 95 theses to a church door, instigating a fundamental conflict between Catholics and Protestants. As a reformation movement, Protestantism under Luther sought "to purify Christianity and return it to its pristine biblical foundation" (Tarnas 1991, p. 234). The Catholic Church was perceived to have experienced irreparable theological decline: "the long-developing political secularism of the Church hierarchy undermining its spiritual integrity while embroiling it in diplomatic and military struggles; the prevalence of both deep piety and poverty among the Church faithful, in contrast to an often irreligious but socially and economically privileged clergy" (Tarnas 1991, p. 234). Moreover, Pope Leo X's authorization of financing the Church by selling spiritual indulgences—the practice of paying money to have one's sins forgiven—was seen as a perversion of the Christian essence. Luther's revolution aimed at bringing back the Christian faith to its roots, where only Christ and the Bible are relevant. In this sense, Protestantism was not only a rebellion against the existing power-structure of the Catholic Church, it was also a conservative fundamentalist movement. The effect of this combination lead to a paradoxical outcome: while the Reformation's "essential character was so intensely and unambiguously religious, its ultimate effects on Western culture were profoundly secularizing" (Tarnas 1991, p. 240). Indeed, the Protestant's work ethic can be seen to lay the foundations for modern capitalism (Weber 1920 and Sect. 7.4.2). Whereas traditionally the pursuit of material prosperity was perceived as a threat to religious life, now, the two are seen as mutually beneficial.

Against the backdrop of the increasing popularity and spread of Protestantism, a counter-reformation in the Catholic Church was launched. It was spearheaded by the Jesuits, a Roman Catholic order established in 1540, dedicated to restoring Church authority. Their emphasis lay on education and they soon became "the most celebrated teachers on the Continent" (Tarnas 1991, p. 246). In this environment the Jesuits would confront Galileo and also the idea of infinitesimals would reemerge.

With respect to Galileo, it is quite perceivable that the Church could have reacted in a very different manner. "As Galileo himself pointed out, the Church had long been accustomed to sanctioning allegorical interpretations of the Bible whenever the latter appeared to conflict with the scientific evidence" (Tarnas 1991, p. 259). Indeed, even some Jesuit astronomers in the Vatican recognized Galileo's genius and he himself was a personal friend of the pope. However, the Protestant threat compounded the perceived risks emanating from any novel and potentially heretical worldview. And so the heliocentric model of the solar system—the Copernican revolution[19] ignited by the Renaissance mathematician, astronomer, and Catholic cleric Nicolaus Copernicus, fostered by Tycho Brahe and Kepler, ultimately finding its full potential expressed through Galileo—was banned by Church officials. In this conflict of religion versus science, Galileo was forced to recant in 1633 before being put under house arrest. Not so lucky was the mystical Neoplatonist philosopher and astronomer Giordano Bruno. He espoused the idea that the universe is infinite and that the stars are like our own sun, with orbiting planets, in effect extending the Copernican model to the whole universe (Singer 1950). This idea suggested a radical new cosmology. Bruno was burned at the stake in 1600. However, the reason for his execution was not his support of the Copernican worldview, but because he was indeed a heretic, holding beliefs which diverged heavily from the established dogma. Next to his liberal view "that all religions and philosophies should coexist in tolerance and mutual understanding" (Tarnas 1991, p. 253), he was a member of the movement know as Hermetism, a cult following scriptures thought to have originated in Egypt

[19]See also Sect. 9.1.3.

at the time of Moses. These heretic beliefs of Bruno on vital theological matters sealed his fate and resulted in a torturous death (Gribbin 2003).

With the Catholic Church's efficient, dedicated, and callous *modus operandi*, why did Luther not get banished as a heretic? First, Pope Leo X long delayed any response to what he perceived as "merely another monk's quarrel" (Tarnas 1991, p. 235). When Luther finally did get stigmatized as a heretic, the political climate in Europe had shifted in a way facilitating the splitting of the cultural union maintained by the Catholic Church as a result of this theological insurgence. A second factor was the "printing revolution" initiated by Johannes Gutenberg's invention of the printing press after 1450. Perhaps marking one of the first viral phenomena, this new technology allowed for the unprecedented dissemination of information. The rise in literacy and the facilitated access to knowledge allowed a new mass of people to participate in discussions which would have been beyond their means not too long a go. Utilizing this new technology, Luther translated the tow Biblical Testaments from Hebrew and ancient Greek into German in 1522 and 1534. This work proved to be highly influential and would help pave the way to the emergence of other new religious denominations, next to Protestantism, as now many people could offer their personal interpretation, further fracturing the unity of Catholicism.

Middle Ages: The Re-emergence of Infinitesimals

Approximately 1,800 years after Archimedes' work on the areas and volumes enclosed by geometrical figures using infinitesimals, there was finally a revival of interest in this idea among European mathematicians in the late 16th Century. A Latin translation of the works of Archimedes in 1544 made his techniques widely available to scholars for the first time. Then, in 1616, the Jesuits first clashed with Galileo for his use of infinitesimals. Indeed, even a Jesuit mathematician was prohibited by his superiors from publishing work deemed to close to this dangerous idea. In the eyes of the Jesuits, if the notion of a continuum made up of infinitely many infinitesimally small units were to prevail "the eternal and unchallengeable edifice of Euclidean geometry would be replaced by a veritable tower of Babel, a place of strife and discord built on teetering foundations, likely to topple at any moment" (Alexander 2014, p. 120). Between the years 1625 and 1658, a cat-and-mouse game would follow, where the Jesuits would condemn the growing interest in infinitesimals, only to be faced with notable publications by mathematicians on the subject. Consult (Alexander 2014) for the details.

Finally, in 1665, the tides turned, as a young Newton experimented with infinitesimals and developed techniques that would become known as calculus. Ten years later, Leibniz independently developed his own version of calculus and publishes the first scholarly paper on the subject in 1684. When Newton published his revolutionary *Philosophiæ Naturalis Principia Mathematica* in 1687 (Newton 1687), a political controversy ensued over which mathematician, and therefore which country, deserved credit. For Newton and Leibniz the idea of infinitesimals was more than just a mathematical curiosity. Crucially, it was related to the reality of physical processes. In Newton's worldview the conception the continuum was generated by motion, and Leibniz famously exclaimed, *natura non facit saltus*—"nature makes no jump" (Bell

2014). Although infinitesimals proved themselves to be spectacularly useful tools, their logical status remained doubtful under mathematical scrutiny. Notable scholars viewed them as unnecessary and erroneous. Such as the likes of George Berkeley, Georg Cantor, and Bertrand Russell (see, for instance, Bell 2014). In the latter half of the 19th Century the debatable concept of the infinitesimal was replaced by the well-defined notion of the limit

$$\lim_{x \to a} f(x) = L. \tag{5.7}$$

The Modern Age

The introduction of the mathematically sound definition of a limit now allowed calculus to be rigorously reformulated in clear mathematical terms, still used today. It is an interesting observation, that the idea of infinitesimals has experienced a renaissance in the last decades, establishing the concept on a logically solid basis. One attempt fuses infinitesimal and infinite numbers, creating what is called nonstandard analysis. A second endeavor employs category theory to meld what is known as smooth infinitesimal analysis. These novel developments shed new light on the nature of the continuum. More details on the history of infinitesimals and the related mathematics are found in Bell (2014), Alexander (2014).

In the following, some technical aspects of differentiation are briefly introduced.

$\Big\{ \oiint$ *|5.3.1-derivatives >*

For a smooth function $f : \mathbb{R} \to \mathbb{R}$ the derivative of f at the point t_0 is defined as

$$\dot{f}(t_0) := \frac{\mathrm{d}}{\mathrm{d}t} f(t_0) = \lim_{t \to 0} \frac{f(t_0 + t) - f(t_0)}{t}. \tag{5.8}$$

In other words, t is taken to infinitesimally approach zero. Because zero is never reached, the fraction is well-defined. For multivalued functions, e.g., vector fields $\mathbf{F} : \mathbb{R}^n \to \mathbb{R}^m$, partial derivatives exist for all components

$$\partial_j F_i(x_1, \ldots, x_n) := \frac{\partial}{\partial x_j} F_i(x_1, \ldots, x_n); \quad i = 1, \ldots, m; \quad j = 1, \ldots, n. \tag{5.9}$$

These expressions can be assembled in a matrix yielding the general notion of the derivative, called the Jacobian matrix

$$\mathcal{J}_F := \begin{bmatrix} \partial_1 F_1 & \cdots & \partial_n F_1 \\ \vdots & \ddots & \vdots \\ \partial_1 F_m & \cdots & \partial_n F_m \end{bmatrix}. \tag{5.10}$$

Table 5.1 Various themes of the notion of the derivative seen to permeate many physical theories as a common thread. It can be understood as a unified mathematical underpinning, a simple but powerful abstract framework encoding the physical world. The acronyms GR and GT refer to general relativity and gauge theory, respectively. G_{SM} is the standard model symmetry group, seen in (4.72)

Domains	Symbols	Equations
Classical mechanics	∂_t, ∂_t^2, ∂_{q^i}, $\partial_{\dot{q}^i}$	(2.1), (3.1), (3.3)
Field theory	∂_μ, ∂_{ψ^i}	(3.6)
Maxwell equations	∂_t, $\nabla\cdot$, $\nabla\times$	(2.4)
Covariant Maxwell equations	∂_μ, $\Box$	(4.16), (4.18)
Quantum operators	$i\partial_t$, ∇/i	(3.51)
Schrödinger equation	$i\partial_t$	(3.24)
Dirac equation	$i\partial\!\!\!/$	(3.41), (3.42)
Coordinate transformation (GR)	$\Delta^{\mu'}_{\ \nu} = \frac{\partial x'^\mu}{\partial x^\nu}$	(4.3)
Curvature (GR)	$[\nabla_X, \nabla_Y] - \nabla_{[X,Y]}$	(4.47)
Covariant derivative (GR)	$\nabla_\mu = \partial_\mu - \Gamma^{-}_{\mu -}$	(4.8)
Covariant derivative (GT)	$D_\mu = \partial_\mu - A^k_\mu \mathrm{X}_k$	(4.11), (4.27)
G_{SM}-invariant derivative	$\mathcal{D}_\mu = \partial_\mu + i\hat{g}G^\alpha_\mu \lambda_\alpha = + igW^i_\mu \tau_i + ig' B_\mu Y$	(4.73)

< *5.3.1-derivatives*| $\oiint$ }

In the end, infinitesimals paved the way to the introduction of the derivative, an essential tool in the first volume of the Book of Nature. Next to the specific expression for the derivatives of functions (e.g., $\dot{f}$, $\partial_i F_j$, and $\mathcal{J}_F$) the main mathematical actors appearing in physical theories are related to partial derivatives. For instance, the partial derivatives can be combined to form a vector, the nabla operator ∇, defined in (2.2). Or the d'Alembertian operator $\Box$ introduced in (4.17). Table 5.1 shows a summary of the various theories in which the notion of the derivative is vital, as it enters the mathematical equations which describe the workings of multiple fundamental processes in the universe. It is truly amazing, how one specific abstract idea can be singled out and seen to play such an enormously successful role in unlocking the secrets of the universe and furnishing a unifying theme for Volume I of the Book of Nature.

In a nutshell:

> The derivative, a cornerstone of *continuous* mathematics, lies at the heart of the *analytical* machinery that is employed to represent *fundamental* aspects of the physical world, as described in the formal encoding scheme outlined in Fig. 5.1 and detailed in Table 5.1.

5.3.2 Discrete Mathematics: From Algorithms to Graphs and Complexity

There exists one abstract concept, found in discrete mathematics, which is bestowed with great explanatory power. It is a formal representation that can capture a whole new domain of reality in that it underpins the algorithmic understanding of complex systems. Metaphorically, the discrete cousin of the continuous derivative is a graph. As a result, the tapestry of mathematics, weaved out of the continuous and discreet strands, has the capacity to unify the two disjoint volumes of the Book of Nature. In other words, human knowledge generation is truly and profoundly driven by mathematics.

Discrete mathematics is as old as humankind. The idea behind counting is to establish a one-to-one correspondence (called a bijection) between a set of discrete objects and natural numbers. Arithmetics, the basic mathematics taught to children, is categorized under the umbrella of discrete mathematics. Indeed, the foundations of mathematics rests on notions springing from discrete mathematics: logic and set theory. Higher discrete mathematical concepts include combinatorics, probability theory, and graph theory. More information on discrete mathematics and its applications can, for instance, be found in Biggs (2003), Rosen (2011), Joshi (1989).

Although continuous mathematics generally enjoys more popularity, discrete mathematics has witnessed a renaissance driven by computer science. The duality of digital information, which is expressed as strings of binary digits—called bits which exist in the dual states represented by 0 or 1—lies at the heart of discreteness. In this sense, the development of computers, and information processing in general, build on insights uncovered in the arena of discrete mathematics. A landmark development in the field of logic was the introduction of Boolean algebra in 1854, in which the variables can only take on two values: true and false (Boole 1854). Then, in 1937, Claude Shannon showed in his master's thesis how this binary system can be used to design digital circuits (Shannon 1940). In effect, Shannon implemented Boolean algebra for the first time using electronic components. Later, he famously laid the theoretical foundations regarding the quantification, storing, and communication of data, in effect inventing the field of information theory (Shannon 1948). The concepts Shannon developed are at the heart of today's digital information theory. Shannon and the notion of information are discussed further in Sect. 13.1.2. In summary, the hallmark of modern computers is their digital nature: they operate on information which adopts discrete values. This property is mirrored by the discrete character of the formal representations used to describe these entities, see, for instance Biggs (2003), Steger (2001a, b). Indeed, the merger of discrete mathematics with computer science has given rise to the new field of theoretical computer science (Hromkovič 2010). In contrast to the technical and applied areas of computer science, theoretical computer science focuses on computability and algorithms. Examples are the methodology concerned with the design of algorithms or the theory regarding the existence of algorithmic solutions.

Paradigm P_1^c (Sect. 5.2.1) emerges as the crucial guiding principle for the formal representation of complexity. A complex system can formally either directly be mapped onto a complex network or described as an evolving network of interacting agents, following algorithmic instructions. Both incarnations find their abstraction in the notion of a graph.

Graph Theory

The discrete counterpart to the derivative, a versatile and universal tool in continuous mathematics, is the notion of a graph. In 1735 Leonard Euler was working on a paper on the seven bridges of Königsberg. The publication of this work (Euler 1941) in effect established the field of graph theory (Biggs et al. 1986; Bollobás 1998). The problem Euler was trying to tackle, was to find a walk through the city that would cross each of the seven bridges only once. Although he could prove that the problem had no solution, the formal tool Euler employed was revolutionary. As detailed, graphs today play an essential role in mathematics and computer science.

In modern terms, the defining features of a graph $G = G(V, E)$ are the set of vertices V, or nodes, which are connected by edges, or links, in a set E, where the edge $e_{ij} \in E$ connects the nodes $v_i, v_j \in V$. The adjacency matrix of a graph $A = A(G)$ maps the graph's topology onto the matrix A_{ij}, allowing further mathematical operations to be performed on G, as now the powerful tools of linear algebra can be utilized. Finally, the number k_i of edges per vertex i is know as the degree. The degree distribution $\mathcal{P}(k)$ succinctly captures the network architecture.

This simple formal structure was utilized by Euler as a representation of the problem at hand: he ingeniously encoded the Königsberg bridges as the links and the connected landmasses as the nodes in a small network. Indeed, Euler anticipated the idea of topology: the actual layout of this network, when it is illustrated, is irrelevant and the essence of the relationships is encoded in the specifics of the abstract idea of the graph itself.

Euler's contribution to graph theory represents only a minuscule fraction of his mathematical productivity and "his output far surpassed in both quantity and quality that of scores of mathematicians working many lifetimes. It is estimated that he published an average of 800 pages of new mathematics per year over a career that spanned six decades" (Dunham 1994, p. 51). Indeed, even his deteriorating eyesight, leading to blindness, "was in no way a barrier to his productivity, and to this day his triumph in the face of adversity remains an enduring legacy" (Dunham 1994, p. 55).

At the end of the 1950s graph theory was extended by the introduction of probabilistic methods. This new branch, called random graph theory, was a fruitful source of many graph-theoretic results and was pioneered by Paul Erdős [20] and his collaborator, Alfréd Rényi (Erdős and Rényi 1959, 1960). A hallmark of these graphs is that their degree distribution $\mathcal{P}(k)$ has the form of a Poisson probability distribution. In other words, the number nodes with high connectivity decreases rapidly.

[20] Recall the peculiar life he chose to live recounted on Page 57 at the end of Sect. 2.2.

$\Big\{ \oiint$ |*5.3.2-graph-theory* >

A random graph comprised of n nodes and l links follows a binomial degree distribution

$$\mathcal{P}(k_i = k) = \binom{n}{k} p^k (1-p)^{n-k}, \tag{5.11}$$

where k_i is the degree of node i and the link probability is given by p (Erdős and Rényi 1960). The first terms gives the number of equivalent choices of such a network. The remaining term describes the probability of a graph with k links and n nodes existing. The average degree $\langle k \rangle$ is now defined as

$$z := \langle k \rangle = \frac{l}{n} = p(n-1). \tag{5.12}$$

The average degree and the degree distribution can be approximated by

$$\mathcal{P}(k) \approx \frac{z^k e^{-z}}{k!}, \tag{5.13}$$

$$z \approx pn. \tag{5.14}$$

Note that (5.13) describes a Poisson distribution. In the limit of large n the approximations become exact. This can be seen by noting that

$$e^{-z} = \lim_{n \to \infty} \left(1 + \frac{-z}{n} \right), \tag{5.15}$$

$$1 = \lim_{n \to \infty} \left(\frac{n!}{n^k (n-k)!} \right). \tag{5.16}$$

The scale-free networks, introduced in Sect. 5.2.3 and establishing the new science of networks, are defined by their degree distribution following a scaling law (see Sect. 6.4.3.3). This can simply be expressed mathematically as

$$\mathcal{P}(k) \sim k^{-\alpha}, \tag{5.17}$$

where the exponent α lies typically between two and three. In detail

$$\mathcal{P}(k) = \frac{k^{-\alpha} e^{-k/\kappa}}{\mathrm{Li}_\alpha (e^{-1/\kappa})}. \tag{5.18}$$

The exponential term in the numerator, governed by the parameter κ, results in an exponential cutoff, the term in the denominator ensures the proper normalization, and $\mathrm{Li}_n(x)$ is the nth polylogarithm of x (Newman et al. 2001; Albert and Barabási 2002). Note that for the limit $\kappa \to \infty$

$$\mathcal{P}(k) = \frac{k^{-\alpha}}{\zeta(\alpha)}, \tag{5.19}$$

where the Riemann ζ-function now acts as the normalization constant.

< *5.3.2-graph-theory*| $\oiint$ }

Whereas the (continuous) analytical machinery used for over three centuries has the power to unlock the secrets of fundamental systems, (discrete) graphs directly tackle complexity. In the pictorial language of Fig. 5.1, complex systems are located on the left side. Graph theory represents their abstract counterpart. In other words, graphs are elevated to the exalted ranks of formal representations able to capture and encode a vast plethora of aspects of the physical world, similar to the abundant usefulness of the derivative.

In closing:

> Complex systems are represented by networks which are formalized as graphs, a notion from of *discrete* mathematics that lies at the heart of the *algorithmic* approach which is employed to represent *complex* aspects of the physical world, as described in the formal encoding scheme seen in Fig. 5.1.

5.3.3 Unity

To summarize, both mathematical variants—the continuous and the discrete— have one particular property which gives them a special status in their volume of the Book of Nature. In other words, each branch has one feature that makes it a powerful tool in the abstract world of formal representations (i.e., the right-hand side of Fig. 5.1). One is the (continuous) operation of differentiation and the other is the (discrete) notion of a graph. While the former unlocks knowledge about the fundamental workings of nature, the latter gives insights into the organizational principles of complex systems.

By introducing the continuous-discrete dichotomy it is possible to give an underpinning to the formal representations seen on the right-hand side in Fig. 5.2. The analytical formal representation is inexorably tied to the continuous mathematical structure while the algorithmic formal representation is intimately related to the discrete mathematical structure. This is illustrated in Fig. 5.7. In this sense, the abstract human thought system called mathematics is not only a very powerful probe into reality, it also unifies the two separate formal representations describing the two different reality domains.

In closing, Fig. 5.8 depicts a grand overview of all the discussed concepts. It contrasts the fundamental-complex, analytical-algorithmic, and continuous-discreet dichotomies encountered in the two volumes of the Book of Nature.

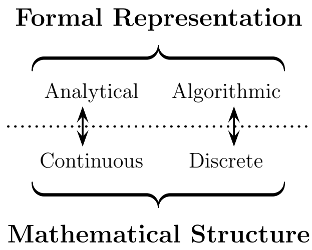

Fig. 5.7 The mathematical structures underlying the two modes of formal representation, unifying the two separate knowledge generation systems within a single formal thought system. As a result, Fig. 5.2 is given more detail

To summarize:

> The cognitive act of translating specific fundamental and complex aspects of the observable universe into formal representations—utilizing analytical (equation-based) and algorithmic (interaction-based) tools—is the basis for generating vast knowledge about the workings of reality. Specifically, the fundamental and complex reality domains of the physical world are encoded into analytical and algorithmic formal representations, respectively. Underpinning these are the continuous and a discrete structures of mathematics.
>
> Digging deeper, continuous mathematics, associated with the analytical formal theme, provides the machinery of derivation, which plays a fundamental role in the physical sciences. In a similar vein, discrete mathematics, the basis of the algorithmic formal theme, offers graphs as a universal abstract tool able to capture complexity. In this sense, mathematics, understood as the totality of its continuous and discrete branches, is the unifying abstract framework on which the process of translation builds upon. This overarching formal framework is hosted in the human mind and mirrors the structure and functioning of the physical world, transforming translation into knowledge generation.
>
> This process of human knowledge generation finds its metaphor in the discovery of the two volumes of the Book of Nature, written in the language of mathematics. A graphical overview is presented in Fig. 5.8. The tremendous success of this endeavor can be seen in the dramatic acceleration of technological advancements in recent times, bearing witness to the increasing ability of the human mind to manipulate the physical reality it is embedded in.

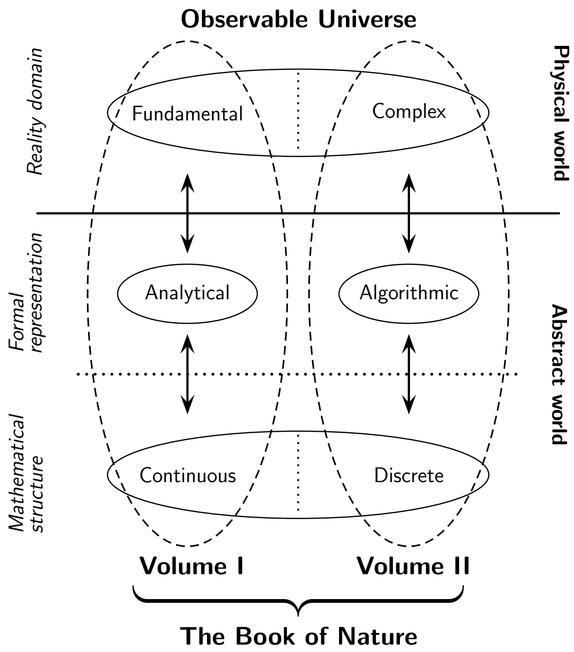

Fig. 5.8 A comprehensive map of human knowledge generation. The observable universe is explained in the Book of Nature, specifically its two volumes. The physical world, comprised of reality domains, finds its formal representation in the abstract world, hosted in the human mind, and unified by the two mathematical structures. See the boxed text for details

5.4 The Book of Nature Reopened

For over 300 years the Book of Nature has revealed insights into the workings of the world. Chapter by chapter, novel understanding was disclosed, from quantum theory to cosmology. The human mind was capable of translating a multitude of quantifiable aspects of reality into formal, abstract representations. Then, by entering this abstract realm, the mind was able to derive new insights, which could be decoded back into the physical world (see Fig. 5.1). This is a truly remarkable feat and the foundation from which the technological advancements of the human species springs.

But this should only be the beginning. It is truly remarkable that what was considered to be the Book of Nature—the analytical understanding of fundamental processes—turns out to only be the first volume in a greater series. In the last decades, humans have witnesses yet another unearthing of an additional volume of the Book of Nature. And just like Volume I, this newly found addition to the Book of Nature Series offers new and deep insights into a domain of reality previously clouded by ignorance: the organization and evolution of complex systems. In other words, the properties of real-world complexity surrounding us become intelligible.

Figure 5.8 shows a conceptualized illustration of this truly remarkable achievement. The knowledge generated in this way is the engine driving humanities astonishing technological advancements, (see also the first section of Chap. 8). In essence, this knowledge generation boils down to acts of translation. As illustrated in Fig. 5.1, a reality domain of the physical world is encoded as a formal representation inhab-

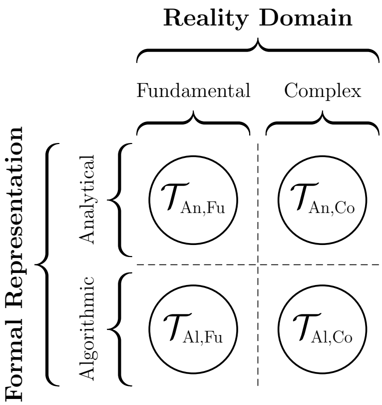

Fig. 5.9 A schematic overview of the possible acts of translation encapsulated in the matrix $\mathcal{T}$: each element represents the encoding of *fundamental* or *complex* aspects of reality into formal representations relating to *analytical* or *algorithmic* facets of the abstract world (compare with Figs. 5.1 and 5.2). Interestingly, in the pursuit of knowledge by the human mind, mostly only two of the four possibilities have been extensively utilized: $\mathcal{T}_{\text{An,Fu}}$ and $\mathcal{T}_{\text{Al,Co}}$ corresponding to Volume I and II in the Book of Nature Series. Adapted from (Glattfelder 2013)

iting the abstract world. Constrained and guided by the rules pertaining to the rich structure of the abstract world, new information can be harnessed, which can then be decoded back into to physical world, yielding novel insights.

The template for this act of translation is given by $\mathcal{T}_{\text{FR,RD}}$, where the label FR denotes the formal representation and RD the reality domain, respectively. Throughout this book it has been argued that both the physical and abstract world should each be split into two categories. The physical is categorizing by the fundamental-complex dichotomy and the abstract by the analytical-algorithmic dichotomy. The two volumes of the Book of Nature can now be understood as follows:

- Volume I corresponds to the analytical encoding of fundamental processes, $\mathcal{T}_{\text{An,Fu}}$.
- Volume II corresponds to the algorithmic encoding of complex processes, $\mathcal{T}_{\text{Al,Co}}$.

Now it becomes apparent that this attempt at categorizing human knowledge generation into the proposed dichotomies adds an additional mystery:

> Why has the successful knowledge generation process, giving the human mind access to the intimate workings of the universe, primarily been based on the translational mechanisms $\mathcal{T}_{\text{An,Fu}}$ and $\mathcal{T}_{\text{Al,Co}}$? What about the two other translation possibilities $\mathcal{T}_{\text{Al,Fu}}$ and $\mathcal{T}_{\text{An,Co}}$?

In Fig. 5.9 all four possible translational mechanisms arising from the dichotomies are shown. Understood as a matrix, primarily the diagonal elements of $\mathcal{T}$ are responsible for lifting humanities' veil of ignorance. What do we know about the other two translational possibilities? Do they represent failed attempts at knowledge generation? If so, what is special about the two successful acts of translation? Or will, in the end, the human mind unearth further volumes in the Book of Nature Series, guided by the two dormant translational possibilities? This will be the focus of the next section.

From a philosophical perspective, this intricate and intimate interaction of the human mind with the physical world raises inevitable and profound questions. For instance, successful knowledge generation via the describes translational mechanisms assumes the existence of three entities: the physical world that accommodates the mental world of the human mind, which discovers or creates the abstract world of formal thought systems, which in turn unlocks secrets of the physical world (a conundrum encountered in Fig. 2.2 of Sect. 2.2.1). In detail:

1. There exists an abstract realm of objects transcending physical reality (ontology).
2. The human mind possesses a quality that allows it to access this world and acquire information (epistemology).
3. The structures in the abstract world map the structures in the physical (structural realism, see Sects. 2.2.1, 6.2.2 and 10.4.1).

5.4.1 *Beyond Volumes I and II*

As observed, the two translational possibilities $\mathcal{T}_{\mathrm{Al,Fu}}$ and $\mathcal{T}_{\mathrm{An,Co}}$ have not been prominently utilized as knowledge generation mechanisms. This could mean two things. First, complex systems are indeed immune to being treated with an equation-based formalism, and, conversely, the same is true for fundamental systems being described algorithmically. Or, these alternative possibilities have only been sparsely explored to date, still leaving behind mostly uncharted terrain. In the following, some attempts at filling in the blanks are described.

The Complex-Analytical Demarcation

Pattern formation in nature is clearly the result of self-organization in space and time. Alan Turning proposed an analytical mechanism to describe biological pattern formation (Turing 1952). He utilized what is known as reaction-diffusion equations. These are partial differential equations used to describe systems consisting of many interacting components, like chemical reactions. Turning's model successfully[21] replicates a plethora of patterns, from sea shells to fish and other vertebrae skin (Meinhardt 2009; Kondo and Miura 2010). In effect, he proposed an analytical approach to complexity.

Running agent-based models can sometimes be computationally costly. However, there exist analytical shortcuts that can be taken. Instead of simulating the complex system, it can be studied by solving a set of differential equations describing the time evolution of the individual agent's degrees of freedom. Technically, this can be achieved by utilizing Langevin stochastic equations. Each such equation describes the time evolution of the position of a single agent (Ebeling and Schweitzer 2001). From

[21] See, for instance, the interactive demonstrations found at http://demonstrations.wolfram.com/TuringPatternInAReactionDiffusionSystem/.

the reaction-diffusion equation, Langevin equations can be derived. See Sect. 7.1.1.1 for the history of the Langevin equations, including Einstein's early work and the Black-Scholes formula for option pricing. Utilizing self-similar stochastic processes for the modeling of random systems evolving in time has been relevant for their understanding (Embrechts and Maejima 2002). See again Sect. 7.1.1.1.

Langevin equations can be solved analytically or numerically. They describe the individual agent's behavior at the micro level. Moving up to a macroscopic description of the system, what is known as the Fokker-Planck partial differential equation describes the collective evolution of the probability density function of a system of agents as a function of time. The two formalism can be mapped into each other (Gardiner 1985). However, as an example, computing 10,000 agents constrained by Langevin equations approximates the macro dynamics of the system more efficiently than an effort directly attempting to solve the equivalent Fokker-Planck differential equation.

Some scholars have argued against the dictum that complex systems are, in general, not susceptible to mathematical analysis and should hence be investigated by the means of simulation analysis (Sornette 2008). Didier Sornette, a physicist, econophysicist, and complexity scientist, offers the insight that the formal analytical treatment of triggering processes between earthquakes can be successfully applied to various complex systems. Examples range from the dynamics of sales of book blockbusters to viewer activity on the YouTube video-sharing website to financial bubbles and crashes (Sornette 2008). Furthermore, he argues that the right level of magnification (level of granularity) in the description of a complex system can reveal order and organization. As a result, pockets of predictability at some coarse-grained level can be detected. This partial predictability approach is potentially relevant for meteorological, climate, and financial systems. However, a big challenge remains in identifying the complex systems that are susceptible to this approach and finding the right level of coarse-graining.

Another modern example of tackling complexity with analytical tools is mathematical biology (to which Turning's pattern formation belongs). Influential work in this field grapples with the mathematization of the theory of evolution, as detailed in Martin Nowak's book "Evolutionary Dynamics: Exploring the Equations of Life" (Nowak 2006). Nowak, a biochemist and mathematician by training, is also a Roman Catholic. His view on the tension between theology and science, especially the conflicts between the theory of evolution and Christianity (Powell 2007):

> Science and religion are two essential components in the search for truth. Denying either is a barren approach.

The Fundamental-Algorithmic Demarcation

Recall from Sect. 5.1.3 the troubles relating to solving gravitational n-body problems. In essence, here it does not suffice to know the analytical encoding of the challenge at hand. The system of differential equations describing the motion of $n \geq 3$ gravitationally interacting bodies cannot be solved analytically. Only for a few simple, albeit important, problems Newton's equation can be solved. Although the exact theoretical solution for the general case can be approximated (via Taylor series or numerical integration) the dynamics are generally best understood utilizing n-body simulations (Valtonen and Karttunen 2006).

The largest such simulation, called the Millennium Run,[22] investigated how matter evolved in the universe over time by reproducing cosmological structure formation. The simulation was comprised of ten billion particles, each representing approximately a billion solar masses of dark matter (Springel et al. 2005). In summary, the dynamics of a fundamental (cosmological) system, comprised of a multitude of gravitating bodies, is not understood analytically via differential equations. Rather, computer simulations, mimicking the forces of interaction in the system, offer theoretical predictions.

Overall, the translational mechanism $\mathcal{T}_{\text{Al,Fu}}$ is a niche, in the sense that it is only sparsely explored and offers speculative concepts. For instance, the ideas espoused by Wolfram in Sect. 5.2.2. He is essentially proposing that cellular automata are the universal tool to decode and understand the universe in all its facets. In effect, "A New Kind of Science" (Wolfram 2002) would represent the knowledge generated by $\mathcal{T}_{\text{Al,Fu}}$ (as well as $\mathcal{T}_{\text{Al,Co}}$). Although Wolfram acknowledges the tremendous success of the mathematical approach to physics, he stresses that many central issues remain unresolved in fundamental physics, where cellular automata could possibly shed new light (Wolfram 2002, Chapter 9). He epitomizes these hopes in the following quote (Wolfram 2002, p. 465):

> And could it even be that underneath all the complex phenomena we see in physics there lies some simple program which, if run long enough, would reproduce our universe in every detail?

Contemporary support for this idea comes from Nobel laureate Gerard 't Hooft, where he proposes an interpretation of quantum mechanics utilizing cellular automata ('t Hooft 2016). Finally, some theoretical physicists propose to describe space-time as a network in some fundamental theories of quantum gravity. For instance, spin networks in loop quantum gravity (see Sect. 10.2.3). Another idea tries to understand emergent complexity as arising from fundamental quantum field theories (Täuber 2008).

Blurring the Lines

Computers have also helped blur the lines between the analytical and algorithmic formal representations. In 1977, the four-color theorem was the first major mathematical theorem to be verified using a computer program (Appel and Haken 1977). "The four-color theorem states that any map in a plane can be colored using four-colors in such a way that regions sharing a common boundary (other than a single point) do not share the same color."[23] Computer-aided proofs of a mathematical theorem are usually very large proofs-by-exhaustion, where the statement to be proved is split into many cases and each case then checked individually. "The proof of the four colour

[22] See https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/.

[23] From http://mathworld.wolfram.com/Four-ColorTheorem.html.

theorem gave rise to a debate about the question to what extent computer-assisted proofs count as proofs in the true sense of the word" (Horsten 2012).

Conclusion

Two flukes of reality allow the universe to be comprehended by the human mind. One is that the structures of the workings of the universe are mirrored by the abstract formal thought systems accessible to the mind. The other is the emergence of complexity from simplicity. The two related aspects of knowledge generation—the dichotomies of the fundamental-analytical and the complex-algorithmic—are captured in Volume I and II of the Book of Nature Series. Both have a mathematical underbelly, being represented by the two sides of a metaphorical coin: the continuous and the discrete. In the next chapter, the contents of Volume II will be disclosed. Just as Chaps. 3 and 4 gave an extract of Volume I, Chaps. 6 and 7 will contain the tale of the understanding of complexity.

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Chapter 6
Volume II: The Simplicity of Complexity

Abstract Whereas most of the cosmos is comprised of rather simple large-scale structures, on Earth, we find breathtaking complexity, down to microscopic scales. Indeed, it appears as though the universe is driven by a propensity to assemble ever more complex structures around us, guided by self-organized and emergent behavior. Naively one would expect complexity to be complicated to comprehend. Luckily, in the universe we inhabit, complex systems are encoded by simple rules of interaction. Like Volume I of the Book of Nature being written in the language of mathematics, Volume II, addressing complexity, is composed of simple algorithms decoding reality. Complex systems theory has a long history and raises philosophical questions. One of its most successful formal tools are networks. In fact, complex networks are ubiquitous in the domains of living and non-living complexity. One particular organizational property in complex systems is akin to a "law of nature," giving rise to universal behavior. These patterns, known as scaling laws, are to be found everywhere.
Level of mathematical formality: medium to low.

We inhabit a very particular place in the universe. The planet we find ourselves residing on is unlike any other patch of cosmic space containing matter. Every day we witness the interaction of a myriad of structures creating a vast richness of intricate behavior. We are surrounded by, and embedded in, a microcosm seething with complexity. Specifically, we are exposed to chemical, biological, and, foremost, technological and socio-economical complexity.

Until very recently in the history of human thought, the adjective "complex" was thought to be synonymous with "complicated"—in other words, intractable. While the universe unveiled its fundamental mysteries through the Book of Nature—the age-old metaphor for the circumstance that the regularities in the physical world are explained mathematically by the human mind—the complexity surrounding us seemed incomprehensible. However, one specific cosmic coincidence allowed the human mind to also tackle and decode the behavior of complex systems. Before disentangling complexity itself, the next section will briefly review the notions introduced throughout the narrative of Part I: the two volumes of the Book of Nature.

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Some general references on complexity are Holland (1995), Gladwell (2000), Johnson (2001, 2009), Strogatz (2004), Fisher (2009), Green (2014), Hidalgo (2015).

6.1 Reviewing the Book of Nature

Chapter 2 opened with the search for the Book of Nature. The belief that the human mind can read the universe like a book and extract knowledge has echoed throughout the ages. Over 300 years ago this belief materialized by the development of Newtonian mechanics. After this initial spark, mathematics reigned supreme as the most resourceful and efficient human knowledge generation system. In Chap. 3 a stunning tale of this success is told. Namely, how the notion of symmetry underlies most of theoretical physics. This then allows for very separate phenomena to be described by overarching and unified theories, as discussed in Chap. 4.

Analyzing this "unreasonable effectiveness of mathematics in the natural sciences" (Wigner 1960) leads to the following observation. The reality domain that is decoded by mathematics (or more generally speaking, formal thought systems) excludes the complexity surrounding us and contained within us. Consequentially, exclusively fundamental aspects of nature—ranging from the quantum foam comprising reality to the incomprehensible vastness of the cosmic fabric—are understood by analytical mathematical representations. This defines a paradigm of knowledge generation, called the *fundamental-analytical* classification here (Sect. 5.1).

It is unfortunate that the understanding of complex phenomena is not contained within this knowledge paradigm. Complexity, characterized by self-organization, structure formation, and emergence, giving rise to adaptive, resilient, and sustainable behavior, defies our mathematical tools. Complex systems transcend equations.[1] Unexpectedly, a few decades ago, some scientists started to see the first hints of something unexpected. Behind the mask of intimidating complexity lurked benign simplicity. More precisely, macroscopic complexity showed itself to be the result of simple rules of interaction at the micro level. In the words of Stephen Wolfram, a theoretical physicist, computer scientist, and entrepreneur (Wolfram 2002, see also Sect. 5.2.2):

> And I realized, that I had seen a sign of a quite remarkable and unexpected phenomenon: that even from very simple programs behavior of great complexity could emerge.
> [. . .]
> It took me more than a decade to come to terms with this result, and to realize just how fundamental and far-reaching its consequences are.

By the turn of the millennium, a new paradigm was born: the *complex-algorithmic* classification of knowledge generation (Sect. 5.2). The simple rules of interaction driving complex systems allow for a computational approach to understanding them. In other words, the mathematical tools are exchanged for algorithms and simulations running on computers.

[1] However, see Sect. 5.4.1 discussing Langevin and Fokker-Planck equations.

In the context of the metaphor of the Book of Nature, the two paradigms of knowledge—the fundamental-analytical and complex-algorithmic dichotomies—represent two volumes. In effect, the Book of Nature is an expanded series comprised of Volume I and Volume II (Sects. 5.3.3 and 5.4). This evolution in the structure of knowledge was saliently highlighted by the eminent theoretical physicist and cosmologist Stephen Hawking (quoted in Chui 2000, p. 29A):

> I think the next century [the 21st Century] will be the century of complexity.

An assertion that is remarkable in the face of Hawking's previous stance, where he predicted the end of theoretical physics in the 1980s and 1990s (see Sects. 4.3.2 and 9.2.2). He then believed that a unified theory of quantum gravityc would soon be found, explaining everything. Even after all the excitement of string/M-theory, we today appear no closer to this goal (see Sect. 10.2.2).

6.2 A Brief History of Complexity Thinking

The term complexity science is not rigorously defined. The study of complex phenomena is not a single discipline, but represents an approach taken by various fields to study diverse complex behavior. In its historical roots one finds a diversity of intellectual traditions. From cybernetics (1940 and 1950s; Wiener 1948), systems theory (1950 and 1960s; Von Bertalanffy 1969), early artificial intelligence research (1950 and 1960s; Turing 1950) to non-linear dynamics, fractal geometry, and chaos theory (1960–1980s; Sects. 5.1.3 and 5.2.2). There exists a plethora of themes being investigated, for instance:

- cellular automata (Sect. 5.2.2);
- agent-based modeling (Sect. 7.3.1);
- algorithmic complexity theory (Chaitin 1977);
- computational complexity theory (Papadimitriou 2003);
- systems biology (Kitano 2002);
- data science (James et al. 2013).

For an illustration visualizing the rich and intertwined history of complexity thinking, see *The Map of Complexity Sciences* and the links within, first published in Castellani and Hafferty (2009) and updated since.[2]

6.2.1 Complex Systems Theory

In the remainder of this chapter, the focus lies on *complex systems theory* (Haken 1977, 1983; Simon 1977; Prigogine 1980; Bar-Yam 1997; Eigen 2013;

[2]Accessible online at http://www.art-sciencefactory.com/complexity-map_feb09.html.

Ladyman et al. 2013), a field emerging from cybernetics and systems theory at the beginning of the 1970s. The theory of complex systems can be understood as an interdisciplinary field of research utilizing a formal framework for studying interconnected dynamical systems (Bar-Yam 1997). Two central themes are self-organization (Prigogine and Nicolis 1977; Prigogine et al. 1984; Kauffman 1993) and emergence (Darley 1994; Holland 1998). The former notion is related to the question of how order emerges spontaneously from chaos in systems which are not in a thermodynamic equilibrium. The latter concept is concerned with the question of how the macro behavior of a system emerges from the interactions of the elements at a micro level. The notion of emergence has a long and muddied history in the philosophy of science (Goldstein 1999). Other themes relating to complex systems theory include the study of complex adaptive systems (Holland 2006) and swarming behavior, i.e., swarm intelligence (Bonabeau et al. 1999). The domains complex systems originate from are mostly socio-economical, biological, or physio-chemical. Some examples of successfully decoding complex systems include earthquake correlations (Sornette and Sornette 1989), crowd dynamics (Helbing et al. 2000), traffic dynamics (Treiber et al. 2000), pedestrian dynamics (Moussaïd et al. 2010), population dynamics (Turchin 2003), urban dynamics (Bettencourt et al. 2008), social cooperation (Helbing and Yu 2009), molecule formation (Simon 1977), and weather formation (Cilliers and Spurrett 1999).

Complex systems are characterized by feedback loops (Bar-Yam 1997; Cilliers and Spurrett 1999; Ladyman et al. 2013), where both damping and amplifying feedback is found. Moreover, linear and non-linear behavior can be observed in complex systems. The term "at the edge of chaos" denotes the transition zone between the regimes of order and disorder (Langton 1990). This is a region of bounded instability that enables a constant dynamic interplay between order and disorder. The edge of chaos is where complexity resides. Furthermore, complex systems can also be characterized by the way they process or exchange information (Haken 2006; Quax et al. 2013; Ladyman et al. 2013). Information is the core theme of Chap. 13.

The study of complex systems represents a new way of approaching nature. Put in the simplest terms, a major focus of science lay on things in isolation—on the tangible, the tractable, the malleable. Through the lens of complexity this focus has shifted to a subtler dimension of reality, where the isolation is overcome. Seemingly single and independent entities are always components of larger units of organization and hence influence each other. Indeed, our modern world, while still being comprised of many of the same "things" as in the past, has become highly networked and interdependent—and, therefore, much more complex. From the interaction of independent entities, the notion of a system emerges. The choice of which components are seen as fundamental in a system is arbitrary and depends on the chosen level of abstraction.

A tentative definition of a complex system is the following:

> A complex system is composed of an ensemble of many interacting (or interconnected) elements.

In other words, there exist many parts, or agents, which interact in a disordered, manner resulting in an emergent property or structure. The whole exhibits features not found in the structure or behavior of the individual parts comprising it. This is a literal example of the adage, that the whole is more than the sum of its parts. The emphasis of this definition lies on the notions of components, multiplicity, and interactions (Ladyman et al. 2013). As mentioned, the observed macroscopic complexity of a system is a result of simple rules of interaction of the agents comprising it at the micro level (Sect. 5.2.2). This unexpected universal modus operandi allows complex systems to be reduced to:

- a set of objects (representing the agents);
- a set of functions between the objects (representing the interactions among agents).

A natural formal representation of this abstraction is a network (Sect. 5.2.1). Now, the agents are characterized by featureless nodes and the interactions are given by the links connecting the nodes. The mathematical structure describing networks is a graph (Sect. 5.3.2). In essence, complex networks (being the main theme of Sect. 6.3) mirror the organizational properties of real-world complex systems.

This insight gives rise to a new interaction-base worldview and marks a departure from a top-down to a bottom-up approach to the understanding of reality. Traditional problem-solving methods have been strongly influenced by the success of the centuries-old reductionist approach taken in science (Volume I of the Book of Nature). However, the unprecedented success of reductionism can not be replicated in the realm of complexity. In the words of the theoretical physicists Hermann Haken, founder of synergetics, the interdisciplinary approach describing self-organization of non-equilibrium systems (Haken 2006, p. 6):

> But the more we are dealing with complex systems, the more we realize that reductionism has its own limitations. For example, knowing chemistry does not mean that we understand life.

In the same vein, a quote taken from an early and much-noticed publication by the physics Nobel laureate Philip Warren Anderson (Anderson 1972, see also Sect. 5.2.1):

> At each stage [of complexity] entirely new laws, concepts, and generalizations are necessary [. . .]. Psychology is not applied biology, nor is biology applied chemistry.

Driven by the desire to comprehend complexity, reductionist methods are replaced or augmented by an embracing of a systems-based and holistic outlook (Kauffman 2008). A revolution in understanding is ignited and a “new science of networks” born (Sect. 5.2.3). In other words, Volume II of the Book of Nature is unearthed.

6.2.2 *The Philosophy of Complexity: From Structural Realism to Poststructuralism*

Realism is a central philosophical theme that is closely intertwined with Volume I of the Book of Nature. By ignoring the pragmatic advice "Shut up and calculate!" given in Sect. 2.2.1—the invitation to focus one's mental capacities on the mathematical machinery driving science instead of grappling with meaning and context—one can wander into the philosophical undergrowth. Here one finds the notion of scientific realism (Ladyman 2016):

> Scientific realism is the view that we ought to believe in the unobservable entities posited by our most successful scientific theories. It is widely held that the most powerful argument in favor of scientific realism is the no-miracles argument, according to which the success of science would be miraculous if scientific theories were not at least approximately true descriptions of the world.

One specific form of scientific realism is structural realism, a commitment to the mathematical or structural content of scientific theories. It is the "belief in the existence of structures in the world to which the laws of mathematical physics may approximately correspond" (Falkenburg 2007, p. 2). In a general sense, structural realism only admits a reality to the way things are related to one another, invoking the metaphor of a network (Wittgenstein 1922, 6.35):

> Laws [...] are about the net and not about what the net describes.

In a similar vein, "the universe is made of processes, not things" (Smolin 2001, Chap. 4). See also Sect. 2.2 for more details.

Structural realism can take on two forms, as the epistemic or ontic versions (Ladyman 1998). Epistemic structural realism is the view that scientific theories tell us only about the form or structure of the unobservable world and not about its true nature. In other words, one cannot know anything about the real nature of things but only how they relate to one another. In contrast, and more radically, ontic structural realism assumes that relations are all that exist, without assuming the existence of tangible entities. In essence, the world is made up solely of structures, a network of relations without relata (Morganti 2011; Esfeld and Lam 2010). While it might seem outlandish to suppose relations without relata, the ideas of symmetry and invariance, discussed in Chap. 2, lend support to ontic structural realism. Symmetry transformations that exchange the individual things that make up a system but leave their relations unchanged become important. Indeed, ontic structural realism has resonated with the intuition of some eminent physicists: "[...] only the relationship of objects to each other can have significance." (Roger Penrose quoted by Lee Smolin in Huggett et al. 1998, p. 291). Furthermore, the philosophy has been proposed as an ontology for quantum field theory (French and Ladyman 2003; Cao 2003; Kuhlmann 2015). Explanations relating to the reality and nature of elementary particles and fields have been found lacking (Kuhlmann 2013):

> Clearly, then, the standard picture of elementary particles and mediating force fields is not a satisfactory ontology of the physical world. It is not at all clear what a particle or a field even is.

Alternatively, "ontic structural realism has become the most fashionable ontological framework for modern physics" (Kuhlmann 2015). See also Kuhlmann (2010) and Sects. 2.2.1 and 10.4.1.

Structural realism is a form of structuralism, the notion that all aspects of reality are best understood in terms of (scientific) constructs of entities, rather than in terms of concrete entities in themselves. Poststructuralism is defined by the rejection of the self-sufficiency of the structures that structuralism posits (Derrida 1993, based on a 1966 lecture). Specifically, knowledge and truths about structures are always subjective. Poststructuralism does not simply represent the polar opposite of structuralism, it has also been interpreted as anti-scientific, as it "stresses the proliferation of meaning, the breaking down of existing hierarchies, the shortcomings of logic, and the failures of analytical approaches" (Cilliers 1998, p. 22). It is a philosophical stance which is difficult to define as it represents a rich tapestry of thinking (Belsey 2002). Poststructuralism is an intellectual stream closely related to postmodernism, which is discussed in detail in Sect. 9.1.4. Notably, poststructuralism and postmodernism have been proposed as philosophies of complexity (Cilliers 1998; Cilliers and Spurrett 1999; Woermann 2016). For instance, the philosopher and complexity researcher Paul Cilliers observes (Cilliers 1998, p. ix):

> The most obvious conclusion drawn from this [poststructural/postmodern] perspective is that there is no overarching theory of complexity that allows us to ignore the contingent aspects of complex systems. If something is really complex, it cannot be adequately described by means of a simple theory.

This outlook implies the following (Woermann 2016, p. 3):

> Along with Edgar Morin, Cilliers argues that complexity cannot be resolved through means of a reductive strategy, which is the preferred methodology of those who understand complexity merely as a theory of causation.

While Volume I of the Book of Nature is rooted in structural realism, Volume II invites a philosophy that transcends the borders of clear-cut and orderly interpretations and opens up to inquisitive exploration (Woermann 2016, p. 1):

> To my mind, the hallmark of a successful philosophy is thus related to the degree to which it resonates with our views on, and experiences in, the world.

A philosophy grappling with complex systems needs to address the following (Cilliers 1998):

- complex systems consist of a large number of elements;
- a large number of elements is necessary, but not sufficient;
- interactions are rich, non-linear, and short-ranged;
- there exist loops in the interactions;
- complex systems tend to be open systems and operate under conditions far from equilibrium;

- complex systems have a rich history in that the past is co-responsible for the present behavior;
- each element in the system is ignorant of the behavior of the system as a whole.

In a nutshell (Cilliers 1998, p. 5):

> Complexity is the result of a rich interaction of simple elements that only respond to the limited information each of the elements are presented with. When we look at the behavior of a complex system as a whole, our focus shifts from the individual element in the system to the complex *structure* of the system. The complexity emerges as a result of the patterns of interaction between the elements.

Finally, in Chap. 2, the notion of Platonism[3] was introduced. Platonic realism posits the existence of mathematical objects that are independent of the mind and language and it is a philosophical stance adopted by many notable mathematicians. Although there also exists a structuralist interpretation of mathematics (Colyvan 2012), other scholars have argued that postmodern thought should be seen as the continuation of debates on the foundations of mathematics (Tasić 2001).

6.3 Complex Network Theory

The key to the success of complex network theory lies in the courage to ignore the complexity of the components of a system while only quantifying their structure of interactions. In other words, the individual components fade out of focus while their network of interdependence comes into the spotlight. Technically speaking, the analysis focuses on the structure, function, dynamics, and topology of the network. Hence the neurons in a brain, the chemicals interacting in metabolic systems, the ants foraging, the animals in swarms, the humans in a market, etc., can all be understood as being represented by featureless nodes in a network of interactions. Only their relational aspects are decoded for information content.

6.3.1 The Ubiquity of Complex Networks

Complex networks are ubiquitous in nature, resulting in an abundance of scientific literature (Strogatz 2001; Albert and Barabási 2002; Dorogovtsev and Mendes 2002, 2003a; Newman 2003; Buchanan 2003; Newman et al. 2006; Caldarelli 2007; Costa et al. 2007; Vega-Redondo 2007; Caldarelli and Catanzaro 2012; Barabási 2016). A great variety of processes are best understood if formally described by complex networks. For instance, the following phenomena found in

[3] The terms mathematical realism and Platonism have been used interchangeably.

- the physical world, e.g.,
  - computer-related systems (Albert et al. 1999; Barabási et al. 2000; Tadić 2001; Pastor-Satorras et al. 2001; Capocci et al. 2006),
  - various transportation structures (Banavar et al. 1999; Guimera et al. 2005; Kühnert et al. 2006),
  - power grids (Albert et al. 2004),
  - spontaneous synchronization of systems (Gómez-Gardenes et al. 2007),
- biological systems, e.g.,
  - neural networks (Ripley 2008; Bullmore and Sporns 2009),
  - epidemiology (Meyers et al. 2005),
  - food chains (Garlaschelli et al. 2003; McKane and Drossel 2005),
  - gene regulation (Brazhnik et al. 2002; Bennett et al. 2008),
  - spontaneous synchronization in biological systems (Gonze et al. 2005),
- social[4] and economic realms, e.g.,
  - diffusion of innovation (Schilling and Phelps 2007; König et al. 2009),
  - trust-based interactions (Walter et al. 2008),
  - various collaborations (Newman 2001a, b),
  - social affiliation (Brown et al. 2007),
  - trade relations (Serrano and Boguñá 2003; Garlaschelli and Loffredo 2004a, c; Reichardt and White 2007; Fagiolo et al. 2008, 2009),
  - shared board directors (Strogatz 2001; Battiston and Catanzaro 2004),
  - similarity of products (Hidalgo et al. 2007),
  - credit relations (Boss et al. 2004; Iori et al. 2008),
  - price correlation (Bonanno et al. 2003; Onnela et al. 2003),
  - corporate ownership structures (Glattfelder and Battiston 2009; Vitali et al. 2011; Glattfelder 2013, 2016; Garcia-Bernardo et al. 2017; Fichtner et al. 2017; Glattfelder and Battiston 2019).

The explosion of research in the field of complex networks has been driven by two changes that have ushered in this new era of comprehending the complex and interdependent world surrounding us. The first is the mentioned departure from reductionist thinking to a systemic and holistic paradigm. The other change is related to the increased influx of data, furnishing the raw material for this revolution. The buzzword "big data" has been replaced by what is established data science. While the cost of computer storage is continually falling, storage capacity is increasing at an exponential rate. Seemingly endless streams of data—originating, for instance, from dynamic natural processes anywhere on the globe, a vast spectrum of observed biological interplay, or countless human endeavors—are continually flowing along global information highways and are being stored in server farms, the cloud, and, importantly, the researchers' local databases.

[4] A general reference is Vega-Redondo (2007).

6.3.2 Three Levels of Network Analysis

Complex systems are characterized by complex networks and graphs are the mathematical entity representing the networks. An adjacency matrix is an object that encodes the graph's topology. As an example, imagine a graph comprised of three nodes n_1, n_2, n_3, n_4 connected by three links l_1, l_2, l_3 such that

$$n_1 \xrightarrow{l_1} n_2, \quad n_1 \xrightarrow{l_2} n_3 \text{ and } n_2 \xrightarrow{l_3} n_3. \tag{6.1}$$

A network layout is shown in Fig. 6.1. The corresponding adjacency matrix is

$$A = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \tag{6.2}$$

Imagine each row and column of the matrix corresponding to a node (ordered by the label). The element $A(1, 3) = 1$ encodes the directed link from node n_1 to node n_3, i.e., l_2. Self-links would be represent by $A(i, i) = 1$ (for $i = 1, 2, 3$). In essence, the physical notion of a network has been translated into a matrix, a mathematical object obeying the powerful rules of linear algebra. More information on graph theory can be found in Sect. 5.3.2.

The study of real-world complex networks can be performed at three levels of abstraction. Level 1 represents the purely topological approach, where the network is encoded as a binary adjacency matrix and links exists (1) or do not (0). The simple example above is already a directed network. Removing the direction of the links yields the following Level 1 adjacency matrix

$$A = \begin{pmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}. \tag{6.3}$$

All the links remain, but the symmetry of the matrix, e.g., $A(1, 3) = A(3, 1)$, removes all traces of directedness. Allowing the links to carry information, i.e., have directions and weights, defines Level 2 (Newman 2004; Barrat et al. 2004; Barthelemy

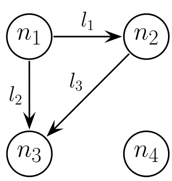

Fig. 6.1 Visualization example of the simple network defined in (6.1)

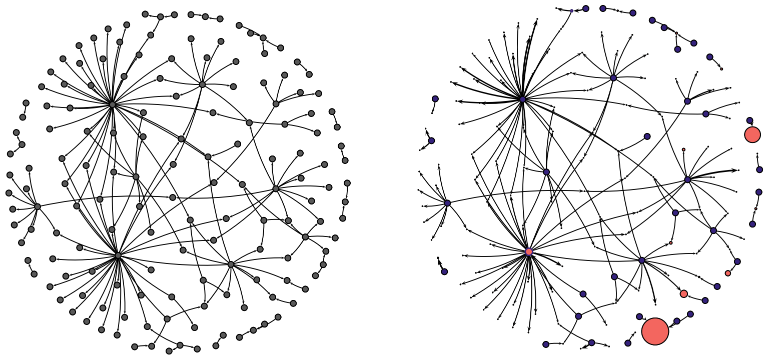

Fig. 6.2 Visualization examples of the same underlying network. (Left) a directed layout. (Right) the full-fledged 3-level layout, where the thickness of the links represents their weight and the nodes are scaled by some non-topological state variable. The graph layouts are taken from Glattfelder (2013)

et al. 2004; Onnela et al. 2005; Ahnert et al. 2007). In the example of Fig. 6.1, the directedness can be augmented by weighted links. Formally, $l_i \in]0, 1]$ for $i = 1, 2, 3$ or, equivalently, $A(i, j) \in]0, 1]$ for $i, j = 1, 2, 3$. Finally, at the highest level of detail, the nodes themselves are assigned a degree of freedom, in the guise of non-topological state variables that shape the topology of the network (Garlaschelli and Loffredo 2004b; Garlaschelli et al. 2005). These variables are sometimes also called fitness (Caldarelli et al. 2002; Servedio et al. 2004; Garlaschelli and Loffredo 2004a; De Masi et al. 2006). See Fig. 6.2 for a visualization of the 3-level approach to complex networks.

However, the Level 3 type analysis of real-world complex networks is very specific. Simply incorporating all three levels of detail into the analysis does not necessarily yield new insights. The specific domain the network originates from has to be considered and the employed network measures require appropriate adaption and tailoring. Only by accounting for the specific nature of the network under investigation new insights can be gained. The example of corporate ownership networks is discussed in Sects. 7.3.2.1 and 7.3.2.2.

6.4 Laws of Nature in Complex Systems

Laws of nature can be understood as regularities and structures in a highly complex universe. They critically depend on only a small set of conditions and are independent of many other conditions which could also possibly have an effect (Wigner 1960). Science is the quest to capture fundamental regularities of nature within formal analytical representations (Volume I of the Book of Nature). So then, are there laws of nature to be found for complex systems (Volume II)?

The quest to discover universal laws in complex systems has taken many turns. For instance, the macroscopic theory of thermodynamics allows arbitrary complex systems to be described from a universal point of view. Its foundations lie in statistical physics, explaining the phenomena of irreversible thermodynamics. A different approach, striving for universality, is synergetics (Haken 1977, 1983). In contrast to thermodynamics, this field deals with systems far away from thermal equilibrium. See Haken (2006) for a brief overview of the aforementioned approaches.

In the following, the focus of universality will lie on a purely empirical and descriptive phenomenological investigation. In this context the question "What are the laws of nature for complex systems?" has a clear answer.

6.4.1 Universal Scaling Laws

The empirical analysis of real-world complex systems has revealed an unsuspected regularity which is robust across a great variety of domains. This regularity is captured by what is known as scaling laws, also called power laws (Müller et al. 1990; Mantegna and Stanley 1995; Ghashghaie et al. 1996; West et al. 1997; Gabaix et al. 2003; Guillaume et al. 1997; Galluccio et al. 1997; Amaral et al. 1998; Barabási and Albert 1999; Ballocchi et al. 1999; Albert et al. 1999; Sornette 2000b; Pastor-Satorras et al. 2001; Dacorogna et al. 2001; Corsi et al. 2001; Newman et al. 2002; Garlaschelli et al. 2003; Newman 2005; Di Matteo et al. 2005; Lux 2006; Kühnert et al. 2006; Di Matteo 2007; Bettencourt et al. 2008; Bettencourt and West 2010; Glattfelder et al. 2011; West 2017). This distinct pattern of organization suggests that universal mechanisms are at work in the structure formation and evolution of many complex systems. Varying origins for these scaling laws have been proposed and insights have been gained from the study of critical phenomena and phase transitions, stochastic processes, rich-get-richer mechanisms and so-called self-organized criticality (Bouchaud 2001; Barndorff-Nielsen and Prause 2001; Farmer and Lillo 2004; Newman 2005; Joulin et al. 2008; Lux and Alfarano 2016). Tools and concepts from statistical physics have played a crucial role in discovering and describing these laws (Dorogovtsev and Mendes 2003b; Caldarelli 2007). In essence:

> Scaling laws can be understood as laws of nature describing complex systems.

Put in the simplest terms, a scaling law is a basic polynomial functional relationship

$$y = f(x) = Cx^{\alpha}, \tag{6.4}$$

characterized by a (positive or negative) scaling parameter α and a constant C. In other words, a relative change in the quantity x results in a proportional relative change in the quantity y, independent of the initial size of those quantities: y always varies as a power of x. A simple property of scaling laws can easily be shown. By

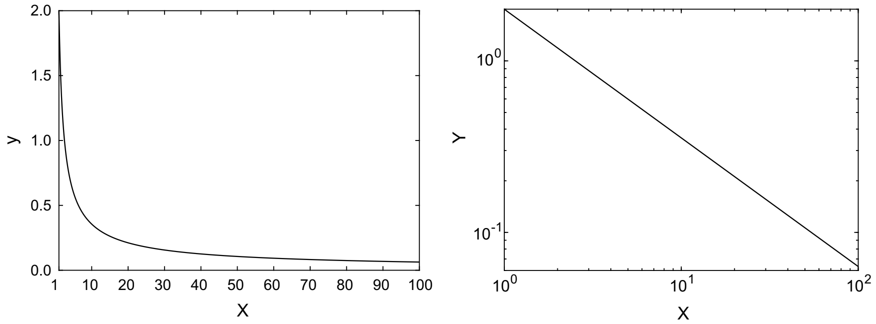

Fig. 6.3 A scaling-law relation. (Left) Graph of the function (6.4) with $\alpha = -0.75$ and $C = 2.0$. (Right) Log-log scale plot of the same function, i.e., (6.6)

varying the value of the function's argument (x), the shape of the function (y) is preserved. As this is true for all scales, the property is called scale invariance. In mathematical terms

$$f(ax) = C(ax)^\alpha = a^\alpha f(x) \sim f(x). \tag{6.5}$$

Another defining property of scaling laws is the trivial form which emerges when the function is plotted. Specifically, a logarithmic mapping yields a linear relationship. Taking the logarithm of (6.4) yields

$$Y = \alpha X + B, \tag{6.6}$$

where $X = \log(x)$ and $B = \log(C)$. See Fig. 6.3 for an illustration and, for instance, Newman (2005), Sornette (2000a) for further details.

Scaling-law relations characterize an immense number of natural processes, prominently in the form of

1. allometric scaling laws;
2. scaling-law distributions;
3. scale-free networks;
4. cumulative relations of stochastic processes.

Before presenting these four types of universal scaling, some historical context is given in the following section.

6.4.2 *Historical Background: Pareto, Zipf, and Benford*

The first study of scaling laws and scaling effects can be traced back to Galileo Galilei. He investigated how ships and animals cannot be naively scaled up, as different physical attributes obey different scaling properties, such as the weight, area, and perimeter (Ghosh 2011). Over 250 years later, the economist and sociologist

Vilfredo Pareto brought the concept of scaling laws to prominence (Pareto 1964, originally published in 1896). While investigating the probability distribution of the allocation of wealth among individuals, he discovered the first signs of universal scaling. Put simply, a large portion of the wealth of any society is owned only by a small percentage of the people in that society. Specifically, the Pareto principle says that 20% of the population controls 80% of the wealth. Hence this observation has also been called the 80-20 rule. To this day, the Pareto distribution is detected in the distribution of income or wealth. A more detailed treatment of Pareto's observed inequality was given by the Lorenz curve (Lorenz 1905). This is a graph representing the ranked cumulative income distribution. At any point on the x-axis, corresponding to the bottom $x\%$ of households, it shows what percentage ($y\%$) of the total income they have. A further refinement was the introduction of the Gini coefficient G (Gini 1921). In effect, G is a statistical measure of inequality, capturing how much an observed Lorenz curve deviates from perfect equality $G = 0.0$. Perfect inequality, or $G = 1.0$, corresponds to a step-function representing a single household earning all the available income. For the United States, in 1979 $G = 0.346$ and in 2013 $G = 0.41$. The interplay between this rise of the Gini coefficient and the rise of the share of total income going to the top earners, seen beginning at the end of the 1970s, is discussed in Atkinson et al. (2011). In 2011, South Africa saw a maximal $G = 0.634$ and in 2014, Ukraine a minimal $G = 0.241$. The data is available from the World Bank.[5]

Another popularizer of the universal scaling patterns found in many types of data, analyzed in the physical and social sciences, was the linguist and philologist George Kingsley Zipf. He studied rank-frequency distributions (Zipf 1949), which order distributions of size by rank. In other words, the x-axis shows the ordered ranks, while the y-axis shows the frequency of observations. For instance, the frequency of the use of words in any human language follows a Zipf distribution. For English, unsurprisingly, the most common words are "the", "of", and "and", while all remaining other ones follow Zipf's law of diminishing frequency. This law, characterized by a scaling-law probability distribution, is the discrete counterpart of the continuous Pareto probability distribution. See also Newman (2005).

A final pattern emerging in seemingly random data samples was discovered by the electrical engineer Frank Benford. He found an unexpected regularity which was only recently shown to be related to Zipf's law (Pietronero et al. 2001; Altamirano and Robledo 2011). In 1881, a seemingly bizarre result was published, based on the observation that the first pages of logarithm books, used at that time to perform calculations, were much more worn than the other pages (Newcomb 1881) . In other words, people where mostly computing the logarithms of numbers for which the first digit was a one: $d_1 = 1$. The phenomenon was rediscovered in 1938 by Benford, who confirmed the pattern for a large number of random variables drawn from geographical, biological, physical, demographical, economical, and sociological data sets. The pattern even holds for randomly compiled numbers taken from newspaper articles. Benford's law is an observation about the frequency distribution of leading

[5] See https://data.worldbank.org/indicator/SI.POV.GINI.

digits (Benford 1938). If $d_1 \in \{1, \ldots, 9\}$ denotes the first digit of a number, then the probability of its occurrence is equal to

$$p(d_1) = \log_{10}\left(\frac{d_1 + 1}{d_1}\right). \tag{6.7}$$

Specifically, $p(1) = 30.1\%$, $p(2) = 17.6\%$, $p(3) = 12.5\%$, $p(4) = 9.7\%$, $p(5) = 7.9\%$, $p(6) = 6.7\%$, $p(7) = 5.8\%$, $p(8) = 5.1\%$, $p(9) = 4.6\%$. In effect, seeing a one as a leading digit in a number is over six times more likely than observing a nine. The law also holds for the second digit d_2 and so on. In general terms, for a number $B \geq 2$, $d_i \in \{1, \ldots, B-1\}$

$$p(d_i) = \log_B\left(\frac{d_i + 1}{d_i}\right). \tag{6.8}$$

First explanations of this phenomena, which appears to suspend the notions of probability, focused on the law's logarithmic nature which implies a scale-invariant distribution. If the first digits universally obey a specific pattern of distribution, this property is thus independent of the measuring system. In other words, conversions from one system of units to other ones—for instance, moving from metric to imperial units—do not affect the pattern. This requirement, that physical quantities are independent of a chosen representation is called covariance and is one of the cornerstones of general relativity (Sects. 4.1 and 10.1.2). In essence, the common sense requirement that the dimensions of arbitrary measurement systems should not affect the measured physical quantities is encoded in Benford's law. In addition, the fact that many processes in nature show exponential growth is also captured by the law, which assumes that the logarithms of numbers are uniformly distributed. In 1996, the law was mathematically rigorously proved. It was shown that, if one repeatedly chooses different probability distributions and then randomly chooses a number according to that distribution, the resulting list of numbers will obey Benford's law (Hill 1995. Hence the law reflects the behavior of distributions of distributions. Benford's law is also present in very distinct phenomena, such as the statistical distribution of leading digits in the prime number sequence (Luque and Lacasa 2009), quantum phase transitions (Sen De and Sen 2011), and earthquake detection (Díaz et al. 2014). The law has also been utilized to detect fraud in insurance, accounting, expenses, or election data, where people forging numbers tend to distribute their digits uniformly.

6.4.3 The Types of Universal Scaling

Notwithstanding the spectacular number of occurrences of scaling-law relations in a vast diversity of complex systems, there are four basic types of scaling laws to be distinguished.

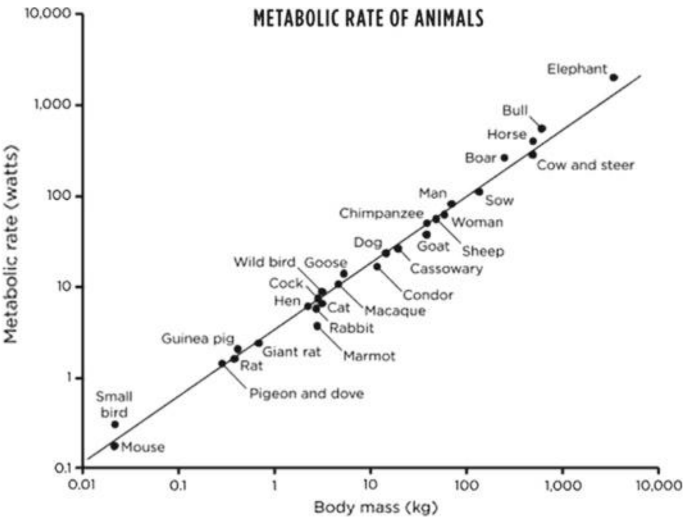

Fig. 6.4 Empirical validation of Kleiber's $\frac{3}{4}$-power law, relating body mass to metabolic rate. Figure taken from West (2017). This scaling relation has been extended to span 27 orders of magnitude to include cell structures and unicellular organisms (West and Brown 2005)

6.4.3.1 Allometric Scaling Laws

Allometric scaling describes how various properties of living organisms change with size. This was first observed by Galileo, when he was analyzing the skeletal structures of mammals of varying size. In 1932, the biologist Max Kleiber discovered that, for the vast majority of animals, the animal's metabolic rate B scales to the $\frac{3}{4}$ power of the animal's mass M (Kleiber 1932). Mathematically

$$B \sim M^{\frac{3}{4}}. \tag{6.9}$$

Thus, a male African bush elephant, weighing an average of 6 tons, has a metabolism roughly 13,320 times slower than a house mouse, weighing 19 grams. In Fig. 6.4 an overview is shown, ranging from mice to humans to elephants. Moreover, the metabolic rate in animals and the power consumption in computers have been found to scale similarly with size and an energy-time minimization principle is postulated which governs the design of many complex systems that process energy, materials, and information (Moses et al. 2016).

Other allometric scaling laws relate the lifespan L and the number of heartbeats H of mammals to their weight M:

$$\begin{aligned} L &\sim M^{\frac{1}{4}}, \\ H &\sim M^{-\frac{1}{4}}. \end{aligned} \tag{6.10}$$

Consequently, heavier animals live longer and have slower heart-rates. As both of these scaling laws have the same absolute value but varying sign for their exponent, a fundamental invariant of life emerges: the number of heart-beats per lifetime is constant (approximately 1.5×10^9). The existence of these biological scaling laws, and the fact that the exponents are always simple multiples of $\frac{1}{4}$, suggest the workings of general underlying mechanisms which are independent of the specific nature of the individual organisms. Hidden behind the mystifying diversity of life lies an organizational process which becomes visible through self-similar scaling laws. This implies the existence of average, idealized biological systems at various scales. More details can be found in West et al. (1997), West and Brown (2005).

Allometric scaling also has medical implications, namely related to drug administration and weight. An example taken from a website[6] offering a calculator which estimates interspecies dosage scaling between animals of different weights: "If the dosage for a 0.25 kg rat is 0.1 mg, then using an exponent of 0.75, the estimated dosage for a 70 kg human would be 6.8 mg. While the dose to weight ratio for the rat is 0.4 mg/kg, the value for the human is only about 0.1 mg/kg." In 1962, two psychiatrists decided to test the effects of the psychedelic substance lysergic acid diethylamide (LSD) on an elephant. The animal weighed about 3,000 kg and the researchers estimated that a dose of about 300 mg would be appropriate. Not taking the non-linear scaling behavior into account, this turned out to be a fatal dose. The elephant died and the ordeal was reported in the prestigious journal *Science* (West et al. 1962). Knowledge of allometric scaling would have revealed the following. For humans, a standard amount of LSD is 100 micrograms.[7] Assuming a body-weight of 70 kg, this dose translates into roughly 1.6 milligrams for an elephant. The administered 300 mg correspond to about 17 mg of LSD for a human. However, there are no verified cases of death by means of an LSD overdose in humans (Passie et al. 2008). See also West (2017).

Allometric scaling laws are also found in the plant kingdom (Niklas 1994). Vascular plants vary in size by about twelve orders of magnitude and scaling laws explain many features. For instance, the self-similar and fractal branching architecture follows a scaling relation. There also exist parallels in the characteristics of plants and animals which are described by allometric scaling with respect to mass: the metabolic rate ($M^{\frac{3}{4}}$) and the radius of trunk and aorta ($M^{\frac{3}{8}}$). See West et al. (1999).

A recent biological scaling law was discovered, describing a universal mathematical relation for folding mammalian brains (Mota and Herculano-Houzel 2015).

6.4.3.2 Scaling-Law Distributions

In 1809, Carl Friedrich Gauss published a monograph in which he introduced fundamental statistical concepts (Gauss 1809). A key insight was the description of random data by means of what is today know as normal (or Gaussian) distributions. To this

[6]See http://clymer.altervista.org/minor/allometry.html.

[7]See https://erowid.org/chemicals/lsd/lsd_dose.shtml, retrieved February 1, 2018.

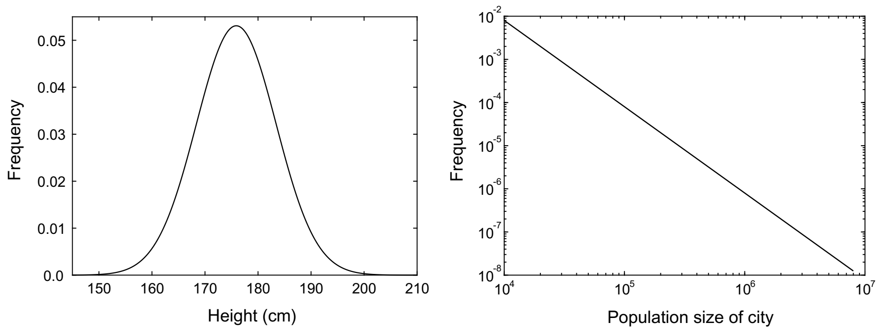

Fig. 6.5 Comparing probability distributions. (Left) A normal distribution showing the heights of 5,647 male individuals, age 20 and over from the US, with $\mu = 175.9$ [cm] and $\sigma = 7.5147$ [cm] in (6.11) (Fryar et al. 2012) (Right). The scaling-law distribution of city sizes in log-log scale, approximated from Newman (2005), with $\alpha = 2.0$ and $C = 800,000$ in (6.12)

day, many phenomena are approximated by this type of probability distribution. For instance, observations related to intelligence (IQ), blood pressure, test results, and height (see Fig. 6.5). Moreover, measurement errors in a variety of physical experiments, under general conditions, will follow a normal distribution. In a nutshell, any random phenomena, related to a large number of small and independent causes, can be approximated by a normal distribution. This statement is made mathematically rigorous by the central limit theorem, to which the ubiquity of normal distributions in nature is linked (Voit 2005). In detail, data which is normally distributed is characterized by the mean (μ), around which most of the observations cluster. The standard deviation (σ) captures the amount of variation in the data. The functional form is given by

$$\mathcal{N}(x, \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \tag{6.11}$$

A precise prediction of this equation is that values less than three standard deviations away from the mean (related to what are called 3-sigma events) account for 99.73% of observations. In other words, it is extremely rare to observe outliers in data following a normal distribution.

In contrast, data following scaling-law distributions represent the other extreme, where very large occurrences are expected and observations span many orders of magnitude. In Fig. 6.5 two examples are shown, in which a normal distribution of height is compared to a scaling-law distribution of city sizes. Scaling-law distributions, quantifying the probability distributions of complex systems, are the most ubiquitous scaling relation found in nature. Expressed in mathematical terms

$$p(x) = Cx^{-\alpha}, \tag{6.12}$$

for $\alpha > 0$. Note that p is a probability density function. The corresponding cumulative distribution function is defined as

$$\mathcal{P}(x) = \int_x^\infty p(x')\mathrm{d}x'. \tag{6.13}$$

If $p(x)$ follows a scaling law with (positive) exponent α, then the cumulative distribution function $\mathcal{P}(x)$ also follows a power law, with an exponent $\alpha - 1$. Pareto's 80-20 rule can be derived using $\mathcal{P}$. In detail, the question, above what point x_F the fraction F of the distribution lies, can be formalized as

$$\mathcal{P}(x_F) = \int_{x_F}^\infty p(x')\mathrm{d}x' = F\int_{x_{\min}}^\infty p(x')\mathrm{d}x'. \tag{6.14}$$

The solution is given by

$$x_F = F^{\frac{1}{-\alpha+1}} x_{\min}. \tag{6.15}$$

From this, the fraction W of wealth in the hands of the richest P percent of the population can be derived as

$$W = P^{\frac{-\alpha+2}{-\alpha+1}}. \tag{6.16}$$

As an example, for the US, the empirical wealth distribution exponent is $\alpha = 2.1$ (Newman 2005). Hence, 86.38% (i.e., $8.638 = 0.2^{-0.1/-1.1}$) of the wealth is held by the richest 20% (0.2). Or, about 64.5% of the wealth is held by the richest 8%. Statistically speaking, cumulative distribution functions perform better, because the tail of the distribution is not affected by the diminishing number observations, as is the case for the density function, where outliers can skew the results.

Scaling-law distributions have been observed in an extraordinary wide range of natural phenomena: from physics, biology, earth and planetary sciences, economics and finance, computer science, demography to the social sciences (Amaral et al. 1998; Albert et al. 1999; Sornette 2000a; Pastor-Satorras et al. 2001; Bouchaud 2001; Newman et al. 2002; Caldarelli et al. 2002; Garlaschelli et al. 2003; Gabaix et al. 2003; Newman 2005; Lux 2005; Di Matteo 2007; Bettencourt et al. 2007; Bettencourt and West 2010; West 2017). It is truly astounding, that such diverse topics as

- the size of cities, earthquakes, moon craters, solar flares, computer files, sand particle, wars and price moves in financial markets;
- the number of scientific papers written, citations received by publications, hits on webpages and species in biological taxa;
- the sales of music, books and other commodities;
- the population of cities;
- the income of people;

- the frequency of words used in human languages and of occurrences of personal names;
- the areas burnt in forest fires;

are all characterized by scaling-law distributions.

As mentioned, processes following normal distributions have a characteristic scale given by the mean (μ) of the distribution. In contrast, scaling-law distributions lack such a preferred scale, as measurements of scaling-law processes can yield values distributed across a vast dynamic range, spanning many orders of magnitude. Indeed, for $\alpha \leq 2$ the mean of the scaling-law distribution can be shown to diverge (Newman 2005). Moreover, analyzing any section of a scaling-law distribution yields similar proportions of small to large events. In other words, scaling-law distributions are characterized by scale-free and self-similar behavior. Historically, Benoît Mandelbrot observed these properties in the changes of cotton prices, which represented the starting point for his research leading to the discovery of fractal geometry (Mandelbrot 1963, see also Sects. 5.2.2, and 5.1.3). Finally, for normal distributions, events that deviate from the mean by, e.g., 10 standard deviations (10-sigma events) are practically impossible to observe. Scaling laws, in contrast, imply that small occurrences are extremely common, whereas large instances become rarer. However, these large events occur nevertheless much more frequently compared to a normal distribution: for scaling-law distributions, extreme events have a small but very real probability of occurring. This fact is summed up by saying that the distribution has a "fat tail" (Anderson 2004). In the terminology of probability theory and statistics, distributions with fat tails are said to be leptokurtic or to display positive kurtosis. The presence of fat tails greatly impacts risk assessments: although most earthquakes, price moves in financial markets, intensities of solar flares, etc., will be very small most of the time, the possibility that a catastrophic event will happen cannot be neglected.

6.4.3.3 Scale-Free Networks

The turn of the millennium brought about a revolution in the fundamental understanding of the structure and dynamics of real-world complex networks (Barabási and Albert 1999; Watts and Strogatz 1998; Albert and Barabási 2002; Dorogovtsev and Mendes 2002; Newman et al. 2006). The discovery of small-world (Watts and Strogatz 1998) and scale-free (Barabási and Albert 1999; Albert and Barabási 2002) networks were the initial sparks, bringing about a new science of networks (Section 6.3.1). A historical outline of events can be found in Sect. 5.2.3. Figure 6.6 shows an example of a scale-free network.

In a nutshell, scale-free networks have a degree distribution following a scaling law. Let $\mathcal{P}(k_i)$ describe the probability of finding a node i in the network with a degree of k_i. In other words, i has k_i direct neighbors and $\mathcal{P}(k_i)$ expresses the probability of occurrences throughout the network. In general, for scale-free networks, the following relation holds

$$\mathcal{P}(k) \sim k^{-\alpha}. \tag{6.17}$$

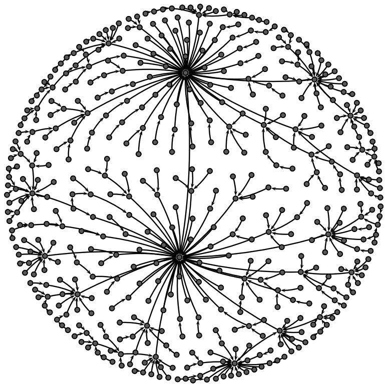

Fig. 6.6 Layout of a scale-free directed network showing two hubs. See Sect. 5.2.3

The detailed expression is given in (5.18) on p. 168 of Sect. 5.3.2, introducing elements of graph theory. For directed networks, one needs to distinguish between the in-degree (k_i^{in}) and out-degree (k_i^{out}).

A prototypical example of a scale-free network is given by the World Wide Web (WWW), the set of all online documents interlinked by hypertext links (Barabási et al. 2000). This should not be confused with the Internet, the global network of interconnected computers that utilize the TCP/IP protocol to link devices. In essence, the vast majority of webpages in the WWW are irrelevant and there exist only a few extremely interconnected hubs. Ranked by page views, the most popular five webpages are Google, YouTube, Facebook, Baidu, and Wikipedia.[8] To illustrate, Google's search engine processes an average of 3.5 billion searches per day.[9] Indeed, the success of Google initially depended on the development of a network measure. In detail, the founders Larry Page and Sergey Brin introduced the PageRank search algorithm, which is based on network centrality[10] (Katz 1953; Hubbell 1965; Bonacich 1987; Borgatti 2005; Glattfelder 2019). In a nutshell, a webpage is important if important webpages link to it. Technically, PageRank assigns a numerical weighting to each element of a hyperlinked set of documents, with the purpose of measuring its relative importance within the set (Brin and Page 1998).

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[8] As ranked by www.alexa.com/topsites/, accessed February 2, 2018.

[9] See http://www.internetlivestats.com/google-search-statistics/, accessed February 13, 2018.

[10] See also Sect. 7.3.2.2.

PageRank is formally defined by an iterative equation PR_i for each node i:

$$PR_i(t+1) = \alpha \sum_{j \in \Gamma(i)} \frac{PR_j(t)}{k_j^{\text{out}}} + \frac{1-\alpha}{N}, \tag{6.18}$$

where $\Gamma(i)$ is the set of labels of the neighboring nodes of i, α is a dampening factor usually set to 0.85, and N is a size coefficient. In matrix notation

$$PR(t+1) = \alpha \mathcal{M} PR(t) + \frac{1-\alpha}{N}\mathbf{1}, \tag{6.19}$$

where $\mathbf{1}$ is the unit column-vector and the matrix $\mathcal{M}$ is

$$\mathcal{M}_{ij} = \begin{cases} 1/k_j^{\text{out}}, & \text{if } j \text{ links to } i; \\ 0, & \text{otherwise.} \end{cases} \tag{6.20}$$

Alternatively, $\mathcal{M} = (K^{-1}A)^t$, if K is the diagonal matrix with the out-degrees in the diagonal and A is the adjacency matrix of the network. The solution is given, in the steady state, by

$$PR = (\mathbb{1} - \alpha\mathcal{M})^{-1}\frac{1-\alpha}{N}\mathbf{1}, \tag{6.21}$$

with the identity matrix ⊮. A solution exists and is unique for $0 < \alpha < 1$.

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Conceptually, the PageRank formula reflects a model of a random surfer in the WWW who gets bored after several clicks and switches to a random page. The PageRank value of a page measures the chance that the random surfer will land on that page by clicking on a link. If a page has no links to other pages, it becomes a sink and therefore terminates the random surfing process, unless $\alpha < 1$. In this case, the random surfer arriving at a sink page, jumps to a random webpage chosen uniformly at random. Hence $(1-\alpha)/N$ in Eqs. (6.18) and (6.19) is interpreted as a teleportation term.

Scale-free networks are characterized by high robustness against the random failure of nodes, but susceptible to coordinated attacks on the hubs. Theoretically, they are thought to arise from a dynamical growth process, called preferential attachment, in which new nodes favor linking to existing nodes with high degree (Barabási and Albert 1999). Albert-László Barabási was highly influential in popularizing the study of complex networks by explaining the ubiquity of scale-free networks with preferential attachment models of network growth. However, the statistician Udny Yule already introduced the notion of preferential attachment in 1925, when he analyzed the power-law distribution of the number of species per genus of flowering plants (Udny Yule 1925). Alternative formation mechanisms for scale-free networks have been proposed, such as fitness-based models (Caldarelli et al. 2002).

6.4.3.4 Cumulative Scaling-Law Relations

A final type of scaling-law relation appears in collections of random variables, called stochastic processes (see Sect. 7.1.1.1). Prominent empirical examples are financial time series, where one finds empirical scaling laws governing the relationship between various observed quantities. Time series are simple series of data points ordered by time. For instance, the price of a security or asset at time t is given by $x(t)$. The collection of prices at different times during some time horizon, i.e., $t \in [t_S, t_E]$, constitutes a series, which can be plotted as a chart. De facto, financial instruments are associated with a spread $s(t)$, quantifying the difference between the ask $x^{ask}(t)$ and the bid $x^{bid}(t)$ prices of the security or asset, quoted to sellers and buyers, respectively. The mid price is defined as

$$x(t) = \frac{x^{ask}(t) + x^{bid}(t)}{2}. \tag{6.22}$$

As prices are quoted discretely, the parameter t can be replaced by a set of time instances t_i. Consequently, $x(t_i)$ can be denoted by x_i, yielding a simpler notation. Price moves are defined as percentages

$$\Delta x_i = \frac{x_i - x_{i-1}}{x_{i-1}}. \tag{6.23}$$

The average price moves for a time horizon is thus

$$\langle \Delta x \rangle = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (\Delta x_j)^2}. \tag{6.24}$$

In Glattfelder et al. (2011) 18 empirical scaling-law relations were uncovered in the foreign exchange market, 12 of them being independent of each other. The foreign exchange market can be characterized as a complex network consisting of interacting agents: corporations, institutional and retail traders, and brokers trading through market makers, who themselves form an intricate web of interdependence. With an average daily turnover of approximately USD five trillion (Bank of International Settlement 2016) and with price changes nearly every second, the foreign exchange market offers a unique opportunity to analyze the functioning of a highly liquid, over-the-counter market that is not constrained by specific exchange-based rules. This market is an order of magnitude bigger than the futures or equity markets (ISDA 2014). An example of such an emerging scaling law in the foreign exchange market is the following: The average time interval $\langle \Delta t \rangle$ for a price change of size

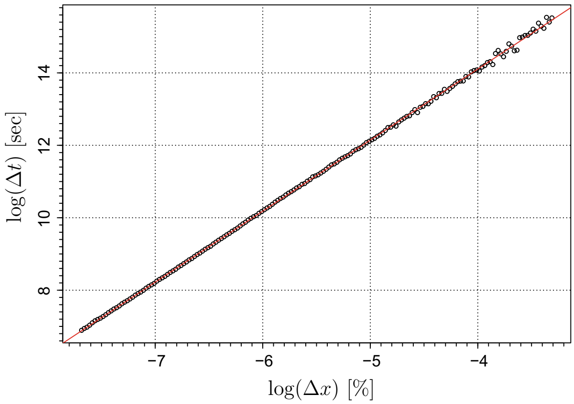

Fig. 6.7 Financial scaling-law relation. The log-log plot shows the empirical results for the EUR/USD currency pair over a five year data sample. The time (Δt) during which a price move of $\Delta x \in [0.045\%, \ldots, 4.0\%]$ happens is related to the magnitude of these moves. The exponent is estimated at $\alpha = 1.9608 \pm 0.0025$. The y-axis data range is approximately from 16 min to 69 days

Δx to occur follows a scaling-law relation

$$\langle \Delta t \rangle \sim \Delta x^{\alpha}. \tag{6.25}$$

Figure 6.7 shows an illustration of this scaling law for the Euro to US Dollar exchange rate. Another cumulative scaling-law relation counts the average yearly number of price moves of size Δx

$$\mathsf{N}(\Delta x) \sim \Delta x^{\alpha}. \tag{6.26}$$

In Fig. 6.8 this scaling law is plotted for 13 currency pairs and a benchmark Gaussian random walk. Finally, a salient novel scaling-law relation unveils that after any directional change of a price move, measured by a threshold δ, the price will continue, on average, to move by a percentage ω. This overshoot scaling law has a trivial form

$$\langle \omega \rangle \sim \delta. \tag{6.27}$$

In other words, any directional change in a time series will be followed by an overshoot of the same size, on all scales. See Glattfelder et al. (2011) for more details and the remaining 15 scaling laws.

These laws represent the foundation of a new generation of tools for studying volatility, measuring risk, and creating better forecasting (Golub et al. 2016). They also substantially extend the catalog of stylized facts found in financial time series (Guillaume et al. 1997; Dacorogna et al. 2001) and sharply constrain the space of possible theoretical explanations of the market mechanisms. The laws can be used to define an event-based framework, substituting the passage of physical time with market activity (Guillaume et al. 1997; Glattfelder et al. 2011; Aloud et al. 2011).

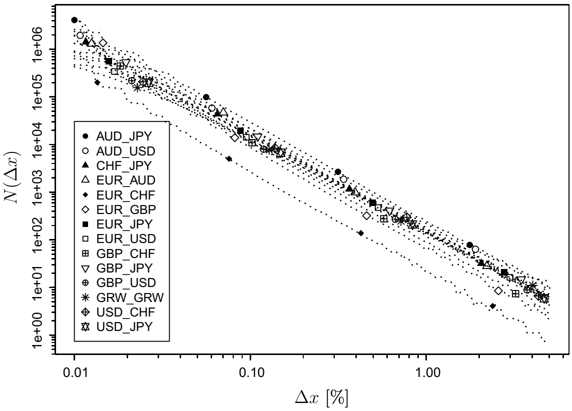

Fig. 6.8 Number of yearly price moves scaling law. Plots based on five years of tick-by-tick data for 13 exchange rates and a Gaussian random walk model. See Glattfelder et al. (2011) for details

Consolidating all these building blocks cumulates in a new generation of automated trading algorithms[11] which not only generate profits, but also provide liquidity and stability to financial markets (Golub et al. 2018). See also Müller et al. (1990), Mantegna and Stanley (1995), Galluccio et al. (1997) for early accounts of the scaling properties in foreign exchange markets.

6.4.3.5 A Word of Caution

Finding laws of nature for complex systems is a challenging task. By design, there exist many levels of organization which interact with each other in theses systems. Moreover, the laws represent idealizations lurking in the murky depths hidden beneath layers of messy data. While the laws of nature relating to Volume I of the Book of Nature are clear-cut and orderly, Volume II struggles with this clarity. The importance of the four types of universal scaling laws previously discussed has been challenged by some.

The debate boils down to the following question: How far can one deviate from statistical rigor to detect an approximation of an organizational principle in nature? In the early days of scaling laws, some physicists have been accused of simply plotting their data in a log-log plot and squinting at the screen to declare a scaling law. However, the statistical criteria for a true scaling law to be found in empirical data are quite involved (Clauset et al. 2009). Recently, the ubiquity of scale-free networks has been questioned (Broido and Clauset 2018).

Network scientists have adapted to such challenges. For one, the strict adherence to a precise power law is relaxed. As an example, a broader class called “heavy-tailed” networks is invoked. Many real-world networks show such a distribution in their degree distribution. In other words, they share the characteristics of a scale-free network (such as robustness and vulnerability) without actually obeying a strict power

[11] The code can be found here: https://github.com/AntonVonGolub/Code.

law. In essence, real-world networks are determined by many different mechanisms and processes which nudge the network away from pure scale-freeness, making them heavy-tailed. However, the biggest and simplest factor responsible for spoiling any neat idealized scaling-law behavior in all real applications could be, in the words of physicist-turned-network scientist Alessandro Vespignani, that (quoted in Klarreich 2018):

> In the real world, there is dirt and dust, and this dirt and dust will be on your data. You will never see the perfect power law.

Nonetheless, perhaps the real impediment that network researchers face is far deeper, echoing the poststructural and postmodern sentiment from Sect. 6.2.2. Again Vespignani (Klarreich 2018):

> There is no general theory of networks.

Barabási replied to the accusations in a blog post.[12] In essence, (Broido and Clauset 2018) utilize a "fictional criterion of scale-free networks," which "fails the most elementary tests."

Conclusion

Here on Earth, complexity is found everywhere. However, only recently has the human mind deciphered the simple rules behind complex phenomena. This insight came hand in hand with the emergence of information technology, allowing this new domain to be algorithmically charted. The prototypical complex system is biological. However, the vast complex systems we humans have created, especially in finance and economics, require a detailed and in-depth discussion. Today, they affect every aspect of life on Earth.

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[12] Called *Love is All You Need—Clauset's Fruitless Search for Scale-Free Networks*, see https://www.barabasilab.com/post/love-is-all-you-need/, posted on March 16, 2018.

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Chapter 7
Applied Complexity: Finance and Economics in a New Light

Abstract The Scientific and the Industrial Revolutions have changed the face of the Earth forever. Today, we enjoy the unparalleled rewards of technological and economic prosperity. The world has merged into one single global network of human activity, creating a complex super-system. Specifically, the cross-fertilization of three spheres of influence has created this successful world order: science and technology, industry and economics, and military interests. The current paradigm is called the doctrine of neoliberalism, justified by neoclassical economics and quantitative finance. However, there is a dark side to all this progress. It takes a heavy toll on the individual human psyche and the global ecosystem. Short-term personal self-realization is pitted against evolutionary cooperation and collective intelligence. The distribution of resources is heavily skewed, giving rise to a culture of inequality. Finally, some crucial questions need to be answered. Is humanity happier today than in the past? Can we actually control the economic and financial systems we have created? Do we need a new paradigm coming from complexity science?
Level of mathematical formality: low.

Arguably, financial markets and economic interactions represent ideal manifestations of complex systems. The understanding of the structure and functioning of markets and economies is perhaps the single most important goal to ensure equitable future prosperity—economic and ecological. Complexity theory could be the key to overcoming the ideological and dogmatic trenches plaguing these sociopolitical endeavors which shape every aspect of human existence. While the application of the tools and methods derived from studying complex systems brought about a wealth of novel understanding in the last decades for computer science, biology, physics, and sociology, finance and economics have been wary and slow to adopt the insights.

The architectures of institutionalized power play an important role in shaping the commercial reality we humans are exposed to, with profound implications for all of life on Earth. In this chapter, a lot of historical context is presented explaining the current paradigm of finance and economics. This allows the systemic defects and structural shortcomings to be better understood, thus possibly setting a new course for the future. At the heart of all economic and financial interactions lies the

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individual human being, driven by personal, long-term self-actualization and tempted by the short-term fruits of greed and fraud. This is thus the key question: How can we foster collective intelligent behavior from individual preferences? Indeed, an age-old challenge faced by evolution itself.

7.1 Terra Cognita

Before sailing off into terra incognita, some notable developments in the history of finance and economics require a discussion. From the emergence of randomness in science, the appearance of a new caste of mathematical wizards, the widespread adoption of a certain brand of economic thinking, the failure of the economic operating system, to the gridlock created by conflicting ideologies, the last 100 years have seen some very critical events unfold.

7.1.1 Some Historical Background

In 1776, Adam Smith presented *An Inquiry into the Nature and Causes of the Wealth of Nations* (Smith 1776). This treatise is considered to be the first modern work of economics. It was inspired by Isaac Newton's revolutionary and foundational work establishing modern physics: *Philosophiæ Naturalis Principia Mathematica* (Newton 1687). Today, finance and economics are fundamentally equation-driven. Mathematics is the bedrock upon which the theories are built upon, reaching ever new heights of esoteric abstraction. At the heart of this evolution stands what is known as a stochastic process: the mathematization of a series of random events unfolding in time. Scholars grappled with this concept for nearly a century until a new profession emerged: the quantitative analyst.

7.1.1.1 Stochastic Processes

The historical rise of financial mathematics is intertwined with major developments in physics. The year 1900 marked a radical turning point in physics. Max Planck was grappling with the problem of black-body radiation, which defied any theoretical explanation. This issue, however, did not appear very fundamental and the general feeling at the time was, that physics had nearly conquered all there is to know about the physical world. In a creative act, Planck introduced an idea[1] that would lead to the uncovering of the quantum realm of reality (see Sect. 4.3.4). This discovery ushered in an era of conceptual challenges about the nature of reality from which physics has (or more precisely, physicists have) to this day not recovered from (see Sect. 10.3.2.2).

[1]The quantization of energy: $E = h\nu$.

One fundamental tenet of quantum theory is its probabilistic character. The old notion of a deterministic clock-work universe is lost forever. Now, nature is hiding eternally behind a veil of probability.

Also in the year 1900, the mathematician Louis Bachelier presented his Ph.D. thesis (Bachelier 1900). He introduced a formalization of randomness called a stochastic process and applied this to the valuation of stock options. Unfortunately, his pioneering work on randomness and mathematical finance was essentially forgotten until the late 1950s. Bachelier based his work on Brownian motion. This is the name name given to the random motion of particles suspended in a fluid, first described by the botanist Robert Brown. He had observed particles in water trapped in cavities inside pollen grains through a microscope (Brown 1828). The mathematical formalization of Brownian motion is called a stochastic process. Today, the continuous-time stochastic process is called a Wiener process, named in honor of the mathematician and philosopher Norbert Wiener.

The year 1905 was Albert Einstein's annus mirabilis. He was working at the Patent Office in Bern and submitted his Ph.D. to the University of Zurich later that year. Einstein also published four papers in 1905, which would rock the foundations of physics. His work on the photoelectric effect (Einstein 1905c) not only gave Planck's theoretical notion of energy quanta a physical reality in terms of photons, further establishing the relevance of quantum theory (albeit to Einstein's dismay, see Sects. 4.3.4 and 10.3.2), it also lead to him being awarded the Nobel prize sixteen years later. In 1905, Einstein also presented the theory of special relativity (Einstein 1905d) and the infamous mass-energy equivalence $E = mc^2$ (Einstein 1905a). His fourth paper of 1905 is less known. Brownian motion had always been lacking any satisfactory explanation. Einstein's paper gave a statistical description of the phenomenon and provided empirical evidence for the reality of the atom, the existence of which was being debated at the time (Einstein 1905b). Specifically, he utilized the mathematics of stochastic processes and today the Wiener process is also known as the Einstein-Wiener process.

Einstein helped introduce a new paradigm with his work on Brownian motion: the stochastic modeling of natural phenomena, where statistics play an intrinsic role and the time evolution of a system is essentially random. Technically, the equation for the Brownian particle is similar to a differential equation describing diffusion. In 1908, the physicist Paul Langevin presented a new derivation of Einstein's results (Langevin 1908). Langevin introduced the first stochastic differential equation, i.e., a differential equation of a "rapidly and irregularly fluctuating random force." Today this "force" is called a random variable, encapsulating the randomness. What was, however, still missing was a rigorous mathematical theory.

Langevin's description represents the micro view on randomness. The Langevin equation describes the evolution of the position of a single "stochastic particle." In 1914, the physicist Adriaan Fokker derived an equation on Brownian motion (Fokker 1914) which Planck proved later. However, the Fokker-Planck equation was applied to quantum mechanics by Planck to no avail. It was later realized that the equation actually describes the behavior of a large population of "stochastic particles." It thus represents the macro view onrandomness complementing the micro view of the Langevin equation. Formally, the Fokker-Planck equation describes the time evolution of the probability density function of the system. Results can be derived more directly using the Fokker-Planck equation than using the corresponding Langevin stochastic differential equations. See also Sect. 5.4.1.

Back in the early 1900s, the mathematician Andrey Markov introduced a prototypical stochastic process, satisfying certain properties (Markov 1906). In essence, a Markov process is memory-less: only the present state of the system influences its future evolution. An example is the Einstein-Wiener process related to Brownian motion, introduced by Bachelier. It is a continuous process (in time and the sample path). A discreet example of a Markov process is a random walk, where the path increments are independent and drawn from a Gaussian normal distribution. In the limit of the step size going to zero, the Einstein-Wiener process is recovered. In general, a Markov process is characterized by jumps (in the sample path), drift (of the probability density function), and diffusion (widening of the probability density function). It is also a solution to a stochastic differential equation. In 1931, the mathematician Andrey Kolmogorov presented two fundamental equations on Markov processes (Kolmogoroff 1931). It was later realized, that one of them was actually equivalent to the Fokker-Planck equation.

Then, in 1942, the mathematician Kiyoshi Itô developed stochastic calculus, finally laying the formal mathematical foundation for the treatment of randomness. This would pave the way for the stellar rise of financial mathematics. In the mid 1950s the economist Paul Samuelson, the first American to win the Nobel Memorial Prize in Economic Sciences (often referred to as the Nobel prize for economics), embraced Brownian motion as a model for the stock market. Bachelier's original work reemerged and the randomness of price movements appeared tamed (Samuelson 1965).

Until now, the understanding of financial markets was strongly influenced by the mathematics of physics. This decoding of reality via formal analytical representations is the paradigm of Volume I of the Book of Nature (see Chap. 2 and Sect. 5.1). It represents the "unreasonable effectiveness of mathematics in the natural sciences" (Wigner 1960). In contrast, Volume II of the Book of Nature contains the algorithmic decoding of complex phenomena (see Sect. 5.2). In this paradigm, algorithms and simulations running in computers replace the mathematical tools for uncovering knowledge, based on the astonishing observation, that simplicity is the fuel for complexity (see Sect. 5.2.2). Historically, the study of financial markets gave one of the first glimpses of Volume II, an extension of the Book of Nature that was unknown to exist at the time. The mathematician Benoît Mandelbrot was observing the properties cotton prices when he uncovered an unintuitive feature. In effect, he discovered the self-similar nature of financial time series (Mandelbrot 1963b). Regardless of the chosen time horizon—days or months—the cotton price charts showed the same characteristics. Today, the modeling of random systems evolving in time utilizing self-similar stochastic processes is fundamental for their understanding (Embrechts and Maejima 2002). Mandelbrot's discovery in 1963 would mark the starting point for his research leading to the seminal discovery of fractal geometry (Mandelbrot

1982) and the emergence of chaos theory, embracing the non-linear behavior of complex phenomena.

The year 1973 marked financial mathematic's coming-of-age. The economists Fischer Black and Myron Scholes, both associated with the University of Chicago, presented a paper that set out to revolutionize finance. With the help of the economist Robert Merton, expanding the mathematical understanding, the 1997 Nobel Memorial Prize in economic sciences would be awarded for their work.[2] Building on Itô's insights, Black and Scholes derived a model of a financial market containing derivative investment instruments. The crucial mathematical insight was a stochastic partial differential equation, called the Black-Scholes equation

$$\frac{\partial V}{\partial t} + \frac{1}{2}\sigma^2 S^2 \frac{\partial^2 V}{\partial S^2} + rS\frac{\partial V}{\partial S} - rV = 0. \tag{7.1}$$

Technically, the formula dictates the price evolution of a European call or put option under the Black-Scholes model. In other words, it gives a theoretical estimate of the price of the derivative. The model can only be applied under certain assumptions and limitations. To this day, the publication has been cited 8,467 times.[3]

The academic success of the Black-Scholes model and the real-world ramifications reveal a pattern also visible in the global financial crisis. In 1993, a hedge fund management firm, called Long-Term Capital Management, was founded. The key people involved where Scholes and Merton. By 1998, the fund had approximately USD 5 billion in assets, controlled over USD 100 billion, and had positions, whose total worth was over a USD 1 trillion.[4] Then disaster struck. In a nutshell[5]:

> Scholes was also a co-founder of the hedge fund Long-Term Capital Management, which was initially extremely successful but later failed spectacularly, which led to a group of large banks bailing them out to prevent an averse reaction in the financial markets.

Today, financial mathematics is an established and active field of economic research (Voit 2005; Hull 2014). The insights from the study of stochastic processes also find their applications in physics, chemistry, and the natural sciences (Gardiner 1985).

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[2]In detail, Black, who was deceased by the time, was mentioned as a contributor and only Scholes and Merton were awarded.

[3]Data from the Web of Knowledge, an academic citation indexing service provided by Thomson Reuters, accessed February 23, 2018.

[4]Taken from https://www.investopedia.com/terms/l/longtermcapital.asp, accessed February 23, 2018.

[5]Taken from https://www.investopedia.com/terms/m/myron-scholes.asp, accessed February 23, 2018.

7.1.1.2 The Rise of the Quant

On the 19th of October 1993, the US House of Representatives voted 264 to 159 to reject further financing for a particle accelerator in Texas. The Superconducting Super Collider (SSC), for which two billion dollars had already been spent, was a mammoth project. Its planned ring circumference was 87.1 kms and the planned collision energy 40 TeV. These specifications dwarf the Large Hadron Collider (LHC) near Geneva in Switzerland, with a ring circumference of 27 kms and a collision energy of 13 TeV. Nonetheless, the LHC is currently the most complex experimental facility ever built, involving scientists from over 100 countries, and the largest single machine in the world.[6] As a technology spin-off, the Worldwide LHC Computing Grid emerged as the largest ever distributed computing grid.

Back in 1993, the SSC's estimated total costs threatened to spiral out of control. Pressured by budget saving, US President Bill Clinton signed a bill officially terminating the project. Like the flap of the mythical butterfly, this event would set out to change the course of finance—and the world—forever. In the words of Stephen Blyth, a professor at Harvard University, reminiscing about the past (Blyth 2014):

> This [the termination of the SSC] was not good news for two of my Harvard roommates, PhD students in theoretical physics. Seeing the academic job market for physicists collapsing around them, they both found employment at a large investment bank in New York in the nascent field of quantitative finance. It was their assertion that derivative markets, whatever in fact they were, seemed mathematically challenging that catalyzed my own move to Wall Street from an academic career.

The "quant" was born (Derman 2004), the quantitative analyst with a scientific background, very well-versed in the cabala of mathematics. As a result, the level of mathematical complexity exploded and financial tools became more abstract and removed from reality. Like a matryoshka doll, the layers of complexity are nested within each other—derivatives of derivatives of derivatives. A dangerous mixture was concocted, between the mathematical wizards and the applied practitioners (Salmon 2009):

> Their [the quants] managers, who made the actual calls [big asset-allocation decisions], lacked the math skills to understand what the models were doing or how they worked.

During the 2008 financial crisis, and the ensuing sovereign debt crisis, everything unraveled. It became painfully clear that ruling financial and economic elites had opened Pandora's box. In a general critique, the physicist and complexity researcher Dirk Helbing laments (quoted in Cho 2009):

> We spend billions of dollars trying to understand the origins of the universe, while we still don't understand the conditions for a stable society, a functioning economy, or peace.

Or more specifically, my observation that (quoted in Smith 2014):

> [...] basically we don't know how these [financial and economic] systems work. We created them, but really they have a life of their own.

[6] See https://home.cern/topics/large-hadron-collider.

The burning question remains: Why did no one predict this global cataclysmic event? It is truly remarkable, that the sum of all this intellectual prowess culminated in such a far-reaching disaster. In hindsight, there where many red flags being ignored.

7.1.2 The Global Financial Crisis

Perhaps the biggest threat to the emergence of adaptive, resilient, and sustainable financial systems is ideology. In the words of Alan Greenspan who served as Chairman of the US Federal Reserve from 1987 to 2006, during a hearing[7] before the Congressional Committee for Oversight and Government Reform about the financial crisis and the role of federal regulators on October 23, 2008:

> Well, remember, though, […] ideology […] is a conceptual framework with the way people deal with reality. Everyone has one. You have to. To exist, you need an ideology. The question is, whether it […] is accurate or not.

Greenspan, who championed the deregulation of the US banking system, concluded:

> What I am saying to you is, yes, I found a flaw. I don't know how significant or permanent it is, but I have been very distressed by that fact. […] I found a flaw in the model that I perceived is the critical functioning structure that defines how the world works, so to speak. […] I was shocked, because I had been going for 40 years or more with very considerable evidence that it was working exceptionally well.

An ideological commitment can tempt oneself to ignore red flags. In a summary by the economist and Nobel laureate Paul Krugman, taken from a *New York Times* article titled "How Did Economists Get It So Wrong" (Krugman 2009):

> They [economists] turned a blind eye to the limitations of human rationality that often lead to bubbles and busts; to the problems of institutions that run amok; to the imperfections of markets—especially financial markets—that can cause the economy's operating system to undergo sudden, unpredictable crashes; and to the dangers created when regulators don't believe in regulation.

Or more scathingly Krugman, quoted in The Economist (2009):

> The past 30 years of macroeconomics was spectacularly useless at best, and positively harmful at worst.

7.1.2.1 The Chicago School

Technically, what is commonly know as the Nobel prize for economics is in fact the Nobel Memorial Prize in economic sciences, established in 1968 by the Swedish National Bank in memory of Alfred Nobel. The creation of this award has received criticism. One notable objection was made by the economist Friedrich August von

[7] See https://www.gpo.gov/fdsys/pkg/CHRG-110hhrg55764/html/CHRG-110hhrg55764.htm.

Hayek, during his speech[8] at the Nobel Banquet, December 10, 1974, after his nomination for the prize:

> Now that the Nobel Memorial Prize for economic science has been created, one can only be profoundly grateful for having been selected as one of its joint recipients, and the economists certainly have every reason for being grateful to the Swedish Riksbank for regarding their subject as worthy of this high honour.
>
> Yet I must confess that if I had been consulted whether to establish a Nobel Prize in economics, I should have decidedly advised against it.
>
> [...] I do not yet feel equally reassured concerning my [...] cause of apprehension. It is that the Nobel Prize confers on an individual an authority which in economics no man ought to possess. This does not matter in the natural sciences. Here the influence exercised by an individual is chiefly an influence on his fellow experts; and they will soon cut him down to size if he exceeds his competence. But the influence of the economist that mainly matters is an influence over laymen: politicians, journalists, civil servants and the public generally. There is no reason why a man who has made a distinctive contribution to economic science should be omnicompetent on all problems of society—as the press tends to treat him till in the end he may himself be persuaded to believe.

These cautionary words of von Hayek would turn out to be prophetic. The University of Chicago has established itself as the leading authority of economic thought. The institution is associated with 29 economic Nobel laureates,[9] far more than any other institution. The "Chicago School" of economics is best known for advocating a particular brand of economic thought, namely the promotion of economic liberalism, intellectually backed by what is know as neoclassical economic theory. In general, government intervention is rejected in favor of allowing the free market and rational individuals to best allocate resources. In detail, neoclassical economics is an economic paradigm that relates supply and demand to an individual's rationality and her ability to maximize utility or profit, in an equilibrium state, where the market is guided by an "invisible hand" (Smith 1776). Neoclassical economics also utilizes heavy mathematical machinery to study various aspects of the economy. The theory is associated with concepts like the market-efficiency hypothesis from financial economics and the trickle-down effect from political economics.

The failure of most economists to foresee the financial crisis is not only a challenge to the economics profession as a whole, but especially to the Chicago School. Indeed, the crisis help deepen the intellectual trenches. In the words of Krugman (2009):

> And in the wake of the crisis, the fault lines in the economics profession have yawned wider than ever. Lucas [Robert Lucas from the University of Chicago] says the Obama administration's stimulus plans are "schlock economics," and his Chicago colleague John Cochrane says they're based on discredited "fairy tales." In response, Brad DeLong of the University of California, Berkeley, writes of the "intellectual collapse" of the Chicago School, and I myself have written that comments from Chicago economists are the product of a Dark Age of macroeconomics in which hard-won knowledge has been forgotten.

[8] See https://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/1974/hayek-speech.html.

[9] See https://www.uchicago.edu/about/accolades/22/.

Prompted by the crisis, some combatants have switched the trenches. For instance, Richard Posner, a University of Chicago economist and judge. In the last decades, the Chicago School economists were successful in displacing another school of economic thought called “Keynesianism.” John Maynard Keynes was an influential economist who died in 1946. While the Chicago School of thought is characterized by laissez-faire economics, in sharp contrast, Keynesian economics advocated that the best way to rescue an economy from a recession is for the government to borrow money and increase demand by infusing the economy with capital to spend. In this context “Richard A. Posner has shocked the Chicago School by joining the Keynesian revival” (Cassidy 2010a). Indeed (Cassidy 2010a):

> Earlier this year, Posner published “A Failure of Capitalism” in which he argues that lax monetary policy and deregulation helped bring on the current slump. “We are learning from it that we need a more active and intelligent government to keep our model of a capitalist economy from running off the rails,” Posner writes. “The movement to deregulate the financial industry went too far by exaggerating the resilience—the self-healing powers—of laissez-faire capitalism.”

Another critique of the Nobel Memorial Prize in economic sciences is motivated by the fact that it awarded the economist Milton Friedman for the 1976 prize in part for his work on monetarism. Friedman was accused of supporting the military dictatorship in Chile. Specifically, a group of Chilean economists, following their training as economists at the University of Chicago, most under Friedman, found in Augusto Pinochet’s regime an ideal breeding ground for the first radical free market strategy implementation in a developing country. The “Chicago Boys” enforced economic liberalization, including currency stabilization, removed tariff protections for local industry, banned trade unions, and privatized social security and hundreds of state-owned enterprises. The results of the implementation of these economic policies have been mixed and analyzed from opposing points of view. Friedman himself called it “the Miracle of Chile.” Others have been less enthusiastic, for instance (Petras and Vieux 1990). Specifically (Steger and Roy 2010, p. 100f.):

> During his [Pinochet] authoritarian rule, Chile’s economy stabilized in terms of inflation and GDP growth rate, but the middle and lower class lost ground as economic inequality increased dramatically. The country’s richest 10% benefited the most from the neoliberal reforms as their incomes almost doubled during the Pinochet years. To this day, Chile has remained one of the world’s 15 most unequal nations. The mixed economic results of the “neoliberal revolution” that swept the country from the 1970s to the 1990s continue to generate heated discussions among proponents and detractors of the Chicago School over the virtues of externally imposing free-market reforms.

7.1.2.2 The Crisis of Mathematics

The rise of the quant also played a crucial role in setting the stage for the disaster of the global financial crisis. Again (Krugman 2009):

> As I see it, the economics profession went astray because economists, as a group, mistook beauty, clad in impressive-looking mathematics, for truth.

For instance, the neoclassical economic model builds on equilibrium theory. In particular, the mathematical framework of the dynamic stochastic general equilibrium (DSGE) models which heavily influence macroeconomics and are actively used by central banks. They assume, by construction, a world which is always in equilibrium, governed by the aggregated behavior of a representative agent maximizing their utility. This paradigm has recently also been criticized by the Nobel laureate Joseph Stiglitz, in the context of the financial crisis (Stiglitz 2018):

> This paper provides a critique of the DSGE models that have come to dominate macroeconomics during the past quarter-century. It argues that at the heart of the failure were the wrong microfoundations, which failed to incorporate key aspects of economic behaviour, e.g. incorporating insights from information economics and behavioural economics. Inadequate modelling of the financial sector meant they were ill-suited for predicting or responding to a financial crisis; and a reliance on representative agent models meant they were ill-suited for analysing either the role of distribution in fluctuations and crises or the consequences of fluctuations on inequality.

Another prominent example of mathematics run amok, is an equation that, through its inappropriate application, helped create a market that turned out to be a castle in the air. In 2000, the mathematician David X. Li presented an equation to measure correlation between unrelated events (Li 2000). The Gaussian copula function was the heart of the theory

$$\Pr\left[T_A < 1, T_B < 1\right] = \Phi_2\left(\Phi^{-1}(F_A(1), \Phi^{-1}(F_B(1), \gamma)\right), \tag{7.2}$$

where F_A and F_B are the distribution functions for the survival times[10] T_A and T_B, Φ_2 is the bivariate accumulative normal distribution function, Φ^{-1} is the inverse of a univariate normal distribution function, and γ is the all-powerful correlation parameter, which reduces the otherwise intractable correlation to a single constant.

The elegant mathematical formula was used to model complex correlated risks. It became ubiquitous in finance and allowed for the supposed accurate pricing of a wide range of investments that were previously too complex. Armed with Li's formula, Wall Street's quants saw great new possibilities (Salmon 2009):

> With his brilliant spark of mathematical legerdemain, Li made it possible for traders to sell vast quantities of new securities, expanding financial markets to unimaginable levels.

At the heart of this new investment universe lurked the collateralized debt obligation (CDO), a type of structured asset-backed security. With Li's magic wand, the CDOs, originally developed for the dull corporate debt markets, could be greatly enhanced. Now, CDOs could potentially be correctly priced for investments that were previously unimaginable, such as mortgages and mortgage-backed securities. The market soared (Salmon 2009):

[10]The time until default.

> The CDS [credit default swap, effectively an insurance against non-payment] and CDO markets grew together, feeding on each other. At the end of 2001, there was $920 billion in credit default swaps outstanding. By the end of 2007, that number had skyrocketed to more than $62 trillion. The CDO market, which stood at $275 billion in 2000, grew to 4.7 trillion by 2006.

Another culprit, enabling the mushrooming chimera, were the ratings agencies. Motivated by the apparent certainty which Li's risk correlation number infused, new structured products were being assembled. One successful idea was to tranche CDO pools, now backed by subprime mortgages, to create triple-A rated securities. The ratings agencies were happy to do this, even if none of the components were themselves anything close to triple-A. For the agencies the conflict of interest is obvious: Don't bite the hand that feeds you. Indeed, the relationship is symbiotic (Taibbi 2013):

> […] banks needed them [ratings agencies] to sign off on the bogus math of the subprime era—the math that allowed banks to turn pools of home loans belonging to people so broke they couldn't even afford down payments into securities with higher credit ratings than corporations with billions of dollars in assets.

The rest is history. Once again, the flapping of a butterfly's wing set of a chain reaction of path-dependent chaos. Subprime lending fueled the housing bubble, the collapse of which lead to the global financial crisis and the ensuing sovereign debt crisis.

Looking back, one might ask oneself how no one could have predicted at least some negative fallout from those practices of Wall Street. Herd mentality can be a strong cognitive bias (Salmon 2009):

> And it [Gaussian copula] became so deeply entrenched—and was making people so much money—that warnings about its limitations were largely ignore.

Essentially, Li's equation assumed that correlation was a constant rather than something dynamic. An assumption that is actually correct most of the time. Only during rare extreme events, like financial crises, markets align and correlations soar (Salmon 2009):

> In hindsight, ignoring those warnings [that correlation is not a constant] looks foolhardy. But at the time, it was easy. Banks dismissed them, partly because the managers empowered to apply the brakes didn't understand the arguments between various arms of the quant universe. Besides, they were making too much money to stop.

Indeed, an unfortunate chain of command had been established, were mathematical prowess and financial acumen becam segregated (Salmon 2009):

> Another [reason] was that the quants, who should have been more aware of the copula's weaknesses, weren't the ones making the big asset-allocation decisions. Their managers, who made the actual calls, lacked the math skills to understand what the models were doing or how they worked.

And the ratings agencies? (Taibbi 2013):

> Why didn't rating agencies build in some cushion for this sensitivity to a house-price-depreciation scenario? Because if they had, they would have never rated a single mortgage-backed CDO.

Only years later, the following became publicly known (Taibbi 2013):

> Thanks to a mountain of evidence gathered for a pair of major lawsuits by the San Diego-based law firm Robbins Geller Rudman and Dowd, documents that for the most part have never been seen by the general public, we now know that the nation's two top ratings companies, Moody's and S&P, have for many years been shameless tools for the banks, willing to give just about anything a high rating in exchange for cash.

In closing (Salmon 2009):

> David X. Li, it's safe to say, won't be getting that Nobel anytime soon. One result of the collapse has been the end of financial economics as something to be celebrated rather than feared. And Li's Gaussian copula formula will go down in history as instrumental in causing the unfathomable losses that brought the world financial system to its knees.

It is fair to say that the mathematical complexity in finance and economics has reached a level where its relevance and meaning is hard to detect. This is similar to the Bogdanov affair in physics, an academic dispute about the relevance of publications in theoretical physics which appeared in reputable, peer-reviewed scientific journals. Some prominent physicists alleged that the contents was in fact just a meaningless combinations of buzzwords and fancy-looking equations. See Sect. 9.1.4 for details. Have finance, economics, and modern theoretical physics transformed into postmodern narratives which defy meaning and understanding, where mathematical incantation has become the sole justification? To illustrate the level of abstraction, the following two equations are extracted from two very different sources. One is a mathematical model describing the evolution of the volatility of an underlying asset, namely the price of an European option on a risky asset with stochastic volatility. The other is from string/M-theory, where "baryon number violation is discussed in gauge unified orbifold models of type II string theory with intersecting Dirichlet branes." But which is which? Is the following equation from theoretical physics?

$$
\begin{aligned}
a_H^{\phi,\psi}(u,v) = {} & \frac{1}{2}\int_\Omega y\frac{\partial u}{\partial x}\frac{\partial \overline{v}}{\partial x}\phi^2\psi^2 + \int_\Omega y\frac{\partial u}{\partial x}\overline{v}\left(\frac{\phi'}{\phi}\right)\phi^2\psi^2 + \frac{\sigma^2}{2}\int_\Omega y\frac{\partial u}{\partial y}\frac{\partial \overline{v}}{\partial y}\phi^2\psi^2 \\
& + \frac{\sigma^2}{2}\int_\Omega \frac{\partial u}{\partial y}\overline{v}\phi^2\psi^2 + \mu\sigma^2\int_\Omega y^2\frac{\partial u}{\partial y}\overline{v}\phi^2\psi^2 + 2\rho\sigma\int_\Omega y\frac{\partial u}{\partial y}\overline{v}\left(\frac{\phi'}{\phi}\right)\phi^2\psi^2 \\
& + \rho\sigma\int_\Omega y\frac{\partial u}{\partial y}\frac{\partial \overline{v}}{\partial x}\phi^2\psi^2 - \int_\Omega (\omega\rho\sigma y^2 - \frac{1}{2}y + r)\frac{\partial u}{\partial x}\overline{v}\phi^2\psi^2 \\
& - \int_\Omega [\omega\sigma^2 y^2 + \kappa(m-y)]\frac{\partial u}{\partial y}\overline{v}\phi^2\psi^2 \\
& - \int_\Omega \left[\frac{1}{2}\omega\sigma^2 y(\omega y^2+1) + \omega y\kappa(m-y) - r\right]u\overline{v}\phi^2\psi^2 .
\end{aligned} \tag{7.3}
$$

Or the next one?

$$
\begin{aligned}
S_{cl} &= \frac{1}{2\pi\alpha'}\int_C d^2z(\partial X\bar{\partial}\bar{X} + \bar{\partial}X\partial\bar{X}) \\
&\equiv \frac{1}{2\pi\alpha'}\int_C d^2z(|\partial X|^2 + |\bar{\partial}X|^2 = V_{11}|v_A|^2 + V_{22}|v_B|^2 + 2\Re(V_{12}v_A v_B^\star), \\
&\Bigg[4\pi V_{ii} = |b_a|^2\int_C d^2z|\omega_{\theta,\theta'}(z)|^2 + |c_a|^2\int_C d^2z|\omega_{1-\theta,1-\theta'}(z)|^2\ [i=1,2], \\
&4\pi V_{12} = b_1\bar{b}_2\int_C d^2z|\omega_{\theta,\theta'}(z)|^2 + c_1\bar{c}_2\int_C d^2z|\omega_{1-\theta,1-\theta'}(z)|^2\Bigg].
\end{aligned}
\tag{7.4}
$$

To the uninitiated, both equations appear to stem from the same esoteric source of hidden symbolism.[11]

Indeed, also the financial behemoths themselves have reached a level of inherent complexity obfuscating transparency and accountability. How else should the following headline be interpreted: "Bank of America Finds a Mistake: \$4 Billion Less Capital." In detail (Eavis and Corkery 2014):

> Bank of America disclosed on Monday that it had made a significant error in the way it calculates a crucial measure of its financial health, suffering another blow to its effort to shake its troubled history.
>
> The mistake, which had gone undetected for several years, led the bank to report recently that it had 4 billion more capital than it actually had.

7.1.2.3 Living in Denial

Returning to the failure of economics in 2008, Lord Adair Turner, then head of the U.K. financial services authority, observed (quoted in Farmer et al. 2012):

> But there is also a strong belief, which I share, that bad or rather over-simplistic and over-confident economics helped create the crisis. There was a dominant conventional wisdom that markets were always rational and self-equilibrating, that market completion by itself could ensure economic efficiency and stability, and that financial innovation and increased trading activity were therefore axiomatically beneficial.

In the same vein, a quote by Jean-Claude Trichet, then Governor of the European Central Bank, in November 2010 (quoted in Farmer et al. 2012):

> When the crisis came, the serious limitations of existing economic and financial models immediately became apparent. Macro models failed to predict the crisis and seemed incapable of explaining what was happening to the economy in a convincing manner. As a policy-maker during the crisis, I found the available models of limited help. In fact, I would go further: in the face of the crisis, we felt abandoned by conventional tools.

These last two quotes can be read as a critique of neoclassical economics. Furthermore, in the words of Krugman (2009):

---

[11] Equation (7.3) is taken from the finance paper (Canale et al. 2017) and (7.4) is from a quantum gravity approach employing higher-dimensional extended D-branes (Chemtob 2007).

> In short, the belief in efficient financial markets blinded many if not most economists to the emergence of the biggest financial bubble in history. And efficient-market theory also played a significant role in inflating that bubble in the first place.

Eugene Fama, an economist of the University of Chicago, Nobel laureate, and the father of the efficient-market hypothesis (Fama 1970) asserted in the aftermath of the financial crisis (quoted in Cassidy 2010b):

> I don't know what a credit bubble means. I don't even know what a bubble means. These words have become popular. I don't think they have any meaning.

Indeed, when ideology turns to dogma, all discourse threatens to plummet to a level of pure subjectivity. When quizzed about Krugman's critique and Posner's intellectual betrayal, Fama commented (quoted in Cassidy 2010a):

> If you are getting attacked by Krugman, you must be doing something right.
>
> He's [Posner] not an economist. He's an expert on law and economics.

The apparent denial and obliviousness of proponents of the Chicago School to the reality of the crisis has been observed by other commentators, such as the physicist and author Mark Buchanan. He reports (Buchanan 2009):

> In an essay in *The Economist*, Robert Lucas, one of the key figures behind the present neo-classical theory of macroeconomic systems, even argued that the tumultuous events of the recent crisis can be taken as further evidence supporting the efficient-markets hypothesis of neo-classical theory, despite the fact that it disputes the possible existence of financial bubbles.

When Fama was asked how his theory of efficient markets had fared in the crisis, he replied (quoted in Cassidy 2010a):

> I think it did quite well in this episode.

Indeed, the true culprit is easily found for him (Cassidy 2010a):

> In addition to accusing the government of causing the subprime problem, Fama argues that it botched its handling of last fall's financial crisis. Rather than bailing out A.I.G., Citigroup, and other firms, Fama says, the Treasury Department and the Federal Reserve should have allowed them to go bankrupt. "Let them all fail," he said, with another laugh.

The Chicago School economist John Cochrane, attacked by Krugman in (2009), defended his position in detail in an article called "How Did Paul Krugman Get It So Wrong?" (Cochrane 2011). To him, the whole fuss is due to the following assertions (Cochrane 2011):

> If a scientist, he [Krugman] might be an AIDS-HIV disbeliever, a creationist or a stalwart that maybe continents do not move after all. […] The only explanation that makes sense to me is that Krugman isn't trying to be an economist: he is trying to be a partisan, political opinion writer.

Bringing the discussion back to are more objective level, the authoritative magazine *The Economist*, known for its economic liberalism, observed the following. Setting the stage (The Economist 2009):

> Of all the economic bubbles that have been pricked, few have burst more spectacularly than the reputation of economics itself. […] In the public mind an arrogant profession has been humbled.

However (The Economist 2009):

> In its crudest form—the idea that economics as a whole is discredited—the current backlash has gone far too far. […] two central parts of the discipline—macroeconomics and financial economics—are now, rightly, being severely re-examined. There are three main critiques: that macro and financial economists helped cause the crisis, that they failed to spot it, and that they have no idea how to fix it.

In detail (The Economist 2009):

> The first charge is half right. Macroeconomists, especially within central banks, were too fixated on taming inflation and too cavalier about asset bubbles. Financial economists, meanwhile, formalised theories of the efficiency of markets, fuelling the notion that markets would regulate themselves and financial innovation was always beneficial. Wall Street's most esoteric instruments were built on these ideas.
>
> But economists were hardly naive believers in market efficiency. Financial academics have spent much of the past 30 years poking holes in the "efficient market hypothesis". A recent ranking of academic economists was topped by Joseph Stiglitz and Andrei Shleifer, two prominent hole-pokers.
>
> […]
>
> The charge that most economists failed to see the crisis coming also has merit. To be sure, some warned of trouble. The likes of Robert Shiller of Yale, Nouriel Roubini of New York University and the team at the Bank for International Settlements are now famous for their prescience. But most were blindsided.
>
> […]
>
> What about trying to fix it? Here the financial crisis has blown apart the fragile consensus between [neoclassical] purists and Keynesians that monetary policy was the best way to smooth the business cycle.
>
> Keynesians, such as Mr Krugman, have become uncritical supporters of fiscal stimulus. Purists are vocal opponents. To outsiders, the cacophony underlines the profession's uselessness.

The article concludes (The Economist 2009):

> Add these criticisms together and there is a clear case for reinvention, especially in macroeconomics. […]
>
> But a broader change in mindset is still needed. Economists need to reach out from their specialised silos: macroeconomists must understand finance, and finance professors need to think harder about the context within which markets work. And everybody needs to work harder on understanding asset bubbles and what happens when they burst. For in the end economists are social scientists, trying to understand the real world. And the financial crisis has changed that world.

Entrenched ideologies do not only plague sociopolitical intellectual thought systems. Even the hard sciences suffer from dogmatic world views. Planck gloomily observed in his autobiography (Planck 1950, pp. 33f.):

> A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.

See also Sect. 9.1.3 on Kuhnian paradigm changes.

But perhaps things are not as bleak as one might think. For instance, forgotten knowledge is reemerging. The crash of 2008 has also been dubbed as the "Minsky Moment," because Hyman Minsky's financial instability hypothesis is widely regarded as having predicted the crisis (Minsky 1992). See also Minsky (2016). In addition, more heterodox ideas are receiving attention from some notable economists (Reinhart and Rogoff 2009; Akerlof and Shiller 2010).

7.2 A Call to Arms

Neoclassical economics has been attacked from many angles in the past decades. Philosophers criticized the whole enterprise as being pseudo-scientific (Latsis 1972), based on the demarcation offered by Imre Lakatos's philosophy of science (Musgrave and Pigden 2016). However, of all the potential design flaws of neoclassical economics—its concepts which are only relevant when all or many strict assumptions hold, the focus on isolated agents, the omission of evolutionary or adaptive dynamics, the exclusion of feedback loops, etc.—one practice is particularly troubling. It is the disregard of empirical data. In other words, the ideas of neoclassical economics transcend any empirical data. This is in stark contrast to a foundational guideline principle in science: "Let the data speak!" The physicist and pioneer of econophysics,[12] Jean-Philippe Bouchaud, has offered continued empirical evidence challenging the neoclassical paradigm and narrative. For instance, the insights that real-world markets are affected by feedback loops and can exhibit endogenous shocks, i.e., destabilize themselves without any external trigger (Bouchaud 2011). Bouchaud summarizes (Bouchaud 2008):

> To me, the crucial difference between physical sciences and economics or financial mathematics is rather the relative role of concepts, equations and empirical data. Classical economics is built on very strong assumptions that quickly become axioms: the rationality of economic agents, the invisible hand and market efficiency, etc. An economist once told me, to my bewilderment: *These concepts are so strong that they supersede any empirical observation*. As Robert Nelson argued in his book, *Economics as Religion*, the marketplace has been deified.

Mathematics without any empirical anchoring will always remain in the Platonic realm of abstractions lacking any real-world application. It does not suffice to math-

[12] The mutual fertilization of physics and economics (Gallegati et al. 2006; McCauley 2006; Sornette 2014), going back to the first observation of heavy tails in financial time series (Mandelbrot 1963a).

ematicize a theory to automatically render it a faithful description of reality. Just by proclaiming the following, no insights are guaranteed (a quote from Chicago School's Robert Lucas from Labini 2016, p. 63):

> Economic theory is mathematical analysis. Everything else is just talk and pictures.

It is astounding how far mathematical economics has ventured from any empirical rooting (Labini 2016, p. 64):

> The most famous work of Samuelson [Nobel laureate Paul Samuelson] is one of the classics of mathematical economics, *"Foundations of Economic Analysis"*. [...] Samuelson, in his book over 400 pages full of mathematical formulas, does not derive a single result that can be compared with observed data. There is even no mention of any empirical data in the book of Samuelson!

So then (Labini 2016, p. 64):

> In conclusion, neoclassical economics, unlike physics, has not achieved either precise explanations or successful predictions through the use of mathematics. Thus, this is the main difference between neoclassical economics and physics.

As a result (Bouchaud 2008):

> Compared to physics, it seems fair to say that the quantitative success of the economic sciences is disappointing.

7.2.1 Embracing Complexity

One key proposition of Part I of this book has been the categorization of human knowledge generation into the two paradigms of the fundamental-analytical and complex-algorithmic dichotomies (see Chap. 5, especially Sect. 5.4). In this context, even if one does tie the mathematical machinery of finance and economics to empirical data, the results are expected to be modest. In essence, we should not search for the understanding of finance and economics in Volume I of the Book of Nature (i.e., the fundamental-analytical paradigm). Indeed, people have started to flip through Volume II for answers (in the complex-algorithmic paradigm). In a nutshell, we do not need the physics of economics but rather, complexity economics.

Some notable complexity researches published an article, titled "Economic Networks: The New Challenges," in the prestigious journal *Science*. They observed (Schweitzer et al. 2009):

> The current economic crisis illustrates a critical need for new and fundamental understanding of the structure and dynamics of economic networks. Economic systems are increasingly built on interdependencies, implemented through trans-national credit and investment networks, trade relations, or supply chains that have proven difficult to predict and control. We need, therefore, an approach that stresses the systemic complexity of economic networks and that can be used to revise and extend established paradigms in economic theory. This will facilitate the design of policies that reduce conflicts between individual interests and global efficiency, as well as reduce the risk of global failure by making economic networks more robust.

The authors conclude (Schweitzer et al. 2009):

> In summary, we anticipate a challenging research agenda in economic networks, built upon a methodology that strives to capture the rich process resulting from the interplay between agents' behavior and the dynamic interactions among them.

Indeed (Catanzaro and Buchanan 2013):

> Our developing scientific understanding of complex networks is being usefully applied in a wide set of financial systems. What we've learned from the 2008 crisis could be the basis of better management of the economy—and a means to avert future disaster.

The invitation to embrace complexity thinking has also been extended to financial economics in a joint publication by complexity researchers, financial practitioners, and economists, including Stiglitz (Battiston et al. 2013):

> The intrinsic complexity of the financial derivatives market has emerged as both an incentive to engage in it, and a key source of its inherent instability. Regulators now faced with the challenge of taming this beast may find inspiration in the budding science of complex systems.

This call to arms has also been made by financial supervisors, regulators, and policymakers. The International Monetary Fund (IMF), in collaboration with the Institute for New Economic Thinking (INET), and the Deutsche Bundesbank hosted a two-day conference on financial networks.[13] In summary, "financial networks [are] key to understanding systemic risk" and in detail (Minoiu and Sharma 2014):

> With financial markets around the world so interconnected, the analysis of "networks" in the financial system would help deepen understanding of systemic risk and is key to preventing future financial crises, say leading researchers and policymakers at a conference on Interconnectedness: Building Bridges between Research and Policy.

Furthermore, European Central Bank Governor Trichet mused (quoted in Farmer et al. 2012):

> [...] we need to develop complementary tools to improve the robustness of our overall framework. In this context, I would very much welcome inspiration from other disciplines: physics, engineering, psychology, biology. Bringing experts from these fields together with economists and central bankers is potentially very creative and valuable. Scientists have developed sophisticated tools for analysing complex dynamic systems in a rigorous way. These models have proved helpful in understanding many important but complex phenomena: epidemics, weather patterns, crowd psychology, magnetic fields.

Finally, Andy Haldane, executive director of financial stability at the Bank of England also weighed in. In an article, aptly titled "To Navigate Economic Storms We Need Better Forecasting," he pointed out (Haldane 2011):

> Finance is a classic complex, adaptive system, similar to an ecosystem. The growth in its scale, complexity and adaptation in the past generation alone would rival that of most other complex systems in the past century. […]
>
> Yet this dense cat's cradle of finance has been woven largely out of sight. At best we are able to snatch passing glimpses of it, for data are incomplete, local and lagging. Making sense of the financial system is more an act of archaeology than futurology.

[13] See http://www.imf.org/external/np/seminars/eng/2014/interconnect/index.htm.

> How so? Because, at least historically, finance has not thought of itself as a system. Instead, financial theory, regulation and data-collection has tended to focus on individual firms. Joining the dots was in no one's job description.
>
> Theorists were partly to blame. Economics has always been desperate to burnish its scientific credentials and this meant grounding it in the decisions of individual people. By itself, that was not the mistake. The mistake came in thinking the behaviour of the system was just an aggregated version of the behaviour of the individual. Almost by definition, complex systems do not behave like this.
>
> Interactions between agents are what matters. And the key to that is to explore the underlying architecture of the network, not the behaviour of any one node. To make an analogy, you cannot understand the brain by focusing on a neuron - and then simply multiplying by 100 billion.

On a personal note, the article the last quote was taken from was prompted by a study I co-authored. The publication was an empirical analysis of the global corporate ownership network (Vitali et al. 2011 and Sect. 7.3.2.1). The research was reported on by the science magazine *New Scientist* (Coghlan and MacKenzie 2011). The article quickly went viral.[14] Two reasons can perhaps explain the wide dissemination and interest. First, the study can be understood as an early comprehensive application of the paradigms of complex systems to economics. Based on data and algorithms, it appeared in a vacuum which stood in stark contrast to the paradigms of neoclassical economics. Second, the article appeared in the very week that the Occupy Wall Street protests became an international phenomenon. *New Scientist* placed the following headline on the front cover of that issue (Coghlan and MacKenzie 2011):

> Exclusive: The network that runs the world
>
> Mathematics reveals the reality behind the anti-capitalist protests

The article itself was titles "Revealed—the capitalist network that runs the world." Negative ramifications soon followed. Some pundits did not believe in the value of applying insights from complex systems in an economic context.[15] Then people who are mesmerized by conspiracy theories understood our study as the unmasking of a global elite—the elusive and all-powerful puppet-masters controlling our very lives.[16] Finally, many people believed that our study was politically motivated, following some agenda, and not a data-driven scientific analysis of a real-world complex economic network. Therefore our study was placed into the realm of belief systems and exposed to ugly political fervor. To give an unsavory example of the depth of the ideological trenches involved, the following e-mail was sent to *New Scientist* in response to their coverage of our research:

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[14]According to the publisher's number of website visits and the ensuing global news coverage. See http://journals.plos.org/plosone/article/comments?id=10.1371/journal.pone.0025995 and https://www.sg.ethz.ch/research/response-media/#pub-208-more-.

[15]See my blog post http://j-node.blogspot.ch/2011/08/network-of-global-corporate-control.html.

[16]Mostly the Illuminati were invoked. See also Appendix F in Glattfelder (2013).

> From: FUCKYOU@COMMIESCUM.COM
> Sent: 24 October 2011 17:58
> To: New Scientist Letters (RBI-UK)
> Subject: Contact Us
> Name: YOU FUCKING COMMIE SCUM
> Country: USA
>
> Message: I HOPE YOU FUCKERS GET TORTURED TO DEATH AFTER YOUR CHILDREN ARE KILLED IN FRONT OF YOU.

On a brighter note, things appear to be slowly changing. More economists are beginning to adopt ideas from complexity economics. Specifically, the relevance of focusing on the analysis of empirical data from a network perspective is recognized, requiring researchers from different fields to join forces. Such interdisciplinary research usually does not find its way into economics journals. However, a recent publication—replicating our study (Vitali et al. 2011) with a different data set and confirming the level of concentration of control in 2007—appeared in the economics journal called *Structural Change and Economic Dynamics* (Brancaccio et al. 2018). The authors also analyze the centralization of control between 2001 and 2016, observing an increase, especially after 2007. Such research also helps uncover blind spots in the orthodox economic thinking, where certain topics are deemed less relevant. For instance, the very notion of power has, interestingly, not received much attention from economists (Glattfelder and Battiston 2019). Moreover, the whole idea of capital centralization (in the sense of ownership and control concentration) has also "never been a very popular subject in the academic literature" (Brancaccio et al. 2018). Indeed (Brancaccio et al. 2018):

> [...] the existence or not of a global tendency of capital to centralize in a few hands, and the related complex structural economic dynamics that may imply, remain an unresolved mystery.

Until now. By inspecting the temporal dynamics of the global ownership network, an increase in global centralization of capital is observed. In summary (Brancaccio et al. 2018):

> In the early years of the 21st century, especially since the 2007 crisis, Marx's thesis of a global tendency towards the centralization of capital seems to find an empirical confirmation.

This is the risk one takes, if one "let's the data speak." Unfashionable ideas, as seen through a particular predominant ideological lens, can suddenly reemerge with empirical backing. In the case at hand (Marx 1867, 1894; Leontief 1938).

7.2.2 *Reforming Finance and Economics*

Analyzing finance and economics with the tools from complexity theory is only a first step. An ideological reform is called for. Specifically, my proclamation that (Glattfelder 2011):

> Ideas relating to finance, economics, politics, society, are very often tainted by people's personal ideologies. I really hope that this complexity perspective allows for some common ground to be found. It would be really great if it has the power to help end the gridlock created by conflicting ideas, which appears to be paralyzing our globalized world. Reality is so complex, we need to move away from dogma.

There have been many propositions put forward, aimed at fixing the state of economics. One has been to admitting that there is actually a problem and calling for a pluralism in economic teaching and thinking. In other words, allowing for heterodox economic theories. For instance, over 65 associations of economics students from over 30 different countries have written an open letter[17] laying out this vision.

Another psychological step away from ideological entrenchment is admitting that there is no "silver bullet." An open-minded and pragmatic approach is called for. In the words of the economist Tim Harford (Harford 2011):

> I'm not trying to say we can't solve complicated problems in a complicated world. But the way we solve them is with humility and to actually use a problem-solving technique that works. Now you show me a successful complex system, and I will show you a system that has evolved through trial and error.

Intellectual myopia is perhaps the biggest challenge in our post-truth era, where everyone is certain their own ideas are correct and all other challenging ones are wrong. In this context, open-mindedness and and a self-critical analysis of one's own beliefs could be the magic cure.

Another major challenge for the still-prevailing paradigm in economics lies in its blind spot: externalities. "An externality is a consequence of an economic activity experienced by unrelated third parties.[18]" The epitome of a negative externality is the failure to factor in ecological constraints into economic thinking. In other words, as long as clean air and water, glaciers and polar caps, forests, biodiversity, etc. do note have a price tag, economic activity will not value them. By not pricing ecological externalities, no incentives preventing irrational behavior are given and no innovation is fostered. It becomes economically viable to extract resources at one end of the world, which, after being shipped to other parts of the world for consumption, are disposed off at yet another location on the globe. For a planet with finite resources, such a linear system spells doom sooner or later, as extraction becomes exploitation and disposal results in pollution (discussed in the Epilogue). Factoring in externalities explicitly means incorporating a complex systems point of view, as this translates into holistic systems thinking explicitly identifying feedback loops.

However, the best way to herald the start of complexity economics would be to present a successful application. Perhaps an obvious implementation is the forecasting of economic turbulences. This vision is outlined in Haldane's article mentioned above, titled "To Navigate Economic Storms We Need Better Forecasting" (Haldane 2011):

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[17] See http://www.isipe.net/open-letter/.

[18] Taken from https://www.investopedia.com/terms/e/externality.asp, accessed February 20, 2018.

> It [a real-time map of financial flows] would allow regulators to issue the equivalent of weather-warnings—storms brewing over Lehman Brothers, credit default swaps and Greece. It would enable advice to be issued—keep a safe distance from Bear Stearns, sub-prime mortgages and Icelandic banks. And it would enable "what-if" simulations to be run—if UK bank Northern Rock is the first domino, what will be the next?

This, however, can only be achieved with data-driven interdisciplinary research, embracing complex networks. Such an approach to finance and economics has the power to comprehensively assess the true state of the system. Complexity thinking can uncover hidden features and patterns of organization which would otherwise go undetected. Especially the mitigation of systemic risk is, by definition, in the domain of complex networks. Its application is an invitation to move away from too-big-to-fail thinking of agents in isolation to a network of interdependence (see Sect. 7.3.2.1). Such a shift can offer crucial information to policy makers (Glattfelder 2016).

7.3 Complexity Finance and Economics

The shift away from analyzing the structure of "things" towards analyzing their patterns of interaction represents a true paradigm shift, and one that has impacted computer science, biology, physics, and sociology. The need to bring about such a shift in the realm of finance and economics was highlighted in the last section. Unfortunately, there exists another major challenge next to the prevailing prohibitive mindset: an unfortunate lack of data in these fields. Whereas the study of complex systems in other domains are affected by data deluge, there is an ironic scarcity of data coming from our countless financial and economic interactions. A lot of the much-wanted data is either proprietary and hence not available from commercial institutions or it is too sensitive to be disclosed by regulatory bodies. Nonetheless, complexity science has slowly been successfully applied to financial and economic systems. In essence, the paradigm shift is characterized by the following elements:

- empirical focus;
- data science;
- algorithm-driven methodology;
- computer simulations;
- decentralized architectures;
- interdisciplinary research;
- a plurality of ideas.

Moreover, at the heart of this approach lie agent-based models and complex network analysis.

7.3.1 Multi-Agent Systems

Agent-based models are prototypical in the complex systems paradigm of decoding nature and human collective behavior (Axelrod 1997; Weiss 1999; Bonabeau 2002; Šalamon 2011; Helbing 2012). They represent a bottom-up approach incorporating the main insight from complexity thinking: the richness of structures comes from the simple rules of interaction of agents (see Sects. 5.2.1 and 5.2.2). Elementary and early examples are cellular automata (see Sect. 5.2.2). In a general context, agent-based models are composed of

- agents (specified at a level of granularity);
- decision-making heuristics and learning rules;
- non-linear interaction topology;
- external conditions;

and are typically implemented as computer simulations. They describe the micro-level interactions leading to the emergence of structure and organization at the macro level. From a conceptual point of view, structural information (represented by the data) is transformed by functional information (representing the algorithm) into pragmatic information, telling the agents how to operate in a specific context (Ebeling et al. 1998).

The most basic setting, where featureless agents interact with each other, can be enhanced. For one, the agents can be allowed to have internal states, where they can store energy and information (Schweitzer 2003). Furthermore, some agent-based models do not require that all the agents interact directly and have complete information about the system. In such settings, an efficient simulation setup has to only process the information to simulate the agents' local and short-time behavior. One technical solution is the blackboard architecture, a fundamental programming paradigm of early artificial intelligence research (Engelmore and Morgan 1988). In essence, the system evolves via the agents writing, reading, and processing information on a centralized "blackboard." A modern variation of this mechanism is the idea of an adaptive landscape (Schweitzer 2003). Every action of each agent changes the state of the adaptive landscape (locally or globally). In turn, the changes in the landscape affect the actions of other agents. A non-linear feedback loop, between the individual and collective behavior, emerges.

An agent-based approach to finance and economics can be understood as the first attempt to apply complexity theory in those fields (Sornette 2014). In essence, these domains are modeled as complex adaptive systems, comprised of interacting autonomous agents (Tesfatsion 2003; LeBaron 2006; Miller et al. 2008). Now, the world has come alive as a dynamic systems of interacting agents. This is the polar opposite of the DSGE models of neoclassical economics, deploying an aggregation of a single representative agent optimizing its utility. Agent-based computational economics replaces the theoretical assumption of a mathematical optimization by these agents in equilibrium by a less restrictive postulate of agents with bounded rationality (Simon 1982) adapting to market forces. In essence, bounded rationality implies that individuals make decisions with limited rationality, due to cognitive limitations, the restricted time to make the decision, and the tractability of the decision problem. In summary, in the words of Trichet (quoted in Sornette 2014):

> First, we have to think about how to characterize the homo economicus at the heart of any model. The atomistic, optimizing agents underlying existing models do not capture behavior during a crisis period. We need to deal better with heterogeneity across agents and the interaction among those heterogeneous agents. We need to entertain alternative motivations for economic choices. Behavioral economics draws on psychology to explain decisions made in crisis circumstances. Agent-based modeling dispenses with the optimization assumption and allows for more complex interactions between agents.

7.3.1.1 ...Of Financial Markets

Financial markets are particularly well suited for agent-based explorations, as they represent a coherent framework for understanding the complexity. Moreover, financial data are generally plentiful, accurate, and readily available. In a nutshell (LeBaron 2006):

> Financial markets are an important challenge for agent-based computational modelers. Financial markets may be one of the important early areas where agent-based methods show their worth, for two basic reasons. First, the area has many open questions that more standard modeling approaches have not been able to resolve. Second there is a large amount of financial data available for testing.

Many agent-based models of financial markets have been proposed (LeBaron 2006; Samanidou et al. 2007). One of the earliest ones analyzed market instability in the wake of the 1987 financial crisis (Kim and Markowitz 1989). Another agent-based model was inspired by a challenge in game theory, called the El Farol Bar problem. It "was inspired by the bar El Farol in Santa Fe which offers Irish music on Thursday nights" (Arthur 1994). Consider 100 people deciding independently each week whether to go to a bar on a certain night. The bar is quite small, and it is no fun to go there if it's too crowded. Every person decides to visit the bar if he or she expects fewer than 60 people to show up. Otherwise the person stays at home. Everyone has to decide at the same time whether they will go to the bar or not. This game-theoretic problem has a famous representation as an agent-based model, called the Minority Game (Challet and Zhang 1997). The model has been applied to financial markets and reflects the competition among a finite number of agents over a resource. In particular, the inductive reasoning implied by the Minority Game leads to a system of many interacting and heterogeneous degrees of freedom, resulting in complex dynamics.

In the context of the scaling properties observed in financial markets (see Sect. 6.4.1), a multi-agent model was proposed which could replicate those universal features. The model incorporates the idea that scaling arises from the mutual interplay of market participants (Lux and Marchesi 1999, 2000). In detail, the scaling properties are generated by the interaction of economic agents with heterogeneous beliefs and strategies in the simulated market. The Lux-Marchesi model was inspired by the study of herd behavior in ant colonies and applications of statistical mechanics to sociology and political sciences (Samanidou et al. 2007).

Another agent-based model, proposed to decode the dynamics of financial markets, is the Cont-Bouchaud model (Cont and Bouchaud 2000). It is a simple model, having only a few free parameters, contrasting the "terribly complicated" Lux-Marchesi model. The traders are quite unsophisticated and exhibit herding behavior, where buyers and sellers group into larger dependent sets, which then move together. The model can reproduce many stylized facts of financial markets: volatility clustering, positive correlations between trading volume and price fluctuations, as well as a power-law distribution of stock price variations. For details, see also Stauffer (2001).

In Andersen and Sornette (2005) another agent-based model was introduced, based on the Minority game on time series of financial returns. It was one of the first models to establish the existence of "pockets of predictability" in stock markets. In other words, the return predictability is a localized phenomenon, in which short periods with significant predictability (the "pockets") appear in otherwise long periods with little or no evidence of return predictability. In contrast, an efficient market is one in which price changes are completely random and unpredictable all the time. In the model the collective organization of agents and of their strategies is the driver of predictability in the market. Namely, transient herding phases in the population of agents leads to the emergence of the pockets of predictability.

7.3.2 Network Thinking

The historical and empirical roots of complex network theory can be found in sociology, as described in Sect. 5.2.3. So, too, the first people to apply network thinking to economics were sociologists. One central theme is that of social capital (Coleman 1990; Burt 1992; Putnam 1993). It is a form of economic capital in which social networks are central and where transactions are motivated by reciprocity, trust, and cooperation. Specifically (Burt 2001):

> Social capital is the contextual complement to human capital. The social capital metaphor is that the people who do better are somehow better connected. Certain people or certain groups are connected to certain others, trusting certain others, obligated to support certain others, dependent on exchange with certain others. Holding a certain position in the structure of these exchanges can be an asset in its own right.

Implicit in this reasoning is the idea of network centrality, where the specific location in the network can bestow a node with added relevance.

In this networked context, the notion of "structural holes" emerges (Burt 1992). A structural hole is understood as a conceptual gap between nodes in the network which have complementary access to information. The notion is similar to the "strength of weak ties" (recall Sect. 5.2.3). "The structural hole argument is that social capital is created by a network in which people can broker connections between otherwise disconnected segments" (Burt 2001), leading to the emergence of the gatekeeper nodes, relaying valuable information between groups. From such networks of interaction a model of the economy can be derived (White 2002). These network-based approaches are empirically motivated and stand in stark contrast to the paradigms of neoclassical economics.

Since the turn of the millennium, the study of complex economic networks has started to gain popularity. For instance, witnessed by the research on

- diffusion of innovation (Schilling and Phelps 2007; König et al. 2009);
- trade relations (Serrano and Boguñá 2003; Garlaschelli and Loffredo 2004a, b; Reichardt and White 2007; Fagiolo et al. 2008, 2009);
- shared board directors (Strogatz 2001; Battiston and Catanzaro 2004);
- similarity of products (Hidalgo et al. 2007);
- credit relations (Boss et al. 2004; Iori et al. 2008);
- price correlation (Bonanno et al. 2003; Onnela et al. 2003);
- corporate ownership structures (Glattfelder and Battiston 2009, 2019; Vitali et al. 2011; Glattfelder 2013, 2016; Garcia-Bernardo et al. 2017; Fichtner et al. 2017).

In the following, the study of corporate ownership networks will be introduced—a field of complexity science which saw its coming of age in the wake of the financial crisis (Glattfelder and Battiston 2009, 2019; Vitali et al. 2011; Coghlan and MacKenzie 2011; Haldane 2011; Battiston et al. 2012).

7.3.2.1 Ownership Networks

A corporation is a legal entity having its own privileges, similar to a natural person. Corporations have limited liability, can sue, borrow or lend money, buy and sell shares, and takeover and merge with other corporations. From its business activities the corporation strives to generate profits. The money required for new investments can come from two external sources. First, debt is sold in the form of bonds to investors or financial institutions. Second, shares of stock can be issued. The stock represents the original capital invested into the business by its founders and serves as a security. It is also referred to as equity securities, or equity for short. The entities owning shares in the stock of a company are called stockholders, or, synonymously, shareholders. An ownership relation represents the percentage of ownership a shareholder has in the firm's equity capital. Each shareholder potentially has the right to a fraction of the firm's revenue (in the form of dividends) and to a voice in the decision making process (meaning voting rights at the shareholder meetings). Hence, a percentage of ownership in the equity capital can yield cash-flow rights and voting rights. All shareholders collectively owning a company have complete control over its strategic business decisions and financial strategies. Next to voting, this control can also be exerted by appointing the board of directors, which in turn elects the senior management.

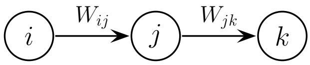
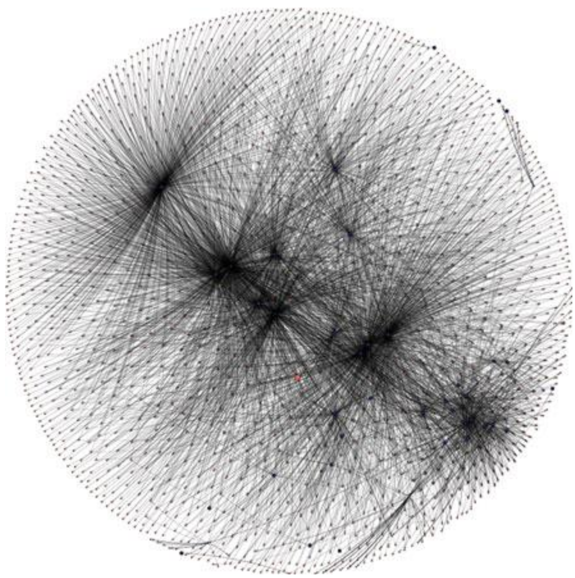


Fig. 7.1 A simple chain of ownership relations. Shareholder i owns W_{ij} percent of company j, which in turn holds W_{jk} percent of company k

In a network context, ownership relations are encoded in the adjacency matrix W describing the network topology (recall Sect. 6.3.2). Thus, for the case where $W_{ij} > 0$, shareholder i owns W_{ij} percent of company j, establishing an ownership link, seen in Fig. 7.1. An ownership network is comprised of various economic actors, including natural persons, families, foundations, research institutes, public authorities, states, and government agencies. However, as shares can only be issued by companies, all other economic actors only have outgoing links (i.e., they cannot be owned). As a result, the connectivity of the network is given by companies holding shares in each other, also called cross-shareholdings. See Fig. 7.2 for an example.

Ownership networks have been studied in different contexts. Pioneering work analyzed the impact of globalization forces (Kogut and Walker 2001) and corporate governance reforms (Corrado and Zollo 2006) over time on the network topology of countries and found that there was an unexpected resilient structure of powerful agents which was unaffected by these external forces. Other work, utilizing a Level 3 type analysis—incorporating weighted and directed links and the value of corporations (proxied by operating revenue), see Sect. 6.3.2—focused on a cross-country analysis. Contrary to textbook belief, it was revealed that in markets with many widely held corporations (mostly in Anglo-Saxon countries), this local distribution

Fig. 7.2 Ownership network layout. The example shows the backbone (Glattfelder and Battiston 2009) of the Japanese stock-market



of ownership actually goes hand in hand with a global concentration of ownership (and control) lying in the hands of few powerful shareholders, only visible from the bird's-eye view given by the network perspective (Glattfelder and Battiston 2009). Finally, the 3-level analysis of the global ownership network revealed the following (Vitali et al. 2011; Glattfelder and Battiston 2019). The network has a hierarchical structure with a tiny, highly interconnected core comprised of the most powerful corporations. In essence, the global ownership network displays fractal properties and by zooming into its fabric one finds a hierarchy of nested substructures and an ultimate distillate of shareholder power: a tiny cabal of mostly financial institutions and asset managers, seen in Fig. 7.3. Furthermore, the overall distribution of (direct and indirect) economic power (in the sense of control or influence) is highly skewed. Effectively, this power is much more unequally distributed than income or wealth.

Such findings have raised eyebrows in the economics community. Especially, as the notion of shareholder power of financial institutions and asset managers was contested at the time. Such corporations were seen as passive owners with no incentives to confront the companies they owned with any form of shareholder activism. Today, the tides are starting to turn (Hill and Thomas 2015):

> Entering the twenty-first century we also enter ongoing debates [about shareholder power], with new developments [...] whose full implications are still working themselves out. [T]his latest iteration of shareholder activism appeared to have genuinely changed the dynamics of shareholder power. [P. 27]
>
> [P]urely passive funds are on a path to owning a majority of US public equity. One result of this trend is likely to be increasing pressure on index funds to find ways to engage in governance activities. [P. 93]
>
> Hedge fund activism is a recent, but now prominent, topic in academic research. Since 2006, scholarship on hedge fund activism has grown from virtually non-existent to mainstream. [P. 93]

Other scholars, also analyzing the global ownership network, have also recently concluded (Fichtner et al. 2017):

> The analysis of the voting behavior underscores that the Big Three [BlackRock, Vanguard, and State Street] may be passive investors, but they are certainly not passive owners. They evidently have developed the ability to pursue a centralized voting strategy—a fundamental prerequisite to using their shareholder power effectively. In addition to this direct exercise of shareholder power, the extent of the concentration of ownership in the hands of the Big Three may also lead to a position of structural power.

The concentration of ownership and power has economy-wide implications. In particular, the challenges related to anti-competitiveness (Azar et al. 2015, 2016), tax avoidance (The Economist 2016a), offshore financial centers (Garcia-Bernardo et al. 2017), and systemic risk (Battiston et al. 2012, 2016) appear in a new, more ominous light. However, by uncovering the otherwise hidden patterns of organization in the data, these network studies are potentially valuable for policy makers (Glattfelder 2016). As an example, the restrictive and myopic too-big-to-fail thinking can be greatly enhanced. By incorporating the network of interaction, one can move beyond the isolation of nodes and embrace the network with a "too-connected-to-fail" perspective. Ultimately, "too-central-to-fail" identifies potential trouble spots

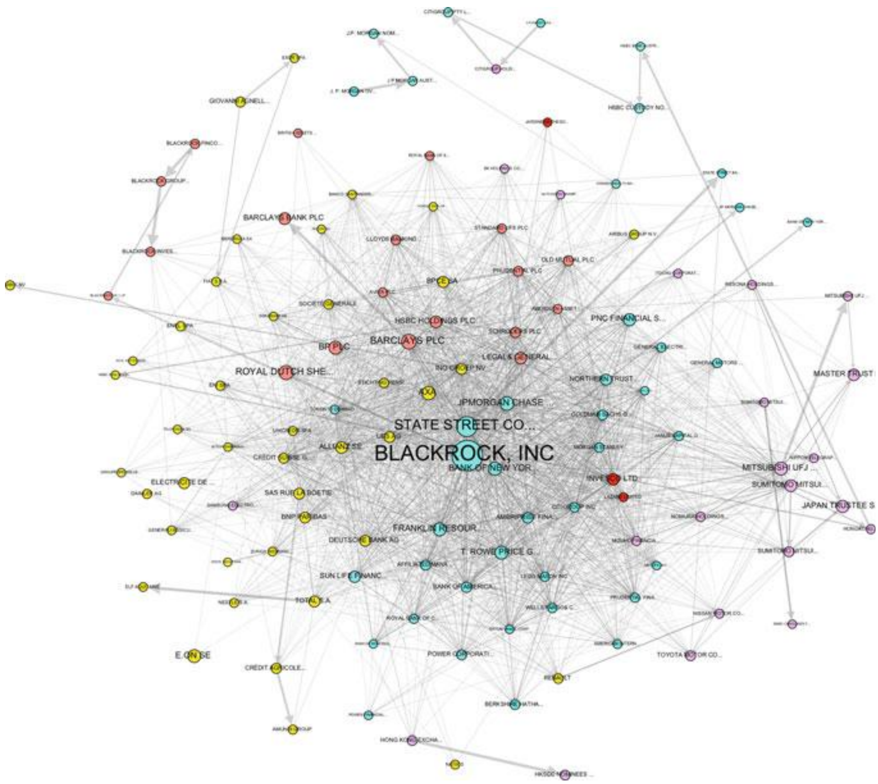


Fig. 7.3 The "super-entity" nested within the global ownership network (Glattfelder and Battiston 2019) of 2012. It is a subnetwork comprised of 128 highly influential nodes—from the financial, energy, and automobile sectors—potentially able to influence 16% of the value within the network, namely about USD 20 trillion. They represent less than 0.0004% of the 35,839,090 actors present in the entire 2012 global ownership network. There are 2,782 ownership links present in the structure. The nodes are scaled by Influence Index. Different shadings reflect a country partitioning (US, GB, remaining EU plus CH, JP, tax havens)

in the system, which only become visible by computing the centrality scores of all the nodes in the network.

7.3.2.2 ...And Network Centrality

The notion of centrality refers to a structural attribute of the nodes in a network which depends on their position in the network (Katz 1953; Hubbell 1965; Bonacich 1972). In general, centrality refers to the extent to which a network is organized around a single node. A popular family of centrality measures is called eigenvector centrality and quantifies the relevance of a node in a network. These are a feedback-type centrality measures, where a node is more central the more central its neighbors are themselves. Google's PageRank is an example of such a centrality measure (Brin and Page 1998), see Sect. 6.4.3.3. A variant of such centrality measures is the vector χ, containing the centrality scores of all the nodes in the network. In matrix notation it is defined as

$$\chi = W\chi + Wv. \tag{7.5}$$

See Glattfelder and Battiston (2009), Vitali et al. (2011), Glattfelder (2013, 2019). In plain words: The centrality score χ_i of node i depends on the centrality scores χ_j of all its neighbors j and their intrinsic node value v_j. In mathematical terms

$$\chi_i = \sum_j W_{ij}\chi_j + W_{ij}v_j. \tag{7.6}$$

The solution to (7.5) is given by

$$\chi = (\mathbb{1} - W)^{-1} W v, \tag{7.7}$$

with the identity matrix $\mathbb{1}$. In essence, the centrality is computed solely from the adjacency matrix W utilizing the (computationally intense) mathematical operation of matrix inversion.

Economic power in ownership networks is equivalent to this network centrality. Consider the following expression

$$p_i = \sum_{j\in\Gamma(i)} W_{ij}v_j, \tag{7.8}$$

where $\Gamma(i)$ is the set of indices of the neighbors of i. In other words, $\Gamma(i)$ denotes all the companies in the portfolio of shareholder i and p_i is a simple proxy for the direct portfolio value of i. In the presence of a network the notion of the indirect portfolio emerges naturally. Now, all downstream nodes reachable (with at least two "hops") from i are included in the calculation, yielding all the following paths

$$\begin{aligned}\hat{p}_i = &\sum_{j\in\Gamma(i)}\sum_{k\in\Gamma(j)} W_{ij}W_{jk}v_k + \cdots + \\ &\sum_{j_1\in\Gamma(i)}\sum_{j_2\in\Gamma(j_1)}\cdots\sum_{j_{m-1}\in\Gamma(j_m)} W_{ij_1}W_{j_1j_2}\cdots W_{j_{m-1}j_m}v_{j_m} + \cdots .\end{aligned} \tag{7.9}$$

As a result, one can assign the sum of the direct and indirect portfolio value in USD to each shareholder i, retrieving the total portfolio value

$$\xi_i = p_i + \hat{p}_i. \tag{7.10}$$

In matrix notation, this can be re-expressed as

$$\xi = \sum_{l=1}^{\infty} W^l v, \tag{7.11}$$

where W^l, by design, encodes all paths of length l in the network. Thus (7.11) considers all paths of all lengths in the network. The vector ξ is the resulting total portfolio value.

By utilizing the series expansion

$$(\mathbb{1} - W)^{-1} = \mathbb{1} + W + W^2 + W^3 + \cdots \tag{7.12}$$

one finds that

$$(\mathbb{1} - W)^{-1} W = W(\mathbb{1} - W)^{-1} = \sum_{n=1}^{\infty} W^n. \tag{7.13}$$

As a consequence

$$\chi = (\mathbb{1} - W)^{-1} W v = \sum_{l=1}^{\infty} W^l v = \xi. \tag{7.14}$$

Thus, the total portfolio value ξ_i, measured in USD, is nothing other than the network centrality measure χ_i, encoding the relevance of nodes in a directed and weighted network where a value v_i is attached to the nodes. This is an elegant example of a Level 3 type network analysis (Sect. 6.3.2), where the context of the real-world network is reinterpreted using pure network measures.

7.4 The Past, Present, and Future of Economic Interactions

The creation of money is perhaps one of the greates collective cognitive revolutions of mankind. It marked the beginning of "a new inter-subjective reality that exists only in people's shared imagination" (Harari 2015, p. 197). It has been argued that the history of money, beginning about 5,000 years ago, is in fact the history of debt and trust (Graeber 2011). In effect, debt is seen as the oldest means of trade, where cash and barter are limited to situations of low trust involving strangers. Money is the universal tool fostering countless human collaborations, from empires to science. Indeed (Harari 2015, p. 294):

> Science, industry and military technology intertwined only with the advent of the capitalist system and the Industrial Revolution. Once this relationship was established, it quickly transformed the world.

From this seed, Europe's global dominance would emerge. "In 1775 Asia accounted for 80 per cent of the world economy" (Harari 2015, p. 312), dwarfing Europe. "In 1950 western Europe and the United States together accounted for more than half of global production" (Harari 2015, p. 312).

The history of money is also the history of human psychology and ethics, where self-interest is pitched against cooperation. Greed and fraud promise short-term enrichment but threaten the long-term formation of an equitable and sustainable society living in ecological balance with the biosphere supporting life on Earth. The shrewd, cunning business acumen of individuals is contrasted by the potential for human collective intelligence, manifested in adaptive, robust, and resilient financial and economic systems. This means that the prevailing architectures of power play a key role in taming or exacerbating complexity.

7.4.1 The Imperial Power of Profit

How did Europe, and the US by extension, achieve world dominance in such a short time-span? The answer lies in the marriage of modern science and capitalism. Specifically, the "military-industrial-scientific complex," which first emerged as a feedback loop between science, empire, and capital 500 years ago, has been the main driving force of supremacy ever since.[19] Scientific knowledge (and inquisitiveness) paired with capital unleashes technological wizardry, which lends wings to imperialism.[20]

And so then, inexorably, the baton was passed on. In a world dominated by Chinese, Muslim, and Indians, the Italian maritime explorer and navigator Christopher Columbus, supported by the Spanish Crown, set out to chart the world in 1492. His discoveries allowed the Spanish to conquer America and claim vast and untapped resources. Boldly charting unknown geographical terrain was only the beginning. By constructing novel capitalist systems, more untapped power could be mobilized. Yet again the baton was passed on.

The Dutch ensured their success through credit. Namely, by founding the world's first stock exchange in Amsterdam, shares in limited liability joint-stock companies could be traded. For instance, the selling of shares of the Dutch East India Company (known as VOC) which helped finance the rise of the Dutch empire and the colonization of Indonesia. Within a century, the Dutch had replaced the global supremacy of the Spanish and Portuguese.

The penultimate baton pass in mankind's race for global hegemony happened when the British empire came to glory—the largest the world has ever seen. Again, a limited liability joint-stock company was at the center of the action. By 1857, the East India Company commanded a private army of over 271,000 troops (Schmidt 1995). Finally, on the 4th of July 1776 the United States Declaration of Independence was signed. With the rise of an all-powerful military-industrial-scientific complex in the US in the 1960s, the fate was sealed and history took its course—a course that may appear inevitable in hindsight. Capitalism and science reign supreme and, with spectacular success, conquer and dominate nearly all domains of human affairs.

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[19] See Harari (2015), especially Chaps. 15 and 16, for details on this section.

[20] See the following section for the Protestant work ethic's role in the foundation of modern capitalism.

7.4.2 *The Dark Side: The Economics of Greed and Fraud*

At its very core, capitalism is based on the trust in the future, allowing for progress. In a nutshell, growth is the main driver of capitalism. It is a feedback loop, where the trust in the future translates into investments and credits which, in turn, result in economic growth, justifying the trust. However, this cycle comes with a human and ecological cost. In the following, the toll on the human psyche is discussed.[21]

7.4.2.1 Self-Interest, Cooperation, Suffering, Meaning, and Happiness

Modern capitalism is truly a novel paradigm in the history of human thought. With Smith's economic manifesto, *An Inquiry into the Nature and Causes of the Wealth of Nations* (Smith 1776), a new universal order emerged, akin to the immutable laws of nature. The all-powerful and all-knowing "invisible hand," guiding markets based on self-interested profits, became canon. In essence (Harari 2015, p. 348):

> Yet Smith's claim that the selfish human urge to increase private profits is the basis for collective wealth is one of the most revolutionary ideas in human history—revolutionary not just from an economic perspective, but even more so from a moral and political perspective. What Smith says is, in fact, that greed is good, and that by becoming richer I benefit everybody, not just myself. *Egoism is altruism.*

Self-Interest

A modern-day proponent of the virtues of selfishness, and the powers of laissez-faire capitalism, was the Russian-American novelist-philosopher Ayn Rand (Rand 1964). She understood overt self-interest as the prime moral virtue and redefined altruism as evil.

Her philosophy of "objectivism" (Peikoff 1993), next to the ethical claims, declares real knowledge to be metaphysically objective and thus skepticism pointless. In other words, reality exists independently of consciousness, the human mind is in direct contact with reality through sense perception, and one can attain objective knowledge from perception through the process of concept formation and inductive logic. While there are arguably some points of contact with logical empiricism (Sect. 9.1.1) and critical rationalism (Sect. 9.1.2), Rand's philosophy represents the polar opposite of postmodernism (Sect. 9.1.4), constructivism (Sect. 9.1.5), relativism (Sect. 9.1.6), and poststructuralism (Sect. 6.2.2)—indeed, it opposes the entire information-theoretic and participatory paradigm discussed in Chaps. 13 and 14.

Her relationship with academic philosophers has been ambiguous. Seen, for instance, in the following (Badhwar and Long 2017):

> For all her popularity, however, only a few professional philosophers have taken her work seriously. As a result, most of the serious philosophical work on Rand has appeared in non-academic, non-peer-reviewed journals, or in books, and the bibliography reflects this

[21] See the Epilogue for the ecological cost.

> fact. We discuss the main reasons for her rejection by most professional philosophers in the first section. Our discussion of Rand's philosophical views, especially her moral-political views, draws from both her non-fiction and her fiction, since her views cannot be accurately interpreted or evaluated without doing so. […]
>
> Her philosophical essays lack the self-critical, detailed style of analytic philosophy, or any serious attempt to consider possible objections to her views. Her polemical style, often contemptuous tone, and the dogmatism and cult-like behavior of many of her fans also suggest that her work is not worth taking seriously. Further, understanding her views requires reading her fiction, but her fiction is not to everyone's taste. It does not help that she often dismisses other philosophers' views on the basis of cursory readings and conversations with a few philosophers and with her young philosophy student acolytes. Some contemporary philosophers return the compliment by dismissing her work contemptuously on the basis of hearsay. Some who do read her work point out that her arguments too often do not support her conclusions. This estimate is shared even by many who find her conclusions and her criticisms of contemporary culture, morality, and politics original and insightful. It is not surprising, then, that she is either mentioned in passing, or not mentioned at all, in the entries that discuss current philosophical thought about virtue ethics, egoism, rights, libertarianism, or markets.

Cooperation

Returning to science and complexity, the case has been made that in fact altruism and cooperation are the successful driving forces behind evolution (Trivers 1971; Axelrod and Hamilton 1981; Axelrod 1997; Nowak and Highfield 2011; Tomasello 2014; Damasio 2018). Indeed (Nowak and Highfield 2011, back cover):

> Some people argue that issues such as charity, fairness, forgiveness and cooperation are evolutionary loose ends, side issues that are of little consequence. But as Harvard's celebrated evolutionary biologist Martin Nowak explains in his ground-breaking and controversial book, cooperation is central to the four-billion-year-old puzzle of life. Indeed, it is cooperation, not competition, that is the defining human trait.

Next to the scientific understanding of the evolutionary benefits of altruism, most religious traditions contain elements sanctifying the virtues of modesty, frugality, humbleness, gratitude, benevolence, and generosity. The motivation being the focus on the afterlife, where this-worldliness holds limited appeal. Indeed, every monk—from Buddhism, Jainism, Hinduism, Christianity, Judaism, and Sufism—epitomizes this ancient ideal: a lifestyle withdrawn from mainstream society, characterized by abstinence from any sensual pleasures and distractions, purely focused on contemplation and meditation. In other words, a chosen life of asceticism. Within this context, the Protestant Reformation brought about a reorientation and a break with the past (Tarnas 1991, p. 246):

> Whereas traditionally the pursuit of commercial success was perceived as directly threatening to the religious life, now the two were recognized as mutually beneficial. […] Within a few generations, the Protestant work ethic, along with the continued emergence of an assertive and mobile individualism, had played a major role in encouraging the growth of an economically flourishing middle class tied to the rise of capitalism.

This profoundly secularizing effect on Western culture is rather paradoxical, as the Reformation's "essential character was so intensely and unambiguously religious" (Tarnas 1991, p. 240 and Sect. 5.3.1). Nonetheless, the road towards a capitalist-consumerist paradigm was paved (Harari 2015, p. 348):

> The new ethic promises paradise on condition that the rich remain greedy and spend their time making more money, and that the masses give free rein to their cravings and passions—and buy more and more.

Suffering

One spiritual tradition singles out greed as a particularly devious and malignant root of suffering. According to the Buddhist tradition, the first teachings that the Buddha gave in Sarnath around 600 B.C.E. after attaining enlightenment (and liberation from *saṃsāra*, the endless cycle of rebirth) are know as the *Dhammacakkappavattana Sutta*.[22] Within the text, the Four Noble Truths are given, outlining the reasons for suffering. The Noble Truth of suffering (*dukkha*) summarizes:

- Birth, aging, sickness, and death are painful.
- Sorrow, lamentation, physical pain, grief, and despair are painful.
- Union with what is disliked and separation from what is liked are painful.
- Not to get what one wants is painful.
- Clinging to the five aggregates that form a person (known as Skandha and relating to matter, sensation, perception, mental formations, and consciousness) is painful.

The Noble Truth of the origin of suffering is unquenchable thirst bound up with passionate greed. Namely, the thirst for sense-pleasures, existence and becoming, and self-annihilation. In essence, suffering arises due to the never-ending and pointless pursuit of ephemeral feelings—the craving and cling to impermanent states and things which are, by their own nature, incapable of creating lasting satisfaction. The Buddhist Wheel of Life (*bhavacakra*) is a symbolic representation of Saṃsāra, the endless cycle of existence. It details the six realms of rebirth. One notable one is the hungry ghost realm (Goodman 2017):

> Hungry ghosts are depicted with large bellies and tiny mouths; driven by greed, they seek endlessly for something to eat or drink, but even when they find a morsel they can swallow, it turns into filth or fire in their mouths.

This appears as a very apt metaphor for unchecked consumerism, lacking any meaning, value, and appreciation. In any case, the Noble Eightfold Path is the Buddha's proposed remedy for suffering. It describes self-experiential practices based on meditation, leading to liberation.

Perhaps when confronted with one's own mortality, one can see clearer and deeper. Looking back at our lives, we can thus identify meaningful or futile endeavors. Bronnie Ware worked as a nurse in a palliative care unit. Her experiences with the

[22] Found in the Pāli Canon, namely the Sutta Pitaka division containing the Saṃyutta Nikāya scripture, Chap. 56, Sutta 11.

dying were captured in her book *Top Five Regrets of the Dying* (Ware 2011). There we can read:

1. I wish I'd had the courage to live a life true to myself, not the life others expected of me.
2. I wish I'd had the courage to express my feelings.
3. I wish I had stayed in touch with my friends.
4. I wish that I had let myself be happier.

However, one regret is central to the context of this section: I wish I hadn't worked so hard. In Ware's words[23]: "All of the men I nursed deeply regretted spending so much of their lives on the treadmill of a work existence."

Meaning

From such a perspective it seems obvious that the accumulation of material wealth appears fruitless and hollow. Faced with the absolute certainty of one's own physical death, the life one chooses to live may feel like an insignificant blink in the grand scheme of existence. To try and fill it with meaning is then possibly more important and rewarding than to fill it with an ephemeral accumulation of wealth. Especially, if many people experience their working lives as dull, devoid of meaning, and ultimately futile.

The anthropologist David Graeber, who became known to a wider audience through his book *Debt: The First 5000 Years* (Graeber 2011), wrote a provocative and controversial article called *On the Phenomenon of Bullshit Jobs* (Graeber 2013). The piece struck a resonance and was widely shared in the Internet.[24] In a nutshell:

> Huge swathes of people, in Europe and North America in particular, spend their entire working lives performing tasks they secretly believe do not really need to be performed. The moral and spiritual damage that comes from this situation is profound. It is a scar across our collective soul. Yet virtually no one talks about it.

Others have also commented on the gloomy and cynical caricature life can become if it is defined solely by the shallow pursuit of the capitalist-consumerist mirage seemingly dictated by society. The economist Tim Jackson succinctly observed (Jackson 2010):

> This is a strange, rather perverse story. Just to put it in very simple terms: it's a story about us, people, being persuaded to spend money we don't have, on things we don't need, to create impressions that won't last, on people we don't care about.

Or, in the slightly different words of the author Nigel Marsh (Marsh 2010):

> And the reality of the society that we're in is there are thousands and thousands of people out there leading lives of quiet, screaming desperation, where they work long, hard hours at jobs they hate to enable them to buy things they don't need to impress people they don't like.

[23]Take from her blog https://bronnieware.com/blog/regrets-of-the-dying/, accessed March 13, 2018.

[24]In 2018, these ideas were expanded and published as a book (Graeber 2018).

Happiness

Maybe it is consoling to note that some economists have placed the pursuit of happiness in the center of their research, giving rise to happiness economics. Indeed (Frey and Stutzer 2002, back cover):

> Curiously, economists, whose discipline has much to do with human well-being, have shied away from factoring happiness into their work.

On a personal note, having worked in the finance industry for over a decade,[25] I feel that only very few people are psychologically equipped with the capabilities to derive sustainable happiness from a large paycheck while remaining independent and free in their life planing.[26] This sentiment was also expressed by a risk and compliance consultant at a major bank (Luyendijk 2011):

> My sense is that a lot of people in finance hate what they do. There's no passion. But they are trapped by the money.

Overall (Haybron 2013, p. 56):

> Affluence is a double-edged sword: it can buffer us from many ills and sate some of our wants. Yet it also tends to increase those wants and creates new vulnerabilities.

Empirical evidence suggest the mechanisms which are at work (Frey and Stutzer 2002, p. 78f.):

> Wants are insatiable. The more one gets, the more one wants. As long as one has a yearly income of $50,000, an income of $100,000 seems a lot. But as soon as one has achieved it, one craves $200,000. The expected marginal utility of income does not seem to decrease much if at all.

Moreover, there appears to be a threshold of income, above which happiness starts to lose its traction (Frey and Stutzer 2002, p. 83):

> At low levels of income, a rise in income strongly raises well-being. But once an annual income of about U.S. $15,000 has been reached, a rise in income level has a smaller effect on happiness. Higher income is still experienced as raising well-being, but at a lower rate. For Switzerland, in contrast, the highest income recipients even report somewhat lower well-being than does the income group immediately below.

Strikingly (Frey and Stutzer 2002, p. 91f.):

> Individuals do not value absolute income, but compare it to the income of relevant others. This opens up the issue of what persons or groups one compares oneself with.

The concept of the "hedonic treadmill" asserts that people adapt to improving economic conditions in such a way that no improvement of happiness is attained (Brickman and Campbell 1971). *The Economist* also chimed in The Economist (2012b), summarizing:

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[25] As a quant (Glattfelder et al. 2010, 2011; Golub et al. 2018a, b).

[26] This assessment was also nurtured by my upbringing, as I was raised in the affluent alpine resort of St. Moritz, exposed to a family business selling luxury foods.

> So levels of income are, if anything, inversely related to felicity. Perceived happiness depends on a lot more than material welfare.

A particularly astounding study compared major lottery winners with paralyzed accident victims (Brickman et al. 1978). It was concluded that happiness is indeed relative and that habituation erodes the impact of ill or good fortune—even for life changing events. The paraplegics exhibited a strong nostalgia effect, making them rate their past as much happier. And surprisingly (Brickman et al. 1978)

> It should be noted, however, that the paraplegic rating of present happiness is still above the midpoint of the scale and that the accident victims did not appear nearly as unhappy as might have been expected.

In contrast, the "lottery winners were not happier than controls and took significantly less pleasure from a series of mundane events" (Brickman et al. 1978).

If such insights, based on individual psychological behaviors, are extended to larger groups, some well-established indices, measuring the development of countries, are challenged. For instance, the gross domestic product (GDP) or the Human Development Index (HDI) are found to be missing nuance. In 2011, the UN General Assembly resolution 65/309 *Happiness: Towards a Holistic Definition of Development*[27] invited the member countries to assess the happiness of their people in an effort to establish a data-driven approach to public policy. The World Happiness Report is now an annual publication of the United Nations,[28] ranking national happiness.[29] Another initiative is the Happy Planet Index,[30] an index of human well-being and environmental impact. In other words, a nation's success depends on its ability to create happy and healthy lives for its citizens within environmental limits. According to this metric, the US is ranked 108th out of 140 indexed countries, with Costa Rica leading the list.

What has Buddhism to say to all of this, as it is inherently a practice to attain (individual and collective) happiness? Basically three things. Happiness is an inner state of being which can be cultivated independently of external factors. Then, meditation, the practice of transforming the mind by observing the mind, is central to that aim. Finally, the feeling of unconditional compassion towards all sentient beings[31] is a direct shortcut to happiness—the antidote to suffering. In essence, altruism is the core concept of Buddhism (Ricard 2013). Buddhism has also attracted the attention of scientists. For one, ancient concepts discovered by Buddhist meditators while observing their own stream of consciousness reveal a reality which is endowed with many of the paradoxes modern physics is grappling with, especially quantum mechanics (Ricard and Trinh 2001)[32]. Furthermore, the cultivation of mindfullness during meditation

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[27] See http://repository.un.org/handle/11176/291712.

[28] Namely, its Sustainable Development Solutions Network.

[29] See http://worldhappiness.report/.

[30] See http://happyplanetindex.org/.

[31] Note that there is not necessarily a restriction to biologically evolved consciousness. See Sect. 14.2.

[32] Historically, the counterculture of the 1960 and 1970s in the US brought about an interest in the bizarre nature of reality—unveiled by the new physical theories—and the concepts of Eastern

has a measurable impact on the brain. This example of brain plasticity manifested by meditators (Lutz et al. 2004) has caught the interests of neuroscinetists (Ricard and Singer 2017). An embodiment of the crossfertilization of science and Buddhism is Matthieu Ricard. He received a Ph.D. in molecular genetics from the Pasteur Institute in 1972. After graduation, Ricard decided to spend the rest of his life practicing Tibetan Buddhism in the Himalayas. In his words (Ricard 2004):

> [Meditation] means familiarization with a new way of being, a new way of perceiving things, which is more in adequation with reality, with interdependence, with the stream and continuous transformation, which our being and our consciousness is.

Ricard has been dubbed by the media as "'the world's happiest man' after a study found remarkably 'happy' patterns of brain activity" (Haybron 2013, p. 60). Indeed (Haybron 2013, p. 60):

> In a number of studies, Ricard has displayed exceptional powers of self-awareness and control. […] In one study researchers subjected him to a loud noise like a gunshot while meditating. He showed little of the normal startle response. This is not normally thought to be the sort of thing a person can control.

In the works of Ricard (Haybron 2013, p. 29):

> By "happiness" I mean here a deep sense of flourishing that arises from an exceptionally healthy mind. This is not a mere pleasurable feeling, a fleeting emotion, or a mood, but an optimal state of being

Lutz et al. (2004) analyzed the brain activity of seasoned meditators (10,000–50,000 hours of practice) inducing a state of "unconditional loving-kindness and compassion." The sturdy found that "their gamma levels leapt 600–800%. […] these jumps in high-amplitude gamma activity are the highest ever reported in the scientific literature apart from pathological conditions like seizures" (Brockman 2009, p. 274).

7.4.2.2 The Fruits of Fraud

Economic success can be interpreted in network terms as centrality. The more successful/central a player is, the more ties are shared with other successful/central players—in formal and informal networks. This can result in a position of privileged information with a tempting potential for leverage. The notion of moral hazard describes a situation where two parties engage in an interaction with incomplete information about each other. Specifically, one party engages in risky behavior knowing that it is protected against the risk and that the other party will incur the cost. Tempted by greed, moral hazards can quickly turn into immoral behavior and fraud.

The financial industry has a troubled history of misconduct. A recent and illuminating example is that of the London Inter-bank Offered Rate, known by its acronym LIBOR. In essence, it represents the average interest rates at which a selection

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mysticism. This is chronicled in Kaiser (2011). Some popular books of the time were (Capra 1975; Zukav 1979).

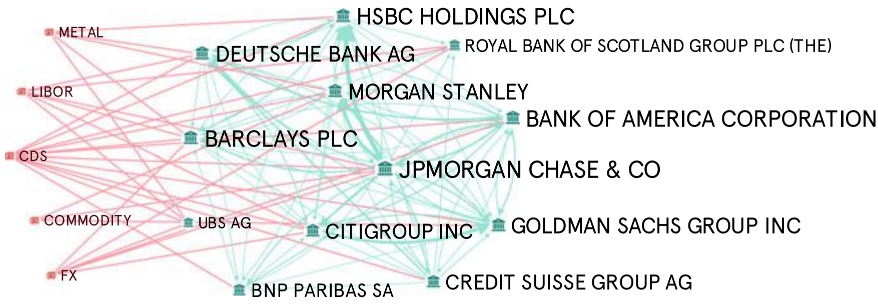

Fig. 7.4 The network of collusion. The 12 major global financial institutions are show which were caught up in one, or more, of the five scandals of systematic market manipulation. The banks are associated via dark undirected links to the scandals. The financial institutions are linked by ownership relations among themselves and the labels are scaled by degree. Details are given in the text and Table 7.1

of major banks may obtain short-term loans in the London interbank market. The LIBOR is the world's most widely-used benchmark for short-term interest rates and it affects a lot of value in the economy. For instance, "at least an estimated $350 trillion in derivatives and other financial products are tied to it" (The New York Times 2012). In order to calculate the LIBOR, every weekday, the 11 to 18 contributor banks are asked to estimate the rate at which they could borrow funds from other banks. From this list of numbers, some of the lowest and highest values are discarded and the average of the remaining ones is taken as the rate for that day. Effectively, the sophistication of a spreadsheets is all that is required to set a number to which vasts amounts of money are tied to. And, of course, honesty.

In 2012, it was uncovered that major global banks had been manipulating this simplistic calculation for perhaps decades, culminating in 2008, when the tweaking of the LIBOR made the financial situation of the banks appear healthier than it actually was during the turmoil of the financial crisis. As a result of the fraudulent collusion, the involved banks where fined about 9 trillion USD[33] and some traders were sentenced to prison.

The LIBOR scandal, unfortunately, was not an isolated incident. Various other systematic market manipulations were discovered. For instance[34]:

- Banks colluded from December 2007 until January 2013 to manipulate the 5.3 trillion-a-day foreign exchange market for their own financial gain. The banks agree to pay USD 4.3 billion to resolve the claims.
- Banks were accused of conspiring to control the USD 16 trillion credit default swap market in violation of US antitrust laws. The banks agree to pay USD 1.9 billion to resolve the claims.

[33] See https://www.investopedia.com/terms/l/libor-scandal.asp, accessed March 15, 2018.

[34] See https://graphcommons.com/graphs/50c0662f-8d69-4853-bbb2-e278f51cfe91/selection/e35063b0-b3e7-4b93-a86e-58f113d5c4df, accessed March 15, 2018.

Table 7.1 A sample of major global banks involved in systematic market manipulations. All numbers are in 1,000 USD. The financial information is taken from the Orbis database (https://orbis.bvdinfo.com/) for 2014. The fines paid are form a seven year time period (2007–2014). See https://blogs.ft.com/ftdata/2015/07/22/bank-fines-data/

Name	Operating revenue	Total assets	Market capitalization	Fines paid
JPMorgan Chase and Co (US)	94,205,000	2,573,126,000	221,810,079	32,375,200
Citigroup Inc (US)	76,288,000	1,842,530,000	147,572,710	15,002,800
Barclays PLC (GB)	39,472,637	2,119,419,949	3,421,530	3,803,000
Deutsche Bank AG (DE)	38,416,571	2,074,537,336	36,323,448	4,658,500
Goldman Sachs Group (US)	34,528,000	56,240,000	74,895,342	2,331,500
Morgan Stanley (US)	31,818,000	801,510,000	60,730,755	2,065,850
UBS AG (CH)	28,068,950	1,074,033,912	79,621,447	4,170,800
Credit Suisse Group AG (CH)	24,952,986	931,616,571	39,379,291	4,507,000
Royal Bank of Scotland (GB)	23,298,065	1,640,031,095	30,889,330	2,341,000

In 2014, a two-year investigation conducted by the Senate Permanent Subcommittee on Investigations accused banks of manipulating commodity prices. In 2015, a bank probe into precious metal collusion opened. It is somewhat surprising that always the same culprits appear in all the scandals. See Fig. 7.4 for the network of involved banks. Table 7.1 shows the numbers involved. In effect, 9 financial institutions, with a combined market capitalization of USD 694,643,932,000, commanding USD 13,113,044,863,000 in assets, paid a total of USD 71,255,650,000 in fines, over a seven year period, to settle charges. While a yearly fine of about USD 10 billion may appear large, it actually only accounts for 2.6% of the combined operating revenue of the institutions in 2014. Considering the amount of money that was potentially gained by the fraud, and the damage that was incurred by society, the fines lose their deterrent effect. Moreover, one wonders if these revelations only represent the tip of the iceberg, representing something more sinister that has been forming for a long time. For instance, Goldman Sachs, has been compared to a "great vampire squid wrapped around the face of humanity, relentlessly jamming its blood funnel into anything that smells like money" and accused of engineering "every major market manipulation since the Great Depression" (Taibbi 2010).

The banks caught up in fraudulent behavior have always stated that the misconduct was perpetrated by isolated individuals—rogue traders. Any culture of systematic fraud and greed was categorically denied by the senior management. In contrast, convicted bankers often claimed that they operated in an environment they believed fostered and rewarded such behavior, where management was complicit in such patterns of misconduct. The Ghanaian UBS trader Kweku Adoboli was convicted of fraud in 2012, and incarcerated, for engaging in unauthorized trading that cost the bank over USD 2 billion. He unsuccessfully appealed against the conviction, relativizing his role by claiming that his senior managers were aware of his actions and encouraged him to take risks (BBC News 2012):

> Adoboli said he had "lost control in the maelstrom of the financial crisis", and was doing well until he changed from a conservative "bearish" position to an aggressive "bullish" stance under pressure from senior managers.

Adoboli's defence lawyer told a jury to blame the institution, not the individual (The Economist 2012a):

> [The lawyer] showcased Mr Adoboli's trial as an indictment of UBS's and other banks' poor reputations. He cited other reported misdemeanors as evidence of a widespread cultural failure: UBS's $50 billion losses from subprime mortgages, its $780 m fine for helping wealthy American's clients shirk tax, accusations of Libor rate-fixing and PPI [payment protection insurance] misselling.

7.4.2.3 The Neoliberal World Order

Classical liberalism was intertwined with the rise of the Enlightenment movement beginning in the late 17th Century. Thinkers like Thomas Hobbes and John Locke argued that all men are free and equal. It followed that (Steger and Roy 2010, p. 5):

> Naturally endowed with the right to life, liberty, and property, humans could legitimately establish only *limited* governments, whose chief task consisted of securing and protecting these individual rights, especially private property.

In essence, classical liberalism celebrated free markets and individual self-expression. The Great Depression, impacting the beginning of the 20th Century, led economic thinkers to reevaluate the role of the government. Especially Keynes, whose influence grew at the time, advocated government spending during economic crisis.[35] The ideas of classical liberalism lost their appeal and justification and only in the middle of the 20th Century they reemerged within the new doctrine of neoliberalism. Yet again, the flapping of a butterfly's wing set of a chain reaction that would change the world for ever.

The founding fathers of neoliberalism probably would never have dared to dream about such a world-spanning success of their ideology when they first met in 1947 in the Swiss resort of Mont Pèlerin. A society was then founded by von Hayek and it soon attracted the interests of like-minded intellectuals, notably Nobel-prize winner Friedman of the Chicago School. A global network of organizations emerged,

[35] As mentioned, the 2008 global financial crisis revitalized the, by then, marginalized ideas of Keynes.

supporting the ideology, which would establish neoliberalism as the world's dominant economic paradigm by the 1990s.

At its core, neoliberalism is a set of beliefs advocating deregulation of the economy, liberalization of trade and industry, and privatization of state-owned enterprises. Inspired by the ideology, policy issues emerged, aimed at restricting governments' powers through minimal taxation and deficit reduction combined with spending restraints. Specifically, the high taxation of wealthy individuals and social welfare programs for all were perceived as fundamentally misguided. Laissez-faire economics and individual self-interest ruled. Neoliberalism has been associated with Ronald Reagan, Margaret Thatcher, Bill Clinton, Tony Blair, Boris Yeltsin, and George W. Bush. The ideology first became visible in the 1980s, with Pinochet's regime, greatly inspired by the Chicago School and Friedman. After that, the ideas spread around the globe. See Steger and Roy (2010) for details.

The Secret of Success

To this day, the prevailing economic orthodoxy is the neoliberal strain of capitalism. It has been argued to be an ideology for the ultra-rich. Indeed, neoliberalism has resulted in spectacular spoils for some. To picture the nearly unfathomable success of the top earners, imagine people's height being proportional to their income. Now imagine the entire adult population of the US walking past you, in ascending order of income, in a single hour. The following would unfold (The Economist 2011):

> The first passers-by, the owners of loss-making businesses, are invisible: their heads are below ground. Then come the jobless and the working poor, who are midgets. After half an hour the strollers are still only waist-high, since America's median income is only half the mean. It takes nearly 45 minutes before normal-sized people appear. But then, in the final minutes, giants thunder by. With six minutes to go they are 12 feet tall. When the 400 highest earners walk by, right at the end, each is more than two miles tall.

Also see Sect. 6.4.2 for the Pareto principle and Sect. 6.4.3.2 for scaling-law distributions. A point in case is hedge fund manager David Tepper. In 2009, he successfully bet that the US government would not let the big banks fail, personally earning him an estimated USD 4 billion that year (Schwartz and Story 2010).

One might point out that such financial spoils are justified as they are based on the willingness to take on risk and the luck of winning. However, the practices of financial institutions appears to paint a different picture (Story 2008):

> For [the investment manager] Dow Kim, 2006 was a very good year. While his salary at Merrill Lynch was $350,000, his total compensation was 100 times that—$35 million. The difference between the two amounts was his bonus, a rich reward for the robust earnings made by the traders he oversaw in Merrill's mortgage business. [...]
>
> But Merrill's record earnings in 2006—$7.5 billion—turned out to be a mirage. The company has since lost three times that amount, largely because the mortgage investments that supposedly had powered some of those profits plunged in value.
>
> Unlike the earnings, however, the bonuses have not been reversed.

The causal relation, that corporate performance is reflected in the compensation of managers, appears to be a thing of the past (Khurana and Zelleke 2009):

> Take the now-infamous example of the recently ousted Merrill Lynch chief John Thain, who not only splurged on his office decor [spending over $1 million] but also had the audacity to propose a $10 million bonus for himself. In recognition of what? A year's work in which the company continued to make bad business decisions, lost about 80% of its value, sold itself to Bank of America to stave off possible collapse and appears to have seriously damaged its buyer's franchise?

Once again, a systemic culture appears to permeate through an entire industry—a culture flirting with greed and fraud. Michael Lewis worked for Salomon Brothers during the end of the 1980s. He then resigned to write the book *Liar's Poker* (Lewis 1990) based on his experiences at the company, befor becoming a financial journalist. Looking back, he recalls (Lewis 2011, p. xiii):

> The willingness of a Wall Street investment bank to pay me hundreds of thousands of dollars to dispense investment advice to grown-ups remains a mystery to me to this day. I was twenty-four years old, with no experience of, or particular interest in, guessing which stocks and bonds would rise and which would fall. [...] Believe me when I tell you that I hadn't the first clue. I'd never taken an accounting course, never run a business, never even had savings of my own to manage. I stumbled into a job at Salomon Brothers in 1985, and stumbled out, richer, in 1988, and even though I wrote a book about the experience, the whole thing still strikes me as preposterous—which is one of the reasons the money was so easy to walk away from. I figured the situation was unsustainable. Sooner rather than later, someone was going to identify me, along with a lot of people more or less like me, as a fraud.

Digging deeper, Geraint Anderson, a former investment banker, also wrote a book about his personal experiences, called *City Boy: Beer and Loathing in the Square Mile* (Anderson 2010). Some of the reviews read[36]:

- London's pernicious financial world reveals itself in all its ugliness. [Daily Mail]
- An effective indictment of the narcissism and decadence of City life. [The Times]
- As a primer to back-stabbing, bullying, drug-taking, gambling, boozing, lap-dancing, this takes some beating. [Evening Standard]

Indeed, one wonders how much of the aggressive and reckless risk taking in finance is fueled by amphetamine-type stimulants and testosterone (Coates 2012). Yet again, everything appears to boil down to human psychology. Dacher Keltner, a professor of psychology, argues that true power requires modesty and empathy, not force and coercion (Keltner 2017). However, he observes (Keltner 2007):

> [...] studies also show that once people assume positions of power, they're likely to act more selfishly, impulsively, and aggressively, and they have a harder time seeing the world from other people's points of view. This presents us with the paradox of power: The skills most important to obtaining power and leading effectively are the very skills that deteriorate once we have power.

[36] Taken from https://www.amazon.com/Cityboy-Geraint-Anderson/dp/0755346181, accessed March 20, 2018.

Perhaps the greatest impact on the human psyche comes from greed. After a former Goldman Sachs executive director resigned, he wrote an opinion piece in the *New York Times*, where he heavily criticizes the firm's ethical culture and moral conduct (Smith 2012):

> The firm changed the way it thought about leadership. Leadership used to be about ideas, setting an example and doing the right thing. Today, if you make enough money for the firm (and are not currently an ax murderer) you will be promoted into a position of influence.

Furthermore, the entire systems appears to be a very uneven playing field—the polar opposite of a meritocracy. Again, an insider reports. Andrew Lahde founded a small hedge fund which came into the spotlight after it returned 866% in one year, betting against the subprime collapse. In 2008, he closed the fund and wrote a "goodbye letter" to his investors. There one can read (Lahde 2008):

> These people who were (often) truly not worthy of the education they received (or supposedly received) rose to the top of companies such as AIG, Bear Stearns and Lehman Brothers and all levels of our government. All of this behavior supporting the Aristocracy, only ended up making it easier for me to find people stupid enough to take the other side of my trades. […]
>
> I now have time to repair my health, which was destroyed by the stress I layered onto myself over the past two years, as well as my entire life—where I had to compete for spaces in universities and graduate schools, jobs and assets under management—with those who had all the advantages (rich parents) that I did not. May meritocracy be part of a new form of government, which needs to be established.
>
> On the issue of the U.S. Government, I would like to make a modest proposal. First, I point out the obvious flaws, whereby legislation was repeatedly brought forth to Congress over the past eight years, which would have reigned in the predatory lending practices of now mostly defunct institutions. These institutions regularly filled the coffers of both parties in return for voting down all of this legislation designed to protect the common citizen. This is an outrage, yet no one seems to know or care about it.

Indeed, the billionaire Warren Buffet wrote an op-ed article in the *New York Times* where he laconically commented:

> These and other blessings [extraordinary tax breaks] are showered upon us [the ultra-rich] by legislators in Washington who feel compelled to protect us, much as if we were spotted owls or some other endangered species. It's nice to have friends in high places.

The claim that unique intelligence, creativity, drive, and hard work result in success appears no longer true. By simply being part of an elite in-group, i.e., possessing a high network centrality, one is potentially rewarded with great wealth. We seem to live in a global plutocratic oligarchy. Indeed, "if wealth was the inevitable result of hard work and enterprise, every woman in Africa would be a millionaire" (Monbiot 2011a). Moreover, the University of St. Gallen in Switzerland, considered to be one of the leading business schools in Europe, offered a lecture on the emergence of new markets, where the increasing importance of innovation is discussed. One of the topics of the course is about leadership, power and conflict (taken from the 2007 syllabus,[37] translation mine):

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[37] This is no longer available, but was first reported here http://j-node.blogspot.ch/2011/10/so-what-about-greed-and-inequality.html.

> Innovation is not generated in the power center (management) of a corporation, but instead, exactly by such employees, who diverge from the prevailing mindset of the company.

It appears to be a fair assessment that the innovative employee will not reap the rewards of his creativity—in contrast to the senior management. An article in the Harvard Business Review asks why so many incompetent men become leaders? The answer (Chamorro-Premuzic 2013):

> In my view, the main reason for the uneven management sex ratio is our inability to discern between confidence and competence.
>
> This is consistent with the finding that leaderless groups have a natural tendency to elect self-centered, overconfident and narcissistic individuals as leaders, and that these personality characteristics are not equally common in men and women.
>
> In other words, what it takes to get the job is not just different from, but also the reverse of, what it takes to do the job well.

But in the end, should we really be concerned about the incomes of the ultra-rich and their lifestyles? They are the praised job creators, trickling down their wealth. Indeed, neoliberalism promises to make us all richer. Or not?

The Rise of Inequality

On the 13th of April 2010, the Dalai Lama tweeted[38]:

> Economic inequality, especially that between developed and developing nations, remains the greatest source of suffering on this planet.

Indeed, today we witness a spectacularly unequal distribution of wealth worldwide. Perhaps this title of an article on a British business news site epitomizes the astounding degree of disparity best (Jacobs 2018):

> Just 9 of the world's richest men have more combined wealth than the poorest 4 billion people.

Inequality is scale-invariant (see Sect. 6.4.1). In other words, it affects all levels of income. As a result, as one can read in an article in the *Wall Street Journal*, titled *The Real Wealth Gap: Between the Rich and Super-Rich* (Frank 2012):

> Forget the 99 versus the one percent. Consider the economic battle raging between the one percent and the 0.0001%.

On the other end of the spectrum, in 2011, there existed 71% of people globally living on USD 10 or less per day (Kochhar 2015). Moreover, the share of people worldwide living on less than USD 1.90 was 766 million in 2013.[39] The majority of the poor live in rural areas, are poorly educated, and over half are under 18 years of age (World Bank 2017). The poorest 2 billion people spend about 50–70% of their income on food (Brown 2011).

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[38] See https://twitter.com/DalaiLama/status/12094518160.

[39] This number, however, has more than halved since 1990.

From a complexity perspective it is not surprising to find that income and wealth are distributed in such an uneven manner. It is a universal feature of complex systems—from non-living and living domains—to display properties which are distributed according to a scaling law (see Sects. 6.4.1 and 6.4.3.2). In a nutshell, such a distribution means that nearly all the entities comprising a complex system are only marginally relevant, while a select few are of paramount importance. Although, from a human perspective this may sound unfair and undemocratic, it reflects a universal organizing principle, unconcerned with human affairs. The challenge then is to either force these distributions to morph into a different form, or, perhaps easier, try and tweak the scaling-law exponent in such a way that the resulting inequality is less pronounced.

Inequality has haunted humanity since the dawn of time. Although it may have been rising for several thousand years (Kohler et al. 2017), there was a brief period when things looked bright. As the world emerged from World War II, the political applications of Keynesian ideas brought about the "golden age of controlled capitalism" from about 1945 until 1975 (Steger and Roy 2010). The American "New Deal" and British "welfarism" resulted in an expanding middle class. High taxation of wealthy individuals and profitable corporations was offset by rising middle-class wages and increased social services. As explained earlier, the 1980s marked the start of the budding success of neoliberalism. Then tings started to change. Empirical research on capitalized income tax data in the US reveals the following. Tracking the evolution of the share of wealth owned by the top richest 10, 1, and 0.1%, respectively, a distinct pattern emerges. Looking at a period from 1930 until 2013, the wealth share resembles a U-shaped function. In other words, starting in 1930 with high inequality, the wealth of the top owners declined, reached a minimum of inequality between 1978 and 1986, only to steadily increase again after. As an example, the share of total household wealth held by the 0.1% richest families was about 23% in 1930, dropped to approximately 7% in 1978, and rose back up to roughly 22% in 2013. For details, see Saez and Zucman (2016). As a result, we started to become accustomed to statistics like (Davies et al. 2008):

> The wealth share estimates reveal that the richest 2 per cent of adult individuals own more than half of all global wealth, with the richest 1 per cent alone accounting for 40% of global assets. The corresponding figures for the top 5% and the top 10% are 71 and 85%, respectively. In contrast, the bottom half of wealth holders together hold barely 1 per cent of global wealth. Members of the top decile are almost 400 times richer, on average, than the bottom 50%, and members of the top percentile are almost 2,000 times richer.

This appears almost quaint when compared to the situation ten years later in 2018, described by the headline mentioned above comparing 9 people to 4 billion people.

Some economists are more concerned about inequality than others (Stiglitz 2012; Piketty 2014; Maxton and Randers 2016). Perhaps Joseph Stiglitz, as an eminent and influential economist, finds the clearest words to explain the mechanisms of the problem next to proposing common sense recommendations. Summarizing the status quo (Stiglitz 2011):

> While the top 1% have seen their incomes rise 18% over the past decade, those in the middle have actually seen their incomes fall. For men with only high-school degrees, the decline has been precipitous—12% in the last quarter-century alone. All the growth in recent decades—and more—has gone to those at the top.
>
> [...]
>
> Those who have contributed great positive innovations to our society, from the pioneers of genetic understanding to the pioneers of the Information Age, have received a pittance compared with those responsible for the financial innovations that brought our global economy to the brink of ruin. First, growing inequality is the flip side of something else: shrinking opportunity.
>
> [...]
>
> But one big part of the reason we have so much inequality is that the top 1% want it that way. The most obvious example involves tax policy. Lowering tax rates on capital gains, which is how the rich receive a large portion of their income, has given the wealthiest Americans close to a free ride.

Moreover (Stiglitz 2016):

> [R]ent-seeking means getting an income not as a reward for creating wealth but by grabbing a larger share of the wealth that would have been produced anyway. Indeed, rent-seekers typically destroy wealth, as a by-product of their taking away from others.
>
> Growth in top incomes in the past three decades has been driven mainly in two occupational categories: those in the financial sector (both executives and professionals) and non-financial executives. Evidence suggests that rents have contributed on a large scale to the strong increase in the incomes of both.
>
> [...]
>
> A second argument centres on the popular misconception that those at the top are the job creators, and giving more money to them will thus create more jobs. Industrialised countries are full of creative entrepreneurial people throughout the income distribution. What creates jobs is demand: when there is demand, firms will create the jobs to satisfy that demand (especially if we can get the financial system to work in the way it should, providing credit to small and medium-sized enterprises).

Unsurprisingly, economic apologists have tried to find justifications (Stiglitz 2011):

> Economists long ago tried to justify the vast inequalities that seemed so troubling in the mid-19th century—inequalities that are but a pale shadow of what we are seeing in America today. The justification they came up with was called "marginal-productivity theory." In a nutshell, this theory associated higher incomes with higher productivity and a greater contribution to society. It is a theory that has always been cherished by the rich. Evidence for its validity, however, remains thin.

Specifically (Stiglitz 2016):

> In the middle of the twentieth century, it came to be believed that "a rising tide lifts all boats": economic growth would bring increasing wealth and higher living standards to all sections of society.
>
> Resources given to the rich would inevitably "trickle down" to the rest. It is important to clarify that this version of old-fashioned "trickle-down economics" did not follow from the postwar evidence. The "rising-tide hypothesis" was equally consistent with a "trickle-up" theory—give more money to those at the bottom and everyone will benefit; or with a "build-out from the middle" theory—help those at the centre, and both those above and below will benefit.

Inequality poses many challenges to society (Stiglitz 2011):

> The more divided a society becomes in terms of wealth, the more reluctant the wealthy become to spend money on common needs. The rich don't need to rely on government for parks or education or medical care or personal security—they can buy all these things for themselves.

In the same vein (Stiglitz 2016):

> [S]ocieties with greater inequality are less likely to make public investments which enhance productivity, such as in public transportation, infrastructure, technology and education. If the rich believe that they don't need these public facilities, and worry that a strong government which could increase the efficiency of the economy might at the same time use its powers to redistribute income and wealth, it is not surprising that public investment is lower in countries with higher inequality.
>
> […]
>
> In fact, as empirical research by the IMF has shown, inequality is associated with economic instability. In particular, IMF researchers have shown that growth spells tend to be shorter when income inequality is high. This result holds also when other determinants of growth duration (like external shocks, property rights and macroeconomic conditions) are taken into account: on average, a 10-percentile decrease in inequality increases the expected length of a growth spell by one half. The picture does not change if one focuses on medium-term average growth rates instead of growth duration. Recent empirical research released by the OECD shows that income inequality has a negative and statistically significant effect on medium-term growth. It estimates that in countries like the US, the UK and Italy, overall economic growth would have been six to nine percentage points higher in the past two decades had income inequality not risen.

Finally (Stiglitz 2011):

> Of all the costs imposed on our society by the top 1%, perhaps the greatest is this: the erosion of our sense of identity, in which fair play, equality of opportunity, and a sense of community are so important.

Stiglitz offers the following recommendations (Stiglitz 2016):

> Reforms include more support for education, including pre-school; increasing the minimum wage; strengthening earned-income tax credits; strengthening the voice of workers in the workplace, including through unions; and more effective enforcement of anti-discrimination laws. But there are four areas in particular that could make inroads in the high level of inequality which now exists.
>
> First, executive compensation (especially in the US) has become excessive, and it is hard to justify the design of executive compensation schemes based on stock options. Executives should not be rewarded for improvements in a firm's stock market performance in which they play no part. […]
>
> Second, macroeconomic policies are needed that maintain economic stability and full employment. […]
>
> Third, public investment in education is fundamental to address inequality. A key determinant of workers' income is the level and quality of education. If governments ensure equal access to education, then the distribution of wages will reflect the distribution of abilities (including the ability to benefit from education) and the extent to which the education system attempts to compensate for differences in abilities and backgrounds. If, as in the United States, those with rich parents usually have access to better education, then one generation's inequality

> will be passed on to the next, and in each generation, wage inequality will reflect the income and related inequalities of the last.
>
> Fourth, these much-needed public investments could be financed through fair and full taxation of capital income. [...]

Finally, Stiglitz makes a gloomy prophecy (Stiglitz 2011):

> Governments have been toppled in Egypt and Tunisia. Protests have erupted in Libya, Yemen, and Bahrain. The ruling families elsewhere in the region look on nervously from their air-conditioned penthouse—will they be next? [...] As we gaze out at the popular fervor in the streets, one question to ask ourselves is this: When will it come to America? In important ways, our own country has become like one of these distant, troubled places.

This sentiment is shared by the billionaire Nick Hanauer. His assessment is quite alarming (Hanauer 2014):

> You probably don't know me, but like you [the article is written as a memo addressed to his fellow billionaires] I am one of those .01%ers, a proud and unapologetic capitalist. I have founded, co-founded and funded more than 30 companies across a range of industries—from itsy-bitsy ones like the night club I started in my 20s to giant ones like Amazon.com, for which I was the first nonfamily investor.
>
> At the same time that people like you and me are thriving beyond the dreams of any plutocrats in history, the rest of the country—the 99.99%—is lagging far behind. The divide between the haves and have-nots is getting worse really, really fast. In 1980, the top 1% controlled about 8% of U.S. national income. The bottom 50% shared about 18%. Today the top 1% share about 20 %; the bottom 50%, just 12%. And so I have a message for my fellow filthy rich, for all of us who live in our gated bubble worlds: Wake up, people. It won't last.
>
> If we don't do something to fix the glaring inequities in this economy, the pitchforks are going to come for us. No society can sustain this kind of rising inequality. In fact, there is no example in human history where wealth accumulated like this and the pitchforks didn't eventually come out.

On a side note, Hanauer also prefers complexity economics over laissez-faire economics (Liu and Hanauer 2016).

It could well be that the unprecedented success of the neoliberal doctrine will lead to its own undoing. A small group of corporations have enjoyed spectacular profits in the last decade. This could turn out to be a fatal bug in the economy's operating system. For one (Davidson 2016):

> Collectively, American businesses currently have \$1.9 trillion in cash, just sitting around. Not only is this state of affairs unparalleled in economic history, but we don't even have much data to compare it with, because corporations have traditionally been borrowers, not savers.

Such inefficiencies pose a threat to capitalism, as profits are an essential part of the system and should be invested. Indeed (The Economist 2016c):

> But high profits across a whole economy can be a sign of sickness. They can signal the existence of firms more adept at siphoning wealth off than creating it afresh [...]

The problem being that excessively high profits signal a lack of competition (The Economist 2016a). Greatly exacerbating the conundrum are the large asset managers. The emergence of all-powerful passive investment funds (recall Sect. 7.3.2.1) threaten the very fabric of capitalism. Some pundits have been candid about their opinion (The Economist 2016b):

> In August [2016] analysts at Sanford C. Bernstein, a research firm, thundered: "A supposedly capitalist economy where the only investment is passive is worse than either a centrally planned economy or an economy with active market-led capital management."

In its extreme conclusion, a financial system comprised mostly of passive funds could indeed spell the end of capitalism (Zweig 2016):

> Even John C. Bogle, the founder of Vanguard Group who launched the first index mutual fund 40 years ago this month, agrees that passive investing can get too big for anybody's good. "What happens when everybody indexes?" he asks. "Chaos, chaos without limit. You can't buy or sell, there is no liquidity, there is no market."

There has been a lot said and written about the perceived evils of neoliberalism. For instance (Monbiot 2007, 2011b, 2016, 2017; Verhaeghe 2014; Ostry et al. 2016; Dillow 2017; Rodrik 2017; Metcalf 2017; Deneen 2018).

7.4.3 The Blockchain: A Decentralized Architecture for the Economy

Adam Smith's intuition about the all-powerful and all-knowing "invisible hand" guiding markets was perhaps not too far off the mark (Smith 1776). He simply misunderstood the mechanisms that would lead to self-correcting and resilient behavior. Indeed, it is surely not unrestrained self-interest which magically allows human systems to display signs of collective intelligence. However, his belief in emergent properties can be interpreted as an early vision of complexity science. Today, we do in fact know what can foster adaptive and robust behavior in complex systems. The blueprint is characterized by decentralization. In other words, the science of simple rules of interaction—encoding complexity—is invoked (see Sect. 5.2.2). The network reigns supreme.

It is an interesting observation that the design of most human systems is governed by a very specific architecture: the pyramid of power. From emperors and empresses, kings and queens, popes, chief rabbis, caliphs, czars, heads of states, generals of the armies, senior academic administrators, presidents of the board of directors, and CEOs, centralized power emanates downwards through a pyramidal organizational structure of subordinates. While this design choice has obvious and historical reasons, a crucial question is how well it can cope with increasing complexity. Indeed, it appears as though in our world today—characterized by accelerating sophistication and interconnectivity—pyramids of control are not sufficient for tackling current and future global challenges. Perhaps our tribal human design patterns have reached their expiry date. Moreover, existing power is often very preoccupied with the retention of power. This can lead to temptations resulting in greed and fraud. In this context, it is consoling to know that nature has always seemed to favor bottom-up approaches engineering and containing complexity (see Sect. 5.2.4)—biologically-driven decentralization.

Today, we are seeing the glimpse of an emerging decentralized architecture for finance and economics. Although still in its infancy, the technology represents a truly novel paradigm with great disruptive potential: The decentralized architecture enforces transparency, security, and auditability by design, in a network where the nodes do not need to trust each other. Since inception, the innovation driving this organizational change has seen many phases in its evolution: from a specific digital-currency to a distributed ledger, hosting and executing code (called smart contracts). Indeed, distributed ledger technology (DLT) represents the third step in the evolution of the Internet:

1. 1985–2000: The Internet of information.
2. 2000–2015: The Internet of services.
3. Since 2015: The Internet of value.

The next step will most likely be the Internet of things,[40] where billions of devices are equipped with an IP address and are assimilated into the network. This vision has also been called Industry 4.0 (after mechanization, mass production, and automatization).

This current wave of decentralization, building upon cryptography, first emerged in 2009 and was initiated by Bitcoin. Originally, most people thought of the crypto-currency as only being useful for criminal activity in the darknet. Moreover, Bitcoin exchanges were plagued by scandals. Only slowly, it was realized that the actual revolution was the underlying database, called the blockchain. In a nutshell, a blockchain is a decentralized, fail-proof, and tamper-proof public ledger. It utilizes cryptography to solve the Byzantine Generals' Problem (Lamport et al. 1982), a problem in consensus-making in a system where communication channels cannot be trusted. In other words, despite the lack of central governance and trust, a blockchain allows a self-governing network (with no middleman) to be trustfully operated. As soon as this innovation was recognized by a wider public, the tides turned. Especially in the finance community:

> Banks put aside suspicion and explore shared database that drives Bitcoin. [(Shubber 2015) in *The Financial Times*]

> Distributed ledgers, or blockchains, have the potential to dramatically reshape the capital markets industry, with significant impact on business models, reductions in risk and savings of cost and capital. (McKinsey & Company Report 2015)

> The technology behind bitcoin could transform how the economy works. (The Economist 2015b)

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[40]See, for instance, IBM's white-paper from 2015, called *Device Democracy*: http://www-01.ibm.com/common/ssi/cgi-bin/ssialias?htmlfid=GBE03620USEN.

To this day, no one knows who is responsible for the invention. There is only the pseudonym Satoshi Nakamoto associated with the designer (Nakamoto 2009). However, he (or she) did leave a message for the world in the first block of the Bitcoin blockchain—the genesis block. It contains a reference to a news article, "The Times 03/Jan/2009 Chancellor on brink of second bailout for banks," thought to be a commentary on the global financial crisis and the instabilities of fractional-reserve banking.[41] Assuming Nakamoto's skeptical demeanor towards banking and finance, he was probably in despair when greed hijacked Bitcoin. In January 2017, a Bitcoin (BTC) was roughly worth 900 USD. By December, the rate had nearly climbed to BTC/USD 20,000. Crypto-millionaires—and billionaires—emerged overnight and the fear of missing out (FOMO) fueled the, predictably unsustainable, rally.

In an interesting twist of events, Switzerland, a historic epicenter of old-school banking,[42] emerged as one of the leading jurisdictions supporting DLT. This quickly lead to a flourishing initial coin offering (ICO) market, where some of the biggest offerings happened in the "crypto valley," describing a geographical area located around Zug and Zurich. An ICO is the crypto-equivalent of an initial public offering (IPO), where the shares of a company are sold on an exchange for the first time. In an ICO, a private company can sell tokens—representing some kind of utility (e.g., access, usage, or voting rights) or promising some reward or benefit—to non-professional investors in a currently still unregulated market.[43] An ICO is based on a promise of future success and often companies only have a vision or technical white-paper to offer as justification. Nonetheless, many start-up companies have been spectacularly successful in raising funds via ICOs. Indeed, the amount of money invested by traditional venture capitalists and angel investors in 2017 has been dwarfed by the ICO money (Rowley 2018), a concept that was still mostly unheard of in 2016. A blockchain platform called EOS, promising to revolutionize everything we know about blockchains, currently raised nearly USD 1 billion.[44] Their ICO is planned to last for a whole year—an unprecedented move. It is remarkable, that a start-up company offering only a vague idea[45] has raised the most capital in the shortest time. Even more astounding: "EOS raises $700M despite token affording no 'rights, uses, purpose, or features'" (Haig 2017). Not surprisingly, this extreme hype invites many scammers and regulators worldwide are nervously observing these developments.

The original goal of cryptography was to establish a secure communication channel in the presence of malicious parties. Indeed, the encryption of messages has a long history. Today, cryptography is based on assumptions about the computational hardness of problems. In a nutshell, cryptography provides a one-way street: it is

[41] See https://en.bitcoin.it/wiki/Genesis_block.

[42] And, notoriously, banking secrecy laws.

[43] As long as the ICO does not constitute the issuance of securities the authorities have not intervened. For instance, a token representing equity is a security. See also the Howey test and the SAFT (Simple Agreement for Future Tokens) project.

[44] See https://eos.io/.

[45] See their white-paper https://github.com/EOSIO/Documentation/blob/master/TechnicalWhitePaper.md.

very easy to digitally encrypt a message, but practically impossible to extract the original message from ciphertext. Next to encryption and secure communication, modern cryptography also addresses the topics of authentication and authorization. In the context of the blockchain, public-key cryptography is essential. See the Diffie-Hellman key exchange (Diffie and Hellman 1976) and the RSA cryptosystem (Rivest et al. 1978). Another core concept is the hash function, a one-way function that maps an arbitrary block of data to a fixed-sized bit string (popular algorithms are MD5, SHA1, or SHA2). A Merkle tree is a data structure assembled from hashes. It is a tree in which every leaf node (i.e., nodes with no descendants) holds some data and every non-leaf node (i.e., nodes with descendants) holds a cryptographic hash of the data of its child nodes. The underlying data structure that powers blockchains is a Merkle tree. Every block contains the current history of valid transactions which are secured using cryptography (by miners) and linked to the existing blockchain, in effect broadcasting the information to all the nodes in the network.

Group theory is also relevant to cryptography. In this book, groups were encountered in the context of symmetry in Chap. 3 (specifically Sects. 3.1.2, 3.1.3, and 3.1.4) and unification in Sect. 5.3.2. Groups can have a continuous (Sect. 5.3.1) or discrete (Sect. 5.3.2) character. For cryptography, discrete groups are relevant. In a nutshell, they are structures that consists of a set of symbols and an operation which combines any two of its elements to form a third one. Modular arithmetic is a system of arithmetic for integers, where for three positive integers a, b, and n

$$a \equiv b \mod n, \tag{7.15}$$

is shorthand for $a - b$ being a multiple of n. As an example, $38 \equiv 14 \mod 12$. Integers modulo a prime number p, with multiplication as the (group) operation, form a group (if all multiples of p are excluded). In such groups, it is hard to compute the discrete logarithm (to some base B). Symbolically, $\log_B(y)$ denotes a number x such that $B^x = y$. For the discrete group, the equation

$$y \equiv B^x \mod p, \tag{7.16}$$

is, in effect, a one-way street. It is very easy to verify the value of y given x, but solving for x in (7.16) is computationally hard. For more on cryptography, see Ferguson et al. (2010), Katz and Lindell (2014), Schneier (2015).

The blockchain, with its open protocols and open-source code, has been hailed as the remedy to many problems. For instance, today about two billion people in the world still do not have a bank account. DLT has the potential to help the unbanked (and underbanked) by allowing them to create their own financial alternatives in an efficient, transparent, and scalable manner (Thellmann 2018). Moreover, Bitcoin promised the possibility of transferring micro-payments around the world. Then, the inherently transparent and unmodifiable audit trail offered by DLT can help combat corruption. As an example, in many countries land registries are badly kept or mismanaged. DLT offers a way for people who do not know or trust each other to create a record of who owns what (The Economist 2015a). Indeed, the very nature of exchanges could be affected, as atomic swaps—cryptographically powered smart contracts that enables two parties to exchange different crypto-currencies or tokens without counterparty risk—allow instant settlement without the need for clearing. In effect, this represents an innovation over traditional over-the-counter (OTC) trading markets, such as the colossal foreign exchange market, with an average daily turnover of approximately USD five trillion (Bank of International Settlement 2016). From a legal perspective, the attributes of tokens (uniqueness, immutability, transferability, enforceability, and controllable access) are similar to those of civil property. In essence, digital or crypto property can be created utilizing blockchains. This concept is now a challenge for legal writers. The list of potential applications and disruptions, initiated by this move from pyramids of hierarchical organization to a distributed and decentralized network of agents, appears endless. However, it is impossible to gauge the future impact of DLT. It is similar to the challenge of trying to asses the potential of the nascent Internet in the early 1990s. No one had the audacity to predict what today has emerged form this initial network, then comprised of a few million computers, now affecting every aspect of modern human life. Experts agree, independent of the development of global regulatory responses, DLT is here to stay. The genie is out of the bottle and we are on a road to decentralized finance.

This is not to say that there aren't many problems plaguing the current blockchain prototypes. The sudden and unexpected success of Bitcoin quickly revealed its flaws. Scalability issues became predominant, leading to latency in the network[46] and skyrocketing transaction fees.[47] Most worryingly, Bitcoin turned out to be an ecological disaster due to its proof-of-work consensus mechanism, leading miners to set up vast data centers that require huge amounts of energy to solve the cryptographic challenge associated with every block (Atkin 2017). In comparison with the Internet, which had to overcome many technological hurdles in its evolution, DLT is also expected to solve many of the current challenges. For instance, there now exists an alternative consensus mechanism, called proof-of-stake, which significantly cuts back on energy use. For addressing scalability constraints, new paradigms are being explored. As an example, researchers have started to look into specific network topologies, essentially transforming the chains of the blockchains into a directed acyclic graph (DAG) of transactions (Lee 2018).

Perhaps the most ambitious vision is to turn blockchains into a global decentralized computing system. If Bitcoin is Blockchain 1.0, then Ethereum[48] is Blockchain 2.0. Essentially, Ethereum is a Turing-complete blockchain, executing code (smart contracts) that can solve any reasonable computational problem. On the horizon, one blockchain project is designing a "decentralized public compute utility" utilizing formal methods from theoretical computer science (such as the rho-calculus computational formalism). The founders acknowledge (Eykholt et al. 2017):

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[46] Visible in the number of unconfirmed transactions: https://blockchain.info/charts/mempool-count.

[47] See https://bitcoinfees.info/.

[48] See https://www.ethereum.org/.

> Together with the blockchain industry, we are still at the dawn of this decentralized movement. Now is the time to lay down a solid architectural foundation. The journey ahead for those who share this ambitious vision is as challenging as it is worthwhile […]

But until the new reality emerges, I guess, the following holds true (Glattfelder 2014):

> I personally believe that there is no fundamental reason, why the systems we humans engineer cannot also exhibit collective intelligence. You know, show behavior that is sustainable, adaptive, and resilient. But for things to change I believe we all have to ask ourselves what is our relationship to money. And if it is conducive to happiness—on a personal and collective level.

Conclusion

Here, Part I ends. The human mind has truly climbed to the summit of knowledge. The two volumes of the Book of Nature have been unearthed. From the fundamental workings of the universe to the perplexing complexity surrounding us, our minds can access an abstract realm of understanding and decode information from it. The edifice of knowledge appears extensive and sturdy.

Despite this apparent success, what remains to be explained are still the same age-old questions vexing the human mind: existential dilemmas, ontological paradoxes, and epistemic uncertainty prevail. Tumbling from the summit, this downfall is chronicled in Part II.

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Part II
The Downfall

Wherein the foundations start to shift and cracks appear the edifice of knowledge.

Chapter 8
A Brief Story of Success: The Manifestation of Knowledge and the Hydra of Ignorance

Abstract It is tempting to declare the victory of the human mind over ignorance. By applying pure thought the workings of the universe are deciphered, from fundamental processes to complex phenomena. Uncertainty has been banished, or so it seems. With pride the insights the mind has uncovered are swiftly translated into technology, bearing witness to the powers of the human intellect. Yet, astonishingly, the grand narrative does not end here. Indeed, it only truly begins. What remains to be explained are still the same age-old questions vexing the human mind. Why is there anything at all? What can I really know? What is the true nature of reality? What exactly is consciousness? What about all the strange cosmic coincidences leading up to this moment? Confronting these questions evokes existential dilemmas, ontological paradoxes, and epistemic uncertainty. The foundations of the edifice of knowledge start to shift and cracks emerge.
Level of mathematical formality: not applicable.

The quest to comprehend the world we live in has taken humanity on a true odyssey—a journey similar to the archetypal hero who "ventures forth from the world of common day into a region of supernatural wonder" (Campbell 2008, p. 23) and returns, bestowed with new powers. Likewise, the inquisitive mind of humans set out to search for the Book of Nature, containing all knowledge of the world, and returned with a mastery able to radically engineer reality. In the poetic words of Joseph Campbell, a scholar of comparative mythology and religion, humanity's journey can be summarized as follows (Campbell 2008, p. 334):

> It is the hero-cycle of the modern age, the wonder-story of mankind's coming to maturity. The spell of the past, the bondage of tradition, was shattered with sure and mighty strokes. The dream-web of myth fell away; the mind opened to full waking consciousness; and modern man emerged from ancient ignorance, like a butterfly from its cocoon, or like the sun at dawn from the womb of mother night.
>
> It is not only that there is no hiding place for the gods from the searching telescope and microscope; there is no such society any more as the gods once supported. The social unit is not a carrier of religious content, but an economic-political organization. Its ideals are not those of the hieratic pantomime, making visible on earth the forms of heaven, but of the secular state, in hard and unremitting competition for material supremacy and resources.

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
https://doi.org/10.1007/978-3-030-03633-1_8

Such a hero's journey is known as a monomyth, as it acts as a template for myths from around the world.

This odyssey of the human mind is recounted in Part I. Chapter 2 describes the realization that mathematics underlies the workings of the world and outlines the ensuing attempts to unearth this Book of Nature. Then, Chaps. 3 and 4 give detailed insights into the mathematization of nature, guided by the notion of symmetry. Under closer inspection, what was assumed to be the entire contents of the Book of Nature is discovered to be only one specific mode of human knowledge generation. The Book of Nature is revealed to be comprised of two volumes. In Chap. 5 a synthesis is given, summarizing and categorizing the possible modes of knowledge generation. The content of Volume II of the Book of Nature, decoding complexity, is revealed in Chaps. 6 and 7. Both volumes are driven by a translational process encoding aspects of the physical world into abstract representations, unified by continuous and discrete mathematics, respectively. The discovery of the two volumes of the Book of Nature uncovers intimate insights into a vast array of fundamental and complex phenomena, ranging from the quantum world to the fabric of the cosmos and the wonder of life in between. This unveiling of knowledge is driving the acceleration of technological advances and is having an unprecedented impact on how human societies organize themselves and interact with their environment (see, for instance, Sect. 7.4.1 and the Epilogue). Indeed, it can hardly be overstated how transformative the understanding of the workings of reality has become.

However, it is an interesting idiosyncrasy of our times that, as a society, we have become increasingly accustomed to the ongoing success of the human mind in probing reality and understanding the world we live in. Indeed, we take many modern aspects of life for granted which would have perplexed many great thinkers not too long ago. Today, even the most breathtaking technological breakthroughs, fostered by this ever growing body of knowledge, describing the universe and ourselves in greater and greater detail, can hardly capture the collective attention span for long. It is as if humanity has come to expect technological wizardry at a steadily accelerating pace. However, simply looking back at, for instance, the evolution of personal computers, information technology, and the Internet in the last decades should instill a sense of awe in everyone. Likewise, looking into the future, anticipating likely advancements in machine learning, artificial intelligence, nanotechnology, bionics, robotics, and autonomous drones, should leave one spellbound. Indeed, genetic engineering (specifically gene editing techniques), brain-computer interfaces, brain-scanning techniques, and pharmacology promise an eerie age of human enhancement just around the corner. Moreover, the socially disruptive potential of the blockchain (Sect. 7.4.3), the Internet of Things, virtual reality, and 3D printing should definitely not be underestimated. We are living at the threshold of a brave new world, materializing itself from pure knowledge. In the words of the historian Yuval Harari (Harari 2015, p. 463):

> […] the next stage of history will include not only technological and organizational transformations, but also fundamental transformations in human identity. And these could be transformations so fundamental that they will call the very term "human" into question.

So, finally, the hero returns home, bestowed with great new powers. The tremendous success of the human mind's capacity to decode reality, and the resulting capabilities for engineering the world we live in through technology, is perhaps the most significant achievement ever to have emerged on Earth or elsewhere. Knowledge has become manifested. In the words of the physicist Marcelo Gleiser (Gleiser 2014, p. 279):

> The grand narrative that is the scientific enterprise must be celebrated as one of the greatest achievements of the human intellect, a true testimonial to our collective ability to jointly create knowledge. Science is a response to our urge to understand, to make sense of the world we live in and of our place in it. It addresses the same age-old questions that have haunted and inspired humanity throughout the ages, questions of origins and endings, of place and meaning. We need to know who we are; we need to know where we are and how we got here. Science speaks directly to our humanity, to our quest for light, ever more light.

Here the monomyth ends—but, alas, not the human mind's struggle.

8.1 Clouds on the Horizon

Why doesn't this spectacularly successful adventure end here? Why doesn't Volume II of the Book of Nature close with the metaphoric final worlds "happily ever after?" It is a great irony—and a magnificent plot twist—that the anticipated ending of this narrative opens up Pandora's box of existential dilemmas, ontological paradoxes, and epistemic uncertainty.

Notwithstanding all the manifested knowledge humans have access to, these age-old questions still stand unanswered:

- Why does anything exist at all? Let alone life and consciousness.
- What can I learn, know, and understand about reality?
- What is reality's true nature?
- What is the true nature of the subjective stream of consciousness which I experience as being myself?
- In retrospect, looking at the 13.772-billion-year history of the universe, a plethora of coincidences guided its chaotic path-dependent evolution to this very moment now. How would the universe look today if time were to rewind and everything re-merged from the Big Bang and self-organized for another 13.772 billion years? And then again?

In a nutshell, the greatest mysteries of existence are still as elusive as ever. Ignorance and uncertainty prevail (Gleiser 2014, p. 280):

> As we probe Nature and master so many of its facets, it is good to remember that the shores of ignorance grow as the Island of Knowledge grows: the ocean of the unknown feeds on our success. It is also good to remember that science only covers part of the Island, that there are many ways of knowing that can and should feed on one another.

8.1.1 Uncertainty

There has been a long tradition of great thinkers expressing self-doubt and uncertainty relating to knowledge. A couple of hundred years B.C.E., in ancient China, Lao Tzu, the founder of Taoism, offered the following musing (Le Guin 1997, Verse 47, p. 62):

> The farther you go, the less you know.

This sentiment has famously been captured by the proverb "the more you know, the less you understand." A little later, Socrates, one of the founders of Western philosophy, chimed in. In essence, "Socrates' historic mission was the discovery of ignorance" (Boorstin 1999, p. 34):

> I know that I know nothing.

This saying, also know as the Socratic paradox, is derived from Plato's account of his teacher Socrates in "The Apology", see for instance Popper (2009, p. xix). A very similar proverb is also attributed to the Chinese philosopher Confucius: "Real knowledge is to know the extent of one's ignorance." Centuries later, the Roman emperor Marcus Aurelius is said to have remarked: "Everything we hear is an opinion, not a fact. Everything we see is a perspective, not the truth."

This self-critical analysis of one's own ignorance can be heard to echo into modern times, as expressed by some of keen thinkers. For instance, the essayist, historian, and philosopher Voltaire, who wrote in a letter to Frederick II of Prussia, dated April 6, 1767:

> Doubt is not a pleasant condition, but certainty is absurd.

Or the eminent mathematician and philosopher and Bertrand Russell (Russell 2009, p. 676):

> One of the painful things about our times is that those who feel certainty are stupid, and those with any imagination and understanding are filled with doubt and indecision.

The influential philosopher of science Karl Popper observed (Popper 2000, p. 50):

> I believe that it is worthwhile trying to discover more about the world, even if this only teaches us how little we know. It might do us good to remember from time to time that, while differing widely in the various little bits we know, in our infinite ignorance we are all equal.

In essence (Popper 2000, p. 50):

> The main source of our ignorance lies in the fact that our knowledge can only be finite, while our ignorance must necessarily be infinite.

Daniel Kahneman, the Nobel laureate who helped develop behavioral economics, had the following to offer (Kahneman 2011, p. 201):

> Paradoxically, it is easier to construct a coherent story when you know little, when there are fewer pieces to fit into the puzzle. Our comforting conviction that the world makes sense rests on a secure foundation: our almost unlimited ability to ignore our ignorance.

This tension between the poles of understanding and ignorance also enters children's books (Milne 1928):

> "Rabbit's clever," said Pooh thoughtfully.
> "Yes," said Piglet, "Rabbit's clever."
> "And he has Brain."
> "Yes," said Piglet, "Rabbit has Brain."
> There was a long silence.
> "I suppose," said Pooh, "that's why he never understands anything."

Indeed, one of the greatest poets let the main character famously allude to the limitations of human knowledge (*The Tragedy of Hamlet, Prince of Denmark*, Act 1, Scene V in Shakespeare 1623):

> There are more things in heaven and Earth, Horatio, than are dreamt of in your philosophy.

While our knowledge of the world has clearly increased dramatically, the realization of the limits of understanding has been more gradual, ambiguous and vague. The growth of uncertainty can be ignored for some time before it poses a serious challenge. In his epic book, called *The Passion of the Western Mind*, the cultural historian Richard Tarnas analyzes the ideas of the last two and a half millennia that have shaped our modern worldview. His verdict on this simultaneous increase in knowledge and uncertainty (Tarnas 1991, p. 325):

> For perhaps the most momentous paradox concerning the character of the modern era was the curious manner in which its progress during the centuries following the Scientific Revolution and the Enlightenment brought Western man unprecedented freedom, power, expansion, breadth of knowledge, depth of insight and concrete success, and yet simultaneously served— first subtly and later critically— to undermine the human being's existential situation on virtually every front: metaphysical and cosmological, epistemological, psychological, and finally even biological.

The most developed theory of ignorance in modern philosophy is that of Immanuel Kant. In a nutshell, his classic *Critique of Pure Reason* (Kant 1781) asserts that (Rescher 2009a, p. 22):

> [...] while we can know the things we encounter in our experiential interactions with the world's realities, those realities as such (the realm of "things in themselves") are inherently unknowable to us.

Reality is split into the distinct realms of *phenomena* and *noumena*—in other words, things as they appear to us and things as they are in themselves. Expressed in greater detail and in the eloquent words of Tarnas (1991):

> [...] in Kant's view, the nature of the human mind is such that it does not passively receive sense data. Rather, it actively digests and structures them, and man therefore knows objective reality precisely to the extent that that reality conforms to the fundamental structures of the mind. The world addressed by science corresponds to principles in the mind because the only world available to the mind is already organized in accordance with the mind's own processes. All human cognition of the world is channeled through the human mind's categories. The necessity and certainty of scientific knowledge derive from the mind, and are embedded in the mind's perception and understanding of the world. They do not derive from nature

> independent of the mind, which in fact can never be known itself. What man knows is a world permeated by his knowledge, and causality and the necessary laws of science are built into the framework of his cognition. Observations alone do not give man certain laws; those laws reflect the laws of man's mental organization. In the act of human cognition, the mind does not conform to things; things conform to the mind [p. 343].
>
> […]
>
> Space and time are thus not drawn from experience but are presupposed in experience. They are never observed as such, but they constitute that context within which all events observed. They cannot be known to exist in nature independently of the mind, but the world cannot be known by the mind without them [p. 343].
>
> […]
>
> For the only world that man knows is the empirical world of phenomena, of "appearances," and that world exists only to the extent that man participates in its construction [p. 345].
>
> […]
>
> Kant's penetrating critique had effectively pulled the rug out from under the human mind's pretensions to certain knowledge of things in themselves, eliminating in principle any human cognition of the ground of the world [p. 351].
>
> […]
>
> The course of modern philosophy unfolded under the impact of Kant's epochal distinctions [p. 351].

See also Sects. 11.2.1 and 14.3.5.

To this day, scientists and philosophers are grappling with certainty, unknowability, and ignorance. Indeed (Rescher 2009a, p. 4):

> One of the most obvious sources of ignorance is the sheer volume of available functional information. […] The vastness of any given person's ignorance is unfathomable.

Exacerbating the problem, our modern interconnected digital world is an ideal host for parasitic misinformation (Seife 2014). Moreover, what is considered as facts is in constant flux (Arbesman 2012). Then again, others have argued that ignorance—not knowledge—is the true engine of science (Firestein 2012). Contemporary philosophers have started to formulate a theory of unknowability, illuminating the practical and theoretical limits to the human mind's capacity to know the world (Rescher 2009b). Also scientists have chimed in. For instance, Noson Yanofsky, a scholar of quantum computing (Yanofsky 2013, p. x):

> While exploring these various limitations in diverse areas [language, philosophy, mathematics, logic, computing, and science], we will see that many of the limitations have a similar pattern. These patterns will be investigated in order to better understand the structure of reason and its limits.

Ignorance raises the thorny issue of skepticism (Stroud 1984; Frances 2005). The conviction that there exists no secure knowledge of the world has been debated for ages. The Western tradition of systematic skepticism goes back to the Greek philosopher Pyrrho of Elis. It is a double-edged sword as it can be used to attack not only unfounded beliefs and superstitions but science itself. As such, skepticism can be utilized as a tool to liberate the mind or as a destructive weapon. Some philosophers have argued that unyielding skepticism is absurd (Rescher 1980). Indeed (Rescher 2009a, p. x):

> The really problematic issue is one the skeptic simply avoids with his all-out denial of knowledge—namely, that of setting out the burden between what is knowable and what is not, exploring its placement and examining its rationale.

Biologist and researcher in the field of parapsychology, Rupert Sheldrake, observes (quoted in Brockman 2008):

> In practice, the goal of skepticism is not the discovery of truth, but the exposure of other people's errors. It plays a useful role in science, religion, scholarship, and common sense. But we need to remember that it is a weapon serving belief or self-interest; we need to be skeptical of skeptics. The more militant the skeptic, the stronger the belief.

In essence, an open mind guided by a healthy level of skepticism is the ideal of an inquisitive and enlightened mind.

8.1.2 Why Anything?

Three centuries ago Gottfried Wilhelm Leibniz, a mathematician, physicists, and philosopher, posed one of the greates questions of all times (Dascal 2008, p. 452):

> Why is there something rather than nothing? For nothingness is simpler and easier than anything.

The question is rephrased by the cosmologist Stephen Hawking (Hawking 2008, p. 142):

> Why does the universe go to all the bother of existing?

This deep and haunting ontological question has inspired many answers coming from philosophy, theology, spirituality, and, ultimately, physics. While some scholars have argued that the question "Why anything?" is illegitimate and improper, others have alleged that "nothingness" is inherently impossible. As an example, Russell simply evaded the question (quoted in Leslie and Kuhn 2013, p. 14):

> I should say that the universe is just there, and that is all.

In a similar vein, the philosopher Ludwig Wittgenstein (quoted in Leslie and Kuhn 2013, p. 14):

> It is nonsense to say that I wonder at the existence of the world, because I cannot imagine it not existing.

Today, some scientists are more empathetic. In the words of the MIT-physicist Sunny Y. Auyang, found in her book *How is Quantum Field Theory Possible?* (Auyang 1995, p. 194):

> The interpretation of quantum field theory presented in the preceding chapters implicitly contains a notion of the mind. The mind is understood not as an intelligent object but as the intelligibility of objects. The eternal mystery of the world is its comprehensibility, and the most profound astonishment lies in the fact that anything is experienced at all.

Assuming the question is legitimate and answerable, there are four main angles of attack (Leslie and Kuhn 2013):

- Existence is a brute fact.
- A transcendent agency created the world. For instance, as suggested by Hindu and Islamic writings, that the universe is "a structure or pattern of activity inside an infinite divine being" (Leslie and Kuhn 2013, p. 1).
- A principle of creativity accounts for existence. Plato suggested that the abstract need for there to be good accounts for why there is a cosmos (Leslie 2001).
- Laws of nature necessitate existence. In this case, once the human mind discovers the ultimate theory of everything, all questions will be answered.

Other attempts at explaining existence address the nature of the reality everything exists in Leslie and Kuhn (2013):

> Again, people have argued that we, together with all the other things in what we call "our universe," could be patterns of activity inside one of the gigantic computers that a technologically advanced civilization might be expected to use for "simulating" universes.

Some thinkers have claimed that existence necessitates at least one mind or some form of distributed consciousness—an entity capable of experiencing something. Physicists have the daunting task of explaining why our universe appears to be fine-tuned for conscious life (Sect. 15.2). In other words, only the perfect fine-tuning of physical constants allows a complexly structured universe to emerge from the Big Bang. The Anthropic Principle—a cosmological principle stating that theories of the universe must be constrained by the necessity to allow human consciousness—and the multiverse (see Sect. 10.3.2.2) have been conjured up as explanations.

The simple question "Why anything?" has inspired many very different explanations (Holt 2012; Leslie and Kuhn 2013). In the end we are left with the words of Nobel laureate Steven Weinberg (quoted in Leslie and Kuhn 2013, p. 15):

> Whatever our final theory of physics, we will be left facing an irreducible mystery. For perhaps there could have been nothing at all. Not even empty space, but just absolute nothing […] If you believe God is the creator, well, why is God that way? The religious person is left with a mystery which is no less than the mystery with which science leaves us.

Indeed (Horgan 2012):

> […] when scientists insist that they have solved, or will soon solve, all mysteries, including the biggest mystery of all [Why anything?], they do a disservice to science; they become the mirror images of the religious fundamentalists they despise.

In physics, the vacuum, i.e., absolutely empty space, is the concept which captures nothingness. It turned out to be a very strange entity, within both quantum field theory (Sect. 10.1.1) and cosmology (Sect. 10.1.2). For further reading on the strange notion of nothingness, see, for instance Genz (1999), Barrow (2000), Close (2009), Weatherall (2016).

8.1.3 A Short Narrative of Cosmic Coincidences

In this very moment, you are consciously reading this sentence in your mind. An astonishing series of events had to occur in the evolution of the universe for this moment to transpire. In a nutshell:

1. From an initial singularity…
2. a fine-tuned universe (Davies 2008) was spawned, furnished with laws of nature (Penrose 2004)…
3. filled with energy, expanding in three spacial dimensions, and evolving in time (Weinberg 1993)…
4. where quantum fluctuations seeded the large scale structure of the universe via gravity (Peacock 1999)…
5. and triggered self-organized structure formation driving the cosmos to ever greater complexity (Eigen 2013)…
6. where fusion ignited the first stars and furnished the first heavy elements, like carbon and oxygen, which got scattered into the cosmos when the stars exploded as supernovae (Carroll and Ostlie 2006)…
7. eons later, the Earth was formed and accumulated water (Robert 2001), which could remain liquid as Earth orbits the Sun at exactly the right distance (the circumstellar habitable zone or Goldilocks zone)…
8. allowing the assembly of organic matter, which could store information and replicate (Dawkins 1976) due to the specific bonding propertied of carbon (Wade Jr. 2012)…
9. sparking the evolution of life on Earth which fundamentally depends on the special anomalies of liquid water (Barrow et al. 2010) and which gradually reached ever higher and higher levels of complexity (Brooker et al. 2013)…
10. this evolutionary process depended on the emergence of the first organisms able to harness the energy emanating from the Sun by unlocking the secret of photosynthesis (Des Marais 2000), an event marking the beginning of the terraforming of an oxygen-filled atmosphere by cyanobacteria (Knoll 2015)…
11. resulting in the self-organized engineering of complex life forms from Eukaryotic cells (Hedges et al. 2004)…
12. later, the emergence of the Cambrian explosion, an evolutionary burst filled the seas with an unprecedented diversity of organisms (Morris 2000)…
13. which, by evolving into a species of insects, started to display a collection of social behaviors, establishing cooperative interactions as a successful template for evolution (Damasio 2018)…
14. the evolutionary process was constantly challenged by the occurrence of various mass extinction events, some leading to the eradication of nearly all of the biodiversity on Earth (Purvis and Hector 2000)…
15. for instance, the Cretaceous extinction event resulting in the perishing of non-avian dinosaurs, thrusting mammals from obscurity to prominence and setting the path for their planetary domination (Rose 2006)…

16. as a lump of organic matter, organized as a neural network comprised of billions of nodes and trillions of links, became self-aware by virtue of electrochemical processes (Siegel and Sapru 2015)…
17. from which a conscious experience sprang and a human observer emerged (Metzinger 2009)…
18. ultimately leading to the demise of all competing human species except one, a single remaining lineage of would-be conquerors of the solar system, by virtue of Homo sapiens' Cognitive Revolution—the capacity for abstract thought in the brain (Harari 2015), igniting culture and language (Laland 2017)…
19. now, a creature had emerged that looked at itself and out into the world with great wonder (Boorstin 1985; Russell 2004; Leslie and Kuhn 2013)…
20. and thus discovered the two volumes of the Book of Nature (Hawking 1988; Tarnas 1991; Wolfram 2002; Gribbin 2003; Bryson 2004; Penrose 2004; Davies 2007; Christian 2011; Eigen 2013; Hoyningen-Huene 2013; Weinberg 2015; Barabási 2016; Damasio 2018)…
21. which allows for the reconstruction of this story and provides the knowledge for the technology able to precisely measure the world and thus verify these series of events.

In retrospect we can look at this cosmic story and simply shrug. It is a brute fact that it unfolded. However, a little contemplation should instill a profound sense of dumbfoundedness and confusion in the light of this unfathomable unlikeliness and cosmic improbability. As observed by the eminent cosmologist Martin Rees and the science writer John Gribbin (Gribbin and Rees 2015, p. 287):

> [T]here is one key ingredient in science, which is highlighted most effectively by the development of anthropic cosmology—a sense of wonder.

What would have happened if any of these fundamental events had not unfolded? Would the mammals still have exited their niche without the Cretaceous mass extinction? Would there then still be traces of terrestrial life on other planets, albeit non-human? What if Isaac Newton, Max Planck, Albert Einstein, Emmy Noether, or Alan Turing had died as infants? What if Adolf Hitler or Gautama Buddha had never been born? The infinite list of alternate realities is mind-numbing.

Some thinkers have confronted this cosmic chance by ascribing the universe a teleological nature (Sect. 15.2.1). For instance, theological arguments invoking an intelligent designer setting everything in place for the story to unfold as scripted. Or the notion of creationism, where a God (or gods) create afresh a contrived universe that looks ancient as it is littered with false empirical evidence. More intriguingly, the idea that reality is a simulation (see Sect. 13.4.2) could solve the problem of cosmic chance as the source code would necessarily dictate the evolution of the program. Or perhaps there exists a still undetected fundamental force in the universe which drives it to ever higher levels of information processing and hence ever more complexity. For instance, the theoretical biologist and complex systems researcher Stuart Kauffman feels "that accident alone cannot have created life; our cosmos must harbor some fundamental order-generating tendency" (Horgan 1997, p. 135).

In such a universe life, consciousness, and computation would inevitably emerge. Or maybe the physical universe is the manifestation of a template universe outside of existence. For instance, a Platonic realm of abstract ideas which project into the physical world and dictate its structure and behavior (see Fig. 2.2 in Chap. 2). This idea invokes the notion of entelechy. This is the principle which realizes or makes actual what is otherwise merely potential. Is our universe a manifestation of an other-world potentiality?

8.2 The Core Enigmas of Existence

The last two section were rather speculative. While they ask profound questions and inspire out-of-the box thinking, it is questionable if there exist any fruitful answers. In contrast, the whole of Part II outlines three problem clusters that are also existential enigmas, but which have the potential to shed new light on the human condition framed in a cosmic perspective. The three core enigmas of existence are phrased as questions:

1. What can I know? (Chap. 9)
2. What is reality? (Chap. 10)
3. What is consciousness? (Chap. 11)

These questions are associated with the corresponding problem clusters illustrated in Fig. 8.1 and discussed in the following. The root of these enigmas can be found in this simple observation (Gleiser 2014, p. 192):

> For starers, everything that we can say about reality goes through our brain.

The flow of subjective experiences each conscious and hence observing entity witnesses, this continuous awareness of our own inner worlds of consciousness we are so familiar with, stands in stark contrast the external world outside of the mind. Yet our fleeting and incorporeal consciousness is embedded in the tangible, physical, and material.

What Can I Know and Understand?

The associated problem cluster comprises the following topics:

> Epistemology, philosophy of science, laws of nature, the crisis of modern science, formal thought systems, and the limits thereof.

See Chap. 9.

The Physical World: What is Reality?

Here we are faced with questions relating to:

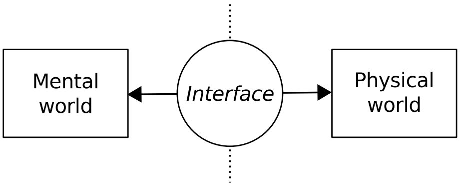

Fig. 8.1 Illustration of the problem clusters discussed in Part II, showing the mental world ("What is consciousness?"), the physical world ("What is reality?") and the interface between the two ("What can I know?"). Recall Fig. 2.2, illustrating the three worlds (the abstract Platonic realm, external physical reality, and the human mind), next to Fig. 2.1, showing the role of the human mind in the interplay between the physical and the abstract realms

Ontology, objectivity, nature of time, nature of matter, quantum gravity, the vacuum, cosmology, and the interpretation of quantum mechanics.

See Chap. 10.

The Mental World: What am I?

Finally, the last problem complex addresses the following issues:

The philosophy of the mind and self, neuroscience, cognitive science, perception, subjectivity, personal identity, mind-body problem, and free will.

See Chap. 11.

Conclusion

After scaling what appeared to be the summit of knowledge, the human mind is suffering the downfall. From multiple angles the comforting certainty of knowledge is attacked. This chapter only attempts to set the stage for the remaining chapters in Part II to fill in the details. For instance, the next chapter introduces elements form the philosophy of science.

While the outlook may appear gloomy, these core enigmas of existence have the potential to transcend the prevailing categories of knowledge and uncover novel aspects of existence. Such a new horizon awaits in Part III.

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Chapter 9
Philosophy and Science: What Can I Know?

Abstract Philosophy is a thorny subject. Many philosophical statements cannot be formally proven, resulting in clever but endless debates. Scientists usually shy away from such ambiguity and retreat into their safe world of perceived clarity. Nevertheless, the philosophical study of nature is the wellspring of science. Simply asking "What is a law of nature?" poses a philosophical challenge. The philosophy of science is concerned with the foundations, methods, and implications of science and how scientists conduct their research. The first attempts to systematize the scientific method was based on common sense: from observations abstract laws are found. This view turned out to be untenable and both inductive and deductive reasoning suffer from conceptual problems. Indeed, science is not an incremental process accumulating knowledge but is greatly influenced by social and cultural conditions. It comes perhaps as no surprise that an animosity exists between science and philosophy. For instance, the controversial philosopher of science, Paul Feyerabend, continually challenged the scientific establishment. Historically, the emergence of modern physics overthrew nearly every postulate of classical science and replaced them with bizarre new concepts, from elusive quantum fluctuations to the fabric of space-time. The aftershocks of this fundamental transformation still echo to this day. On the one hand the universe is, miraculously, comprehensible to the human mind, but on the other hand scientific progress appears to be slowing down. Paradoxically, every question answered raises more and harder questions and theories appear to be losing meaning. If asked, some scientists will admit to these shortcomings: uncertainty and ignorance are inherent and ubiquitous in science. The final blow to a clear foundation of knowledge comes from the discoveries that incompleteness and randomness lurk at the heart of mathematics.
Level of mathematical formality: low.

Science works! This is attested by the spectacular display of human technological prowess. Indeed, technological advancements, made possible by the scientific understanding of the universe, are becoming ever more disruptive and frequent. How is it then justifiable to speak of the crisis of science and even allude to the end of science?

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
https://doi.org/10.1007/978-3-030-03633-1_9

This chapter will explore between the poles of perceived knowledge and inescapable ignorance—between the illusion of certainty and limits of reason.

9.1 The Philosophy of Science

Even the simplest of questions can have the power to open Pandora's box of existential dilemmas. All attempts to answer the innocent question "What can I know?" have been inconclusive at best. This question has a long history that has accompanied mankind during its efforts to scale the mountain of knowledge and has continued to eluded the conceptual grasp of our minds.

The journey begins with one of history's first scientists (Grant 2002, p. 33):

> No one in the history of civilization has shaped our understanding of science and natural philosophy more than the great Greek philosopher and scientist Aristotle (384–322 B.C.), who exerted a profound and pervasive influence for more than two thousand years [...].

As one of the first thinkers he introduce logic as a means of reasoning. He had a clear vision of what knowledge constitutes and he founded it on intuition (Ross 1963, Book VI, Chapter 6):

> Scientific knowledge is judgment about things that are universal and necessary, and the conclusions of demonstration, and all scientific knowledge, follow from first principles [but] it is intuitive reason that grasps the first principles.

Nearly two thousand years later, not much had changed. But then, in 1620, the philosopher Francis Bacon presented modifications to Aristotle's ideas (Bacon 2000). In essence, a new logic, a reductionist approach, the focus on inductive reasoning, and the aspiration that scientific knowledge should foster technology, introduced what has become known as the modern scientific method. Bacon paved the way for a new, contemporary understanding of scientific inquiry. Approximately at the same time, Robert Boyle, seen by some as one of the founder of modern chemistry, was instrumental in establishing experiments as the cornerstone of physical sciences, working with an air pump (Boyle 1682; Shapin and Schaffer 2011).

The folowing six sections are adapted and expanded from Glattfelder (2013).

9.1.1 Logical Empiricism

By the early 20th Century, the notion that science is based on experience (i.e., empiricism) and logic, where knowledge is intersubjectively testable, has had a long history. The philosophical school of logical empiricism (or logical positivism) tried to formalize these ideas. Notably, utilizing the tools of mathematical logic, which had matured extensively under the contributions of Betrand Russell.[1] The *Vienna Circle*, a group

[1] See also Sect. 2.2.

of philosophers, scientist, and mathematics meeting regularly from 1924 to 1936 at the University of Vienna, was a major social hub of the movement. Some notable proponents were Rudolf Carnap, Kurt Gödel, Otto Neurath, Karl Popper, Hilary Putnam, Willard Van Orman Quine, Hans Reichenbach, and Ludwig Wittgenstein (Creath 2013). See also Sect. 2.2.1.

In this paradigm, science is viewed as a building comprised of logical building blocks based on an empirical foundation. A theory is understood as having the following structure:

Observation → Empirical concepts → Formal notions → Abstract laws

In essence, a sequence of ever higher abstractions. This notion of unveiling laws of nature by starting with individual observations is called inductive reasoning. Conversely, deductive reasoning starts with the abstract laws and seeks knowledge by finding a tangible factual description.

What started off as a well-founded and legitimate inquiry into the workings of nature soon faced serious difficulties and the opposition of influential scholars, some even from within the movement. As an example, Popper later claimed to have "killed" logical empiricism. Problems appeared on many fronts. For instance:

1. How can one construct pure formal concepts that solely reflect empirical facts without already anticipating a theoretical framework?
2. How does one link theoretical concepts (like electrons, inflational cosmology, Higgs bosons, utility functions in economics, …) to experiential notions?
3. How can one distinguish science from pseudo-science?

Somewhat technical, these challenges highlight that the logical empiricists where engaging with the notion of knowledge at a very subtle level, invoking the proverb "the devil is in the details." However, some glaring problems surfaced as well. One central issue concerns the legitimacy of inductive logic: can inductive reasoning lead to new knowledge? Not really, as deriving a generalization from multiple observations or repeated experiences is unjustified:

1. black swan: no matter how often I observe white swans, I cannot exclude the existence of a non-white one;
2. the future resembles the past: to assume that a sequence of events in the future will occur like it always has in the past, requires the complete knowledge of how the future evolves from the present according to laws of nature[2];
3. from the particular to the general: for instance, declaring that all wooden bodies float, based on the observation that a single piece of wood floats, is untenable without infusing additional, auxiliary knowledge, like Archimedes' principle.

The problem of inductive reasoning in logic then also challenges notions of causality and causal relations. See Brun and Kuenzle (2008).

So, in 1967, the philosopher John Passmore declared: "Logical positivism, then, is dead, or as dead as a philosophical movement ever becomes" (as quoted in Creath 2013).

[2]Which themselves could change in time.

9.1.2 Critical Rationalism

While empiricism historically was shaped by the insights of John Locke and David Hume, that all knowledge stems from experience, rationalism was crucially influenced by René Descartes and Gottfried Wilhelm Leibniz: knowledge can have aspects that do not stem from experience, i.e., there is an immanent reality to the mind.

The critical rationalists believed they could fix the problems the logical empiricists had faced. Popper was a key figure advancing this epistemological philosophy (Popper 1934). The central theme, referred to by the adjective "critical," revolves around the idea of falsifiability or fallibility. The idea, that insights gained by pure thought can never be justified but only critically tested by experience and thus discarded if discrepancies are observed. In a nutshell, no number of experiments can ever be used to prove a theory, but a single experiment suffices to contradict an established theory. Moreover, any claims of ultimate justification only lead to the so-called Münchhausen[3] trilemma (Albert 1968). That is, one of the following consequences will necessarily be encountered by any attempt to prove a truth:

1. an infinite regress of justifications;
2. circular reasoning;
3. axiomatic or dogmatic termination of reasoning.

To address the problem of inductive reasoning, the critical rationalist turned the tables. Now, from a currently (not falsified) theory or premise, a logically certain conclusion is sought, which can be observed in nature. This top-down logic moves from the abstract to the empirical. As a result, science is no more understood as a linear accumulation of knowledge, metaphorically assembling the edifice of science. In its new incarnation, science is a construct that is invented by people who relentlessly test and adapt its contents. The progression of science is hence seen as an evolutionary, organic process.

Ultimately however, also the school of critical rationalism faced insurmountable challenges. In a nutshell (Brun and Kuenzle 2008):

1. How can basic formal concepts be derived from experience without the help of induction and how can they be shown to be true?
2. What parts of a theory need to be discarded once it is falsified?

But most crucially, the principle of deduction is also plagued by epistemic problems. For how can these principles of deduction be justified in the first place? Moreover (Markie 2015):

> Intuition and deduction can provide us with knowledge of necessary truths such as those found in mathematics and logic, but such knowledge is not substantive knowledge of the external world. It is only knowledge of the relations of our own ideas.

[3] A reference to the fictional character Baron Münchhausen, who once famously pulled himself (and the horse on which he was sitting) out of a swamp by his own hair.

A colorful account, of how the conclusion of even a simple deductive argument cannot be logically enforce, can be found in one of the writings of Lewis Carroll, the mathematician who conceived the *Alice in Wonderland* stories (Carroll 1895).

This is indeed a surprising turn of events. Induction and deduction ultimately fail as rigorous logical tools to generate knowledge of the outer world. Furthermore, many technicalities prevent, or seriously challenge, a clear understanding and justification of what is actually going on in the scientists' minds when they engage in science. But perhaps science never was what we humans have idealized it to be for millennia. Perhaps science is a messier and murkier enterprise after all.

9.1.3 The Kuhnian View

Thomas Kuhn's enormously influential work on the history of science is called the *The Structure of Scientific Revolutions* (Kuhn 1962). He irrevocably overthrew the idealized notion that science is an incremental process accumulating more and more knowledge. Instead, he identified the following phases in the evolution of science:

1. prehistory: many schools of thought coexist and controversies are abundant;
2. history proper: one group of scientists establishes a new solution to an existing problem which opens the doors to further inquiry and a so called *paradigm* emerges;
3. paradigm based science: unity in the scientific community on what the fundamental questions and central methods should be (generally a problem or puzzle solving process within the boundaries of unchallenged rules, analogous to solving a Sudoku challenge);
4. crisis: more and more anomalies and boundaries start to appear, questioning and challenging the established rules;
5. revolution: a new theory and *Weltbild* takes over solving the anomalies and a new paradigm is born.

Kuhn cites the Copernican revolution as an example. Puzzled by the movements of planets and stars in the night sky, ancient humans offered many colorful myths as explanation. Then, around 100 C.E., Claudius Ptolemy had a breakthrough with his geocentric model, building on insights gained by Aristotle and others. Suddenly, fairly accurate predictions could be made about celestial mechanics. With time it became more and more apparent, that the model needed to be adapted and adjusted to account for new observational data. Employing ever more epicycles, that is circles within circles, it was hoped that the model's predictions would increase in accuracy. However, the mixing of epicycles led to a nearly unworkable system by the time Nicolaus Copernicus entered the scene, in the mid 16th Century. He boldly laid out a new paradigm by placing the sun at the center of the solar system (Copernicus 1543). Initially, the heliocentric model was not preciser than the geocentric model. Only the verification of novel predictions brought the final success, establishing the new paradigm.

Another core concept found in *The Structure of Scientific Revolutions* is called *incommensurability*. The term was introduced in the early 1960s by Kuhn and, independently, by the radical philosopher of science Paul Feyerabend (Preston 1997). Basically, if a scientist is too deeply embedded and invested in a specific conceptual framework, worldview, or paradigm, he or she will be unable to understand the reasoning of an outsider scientist, constrained by their own paradigm. More technically, every rule is part of a paradigm and there exist no trans-paradigmatic rules. The consequences are startling: the languages within different paradigms do not overlap enough to enable scientists to compare their theories. While Kuhn understood incommensurability as locally confined and only applicable to some terms and concepts, Feyerabend saw this as a global feature affecting every theory. In effect, scientists are plagued by blind spots and other cognitive biases (Sects. 11.3.2 and 14.4.2). More on Feyerabend and his unapologetic belief, see Sect. 9.1.6 below.

Perhaps a nice illustration of such myopia among scientists can be found in the controversy surrounding the reality of the (electromagnetic 4-vector) potential A_μ. This is the quantum field underlying the electric and magnetic fields and was introduced in the context of gauge theory. For nearly thirty years people believed that it could not produce any observable effects and was hence a fictitious filed. Then, however, a simple but ingenious experiment established the reality of the potential field, verified by the Aharonov-Bohm effect. In the words of Nobel laureate Richard Feynman (Feynman et al. 1964, p. 15–12):

> The implication was there all the time, but no one paid attention to it. Thus many people were rather shocked when the matter was brought up. [...]. It is interesting that something like this can be around for thirty years but, because of certain prejudices of what is and is not significant, continues to be ignored.

See Sect. 4.2 for details on the potential A_μ, defined in (4.12), its role in gauge theory, and the Aharonov-Bohm effect.

Another disturbing consequence of Kuhn's inquiries is that scientific revolutions are not at all rational processes governed by insights and reason. To the contrary, as Max Planck outlines in his autobiography (Planck 1950, pp. 33f.):

> A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.

Quite a dire analysis indeed, far removed from the idealized scientist's eureka moment. In the same vein, the words of Nobel laureate Steven Weinberg (Weinberg 2003, p. 191):

> Kuhn made the shift from one paradigm to another seem more like a religious conversion than an exercise in reason. He argued that our theories change so much in a paradigm shift that it is nearly impossible for scientists after a scientific revolution to see things as they had been seen under the previous paradigm.

Kuhn goes on to give additional blows to a commonsensical understanding of science with the help of Norwood Hanson and Quine:

1. every human observation of reality contains an a priori theoretical framework: this implies that two scientists looking at the same aspect of reality do not necessarily see the same things;
2. underdetermination of belief by evidence: any theory can be made compatible with recalcitrant observations by adaptions made to the background assumptions and thus data do not determine theories;
3. every experiment is based on auxiliary hypotheses: initial conditions, the proper functioning of the apparatus, the chosen experimental setup, the selected modes for interpreting the experimental data (what exactly are the scientists at CERN seeing, when they observe subatomic particles as peaks in a diagram, the abstract information the LHC relays from the quantum world?).

See Hanson (2010), Quine (1951), and also Brun and Kuenzle (2008).

What are the consequences of these unexpected and profound failings of the most simplest premises one would wish science to be grounded on? If logic, empiricism, objectivity, rationality, cohesion, structure, method, and a foundation are not inherently found in the way real humans conduct science, what are we left with? Indeed, people slowly started to realize the very serious consequences illuminated by the relentless but diligent inquiry led by the philosophy of science.

9.1.4 Postmodernism

Modernism describes the development of the Western industrialized society since the beginning of the 19th Century. Central ideas were the understanding that there exist objective true beliefs and that progression is always linear, steadily improving the status quo.

Postmodernism replaces these notions with the conviction that many different opinions and forms can coexist and even find acceptance. Core ideas are diversity, differences and intermingling. In the 1970s postmodernism is seen to enter cultural thinking, impacting art, music, and architecture. It is a notoriously hard concept to define due to its multifaceted nature. One attempt at a succinct definition centers around the idea of the meta-narrative. This is a narrative about narratives, relating to meaning, experience, and knowledge, which offers legitimation to a society. Then, in the words of the philosopher, sociologist, and literary theorist Jean-François Lyotard (Lyotard 1984. p xxiv):

> I define postmodern as incredulity toward meta-narratives.

Abroader and more vivid characterization is offered by Tarnas (1991, excerpts from the Chapter "The Postmodern Mind", p. 396f.):

> What is called postmodern varies considerably according to context, but in its most general and widespread form, the postmodern mind may be viewed as open-ended, indeterminate set of attitudes that has been shaped by a great diversity of intellectual and cultural currents.

> There is an appreciation of the plasticity and constant change of reality and knowledge, a stress on the priority of concrete experience over fixed abstract principles, and a conviction that no single a priori thought system should govern belief or investigation. It is recognized that human knowledge is subjectively determined by a multitude of factors; that objective essences, or things-in-themselves, are neither accessible nor possible; and that the value of all truths and assumptions must be continually subjected to direct testing. The critical search for truth is constrained to be tolerant of ambiguity and pluralism, and its outcome will necessarily be knowledge that is relative and fallible rather than absolute or certain.
>
> Reality is not a solid, self-contained given but a fluid, unfolding process, an "open universe," continually affected and molded by one's actions and beliefs. […]. Reality is in some sense constructed by the mind, not simply perceived by it, and many such constructions are possible, none necessarily sovereign.
>
> Hence all meaning is ultimately undecidable, and there is no "true" meaning. No underlying primal reality can be said to provide the foundation for human attempts to represent truth. […]. The multiplicity of incommensurable human truths exposes and defeats the conventional assumption that the mind can progress ever forward to a nearer grasp of reality.

Indeed, postmodernism can be understood as a call to cultivate one's own inner authority (Tarnas 1991, p. 404):

> The postmodern collapse of meaning has thus been countered by an emerging awareness of the individual's self-responsibility and capacity for creative innovation and self-transformation in his or her existential and spiritual response to life.

Such personal exposure to postmodernism in everyday life is perhaps nicely captured by Sarah Kay's experience. She is known for her spoken-word poetry and while teaching a class, Kay came up with the assignment to write a list of "10 Things I Know to be True." By comparing one's own list with the lists of enough other people one can observe the following[4]:

1. affirmation: someone has the exact same, or very similar, things as you have on your list;
2. dissonance: someone has the complete and total opposite to something you know is true;
3. novel thoughts: someone has something you have never even heard of before;
4. limited scope: someone has something you thought you knew everything about, but they are introducing a new angle to look at it or are offering an extended scope.

As expected, many scientists were unsympathetic to such an outlook on life and recoiled at most of the ideas associated with postmodernism. Physicist David Deutsch sees postmodern as "bad philosophy" and criticizes (Deutsch 2011, p. 314):

> It [postmodernism] is a narrative that resists rational criticism or improvement, precisely because it rejects all criticism as mere narrative. Creating a successful postmodernist theory is indeed purely a matter of meeting the criteria of the postmodernist community—which have evolved to be complex, exclusive and authority-based. Nothing like that is true of rational ways of thinking.

[4]See Kay's 2011 TED talk.

But not only postmodernism, with its radical epistemology and ontology, faced fierce opposition from scientists, indeed the whole idea of philosophy in general. Some scientists believe it is an irrelevant enterprise, as echoed in a quip usually attributed to Feynman: "The philosophy of science is about as useful to scientists as ornithology is to birds." Others have openly expressed their contempt, like the eminent physicist Freeman Dyson. In an article he wrote, reviewing the book of a philosopher (Holt 2012), he described today's philosophers as "a sorry bunch of dwarfs" compared to the giants of the past and portrayed contemporary philosophy as "a toothless relic of past glories" (Dyson 2012). Such scornful attitudes can perhaps be understood as the aftershocks of the Science Wars of the 1990s. Scientists then accused certain philosophers of having effectively rejected realism, objectivity, and rationality. They believed the scientific method, and even scientific knowledge, to be under siege.[5]

In this environment, some scientists sought to defend their cherished enterprise from postmodern attacks they perceived as anti-intellectual. In one incidence, called the Sokal hoax, physicist Alan Sokal got a nonsensical paper published in a journal of postmodern cultural studies. Already the grandiloquent title does not disappoint: "Transgressing the Boundaries: Towards a Transformative Hermeneutics of Quantum Gravity" (Sokal 1996). By flattering the editor's ideology with nonsense that sounds scientific and meaningful, Sokal got his 35 page long article, with profuse citations, accepted for publication. Indeed, the text is mainly a conflation of academic terms and buzzwords with sociopolitical and economic notions, as illustrated by the following except (Sokal 1996, p. 242):

> Thus, a liberatory science cannot be complete without a profound revision of the canon of mathematics. As yet no such emancipatory mathematics exists, and we can only speculate upon its eventual content. We can see hints of it in the multidimensional and nonlinear logic of fuzzy systems theory; but this approach is still heavily marked by its origins in the crisis of late-capitalist production relations. Catastrophe theory, with its dialectical emphases on smoothness/discontinuity and metamorphosis/unfolding, will indubitably play a major role in the future mathematics; but much theoretical work remains to be done before this approach can become a concrete tool of progressive political praxis.

Interestingly, modern physics has also suffered a similar embarrassment in 2002. Indeed, editors of scientific journals can just as easily succumb to imagining meaning where there is perhaps only empty jargon. The Bogdanov affair centers around the French twins and TV personalities Igor and Grichka Bogdanov. They enjoyed celebrity status and hosted a French science fiction television program. Today, they attract a lot of curiosity due to their physical appearance. What appears to be the result of extreme plastic surgery, gives the twins an eerie extraterrestrial look: drastically pronounced chins, cheekbones, and lips. The Bogdanov affair was an academic dispute regarding the legitimacy of the work produced by the twins. This included a series of theoretical physics papers published in reputable, peer-reviewed scientific journals, and their Ph.D. thesis, awarded by the University of Bourgogne in 2000.

[5]This splitting of the intellectual life into the cultures of sciences and the humanities was already diagnosed in 1959 (Snow 1993). An attempt to reconcile the two fronts can be found in Labinger and Collins (2001).

It was alleged that the contents was a meaningless combinations of buzzwords and the affair was covered in the mainstream media. The matter has also been referred to as the “reverse Sokal” hoax. To this day the Bogdanov twins have insisted upon the validity of their work, however, the controversy has prompted reflections upon the peer-review system. Declan Butler, a senior reporter for Nature Magazine, had the following to offer (Butler 2002):

> Take a deep breath, and give the following sentence a go. “We demonstrate that the lorentzian signature of the space-time metric $(+++-)$ is not fixed at the Planck scale and shows ‘quantum fluctuation’ between the lorentzian and euclidean $(+++)$ forms until the 0 scale where it becomes euclidean $(++++)$.” Confused? Don’t worry, you’re in good company. Physicists around the world have been unable to agree on whether the Ph.D. thesis this line comes from is good, bad or a hoax. [...]. So are the papers good science or not? Enquiries by Nature show that few theoretical physicists, including some who reviewed the brothers’ Ph.D. theses, are completely certain.

Has modern physics itself really transformed into a postmodern narrative that defies meaning, clarity, and understanding? An edifice lingering in a state of undecidability? See Chap. 10.

On a more humorous note, the website http://www.snarXiv.org/ is aimed at spoofing the theoretical, high-energy physics section of the popular scientific archive for electronic preprints http://www.arXiv.org, by automatically generating[6] meaningless titles and abstracts, infused with a barrage of buzzwords. As an example, consider the following:

> **Penrose Limit of AdS_4 x $N^{0,1,0}$ and N=3 Gauge Theory**
>
> C. Ahn
>
> Comments: 14 pages
> Subjects: High Energy Physics - Theory (hep-th)
>
> *We consider M-theory on AdS_4 x $N^{0,1,0}$ where $N^{0,1,0}$= (SU(3) x SU(2))/(SU(2) x U(1)). We review a Penrose limit of AdS_4 x $N^{0,1,0}$ that provides the pp-wave geometry of AdS_4 x S^7. There exists a subsector of three dimensional N=3 dual gauge theory, by taking both the conformal dimension and R-charge large with the finiteness of their difference, which has enhanced N=8 maximal supersymmetry. We identify operators in the N=3 gauge theory with supergravity KK excitations in the pp-wave geometry and describe how the N=2 gauge theory operators originating from both N=3 short vector multiplet and N=3 long gravitino multiplet fall into N=8 supermultiplets.*

[6]Based on what is known as context free grammar.

On Black Branes Wrapping a S^n

Q. B. Schwartz, I. U. 't Hooft

Comments: 7 pages, based on a talk given on Georgi's 80th birthday
Subjects: High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)

Substantial progress has been made over the last decade demystifying QED on Sp(2) quotients of moduli spaces of Calabi-Yau m-folds of Ext^m(R,Q) holonomy. We establish an elegant correspondence between vortex equations in M-Theory and integration cycles on AdS_m. Unparticle physics with gauge group E_8 deformed by local F-terms is also investigated. While reviewing bubble nucleation at the weak scale, we check that, as we will see in this paper, orientifold planes at the center of the galaxy are simple. Quite simply, magnetic-duality in QED deformed by Wilson lines is the final component in extending the fine-tuning problem.

Which title and abstract belongs to a legitimate contribution? For which one would you expect that there actually exists an article, building on the previous work of others, as highlighted by the many technical expressions introduced in the abstract, uncovering a novel detail of specialist knowledge? The author of the spoof website even based an online game on this idea, where the player is offered two titles, an actual high-energy physics paper from the arXiv, and a completely fake title randomly generated by the snarXiv. The aim of the game is to spot as many fake titles as possible.

However, postmodernism is only the tip of the iceberg of epistemic threats to knowledge and certainty. For one, it invokes the ghost of extreme skepticism in the form of solipsism, the belief that only one's own mind is certain to exist while any other knowledge is necessarily unsure. A feeling epitomized by Descartes' infamous sentence "*cogito ergo sum*" (Descartes 1937) and George Berkeley's notorious denial of a material external reality in favor of a reality exclusively comprised of minds and their ideas (Downing 2013). But more unsettling, postmodernism opens the doors to the Scylla and Charybdis of constructivism and relativism, discussed next.

See Sect. 6.2.2 for the related notion of poststructuralism. Indeed, postmodernism (Cilliers and Spurrett 1999) and poststructuralism (Sect. 6.2.2) are the preferred philosophies of complexity. Moreover, note the debate on the foundations of mathematics and the roots of postmodern thought (Tasić 2001).

9.1.5 Constructivism

Kuhn's analysis challenges the objective and universal nature of scientific knowledge. In essence, this knowledge is demoted to an edifice contingent upon the idiosyncrasies of human beings and their social and cultural imprintings. This predicament is lamented by Weinberg (2003, p. 190f.):

> What does bother me on reading [*The Structure of Scientific Revolutions*] and some of Kuhn's later writings is his radically skeptical conclusions about what is accomplished in the work of science. And it is just these conclusions that have made Kuhn a hero to the philosophers, historians, sociologists, and cultural critics who question the objective character of scientific knowledge, and who prefer to describe scientific theories as social constructs, not so different in this respect from democracy or baseball.

Furthermore (Weinberg 2003, p. 192):

> If the transition from one paradigm to another cannot be judged by any external standard, then perhaps it is culture rather than nature that dictates the content of scientific theories.

This impact of the social and cultural conditions on science is today studied under the label of the sociology of scientific knowledge. Proponents of the University of Edinburgh and the University of Bath poularized this field of inquiry (Bloor 1976; Shapin et al. 1985; Collins 1985; Shapin 1994).

In effect, what is being proposed here is the notion that knowledge is effectively constructed: always a product of the different factors conditioning scientists. An example of such culturally influenced constructions is related to gender. Feminist critiques of science have been thematically linked to the sociology of scientific knowledge, namely the marginalization of points of view based on gender, ethnicity, socio-economic status, and political status. Given science's long tradition of excluding women as practitioners, such critique is not unwarranted. The view that women are unfit for science, or vice versa, has been haunting the minds of male scientists since the beginning. For more on the feminist perspective on science, see Crasnow et al. (2015).

But more in general, constructivism maintains that all humans construct personal knowledge and meaning from the interactions of their subjective experiences and their ideas. Constructivist epistemology is a branch of the philosophy of science that argues that science is simply a product of such mental constructs, devised to explain the sensory experiences of the natural world. Essentially, scientific knowledge is merely constructed by the current scientific community, seeking to understand and build models of the world. More on constructivism can be found in Watzlawick (1984), Jonassen (1991), Perkins (1999).

The philosopher Ernst von Glasersfeld further added an uncompromising twist to theses ideas by introducing the notion radical constructivism (Von Glasersfeld 1984, 1989, 2002). In this relentless version, constructivism fully abandons objectivity. Or in the words of the physicist Heinz von Foerster (Schülein and Reitze 2002, p. 174, translation mine):

> Objectivity is the illusion that observations are made without an observer.

At its heart, radical constructivism questions the validity of any external sensory input. The subjective observer is placed at the center of the experience, but without the means to probe the external world conclusively. An analogy would be the submarine captain who has to rely on instruments to indirectly gain knowledge about the outside world. In detail, it is understood that perception never yields a faithful image of outer reality but is always an inner construction, derived from sensory input but dependent on the cognitive apparatus of each individual. Indeed, radical constructivists are motivated and validated by modern insights gained by neuroscience. Instead of reality being passively recorded by the brain, it is thought to be actively constructed by it. In effect, our brains sample just a small bit of the surrounding physical world from which normal perception is constructed. This "normal" mode of experiencing reality hardly differs from hallucinations or dreams which are not at all anchored by external input. The enigma of perception, and neuroscience in general, will be discussed in greater detail in Chap. 11.

9.1.6 Relativism

Constructivism opens the door to the next epistemic threat: relativism. If knowledge is constructed and hence contingent, then it can be rational for a group A to believe a fact $\mathcal{P}$, while at the same time it is rational for group B to believe in negation of $\mathcal{P}$. Again, in the words of Weinberg (2003, p. 192):

> If scientific theories can be judged only within the context of a particular paradigm, then in this respect the scientific theories of any one paradigm are not privileged over other ways of looking at the world, such as shamanism and creationism.

Relativism is the antipodal idea of absolutism. Whereas absolutism gives comforting certainty and clarity, offering solace to both scientifically and religiously minded people by invoking the idea of objective or absolute truth, relativism is a direct existential assault undermining and tainting any notion relating to meaning, truth or belief. Relativism summons disconcerting feelings of doubt, uncertainty, and ambiguity. Recall the long history of thinkers troubled by self-doubt and ambivalent knowledge, detailed in Sect. 8.1.

It is an interesting, albeit expected, observation that theologians and scientists alike show the same deep-seated disdain towards the idea of relativism: it is a double-edged sword threatening any institutionalized orthodoxy or scientific consensus. In the words of Joseph Ratzinger, delivered in his homily at the beginning of the conclave in 2005 from which he would emerge as Pope Benedict XVI:

> We are building a dictatorship of relativism that does not recognize anything as definitive and whose ultimate standard consists solely of one's own ego and desires.

On June 6, 2005, as Pope, he was quick to reiterate this point in the "Address of His Holiness Benedict XVI to the Participants in the Ecclesial Diocesan Convention of Rome":

> Today, a particularly insidious obstacle to the task of educating is the massive presence in our society and culture of that relativism which, recognizing nothing as definitive, leaves as the ultimate criterion only the self with its desires. And under the semblance of freedom it

> becomes a prison for each one, for it separates people from one another, locking each person into his or her own "ego".

Also Pope Benedict XVI's reformist and liberal successor, Pope Francis, adheres to this belief, viewing relativism as a vice which "makes everyone his own criterion and endangers the coexistence of peoples" (as seen in his address to the Diplomatic Corps accredited to the Holy See, on March 22, 2013).

In contrast, relativism is more prevalent in Eastern thought systems, where ideas are widespread that carry more holistic or pantheistic rings. An example can be found in Jainism, an ancient, radically non-violent Indian religion, that shares in its cosmology many of the elements of pre-Socratic Greek philosophies (see Nakamura 1998 and Sect. 3.1). In essence (Nakamura 1998, p. 167):

> The fundamental standpoint of Jainism [...] signifies that the universe can be looked at from many points of view, and that each viewpoint yields a different conclusion. Therefore, no conclusion is decisive.

At its heart, "Jainism shows extreme caution and anxiety to avoid all possible dogma in defining the nature of reality" (Nakamura 1998, p. 169).

In Western philosophy, relativism can be attributed to the Greek thinkers Heraclitus and Protagoras. So, even before Aristotle would set out to revolutionize the way we think about reality, a process ultimately leading to science, the seeds of relativity were sown, which would, about two and a half millennia later, prompt thinkers to view science as just one of many ways of knowing the world. In this context we encounter the influential, colorful, and controversial philosopher of science, Paul Feyerabend. He was truly the *enfant terrible* of relativism (Kidd 2011):

> Feyerabend was famously dubbed "the worst enemy of science" by *Science*, and even today philosophers of science will tend to associate his name with anti-science polemics, defences of voodoo and astrology, and more besides.

This is perhaps not surprising, looking at the titles of the books he published:

1975 *Against Method: Outline of an Anarchistic Theory of Knowledge* (Feyerabend 2008);
1987 *Farewell to Reason* (Feyerabend 1999);
1993 *The Tyranny of Science* (Feyerabend and Oberheim 2011).

Indeed, Feyerabend initially gained notoriety for his anarchistic rallying cry "anything goes," a vision of scientific anarchy that would send shivers down the spins of many scientists. In his own words (Feyerabend 2008, p. 9):

> The following essay is written in the conviction that *anarchism*, while perhaps not the most attractive *political* philosophy, is certainly excellent medicine for *epistemology*, and for the *philosophy of science*.

In essence, he observed (Feyerabend 2008, p. 1):

> The events, procedures and results that constitute the sciences have no common structure.

In Feyerabend (2008) he outlined his program for the philosophy of science. It is a very sympathetic, open-minded, idiosyncratic, and personal exposé. In an analytical index, Feyerabend offers a sketch of the main argument, summarized as a few sentences per chapter (Feyerabend 2008, p. 5f.):

Intro. Science is an essentially anarchic enterprise: theoretical anarchism is more humanitarian and more likely to encourage progress than its law-and-order alternatives.

Chapter 1 This is shown both by an examination of historical episodes and by an abstract analysis of the relation between idea and action. The only principle that does not inhibit progress is: *anything goes*.

Chapter 2 For example, we may use hypotheses that contradict well-confirmed theories and/or well-established experimental results. We may advance science by proceeding counterinductively.

Chapter 3 The consistency condition which demands that new hypotheses agree with accepted *theories* is unreasonable because it preserves the older theory, and not the better theory. Hypotheses contradicting well-confirmed theories give us evidence that cannot be obtained in any other way. Proliferation of theories is beneficial for science, while uniformity impairs its critical power. Uniformity also endangers the free development of the individual.

Chapter 4 There is no idea, however ancient and absurd, that is not capable of improving knowledge. […]

Chapter 5 No theory ever agrees with all the facts in its domain, yet it is not always the theory that is to blame. Facts are constituted by older ideologies, and a clash between facts and theories may be proof of progress. […]

Chapter 11 […] Copernicanism and other essential ingredients of modern science survived only because reason was frequently overruled in the past.

Chapter 17 Neither science nor rationality are universal measures of excellence. They are particular traditions, unaware of their historical grounding.

Chapter 18 Yet it is possible to evaluate standards of rationality and to improve them. The principles of improvement are neither above tradition nor beyond change and it is impossible to nail them down.

Chapter 19 Science is neither a single tradition, nor the best tradition there is, except for people who have become accustomed to its presence, its benefits and its disadvantages. […]

Of course, Feyerabend also espoused very radical and provocative ideas. For instance Feyerabend (2008, p. 238):

> In a democracy it [science] should be separated from the state just as churches are now separated from the state.

As expected, such utterances helped draw the wrath of the scientific community. Feyerabend was heavily criticized and vilified. However, accusations were often countered by him pointing out where he had been misinterpreted and by reemphasizing his ruthless commitment to open-mindedness. Like in the following example (Feyerabend 2008, p. 122):

> A few years ago Martin Gardner, the pitbull of scientism, published an article with the title "Anti-Science, the Strange Case of Paul Feyerabend" *Critical Inquiry*, Winter 1982/83. The valiant fighter seems to have overlooked these and other passages [in *Against Method*]. I am not against science. I praise its foremost practitioners and (next chapter) suggest that their procedures be adopted by philosophers. What I object to is narrow-minded philosophical interference and a narrow-minded extension of the latest scientific fashions to all areas of human endeavor—in short what I object to is a rationalistic interpretation and defense of science.

Perhaps what infuriated Feyerabend's critics the most was the adaptability of his beliefs, as one might expect from a relativist (Feyerabend 2008, p. 268):

> In a critical notice of my book *Farewell to Reason* Andrew Lugg suggests "that Feyerabend and likeminded social critics should treat relativism with the disdain that they normally reserve for rationalism". This I have now done, in *Three Dialogues of Knowledge* where I say that relativism gives an excellent account of the relation between dogmatic world-views but is only a first step towards an understanding of live traditions, and in *Beyond Reason: Essays on the Philosophy of Paul Feyerabend*, where I write "relativism is as much of a chimera as absolutism (the idea that there exists an objective truth), its cantankerous twin". [...] In both cases I raise objections against relativism, indicating why I changed my mind and mention some of the remaining difficulties.

With refreshing candidness he confessed (quoted in Horgan 1997, p. 50):

> I have opinions that I defend rather vigorously, and then I find out how silly they are, and I give them up.

Furthermore, as one might expect, Feyerabend adhered to no systematicity in his work, often emphasizing the ad hoc and random nature of his undertakings. For instance, as seen in the analytical index (Feyerabend 2008, p. 8f.):

> Chapter 20 The point of view underlying this book is not the result of a well-planned train of thought but of arguments prompted by accidental encounters.

Or more generally (Feyerabend 2008, p. 159):

> "Anything goes" does not mean that I shall read every single paper that has been written—God forbid!—it means that I make my selection in a highly individual and idiosyncratic way, partly because I can't be bothered to read, partly because I can't be bothered to read what doesn't interest me—and my interests change from week to week and day to day—partly because I am convinced that humanity and even Science will profit from everyone doing his own thing [...].

Perhaps Feyerabend was indeed profoundly misunderstood, a fact he himself would probably never worry about and try to amend. To illustrate, a more sympathetic reading of Feyerabend (Kidd 2011):

> *The Tyranny of Science* should therefore be interpreted as Feyerabend's attempts to dissolve conflicts and establish harmony between science, society, and philosophy, on the one hand, and between scientists, philosophers, and the public, on the other. The concerns and alarms that concerned Feyerabend are not the exclusive preserve of any of those domains—scientific, public, or philosophical—and to properly understand and address them each must cooperate with the other. Tyranny only arises when one of those would try to dominate the others, and Feyerabend's book offers an engaging and entertaining case against such tyranny.

9.2 The Evolution of Science

During the meandering evolution of science many pressing issues have been raised, relating to truth, knowledge, and beliefs. Inconspicuous and commonsensical ideas of rationality, objectivity, and universality came under siege. However, more drastically, and despite the remarkable success of science in continually uncovering knowledge of the world, our idea of reality itself emerged as conceptually flawed. A paradox surfaced (Tarnas 1991, p. 333):

> For at the same time that modern man was vastly extending his effective knowledge of the world, his critical epistemology inexorably revealed the disquieting limits beyond which his knowledge could not claim to penetrate.

The envisaged role of the human being, taken to be that of the detached onlooker observing and interpreting a world of mind-independent objects, began to pose a problem. Indeed, our common sense and intuition, longing for an objective reality which can be comprehended by the human mind through unambiguous, justified knowledge of true facts, started to appear misguided. Today we know that "fundamental physics has a long history of disregarding our common sense notions" (Gefter 2012).

Ironically, harmless-looking anomalies[7] led to the absolutely unexpected discoveries of new realms of reality, fundamentally and irreversibly disrupting the prevailing classical worldview. One was the uncovering of the discrete nature of reality, as revealed by quantum phenomena (Sect. 4.3.4), the other was the finding of the malleability of space and time (special and general relativity, discussed in Sects. 3.2.1 and 4.1 and 10.1.2, respectively). The deeper the human mind probed reality, the more outlandish the stories became that it has to tell itself about these new planes of existence. Troublingly (Tarnas 1991, p. 358):

> [...] the concepts derived from the new physics not only were difficult for the layperson to comprehend, they presented seemingly insuperable obstacles to the human intuition generally: a curved space, finite yet unbounded; a four-dimensional space-time continuum; mutually exclusive properties possessed by the same subatomic entity; objects that were not really things at all but processes or patterns of relationships; phenomena that took no decisive shape until observed; particles that seemed affect each other at a distance with no known causal link; the existence of fundamental fluctuations of energy in a total vacuum.

These issues are discussed in Chap. 10. The possible implications are truly unsettling to the Western mind and many of humanity's century old concepts and beliefs appear to be in danger. The ramifications of such uprooting discoveries left scars in the psyche of scientists (Tarnas 1991, p. 356):

> By the end of the third decade of the twentieth century, virtually every major postulate of the earlier scientific conception had been controverted: the atoms as solid, indestructible, and separate building-blocks of nature, space and time as independent absolutes, the strict mechanistic causality of all phenomena, the possibility of objective observation of nature.

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[7] The inconsistent theoretical calculations of black-body radiation, discussed in Sect. 4.3.4, and the constant speed of light, seen in Sect. 3.2.1.

> Such fundamental transformation in the scientific world picture was staggering, and for no one was this more true than the physicists themselves. Confronted with the contradictions observed in subatomic phenomena, Albert Einstein wrote: "All my attempts to adapt the theoretical foundation of physics to this knowledge failed completely. It was as if the ground had been pulled out from under one, with no firm foundation to be seen anywhere upon which one could have built." Heisenberg similarly realized that "the foundations of physics have started moving... [and] this motion has caused the feeling that the ground would be cut from science."

See Chap. 10 for an overview of the struggles of physicsc in general and Sect. 10.3.2 for specific introduction to the bizarre realm of the quantum.

What did other practitioners of science have to say to all of this? At first, the philosophical conundrums of the novel physical theories were acknowledged. Indeed, any understanding of the newly discovered subatomic reality appeared to require the reintegration of philosophy into science (Kaiser 2011, p. 2):

> Most of its [quantum mechanics] creators—towering figures like Niels Bohr, Werner Heisenberg, and Erwin Schrödinger—famously argued that quantum mechanics was first and foremost a new way of thinking. Ideas that had guided scientists for centuries were to be cast aside Bohr constantly spoke of the "general epistemological lessons" of the new quantum era.

However, after World War II, the philosophically inspired attempts at understanding the quantum world quickly faded, nearly vanishing during the Cold War with the emerging new rallying cry: "Shut up and calculate!" (see Sect. 2.2.1). With the scope of physics steadily increasing, mathematical prowess became the most vital skill, leaving not much room for grander musings. The question of what the mathematical symbols being manipulated really mean were ignored as was their relationship to reality. The attitudes scientists adopted towards philosophy now ranged between indifference and hostility. As mentioned above, some eminent physicists are on record expressing their contempt for philosophy. Needles to say, philosophers insisted on analyzing these conceptual puzzles, pestering the scientists. Understandably, it is hard to accept that the sanctity of science can be soiled by the very human nature of scientists (recall Sect. 9.1.5). Moreover, it is not easy to admit that (Tarnas 1991, p. 358):

> Physicists failed to come to any consensus as to how the existing evidence should be interpreted with respect to defining the ultimate nature of reality. Conceptual contradictions, disjunctions, and paradoxes were ubiquitous, and stubbornly evaded resolution. A certain irreducible irrationality, already recognized in in the human psyche, now emerged in the structure of the physical world itself.

Perhaps it is consoling to some scientists that philosophy itself also suffer in the modern era (Tarnas 1991, p. 354):

> As philosophy became more technical, more concerned with methodology, and more academic, and as philosophers increasingly wrote not for the public but for each other, the discipline of philosophy lost much of its former relevance and importance for the intelligent layperson, and thus much of its former cultural power.

9.2.1 The Comprehensible Universe

Of all the magnificent capabilities of the modern human mind, one is especially curious: the ability to be unimpressed by existence. While as children we are dumbfounded by the unfathomable reality encompassing us, as adults we are so often caught up in our bland daily routines that we cease to wonder. But not everyone. The philosopher Alan Watts confessed (Watts 1971 p. 23):

> As Aristotle put it, the beginning of philosophy is wonder. I am simply amazed to find myself living on a ball of rock that swings around an immense spherical fire. I am more amazed that I am a maze—a complex wiggliness, an arabesque of tubes, filaments, cells, fibers, and films that are various kinds of palpitation in this stream of liquid energy.

In a similar vein, Einstein's musings (Einstein 2007, p. 5):

> The fairest thing we can experience is the mysterious. It is the fundamental emotion which stands at the cradle of true art and science. He who knows it not and can no longer wonder, no longer feel amazement, is as good as dead, a snuffed-out candle.

Ranking second, after blissful wonder, is perhaps the realization that reality can be comprehended. Indeed, it is a striking hidden assumptions of science that the universe is understandable to the human mind. Why should the mysterious workings of the grand universe find a correspondence in our minds and hence a correlate in our brains? Why should the formal abstract thoughts systems the human mind can access—even while sitting in Plato's cave—relate to anything in the outer world? Why is there an overlap between inner and outer structures? In other words, why does a Book of Nature exist at all and why is it written in a language the human mind can read? These issues are detailed in Part I.

This astounding fact has had an enchanting effect on some eminent scientists. For instance, the theoretical physicist, mathematician, and Nobel laureate Eugene Wigner. In 1960 he published an article with the striking title: *The Unreasonable Effectiveness of Mathematics in the Natural Sciences*[8] (Wigner 1960). There he observed:

> [T]he enormous usefulness of mathematics in the natural sciences is something bordering on the mysterious and [...] there is no rational explanation for it.
>
> [I]t is not at all natural that "laws of nature" exist, much less that man is able to discover them.
>
> [T]he two miracles of the existence of laws of nature and of the human mind's capacity to divine them.
>
> [F]undamentally, we do not know why our theories work so well.

Also Einstein did not hide his bewilderment (Isaacson 2007, p. 462):

> The eternal mystery of the world is its comprehensibility.
>
> The fact that it is comprehensible is a miracle.

[8]It is tempting to add the "unreasonable simplicity of complexity" to this line of musing, which miraculously makes the complex systems surrounding us accessible and comprehensible, as described in Sect. 5.2.1.

Even as one of the greatest minds in physics he did not resist the temptation to express his views on science in an unscientific way which would have been scorned by many scientists had they been uttered by a lesser colleague (Einstein 1918):

> The supreme task of the physicist is to arrive at those universal elementary laws from which the cosmos can be built up by pure deduction. There is no logical path to these laws; only intuition, resting on sympathetic understanding of experience, can reach them.

Einstein continues (Einstein 1918):

> The state of mind which enables a man to do work of this kind [science] is akin to that of the religious worshiper or the lover; the daily effort comes from no deliberate intention or program, but straight from the heart.

Also the great cosmologist Stephen Hawking was tempted to dive deep into the metaphysical underbelly (Hawking 2008, p. 142):

> What is it that breathes fire into the equations and makes a universe for them to describe?

To escape such metaphysical and existential challenges, scientists have been know to invoke the concept of beauty or some kind of divinity. Recall the words of the theoretical physicist and Nobel laureate Steven Weinberg from Sect. 4.4:

> We believe that, if we ask why the world is the way it is and then ask why that answer is the way it is, at the end of this chain of explanations we shall find a few simple principles of compelling beauty.

Again, Einstein (Isaacson 2007, p. 388f.):

> I believe in Spinoza's God, who reveals himself in the harmony of all that exists, not in a God who concerns himself with the fate and the doings of mankind.

The rationalist philosopher Baruch Spinoza offered a vision of God as the essence of the universe (Nadler 2016):

> God is the infinite, necessarily existing (that is, uncaused), unique substance of the universe. There is only one substance in the universe; it is God; and everything else that is, is in God.

Some have described such an understanding of God as pantheistic while others have seen links to Hinduism (Van Bunge and Klever 1996). In Einstein's own words (Frankenberry 2008, p. 147):

> Every one who is seriously involved in the pursuit of science becomes convinced that a spirit is manifest in the laws of the Universe—a spirit vastly superior to that of man, and one in the face of which we with our modest powers must feel humble.

Einstein would later define a principle of cosmic religion, see Sect. 15.3.1.

Even though Einstein's intuition was so acute that it allowed him to access and uncover new facets of reality that were unimaginable before him, he appeared to have hit a dead end while pondering quantum phenomena. Not only did he reject their reality, tragically, his attempts at an alternative formulation would preoccupy his mind in vain until his death (see Sects. 4.3.4, 10.3.2.1, and 4.3.5). Perhaps this next quote from him best summarizes the inner turmoil felt by the practitioners of science (quoted in Hoffmann and Dukas 1973, p. vii):

> One thing I have learned in a long life: That all our science, measured against reality, is primitive and childlike—and yet it is the most precious thing we have.

Moreover, Einstein held the following personal conviction (quoted in Dukas and Hoffmann 2013, p. 39):

> What I see in Nature is a magnificent structure that we can comprehend only very imperfectly, and that must fill a thinking person with a feeling of humility.

Returning to philosophy, one may ask the following question: What if the observable and comprehensible universe is only a slice of the totality of reality? What if the fabric of reality is vastly richer than we can perceive and fathom? Such a concession would allow for the notions of teleology and entelechy to enter the picture as explanatory templates, without the need to invoke the divine. Such musings are entertained in Part III.

9.2.2 The End of Science?

In the history of science, there have been many occasions where it was believed that nearly all of the workings of the universe had been decoded. Again and again, tempted by the dream of being only a small step away from a complete description of nature, scientists have made exuberant claims. For instance Graham et al. (1983, p. 38):

> Indeed, it seemed to some physicists in the closing year of the nineteenth century that taken together, Newton's celestial mechanics and Maxwell's equations indicated that the prospect of completing physics was in sight.

In the words of the eminent experimentalist Albert A. Michelson in 1894 (quoted in Graham et al. 1983, p. 38):

> While it is never safe to affirm that the future of physical science has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice. It is here that the science of measurement shows its importance—where quantitative work is more to be desired than qualitative work. An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals.

Then, in 1920 (Hawking 1980, p. 1):

> [...] Max Born told a group of scientists visiting Göettingen that "Physics, as we know it, will be over in six months."

In 1980, Stephen Hawking gave his inaugural lecture as Lucasian professor of mathematics at the University of Cambridge, England, titled *Is the End in Sight for Theoretical Physics?* He opened with (Hawking 1980):

> In this lecture I want to discuss the possibility that the goal of theoretical physics might be achieved in the not too far future, say, by the end of the century. By this I mean that we might have a complete, consistent and unified theory of the physical interactions which would describe all possible observations.

Ten years later Hawking updated his prediction: "Give it twenty or twenty-five years" (Ferguson 2011, p. 214; see also Sect. 4.3.2). However, in 1998 the optimism started to diminish (Smith 2016):

> It doesn't look as if we are going to quite make it.

Finally, in 2002 (Hawking 2002):

> Some people will be very disappointed if there is not an ultimate theory, that can be formulated as a finite number of principles. I used to belong to that camp, but I have changed my mind.

The end of science, in the sense that everything there is to know became known to the human mind, never transpired. The science journalist John Horgan took a more sinister take on the end of science in his book of the same name (Horgan 1997). He argued that science is loosing its momentum to uncover knowledge, slowly grinding to a halt. For the book, he interviewed prominent scientists and philosophers. The likes of Popper, Kuhn, Feyerabend, Daniel Dennett, Hawking, Weinberg, Feynman, Dyson, Roger Penrose, Murray Gell-Mann, Sheldon Glashow, Edward Witten, John Wheeler, David Bohm, Philip Anderson, Ilya Prigogine, Mitchell Feigenbaum, Gregory Chaitin, John Casti, Francis Crick, Richard Dawkins, Stuart Kauffman, and Edward O. Wilson. Horgan identifies the demise of progress in

- the end of philosophy;
- the end of physics;
- the end of cosmology;
- the end of evolutionary biology;
- the end of social science;
- the end of neuroscience;
- the end of chaoplexity (the portmanteau of chaos and complexity);
- the end of machine science.

Naturally, many people were not amused. The biologist Lynn Margulis perhaps captured this best (quoted in Horgan 2015):

> He's a very nice guy and he wrote a very bad book.

Looking back, Horgan assesses (Horgan 2015):

> The re-launch [Basic Book's 2015 edition of *The End of Science*] has stirred up many memories—and forced me to evaluate my thesis. My book has now sustained almost two decades worth of attacks, some triggered by genuine scientific advances, from the completion of the Human Genome Project to the discovery of the Higgs boson. So do I take anything back?
>
> Hell no.

In a nutshell, taken from the preface of the new edition (Horgan 2015):

> Our descendants will learn much more about nature, and they will invent gadgets even cooler than smart phones. But their scientific version of reality will resemble ours, for two reasons: First, ours […] is in many respects true; most new knowledge will merely extend and fill in our current maps of reality rather than forcing radical revisions. Second, some major remaining mysteries—Where did the universe come from? How did life begin? How, exactly, does a chunk of meat make a mind?—might be unsolvable.

Indeed, today, we are still waiting for a coherent and unified theory describing the physical world. Or, at least, a theory of quantum gravity (Sect. 10.2). Unfortunately, the outlook is as bleak as ever and the understanding of ourselves and the world we live in continues to run into dead ends. It is as if nature enjoys teasing the human mind, by pretending to reveal her workings, only to present us with the next enigmas and then turn away. Science has become like the Red Queen in Lewis Carroll's writings about Alice's adventures in wonderland: by running faster and faster she stays at the same place. Similarly, science discovers more and more knowledge without fundamentally progressing anymore. For an assessment of the status of modern theoretical physics see Baggott (2013), Unzicker and Jones (2013).

Furthermore, science has been beset by various crisis. For instance, the reproducability crisis (Baker 2016):

> More than 70% of researchers have tried and failed to reproduce another scientist's experiments, and more than half have failed to reproduce their own experiments. Those are some of the telling figures that emerged from *Nature's* survey of 1,576 researchers who took a brief online questionnaire on reproducibility in research.

The application of bad statistics (Nieuwenhuis et al. 2011) has also raised questions. Analyzing 513 papers published in five prestigious neuroscience journals over two years, 157 studies where identified where a potential statistical fallacy could have been committed. Indeed, out of these publications, 50% contained the error. Generally, the whole notion of statistical significance can be called into question (Ziliak and McCloskey 2008). Moreover, as science advances, it relies more and more heavily upon very complex machinery and highly sophisticated software. This can be another source of error. For instance, a bug found in the software used by researchers to interpret fMRI data was found to result in false positive rates up to 70%, calling 15 years of research into question (Reynolds 2016). Some researchers have even alleged that "most published research findings are false" (Ioannidis 2005). The observation, that the number of scientific retractions is increasing (Steen et al. 2013), could be a sign of scientific self-correction or simply the result of poor scientific practices (Smaldino and McElreath 2016).

However, perhaps the biggest threat to science are the scientists themselves. Like any other social human endeavor, academia can be plagued by blind obedience to authority,[9] groupthink, corruption, and fraud. Furthermore, the unrelenting pressure to "publish or perish" expects scientists to be inexhaustible creative content-providers—with very possible negative consequences (Smaldino and McElreath 2016). The following anecdotes highlights some of these problems.

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[9] Recall the initial opposition to quasicrystals in Sect. 5.1.3.

A publication in the prestigious *Proceedings of the National Academy of Sciences* (*PNAS*) claimed to have detected a universal pattern in how complex systems organize (Preis et al. 2011). Specifically, the authors reported on scaling laws found in financial data.[10] The study became famous not only among quantitative analysts. However, when the physicist, econophysicist, and complexity scientist Didier Sornette reproduced the study utilizing purely random data, surprisingly, the same patterns emerged. A "selection of biased statistical subsets of realizations in otherwise featureless processes such as random walks" (Filimonov and Sornette 2012) was responsible for the signal. In other words, the publication was meaningless, as the researchers did not reject the null hypothesis. To his utter dismay, when Sornette submitted these findings to *PNAS*, his paper was rejected. In an open letter he vented his frustration[11]:

> Dear Editor,
>
> As a coauthor of the paper *Spurious switching processes in financial markets* that you just rejected, I cannot remain silent and have to express my concern with how science is handled in general in journals such as *PNAS*. You are not alone as *Science* and *Nature* have in general the same reactions. I know that you will not change your mind in this instance, but I do hope that, little by little, the whole editorial community may become a bit wiser over time.
>
> In a nutshell, your policy stating "it would have to go beyond a simple refutation of the earlier work and significantly add to the field", implies
>
> 1. a fundamental error can remain published as "truth" in *PNAS* without the normal debate that should be the domain of real science. In my opinion, this is especially harmful to Science, given that this specific spurious claim for discovery has been highly publicized in different journals, in the media and many conferences.
> 2. a paper that does the solid work to demonstrate that the spurious claim is unsupported will most likely be considered as "not adding significantly to the field". In other words, we can add "shit" to the field but we cannot correct and remove "shit" from the field, and in so doing teach how to develop better statistical tests. […]
>
> I hope that any editor could realize the moral hazard and wrong incentives permeating more and more the sociology of science encouraged by editors such as you (no personal attack, I know that you are just following "orders" of a general stance dictated by editorial boards of journals), in a way analogous to a graft from the scandalous behaviors observed in the financial industry.
>
> Excuse my strong colorful words, but I consider that they convey my shock and repulsion to what I consider a violation of good scientific endeavor.
>
> Sincerely,
> Prof. D. Sornette

In 1956, two researchers applied a recently developed technique for analyzing human cells and counted 46 chromosomes. This was puzzling, as everyone familiar with biology knew that the correct answer was, since 1912, 48. After consulting with colleagues, it emerged that, surprisingly, other researcher had encountered the same problem. Some even stopped their work prematurely, as they could only find 46 of

[10] For actual scaling laws in finance, see Sect. 6.4.3.4.

[11] See http://www.er.ethz.ch/media/essays/PNAS.html.

the 48 chromosomes which had to be there. Not our two researchers, who boldly, and correctly, claimed that everyone else was wrong. See Arbesman (2012). In a similar vein, albeit more trivial, how many scientists know the following (Dicken 2018, back cover):

> When Galileo dropped cannonballs from the top of the Leaning Tower of Pisa, he did more than overturn centuries of scientific orthodoxy. At a stroke, he established a new conception of the scientific method based upon careful experimentation an rigorous observation […].
>
> The problem is that Galileo never performed his most celebrated experiment in Pisa. In fact, he rarely conducted any experiments at all.

Also recall Sect. 5.3.1 describing the initially favorable relationship Galileo and the Church enjoyed.

Finally, it is worth noting that science has no intrinsic aim, other than blind advancement, and is also not goal-driven. Kuhn famously and influentially argued that sciences progresses by sudden, unforeseeable disruptions. Initially, he viewed these paradigm shifts in science (recall Sect. 9.1.3) as being based on faith, fashion, and peer pressure, where evidence and reason only play a minor role. Moreover, he believed science was largely a non-rational activity. Kuhn later moderated his tone and offered a less radical vision of his ideas. For instance, the notion that there exist no algorithms for theory choice in science—scientific progress is inherently opaque. See Okasha (2002). In any case, how free are scientists really to steer the direction of research? As an example (Harari 2015, p. 303):

> During the past 500 years modern science has achieved wonders thanks largely to the willingness of governments, businesses, foundations and private donors to channel billions of dollars into scientific research.
>
> […]
>
> Why did the billions start flowing from government and business coffers into labs and universities? In academic circles, many are naive enough to believe in pure science. They believe the government and businesses altruistically give them money to pursue whatever research projects strike their fancy.

Essentially (Harari 2015, p. 304):

> Scientists themselves are not always aware of the political, economic and religious interests that control the flow of money; many scientists do, in fact, act out of pure intellectual curiosity. However, only rarely do scientists dictate the scientific agenda.

Today, many scientists feel a lot of pressure, as they see the amount of scientific funding declining globally. More and more time is spent drafting funding proposals, which can drain a lot of resources from research (Powell 2016). Aspects relating to marketing and bureaucracy become relevant. Will science simply come to an end because the general population fails to see its benefits anymore and many politicians will thus be happy to pull the plug? A very real concern, in our post-truth world, where a climate of rising populism sees experts as a threat.

9.2.3 The Fractal Nature of Knowledge

The epitome of scientific progress is recounted by the theoretical physicist Sidney Coleman (quoted in Moriyasu 1983, p. 119):

> There is a popular model of a breakthrough in theoretical physics. A field of physics is afflicted with a serious contradiction. Many attempts are made to resolve the contradiction; finally, one succeeds. The solution involves deep insights and concepts previously thought to have little or nothing to do with the problem. It unifies old phenomena and predicts unexpected (but eventually observed) new ones. Finally, it generates new physics: the methods used are successfully extended beyond their original domain.

While such upheavals were common in the past, today they have become exceedingly rare events. The increments at which science progresses appear to be becoming infinitesimal. Knowledge seems to posses a fractal-like nature, akin to an abstract space into which the human mind can zoom in indefinitely and the richness of structure does not diminish.

This paradox has been observed by some thinkers. In the words of Deutsch (2011, p. 64):

> The deeper an explanation is, the more new problems it creates. That must be so, if only because there can be no such thing as an ultimate explanation: just as “the gods did it” is always a bad explanation, so any other purported foundation of all explanations must be bad too.

Similarly, Popper's eloquent prose, taken from Popper (1992, p. 8):

> I think there is only one way to science—or to philosophy, for that matter: to meet a problem, to see its beauty and fall in love with it; to get married to it and to live with it happily, till death do ye part—unless you should meet another and even more fascinating problem or unless, indeed, you should obtain a solution. But even if you do obtain a solution you may then discover, to your delight, the existence of a whole family of enchanting, though perhaps difficult, problem children.

In his widely acclaimed bestselling novel *Zen and the Art of Motorcycle Maintenance*, which was rejected by over hundred publishers, Robert M. Pirsig addresses related issues. The book “should in no way be associated with that great body of factual information relating to orthodox Zen Buddhist practice,” neither is it “very factual on motorcycles” (Pirsig 1981, Author's Note). It is, however, a miniature study of the art of rationality itself. Pirsig argues that although thought may find truth, it may not be valid for all experiences. Again, the closer one examines a phenomenon, the more perplexing it becomes as every explanation seems to open the door to countless new puzzles (Pirsig 1981, p. 101):

> The more you look, the more you see. [A]s you try to move toward unchanging truth through the application of scientific method, you actually do not move toward it at all. You move away from it! It is your application of scientific method that is causing it to change!

Finally (Pirsig 1981, p. 101):

> Through multiplication upon multiplication of facts, information, theories and hypotheses, it is science itself that is leading mankind from single absolute truths to multiple, relative ones.

These words have a distinct postmodern ring to them. Finally, Wheeler, offers a haunting paradox (quoted in Horgan 1997, p. 84):

> At the heart of everything is a question, not an answer. When we peer down into the deepest recesses of matter or at the farthest edge of the universe, we see, finally, our own puzzled faces looking back at us.

9.3 The Practitioners of Science

Usually, scientists aren't very vocal about their personal experiences of practicing science. Science is a craft not to be burdened with intangible and immaterial overhead—in stark contrast to philosophers, whose trade it is to unearth vexing issues relating to the nature of knowledge, reality, and the human mind. The problem with knowing what beliefs scientists hold dear is that, by definition, this information is non-scientific. Hence, one searches for such revelations in the peer-reviewed literature without avail.[12] Sometimes though, scientists will give a glimpse of their inner worlds in popular science books they author. Other times, they are explicitly asked to reveal their very personal ideas about the universe.

In 1988, the literary agent and author John Brockman founded the *Edge Foundation*.[13] It has become an intellectual platform for scientists and deep thinkers to directly convey their thoughts to the public in a readily accessible manner to non-specialist. The tag-line on their website reads:

> To arrive at the edge of the world's knowledge, seek out the most complex and sophisticated minds, put them in a room together, and have them ask each other the questions they are asking themselves.

Since 1998, the *Edge* poses an annual question[14] to a diverse group of physicists, mathematicians, biologists, computer scientists, philosophers, etc. In 2005, the question was: What do you believe is true even though you cannot prove it? The compilation of the answers was published as a book edited by Brockman, titled *What We Believe but Cannot Prove: Today's Leading Thinkers on Science in the Age of Certainty* (Brockman 2006). Ever since, the annual question has resulted in a book:

[12]Naturally, some exceptions exist. For instance, Springer's *The Frontiers Collection*, where this book is published in, "is intended to encourage active scientists in all areas to ponder over important and perhaps controversial issues beyond their own speciality."

[13]See: http://www.edge.org.

[14]See: http://www.edge.org/annual-questions.

2006 What is your dangerous idea? (Brockman 2007a)
2007 What are you optimistic about? (Brockman 2007b)
2008 What have you changed your mind about? (Brockman 2009)
2009 What will change everything? (Brockman 2010)
2010 How is the Internet changing the way you think? (Brockman 2011)
2011 What scientific concept would improve everybody's cognitive toolkit? (Brockman 2012)
2012 What is your favorite deep, elegant, or beautiful explanation? (Brockman 2013)
2013 What should we be worried about? (Brockman 2014)
2014 What scientific idea is ready for retirement? (Brockman 2015a)
2015 What do you think about machines that think? (Brockman 2015b)
2016 What do you consider the most interesting recent [scientific] news? (Brockman 2016)
2017 What scientific term or concept ought to be more widely known? (Brockman 2017)
2018 What is the last question?

Browsing through these book will give the reader insights into the amazing diversity and creativity of ideas. Naturally, many of the revealed beliefs are polar opposites—divergence and contradictions abound. Nonetheless, in such moments of honesty and intimacy we can glimpse behind the scenes and gauge the minds of contemporary intellectuals.[15] What becomes apparent is that many thinkers can acknowledge limits in knowledge and accept uncertainty and ambiguity—and even ignorance. Looking back at the spectacular success of human knowledge generation (see Part I), we are, somewhat anxiously, anticipating a future, where from the borders of knowledge radical and transcending new visions of the true nature of reality and consciousness are expected to emerge (see Part III).

9.3.1 On Philosophy

Sam Harris (Brockman 2015a):

> Search your mind, or pay attention to the conversations you have with other people, and you will discover that there are no real boundaries between science and philosophy.
>
> We must abandon the idea that science is distinct from the rest of human rationality.

Rebecca Newberger Goldstein (Brockman 2015a):

> You can't argue for science making philosophy obsolete without indulging in philosophical arguments. You're going to need to argue, for example, for a clear criterion for distinguishing between scientific and non-scientific theories of the world.
>
> A triumphalist scientism needs philosophy to support itself.

[15] Note that it can be considered an honor to be asked to answer an annual question.

Paul Bloom (Brockman 2012):

> Scientists can reject common wisdom, they can be persuaded by data and argument to change their minds. It is through these procedures that we have discovered extraordinary facts about the world, such as the structure of matter and the evolutionary relationship between monkey and man.
>
> The cultivation of reason isn't unique to science; other disciplines such as mathematics and philosophy possess it as well. But it is absent in much of the rest of life.

Melanie Swan (Brockman 2013):

> Therefore some of the best explanations may have the parameters of being intuitively beautiful and elegant, offering an explanation for the diverse and complicated phenomena found in the natural universe and human-created world, being universally applicable or at least portable to other contexts, and making sense of things at a higher order. Fields like cosmology, philosophy, and complexity theory have already delivered in this exercise: they encompass many other science fields in their scope and explain a variety of micro and macro scale phenomena.

9.3.2 On Objectivity, Truth, Knowledge, and Certainty

Gavin Schmidt (Brockman 2015a):

> We continually read about the search for the one method that will allow us to cut through the confusion, the one piece of data that tell us the "truth", or the final experiment that will "prove" the hypothesis. But almost all scientists will agree that these are fool's errands—that science is [a] method for producing incrementally more useful approximations to reality, not a path to absolute truth.

Mihaly Csikszentmihalyi (Brockman 2015a):

> What needs to be retired is the faith that what scientists say are objective truths, with a reality independent of scientific claims. Some are indeed true, but others depend on so many initial conditions that they straddle the boundary between reality and fiction.

Scott Sampson (Brockman 2015a):

> One of the most prevalent ideas in science is that nature consists of objects.
>
> Yet this pervasive, centuries-old trend toward reductionism and objectification tends to prevent us from seeing nature as subjects, though there's no science to support such myopia.

Alan Kay (Brockman 2006):

> When we guess in science we are guessing about approximations and mappings to languages, we are not guessing about "the truth" (and we are not in a good state of mind for doing science if we think we are guessing "the truth" or "finding the truth"). This is not at all well understood outside of science, and there are unfortunately a few people with degrees in science who don't seem to understand it either.

Timothy Taylor (Brockman 2006):

> If science fetishized truth, it would be religion, which it is not.

Michael Shermer (Brockman 2006):

> Our knowledge of nature remains provisional because we can never know if we have final Truth.
>
> In science, knowledge is fluid and certainty fleeting.

Clifford Pickover (Brockman 2014):

> Should we be so worried that we will not really be able to understand subatomic physics, quantum theory, cosmology, or the deep recesses of mathematics and philosophy? Perhaps we can let our worries slightly recede and just accept our models of the universe when they are useful.

Nicholas G. Carr (Brockman 2017):

> But what if our faith in nature's knowability is just an illusion, a trick of the overconfident human mind?

Lawrence M. Krauss (Brockman 2017):

> Nothing feels better than being certain, but science has taught us over the years that certainty is largely an illusion. In science, we don't "believe" in things, or claim to know the absolute truth.

9.3.3 On Laws of Nature, Reality, and Science

Lawrence M. Krauss (Brockman 2015a):

> [T]he laws of nature we measure may be totally accidental, local to our environment (namely our Universe), not prescribed with robustness by any universal principle, and by no means generic or required.
>
> [T]here may be nothing fundamental whatsoever about the "fundamental" laws we measure in our universe. They could simply be accidental. Physics becomes, in this sense, an environmental science.

Gregory Benford (Brockman 2009):

> I once thought that the laws of our universe were unquestionable, in that there was no way for science to address the question. Now I'm not so sure. Can we hope to construct a model of how laws themselves arise?

Charles Seife (Brockman 2009):

> Science is about freedom of thought, yet at the same time it imposes a tyranny of ideas.

Colin Tudge (Brockman 2009):

> I have changed my mind about the omniscience and omnipotence of science. I now realize that science is strictly limited, and that it is extremely dangerous not to appreciate this.

Haim Harari (Brockman 2009):

> The public thinks, incorrectly, that science is a very accurate discipline where everything is well defined.

Donald D. Hoffman (Brockman 2015a):

> Observation is the empirical foundation of science. The predicates of this foundation, including space, time, physical objects and causality, are a species-specific adaptation, not an insight.

Ian Bogost (Brockman 2015a):

> To think that science has a special relationship to observations about the material world isn't just wrong, it's insulting.
>
> But ironically, in its quest to prove itself as the supreme form of secular knowledge, science has inadvertently elevated itself into a theology. Science is not a practice so much as it is an ideology.

Satyajit Das (Brockman 2015a):

> While not strictly a scientific theorem, anthropocentrism, the assessment of reality through an exclusively human perspective, is deeply embedded in science and culture.
>
> Like a train that can only run on tracks that determine direction and destination, human knowledge may ultimately be constrained by what evolution has made us.
>
> Science, paradoxically, seems to also have inbuilt limits. Like an inexhaustible Russian doll, quantum physics is an endless succession of seemingly infinitely divisible particles. Werner Heisenberg's uncertainty principle posits that human knowledge about the world is always incomplete, uncertain and highly contingent. Kurt Gödel's incompleteness theorems of mathematical logic establish inherent limitations of all but the most trivial axiomatic systems of arithmetic.

Sarah Demers (Brockman 2015a):

> Of course, including aesthetic considerations in the scientific toolbox has resulted in huge leaps forward.
>
> At this stage, with 96% of the universe's content in the dark, it is a mistake for us to put aesthetic concerns in the same realm as contradictions when it comes to theoretical motivation. With no explanation for dark energy, no confirmed detection of dark matter and no sufficient mechanism for matter/antimatter asymmetry, we have too many gaps to worry about elegance.

Max Tegmark (Brockman 2009):

> After all, physical reality has turned out to be very different from how it seems, and I feel that most of our notions about it have turned out to be illusions.
>
> From your subjectively perceived frog perspective, the world turns upside down when you stand on your head and disappears when you close your eyes, yet you subconsciously interpret your sensory inputs as though there is an external reality that is independent of your orientation, your location and your state of mind.

Jean Paul Schmetz (Brockman 2006):

> […] our body of scientific knowledge is surely full of statements we believe to be true but will eventually be proved to be false.

Donald D. Hoffman (Brockman 2016):

> Nobel Laureate David Gross observed, "Everyone in string theory is convinced...that space-time is doomed. But we don't know what it's replaced by." Fields medalist Edward Witten also thought that space and time may be "doomed." Nathan Seiberg of the Institute for Advanced Study at Princeton said, "I am almost certain that space and time are illusions. These are primitive notions that will be replaced by something more sophisticated."

Tor Nørretranders (Brockman 2010):

> The visual world, what we see, is an illusion, but then a very sophisticated one. There are no colours, no tones, no constancy in the "real" world, it is all something we make up. We do so for good reasons and with great survival value.

9.3.4 On Ignorance and Irrationality

Paul Saffo (Brockman 2015a):

> The science establishment justifies its existence with the big idea that it offers answers and ultimately solutions. But privately, every scientist knows that what science really does is discover the profundity of our ignorance.

Robert Provine (Brockman 2015a):

> We fancy ourselves intelligent, conscious and alert, and thinking our way through life. This is an illusion. We are deluded by our brain's generation of a sketchy, rational narrative of subconscious, sometimes irrational or fictitious events that we accept as reality.

Tom Griffiths (Brockman 2015a):

> And when psychology experiments show that people are systematically biased in the judgments they form and the decisions they make, we begin to question human rationality.

Alex Pentland (Brockman 2015a):

> It is time that we dropped the fiction of individuals as the unit of rationality, and recognized that we are embedded in the surrounding social fabric.

Margaret Wertheim (Brockman 2006):

> In truth our ignorance is vast—and personally I believe it will always be so.

Dylan Evans (Brockman 2017):

> If we could represent the knowledge in any given brain as dry land, and ignorance as water, then even Einstein's brain would contain just a few tiny islands scattered around in a vast ocean of ignorance. Yet most of us find it hard to admit how little we really know.

9.3.5 *On the Mind*

Susan Blackmore (Brockman 2015a):

> Consciousness is not some weird and wonderful product of some brain processes but not others. Rather, it is an illusion constructed by a clever brain and body in a complex social world. We can speak, think, refer to ourselves as agents and so build up the false idea of a persisting self that has consciousness and free will.

Jerry A. Coyne (Brockman 2015a):

> In short, the traditional notion of free will—defined by Anthony Cashmore as "a belief that there is a component to biological behavior that is something more than the unavoidable consequences of the genetic and environmental history of the individual and the possible stochastic laws of nature"—is dead on arrival.

Tania Lombrozo (Brockman 2015a):

> In our enthusiasm to find a scientifically-acceptable alternative to dualism, some of us have gone too far the other way, adopting a stark reductionism. Understanding the mind is not just a matter of understanding the brain.

Bruce Hood (Brockman 2015a):

> We know that the self is constructed because it can be so easily deconstructed through damage, disease and drugs. It must be an emergent property of a parallel system processing input, output and internal representations. It is an illusion because it feels so real, but that experience is not what it seems.

Daniel Goleman (Brockman 2009):

> Science found that, compared to novices, highly adept meditators generated far more high-amplitude gamma wave activity—which reflects finely focused attention—in areas of the prefrontal cortex while meditating.
>
> The seasoned meditators in this study—all Tibetan lamas—had undergone cumulative levels of mental training akin to the amount of lifetime sports practice put in by Olympic athletes: 10,000 to 50,000 hours. Novices tended to increase gamma activity by around 10 to 15 percent in the key brain area, while most experts had increases on the order of 100 percent from baseline. What caught my eye in this data was not this difference between novices and experts (which might be explained in any number of ways, including a self-selection bias), but rather a discrepancy in the data among the group of Olympic-level meditators.
>
> Although the experts' average boost in gamma was around 100 percent, two lamas were "outliers": their gamma levels leapt 700 to 800 percent. This goes far beyond an orderly dose-response relationship—these jumps in high-amplitude gamma activity are the highest ever reported in the scientific literature apart from pathological conditions like seizures. Yet the lamas were voluntarily inducing this extraordinarily heightened brain activity for just a few minutes at a time—and by meditating on "pure compassion," no less.
>
> I have no explanation for this data, but plenty of questions. At the higher reaches of contemplative expertise, do principles apply (as the Dalai Lama has suggested in dialogues with neuroscientists) that we do not yet grasp? If so, what might these be? In truth, I have no idea. But these puzzling data points have pried open my mind a bit as I've had to question what had been a rock-solid assumption of my own.

Lutz et al. (2004) is the publication Goleman is referring to here. See also Sect. 7.4.2.1 for an account of Matthieu Ricard, a molecular geneticist turned Buddhist monk, displaying exceptional powers of self-awareness and control, in the context of compassion and meditation.

9.3.6 And More

W. Daniel Hillis (Brockman 2015a):

> The cause-and-effect paradigm works particularly well when science is used for engineering, to arrange the world for our convenience. In this case, we can often set things up so that the illusion of cause-and-effect is almost a reality.
>
> The notion of cause-and-effect breaks down when the parts that we would like to think of as outputs affect the parts that we would prefer to think of as inputs. The paradoxes of quantum mechanics are a perfect example of this, where our mere observation of a particle can "cause" a distant particle to be in a different state. Of course there is no real paradox here, there is just a problem with trying to apply our storytelling framework to a situation where it does not match.

Nigel Goldenfeld (Brockman 2015a):

> If the stuff that makes the universe is strongly connected in space and not usefully thought of as the aggregate of its parts, then attributing a cause of an event to a specific component may not be meaningful either. Just as you can't attribute the spin of a proton to any one of its constituents, you can't attribute an event in time to a single earlier cause. Complex systems have neither a useful notion of individuality nor a proper notion of causality.

Marcelo Gleiser (Brockman 2015a):

> The trouble starts when we take this idea too far and search for the *Über*-unification, the Theory of Everything, the arch-reductionist notion that all forces of nature are merely manifestations of a single force. This is the idea that needs to go. And I say this with a heavy heart; my early career aspirations and formative years were very much fueled by the impulse to unify it all.
>
> Why do so many insist in finding the One in Nature while Nature keeps telling us it's really about the Many? For one thing, the scientific impulse to unify is crypto-religious. The West has bathed in monotheism for thousands of years [...].
>
> The belief is that nature's ultimate code exists in the ethereal world of mathematical truths and we can decipher it. Recent experimental data has been devastating to such belief [...].
>
> We may hold perfection in our mind's eye as a sort of ethereal muse. Meanwhile nature is out there doing its thing. That we manage to catch a glimpse of its inner workings is nothing short of wonderful.

Marcelo Gleiser (Brockman 2009):

> The model of unification, which is so aesthetically appealing, may be simply this, an aesthetically appealing description of Nature, which, unfortunately, doesn't correspond to physical reality. Nature doesn't share our myths.

9.4 The Limits of Mathematics

The metaphor of the Book of Nature relies on the assumption that mathematics is the sole source of all exact knowledge of the world. By translating aspects of the physical world into formal abstractions, the human mind can unlock novel understanding of the workings of the universe (Sect. 2.1). Indeed, mathematical beauty was understood as a guiding principle in physics and a seemingly simple principle of symmetry unearthed some of the deepest understanding of reality (Chaps. 3 and 4). Platonism is the notion that a realm of perfect abstractions exists where all mathematical entities reside. In other words, mathematics has its own reality. In this sense, mathematics is discovered and not invented by the human mind. Notwithstanding the philosophical issues which are implied (Sect. 2.2.1), many of the greatest mathematicians were and are self-proclaimed Platonists (Sect. 2.2).

9.4.1 *Inherent Randomness*

Similar to the decline of science and philosophy chronicled in this chapter, mathematics also experienced a demotion. Ironically, at a time when mathematicians were establishing the foundations of mathematics, based on a complete set of consistent axioms,[16] disaster struck. Out of nowhere, Kurt Gödel—also a defender of mathematical Platonism—destroyed any hopes of establishing a solid foundation of mathematics. His incompleteness theorems proved that every formal axiomatic system containing basic arithmetic is inconsistent and incomplete (Sect. 2.2). In other words, the basic expectations, that a statement is true because there is a proof of the statement and that if a statement is true there is a proof of the statement, are—to everyone's dismay—untenable.

Building on Gödel's work, Alan Turing expanded the scope of the conundrum to computation (Turing 1936). In essence, the uncertainty discovered by Gödel now spread and plagued the mathematical foundations of the newly emerging computer science. Turing's so-called halting problem is about undecidability. It is impossible for a computer to decide in advance whether a given program will ever finish its task and halt. The only way to find out if a program will ever halt is to run it and wait—ten minutes, ten billion years, or forever. See also Sect. 13.1.2.

Decades later, the mathematician and computer scientist Gregory Chaitin continued where Turing left off, yet again extending Gödel's haunting legacy. He translated Turing's question, of whether a program halts, into a real number between 0 and 1. In essence, this uncomputable number—called Omega—reflects the probability that an arbitrary computer program will eventually halt (Chaitin 1975). "It's the outstanding

[16]Recall that axioms within any logical system can, by definition, not be proved by that system. Axioms are just a given, supporting the mathematical structure built upon them—they themselves are floating in the abstract abyss.

example of something which is unknowable in mathematics," Chaitin says (quoted in Chown 2001).

Unfortunately, Omega is more than an academic curiosity. It is not some esoteric number appearing at the fringes of mathematics. Chaitin's halting probability is intimately linked to simple mathematical operations, such as the addition and multiplication of whole numbers. Randomness lurks at the heart of mathematics. After decades of fundamental research, the verdict is out (Calude and Chaitin 1999):

> [...] randomness is as fundamental and as pervasive in pure mathematics as it is in theoretical physics. In our opinion it also gives further support to "experimental mathematics", and to the "quasi-empirical" view of mathematics which says that although mathematics and physics are different, it is more a matter of degree than black and white.

For millennia, people have regarded mathematics as an outstanding intellectual construction of humankind. Mathematics was viewed as the pinnacle of rational thinking and human reasoning. Alas, today we know, as explained in the words of Chaitin, that (quoted in Chown 2001):

> Mathematicians are simply acting on intuition and experimenting with ideas, just like everyone else. Zoologists think there might be something new swinging from branch to branch in the unexplored forests of Madagascar, and mathematicians have hunches about which part of the mathematical landscape to explore. The subject is no more profound than that.
>
> Most of mathematics is true for no particular reason. Maths is true by accident.

Chaitin's mathematical curse grows worse. There exist even more disturbing numbers, called Super-Omegas (Becher et al. 2001). All these "incalculable numbers reveal that mathematics is not simply moth-eaten, it is mostly made of gaping holes. Anarchy, not order, is at the heart of the Universe" (Chown 2001). This is a truly unexpected and devastating blow to the supremacy of mathematics and any intellectual tradition building upon it. Indeed (Chaitin 2005, p.146):

> Let me repeat: formal axiomatic systems are a failure!

There exists a real-world problem related to randomness. In 1930, the philosopher, mathematician, and economist Frank P. Ramsey proved an innocuous theorem in graph theory (Ramaey 1930). In detail, the proof concerned itself with the relationship between groups of points in a network. This turned out to have deep implications, as a "network" can be a collection of all manner of things, from computers in an network, people at a dinner party, or stars in the night sky. In essence, pattern-free randomness is impossible. Every random collection of things will contain patterns: mysterious order emerges from apparent randomness (indeed, recall Benford's law from Sect. 6.4.2). Ramsey theory says that this order is not only likely, but becomes inevitable as the number of nodes in the network increases. Adding insult to injury, our minds suffer from apophenia, a cognitive bias describing the tendency to perceive connections and meaning between unrelated things (see Sect. 11.3.2 for more on cognitive biases). We are truly exposed to a profound randomness/pattern dichotomy: from the fundamental randomness in the theories the human mind devises, to the pattern-formation emerging out of randomness, to the mind's propensity to see patterns everywhere—the illusion of order in a random universe.

A final example of the failings of mathematics relates to politics. Specifically, clear and justified rules for apportionments in a political system produce results which are unexpected and appear to violate common sense. Such deficiencies are summarized in the apportionment paradoxes and question rational decision-making (Arrow 1950; Balinski and Young 1975, 2001). Indeed (Deutsch 2011, p. 333):

> Sometimes politicians have been so perplexed by the sheer perverseness of apportionment paradoxes that they have been reduced to denouncing mathematics itself. Representative Roger Q. Mills of Texas complained in 1882, 'I thought …that mathematics was a divine science. I thought that mathematics was the only science that spoke to inspiration and was infallible in its utterances [but] here is a new system of mathematics that demonstrates the truth to be false.'

9.4.2 Losing Meaning

In Sect. 9.1.4 above, the following question was asked:

> Has modern physics itself really transformed into a postmodern narrative that defies meaning, clarity, and understanding?

The same question can be posed for mathematics. As the discipline becomes ever more technical, detailed, and abstract, fewer and fewer people can understand its subtlety and profundity.

Consider Fermat's Last Theorem of 1637 (Wiles 1995):

Theorem 9.1 *There are no non-zero solutions to the equation* $x^n + y^n = z^n$*, where* x, y, x*, and* n *are integers for* $n > 2$.

It took over 350 years before, in 1995, Andrew Wiles presented a proof. It ran to over hundred pages and employed novel, previously unrelated, mathematical methods (Wiles 1995). What could be more demanding than a 100-page proof? Perhaps a proof which a computer carried out. The four-color theorem (Sect. 5.4.1) was proved in such a way. This raises the question "about whether a 'proof' that no one understand is a proof" (Colyvan 2012).

Then there is the tale of Shinichi Mochizuki (Castelvecchi 2015):

> Sometime on the morning of 30 August 2012, Shinichi Mochizuki quietly posted four papers on his website.
>
> The papers were huge—more than 500 pages in all—packed densely with symbols, and the culmination of more than a decade of solitary work. They also had the potential to be an academic bombshell. In them, Mochizuki claimed to have solved the abc conjecture, a 27-year-old problem in number theory that no other mathematician had even come close to solving. If his proof was correct, it would be one of the most astounding achievements of mathematics this century and would completely revolutionize the study of equations with whole numbers.
>
> Everyone—even those whose area of expertise was closest to Mochizuki's—was just as flummoxed by the papers […]. To complete the proof, Mochizuki had invented a new branch of his discipline, one that is astonishingly abstract even by the standards of pure

> maths. “Looking at it, you feel a bit like you might be reading a paper from the future, or from outer space,” number theorist Jordan Ellenberg, of the University of Wisconsin-Madison, wrote on his blog a few days after the paper appeared.

Then, in 2016 (Castelvecchi 2009):

> Nearly four years after Shinichi Mochizuki unveiled an imposing set of papers that could revolutionize the theory of numbers, other mathematicians have yet to understand his work or agree on its validity—although they have made modest progress.

Finally, in 2017 (Revell 2017):

> “A small number of those close to Mochizuki claim to understand the proof, but they have had little success in explaining their understanding to others,” wrote Peter Woit at Columbia University in a blog post.

It does not help that mathematicians can be strange creatures (Castelvecchi 2015):

> Mochizuki, however, did not make a fuss about his proof. The respected mathematician […] did not even announce his work to peers around the world. He simply posted the papers, and waited for the world to find out.
>
> Adding to the enigma is Mochizuki himself. He has so far lectured about his work only in Japan, in Japanese, and despite being fluent in English, he has declined invitations to talk about it elsewhere. He does not speak to journalists; several requests for an interview for this story went unanswered.

This tendency work in isolation and avoid interactions with the world has similarities to another ingenious mathematician’s conduct which also alienated the community. Grigori Perelman shot to fame in 2003 after solving the century-old Poincaré conjecture (Singer 2004). For this achievement he was awarded the prestigious Fields Medal, considered to be the greatest accolade in mathematics. In addition, he was awarded the $1 million Millennium Prize[17] in recognition of his proof. Perelman, unprecedentedly, declined both prizes and noted (quoted in BBC News 2010):

> I’m not interested in money or fame.
>
> I don’t want to be on display like an animal in a zoo. I’m not a hero of mathematics. I’m not even that successful; that is why I don’t want to have everybody looking at me.

Mathematics not only defies meaning when we don’t understand what is going on, but, more seriously, also when we do understand. For instance, the deeply counterintuitive Tarski-Banach theorem (Banach and Tarski 1924) states that (Colyvan 2012, p. 152):

> […] a solid sphere can be decomposed into a finite number of pieces, the pieces moved around via rigid rotations and translations, and recombined into two spheres, each equal in volume to the first.

As a further counterintuitive example, consider the following equation

[17] See http://www.claymath.org/millennium-problems/poincar%C3%A9-conjecture.

Theorem 9.2

$$1+2+3+4+5+6+\cdots = -\frac{1}{12}. \tag{9.1}$$

How can the sum of all positive integers be a negative fraction?

Proof Let $S_1 = 1-1+1-1+1-1+\cdots$ Then

$$\begin{aligned} 1-S_1 &= 1-(1-1+1-1+1-\cdots) \\ &= 1-1+1-1+1-1+\cdots = S_1. \end{aligned} \tag{9.2}$$

Hence

$$S_1 = \frac{1}{2}. \tag{9.3}$$

Let $S_2 = 1-2+3-4+5-6+\cdots$ Then

$$\begin{aligned} 2S_2 &= 1-2+3-4+5-6+\cdots \\ &\quad +1-2+3-4+5-\cdots \\ &= 1-1+1-1+1-1+\cdots = S_1 = \frac{1}{2}. \end{aligned} \tag{9.4}$$

Hence

$$S_2 = \frac{1}{4}. \tag{9.5}$$

Now consider

$$\begin{aligned} S-S_2 =& 1+2+3+4+5+6+\cdots \\ &-(1-2+3-4+5-6+\cdots) \\ =& 0+4+0+8+0+12+\cdots \end{aligned} \tag{9.6}$$

Or, equivalently

$$S-S_2 = 4(1+2+3+4+5+6+\cdots) = 4S. \tag{9.7}$$

Substituting (9.5) yields

$$S-\frac{1}{4} = 4S, \tag{9.8}$$

or $S = -\frac{1}{12}$.

□

This bizarre proof highlights the failure of human intuition when faced with infinite sums. A rigorous proof of Theorem 9.2, looking less like arithmetic sleight-of-hand, can be found using the Riemann zeta function (Stopple 2003)

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}, \tag{9.9}$$

with

$$S = \zeta(-1) = -\frac{1}{12}. \tag{9.10}$$

However, even more puzzlingly, Theorem 9.2 is relevant in modern theoretical physics, as it constrains bosonic string theory to 26-dimensional space-time (Polchinski 2005, p. 22).

A further example of a deep and eerie connection between mathematics and reality is the number π. It is defined as the ratio of the circumference of a circle to its diameter. It is an irrational number (i.e., it cannot be expressed as a fraction) and it is also a transcendental number (i.e., it is not the solution of any polynomial with rational numbers as coefficients). π has an infinite number of digits in its decimal representation and no repeating pattern ever occurs. Magically, the formula for π appears in a basic calculation in the physics of the hydrogen atom (Friedmann and Hagen 2015). Then there is the claim that the distribution of the prime numbers follow the energy levels of a quantum system (Bender et al. 2017).

Initially, mathematics gave structure and order to human thinking. In the realm of the abstract, clear rules inexorably dictated its inner workings. The domain of relevance of mathematics exploded with the discovery of Volume I of the Book of Nature (Chaps. 2, 3, 4, and 5). This unprecedented and extraordinary success is overshadowed by the discovery of the irreparable incompleteness and randomness in the foundations of mathematics. Moreover, how legitimate is a discipline, which can only be comprehended by a hand-full of initiated people?

Conclusion

We are faced with a monumental, inexplicable, and insurmountable paradox. The human mind's journey into the realm of abstractions explains the rise of Homo sapiens (Harari 2015). Over millennia, we, as a species, have constructed layer after layer of fictional reality on top of objective reality. Religion, money, and nations are prime examples of abstract structures fostering human cooperation and evolution. Finally, laws of nature, elementary particles, and fundamental forces joined the mosaic of abstractions. However, nothing was more momentous than the human mind's conquering of the abstract plane of mathematics. Now, there was nothing stopping Homo sapiens conquering the universe (Harari 2015, p. 294):

> Science, industry and military technology intertwined only with the advent of the capitalist system and the Industrial Revolution. Once this relationship was established, however, it quickly transformed the world.

This miraculous rise to dominance, aided by the mind's capacity to decipher the workings of the universe, is, perplexingly, accompanied by the loss of certainty and meaning. Today, the edifice of science has a distinct postmodern veneer. It appears to be a Byzantine patchwork of knowledge fragments, lacking an overarching and unifying framework—isolated islands of knowledge with no common structure. Science has become like a static mosaic which is forever expanded by adding ever smaller and smaller pieces to it. Worst of all, the whole edifice of science appears to be floating in empty space, lacking any foundation. After millennia of human knowledge generation, today, the inherent limitations to knowledge seem inescapable. Even the realm of beautiful and timeless abstractions is affected by this decline in certainty and meaning. We appear to be lost in mathematical translation, where hyper-abstraction and obscurity reign. Are mathematics and science simply true by accident?

Admitting the limitations of knowledge would seem like a sober and pragmatic way to bypass such predicaments. After all, exposing the limits of human knowledge does not affect the nature of reality. So, can we find comfort and clarity in examining reality itself—in effect, moving from epistemology to ontology?

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Chapter 10
Ontological Enigmas: What is the True Nature of Reality?

Abstract Observed from a distance, the edifice of science appears impressive—a robust and coherent body of knowledge. However, tiny cracks become visible if one looks closer. Unexpectedly, and drastically, these cracks become chasms. The whole monumental structure of knowledge falls apart like a house of cards. These fault-lines appear as soon as one inquires about the true nature of reality. Space, time, and matter emerge as alien concepts, incomprehensible to the mind. Of the many open questions in physics, perhaps the most pressing deficiency can be attributed to quantum field theory. Specifically, what it has to say about the vacuum. Then, the most obvious shortcoming is the incompatibility of quantum theory and general relativity. No testable theory of quantum gravity exists. String/M-theory and loop quantum gravity may be elegant and powerful mathematical frameworks, but their relationship to reality is dubious. Moreover, our universe, accommodating life and consciousnesses, appears as the result of delicate fine-tuning at many levels. Inexplicably, nearly the entire energy-matter content of the universe is unknown to us. But most astonishingly, the fundamental quantum level of reality, discovered by chance, tells us outlandish stories about the nature of the universe. All our cherished intuitions about reality are under attack: determinism, causality, and an objective and mind-independent world. Indeed, at the core of reality, a bizarre, holistic structural connectivity appears to emerge. To tackle these enigmas, physicists have conjured up fantastic ontologies: higher-dimensional space-time or the multiverse, in which our universe is just one instance out of an infinitude. Other physicists have resorted to mysticism. By analyzing the actual ontology of reality, one is forced to ask the following questions. Does matter exists? Is time an illusion? Tentative answers suggest: no and yes.
Level of mathematical formality: intermediate.

In 2012, history was written. CERN's Large Hadron Collider[1] (LHC) had detected the signature of an elusive new particle in the deep fabric of reality. This revolutionary finding confirmed the last and final missing particle anticipated by the hugely

[1] See also Sect. 7.1.1.2.

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
https://doi.org/10.1007/978-3-030-03633-1_10

successful standard model of particle physics (Sect. 4.4). This amalgamation of ideas (Sects. 4.2 and 4.3) predicted the existence of the Higgs boson, based on what is called the Higgs mechanism (Sect. 4.2.1), a theory developed in the 1960s. The following statement can be read on CERN's webpage[2]:

> On 4 July 2012, the ATLAS and CMS experiments at CERN's Large Hadron Collider announced they had each observed a new particle in the mass region around 126 GeV. This particle is consistent with the Higgs boson predicted by the Standard Model. The Higgs boson, as proposed within the Standard Model, is the simplest manifestation of the Brout-Englert-Higgs mechanism.

Indeed, a momentous discovery. Again, from CERN's webpage (See footnote 2):

> On 8 October 2013 the Nobel prize in physics was awarded jointly to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

Unfortunately, the fourth of July 2012 was a bad day for physics. In the words of mathematical physicist Peter Woit (quoted in Brockman 2015, p. 72.):

> The observation at the LHC of the Higgs [...] has caused great consternation among theorists. Something has happened that should not have been possible according to the forty-year-old reasoning now well-embedded in textbooks.

In essence, the discovery of that particular flavor of Higgs boson was the worst observation possible. It confirmed, and fully exposed, a deep schism between theoretical physics and reality. After all the breathtaking success of physics in decoding the intimate workings of reality in the last century (Chaps. 3 and 4)—indeed, after over three centuries of unstoppable triumphal procession (Chap. 2 and Sects. 5.1 and 5.3)—the whole abstract machinery threatens to grind to a halt. At the core of this dissonance lies the apparent impossibility to construct a quantum theory of gravity. Quantum gravity, unexpectedly, emerged as the elusive, but highly anticipated, holy grail of physics, as it would represent the last missing step fully unifying all the physical forces in the universe (Sect. 4.3)—a neat "theory of everything."

The standard model of particle physics, albeit being an incredibly accurate theory, does not include gravity in its mathematical representation of reality. Theoretical physicists have been grappling with this omission since the late 1960s, when string theory was born (Sect. 4.3.2). However, for string theory—and M-theory, its modern incarnation—to work, reality has to display some very particular properties (discussed below). Disappointingly, the "plain vanilla" Higgs particle that was discovered "threatens to close a chapter of 20th century physics without a hint of how to start writing the next page" (Cliff 2013). We are stuck with two spectacularly accurate fragments of isolated knowledge which simply wont mesh. The standard model and general relativity (introduced below) are at insurmountable odds with each other and no experimental hint is in sight. We are left in the dark, knowing that

[2] See https://home.cern/topics/higgs-boson.

the cone of light representing our knowledge is only illuminating a limited part of reality. Ignorance abounds.

The problem of quantum gravity is, however, only one of the failings which are appearing to bring modern theoretical physics to its knees. This chapter will illuminate this crisis in understanding. In light of these revelations, it should be expected that even the most sympathetic defenders of knowledge can acknowledge the feelings of gloom expressed in the last chapter. Namely, that certainty appears futile, explanations seem useless, and all knowledge is ultimately based on that which we cannot prove. Every answer we pry from nature is met by the appearance of a handful of deeper and harder questions (Sect. 9.2.3). Science never truly was the endeavor to unearth the "absolute truth," but represents an incremental, approximate, and fallible approach to reality (Sects. 9.1.6 and 9.3). Indeed, science is a complex social human undertaking (Sect. 9.1.3 and 9.1.5), plagued by all the shortcomings affecting any human effort to organize and collaborate (Sect. 9.2.2). Finally, mathematics is inherently flawed, rendering it a questionable foundation for science (Sect. 9.4). The clouds on the horizon (Chap. 8) have become frighteningly dark skies.

Before addressing the challenge of quantum gravity and beyond, a selection of open questions in physics is presented. This should convey the scope and depth of the problems facing the human mind in its quest to comprehend the universe. Perhaps the following questions can never be answered:

- Why do three spatial dimensions appear to exists?
- Why does the nature of space and time depend on how it is observed from a reference frame (i.e., the malleable fabric of space-time)?
- Why the quantum nature of the atomic realm?
- Why is the quantum realm so utterly bizarre and alien to our conceptualization?
- Why are the values of the fundamental constants what they are?
- What principle lies behind the self-organizing structure formation seen at all scales?
- Why the zoo of elementary particles? Indeed, when the plethora of new subatomic entities emerged, a Nobel laureate quipped, "who ordered that?"
- Do protons decay?
- Why is there an arrow of time?
- What is the nature of time?
- What physics lies at the heart of the mathematical singularities incapable of penetrating reality any further?
- What happened at (or even before) the Big Bang?
- Is our universe infinite or finite in extent?
- Why does the universe appear to be left-handed, harboring left-handed life (i.e., the origins of chirality)?
- Why all the cosmic coincidences (Sect. 8.1.3)?

More specifically and technically:

- Why is the universe not made up of equal parts of matter and antimatter (Sakharov 1967), as the Big Bang produced an equal mixture of both? [Baryogenesis, baryon asymmetry]

- Why is there an anomaly appearing in the cosmic microwave background radiation which appears to give special significance to the location of Earth within the entire universe (Sect. 10.3.1)? [Unfortunately named the “axis of evil”]
- Why does one of the oldest galaxies ever to be observed (EGSY8p7) appear to contradict the current cosmological narrative of the universe (Zitrin et al. 2015)?
- What is the origin of the dark spot detected in the cosmic microwave background radiation (Cruz et al. 2005), which appears unexplained within the standard cosmological model (Mackenzie et al. 2017)?
- Is the origin of gold and other heavy elements due to the collision of neutron stars (Perkins 2018)?
- What is the nature of the energy density of empty space? [Dark energy; see Sect. 10.3.1]
- What is the nature of the majority of the unknown matter content of the universe? [Dark matter; see Sect. 10.3.1]
- What is the connection between information and black holes? [Black hole information paradox; see Sect. 13.4.1]
- Why is gravity so weak? [Hierarchy problem; see in the following text]
- Why do we observe homogeneity of causally disconnected regions of space? [Horizon problem; see in the following text]

As expected, many potential answers to these questions have been offered. For instance, the dimensionality of space could have a mathematical underpinning, related to the emergence of complexity. Distortionless wave propagation is only possible in an odd number of dimensions and radially symmetric wave propagation can only occur in one or three dimensional space (Morley 1985). Furthermore, the strength of gravity in three dimensions depends on the distance squared between massive objects. In two dimensions, it depends only on the distance, whereas in four dimensions it is related to the distance cubed. In essence, in a two-dimensional world gravity would be too strong, and in four dimensions too weak, for the formation of complex structures in the universe. Or perhaps the dimensionality of space is constrained by the second law of thermodynamics and entropy (Gonzalez-Ayala et al. 2016). Even more intriguingly, the four-dimensional fabric of space-time has very special properties. Mathematically, it is described by a manifold. In general, equipping manifolds with so-called smooth structures allows for rigorous mathematical analysis on them. Space-time, i.e., the abstract 4-manifold representing it, allows for infinitely many (i.e., an uncountable number) such smooth structures. In all other dimensions there only exists a finite number. Then, the solution to the smooth Poincaré conjecture has been proven in all dimensions other than four. In a similar vein, expressed in the technical language of topology, for a four-dimensional cobordism[3] defined on 4-manifolds, it is unknown whether a specific theorem[4] holds. Does abstract mathematical richness translate into emergent physical complexity (Donaldson and Kronheimer 1990; Friedman and Morgan 1998; Scorpan 2005)?

---

[3] A mapping between manifolds.

[4] The h-cobordism theorem.

For the hierarchy problem, supersymmetry (Sect. 4.3.2) has been invoked. This new symmetry property of reality[5] is also a prerequisite for string theory. Indeed, many physicists had hoped that the LHC would produce some evidence of supersymmetry. Finally, the horizon problem in cosmology is address by what is known as inflation. This is a postulated exponential, but extremely brief, expansion of space in the early universe, around 10^{-36} seconds after the Big Bang singularity (Guth 1981; Collins et al. 1989; Peacock 1999; Peebles 1993; Penrose 2004). A generic explanation for all the apparent coincidences and opaque aspects of existence is the Anthropic Principle. It simply states that all theories of the universe must be constrained by the necessity to allow human consciousness to emerge. For instance, in the words of Andrei Linde, known for his theories on cosmic inflation (quoted in Brockman 2015, p. 46):

> There are many strange coincidences in our world. The mass of the electron is 2,000 times smaller than the mass of the proton. Why? The only "reason" is that if it were even a little different, life as we know it would be impossible. The masses of the proton and neutron almost coincide. Why? If the masses of either were even a little different, life as we know it would be impossible. The energy of empty space in our part of the universe is not zero, but a tiny number—more than a 100 orders of magnitude below the naïve theoretical expectations [zero-point energy]. Why? The only explanation we have is that we couldn't live in a world with a larger vacuum energy.

This ludicrous discrepancy between the observed density of the vacuum and the calculated zero-point energy of quantum fields prompted the Nobel laureate Steven Weinberg to call it "the worst failure of an order-of-magnitude estimate in the history of science" (quoted in Jones and Lambourne 2004, p. 355). The core of this enigma relates to the failings of the human mind in conceiving a quantum theory of gravity, a drama unfolding on the main stage of theoretical physics for decades.

10.1 The Worst Prediction in Physics

Totally empty space is not empty at all. This is a consequence of one of the fundamental, and strange, laws of quantum mechanics. Heisenberg's uncertainty principle describes this behavior, which is related to knowledge, information, and, evidently, certainty. The uncertainty principle states that there exists a fundamental limit to the precision with which certain pairs of physical properties of a particle can be known (Heisenberg 1927). This lack of information is, however, not due to any lack of human ability or ingenuity, but represents a fundamental limit to how much knowledge reality is willing to reveal. For instance, time and energy are two such complementary pairs of properties. The smaller the time window is defined in which a particle is observed, the less certain we can be of its energy state during that time. This is mathematically codified as the time-energy uncertainty relation

[5] For the important role symmetry plays in physics, see Chap. 3.

$$\Delta t \Delta E \geq \frac{\hbar}{2}. \tag{10.1}$$

In a vacuum, all quantum fields are in their zero-energy state and hence no particles are manifested. However, the loophole of the uncertainty principle allows for the temporary manifestation of particles, which exist only so briefly as to not violate it. These vacuum fluctuations represent an inherent fuzziness in the amount of energy contained at every point in space: The quantum vacuum is a seething ocean of activity. As a result, the energy content of empty space—the vacuum energy density—and the lowest energy a quantum field can have—the zero-point energy—are both larger than zero. However, there turned out to be an extraordinarily large discrepancy between these two values (Adler et al. 1995). In Weinberg's view, this represented the worst failure of any scientific estimate.

The unexpected energy density of the vacuum has important consequences for general relativity (describing gravity) and cosmology. Indeed, it caught Albert Einstein off guard and leads to one of the greatest mysteries of the cosmos, represented by the cosmological constant (and dark energy), discussed below. On the other hand, the huge divergence between the theoretical and empirical values of the vacuum energy exposed a glaring flaw in quantum field theory, one of the most successful theories known to the human mind. Today, this is one of the greatest unsolved problems in physics. In essence, we desperately need a theory of quantum gravity to resolve these enigmas.

10.1.1 The Quantum Field

In the formalism of quantum field theory, space itself is comprised of fundamental quantum fields, one for each type of existing elementary partice. Vibrations in theses fields manifest themselves as physical entities. For instance, an observed electron is, in the language of this formalism, simply a localized oscillation in the corresponding quantum field. In Fig. 4.1 all the existing particles, described by quantum fields, are listed. The matter fields are classified as fermions due to their half-integer spin. These are the quarks (making up all composite matter, like neutrons or protons) and leptons (e.g., the electron). The three non-gravitational forces are associated with (gauge) bosons, carrying spin 1. Virtual photons (γ) mediate the electromagnetic force, virtual gluons (g) the strong nuclear force, and virtual Z and $W^{\pm}$ bosons the weak force. The Higgs particle (h) is a (scalar) spin-0 boson, responsible for generating the mass of particles via the Higgs mechanism (Sect. 4.2.1).

To compute the energy density of the vacuum in quantum field theory, the following intuitive reasoning is used. An energy density is generally defined as the energy per volume. As every point in space represents a potential particle oscillation in quantum field theory, all such zero-point energy contributions need to be summed up. This can be analytically expressed utilizing the oscillation frequency ω of all possible oscillators, yielding the energy density of the vacuum in quantum field theory to be

$$\rho_{\text{qft}} \propto \int_0^{\tilde{\omega}} \omega^3 d\omega, \tag{10.2}$$

where ρ_{qft} depends on a frequency cut-off $\tilde{\omega}$ required to make the result finite. Frequency and energy are fundamentally related concepts and are linked via the Planck-Einstein relation $E = \hbar\omega$. The Planck energy $\bar{E}$ represents the energy scale at which elementary particles are also expected to be affected by general relativity. It is thus the likely threshold of quantum gravity. Inserting the associated frequency into (10.2) results in a vacuum energy density of

$$\bar{\rho}_{\text{qft}} \approx 10^{76}[\text{GeV}]^4 \approx 10^{114}\ [\text{erg/cm}^3]. \tag{10.3}$$

See Rugh and Zinkernagel (2002) for details. This huge value was initially skeptically acknowledged by physicists. However, the true absurdity of that number only became apparent after it was possible to empirically estimate the vacuum energy. These turns of events astonished physicists. After all, quantum field theory had made one of the most accurate predictions in science: the Lamb shift (Lamb and Retherford 1947). Furthermore, in the history of quantum field theory all the appearing problems in the formalism could always be reconciled in some way. Unfortunately, not this time with the vacuum energy.

Indeed, quantum field theory has always been a messy affair. Vastly complex calculations emerged from its mathematical underbelly and often, these led to meaningless infinities. The first attempts to tame the complexity came in the form of approximations. Perturbation theory allowed physicists to find solutions to problems, by starting from the exact solution of a related, albeit simpler problem. The exact value is approached by adding many small perturbations. However, infinities still plagued the formalism. In a next step, a trick was utilized to tame these as well. Renormalization is a collection of techniques which capture the infinite terms from quantum field theory in finite experimental numbers. However, for every infinity to be treated, laboratory measurements are required. For details on perturbation theory and renormalization, see, for instance Peskin and Schroeder (1995). Finally, the breakthrough came from an unexpectedly simple, and somewhat strange, approach.

In 1942, a young Richard Feynman presented his thesis in which he offered a novel interpretation of quantum mechanics (Feynman 1942). This work laid the foundation for what became known as the path integral formulation (Feynman 1948; Feynman and Hibbs 1965). It is a description of quantum theory that generalizes the action principle of classical mechanics. This action is defined as an integral over time, taken along the path of the system's evolution

$$\mathcal{S} = \int_{t_1}^{t_2} L dt, \tag{10.4}$$

where L is the Lagrangian describing the system (Sect. 3.1.1). By minimizing the action the equations of motion can be derived.[6] In effect, Feynman's quantum paths track all possible paths between two locations, where each path adds to the probability amplitude.[7] Of all the infinite potential paths a particle can take, most cancel out and only observable ones remain. Loosely stated, the path integral approach is like a modified double-slit experiment, where there are infinitely many slits on infinitely many screens.

Inspired by this success, Feynman ventured on. If all potential paths need to be considered between two locations for the proper dynamics of quantum particles to emerge, why not consider all possible events unfolding between measurements to understand interactions? By postulating that all events that could occur between measurements will occur, the fundamental key to quantum field theory was found. The exact mathematical expressions corresponding to this somewhat hand-waving assertion are found in the infamous Feynman diagrams (Feynman 1949; Veltman 1994). In essence, the elementary diagrams are shorthand for the exact mathematical phrases. Now these compellingly simple diagrammatic rules guide the incredibly intricate mathematics of quantum field calculations. Moreover, Feynman diagrams plus renormalization solve the problem of the bothersome infinities and yield highly accurate calculations. A key ingredient in Feynman diagrams is the notion that a positron (the electron's antiparticle) is understood as being an electron moving backwards in time.[8] Moreover, virtual particles, existing in a meta-reality below the threshold of the uncertainty principle, are the drivers of the interactions in quantum field theory. See Fig. 10.1 for an example of a Feynman diagram. It corresponds to the following contribution to the total probability of two electrons scattering

$$\mathcal{M} = \bar{u}_1 i e \gamma^{\mu} u_1 \frac{-i g_{\mu\nu}}{p^2} \bar{u}_2 i e \gamma^{\nu} u_2, \tag{10.5}$$

where u_i represent the initial electron quantum states, $\bar{u}_i$ the final ones, each vertex contributes an interaction term $ie\gamma^{\sigma}$, and $-ig_{\mu\nu}/p^2$ describes the virtual photon (Peskin and Schroeder 1995). In the end, our interpretation of the entities and mechanisms appearing in the Feynman diagrams is irrelevant. Only the topology of each diagram is relevant and has physical relevance. In other words, every vertex contributes to the probability amplitude.

Out of this framework, modern quantum field theory emerged, the most predictive formulation of quantum mechanics (Kaku 1993; Peskin and Schroeder 1995; Ryder 1996). A fertile ground from which the quantum theory of electrodynamics sprang, describing all interactions involving electrically charged particles by means of the exchange of photons (Feynman 1985). Later, quantum chromodynamics blossomed, a theory describing the strong interaction between quarks and gluons, the

[6] See the Euler–Lagrange equation (3.1).

[7] The wave function of the Schrödinger equation is a probability amplitude, see Sect. 3.1.4. Indeed, Feynman was able to derive Schrödinger's equation from scratch using the path integral formalism.

[8] An idea he said he had stolen from John Wheeler (Gefter 2014).

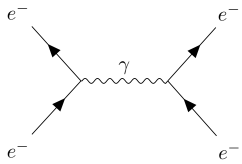

Fig. 10.1 One possible Feynman diagram for two electrons e^- scattering by interacting via a virtual photon γ. The corresponding mathematical expression is given in (10.5)

fundamental particles that make up composite matter (hadrons) such as protons and neutrons (Greiner et al. 2007). The culmination of all non-gravitational forces into a single quantum field framework is the standard model of particle physics (Sect. 4.2, especially the Higgs mechanism seen in Sects. 4.2.1, 4.3 and 4.4). Yes, those were the days, when theoretical physics progressed like a puzzle being assembled, where every new piece neatly fit into the growing whole. After this spectacular success, no wonder physicists expected the quantum theory of gravity to be around the corner.

On a side note, quantum fields were encountered at different stages in the narrative of this book. For instance, appeared in the contexts of Noether's theorem (Sect. 3.1.4, the Lorentz group (Sect. 3.2.2.1), and the history of gauge theory (Sect. 4.2). An overview of the conceptual developments of field theory—from the field concepts in general relativity to quantum and gauge fields—can be found in Cao (1998).

10.1.2 Einstein's Biggest Blunder

How could physicists gauge how bad the calculation of the quantum field vacuum energy really is? In other words, what should $\bar{\rho}_{\text{qft}}$ be compared to? The answer comes from cosmology and it is associated with a telling story in the development of general relativity.

The theory of general relativity is perhaps the most aesthetically pleasing theory in physics (Einstein 1915; Misner et al. 1973). It expresses deep intuition about the workings of reality[9] in the language of differential geometry (Fig. 5.3). Next to quantum field theory, it is the most accurate and successful theory describing the universe. From a physical principle—the equivalence principle, Einstein's "happiest thought of his life" (Sect. 4.1)—a mathematical formalism is developed, guided by the powers of symmetry (Chap. 3). In detail, the principle of covariance is invoked (Sect. 4.1). Einstein killed the classical force of gravity and resurrected it as the curvature in the four-dimensional space-time continuum.

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The gravitational field equations are

[9]This tale is told in Sect. 4.1.

$$G^{\mu\nu} = -\frac{8\pi G}{c^4} T^{\mu\nu}, \tag{10.6}$$

relating the Einstein tensor $G^{\mu\nu}$ to the energy-momentum tensor $T^{\mu\nu}$. The constant G is Newton's gravitational constant and c is the speed of light in a vacuum. Usually, the energy-momentum tensor of a perfect fluid is employed in this context

$$T^{\mu\nu} = (\rho + \frac{p}{c^2})u^\mu u^\nu - p g^{\mu\nu}, \tag{10.7}$$

where ρ and p denote the density and pressure, respectively, of a fluid with 4-velocity u^μ. The Einstein tensor encodes the geometry of space-time

$$G^{\mu\nu} = R^{\mu\nu} - \frac{1}{2} g^{\mu\nu} R, \tag{10.8}$$

utilizing the Ricci tensor $R^{\mu\nu}$ and the curvature scalar R. The Ricci tensor itself is derived from the Riemann tensor $R^{\sigma}{}_{\mu\nu\lambda}$

$$R_{\mu\nu} = R^{\lambda}{}_{\mu\nu\lambda}, \tag{10.9}$$

while the curvature scalar is a contraction of the Ricci tensor

$$R = g^{\mu\nu} R_{\mu\nu}. \tag{10.10}$$

Finally, the Riemann tensor is a function of the Christoffel symbols $\Gamma^{\nu}{}_{\mu\lambda}$ (Sects. 3.1.1 and 4.1) which themselves are defined through the metric $g^{\mu\nu}$. In essence, the metric codifies all structural aspects of space-time, out of which the Einstein tensor draws its predictive power. See Misner et al. (1973), Peacock (1999), Peebles (1993).

< *10.1.2-general-relativity*| $\oiint$ }

However, what kind of cosmology can be derived from (10.6)? In 1917, Einstein idealized the universe as a 3-sphere uniformly filled with matter. The result of this calculation was that the radius of such a 3-sphere increases with time (Nussbaumer 2014). This was a momentous discovery, as the equations predicted the expansion of the universe. There, in the neat formal language of general relativity, the revelation of an origin to our universe was found. This shocked Einstein, as the prevailing philosophy in the Western world at the time was that "the heavens endure from everlasting to everlasting" (Misner et al. 1973, p. 409). The idea of a dynamical universe, spawning from a Big Bang, was preposterous.

In hindsight it is a tragic footnote of history, that if Einstein had been truly open-minded and had radically trusted his theory, the prediction of the expansion of the universe would have ranked as one of the most amazing scientific discoveries. In another unfortunate turn of events, the Catholic Priest and astronomer Georges Lemaître, analyzing Einstein's equations in the context of recent observations in cosmology, postulated the expansion of the universe. He published this finding in a little known Belgian scientific journal (Lemaître 1927). The discovery went unnoticed. In 1929, Edwin Hubble empirically observed that the light originating from remote galaxies was redshifted (Hubble 1929). In other words, the more distant the galaxies were, the more shifted the light reaching us from them was. A straightforward interpreted was that all the galaxies are actually receding from earth. Indeed, the observed redshift was precisely what Lemaître had predicted. So it was true, our universe had a beginning and was expanding at every point.

However, back in 1917 Einstein proposed an extension of general relativity which would remedy the problem of an expanding universe (Einstein 1917). From this modified version, a static and unchanging universe could emerge. Einstein introduced a scalar quantity Λ, called the cosmological constant, into his field equation[10]

$$G^{\mu\nu} + \Lambda g^{\mu\nu} = -\frac{8\pi G}{c^4} T^{\mu\nu}. \tag{10.11}$$

This simple tweaking of the formalism had deep consequences. For one, the left-hand side of the field equations is not zero anymore in flat space-time, implying a curvature of empty space. When the experimental verification of the expansion of the universe was established, Einstein repudiated the cosmological constant and called it "the biggest blunder of my life" (quoted in Freedman 2004, p. 10). However, the cosmological constant, like a genie let out of a bottle, refused to disappear.

Today, a modern interpretation of (10.11) is

$$G^{\mu\nu} = -\frac{8\pi G}{c^4}\left(T^{\mu\nu} + \frac{c^4 \Lambda}{8\pi G} g^{\mu\nu}\right) = -\frac{8\pi G}{c^4}\left(T^{\mu\nu} + T^{\mu\nu}_{\text{vac}}\right). \tag{10.12}$$

By moving the cosmological constant to the right-hand side of the field equation, it can be reinterpreted as the energy-momentum tensor of the vacuum

$$T^{\mu\nu}_{\text{vac}} = \frac{c^4 \Lambda}{8\pi G} g^{\mu\nu} = c^2 \rho_\Lambda g^{\mu\nu}. \tag{10.13}$$

Seemingly out of nowhere, an energy density of the vacuum emerges, driven by the cosmological constant

$$\rho_\Lambda = \frac{c^2 \Lambda}{8\pi G}. \tag{10.14}$$

Associated with this energy density is a peculiar negative-pressure equation of state

$$p_\Lambda = -c^2 \rho_\Lambda. \tag{10.15}$$

[10]It is necessarily attached to the metric in order for covariance to be upheld.

This implies that in the expanding universe this negative pressure produces an amount of work.[11] As a counterintuitive result, the energy density of the vacuum does not decrease as the universe expands, but remains constant. See Misner et al. (1973), Peacock (1999), Rugh and Zinkernagel (2002).

This whole exercise may appear rather ad hoc and unpersuasive. However, a positive cosmological constant, tied to a non-zero vacuum energy, accelerates the expansion of the universe (Carroll 2001). The older the universe is, the faster its fabric is exploding. In 1998, this aspect of our universe was discovered (Perlmutter et al. 1998), leading to a Nobel prize being awarded in 2011. In a strange turn of events, a theory was modified to account for a belief and this modification unexpectedly then led to one of the profoundest predictions in cosmology. With the discovery of the accelerated expansion of the universe, an eighty-one-year-old chapter closes. Unfortunately, it is followed by a new chapter fraught with more puzzles (Sect. 10.3.1).

To end this section, it remains to be said that the vacuum energy can be calculated from (10.14) by employing the estimated value of the cosmological constant. Recently, the Planck Collaboration, a big science undertaking, presented the newest estimates for the cosmological parameters (Planck Collaboration et al. 2016). They measured the Hubble "constant" to be

$$H_0 \approx 67.74 \text{ [km/sMpc]}. \tag{10.16}$$

The ratio between the vacuum energy and the critical density[12] is found to be

$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_{\text{crit}}} \approx 0.6911. \tag{10.17}$$

From these two values the cosmological constant can be computed as

$$\Lambda = \frac{3}{c^2} H_0^2 \Omega_\Lambda \approx 1.11 \times 10^{-52} \text{ [m}^{-2}\text{]}. \tag{10.18}$$

Putting this value into (10.14) uncovers the energy density of the vacuum

$$\rho_\Lambda \approx 5.95 \times 10^{-27} \text{ [kg/m}^3\text{]} \approx 5.35 \times 10^{-9} \text{ [erg/cm}^3\text{]}. \tag{10.19}$$

The last approximation is retrieved by noting that 1 [kg] $\approx 8.99 \times 10^{23}$ [erg]. Comparing $\bar{\rho}_{\text{qft}}$ from (10.3) with ρ_Λ reveals the true extent of the incompatibility—or better, the complete failing of quantum field theory to yield a sensible answer. However, in defense of quantum field theory, making this misguided calculation appear even more puzzling, comes the Casimir effect (Casimir and Polder 1948). It was postulated that there should exist a bulk effect of the virtual particles on the vacuum. Specifically, the idea was that it should be possible to reduce the vacuum energy between two conducting plates brought very closely together, resulting in a pres-

[11]Mathematically, $-p_\Lambda dV \propto \rho_\Lambda dV$.

[12]This is related to a flat spatial geometry, see Sect. 10.3.1.

sure difference which would exert a force. This quantum field theory effect could be measured, albeit decades later (Lamoreaux 1997). The status of zero-point energy in quantum field theory is thus highly ambiguous. Indeed (Peacock 1999, p. 184):

> So, far from resolving the conceptual problems about vacuum energy, the Casimir effect merely muddies the waters. [...] In this respect, it it illustrates well the general philosophy of quantum field theory, which has been to sweep the big conceptual difficulties under the carpet and get on with calculating things.

Recall the rallying cry "Shut up and calculate!" from Sect. 2.2.1.

For further reading on the strange physics of nothingness, the vacuum, and voids, see, for instance Genz (1999), Barrow (2000), Close (2009), Weatherall (2016).

10.2 Quantum Gravity: The Cutting-Edge of Theoretical Physics

At first, the irreconcilable tension between the forces of gravity and the remaining three quantum forces was subtle. As so often in the history of physics, nature challenged the human mind with puzzles and paradoxes, only to ignite ingenuity and spark creativity. This time, however, the mind did not succeed in overcoming the obstacles. Nature was persistent and refused to reveal this most fundamental enigma. We appear to be stuck with two categorically incompatible theories of reality, describing the vast cosmos (general relativity introduced above) and the very small (the quantum field theories discussed above, unified in the standard model, Sect. 4.4). Each theory represents an immensely powerful predicting mechanisms, but both miss a fundamental ingredient. At their point of contact, they fail spectacularly, plunging theoretical physics into oblivion. In an effort to figure out what is going on, physicists have resorted to radical measures and have invoked extraordinary and exotic ontologies for reality. In summary (Callender and Huggett 2001, back cover):

> The greates challenge in fundamental physics is how quantum mechanics and general relativity can be reconciled in a theory of "quantum gravity". The project suggests a profound revision of our notions of space, time and matter, and so has become a key topic of debate and collaboration between physicists and philosophers.

10.2.1 Simple Quantum Gravity

General relativity and quantum field theory tell two very different stories when it comes to gravity. In the abstract formalism Einstein revealed, gravity does not exist as a force anymore. It is simply an effect of the warping and twisting of the space-time continuum due to matter. In quantum field theory, the forces are mediated via virtual quantum particles (Fig. 4.1). An example is seen in the Feynman diagram in Fig. 10.1. As a consequence, if we want to quantize gravity, then there should exist a corresponding force-carrying gauge boson called the graviton. The heart of the conceptual problem is the following (Giulini et al. 2003, p. v):

> On one side, quantum theory, in its usual formulation and orthodox interpretation, requires an ambient non-dynamical spacetime. On the other side, gravity, as described by general relativity, requires a dynamical geometry of spacetime which is coupled to all material processes within. This implies that at least one of these theories cannot be fundamentally correct.

How can a physical theory be spectacularly accurate in its predictions and, at the same time, be fundamentally incorrect?

Even more troubling, the role time plays in both theories is also incompatible. In quantum mechanics, time is an absolute external element, whereas in general relativity time is an elementary part of the dynamic space-time continuum. In technical words, quantum mechanics is background-dependent while general relativity is background-independent. The first attempt at a theory of quantum gravity resulted in the Wheeler-DeWitt equation (DeWitt 1967; Wheeler 1968). In essence, it is a wave function of space. Unfortunately, the equation was riddled with problems. Foremost, time appears to be lost. In detail, this quantum gravity equation is independent of the time parameter. But how then can the evolution of something happening in time be calculated? Indeed, time represents a deep problem lurking at the foundations of reality (see Sect. 10.4.2 below).

Tinkering with the equations of quantum gravity, many angles of attack have been proposed. For instance

- Alain Connes' noncommutative geometry (Connes 1994).
- Roger Penrose's twistor theory (Penrose and MacCallum 1973).
- Topological quantum field theory (Smolin 1995b).

However, two main approaches stand out. One begins with quantum field theory and adds gravity.[13] The other starts with general relativity and then adds quantum properties. The former attempt has received a tremendous amount of publicity under the name of string theory. Indeed, in the theoretical physics community it was touted as the "only game in town." The latter approach to quantum gravity is known as loop quantum gravity. Today, these two theories are the most promising hopes of merging general relativity with quantum mechanics (Smolin 2001). For a general overview of the history of quantum gravity, see Rovelli (1998, 2002).

10.2.2 String/M-Theory

The colorful, surprising, and sometimes haphazard history of string theory, ultimately culminating in M-theory, was described in Sect. 4.3.2. The accidental discovery of superstrings resulted in one of the most creative outbursts in theoretical physics. To

[13]Note that simply transporting quantum field theory into curved space does not suffice. Attempts at this are found in Birrell and Davies (1994).

illustrate, between 1999 and 2008, roughly 800–900 scientific papers were published on the subject each year, totaling over 8,000 contributions (Bradlyn 2009). However, string theory's popularity can also be attributed to fashion rather than solely being justified as an inevitable necessity. This is in the spirit of the philosophers of science Thomas Kuhn (Sect. 9.1.3) and Paul Feyerabend (Sect. 9.1.6), who identified an element of irrationality in the evolution of science. The science writer Gary Taubes recalls an encounter with the theoretical physicist Alvaro de Rujula (quoted in Woit 2006, p. 222):

> On August 4, 1985, I sat in the cantina at CERN drinking beer with Alvaro de Rujula. […] De Rujula predicted that 90% of the theorists would work on superstrings […] because it was fashionable.

As a result there was also a perceived lack of options for theorists. In the words of the Nobel laureate David Gross, one of the founders of string theory, in 1987 (quoted in Woit 2006, p. 221):

> So I think the real reason why people have gotten attracted by it [string theory] is because there is no other game in town.

In the words of Joseph Polchinski, another string theory pioneer (quoted in Penrose 2004, p. 892):

> [A]ll good ideas are part of string theory.

In the wake of this pursuit of quantum gravity, a lot of abstract mathematical machinery was conceived of Hatfield (1992), Duff (1999), Kaku (2000), Polchinski (2005a, b), Green et al. (2012a, b), Rickles (2014). Indeed, string/M-theory is responsible for producing entirely new and esoteric branches of mathematics (Sect. 2.1.4). However, the mathematical machinery is constrained by some very specific requirements for it to be consistent. If these formal constraints are translated into reality, the universe we inhabit possesses some very remarkable properties. In other words, string/M-theory invokes a radically new ontology. Crucially, the formalism relies on the existence of

- supersymmetry;
- higher-dimensional space-time.

Supersymmetry is an elegant novel symmetry relating the matter particles (fermions) to the force carrying particles (bosons). It is a powerful tool, unlocking many abstract abilities (Sect. 4.3.2). However, it comes with a hefty price, as it requires the number of existing particles to be doubled—each matter fermion and gauge boson must have its supersymmetric partner. In effect, supersymmetry conjures up a mirror world to the particles listed in Fig. 4.1. Higher-dimensional physics has a pre-string theory origin (Sect. 4.3.1). In the context of M-theory, space is a colossal ten-dimensional structure, weaving an eleven-dimensional space-time fabric we supposedly inhabit. The extra dimensions we cannot observe are rendered invisible as they "wrap" upon themselves. In technical parlance, the additional spacial dimensions are compactified on special geometries called Calabi-Yau manifolds (Sect. 4.3.2). Alas, the LHC still refuses to produce any shred of experimental evidence for this new kind of physics.

But what about the predictive power of this abstract formalism? What novel physics is associated with this impressive mathematical behemoth? Returning to the notion of the vacuum,string/M-theory has much to say—too much. In a nutshell, the process of retrieving our four-dimensional universe from the eleven-dimensional M-theory template via compactification allows for a lot of freedom. Our universe, specifically the vacuum of our universe, is just one possible state in a vast landscape of possible vacua (Susskind 2007). Indeed, estimates suggest that there exist an inconceivable 10^{500} such vacua (Douglas 2003; Tetteh-Lartey 2007). In comparison, there are an estimated 10^{80} atoms in the entire universe. So one wonders (Woit 2006, p. 239):

> The possible existence of, say, 10^{500} consistent different vacuum states for superstring theory probably destroys the hope of using the theory to predict anything.

However, string theorists are not easily discouraged (Woit 2006, p. 239):

> In recent years, [Leonard] Susskind, one of the codiscoverers of string theory, has begun to argue that this ability of the theory to be consistent with just about anything should actually be thought of as a virtue.

See Susskind (2006) for Susskind's thoughts on this.

The theoretical physicist Woit, a staunch critic of string theory,[14] as can be guessed from the excerpts quoted above from his book on string theory called *Not Even Wrong*[15] (Woit 2006), continues his negative assessment (Brockman 2015, p. 70f.):

> For anyone currently thinking about fundamental physics, this latest *Edge* question[16] is easy, with an obvious answer: string theory. The idea of unifying physics by positing strings moving in ten space-time dimensions as fundamental entities was born in 1974, and became the dominant paradigm for unification from 1984 on. After 40 years of research and literally tens of thousands of papers, what we've learned is that this is an empty idea. It predicts nothing about anything, since one can get pretty much any physics one wants by appropriately choosing how to make six of the ten dimensions invisible.
>
> According to string theorists, we live in an obscure corner of a multiverse where anything goes, and this "anything goes" fits right in with string theory, so fundamental physics has reached its end-point.
>
> The observation at the LHC of the Higgs, but no superpartners, has caused great consternation among theorists. Something has happened that should not have been possible according to the forty-year-old reasoning now well-embedded in textbooks.

Others chimed in as well, like the mathematical physicist Frank Tipler (Brockman 2015, p. 68.):

[14] See also his blog https://www.math.columbia.edu/~woit/wordpress/.

[15] A phrase generally attributed Wolfgang Pauli, describing a theory which can neither be proven correct nor falsified.

[16] What scientific idea is ready for retirement? See Sect. 9.3 for more.

> As it was in the beginning of modern science, so it should be now. We should keep the fundamental requirement that experimental confirmation is the hallmark of true science. Since string theorists have failed to propose any way to confirm string theory experimentally, string theory should be retired, today, now.

Indeed, the attempts to justify string/M-theory based on non-empirical arguments, for instance, Dawid (2013), have been met with grave concerns (Ellis and Silk 2014; Rovelli 2016). The cosmologist Sean Carroll continues the skeptical assessment (quoted in Cole 2016):

> Answering deep questions about quantum gravity has not really happened. They have all these hammers and they go looking for nails. That's fine. But it isn't fine if you forget that, ultimately, your goal is describing the real world.

Finally, the string pioneer Gross again (quoted in Cole 2016):

> There was a hope. A moment. We even thought for a while in the mid-'80s that it [string theory] was a unique theory. After a certain point in the early '90s, people gave up on trying to connect to the real world. The last 20 years have really been a great extension of theoretical tools, but [with] very little progress on understanding what's actually out there.

Today, string theory has taken on a life of its own. In the words of the mathematical physicist Robbert Dijkgraaf, "things have gotten almost postmodern" (quoted in Cole 2016). Although it has not emerged as the promised theory of quantum gravity, string theory remains a useful formal tool in theoretical physics and mathematics.

There has been a lot of bitterness and rancor between the supporters and skeptics of string/M-theory. Counterbalancing the flood of publications is a growing body of literature not only questioning the validity of string/M-theory—and its inability to produce any foreseeable prediction—but also modern theoretical physics as a whole Woit (2006), Smolin (2007), Baggott (2013), Unzicker and Jones (2013), Hossenfelder (2018). We are again reminded of the end of science (Sect. 9.2.2). Naturally, such criticism was faced with fierce opposition. Woit, describing the reaction of two string theory graduates to some of his criticism, reports (Woit 2006, p. 223):

> [They] were of the opinion that I was an incompetent idiot threatening to hold back the progress of science.

Perhaps the most vocal, unapologetic, and aggressive defender of string theory is Luboš Motl. Unknown and isolated, he was a young undergraduate physics student in the Czech Republic. In 1996, Motl uploaded a string theory paper to an online scientific archive for preprints, called the arXiv (Motl 1996). While submissions to the archive are not considered to be scientific publications, as they are not peer reviewed, the arXiv enjoys huge popularity. Motl's submission impressed established string theorists and he ended up with a scholarship to Rutgers, where he graduated. The next step in this amazing career was an assistant professorship at Harvard University, starting in 2004. See Glanz (2001). In 2007, his stellar rise came to a premature end. He left Harvard and returned to the Czech Republic and has not published a single piece of research since. He has, however, become a prolific blogger.[17] Motl's

[17] See https://motls.blogspot.com/.

blog, which he calls the "supersymmetric world from a conservative viewpoint," is a platform for his political activism, climate change skepticism, and criticism of anything he perceives as anti-string theory. The following is an account of the theoretical physicist and quantum gravity researcher Sabine Hossenfelder, author of Hossenfelder (2018), relating to her interactions with Motl in 2007. She writes on her blog:[18]

> Luboš has repeatedly insulted me, my husband and my friends. He has misquoted me, and used alleged quotations of mine to insult others. He has an incredible amount of times accused me of having said things I never said, only to then explain, based on this, that I am "stupid", "silly", and "a crackpot" with "crackpot friends". He is in no way interested in understanding my opinion, or my point of view. He has proclaimed I should not have a Ph.D., that my "female brain" only "parrots nonsense" and all my papers are "bullshit"—the latter evidently without having read them. He has treated others the same way previously, and will probably proceed doing so.
>
> As to present date he has made a habit out of producing distorted echos of my posts or comments at other people's blogs. He never acknowledges discussions we have had earlier, which he usually ends with retreating to insults when he runs out of arguments. Luboš Motl either is indeed as unable to understand other people's opinions as he pretends, or he chooses to do so deliberately.

Such animosity is not an isolated case. An example of a Motlesque online attack is the following[19]:

> I must tell you that before 2006, everyone would agree that [Lee] Smolin[20] was a crank and Woit was an irrelevant grumpy guy outside whose importance for physics was exactly zero.
>
> [...]
>
> Lee Smolin, a far-left radical and a former (and current?) hippie, has also brought an extremely thick layer of politically correct victimism to the field.

Perhaps such antics were responsible for the unfortunate and abrupt end of Motl's budding science career. On a side note, he defended the Bogdanov brothers in what is known as the Bogdanov affair (Sect. 9.1.4).

However, perhaps the most fruitful criticism of string/M-theory comes from the proponents of loop quantum gravity. After all, they are claiming to solve the conundrum of quantum gravity with very different tools.

10.2.3 Loop Quantum Gravity

In the history of quantum gravity the formal approach known as loop quantum gravity played a subordinate role. Naturally, as there was conceived to be only "one game in town." In its roots, loop quantum gravity extends the classical theory of

[18] See http://backreaction.blogspot.com/2007/08/lubo-motl.html, retrieved June 21, 2018.

[19] See https://motls.blogspot.com/2010/02/aspects-of-expanding-crackpottery-in.html, retrieved June 21, 2018.

[20] One of the main contributors to loop quantum gravity and appearing in the next sections.

general relativity. One crucial ingredient was supplied by the mathematical physicist and cosmologist Penrose in the 1970s, called spin networks[21] (Penrose 1971). These networks represent quantum states of particles and their interactions. More technically, a spin network is a graph carrying labels, related to representations of symmetry groups (Sect. 3.1.4), on its links and nodes. 24 years later, this idea surprisingly re-emerged, as spin networks were found to represent the states of loop quantum gravity (Rovelli and Smolin 1995b; Baez 1995). During those years, a key insight was Ashtekar (1987), building on Sen (1982). In essence, the foundation of this new theory of quantum gravity was laid, based on the notion of quantum geometry, i.e., quantum space-time (Rovelli and Smolin 1995a; Loll 1995).

This can be seen as the first fundamental proposition for a new ontology of reality. Space itself is now finite, composed of discrete, quantized "atoms." In effect, there exists a lower limit to the resolution of the universe as there are no arbitrarily small chunks of space. Similarly to the way quantum theory constrained reality to be comprised of finite quanta of energy, loop quantum gravity posits the discrete nature of space itself. Mathematically, the area (volume) of a given physically defined surface (spatial region) is expressed as an operator which has a discrete spectrum of eigenvalues. However, in such a world, the origin of this finite structure of reality becomes a question. More generally, why aren't space and energy states continuous and why is the speed of light finite? Recall the tension between the discrete (Sect. 5.3.2) and the continuous (Sect. 5.3.1) discussed in Chap. 5—in essence, the discrepancy between the finite and infinite in the formal thought systems of the mind. Indeed, in the categories of human knowledge generation, seen in Fig. 5.9, the spin networks of loop quantum gravity can be attributed to the fundamental-algorithmic demarcation, in contrast to the fundamental-analytical classification of the rest of the edifice of physics (Sect. 5.4.1). Perhaps this venture into the domain of formal discreteness has the power to unveil some desperately needed new insights.

The development of loop quantum gravity continued and many of the challenges were met (Thiemann 1996). The evolution of a spin network is described by what is called a spin foam and yields the dynamics of the theory (Reisenberger and Rovelli 1997; Barrett and Crane 1998). The Bekenstein-Hawking black hole entropy (Bekenstein 1973; Hawking 1974) is computed within loop quantum gravity (Smolin 1995; Rovelli 1996) as well as within string theory (Strominger and Vafa 1996), almost at the same time. This is discussed in the context of the holographic principle in Sect. 13.4.1. In a nutshell, loop quantum gravity is a proposed theory of quantum gravity—carrying much less conceptual baggage compared to string theory—characterized as being non-perturbative, background-independent, and diffeomorphism invariant. The last property is related to the principle of covariance in general relativity (Sect. 4.1). A well defined version of the Wheeler-DeWitt equations was successfully found with loop quantum gravity (Jacobson and Smolin 1988).

In the simplest of terms, the reality in string theory—albeit being supersymmetric and higher-dimensional—is made of tiny vibrating strings, explaining all observable phenomena. In contrast, loop quantum gravity is concerned with the quantum proper-

[21] For details on graph theory and complex networks, see Sect. 6.3.

ties of space-time itself, its structure being a fine fabric woven out of finite loops. Both approaches had long been thought to be incompatible with each other. Now some theorists are expressing doubts and are suggesting similarities (Gambini and Pullin 2014; Cartwright 2017). Indeed, loop quantum gravity has been expressed in higher dimensions incorporating supersymmetry (Bodendorfer et al. 2013). However, at the end of the day, any theory of quantum gravity needs to be empirically validated. Until then, we are left with the words of the mathematician Eric R. Weinstein (Brockman 2015, p. 60):

> [I]t is hard to find a better candidate for an intellectual bubble than that which has formed around the quest for a consistent Theory of Everything physical, reinterpreted as if it were synonymous with "quantum gravity." If nature were trying to send a polite message that there is other preliminary work to be done first before we quantize gravity, it is hard to see how she could send a clearer message than dashing the Nobel dreams for two successive generations of Bohr's brilliant descendants.

For further reading—technical and non-technical—on loop quantum gravity, see, for instance Smolin (2001), Baez (2000), Thiemann (2006, 2007), Rovelli (2008), Chiou (2015), Rovelli (2017). Finally, an insightful book by Smolin, arguing for an evolutionary angle of attack on cosmology and existence, called *The Life of the Cosmos* (Smolin 1997).

10.3 The Large and the Small

In the last sections, much of the focus of the discussion has been placed on the nature and structure of physical theories, from quantum field theory to quantum gravity. However, the question remains: What is the true nature of reality? What do we know about reality's ontology? One way to address this issue is to analyze how the universe structures itself at very small and very large scales.

10.3.1 Cosmological Conundrums

Building on the field equations of general relativity (10.6), a lot of effort has been made to find exact solutions. These solutions tell us about the organizing principles of the cosmos. The Friedmann–Lemaître–Robertson–Walker metric is such an exact solution, describing a homogeneous, isotropic, and expanding (or contracting) universe (Friedman 1922; Lemaître 1927; Robertson 1935; Walker 1937). The result of inserting this specific metric into Einstein's equations is a set of differential equations, called Friedmann's equations. These equations reveal the astonishing fact that there exists a direct connection between the matter density of the universe and its global geometry. In detail, this is expressed by the critical density

$$\rho_c = \frac{3H^2}{8\pi G}, \tag{10.20}$$

where H is the Hubble parameter and G Newton's gravitational constant. A universe with a matter density above this value will be spatially closed, while a lower-density universe will be spatially open. In a two-dimensional toy universe, a sphere is an example of a closed geometry, while a saddle point represents an open one. At the critical density, this two-dimensional model universe would be a flat sheet. As a consequence, ρ_{crit} is the parameter which determines if our universe is static or not. A larger matter density ρ_{m} will eventually lead to a collapsing universe, whereas a smaller value will result in a forever expanding universe. To capture this behavior, the variable Ω_{m} is introduced, as the ratio between the matter density and the critical density

$$\Omega_{\text{m}} = \frac{\rho_{\text{m}}}{\rho_{\text{crit}}} = \frac{8\pi G\rho}{3H^2}. \tag{10.21}$$

Now $\Omega_{\text{m}} = 1$ represents a universe with a matter density such that it is static. However, from Sect. 10.1 we know that empty space also has an energy density. As a consequence, the total density of the universe is determined by two contributions, related to (10.21) and (10.17).

$$\rho_{\text{total}} = \rho_{\text{m}} + \rho_{\Lambda}. \tag{10.22}$$

Recent measurements from Planck Collaboration et al. (2016) have established that

$$\Omega_{\text{m}} = \frac{\rho_{\text{m}}}{\rho_{\text{crit}}} = 0.3089 \pm 0.0062, \qquad \Omega_{\Lambda} = \frac{\rho_{\Lambda}}{\rho_{\text{crit}}} = 0.6911 \pm 0.0062. \tag{10.23}$$

In other words, the content of our universe is comprised of 30.89% matter and 69.11% vacuum energy.[22]

Regrettably, no one knows what the true origin and nature of this vacuum energy density is. It is labeled dark energy and there exist many competing explanations for it. The simplest comes from introducing the cosmological constant (Sect. 10.1.2). However, this raises the issue about the fundamental struggle to construct a theory of quantum gravity (Sect. 10.1). Another proposed solution is called quintessence, where a time-varying Higgs-like field[23] is responsible for the emergence of dark energy (Caldwell et al. 1998). Others have argued that dark energy does not actually exist and that it is simply a measurement artifact (Mattsson 2010). Finally, recent observations that the universe's accelerated expansion appears to be faster than assumed do not help (Castelvecchi 2016; Amit 2017). Once again, we are reminded of the boundaries of our knowledge. An anomaly persists, which no one knows how

[22]Note that, although $\Omega_{\text{total}} = \Omega_{\text{m}} + \Omega_{\Lambda} = 1$, the current standard model of cosmology, known as the Lambda-CDM model, predicts that our universe is spatially approximately flat and will expand forever, regardless of whether the total density ρ_{total} is above or below the critical density.

[23]Formally related to a scalar spin-zero particle.

to address. Yet again, we are left in the dark when it comes to the ontology of reality. And the situation gets worse.

Perhaps one of the most pressing and fundamental challenges in cosmology is the following. There exist two possible methods by which we can observe the structure of the universe. One is related to measurements of the electromagnetic radiation reaching Earth, the other is a consequence of the effects of gravity itself. The problem is that (Peacock 1999, p. 353):

> In an ideal world, these two routes [...] would coincide; in practice, the gravitational route is able to detect more mass by a factor of up to ten than can be detected in any other way.

This is a spectacularly setback. Our observations of the cosmos are incomplete or are at odds with each other. Here is where dark matter comes in Zwicky (1933), Rubin et al. (1980). It is a theorized form of matter that is believed to account for this discrepancy. However, a crucial problem is that no one knows what this type of matter is made of. It cannot be ordinary matter, i.e., it must be non-baryonic matter.[24] Recent measurements have established, that the 30.89% matter content of the universe is made up of only about 4.86% ordinary matter and 26.03% is due to dark matter (Planck Collaboration et al. 2016).[25] In other words, of all the matter in the universe, approximately 84.26% is unaccounted for.

In summary, the matter-energy content of the whole universe is comprised of ordinary matter, dark matter, and dark energy

$$\Omega_{\mathrm{m}} + \Omega_{\mathrm{dm}} + +\Omega_{\mathrm{de}} = 1, \tag{10.24}$$

$$0.0486 + 0.2603 + 0.6911 \approx 1. \tag{10.25}$$

To conclude, a staggering 95.14% of all that exists in the universe is unknown to us. We can only detect indirect traces of it. From a philosophical perspective, this represents a cataclysmic turn of events. Everything the human mind has ever directly perceived is only a tiny slice of reality.

Despite this profound ignorance, and upping the ante, there are hints which speak of a privileged status of life on Earth. In the introduction to this chapter, the "axis of evil" was mentioned. This is an anomaly in the cosmic microwave background radiation which appears to give special significance to the location of Earth within the entire universe (Cho 2007). Naturally, most researchers understand this to be a statistical fluke. However, joining this spatial fluke is a temporal one. It is called the coincidence problem (Velten et al. 2014):

> The observational fact that the present values of the densities of dark energy and dark matter are of the same order of magnitude, $\rho_{\mathrm{de}}/\rho_{\mathrm{dm}} \sim \mathcal{O}(1)$, seems to indicate that we are currently living in a very special period of the cosmic history. Within the standard model, a density ratio of the order of one just at the present epoch can be seen as coincidental since it requires very special initial conditions in the early Universe. The corresponding "why now" question constitutes the cosmological "coincidence problem".

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[24] Baryons are subatomic particles comprised of three quarks, such as neutrons and protons. See also Fig. 4.1.

[25] Computed from the empirical value of $\Omega_{\mathrm{b}} h^2$ by noting that $h = H_0/100$.

Given such bizarre coincidences, it is very tempting to console oneself with the Anthropic Principle (Sect. 15.2). The universe happens to be perfectly fine-tuned in such a way, that it not only allows for conscious life to emerge, but necessitates all the coincidences in the cosmic evolution that we can identify. After all, if this were not the case, no one would be wondering about them in the first place.

10.3.2 The Weird Quantum Realm of Reality

If the universe appears incomprehensible at large scales, then at small scales it truly transcends any meaning—all our human conceptuality threatens to fail. Our common-sense intuitions about reality, built on observing the world from a human perspective, are jeopardized. Even Feynman, despite his spectacular success in devising a mathematical formalism accurately describing quantum phenomena, confessed (Feynman 1967, p. 129):

> I think I can safely say that nobody understands quantum mechanics.

He then goes on to say (Feynman 1967, p. 129):

> I am going to tell you what nature behaves like. If you will simply admit that maybe she does behave like this, you will find her a delightful, entrancing thing. Do not keep saying to yourself, if you can possibly avoid it, "But how can it be like that?" because you will get "down the drain", into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.

In 1901, Max Planck stumbled upon the quantum realm of reality by chance (Sect. 4.3.3). Indeed, his radical postulation of the existence of discrete quanta, giving birth to quantum physics, was an act of despair: "I was ready to sacrifice any of my previous convictions about physics" (quoted in Longair 2003, p. 339). Until that day in 1901, eminent physicists had began to foresee the end of physics, as apparently everything about reality was understood (Sect. 9.2.2). This accidental discovery opened up Pandora's box of philosophical conundrums. The philosopher Ernst von Glasersfeld, who coined the term radical constructivism,[26] observed (quoted in Schülein and Reitze 2002, p. 175, translation mine):

> Modern physics has conquered domains that display an ontology that cannot be coherently captured or understood by human reasoning.

Even Niels Bohr, one of the founding fathers of quantum mechanics, admitted (quoted in Sundermeyer 2014, p. 168):

> If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet.

In a nutshell, quantum physics confronts us with epistemic and ontic enigmas:

1. Reality, for the first time, revealed a discrete and finite structure.
2. The foundations of reality are inherently probabilistic.

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[26]For "ordinary" constructivism, see Sect. 9.1.5.

3. The on-off dichotomy of binary logic is transcended.
4. The act of measuring a quantum property affects the quantum property.
5. There is a fundamental limit to the knowledge which nature is willing to reveal.
6. At a fundamental level, the local realism of classical reality cannot be upheld.

However, once these weird properties are formalized and re-expressed mathematically, there is no stopping the success of quantum mechanics.[27] We can translate the above list into the language of physics and thus sidestep the philosophical interpretations[28]:

1. Quanta—the smallest energy scale of particles (Feynman et al. 1965; Sakurai 1994; Messiah 2000).
2. Probability amplitudes and Schrödinger's wave equation (3.24).
3. Wave-particle duality and the superposition of quantum states (Feynman et al. 1965; Sakurai 1994; Messiah 2000).
4. The collapse of the wave function—if it collapses at all (Feynman et al. 1965; Sakurai 1994; Messiah 2000).
5. Heisenberg's uncertainty principle (Sect. 10.1).
6. Bell's theorem and entanglement (the focus of this section).

Naturally, there exists a vast body of literature on quantum physics, including layman's guides and a plethora of esoteric interpretations, grappling with these notions.

However, one of the most surprising properties of the quantum realm is perhaps the phenomena of entanglement, related to the uncanny foundation of reality. In essence, quantum mechanics destroys the notion of local realism. This is the merger of two commonsensical and tried assumption:

1. Locality: No signal can travel faster than the speed of light, as postulated by special relativity (this is related to causality as seen in Sect. 3.2.1), and objects are only directly influenced by their local surroundings.
2. Realism: Nature exists independently of the human mind. Specifically, measurable properties of a physical system exist prior to their observation.

The rejection of local realism and its consequences opens a colorful chapter in the history of physics.

10.3.2.1 Entanglement: From Einstein to the Hippies

Einstein famously opposed quantum physics. He did not trust the probabilistic foundation of the theory. This is ironic, as he was instrumental in the creation of the theory (Sect. 4.3.4). Einstein, together with two junior colleagues, devised an ingenious thought experiment, which would expose the inadequacy of quantum mechanics for all to see. The Einstein-Podolsky-Rosen (EPR) paradox was born. The idea

[27] That is, until it encounters the zero-point energy problem in quantum field theory and quantum gravity in general, as discussed above.

[28] Truthful to the dictum "Shut up and calculate!" from Sect. 2.2.1.

demonstrates that the formal tools utilized by the theory do not provide a complete description of physical reality. In detail, quantum mechanics appears to allow for the instantaneous transmission of information, potentially violating special relativity. Einstein called this disapprovingly "spooky action at a distance" (quoted in Kaiser 2011, p. 30). In effect, the team had inadvertently discovered the possibility of correlated quantum states or entanglement (Einstein et al. 1935).

Nine years passed. Einstein, who died in 1955, spent the last two decades of his life obsessed with developing a unified field theory (Sect. 4.3.5). Then, in 1964, the physicist John Stewart Bell presented groundbreaking work on the EPR paradox. Bell's theorem places a constraint on quantum mechanics (Bell 1964). By assuming local realism, Bell could derive and prove a set of inequalities. He then went on to demonstrate how specific cases thereof where violated by actual quantum mechanical predictions. In effect, Bell's theorem proved that any physical theory which incorporates local realism cannot reproduce the observable predictions of quantum mechanics. Shockingly, entanglement appeared to be an actual property of the quantum realm. Unsurprisingly, the theorem emerged as the core of the controversy surrounding the interpretation of quantum mechanics (Kosso 1998; Maudlin 2011; Becker 2018).

When a group of particles share spatial proximity, it can happen that the quantum states describing the individual particles merge and the whole system must now be described by a single quantum state. Each particle can no longer be described independently of the state of the other ones anymore. This property is called entanglement and persists independently of the spatial distributions of the system's particles. As a result, the measurements of physical properties are correlated. In effect, measuring such a property of an entangled particle will instantaneously affect its entangled cousins—even if they are at the other end of the universe. Some mysterious structural connectivity glues entangled particles together, which appears to transcends space and time. Bell's theorem, building on the EPR paradox designed to invalidate quantum mechanics, has been experimentally verified (Freedman and Clauser 1972; Aspect et al. 1981; Giustina et al. 2013; Gröblacher et al. 2007; Hensen et al. 2015; The BIG Bell Test Collaboration 2018). Entanglement has been experimentally observed for greater and greater distances (Aspelmeyer et al. 2003; Yin et al. 2012, 2017), from 600 m to 1,200 km. However, this whole matter has inadvertently escaped the secure grounding of physics and has ventured into philosophy. As can be expected, discussions abound and the implications are still being debated (Wiseman 2014).

Today, entanglement plays a central role in quantum information theory and quantum computation. Specifically, quantum encryption crucially depends on a fundamental insight, known as the no-cloning theorem. The discovery of this theorem was historically connected to the issues surrounding entanglement. The consequential no-cloning theorem could have, however, been lost to humanities' collective mind, were it not for an eccentric group of physicists at Berkeley in the 1970s (Kaiser 2011, p. xxiiiff.):

> The group of hippies who formed the Fundamental Fysiks Group saved physics in three ways. First concerned style and method. […] More than most of their generation, they sought to recapture the big-picture search for meaning that had driven their heroes—Einstein, Bohr, Heisenberg, and Schrödinger […] Second, members of the Fundamental Fysiks Group latched onto a topic, known as “Bell’s theorem,” and rescued it from a decade of unrelenting obscurity. […] The hippie physicists’ concerted push on Bell’s theorem and quantum entanglement instigated major breakthroughs—the third way the saved physics.

Indeed, relating to the group’s first contribution, during those years “physicists who showed any interest in the foundations of quantum mechanics labored under a ‘stigma,’ as powerful and keenly felt as any wars on religion or McCarthy-like political purges” (Kaiser 2011, p. 46). Concerning the second contribution, at that time, one “could find few physicists who seemed to care” about Bell’s theorem from 1964. One of the charter members of the group, the Berkeley theoretical physicists Henry Stapp—a collaborator of Wolfgang Pauli, Werner Heisenberg, and John Wheeler—was “in all likelihood the first physicists in the United States to pay attention to Bell’s theorem” (Kaiser 2011, p 55). However (Kaiser 2011, p. xxv):

> The most important [contribution of the Fundamental Fysiks Group] became known as the “no-cloning” theorem,” a new insight into quantum theory that emerged from spirited efforts to wrestle with hypothetical machines dreamed up by members of Fundamental Fysiks Group. Akin to Heisenberg’s famous uncertainty principle, the no-cloning theorem stipulates that it is impossible to produce perfect copies (or “clones”) of an unknown or arbitrary quantum state. Efforts to copy the fragile quantum state necessarily alter it.

Notably (Kaiser 2011, p. xxv):

> Less well known is that the no-cloning theorem emerged directly from the Fundamental Fysiks Group’s tireless efforts—at once earnest and zany—to explore whether Bell’s theorem and quantum entanglement might unlock the secrets of mental telepathy and extrasensory perception, or even enable contact with spirits of the dead.

In a nutshell, members of the Fundamental Fysiks Group learned about Bell’s obscure theorem in 1967. Entranced by this vision of non-locality, John Clauser worked on devising an experiment to test the theorem. He later succeeded with a collaborator (Freedman and Clauser 1972). Now, with the certainty that entanglement exists, the group brainstormed about the implications. To them, a logical conclusion was the possibility of faster-than-light information transfer. A potential application was drafted, called the “superluminal telegraph” (Herbert 1975). A matured version appeared seven years later (Herbert 1982). When this proposed experiment, demonstrating superluminal effects, was published, many physicists believed “that it should work” (Kaiser 2011, p. 224). Others worked hard to discover a loophole in the argumentation. Indeed, this loophole unexpectedly turned out to be the no-cloning theorem (Wootters and Zurek 1982; Dieks 1982; Ghirardi and Weber 1983). In summary (Kaiser 2011, p. 196):

> The all important no-cloning theorem was discovered at least three times, by physicists working independently of each other. But each discovery shared a common cause: one of Nick Herbert’s remarkable schemes for a superluminal telegraph.

The novel insight launched a major technological advance, as the no-cloning theorem lies “at the heart of today’s quantum encryption technology” (Kaiser 2011, p. 196). Indeed (Kaiser 2011, p. 196f.):

> Little could [the members of the Fundamental Fysiks Group] and others know that their dogged pursuit of faster-than-light communication—and the subtle reason for its failure—would help launch a billion-dollar industry.

Remarkably (Kaiser 2011, p. xvii):

> Despite the significance of quantum information science today, the Fundamental Fysiks Group’s contributions lie buried still, overlooked and forgotten in physicists’ collective consciousness. [...] Indeed, from today’s vantage point it may seem shocking that anything of lasting value could have come from the hothouse of psychedelic drugs, transcendental meditation, consciousness expansion, psychic mind-reading, and spiritualist séances in which several members dabbled with such evident glee. History can be funny that way.

Although, at the time, the hippie physicists did attract a lot of attention (Kaiser 2011, p. xxiif.):

> The inherent tensions that historians have begun to identify within the hippie counterculture [...] help explain the wide range of followers whom the Fundamental Fysiks Group inspired. Their efforts attracted equally fervent support from stalwarts of the military-industrial complex as from storied cultivators of flower power [...].

For more on entanglement and the history of quantum mechanics, see Sect. 4.3.4.

10.3.2.2 The Interpretation of Quantum Mechanics

To this day, the interpretation of quantum mechanics is a hotly debated issue. In other words, there exists no consensus about the ontology this theory is telling us about. For most physicists, the interpretation of quantum mechanics clearly lies in the domain of philosophy and is thus irrelevant to the success of the mathematical formalism in decoding the workings of nature: “Shut up and calculate!” (Sect. 2.2.1). Perhaps this attitude is best captured by one of the founders of quantum field theory (Kaiser 2011, p. 111f.):

> Despite his wide-ranging interests, Feynman had long been skeptical about philosophy. One of his many beloved anecdotes, told and retold later in life, centered on his frustration with a philosophy course through which he had suffered as an undergraduate. [...] the thorny matters of how to interpret the quantum formalism were all “in the nature of philosophical questions. They are not necessary for the further development of physics.”

Not everyone appears to agree. In the words of Einstein (quoted in Becker 2018, p. 288):

> So many people today—and even professional scientists—seem to me like somebody who has seen thousands of trees but has never seen a forest. A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is—in my opinion—the mark of distinction between a mere artisan or specialist and a real seeker after truth.

In any case, the history of the mathematical formalism of quantum mechanics evolved in an orderly fashion:

- Planck introduces quanta to explain black-body radiation (Planck 1901).
- Einstein interprets light as being made up of quantized particles, called photons, winning him the Nobel prize (Einstein 1905).
- Bohr computes the quantized orbits of electrons in hydrogen atoms (Bohr 1913).
- Louis de Broglie presents his thesis arguing that particles are simultaneously waves and vice versa (De Broglie 1924).
- Heisenberg devises the first mathematical description of quantum mechanics, called matrix mechanics (Heisenberg 1925).
- Schrödinger rewrites de Broglie's wave-particle duality in terms of probability amplitudes, called wave functions, and derives their wave equation (Schrödinger 1926a, b, c, d).
- Paul Dirac introduces infinite-dimensional Hilbert spaces in which operators represent physical observables, uniting matrix mechanics with the mechanics of the wave functions (Dirac 1930).

In contrast, the conceptual understanding of the mathematical formalism and the assumptions about the true nature of the quantum reality has remained highly controversial—to this day. The phenomena of quantum physics are very reluctant to fit into any coherent ontological framework. It is, however, very clear that not everything in our classical worldview can be right. Furthermore, is the weirdness encountered in quantum physics epistemic or ontic? The main themes of the philosophical challenges presented by the quantum world relate to:

- the tension between causal and probabilistic laws;
- the status of determinism;
- the interpretation of unobserved entities;
- the issue of local realism.

As discussed above, the status of local realism—a world in which reality is independent from observation and no faster-than-light signals exist—has taken a heavy toll. Indeed, it is not even a matter of choosing which attribute to believe in Gröblacher et al. (2007):

> Our result suggests that giving up the concept of locality is not sufficient to be consistent with quantum experiments, unless certain intuitive features of realism are abandoned.

To make matters worse, the exact level of entanglement appears fine-tuned (Clark 2017):

> There's nothing stopping the quantum world having different levels of underlying correlation—largely uncorrelated worlds are possible within the broad sweep of the theory, as are ones that are far more connected. But only a universe with the exact level of weirdness that corresponds to entanglement produces the rich tapestry of phenomena, including life, that ours does.

Finally, the Kochen-Specker theorem highlights another subtlety of the quantum world (Bell 1966; Kochen and Specker 1967). It is related to Bell's famous theorem. In effect, quantum mechanics logically forces one to renounce one of the three following assumptions (Held 2018):

1. All observables defined for a [quantum mechanical] system have definite values at all times.
2. If a [quantum mechanical] system possesses a property (value of an observable), then it does so independently of any measurement context, i.e. independently of *how* that value is eventually measured.
3. There is a one-one correspondence between properties of a quantum system and projection operators on the system's Hilbert space.

The last assumption is, of course, the cornerstone of the mathematical formalism of quantum mechanics.

In 2011, a survey was taken at a conference on *Quantum Physics and the Nature of Reality* in Austria. Thirty-three participants—all experts on the matter—answered various questions (Schlosshauer et al. 2013). "Do you believe that physical objects have their properties well defined prior to and independent of measurement?" resulted in roughly a 50/50 split of opinions. 64% believed that randomness is a fundamental concept in nature. Relating to the measurement problem, opinions diverged. Some believed it was a pseudoproblem, others thought it was solved, while again others perceived it as a threat to quantum mechanics. To the question "What is your favorite interpretation of quantum mechanics?" 42% of respondents answered with "the Copenhagen interpretation," representing the most popular choice. This was the first attempt at an orthodox interpretation, going back to Bohr in the late 1920s. One hallmark is that realism is abandoned. When unobserved, reality exists in a state of indeterminacy—things exist in a spooky superposition of possible states. It is as if reality is comprised of ghost worlds interacting with each other. By observing reality, i.e., by measuring properties, this possibility space collapses into a single reality we can observe. Mathematically speaking, the probabilistic wave function, encoding the superposition of states, collapses and a definite reality is observed, in accordance with our classical world (Omnès 1994; Torretti 1999). This marks the transition between the quantum and the classical realms of reality. Puzzled by these notions, Einstein asked a fellow physicist whether he really believed that the moon exists only when he look at it (Pais 1979). In time, other interpretations have been put forward. For instance, ranked by the popularity in the 2011 survey:

- Information-based/information-theoretical (see Sect. 13.2).
- Everett (many worlds and/or many minds).

Interestingly (Becker 2018, p. 287):

> Every interpretation has its critics (though the proponents of basically every non-Copenhagen interpretation are usually agreed that Copenhagen is the worst of the lot).

Quantum mechanics has turned some physicists into tea-leaf readers. David Deutsch interprets the interference pattern appearing in the double-slit experiment—a consequence of the bizarre fact that light and matter both behave like waves and particles—as conclusive proof of a new ontology. A breathtakingly vast new ontology, where reality is mind-numbingly bigger but most of it is invisible. In his words (Deutsch 1998, p. 46):

> Single-particle interference experiments such as I have been describing show us that the multiverse exists […].

Not everyone believes that the shadows in those experiments prove that the universe we inhabit is part of a unimaginable ensemble of universes, called the multiverse. The idea goes back to the thesis of Hugh Everett who developed the many-worlds interpretation of quantum mechanics (Everett III 1957; DeWitt and Graham 1973). He denied that the wave function collapses at all and replaces this conceptual cornerstone with the radical new concept of reality splitting into branches, or worlds. In essence, there are infinitely many realities "out there," existing in "parallel" to ours. "Every possible outcome of every possible quantum choice is realized in one world or another" (Gribbin 1999, 272). As an example, in Schrödinger's cat thought experiment—aimed at illustrating the absurdity of the Copenhagen interpretation when applied to macroscopic objects, like cats (Schrödinger 1935)—the cat is in a superposition of states, meaning it is simultaneously alive and dead. Once an observer opens the box, the universe branches and two realities emerge, one where the cat is dead and one where the cat is alive. Despite the hefty ontological price one pays to resolve some of the quantum puzzles, the notion of the multiverse is very popular among cosmologists and string theorists (Susskind 2006; Carr 2007). Indeed, one of the last publications of the eminent cosmologist Stephen Hawking, appearing posthumously, argues for a multiverse (Hawking and Hertog 2018). But not everyone is convinced. For instance, the cosmologist Paul Steinhardt (Brockman 2015, p. 56ff.):

> A pervasive idea in fundamental physics and cosmology that should be retired: the notion that we live in a multiverse in which the laws of physics and the properties of the cosmos vary randomly from one patch of space to another. According to this view, the laws and properties within our observable universe cannot be explained or predicted because they are set by chance. […] Over the entire multiverse, there are infinitely many distinct patches. Among these patches, in the words of Alan Guth, "*anything* that can happen will happen—and it will happen infinitely many times". Hence, I refer to this concept as a Theory of Anything.
>
> Any observation or combination of observations is consistent with a Theory of Anything. No observation or combination of observations can disprove it. Proponents seem to revel in the fact that the theory cannot be falsified. The rest of the scientific community should be up in arms since an unfalsifiable idea lies beyond the bounds of normal science.
>
> Why, then, consider a Theory of Anything, that allows any possibility, including complicated ones? The motivation is the failure of two favorite theoretical ideas—inflationary cosmology and string theory. Both were thought to produce a unique outcome.
>
> Despite laudable efforts by many theorists to save the theory [inflation], there is no solid reason known today why inflation should cause our observable universe to be in a pocket with the smoothness and other very simple properties we observe.
>
> Instead of predicting a unique possibility for the vacuum state of the universe and particles and fields that inhabit it, our current understanding of string theory is that there is a complex landscape of vacuum states corresponding to exponentially different kinds of particles and

> different physical laws. The set of vacuum space contains so many possibilities that, surely, it is claimed, one will include the right amount of vacuum energy and the right kinds of particles and fields.
>
> I suspect that the theories would never have gained the acceptance they have if these problems had been broadly recognized at the outset. Historically, if a theory failed to achieve its goals, it was improved or retired. In this case, though, the commitment to the theories has become so strong that some prominent proponents have seriously advocated moving the goalposts.
>
> I draw the line there. Science is useful insofar as it explains and predicts why things are the way they are and not some other way. [...] A Theory of Anything is useless because it does not rule out any possibility and worthless because it submits to no do-or-die tests.
>
> Because an unfalsifiable Theory of Anything creates unfair competition for real scientific theories, leaders in the field can play an important role by speaking out—making it clear that Anything is not acceptable—to encourage talented young scientists to rise up and meet the challenge.

Taking the many-worlds interpretation to the next level is the many-minds interpretation (Zeh 1970). It proposes that the distinction between the worlds should be made at the level of the mind of an individual observer. In this version the human minds branch into infinity. At the end of the day, every interpretation is exactly that, an interpretation. They all account for the status quo without offering any testable prediction or new tangible insight. There is no way of knowing what is actually going on at the quantum level of reality. The amount of intellectual effort—scientific and philosophical—going into this debate is as astounding as it is inconclusive (Bohm and Stapp 1993; Omnès 1994, 1999; Reichenbach 1998; Kosso 1998; Torretti 1999; Maudlin 2007, 2011; Jaeger 2009; Gisin 2014; Lewis 2016; Rickles 2016; d'Espagnat and Zwirn 2017; Becker 2018). The range of ideas is impressive, incorporating mystic notions. For instance, the preferred status of consciousness (Kosso 1998; Stapp 2011) or the concept of holism (Lewis 2016).

Making matters worse is a batch of troubling quantum experiments. The epitome of such a mid-bending experiment is Wheeler's delayed choice experiment (Wheeler 1978). In essence, a choice made now by an observer can change or edit the past of a photon. Indeed, a choice made now can, in principle, affect the past at arbitrarily distant times. In the words of Wheeler (quoted in Jacques et al. 2007):

> [W]e have a strange inversion of the normal order of time. We, now, by moving the mirror in or out [in the experimental setup] have an unavoidable effect on what we have a right to say about the already past history of that photon.

Again, the experiments show that quantum mechanics is correct (Hellmuth et al. 1987; Lawson-Daku et al. 1996; Jacques et al. 2007; Manning et al. 2015) and, again, the interpretations of the strange reality they tells us about are inconclusive (Becker 2018). In a modified version of the delayed choice experiment, the authors conclude (Ma et al. 2012):

> If one views the quantum state as a real physical object, one could get the seemingly paradoxical situation that future actions appear as having an influence on past and already irrevocably recorded events.

Immediately, they also offer their own interpretation proposing a solution to the infuriating enigma:

> However, there is never a paradox if the quantum state is viewed as to be no more than a "catalogue of our knowledge."

Other researchers have tried to combine the effects of quantum mechanics with special relativity. They conclude (Stefanov et al. 2002):

> This [...] stresses the oddness of quantum correlations. Not only are they independent of the distance, but also it seems impossible to cast them in any real time ordering. [...] Hence one can't maintain any causal explanation in which an earlier event influences a later one by arbitrarily fast communication. In this sense, quantum correlations are a basic (i.e. primary) concept, not a secondary concept reducible to that of causality between events: Quantum correlations are directly caused by the quantum state in such a way that one event cannot be considered the "cause" and the other the "effect".

Finally, the bizarre quantum effects have been brought closer to our classical world by entangling comparably large objects, like buckyballs (Nairz et al. 2003) or millimeter sized diamonds (Lee et al. 2011).

This is a truly unexpected turn of events. By stumbling upon the quantum realm all intuition and common sense is threatened. Determinism, causality, the arrow of time, a mind-independent reality, spatial separation all appear at odds with the quantum reality we can so accurately measure. In the words of the philosopher of science and mathematician, Tim Maudlin (Maudlin 2011, p. 223):

> One way or another, God has played us a nasty trick. The voice of Nature has always been faint, but in this case it speaks in riddles and mumbles as well. Quantum theory and Relativity seem not to directly contradict one another, but neither can they be easily reconciled. Something has to give: either Relativity or some foundational element of our world-picture must be modified. Physicists may glory in the challenge of developing radically new theories in which non-locality and relativistic space-time structure can more happily co-exists. Metaphysicians may delight in the prospect of fundamentally new ontologies, and in the consequence testing and stretching of conceptual boundaries. But the real challenge falls to the theologians of physics, who must justify the ways of a Deity who is, if not evil, at least extremely mischievous.

However, there is a glimmer on the horizon. In the survey of Schlosshauer et al. (2013), 76% of respondents identified quantum information as "a breath of fresh air for quantum foundations." See Chap. 13 for more details on an information-theoretic reality and Sect. 13.2.1 for the implications for quantum mechanics. See also Sect. 14.4.1 for the idea of QBism.

A final contentious issue in the interpretation of quantum mechanics is the notion of free will. For a detailed discussion in the context of quantum mechanics and neuroscience, see Sect. 11.4.1.

10.4 The Nature of Reality

The analysis of the structure of reality at small and large scales has unearthed a dramatic fact: the nature of reality is unknown to the human mind. The insights of millennia about the nature of reality have been discredited. We are left with glimpses of incompatible fragments of reality floating in a void of the unknown. The very notion of materialism now appears misguided. Our worldview has shattered. The current paradigm shift we are witnessing is momentous. To summarize (Davies and Gribbin 2007):

> It is fitting that physics—the science that gave us materialism—should also signal the demise of materialism. During this century the new physics has blown apart the central tenets of materialist doctrine in a sequence of stunning developments. First came the theory of relativity, which demolished Newton's assumptions about space and time—assumptions that still hold sway in our everyday "common-sense" view of the world. The very arena in which the clockwork Universe acted out its drama was now exposed as subject to shifting and warping. Then came quantum theory, which totally transformed our image of matter. The old assumption that the microscopic world of atoms was simply a scaled-down version of the everyday world had to be abandoned. Newton's deterministic machine was replaced by a shadowy and paradoxical conjunction of waves and particles, governed by the laws of chance rather than the rigid rules of causality. An extension of the quantum theory, known as quantum field theory, goes beyond even this; it paints a picture in which solid matter dissolves away, to be replaced by weird excitations and vibrations of invisible field energy. In this theory, little distinction remains between material substance and apparent empty space, which itself seethes with ephemeral quantum activity.

It is then perhaps no wonder that more sympathetic physicists, open to the conceptual and philosophical challenges at hand, have developed rather ambiguous relationships with reality. The documentary film *Das Netz*,[29] by Lutz Dammbeck, chronicles the emergence of the Internet and highlights potential ties to art and culture. To that end, the filmmaker interviewed various artists, counterculture figures, psychonauts, scientists, and the infamous neo-luddite known as the Unabomber. The physicist and philosopher Heinz von Foerster, known for his foundational work on second-order cybernetics (Von Foerster 2003) and his radical constructivism,[30] was also featured. He was ninety years old at the time of the interview in 2002. Following is the transcript (begining approximately at one hour and twelve minutes, translation mine):

> Von Foerster alleges that there is no foundation to science and that all theories are correct, as they are just stories which are deduced from other stories.
>
> *Dammbeck:* What will this all lead to? How will things proceed?
>
> *Von Foerster:* With eternal deduction.
>
> *Dammbeck:* But there have to be limits somewhere?
>
> *Von Foerster:* Precisely not. That's the beauty of it. You can always proceed.
>
> *Dammbeck:* In logic.
>
> *Von Foerster:* Yes, precisely.
>
> *Dammbeck:* But in reality?
>
> *Von Foerster:* [clearly agitated] Where is this reality? Where do you find it?

This would be his last interview. Von Foerster died in October of that year. Others have been calmer in their assertions. Anton Zeilinger, one of the pioneers of quantum information, states (Zeilinger 2010, p. 266):

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[29] see http://www.t-h-e-n-e-t.com.

[30] For "ordinary" constructivism, see Sect. 9.1.5.

> So in general, we have to conclude that while some commonsense pictures of the world are not tangible anymore in view of quantum physics, it is not really clear how a new view of the world would work. One point is clear. The predictions of quantum mechanics are so precisely confirmed in all experiments that it is very unlikely, to say the least, that quantum mechanics is an incorrect description of nature.

Even string theory took an unexpected turn with the discovery of the amplituhedron (Arkani-Hamed and Trnka 2014). This is a geometric structure encoding the probability of particle interactions. In detail, the scattering amplitude of particles corresponds to the volume of this object. A simple conception is that amplituhedrons are "Feynman diagrams on steroids." The only problem is that one has to give up the entire notion of space-time.

10.4.1 Does Matter Exist?

Perhaps the most obvious trick that reality plays is the illusion of solidity of objects. The tangible aspect of material objects, the very sensation of the physical, is based on cloaking nothingness. Consider a hydrogen atom in its ground state. This is simply a proton orbited by an electron. Note that a proton is made up of other elementary particles (quarks) while the electron is itself an elementary particle. Moreover, approximately 99.95% of the atom's mass is due to the presence of the heavy proton. The radius of a hydrogen atom is given by the Bohr radius and the newest measurements of the radius of the proton can be found in Pohl et al. (2010). By calculating the corresponding volumes of the hydrogen atom and the proton, utilizing $V = 4/3\pi r^3$, the following is revealed: 99.9999999999996% of a hydrogen atom is empty space. Solidity is not a result of an actual matter content, but a property resulting from the interactions of electrons. In fact, loosely stated, chemistry can be considered as the science of studying how the mysterious sharing of atom's electrons results in tangible molecular structures. Furthermore, we are not even sure about the actual size of protons. The proton radius puzzle is a result of the discrepancy between two methods of measurement (Pohl et al. 2010, 2016). Yet again, we are to conclude Stajic (2016):

> This independent discrepancy points to [an] experimental or theoretical error or even to physics beyond the standard model.

Philosophers of science, confronted with the emerging puzzles related to a solid foundation of reality, but not necessarily invested in the current scientific paradigm, have began to raise questions. Davies and Gregersen (2014):

> [O]ne begins to wonder whether there is something fundamentally flawed in the idea of a world built up out of matter [p. 50].
>
> One has the sense that, at the end of the day, the speculation of the philosophers and the data from the scientists are pointing in the same surprising direction. At the root of all physical reality is not "primary matter" [p. 72].

Some physicists have also began to doubt.

The renowned physicists Hans-Peter Dürr was first a student, then an assistant and collaborator, and finally a friend of Heisenberg. In 1978, Dürr became his successor as the director of the Max-Planck-Institute for Physics in Munich. Next to his professional work on quantum mechanics, Dürr's interests included the philosophical implications of quantum physics (Dürr 1986) and environmental issues. Towards the end of his life, he espoused a mystical view of reality and made the bold claim that matter does not exists (Dürr 2012, p. 44f., translation mine):

> As a physicist I have spent fifty years—my entire research career—asking myself what exactly underlies matter. The final outcome is simple: Matter does not exist! Therefore I have worked fifty years on a notion that is inexistent. This was an extraordinary experience: Learning that something, whose reality everyone is convinced of, in the end, does not exist.
>
> [...]
>
> Theses crises [in the interpretation of quantum mechanics] are all related to the fact that we have an absolutely incorrect understanding of the world. We have let ourselves get squeezed into a tight conception of reality which does not possess any solutions.
>
> [...]
>
> At the core of our reality there is no foundation, but a source, something alive.

In more cautious words (Davies and Gregersen 2014, p. 72)

> One has the sense that, at the end of the day, the speculation of the philosophers and the data of scientists are pointing in the same surprising direction. At the root of all physical reality is not "primary matter" or little atoms of "stuff."

From a philosophical point of view, there have also been propositions to abandon the notion of tangible elementary particles. The ideas is that physics is forcing us to resort to fictitious concepts in describing fundamental properties of reality. Indeed (Davies and Gribbin 2007, p. 21):

> Generally, the more science moves away from common sense, the harder it is to decide what constitutes a mere model and what is supposed to be a faithful *description* of the real world.

In particular, quantum fields do not yield a satisfactory ontology of the physical world (Kuhlmann 2010). They are a wonderful mathematical tool, but lack any intrinsic reality. However, with what should we then replace the notion of particles? The answer comes from structural realism (see also Sects. 2.2.1 and 6.2.2). The only information we can pry from nature is how things are related to one another. The true nature of the things themselves is always hidden, but the networks of relations can be known and is real. This strong version of structuralism is called ontic structural realism (Kuhlmann 2010; Esfeld and Lam 2010; Morganti 2011). Recall the success of networks in describing complex phenomena (Sect. 5.2.3). Perhaps they can also be utilized in the description of the fundamental realm of reality (in the spirit of the fundamental-algorithmic knowledge generation, seen in Fig. 5.9 of Sect. 5.4.1). This is reminiscent of the spin networks introduced in Sect. 10.2.3. Indeed, "ontic structural realism has become the most fashionable ontological framework for modern physics" (Kuhlmann 2015). Again, in the words of the philosopher of science Meinard Kuhlmann (Kuhlmann 2013):

> You may find it is strange that there could be relations without relata—without any objects that stand in that relation. It sounds like having a marriage without spouses. [...] All in all, structural realism is a provocative idea but needs to be developed further before we will know whether it can rescue us from our interpretive trouble.

The problematic notion of matter, its history and philosophy, is also discussed in detail in Davies and Gregersen (2014) in the context of information. This theme will reemerge in Chap. 13.

10.4.2 Is Time an Illusion?

If the notion of mass appeared thorny, then the idea of time is truly vexing. Yet again, the human mind is confronted with a deep and upsetting paradox. Time is a concept which is so familiar and immediate, so fundamental to existence, yet emerges as inherently incomprehensible, transcending any formal understanding. Indeed (Du Sautoy 2016, p. 241):

> Most attempts to define time very quickly run into difficulties that become quite circular. [...] The fourth-century theologian St. Augustine summed up the difficulty in his *Confessions*: "What then is time? If no one asks me, I know: if I wish to explain it to one that asketh, I know not."

In the context of science (Cham and Whiteson 2017, p. 140):

> [Q]uestions about the nature of time are very deep, and the answers have the potential to shake the very foundations of modern physics. [...] This topic is so out there that very few scientists are working on it directly. It is mostly the province of emeritus professors and a few dedicated younger researchers willing to wade into such risky territory.

Without time, nothing can happen. Yet, what is "now?" And why does it appear to be eternally locked in the delicate and ephemeral transition between the future to the past? Indeed, what aligns the arrow of time in the first place? The nature of time represents the final crisis in the exploration of the true nature of reality. It has challenged physicists and philosophers alike (Falk 2008, p. 272f.):

> And yet some of the most basic questions about the nature of time remain unanswered. To begin with, there's that pesky issue of time "flowing." Does time truly "pass by" in some tangible way? It is an ancient question, one that begins in earnest with the conflicting views of Parmenides and Heraclitus; one that has troubled the greatest minds from Augustine to Newton, from Kant to Einstein. Is time nothing more than change? Or is it more fundamental—is it the mysterious entity that *makes change possible*, a kind of foundation on which the universe is built? Or is it just the opposite: as much as we like to speak of the "river of time," could the river be dry, its flow an illusion?

The laws of physics have always been at odds with time. For instance, the immutable direction of time, flowing from the future into the past, finds no correspondence in the laws of physics. Our formal mathematical representations of reality are all agnostic to the direction of the flow of time. Technically, they are symmetric under time translations.[31] In detail (Zeh 2007, p. 1):

> The asymmetry of Nature under a "reversal of time" (that is, a reversal of motion and change) appears only too obvious, as it deeply affects our own form of existence. If physics is to justify the hypothesis that its laws control everything that happens in Nature, it should be able to explain (or consistently describe) this fundamental asymmetry which defines what may be called a *direction in time* or even—as will have to be discussed—a direction *of* time. Surprisingly, the very laws of Nature are in pronounced contrast to this fundamental asymmetry: they are essentially symmetric under time reversal. It is this discrepancy that defines the enigma of the direction of time [...].

The existence of the arrow of time is usually explained as follows. The universe started its existence after the Big Bang in a state of extremely low entropy—characterized by perfect order. Ever since, the second law of thermodynamics is relentlessly driving the universe to higher levels of entropy and disorder. In effect, the arrow of time emerges from the special initial conditions at the birth of the universe (Reichenbach 1999; Zeh 2007). However, in this explanatory framework one has to account for this low entropy beginning. Some theorists have argued that this, in fact, leads to two arrows of time, where there is also a backwards flow of time from the past into the future. The universe is basically time-symmetric (Carroll and Chen 2004). Recall from above, that Feynman took the interpretation very seriously, that a positron is an electron flowing backwards in time (Sect. 10.1.1). The notion of time flowing backwards has also appeared in another attempt to understand the nature of time. By putting space and time on equal footing, in other words, by restoring the symmetry between space and time, a forwards and backwards arrows of time appear (Vaccaro 2016).

Perhaps the most devastating blow to the concept of time came from Einstein. Special relativity posits that time is a local event for every observer. Depending on the speed and gravitational exposure an inertial frame has, the flow of time will be altered in comparison to other reference frames. In other words, the notion of simultaneity becomes arbitrary. Different observers will always argue about what is happening "now." This implies that an observer's potential future can already have unfolded in another observer's past. Furthermore, the space-time continuum is now an atemporal, static block universe. There exists no "now," or equivalently, all "nows" are equal (Sect. 3.2.1). Einstein believed in his theory. Two weeks before his death, he wrote: " For those of us who believe in physics, the distinction between past, present and future is only a stubbornly persistent illusion" (Wuppuluri and Ghirardi 2017, p. 469). In a nutshell (Slezak 2013):

> We might think of time flowing from a real past into a not-yet-real future,[32] but our current theories of space and time teach us that past, present and future are all equally real—and

[31] To be precises, taking some very rare events in particle physics into account, the laws are invariant under charge, parity, and time reversal symmetry (CPT). In effect, if a movie of particle interactions is played backwards, it also must be reflected in a mirror and the particles replaced by their antiparticles for this to yield a valid description of reality.

[32] Note that one can imagine time itself as moving from the past into the future, or, equivalently, that the future is observed as vanishing in the past.

> fundamentally indistinguishable. Any sense that our "now" is somehow special, or that time flows past it, is an illusion we create in our heads.

Naturally not everyone agrees, for instance Ellis and Rothman (2010). Einstein's time-legacy does not stop with special relativity. A particular solution to the equations of general relativity was discovered, allowing for closed time-like curves (Gödel 1949). Essentially, these valid solutions imply the possibility of time travel, backwards in time. Then, the strange quantum experiments described above (Sect. 10.3.2.2) have also strongly indicated that a causal time-ordering is hard to uphold. The specter of retrocausality raises its head. Moreover, what we know about time from quantum gravity is also troubling. Recall that the Wheeler-DeWitt equations (Sect. 10.2.1)—combining general relativity and quantum mechanics and reappearing in loop quantum gravity—leave out time altogether. The theory predicts a static state of the universe. Modern theoretical results, based on merging quantum mechanics and general relativity, have also not been helpful. By entangling quantum clocks with gravity, researchers discovered an inherent fuzziness of time. Any clock that is used to measure time will inadvertently "blur" the flow of time in its surrounding space (Ruiz et al. 2017). Going further, some physicists have argued that time is not a fundamental property of the universe: It is an emergent feature of reality. Specifically, time is a side-effect of quantum entanglement (Page and Wootters 1983; Moreva et al. 2014). Others, again, have simply denied the reality of time.

The philosophy of time offers two basic approaches to time (McTaggart 1927). The A-theory of time simply claims that time flows from the future, through the present, into past. This is what our naive intuition and perception tell us. In contrast, the B-theory of time speaks of a tenseless time. The flow of time is an illusion and the past, the present, and the future are all real. In this sense, Einstein is alive. This counterintuitive view of time is what physics appears to be telling us. The physicist Julian Barbour is a staunch advocate, defending time's illusory nature (Barbour 1999, 2001). In his words (quoted in Steele 2013):

> The flow of time is an illusion, and I don't know very many scientists and philosophers who would disagree with that, to be perfectly honest. The reason that it is an illusion is when you stop to think, what does it even mean that time is flowing? When we say something flows like a river, what you mean is an element of the river at one moment is in a different place of an earlier moment. In other words, it moves with respect to time. But time can't move with respect to time—time is time. A lot of people make the mistake of thinking that the claim that time does not flow means that there is no time, that time does not exist. That's nonsense. Time of course exists. We measure it with clocks. Clocks don't measure the flow of time, they measure intervals of time. Of course there are intervals of time between different events, that's what clocks measure.
>
> Time and space are the framework in which we formulate all of our current theories of the universe, but there is some question as to whether these might be emergent or secondary qualities of the universe. It could be that fundamentally the laws of the universe are formulated in terms of some sort of pre-space and time, and that space-time comes out of something more fundamental.
>
> This dichotomy between space-time being emergent, a secondary quality—that something comes out of something more primitive, or something that is at the rock bottom of our description of nature—has been floating around since before my career. John Wheeler believed in and wrote about this in the 1950s.

> The problem is that we don't have any sort of experimental hands on that. You can dream up mathematical models that do this for you, but testing them looks to be pretty hopeless.

Barbour's ideas are not mainstream. However, his theorizing about time also flows into speculations about quantum gravity (Falk 2008, p. 149):

> Part of the problem with "time," [Barbour] explains, is that our two best theories—general relativity and quantum theory—treat it very differently. "It's like two children sort of quarreling over a toy they want," he says. "But the trouble is, each wants something different." He believes the only solution [for a theory of quantum gravity] is to remove the toy. We have to abandon the notion of time.

His views have influenced some proponents of loop quantum gravity (Falk 2008, p. 149):

> [Smolin] has said in the past that Barbour, in particular, has been a "philosophical guru" for him. He especially admires Barbour's approach to quantum gravity; many who have tackled the issue have displayed "sloppy thinking," Smolin says, while Barbour has "really thought it through."

Another pioneer of loop quantum gravity, Carlo Rovelli, agrees with Barbour's assessment about the reality of time (Callender and Huggett 2001, p. 114):

> At the fundamental level, we should, simply, forget time.

A claim Rovelli is also defending in his recent book (Rovelli 2018). In contrast, Smolin is still trying to save time (Smolin 2013; Unger and Smolin 2015). He argues (Brockman 2009, p. 149):

> It is becoming clear to me that the mystery of the nature of time is connected with other fundamental questions such as the nature of truth in mathematics and whether there must be timeless laws of nature. Rather than being an illusion, time may be the only aspect of our present understanding of nature that is not temporary and emergent.

Another angle of attack on time can be found in Muller (2016). Now, time is expanding and at the edge of new time is what we experience as "now."

In the end, the mystery of time breaks down at the border between objectivity and subjectivity. Indeed, this boundary appears as a major fault line in the human narrative of the world. In the words of Schülein and Reitze (2002, p. 174, translation mine):

> Objectivity is the illusion that observations are made without an observer.

The objective description of time tells a fundamentally different story to what our senses are telling us. This has lead some thinkers to relabel the problem of time as a problem of consciousness (Falk 2008, p. 273):

> Perhaps millions of years of biological evolution, coupled with thousands of years of cultural and linguistic evolution, have shaped our minds in such a way that we imagine such a flow [of time] where none exists.
>
> [...]
>
> Is the passage of time something our brains assemble out of a swirl of sensory data and then present to us as though it were real? Is the process so efficient, perhaps, that we imagine that

> the finished product was "out there" all along? For some thinkers, the "self" itself is such a construction—in which case time might simply be one facet of a much richer cognitive assembly.

The "now" is the crux. Our consciousness appears to be inevitably embedded in the flow of time—indeed the "now" is the only arena consciousness can act in—whereas reality itself seems less restrictive on the causal ordering of events. This insight can be experimentally and theoretically substantiated. The enigma of consciousness is the topic of the next chapter.

Conclusion

Unexpectedly, and to everyone's great dismay, the Book of Nature turned out to be an incomplete translation. The original appears to be written in an alien language, incomprehensible to the human mind, encompassing vastly greater knowledge. Nonetheless, the Book of Nature uncovers enough insights into the workings of reality to allow human ingenuity to engineer technology. But apart from offering fragments of knowledge, it is stubbornly silent, or outright inconsistent and paradoxical, when it comes to the true nature of things. Space, time, and matter transcend any human conceptuality. We are left with a make-shift and incomplete ontology of reality. The borders of our knowledge open up to an abyss of ignorance. In the final analysis, reality's ontology is maybe such that the human mind will never fundamentally be able to grasp it. In the words of the Nobel laureate Percy W. Bridgman (as quoted in Tarnas 1991, p. 358):

> The structure of nature may eventually be such that our processes of thought do not correspond to it sufficiently to permit us to think about it at all. […] The world fades out and eludes us. […] We are confronted with something truly ineffable. We have reached the limit of the vision of the great pioneers of science, the vision, namely, that we live in a sympathetic world in that it is comprehensible by our minds.

Such limitations to knowledge were long suspected. Einstein posited (quoted in Gaither 2012, p. 1419):

> The human mind is not capable of grasping the Universe. We are like a little child entering a huge library. The walls are covered to the ceilings with books in many different tongues. The child knows that someone must have written these books. It does not know who or how. It does not understand the languages in which they are written. But the child notes a definite plan in the arrangement of the books—a mysterious order which it does not comprehend, but only dimly suspects.

For more on the idea that the laws of nature are makeshift and arbitrary, as opposed to sublime, inevitable, and self-contained, see Cossins (2018).

In the final analysis (Westerhoff 2011):

> If we follow scientific reduction all the way down, we end up with stuff that certainly does not look like tiny pebbles or billiard balls, not even like strings vibrating in a multidimensional space, but more like what pure mathematics deals with [p. 51].

> The moral to draw from the reductionist scenario […] seems to be that either what is fundamental is not material, or that nothing at all is fundamental [p. 54].

If looking out into reality leaves us dumbfounded, perhaps we then should look inside and gaze into our own inner realities. Now the enigma of consciousness appears on the horizon.

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Chapter 11
Subjective Consciousness: What am I?

Abstract Consciousness is a fact. In this very moment your eyes are scanning these words and your mind is creating understanding of and context for the contents utilizing memory. However, astonishingly, we don't know how to accommodate consciousness into our scientific view of the world. Until quite recently, the nation of consciousness was taboo for scientists and philosophers alike. Today, a central problem is: How does the feeling of subjective experience emerge from neural activity? As a corollary: How does the ethereal mind interact with the physical world? Insights from neuroscience have uncovered that our perceptions of reality are not faithful representations, but constructed virtual reality simulations. Memories are also constructed and not retrieved. The sense of self is a result of a complex cognitive effort. The role of our consciousness is to narrate and rationalize the decisions emerging from the subconscious brain, in retrospect. Context and expectations influence and shape perceptions and experiences. The human mind exhibits countless irrational behaviors—cognitive biases abound. The mind can also suffer from a wide array of pathologies. Finally, free will is a very controversial topic, as experiments question its reality.
Level of mathematical formality: not applicable.

The phenomenon of consciousness represents the last enigma. After the long journey of the human mind—attempting to decode the workings of the universe—it has returned and is now facing its own existence. Just as the understanding of the fundamental nature of reality turned out to be an elusive quest, the challenge of understanding one's own mind appears truly stupendous. The psychologist Susan Blackmore summarizes (Blackmore 2005, p. 1):

> What is consciousness? This may sound like a simple question but it is not. Consciousness is at once the most obvious and the most difficult thing we can investigate. We seem either to have to use consciousness to investigate itself, which is a slightly weird idea, or have to extricate ourselves from the very thing we want to study.

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
https://doi.org/10.1007/978-3-030-03633-1_11

Consciousness is not only a vexing problem for scientists and philosophers alike, it is also a deep mystery for every conscious being. On the one hand it is so familiar. Indeed, my conscious experiences of the world and of dreams—flowing in the river of time, eternally locked into this moment of "now"—is all that I know. I am intimately and fundamentally a manifestation of my consciousness. On the other hand, consciousness creates an insurmountable schism: reality divides into the inner and outer world. My first-person subjective experience is pitted against an outer, objective reality. The two realities collide. One is characterized by "what does it feel like?" and the other by "out there." The observer and the observed emerge. The central conundrum is the following. How do our brains conjure up subjective, conscious experiences? In other words, where is the greenness of green to be found in our brains? After all, it is mediated by intrinsically featureless electromagnetic radiation with a wavelength between 495 and 570 nm. In more technical language, what are the neural correlates of consciousness (i.e., the pinpointed electrochemical neuronal activity in the brain) of qualia (i.e., the subjective conscious experiences)? Even more puzzling is meta-cognition: the thinking about thinking or the awareness of one's awareness. The mind can relate to the mind as a mind.

The neuroscience pioneer Christof Koch summarized the enigma as follows (Koch 2012, p. 23):

> Without consciousness there is nothing. The only way you experience your body and the world of mountains and people, trees and dogs, stars and music is through your subjective experiences, thoughts, and memories. You act and move, see and hear, love and hate, remember the past and imagine the future. But ultimately, you only encounter the world in all of its manifestations via consciousness. And when consciousness ceases, this world ceases as well.
>
> Many traditions view humans as having a mind (or psyche), a body, and a transcendental soul. Others reject this tripartite division in favor of a mind-body duality. The ancient Egyptians and Hebrews placed the psyche in the heart, whereas the Maya located it in the liver. We moderns know that the conscious mind is a product of the brain. To understand consciousness, we must understand the brain.
>
> But there's the rub. How the brain converts bioelectrical activity into subjective states, how photons reflected off water are magically transformed into the percept of iridescent aquamarine mountain tarn is a puzzle. The nature of the relationship between the nervous system and consciousness remains elusive and the subject of heated and interminable debates.

Since 1995, specialists and interested laypersons flock to the picturesque Swiss city of Lucerne every two years. The focus of the *Swiss Biennial on Science, Technics + Aesthetics*[1] lies on contemporary challenges to knowledge. Topics range from quantum physics to cosmology. Over the years, many intellectuals[2] have presented their thoughts, the likes of Heather A. Berlin, Hans-Peter Dürr, Marcelo Gleiser, Stuart Hameroff, Donald D. Hoffman, John Horgan, Brian Josephson, Koch, Lawrence M. Krauss, Roger Penrose, Dean Radin, Martin Rees, Matthieu Ricard, Abner Shimony, Henry Stapp, Franz X Vollenweider, Anton Zeilinger, and the Dalai

[1] See http://www.neugalu.ch/e_index.html.

[2] Of these, most have appeared in this book's narrative. See the Name Index.

Lama's English translator, Thupten Jinpa. In 2001, the eminent philosopher Ernst von Glasersfeld summarized (von Glasersfeld 2001):

> Every two years René Stettler, the owner and director of the Neue Galerie of Lucerne, organizes a two-day symposium for scientists, philosophers, and artists to present and discuss their views on a topic thought to be of interest to a general audience. The main purpose of these events is to foster interdisciplinary discussion and the New Gallery sees itself as a "cultural laboratory". This year's symposium had the title "The Enigma of Consciousness" and attracted between four and five hundred people, filling in the city's theatre.

In 2016 and 2018 the topic was, yet again, *The Enigma of Consciousness*. A diverse list of speakers addressed the issue, including scholars of Buddhism, anthropology, and Amazonian shamanism.[3] Some conclusions from the conference are discussed in Sect. 14.2.2.

It has become apparent that the enigma of consciousness entails a large complex of problems. Challenges originate from issues as diverse as free will, quantum theory, psychoactive drugs, altered states of consciousness, contemplative traditions, meditation, information processing, virtual reality, and artificial intelligence. Indeed, we now have to ask ourselves how unique our human consciousness is. There is very compelling evidence that many animals also have an inner sensation that "it feels like something." Perhaps even insects. The fact that animals possess complex inner worlds—with great capacity for suffering—represents a pressing, albeit mostly ignored, ethical challenge when it comes to industrial livestock production. For instance, in 2016, approximately 65.8 billion chickens, 1.5 billion pigs, and 302 million cattle were slaughtered globally.[4] Viewed from a historical perspective (Harari 2015, p. 104f.):

> Domesticated chickens and cattle may well be an evolutionary success story, but they are also among the most miserable creatures that ever lived.

To this day, the nature of consciousness is as elusive as ever, despite the tremendous advancements in neuroscience and clinical technology of the last decades. As such, the issue has the potential to attract a lot of publicity—and funding. Henry Markram is a controversial neuroscientist (Schneider 2016):

> [His] research proposal received the biggest research funding grant in history: one billion Euros from the European Union,[5] for his "brainchild" (as journalists dubbed it), the Human Brain Project. The modest promise Markram originally made to secure this mind-boggling mountain of cash: he intended to simulate the entire human brain in his supercomputer by 2023, the possibility of artificial consciousness specifically not excluded.

Unfortunately, events did not unfold as planned (Schneider 2016):

> Now however, his consortium partners took over, Markram was dethroned in a scientists' coup and pushed aside to tinker on his seemingly less ambitious, but just as science-fictionary

[3] See http://www.neugalu.ch/pdf/programme_broch_18.pdf.

[4] See the database of the Food and Agriculture Organization of the United Nations: http://www.fao.org/faostat/en/#data/.

[5] See https://ec.europa.eu/digital-single-market/en/human-brain-project.

> mouse Blue Brain simulation.[6] Once in control of almost everything and everyone, with all the big money going through his hands, Markram is now only one of 12 project leaders and far from being the boss.

This, after (Abbott 2015):

> [M]ore than 150 leading neuroscientists sent a protest letter to the European Commission, charging, among other things, that the committee was acting autocratically and running the project's scientific plans off course. Led by the charismatic but divisive Henry Markram, a neuroscientist at the Swiss Federal Institute of Technology in Lausanne (EPFL), which is coordinating the HBP [Human Brain Project], the committee had stirred up anger in early 2014 when it revealed plans to cut cognitive neuroscience from the initiative.

The controversy continues (Schneider 2016):

> After 3 years and almost EUR 150 Mio spent, HBP [Human Brain Project] delivered no published results worth mentioning.

This lack of progress, despite the availability of vast resources, makes consciousness an even more mystifying phenomenon. Indeed (Burkeman 2015):

> It would be poetic—albeit deeply frustrating—were it ultimately to prove that the one thing the human mind is incapable of comprehending is itself.

Koch succinctly captures the essence of this discrepancy (Koch 2012, p. 23):

> [A]stronomy can make testable statements about an event that took place 13.7 billion years ago [referring to NASA's Cosmic Background Explorer data]! Yet something as mundane as a toothache, right here and now, remains baffling.

Perhaps this assessment can be placed in a different context. After all, the human brain is the most complex structure we have discovered in the universe.[7] That is, if we look from the outside. Looking from the inside, we would never guess that behind our eyes something as intricate and sophisticated is lurking in the silent darkness of our skulls.

11.1 The History and Philosophy of Our Minds

The enigma of consciousness has entranced the human mind since it became aware. However, a new chapter in the saga opened over two decades ago (Burkeman 2015):

> One spring morning in Tucson, Arizona, in 1994, an unknown philosopher named David Chalmers got up to give a talk on consciousness […]. Though he didn't realize it at the time, the young Australian academic was about to ignite a war between philosophers and scientists, by drawing attention to a central mystery of human life—perhaps *the* central mystery of human life—and revealing how embarrassingly far they were from solving it.

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[6] A Swiss national initiative that aimes at creating a digital reconstruction of the brain by reverse-engineering mammalian brain circuitry. See https://bluebrain.epfl.ch/.

[7] Chapter 6 details the science of complex systems.

Indeed, in serious academic circles, the notion of consciousness was taboo (Burkeman 2015):

> By the time Chalmers delivered his speech in Tucson, science had been vigorously attempting to ignore the problem of consciousness for a long time.
>
> [...]
>
> As late as 1989, writing in the International Dictionary of Psychology, the British psychologist Stuart Sutherland could irascibly declare of consciousness that "it is impossible to specify what it is, what it does, or why it evolved. Nothing worth reading has been written on it."

Then, in 1990 Francis Crick, the co-discoverer of the double helix, wrote an article with Koch, called *Towards a Neurobiological Theory of Consciousness*. It opens as follows (Crick and Koch 1990):

> It is remarkable that most of the work in both cognitive science and the neurosciences makes no reference to consciousness (or "awareness"), especially as many would regard consciousness as the major puzzle confronting the neural view of the mind and indeed at the present time it appears deeply mysterious to many people.

As a scientist, it is always risky to go against the established status quo. Indeed, Koch recalls (quoted in Burkeman 2015):

> A senior colleague took me out to lunch and said, yes, he had the utmost respect for Francis [Crick], but Francis was a Nobel laureate and a half-god and he could do whatever he wanted, whereas I didn't have tenure yet, so I should be incredibly careful. Stick to more mainstream science! These fringey things—why not leave them until retirement, when you're coming close to death, and you can worry about the soul and stuff like that?

This highlights yet another example of an entrenched scientific paradigm in the Kuhnian view (Sect. 9.1.3). It is not always the unquenchable thirst for knowledge that gets to set the scientific agenda, but often mundane constraints coming from authority outlawing certain ideas. It is then up to maverick scientists to herald the start of a new paradigm.[8] However, the stigmatization of consciousness can still be felt today. In the words of the neuroscientist Antonio Damasio (Damasio 2011):

> This [the conscious mind] is a mystery that has really been extremely hard to elucidate. All the way back into early philosophy and certainly throughout the history of neuroscience, this has been one mystery that has always resisted elucidation, has got major controversies. And there are actually many people that think we should not even touch it; we should just leave it alone, it's not to be solved.

Whereas neuroscientists and cognitive scientists can retreat back into the specificities and technical details of their research, philosophers are exposed to the full brunt of the controversy (Burkeman 2015):

> The consciousness debates have provoked more mudslinging and fury than most in modern philosophy, perhaps because of how baffling the problem is: opposing combatants tend not merely to disagree, but to find each other's positions manifestly preposterous.

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[8] The mathematical physicist and cosmologist Penrose also pioneered the scientific approach to consciousness (Penrose 1989, 1994, 1997; Hameroff and Penrose 2014).

It did not help when Chalmers started to talk about zombies (Chalmers 1996). He stresses (quoted in Burkeman 2015):

> Look, I'm not a zombie, and I pray that you're not a zombie but the point is that evolution could have produced zombies instead of conscious creatures—and it didn't!

The zombie scenario goes as follows (Burkeman 2015):

> [I]magine that you have a doppelgänger. This person physically resembles you in every respect, and behaves identically to you; he or she holds conversations, eats and sleeps, looks happy or anxious precisely as you do. The sole difference is that the doppelgänger has no consciousness; this—as opposed to a groaning, blood-spattered walking corpse from a movie—is what philosophers mean by a "zombie".

This idea is reminiscent of solipsism, the radically skeptical stance that only one's own mind is known to exist. Not everyone was intrigued (Burkeman 2015):

> The withering tone of the philosopher Massimo Pigliucci sums up the thousands of words that have been written attacking the zombie notion: "Let's relegate zombies to B-movies and try to be a little more serious about our philosophy, shall we?" Yes, it may be true that most of us, in our daily lives, think of consciousness as something over and above our physical being—as if your mind were "a chauffeur inside your own body", to quote the spiritual author Alan Watts. But to accept this as a scientific principle would mean rewriting the laws of physics. Everything we know about the universe tells us that reality consists only of physical things: atoms and their component particles, busily colliding and combining. Above all, critics point out, if this non-physical mental stuff did exist, how could it cause physical things to happen—as when the feeling of pain causes me to jerk my fingers away from the saucepan's edge?

In his 1994 talk, Chalmers rocked the boat of the philosophy of the mind by introducing the "hard problem of consciousness" (Chalmers 1995). The "easy problem" of consciousness relates to explaining the brain's dynamics in terms of the functional or computational organization of the brain. The hard problem can be related to an observation by the mathematician and philosopher Alfred N. Whitehead (Whitehead 1953, p. 68):

> But the mind in apprehending also experiences sensations which, properly speaking, are qualities of the mind alone.

In essence, the hard problem of consciousness is the challenge of explaining how and why we have phenomenal experiences (qualia). How do 1,400 g of organic matter, organized as a neural network and constrained by the laws of nature, give rise to first-person conscious experiences? How do sensations acquire their specific characteristics such as colors and tastes? More specifically, how do neurophysiological and biochemical processes translate into phenomenal and subjective perception? This issue had already baffled the biologist Thomas Huxley in 1866 (quoted in McGinn 2004, p. 56):

> How it is that anything so remarkable as a state of consciousness comes about as a result of irritating nervous tissue, is just as unaccountable as the appearance of the Djinn when Aladdin rubbed his lamp in the story.

The cognitive scientist Donald D. Hoffman reiterates (Hoffman 2015):

> Now, Huxley knew that brain activity and conscious experiences are correlated, but he didn't know why. To the science of his day, it was a mystery. In the years since Huxley, science has learned a lot about brain activity, but the relationship between brain activity and conscious experiences is still a mystery.

Essentially, the hard problem of consciousness is a reiteration of the mind-body problem. This dualism—the schism between the physical body and an ethereal mind—goes back to the philosopher, mathematician, and scientist René Descartes (Descartes 1641). Cartesian dualism contrasts monism, which is the notion that there exists only one fundamental essence. In greater detail, in the words of the psychologist Tania Lombrozo (quoted in Brockman 2015, p. 271ff.):

> In the beginning, there was dualism. Descartes famously posited two kinds of substance, non-physical mind and material body. Leibniz differentiated mental and physical realms. But dualism faced a challenge—explaining how mind and body interact.
>
> We now know, of course, that mind and brain are intimately connected. Injuries to the brain can alter perceptual experience, cognitive abilities, and personality. Changes in brain chemistry can do the same. [...]
>
> In fact, it appears the mind is just the brain. [...]
>
> Or maybe not.
>
> In our enthusiasm to find a scientifically acceptable alternative to dualism, some of us have gone too far the other way, adopting a stark reductionism. Understanding the mind is not just a matter of understanding the brain. But then, what is it a matter of? Many alternatives to the *mind=brain* equation seem counterintuitive or spooky. Some suggest that the mind extends beyond the brain to encompass the whole body, or even parts of the environment, or that the mind is not subject to the laws of physics.
>
> [...]
>
> Rejecting the mind in an effort to achieve scientific legitimacy—a trend we've seen with both behaviorism and some popular manifestations of neuroscience—is unnecessary and unresponsive to the aims of scientific psychology. Understanding the mind isn't the same as understanding the brain. Fortunately, though, we can achieve such understanding without abandoning scientific rigor.

Naturally, not everyone believes that the hard problem of consciousness even exists. The famous philosopher Daniel Dennett, for instance, sees consciousness as a "bag of tricks." Like any magic performance, we are enthralled by it only as long as we do not know how it was done. Once we know the trick, the illusion disappears and we are disappointed. By simply studying the brain, according to Dennett, we will soon be able to uncover all of its magic. A central claim, made in his book *Consciousness Explained*, is that qualia do not—indeed, cannot—exist (Daniel 1991). In effect, the hard problem of consciousness vanishes, and with it all the zombies. In greater detail (Burkeman 2015):

> Not everybody agrees there is a Hard Problem to begin with—making the whole debate kick-started by Chalmers an exercise in pointlessness. Daniel Dennett, the high-profile atheist and professor at Tufts University outside Boston, argues that consciousness, as we think of it, is an illusion: there just isn't anything in addition to the spongy stuff of the brain, and that spongy stuff doesn't actually give rise to something called consciousness. Common sense may tell us there's a subjective world of inner experience—but then common sense told us that the sun orbits the Earth, and that the world was flat. Consciousness, according to Dennett's theory,

> is like a conjuring trick: the normal functioning of the brain just makes it look as if there is something non-physical going on. To look for a real, substantive thing called consciousness, Dennett argues, is as silly as insisting that characters in novels, such as Sherlock Holmes or Harry Potter, must be made up of a peculiar substance named "fictoplasm"; the idea is absurd and unnecessary, since the characters do not exist to begin with. This is the point at which the debate tends to collapse into incredulous laughter and head-shaking: neither camp can quite believe what the other is saying. To Dennett's opponents, he is simply denying the existence of something everyone knows for certain: their inner experience of sights, smells, emotions and the rest. (Chalmers has speculated, largely in jest, that Dennett himself might be a zombie.) It's like asserting that cancer doesn't exist, then claiming you've cured cancer; more than one critic of Dennett's most famous book, *Consciousness Explained*, has joked that its title ought to be *Consciousness Explained Away*. Dennett's reply is characteristically breezy: explaining things away, he insists, is exactly what scientists do. When physicists first concluded that the only difference between gold and silver was the number of subatomic particles in their atoms, he writes, people could have felt cheated, complaining that their special "goldness" and "silveriness" had been explained away. But everybody now accepts that goldness and silveriness are really just differences in atoms. However hard it feels to accept, we should concede that consciousness is just the physical brain, doing what brains do.

Chalmers replies (Chalmers 2014):

> My friend Dan Dennett, who's here today, has one [radical idea about consciousness]. His crazy idea is that there is no hard problem of consciousness. The whole idea of the inner subjective movie involves a kind of illusion or confusion. Actually, all we've got to do is explain the objective functions, the behaviors of the brain, and then we've explained everything that needs to be explained. Well I say, more power to him. That's the kind of radical idea that we need to explore if you want to have a purely reductionist brain-based theory of consciousness. At the same time, for me and for many other people, that view is a bit too close to simply denying the datum of consciousness to be satisfactory. So I go in a different direction. In the time remaining, I want to explore two crazy ideas that I think may have some promise.

More on Chalmers' crazy ideas will follow in Chap. 14. Blackmore also rejects dualism and thus the validity of the hard problem of consciousness. Specifically, she questions the idea of neural correlates of consciousness. In detail, Blackmore argues (quoted in Brockman 2015, p. 141ff.):

> Consciousness is a hot topic in neuroscience and some of the brightest researchers are hunting for the neural correlates of consciousness (NCCs)—but they will never find them. The implicit theory of consciousness underlying this quest is misguided and needs to be retired.
>
> The idea of the NCCs is simple enough and intuitively tempting. If we believe in the "hard problem of consciousness"—the mystery of how subjective experience arises from (or is created by or generated by) objective events in a brain—then it's easy to imagine that there must be a special place in the brain where this happens. Or if there is no special place then some kind of "consciousness neuron", or process or pattern or series of connections. [...]
>
> The trouble is it depends on a dualist—and ultimately unworkable—theory of consciousness. The underlying intuition is that consciousness is an added extra—something additional to and different from the physical processes on which it depends. [...]
>
> Dualist thinking comes so naturally to us. We feel as though our conscious experiences are of a different order from the physical world. But this is the same intuition that leads to the hard

> problem seeming hard. It is the same intuition that produces the philosopher's zombie—a creature that is identical to me in every way except that it has no consciousness. […]
>
> Consciousness is not some weird and wonderful product of some brain processes but not others. Rather, it is an illusion constructed by a clever brain and body in a complex social world. We can speak, think, refer to ourselves as agents and so build up the false idea of a persisting self that has consciousness and free will.

Very Short Introductions is a book series published by the Oxford University Press. The books offer, as the name suggests, very concise introductions to various topics, ranging from happiness (Haybron 2013) to reality (Westerhoff 2011). There are currently 622 titles.[9] Blackmore wrote the one on consciousness (Blackmore 2005). There we can read:

> It seems we have some tough choices in thinking about our own precious self. We can hang on to the way it feels and assume that a persisting self or soul or spirit exists, even though it cannot be found and leads to philosophical troubles. We can equate it with some kind of brain process and shelve the problem of why this brain process should have conscious experiences at all, or we can reject any persisting entity that corresponds to our feeling of being a self. I think that intellectually we have to take this last path. The trouble is that it is very hard to accept in one's own personal life. It means taking a radically different view of every experience. It means accepting that there is no one who is having these experiences. [P. 81]
>
> […]
>
> There are two really fundamental assumptions that almost everyone makes. The first is that experiences happen to someone; that there cannot be experiences without an experiencer. […] This has to be thrown out. The second assumption is that experiences flow through the conscious mind as a stream of ideas, feelings, images, and perceptions. The stream may break, change direction, or be disrupted, but it remains a series of conscious events in the theater of the mind. […] This has to be thrown out. […] This is how the grand delusion of consciousness comes about. We humans are clever, speaking, thinking creatures who can ask ourselves the question "Am I conscious now?". Then, because we always get the answer "yes", we leap to the erroneous conclusion that we are always conscious. The rest follows from there. [P. 128f.]

To some, these assertions may sound deeply troubling and existentially threatening. This reaction, however, could be a result of specific socio-cultural and religious programming. Again, Blackmore (2005, p. 68):

> Among religions, Buddhism alone rejects the idea of self. […] [The historical Buddha] taught that human suffering is caused by ignorance and in particular by clinging to a false notion of self; the way out of suffering is to drop all the desires and attachments that keep recreating the self. Central to his teaching therefore, is the idea of no-self. This is not to say that the self does not exists, but that it is illusory—or not what it seems.

For more on the notion of suffering and happiness in Buddhism, see Sect. 7.4.2.1. For the exceptional display of mental prowess of Buddhist meditators, see Sect. 9.3.5.

The rejection of dualism by scientists and philosophers is mainly motivated by a fundamental assumptions regarding the nature of reality. Namely, the conviction

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[9] See https://global.oup.com/academic/content/series/v/very-short-introductions-vsi/, accessed July 4, 2018.

that the reductionist materialist paradigm is the best, and perhaps only, template for decoding reality. This, of course, is a very sensible approach. However, one should not forget that reductionism is a tool—perhaps even a philosophy—for dealing with the nature of reality and is not a theory in itself. Moreover, materialism is based on the intuitions a human mind acquires, based on its perception of reality. In the context of this book, we know that reductionism, while being spectacularly successful (Sect. 5.1) in understanding the fundamental processes of nature (Chaps. 3 and 4), fails as a explanatory matrix (Sect. 5.2) for complex phenomena (Chap. 6). Furthermore, the notion of materialism, in the framework of our best theory of the microscopic world, appears highly problematic to be upheld (Sects. 10.3.2 and 10.4). Indeed, the very notion of scientific inquiry is plagued by a multitude of issues (Chap. 9). Recall from the end of the last chapter (Westerhoff 2011):

> If we follow scientific reduction all the way down, we end up with stuff that certainly does not look like tiny pebbles or billiard balls, not even like strings vibrating in a multidimensional space, but more like what pure mathematics deals with. [P. 51]
>
> The moral to draw from the reductionist scenario [...] seems to be that either what is fundamental is not material, or that nothing at all is fundamental. [P. 54]

In the end, one sides with Chalmers or Dennett based on deeply held assumptions and beliefs about the nature of reality and the self. Of course, both sides will insist that they are justified in their assessments based on a rational, intellectual, and inevitable decision-making process—but this too is just an illusion. The conclusion is as obvious as it is disheartening. Our minds have cultivated intuitions and constructed narratives about the universe and ourselves which are simply false. However, which ones have to be exchanged, and what should fill the void, is the fuel for potentially endless debates. Some personal insights on the mind, collected from various thinkers, can be found in Brockman (2011), Marcus and Freeman (2015).

11.2 Modern Neuroscience

In the preceding section, the mind used itself as a tool to try and understand itself. In other words, the mind contemplated its own existence—the philosophy of the mind was born. However, what happens if we expose the human mind to the contemporary tools of science? In the preface of the textbook *Foundational Concepts in Neuroscience* we can read (Presti 2016, p. xiii):

> Neuroscience—the science of brain and behavior—is one of the most exciting fields in the landscape of contemporary science. Its rapid growth over the last several decades has spawned many discoveries and a large number of popular books. Contemporary news is filled with stories about the brain, brain chemistry, and behavior. Photos and drawings of brains and nerve cells grace the pages of newspapers and magazines.

The recent explosion we are witnessing in the field of neuroscience is driven by technology. Again, the human mind is ingenious enough to decode reality in a way that allows for the engineering of technology (the genesis of this knowledge generation process is described in Chap. 2). Specifically, the new found ability of the mind to observe its own physiological basis—its rooting in reality—has shone a bright light on this previously obscure topic. Indeed, the clinical technology uncovering the brain's activity has come a long way: from electroencephalography (EEG), computed tomography scans (CT), positron-emission tomography (PET), functional magnetic resonance imaging (fMRI), to magnetoencephalography (MEG). Perhaps the most stunning and beautiful image of the human brain is the connectome,[10] a map of neural connections in the brain. It uncovers the brain's wiring diagram (Sporns et al. 2005). The casual reader might gloss over the fact that some of these diagnostic technologies utilize highly evolved technology. PET detects antimatter (see Fig. 4.1) and MEG employs superconducting quantum interference devices. Some researchers have used artificial intelligence, specifically, machine learning algorithms, to reconstruct the original picture, given an fMRI scan of a person looking at that picture (Shen et al. 2017). Other examples of how modern technology can read our minds can be, for instance, found in the articles published in the *New Scientist*, a weekly magazine covering aspects of science and technology. These range from Brown (2017) recording the inner monologues in our minds (Thomson 2014) to brain implants allowing paralyzed people to type with their thoughts (Hamzelou 2017). Neuroscientists can now follow a thought as it moves through the brain (Haller et al. 2018).

Exposing the intimate experiences within our brains has mind-numbing potential. But there are also reasons to be cautious. There exists a lot of "neuro-bunk" (Crockett 2012)—myths about the brain. From the role of mirror neurons[11] to the importance of oxytocin,[12] many spectacular claims have been debunked. For instance Crockett (2012):

> So speaking of love and the brain, there's a researcher, known to some as Dr. Love, who claims that scientists have found the glue that holds society together, the source of love and prosperity. […] [I]t's a hormone called oxytocin. You've probably heard of it. So, Dr. Love bases his argument on studies showing that when you boost people's oxytocin, this increases their trust, empathy and cooperation. So he's calling oxytocin "the moral molecule."
>
> Now these studies are scientifically valid, and they've been replicated, but they're not the whole story. Other studies have shown that boosting oxytocin increases envy. It increases gloating. Oxytocin can bias people to favor their own group at the expense of other groups. And in some cases, oxytocin can even decrease cooperation.

Furthermore (Jarrett 2013):

> Neuroscientist V.S. Ramachandran says these cells [mirror neurons] shaped our civilisation; in fact he says they underlie what it is to be human—being responsible for our powers of empathy, language and the emergence of human culture, including the widespread use of tools and fire. When mirror neurons don't work properly, Ramachandran believes the result is autism.
>
> For the record, a detailed investigation earlier this year found little evidence to support his theory about autism. Other experts have debunked Ramachandran's claims linking mirror neurons to the birth of human culture.

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[10] See http://www.humanconnectomeproject.org/gallery/.

[11] Neurons that fire when an action is performed and also when that action is observed in others.

[12] A hormone that acts as a neurotransmitter.

The referenced study is Kilner and Lemon (2013). Also, recall the bug in the fMRI software potentially affecting 15 years of research (Sect. 9.2.2).

11.2.1 Perceiving the Outer World

Perhaps the most astonishing story neuroscientists tell us is about perception—the very way we known about an external world. Yet again, a very basic intuition we hold is deeply flawed: the notion that our eyes translate electromagnetic radiation into electrical impulses from which the brain reconstructs a faithful image of the world. In the words of the neuroscientist David Eagleman (Eagleman 2011):

> [O]ur brains sample just a small bit of the surrounding physical world. [P. 77]
>
> Instead of reality being passively recorded by the brain, it is actively constructed by it. [P. 82]
>
> You're not perceiving what's out there. You're perceiving whatever your brain tells you. [P. 33]

Indeed (Eagleman 2016, p. 73):

> Despite the feeling that we're directly experiencing the world out there, our reality is ultimately built in the dark, in a foreign language of electrochemical signals. The activity churning across vast neural networks gets turned into your story of this, your private experience of the world: the feeling of this book in your hands, the light in the room, the smell of roses, the sound of others speaking.

If our perception of reality is not a faithful image of the outer reality, what is it then? Research suggests (Seth 2017):

> So perception—figuring out what's there—has to be a process of informed guesswork in which the brain combines these sensory signals with its prior expectations or beliefs about the way the world is to form its best guess of what caused those signals. The brain doesn't hear sound or see light. What we perceive is its best guess of what's out there in the world.
>
> […]
>
> Instead of perception depending largely on signals coming into the brain from the outside world, it depends as much, if not more, on perceptual predictions flowing in the opposite direction. We don't just passively perceive the world, we actively generate it. The world we experience comes as much, if not more, from the inside out as from the outside in.
>
> […]
>
> If hallucination is a kind of uncontrolled perception, then perception right here and right now is also a kind of hallucination, but a controlled hallucination in which the brain's predictions are being reined in by sensory information from the world. In fact, we're all hallucinating all the time, including right now. It's just that when we agree about our hallucinations, we call that reality.

Eagleman also agrees (Eagleman 2011, p. 46):

> [W]hat we call normal perception does not really differ from hallucinations, except that the latter are not anchored by external input.

In other words, the perception of the external world is a virtual reality simulation (Hoffman 2000).

This existentially challenging claim can perhaps be best understood in the context of visual illusions (Lotto 2012):

> So, tomorrow morning when you open your eyes and look "out into" the world, don't be fooled. You're in fact looking in. You're not seeing the world covered in a blue blanket at all; you're seeing *a* world... an internal map of value-relations derived from interactions within a particular, narrow context.
>
> And yet color is the simplest sensations the brain has. What may surprise you is that even at this most basic level we never see the light that falls onto our eyes or even the real-world source of that light. Rather, neuroscience research tells us that we only ever see what proved useful to see in the past. Illusions are a simple but powerful example of this point.

There exist many examples of such illusions (Shepard 1990). The crux of the issue is that the illusion can never be deconstructed by the intellect. Any knowledge or understanding of the illusion remains virtually powerless to diminish the magnitude of the illusion. Moreover, we know that our visual perception suffers from some severe restrictions. For instance, there exists a significant blind spot in our visual field where the optic nerve passes through the optic disc of the retina (Ramachandran and Gregory 1991). This lack of photoreceptor cells cuts a hole into the visual field. Indeed, the area of sharp central vision is restricted to the fovea, a structure in the inner retinal surface. As a result, our visual field only has a high-resolution part which is approximately the size of a thumbnail held at arm's length (Fairchild 2005). Then, our peripheral vision is very limited. It is low-resolution and mostly monochromatic (Anderson et al. 1991). Moreover, our eyes are constantly in motion, erratically scanning the visual field (Deubel and Schneider 1996):

> When we inspect a visual scene, periods of fixation are interrupted by fast ballistic movements of the eyes, the saccades. By means of these goal-directed eye movements, the fovea is brought to "interesting spots" of the scene. For instance, a common observation is that when a subject views the picture of a person, the nose and mouth are fixated more often and first in sequence compared to other objects of the picture, such as spots on the cheek.

My personal subjective experience of vision denies these aspects. I perceive a continuous, steady, high-resolution, chromatic picture of the world, which covers my entire field of vision. The visual hallucination of the world that I continually experience is a very immediate and compelling one. This constant stream of my perception of reality is, however, also temporally restricted (Herzog et al. 2016):

> We experience the world as a seamless stream of percepts. However, intriguing illusions and recent experiments suggest that the world is not continuously translated into conscious perception. Instead, perception seems to operate in a discrete manner, just like movies appear continuous although they consist of discrete images.

Finally, the entire perception of time itself is a mental construct akin to an illusion and very malleable (Hodinott-Hill et al. 2002; Eagleman 2008).

If our trusted visual perception of the world is indeed an inaccurate representation of it, we should expect ramifications. The McGurk effect is a fascinating example of how visual information can affect auditory perception (McGurk and MacDonald

1976). Specifically, seeing the lips of a person form certain inaudible sounds alters the perception of an actual sound. Change blindness is another such striking example of perceptive deficiency. It is a phenomenon which occurs when a change in a visual stimulus is not detected by the observer. It turns out that humans are very bad at noticing even major differences introduced into an image while it flickers off and on again. In other words, we can be oblivious to changes happening right in front of our very own eyes. Indeed (Simons and Levin 1997):

> Given failures of change detection, we must question the assumption that we have a detailed representation of our visual world.

This effect can be dramatically increased if the observer's attention is captured, a phenomenon known as selective attention. The results are disheartening. The human mind is astonishingly restricted when perceiving reality. In detail (Chabris and Simons 2009, p. xi, 5f.):

> About twelve years ago, we conducted a simple experiment with the students in a psychology course we were teaching at Harvard University. To our surprise, it has become one of the best-known experiments in psychology. It appears in textbooks and is taught in introductory psychology courses throughout the world.
>
> […]
>
> With our students as actors and a temporarily vacant floor of the psychology building as a set, we made a short film of two teams of people moving around and passing basketballs. One team wore white shirts and the other wore black. […]
>
> They [the students] asked volunteers to silently count the number of passes made by the players wearing white while ignoring any passes by the players wearing black. The video lasted less than a minute.[13] […]
>
> Immediately after the video ended, our students asked the subjects to report how many passes they'd counted. […] The pass-counting task was intended to keep people engaged in doing something that demanded attention to the action on the screen, but we weren't really interested in pass-counting ability. We were actually testing something else: Halfway through the video, a female student wearing a full-body gorilla suit walked into the scene, stopped in the middle of the players, faced the camera, thumped her chest, and then walked off, spending about nine seconds onscreen. After asking the subjects about the passes, we asked the more important questions:
>
> Q: Did you notice anything unusual while you were doing the counting task?
>
> A: No.
>
> […]
>
> Q: Did you notice *anyone* other than the players?
>
> A: No.
>
> Q: Did you notice a gorilla?
>
> A: A what?!?
>
> Amazingly, roughly half of the subjects in our study did not notice the gorilla! Since then the experiment has been repeated many times, under different conditions, with diverse audiences, and in multiple countries, but the results are always the same: About half the people fail to see the gorilla.

[13] See http://www.theinvisiblegorilla.com/gorilla_experiment.html.

Our mind's capacity to perceive an inaccurate representation of reality is not restricted to vision. The expectation and context of any experience can alter how this experience is perceived. One experiment in particular will make oenologists despair (Plassmann et al. 2008):

> We propose that marketing actions, such as changes in the price of a product, can affect neural representations of experienced pleasantness. We tested this hypothesis by scanning human subjects using functional MRI while they tasted wines that, contrary to reality, they believed to be different and sold at different prices. Our results show that increasing the price of a wine increases subjective reports of flavor pleasantness as well as blood-oxygen-level-dependent activity in medial orbitofrontal cortex, an area that is widely thought to encode for experienced pleasantness during experiential tasks.

Believing that a wine is expensive results in it tasting better, irrespective of the actual quality. This is not imagined, as the brain will construct an actual experience of reality based on the priming. The experiment has recently been redone (Schmidt et al. 2017):

> Informational cues such as the price of a wine can trigger expectations about its taste quality and thereby modulate the sensory experience on a reported and neural level.

Expectations related to experiences change how they are perceived across a variety of sensory domains, including pain (Schmidt et al. 2017), vision (Summerfield and De Lange 2014), smell (De Araujo et al. 2005), and hearing (Kirk et al. 2009). While it seems astounding that expectations shape the way we taste, see, hear, and smell, the finding that pain is also under the influence of our mind's expectations appears preposterous. Indeed, if you believe that the pain you feel is the result of an intentional act, it will hurt more than if you thought it was administered unintentionally (Gray and Wegner 2008).

Where does this leave us? Our closest intuitions about the world fails. Everything we thought was "out there" is mostly in the mind. What we call our sober state of consciousness is in fact an elaborate hallucination—an internal simulation—guided by some external stimuli. What we perceive is a creation of our minds. However, we still should be confident that the objects in our minds correspond to objects "out there." If evolution has tailored the human mind to construct an internal simulation of an external reality, we should expect it to be a fairly accurate one. Even if the true nature of reality is forever beyond our reach, our senses should still give us an approximation.

We know that we only perceive a tiny fraction of the physical universe. We see just a tiny slice of the entire electromagnetic spectrum. The same is true for the frequency range of human hearing. We are oblivious to much of the richness of the cosmos, as we cannot feel gravity. We are blind and deaf to the forces and activity of the seething atomic realm. "Tens of billions of neutrinos from the sun traverse each square centimeter of the Earth every second" without us noticing (Fukuda et al. 1998). Although we are blind to many aspects of reality, surely evolution ensured that we at least glimpse the ones important for survival and gene reproduction. Well (Gefter 2016):

> Not so, says Donald D. Hoffman, a professor of cognitive science at the University of California, Irvine. Hoffman has spent the past three decades studying perception, artificial intelligence, evolutionary game theory and the brain, and his conclusion is a dramatic one: The world presented to us by our perceptions is nothing like reality. What's more, he says, we have evolution itself to thank for this magnificent illusion, as it maximizes evolutionary fitness by driving truth to extinction.

In a nutshell, Hoffman argues (quoted in Nave 2016):

> Evolution isn't about truth, it's about making kids. Every bit of information that you process costs calories, meaning that's more food you need to kill and eat. So an organism that sees all of reality would never be more fit than one tuned only to see what it needs to survive.

The following example is offered (quoted in Nave 2016):

> Australian jewel beetle's reproductive strategy proceeded very effectively. Then, Homo sapiens—and its habit of dumping used beer bottles—entered the picture. Unable to distinguish between these brown glass containers and the shell of a potential mate, the male beetles began attempting to copulate with discarded vessels.

The beetles nearly went extinct. Hoffman explains (Hoffman 2015):

> The Australian jewel beetle is dimpled, glossy and brown. […] Now, as it happens, these bottles are dimpled, glossy, and just the right shade of brown to tickle the fancy of these beetles. […] Now, the males had successfully found females for thousands, perhaps millions of years. It looked like they saw reality as it is, but apparently not. Evolution had given them a hack. A female is anything dimpled, glossy and brown, the bigger the better.

To test the hypothesis that natural selection does, in fact, not favor veridical perception, Hoffman ran computer simulations (Mark et al. 2010). He reports (Hoffman 2015):

> So, in my lab, we have run hundreds of thousands of evolutionary game simulations with lots of different randomly chosen worlds and organisms that compete for resources in those worlds. Some of the organisms see all of the reality, others see just part of the reality, and some see none of the reality, only fitness. Who wins?
>
> Well, I hate to break it to you, but perception of reality goes extinct. In almost every simulation, organisms that see none of reality but are just tuned to fitness drive to extinction all the organisms that perceive reality as it is. So the bottom line is, evolution does not favor veridical, or accurate perceptions. Those perceptions of reality go extinct.

This work has been further elaborated (Hoffman and Singh 2012). If the human mind does not see reality per se—the noumenon—what does it then perceive? Hoffman offers the interface theory of perception (Hoffman et al. 2015). In his words (Hoffman 2015):

> Well, fortunately, we have a very helpful metaphor: the desktop interface on your computer. Consider that blue icon for a TED Talk that you're writing. Now, the icon is blue and rectangular and in the lower right corner of the desktop. Does that mean that the text file itself in the computer is blue, rectangular, and in the lower right-hand corner of the computer? Of course not. Anyone who thought that misinterprets the purpose of the interface. It's not there to show you the reality of the computer. In fact, it's there to hide that reality. You don't want to know about the diodes and resistors and all the megabytes of software. If you had to deal with that, you could never write your text file or edit your photo. So the idea is that

> evolution has given us an interface that hides reality and guides adaptive behavior. Space and time, as you perceive them right now, are your desktop. Physical objects are simply icons in that desktop.

In other words, we should take the symbols we perceive—for instance, snakes and trains—seriously, but not literally. In effect, what Hoffman is arguing is that (quoted in Brockman 2006, p. 91):

> Consciousness is all that exists. Space-time and matter never were fundamental denizens of the universe but have always been among the humbler contents of consciousness.

This sounds like a modern version of the intuitions Immanuel Kant cultivated in his radical *Critique of Pure Reason* (Kant 1781). There we can read in the *Transcendental Aesthetic* (translated by Meiklejohn 2003):

> From this investigation it will be found that there are two pure forms of sensuous intuition, as principles of knowledge a priori, namely, space and time. [§1]
>
> Space is nothing else than the form of all phenomena of the external sense, that is, the subjective condition of the sensibility, under which alone external intuition is possible. [§4]
>
> Time is nothing else than the form of the internal sense, that is, of the intuitions of self and of our internal state. [§7]
>
> [...] if we take away the subject, or even only the subjective constitution of our senses in general, then not only the nature and relations of objects in space and time, but even space and time themselves disappear; and that these, as phenomena, cannot exist in themselves, but only in us. [§9]

Hoffman's ideas about consciousness and reality, for instance, criticized here (Cohen 2015), will reappear in the context of Chap. 14.

11.2.2 *Perceiving the Inner World*

If our sober state of consciousness, tricking us into believing we are perceiving an external world, is a hallucination, then dreams themselves represent the ultimate virtual reality. Thomas Metzinger is a theoretical philosopher and a philosopher of the mind. His view on consciousness, which he calls the *Ego Tunnel* (Metzinger 2009), is that the self is an illusion. Our conception of a self is akin to a tunnel-vision-like experience of reality. Indeed Metzinger explains (quoted in Flanagan 2009):

> The phenomenal Ego is not some mysterious thing or little man inside the head but the content of an inner image...By placing the self-model within the world-model, a center is created. That center is what we experience as ourselves, the Ego.

In other words, our sense of self is a virtual simulation within a larger virtual reality comprising the external world.

During the night of May 6, 1986, Metzinger was dreaming an out-of-body experience (OBE). He reports (Metzinger 2009, p. 133f.):

> When I became afraid of not being able to sustain the condition much longer, I flew back up, somehow returned to my physical body, and awoke with a mixture of great pride and joy. [...] I jumped out of bed and went over to my sister (who slept in the same room), woke her up, and told her, with great excitement, that I had *just* managed to do it again [dream of an OBE], that I had *just* been down in the garden, bouncing around on the lawn a minute ago. My sister looked at her alarm clock and said, "Man, it's quarter to three! Why did you wake me up? Can't this wait until breakfast? Turn out the light and leave me alone!" She turned over and went back to sleep. I was a bit disappointed at this lack of interest. [...]
>
> At that moment, I woke up. I was not upstairs in my parents' house in Frankfurt but in my basement room, in the house I shared with four friends about thirty-five kilometers away. It was not quarter to three at night; the sun was shining and I had obviously been taking a short afternoon nap. [...] I was unsure how real *this* situation was. I did not understand what had just happened to me. I didn't dare move, because I was afraid I might wake up again, into yet another ultrarealistic environment.

Metzinger not only had experienced a lucid dream with an OBE, he also witnessed the phenomenon of false awakening. This is a vivid dream about one's own awakening from sleep. To this day, Metzinger is still affected by that episode. He explains (Metzinger 2009, p. 134f.):

> To wake up twice in a row is something that can shatter many of the theoretical intuitions you have about consciousness—for instance, that the vividness, the coherence, and the crispness of a conscious experience are evidence that you are really in touch with reality. Apparently, what we call "waking up" is something that can happen to you at any point in phenomenological time. This is a highly relevant empirical fact for philosophical epistemology. [...] False awakenings demonstrate that consciousness is never more than the appearance of a world. There is no certainty involved, not even about the state, the general category of conscious experience in which you find yourself. So, how do you know that you actually woke up this morning? Couldn't it be that everything you have experienced was only a dream?

This is very unsettling. Not only are our perceptions of reality hallucinations, we can also never be sure about the nature of any experience we are having. In other words, the entirety of synthetic experiences—be they dreams, psychosis, or psychedelic trips—are indistinguishable from "real" experiences. In fact, experiencing a self and a world constitutes reality-independent consciousness.

But why do we dream? No one knows for sure. Monitoring rat's brains appears to show that they dream about running down a corridor to collect food that was inaccessible during the day, meaning that they dream of a better future (Ólafsdóttir et al. 2015). In humans, dreaming has been associated with forgetting unnecessary information, called reverse learning (Crick et al. 1983; Shepherd 1983), keeping the brain functioning in the continual activation theory (Zhang 2005), processing emotional events for mental health (Walker and van Der Helm 2009), overall problem-solving activities (Barrett 1993), and memory capabilities (Wamsley et al. 2010; Wamsley and Stickgold 2011). Others have argued that dreaming is an epiphenomenon, meaning it has no function as such (Flanagan 2000). In any case, dreaming is a very creative activity. The discovery of the molecular structure of benzene by August Kekulé was inspired by a dream (Schultz 1890)—ushering in the science of organic chemistry. The neurologists Otto Loewi successfully reconstructed an experiment he had dreamt of, winning him a Nobel prize (York III 2004). The unusual and extremely talented mathematician Srinivasa Ramanujan claimed that the goddess of Namakkal would visit him in his dreams and show him the equations (Sect. 2.2). However, the often-cited anecdote that Niels Bohr discovered his Nobel prize winning model of the atom in a dream appears to be an urban legend (Runco and Pritzker 1999, p. 600). Today, a drug exists that can induce lucid dreaming (LaBerge et al. 2018).

Every day, the most remarkable thing happens to me. I wake up. Instantly, the memories of who I am enter my mind. I start to sense myself and the external world I woke up to. Then I open my eyes. If I choose to believe the neuroscientists and philosophers, I should be skeptical of the perceptions my brain forms about the external world. I should assign them a status similar to dreams. However, I can, at least, rely on the faithfulness of my own memories? After all, without memory the continuous flow of subjective experiences threatens to disintegrate. Without memory, I exists only in the now, with no autobiographical trail extending into the past and I have no manual for interacting with the world and other conscious beings. When I am snowboarding, my brain relies on nondeclarative memories. In contrast, declarative memory gives me access to stored knowledge. Nearly everything depends on memory. As can be expected, understanding memory in the human brain is a daunting task. It is known that long-term memory relies on synaptic plasticity. This is the way the brain forms new synapses or varies the strength of existing ones (Martin et al. 2000). In general (Foster 2009, p. 13f.):

> As we have seen from the work of [Frederick] Bartlett [(Bartlett 1932)], memory is not a veridical copy of the world, unlike a DVD or video recording. It is perhaps more helpful to think of memory as an influence of the world on the individual. Indeed a *constructivist approach* describes memory as the combined influences of the world and the person's own ideas and expectations. […] So an event, as it occurs, is constructed by the person who experienced it. […]
>
> Later, when we come to try to remember that event [for instance, watching a movie], some parts of the film come readily to mind, whereas other parts we may re-construct—based on the parts that we remember and on what we know or believe must have happened. […] In fact, we are so good at this sort of re-construction (or "filling in the gaps") that we are often consciously unaware that it is happening. […] This is an especially worrying consideration when we reflect on the degree to which people can feel that they are "remembering" crucial features of a witnessed murder or a personally experienced childhood assault, when—instead—they may be "reconstructing" these events and filling in missing information based on their general knowledge of the world.

Today, we know that eyewitness testimonies can be frighteningly inaccurate and the errors frequent—with far-reaching and dramatic consequences (Buonomano 2011). Two victims of false eyewitness testimonies are campaigning together for changes in the judicial system (Thompson-Cannino et al. 2009). Jennifer Thompson-Cannino was raped as a young woman in 1984. She falsely identified Ronald Cotton as the perpetrator who was then sentence to life for a crime he did not commit. After eleven years the real rapist was found and identified with, at the time, novel DNA fingerprinting technology. Cotton and Thompson-Cannino now are, together, vocal activists. The fallibility of human memory has motivated specialists to request a more scientific approach to trial evidence (Fraser 2012).

Even more worrying and troubling than misremembering the past are entirely false memories masquerading as ambassadors of the past. This can happen when memories are distorted through the incorporation of new information. In other words, the act of retrieving memories also has a component of storage. Using the metaphor of computer memory, reading information also results in writing. A benign version of this is called the misinformation effect (Loftus 2005). The very nature of the kind of questions people are asked can affect their answers—slight cues or suggestions can be incorporated into a person's memory and claimed as theirs. This can lead to the disturbing phenomenon of false memories. Researchers have managed to implant false memories (for instance, remembered words) in experiments (Roediger and McDermott 1995). Indeed (Foster 2009, p. 78):

> Less benignly, it is also possible to create—using suggestions and misleading information—memories for "events" that the individual believes very strongly happened in their past but which are, in fact, false.

For instance, convincing people that, as a child, they were lost in a shopping mall (Loftus et al. 1996). Amazingly (Eagleman 2016, p. 26):

> They [the participants in the experiment] may start to remember a little bit about it [the false memory of being lost in a mall]. But when they come back a week later, they're starting to remember more. [...] Over time, more and more detail crept into the false memory.

The fabrication of memories does not only happen under experimental conditions. In the 1980s and early 1990s therapists and counselors started to uncover "repressed" memories in patients—with dramatic consequences. Luckily, today we know about false memories. One victim reported (Buonomano 2011, p. 57):

> At the end of 2 1/2 years of therapy, I had come to fully believe that I had been impregnated by my father twice. I remember that he had performed a coat hanger abortion on me with the first pregnancy and that I performed the second coat hanger abortion myself.

Gynecological examinations spoke of an entirely different past. False memories lie on one side of the memory spectrum. In contrast, people who suffer from the neurological disorder called hyperthymesia remember an excessive number of their experiences. Often, a person with hyperthymesia can remember any day of their life, going back to childhood, with great detail. However (Rodriguez McRobbie 2017):

> Most have called it [hyperthymesia] a gift but I call it a burden. I run my entire life through my head every day and it drives me crazy.

Other researchers have been able to manipulate memories in mice—literally. Using optogenetic techniques,[14] the scientists could trigger a fear response in mice by activating a previously formed memory of fear (Liu et al. 2012). Then, three years later, researchers implanted false memories into the minds of mice during sleep (De Lavilléon et al. 2015). Not only is our mind susceptible to fictitious content, it can also, in theory, be edited.

[14] This is a technique in which laser light is utilized to control live neurons which have been modified to be light-sensitive.

If our dreams and memories are constructs of the brain, what about our sense of identity, our "self?" Indeed, in the words of the clinical neuropsychologist Paul Broks, quoted by the philosopher Julian Baggini (Baggini 2011):

> We have a deep intuition that there is a core, an essence there, and it's hard to shake off, probably impossible to shake off, I suspect. But it's true that neuroscience shows that there is no centre in the brain where things do all come together.

The question is, if we are our self or if we have a self (Baggini 2011):

> But if you think of yourself as being, in a way, not a thing as such, but a kind of a process, something that is changing, then I think that's quite liberating.

Akin to a waterfall, which persist as a collective entity, while at every instant in time its actual structure and composition changes, so too our self emerges out of the stream of consciousness. We have already heard prominent scholars argue that the self is an illusion, for instance Blackmore, Dennett, and Metzinger. The self, or the conscious mind, is not the only phenomenon that arises in a brain. There is a lot of activity going on in the subconscious depth, below the threshold of awareness. Indeed (Eagleman 2011, p. 9):

> The conscious mind is not at the center of the action in the brain; instead, it is far out on a distant edge, hearing but whispers of the activity.

Eagleman calls the constant activity in the subconscious parts of the brain—steering much of the conscious decision making—alien subroutines (Eagleman 2011, p. 133):

> Not only do we run alien subroutines; we also justify them. We have ways of retrospectively telling stories about our actions as thought the actions were always our idea. [...] We are constantly fabricating and telling stories about the alien processes running under the hood.

In effect, the conscious self is relegated to the role of a grand narrator, without much actual power or control. Your conscious mind feels like the center of control, but, in fact, it is just retelling the stories of control it is hearing about (Eagleman 2016, p. 73):

> Your brain serves up a narrative—and each of us believes whatever narrative it tells. Whether you're falling for a visual illusion, or believing the dream you happen to be trapped in, or experiencing letters in color [i.e., synesthesia], or accepting a delusion as true during an episode of schizophrenia, we each accept our realities however our brains script them.

Moreover, much of our mental makeup is contingent (Eagleman 2016, p. 76):

> It's not simply that you are attracted to humans over frogs or that you like apples more than fecal matter—these same principles of [evolutionary] hardwired thought guidance apply to all your deeply held beliefs about logic, economics, ethics, emotions, beauty, social interactions, love, and the rest of your mental landscape.

Complex social behavior, like trust and fairness, depend on what molecules are present in the brain at a certain time (Kosfeld et al. 2005; Crockett et al. 2008). Perhaps a task as mundane as eating a sandwich can increase your level of empathy (Danziger et al. 2011). Indeed (Eagleman 2016, p. 206):

> The exact levels of dozens of other neurotransmitters—for example, serotonin—are critical for who you believe yourself to be.

For the effects of dopamine on decision making, see Sharot et al. (2009).

Finally, after all these intuitional certainties about our outer and inner perception have been deconstructed and exposed as contingent, malleable, and ambiguous, what is the status of our own body? How much of it is under our control and how much of it do we sense? In 1998, a now-classic experiment was performed. In the rubber-hand illusion, researchers achieved a feat in which healthy subjects experienced an artificial limb as part of their own body (Botvinick and Cohen 1998). In other words, the mind incorporated an artificial object into its self-model and discarded a real part of its own body. Body perception, too, is a mental construct which can easily be deconstructed. Indeed (Metzinger 2009, p. 76f.):

> In a similar experiment, [(Armel and Ramachandran 2003)] if one of the rubber fingers was bent backwards into a physiologically impossible position, subjects not only experienced their phenomenal finger as being bent but also exhibited a significant skin-conduction reaction […] Only two out of one hundred and twenty subjects reported feeling actual pain, but many pulled back their real hands and widened their eyes in alarm or laughed nervously.

Utilizing virtual reality applications, scientists could induce the illusion of body swapping (Petkova and Ehrsson 2008). The abstract reads:

> This effect was so strong that people could experience being in another person's body when facing their own body and shaking hands with it. Our results are of fundamental importance because they identify the perceptual processes that produce the feeling of ownership of one's body.

In the words of Metzinger, describing a similar experiment (Blanke and Metzinger 2009) he devised to induce virtual OBEs (Metzinger 2009, p. 99f.):

> As I watched my own back being stroked, I immediately had an awkward feeling: I felt subtly drawn towards my virtual body in front of me, and I tried to "slip into" it.

This section on inner and outer perception represents only the tip of the iceberg regarding the unexpectedly bizarre status of consciousness, unknown even to the conscious perceiver itself. The human mind, as will be seen, has a seemingly inexhaustible capacity for irrationality. And once the brain breaks down, things get truly terrifying.

11.3 Impressionable Consciousness

We all feel in control of our minds and decisions. However, these experiences arising in our consciousness can be influenced by other beings, even nonhuman lifeforms. The human body is a host to a universe of microorganisms, including bacteria, archaea, protists, fungi, and viruses. The collective genomes of these microorganisms—for instance, residing our guts, mouths, and noses—is called the microbiome. Indeed, an average human is comprised of about 30 trillion human cells and 39 trillion bacteria (Abbott 2016). In health, the relationship with these microbial aliens in our bodies is symbiotic. While it appears obvious that the gut's microbiome assists digestion, a link between it and the brain, opening a window on behavior, sounds outlandish. However (Smith 2015):

> A growing body of data, mostly from animals raised in sterile, germ-free conditions, shows that microbes in the gut influence behaviour and can alter brain physiology and neurochemistry.

The microbes also play a role in the development of the mammalian brain (Heijtz et al. 2011; Ogbonnaya et al. 2015). Moreover, the gut-brain axis allows the microbiome to influence anxiety and depression (Foster and Neufeld 2013). While most studies are based on animal experiments (Smith 2015):

> Clues about the mechanisms by which gut bacteria might interact with the brain are starting to emerge, but no one knows how important these processes are in human development and health.

Especially the link between gut microbiota and potential behavior is an intriguingly hot topic (Cryan and Dinan 2012). Perhaps your "gut feeling" is indeed based upon an extension of your cerebral capabilities, aided by tiny organisms. The astrobiologist Nigel Goldenfeld summarizes (Brockman 2015, p. 27):

> [Y]ou're in some sense not even human. You have perhaps 100 trillion bacterial cells in your body,[15] numbering 10 times more than your human cells and containing 100 times as many genes as your human cells. These bacteria aren't just passive occupants of the zoo that is you. They self-organize into communities within your mouth, guts, and elsewhere, and these communities—microbiomes—are maintained by varied, dynamic patterns of competition and cooperation between the various bacteria, which allow us to live.
>
> Your gastrointestinal microbiome can generate small molecules that may be able to pass through the blood-brain barrier and affect the state of your brain. Although the precise mechanism isn't yet clear, there's growing evidence that your microbiome may be a significant factor in mental states such as depression and autism.

A healthy microbiome promotes the health in its host and may also be beneficial for mental health. Other microorganisms are not so beneficial. For instance, the parasitic brain infection called toxoplasmosis, affecting about thirty percent of all humans, is associated with intermittent explosive disorder or IED (Coccaro et al. 2016). IED is characterized by fierce outbursts of anger and violence which represent disproportionate reactions to the situation at hand. Perhaps the last episode of road rage you witnesses was steered by tiny, multi-cellular organisms. How much of the behaviors we witness in our fellow humans—and ourselves—is the result of alien organisms high-jacking our cognitive apparatus?

Another line of research tries to identify how behaviors can be transmitted via genes. In other words, how the choices of your ancestors can leave a mark in you. Specifically, the challenge lies in understanding how experiences can result in transgenerationally inherited behavior. For instance, how parental olfactory experience

[15] This number was assumed before a more accurate estimate appeared (Abbott 2016).

influences the behavior and neural structure in subsequent generations of mice (Dias and Ressler 2014). Indeed, the trauma suffered by Holocaust survivors appears to have left a genetic imprint in the DNA of their children (Yehuda et al. 2016). In mice, genetic imprinting from traumatic experiences carries through at least two generations (Callaway 2013). Again, one is forced to ask the question of how much of me is actually me? How much of my behavior is self-determined and how much is induced by external factors?

11.3.1 The Gullible Mind

Philip Zimbardo was the leader of the notorious 1971 Stanford Prison Experiment. This was a study of the power of institutions to influence individual behavior, which quickly turned bad (Zimbardo 1971). Two dozen volunteers were randomly assigned to be prisoners and guards in a mock prison. The experiment soon spiraled out of control, as the "guards" developed authoritarian traits and subjected the "prisoners" to psychological torture, while the "prisoners" seemed to passively accept their fate. Zimbardo recalls, showing a portrait (Zimbardo 2008):

> This is the woman who stopped the Stanford Prison Study. When I said it got out of control, I was the prison superintendent. I didn't know it was out of control. I was totally indifferent. She saw that madhouse and said, "You know what, it's terrible what you're doing to those boys. They're not prisoners nor guards, they're boys, and you are responsible." And I ended the study the next day. The good news is I married her the next year.

Zimbardo identifies the following mechanisms which persuades normal people to commit acts of evil:

- a mindless first small step down the road to evil;
- dehumanization of others;
- de-individuation of self (anonymity);
- diffusion of personal responsibility;
- blind obedience to authority;
- uncritical conformity to group norms;
- passive tolerance of evil (inaction, indifference).

Recently, the validity of the study has been questioned,[16] prompting Zimbardo's response.[17] In any case, history is the witness of apparently normal human beings descending into abject cruelty.

Another famous experiment, relating to the innate capacity of humans to subdue others, is Stanley Milgram's[18] obedience, or shock, experiment (Milgram 1965). In a nutshell (NPR 2013):

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[16]See http://www.prisonexp.org/links/#criticisms.

[17]See http://www.prisonexp.org/links/#responses.

[18]Milgram was also the author of the famous "six degrees of separation" experiment, seen in Sect. 5.2.3.

> In the early 1960s, Stanley Milgram, a social psychologist at Yale, conducted a series of experiments that became famous. Unsuspecting Americans were recruited for what purportedly was an experiment in learning. A man who pretended to be a recruit himself was wired up to a phony machine that supposedly administered shocks. He was the "learner." [...]
>
> The unsuspecting subject of the experiment, the "teacher," read lists of words that tested the learner's memory. Each time the learner got one wrong, which he intentionally did, the teacher was instructed by a man in a white lab coat to deliver a shock. With each wrong answer the voltage went up. From the other room came recorded and convincing protests from the learner—even though no shock was actually being administered.
>
> The results of Milgram's experiment made news and contributed a dismaying piece of wisdom to the public at large: It was reported that almost two-thirds of the subjects were capable of delivering painful, possibly lethal shocks, if told to do so. We are as obedient as Nazi functionaries.

However, recent research into the subject reveals a somewhat different picture. It appears as though Milgram manipulated the findings by exaggerating and downplaying results to suit the narrative (Perry 2013).

Is there a way to measure how susceptible people are to being manipulated? In other words, what fraction of the population can be instrumentalized? Unfortunately, we do not know this. However, we do know that our minds constantly manipulate themselves. In 1999, two psychologists made a groundbreaking discovery of human nature, albeit a disenchanting one. In an experiment, the test subjects were asked to perform tasks related to humor, grammar, and logic. Then the participants were asked to judge their own performance and ability. The result is the infamous Dunning–Kruger effect (Kruger and Dunning 1999). Grossly incompetent people lack the skill to identify their own lack of skill. This leads to an inflated and distorted self-perception. In summary (Kruger and Dunning 1999):

> The authors suggest that this overestimation occurs, in part, because people who are unskilled in these domains suffer a dual burden: Not only do these people reach erroneous conclusions and make unfortunate choices, but their incompetence robs them of the metacognitive ability to realize it.

The tag line "unskilled and unaware" was born. In contrast, highly competent people are troubled by doubt and indecision, resulting in a self-conscious and distorted perception of themselves as well. The study has been reproduced since (Krueger and Mueller 2002)—however, with a different interpretation which the original authors challenge (Kruger and Dunning 2002)—and some nuances have been detected (Burson et al. 2006), next to the influence of cultural differences between US Americans and Japanese (Heine et al. 2001). The Dunning–Kruger effect is pervasive in our post-truth world (Chap. 12), where confidence is so often confused with competence.

Indeed, it is possible that political ideology stems from specific cognitive traits in humans. Early research includes (Adorno et al. 1950). Newer findings identify a key deliminator in the psychology of liberals and conservatives. In one study, conservatives tended to register greater physiological responses to negative aspects than their more liberal counterparts (Hibbing et al. 2014). Another study showed that conservatives were more likely to remember things that evoked negative emotions, like images of war, snakes, and road kill (Mills et al. 2016). Yet another study concluded (van Prooijen et al. 2015):

> Our study reveals that negative political emotions and outgroup derogation are stronger among the extremes than among the moderates. These phenomena are attributable to the fear that people at both the left and the right extreme experience as a result of societal and economic developments. It is concluded that fear flourishes mostly among the extremes.

Other "neuropolitical" studies highlight the differences in the minds of people (Jost and Amodio 2012):

> [A] meta-analytic review of 88 studies conducted in 12 countries between 1958 and 2002, which confirmed that both situational and dispositional variables associated with the management of threat and uncertainty were robust predictors of political orientation. Specifically, death anxiety, system instability, fear of threat and loss, dogmatism, intolerance of ambiguity, and personal needs for order, structure, and closure were all positively associated with conservatism (or negatively associated with liberalism). Conversely, openness to new experiences, cognitive complexity, tolerance of uncertainty, and self-esteem were all positively associated with liberalism (or negatively associated with conservatism). Subsequent research has also demonstrated that liberals exhibit stronger implicit as well as explicit preferences for social change and equality when compared with conservatives.

In detail, the authors analyzed ideological differences in the context of neuroanatomical structures (Jost and Amodio 2012):

> [L]arger ACC [anterior cingulate cortex] volume was associated with greater liberalism (or lesser conservatism). Furthermore, larger right amygdala volume was associated with greater conservatism (or lesser liberalism). [...] Given that the ACC is associated with conflict monitoring and the amygdala is centrally involved in physiological and behavioral responses to threat, this neuroanatomical evidence appears to lend further support to the notion that political ideology is linked to basic neurocognitive orientations toward uncertainty and threat.

However (Jost and Amodio 2012):

> It is also important to point out that in all neuroscientific studies of political orientation, the direction of causality is ambiguous; it could be that (a) differences in brain activity lead to liberal-conservative ideological differences, or (b) embracing liberal vs. conservative ideologies leads to differences in brain structure and function.

Other researchers claim (Hodson and Busseri 2012):

> In conclusion, our investigation establishes that cognitive ability is a reliable predictor of prejudice. Understanding the causes of intergroup bias is the first step toward ultimately addressing social inequalities and negativity toward out-groups. Exposing right-wing conservative ideology and inter-group contact as mechanisms through which personal intelligence may influence prejudice represents a fundamental advance in developing such an understanding.

Linking lower cognitive abilities with prejudice and right-wing ideology will, most likely, be shrugged off by the stigmatized group as resulting from a liberal research agenda of the scientists. In any case, humans like to belong to groups which then allows them to villainize non-group members. Studies show that even in groups created by random, in which the members should have no reason to discriminate against the out-group, exactly this, in fact, does happen (Tajfel and Turner 1979). Moreover, people are willing to tolerate unethical behavior from the members of their own group (Ariely 2009):

> If somebody from our in-group cheats and we see them cheating, we feel it's more appropriate, as a group, to behave this way. But if it's somebody from another group, [...] all of a sudden people's awareness of honesty goes up.

Unfortunately, there appears to be a natural tendency in the human mind towards prejudice. Such implicit biases can be measured (Eagleman 2011, p. 60):

> Imagine that you sit down in front of two buttons, and you're asked to hit the right button whenever a positive word flashes on the screen (joy, love, happy, and so on), and the left button whenever you see a negative word (terrible, nasty, failure). Pretty straightforward. Now the task changes a bit: hit the right button whenever you see a photo of an overweight person, and the left button whenever you see a photo of a thin person. Again, pretty easy. But for the next task, things are paired up: you're asked to hit the right button when you see either a positive word or an overweight person, and the left button whenever you see a negative word or a thin person. In another group of trials, you do the same thing but with the pairings switched—so you now press the right button for a negative word or a thin person.
>
> The results can be troubling. The reaction times of subjects are faster when the pairings have a strong association unconsciously. For example, if overweight people are linked with a negative association in the subject's unconscious, then the subject reacts faster to a photo of an overweight person when the response is linked to the same button as a negative word. During trials in which the opposite concepts are linked (thin with bad), subjects will take a longer time to respond, presumably because the pairing is more difficult. This experiment has been modified to measure implicit attitudes toward races, religions, homosexuality, skin tone, age, disabilities, and presidential candidates.

However, while such tests give a reliable picture at an aggregate level, it is unclear how accurate they are for detecting individual biases or racism (Lopez 2017).

If biases and prejudices are widespread neural patterns in our brains, can these be manipulated? Indeed, something as innocuous as a magnet can do the trick. Specifically, using transcranial magnetic stimulation to temporarily shut down specific regions of the brain (University of York 2015):

> New research involving a psychologist from the University of York has revealed for the first time that both belief in God and prejudice towards immigrants can be reduced by directing magnetic energy into the brain. [...]
>
> The researchers targeted the posterior medial frontal cortex, a part of the brain located near the surface and roughly a few inches up from the forehead that is associated with detecting problems and triggering responses that address them.
>
> [...] people in whom the targeted brain region was temporarily shut down reported 32.8% less belief in God, angels, or heaven. They were also 28.5% more positive in their feelings toward an immigrant who criticised their country.

The study is found here (Holbrook et al. 2015). Researchers who have scanned the brains of subjects conclude (Harris et al. 2009):

> [R]eligious thinking is more associated with brain regions that govern emotion, self-representation, and cognitive conflict, while thinking about ordinary facts is more reliant upon memory retrieval networks.

11.3.2 The Irrational Mind

In 1978, Herbert A. Simon was awarded the Nobel Memorial Prize in economic science.[19] His work was centered around human rationality. Indeed, neoclassical economics (Sects. 7.1.2.1, 7.1.2.3, and 7.2) painted a highly optimistic picture of individuals' rationality in the context of economic choices. People were thought to always maximize a perceived utility. Simon's work questioned these assumptions of perfect rational decision-making in his concept of bounded rationality (Simon 1972). Nearly a quarter of a century later, in 2002, the psychologist Daniel Kahneman was awarded the Nobel Memorial Prize in economic sciences "for having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty".[20] He pioneered the filed of behavioral economics which is steadily growing. In 2017, Richard Thaler, another behavioral economist, received the award for the idea of "nudging" people towards doing what is best for them (Thaler and Sunstein 2008).

Today, behavioral economics has uncovered a trove of embarrassing findings exposing innate and ubiquitous human irrationality. Kahneman was already quoted in Sect. 8.1.1, when he remarked:

> Our comforting conviction that the world makes sense rests on a secure foundation: our almost unlimited ability to ignore our ignorance.

Indeed, the human mind falls prey to an astonishingly wide array of cognitive biases, logical fallacies, and self-deception (Buonomano 2011; McRaney 2012; Hallinan 2014). For instance:

- Confirmation bias: ignoring information which threatens pre-existing beliefs.
- Gambler's fallacy: believing that the observation of previous events influences future outcomes.
- Neglecting probability: underestimating a risk (e.g., the probability of a car crash) while inflating others (e.g., the probability of a plane crash).
- Observational selection bias: noticing a novel feature more often and assuming that the frequency of appearances has increased.
- Status-quo bias: inertia towards change.
- Negativity bias: bad news captures more attention.
- Bandwagon effect: groupthink or group pressure.
- Projection bias: assuming others tend to think like oneself.
- The current moment bias: favoring pleasure in the "now."
- Anchoring effect: relying too heavily on an initial piece of information.
- Availability heuristic: confusing ease of remembering with frequency of occurrence.

[19] See Sect. 7.1.2.1 for more information on this award, commonly known as the Nobel prize for economics.

[20] See https://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/2002/.

In one experiment, subjects were asked to write down either three or nine reasons why they loved their partner. People who wrote down only three things reported that they loved their partner more than those who had to write down nine. The reason being that (Banaji 2006):

> Who has nine amazing properties? So by the time you get to number five you're struggling. Six is hard and seven is almost impossible. And you make eight and nine up.

Other subjects were asked to first memorizes the last four digits of their social security number and then to estimate the number of doctors in New York City. The correlation between the two numbers was around 0.4 (reported in Hubbard 2014, p. 308). In other experiments, the actual decisions of people was influenced (Ariely 2008a):

> This was an ad in *The Economist* a few years ago that gave us three choices: an online subscription for 59 dollars, a print subscription for 125 dollars, or you could get both for 125.

To visualize:

A One-year online subscription $59.
B One-year subscription to the print edition $125.
C One-year subscription to the online and print edition $125.

The story continues:

> Now I looked at this, and I called up The Economist, and I tried to figure out what they were thinking. And they passed me from one person to another to another, until eventually I got to the person who was in charge of the website, and I called them up, and they went to check what was going on. The next thing I know, the ad is gone, no explanation.
>
> So I decided to do the experiment that I would have loved *The Economist* to do with me. I took this [the ad] and I gave it to 100 MIT students. I said, "What would you choose?" These are the market shares—most people wanted the combo deal [i.e., Choice C with 84% and Choice A with 16%]. [...]
>
> But now, if you have an option that nobody wants, you can take it off, right? So I printed another version of this, where I eliminated the middle option [Choice B]. I gave it to another 100 students. Here is what happened: Now the most popular option became the least popular, and the least popular became the most popular [i.e., Choice C went from 84% to 32%, while Choice A went from 16% to 68%].
>
> What was happening was the option that was useless, in the middle, was useless in the sense that nobody wanted it. But it wasn't useless in the sense that it helped people figure out what they wanted. In fact, relative to the option in the middle, which was get only the print for 125, the print and web for 125 looked like a fantastic deal. And as a consequence, people chose it. [...]
>
> What is the general point? The general point is that, when we think about economics, we have this beautiful view of human nature. "What a piece of work is a man! How noble in reason!" We have this view of ourselves, of others. The behavioral economics perspective is slightly less "generous" to people [...].

Next to economic decisions also ethical choices can be influenced (Ariely 2009):

> So, we got people to the lab, and we said, "We have two tasks for you today." First, we asked half the people to recall either 10 books they read in high school, or to recall The

> Ten Commandments, and then we tempted them with cheating. Turns out the people who tried to recall The Ten Commandments—and in our sample nobody could recall all of The Ten Commandments—but those people who tried to recall The Ten Commandments, given the opportunity to cheat, did not cheat at all. It wasn't that the more religious people—the people who remembered more of the Commandments—cheated less, and the less religious people—the people who couldn't remember almost any Commandments—cheated more. The moment people thought about trying to recall The Ten Commandments, they stopped cheating.

Indeed, our sens of morality is easily manipulated. The abstract of a study reads (Bateson et al. 2006):

> We examined the effect of an image of a pair of eyes on contributions to an honesty box used to collect money for drinks in a university coffee room. People paid nearly three times as much for their drinks when eyes were displayed rather than a control image. This finding provides the first evidence from a naturalistic setting of the importance of cues of being watched, and hence reputational concerns, on human cooperative behaviour.

More on how the human mind decides to deceive others and itself is found in Ariely (2012). Other experiments have shown that people will abandon their judgments under group pressure. Specifically (Asch 1951):

> The critical subject was submitted to two contradictory and irreconcilable forces—the evidence of his own experience of an utterly clear perceptual fact and the unanimous evidence of a group of [perceived] equals [who were actors].

A sizable fraction of participants yielded to the pressure. Another way to influence behavior is through smell. The positive effect of citrus scent on cleaning related behavior (the frequency of participants' crumb removal while eating) was measured in Holland et al. (2005). The link between testosterone and risk appetite is also known (Coates 2012). This impacts traders (Sect. 7.4.2.3).

Kahneman distinguishes between the experiencing self, "who lives in the present and knows the present" and the remembering self, which "is the one that keeps score, and maintains the story of our life." The two selves are in conflict with each other. For instance, in remembering time (Kahneman 2010):

> From the point of view of the experiencing self, if you have a vacation, and the second week is just as good as the first, then the two-week vacation is twice as good as the one-week vacation. That's not the way it works at all for the remembering self. For the remembering self, a two-week vacation is barely better than the one-week vacation because there are no new memories added.

Kahneman also categorizes thinking into two components: fast and slow. While the former is characterized by unconscious and automatic responses, the latter is an effortful and logical process. To illustrate fast thinking, consider the following (Kahneman 2011, p. 44). A bat and ball cost \$1.10. The bat costs one dollar more than the ball. How much does the ball cost? Most people think of 10 cents. This is, of course, seen to be wrong once we do the calculation via slow thinking. Then, if a message is printed in bright blue or red—compared to middling shades of green, yellow, or pale blue—it is more likely to be believed (Kahneman 2011, p. 63). Test performances, pitting fast and slow thinking against each other, turn out to be better if the font the test is written in is bad. The cognitive strain of reading barely legible text makes the brain perform better in its slow mode (Kahneman 2011, p. 65). Such examples go on and on. It is truly humbling, if not frightening, how error-prone and susceptible our minds are, while, at the same time claiming rationality and autonomy. See, for instance, Ariely (2008b), Kahneman (2011) for the trove of experiments unmasking human irrationality.

Even without performing such experiments, the limits of the human mind become apparent. For one, humans are very bad at dealing with probabilities. Consider the following situation (Gigerenzer and Hoffrage 1995):

> The probability of breast cancer is 1% for a woman at age forty who participates in routine screening. If a woman has breast cancer, the probability is 80% that she will get a positive mammography. If a woman does not have breast cancer, the probability is 9.6% that she will also get a positive mammography. A woman in this age group had a positive mammography in a routine screening. What is the probability that she actually has breast cancer?

This type of scenario deals with conditional probabilities, e.g., false positives. Alarmingly, even physicians get the answer very wrong. Out of 100 doctors, 95 gave an estimation between 70$ and 80% (Gigerenzer and Hoffrage 1995). The correct mathematical formalism to deal with such probabilities is Bayesian inference. Applying Bayes' theorem (Bayes 1763), the correct and highly unintuitive answer is found to be 7.8%. Another example is the Monty Hall problem. It is based off of a television game show and is, by now, a well-known mathematical brainteaser. A contestant is placed in front of three doors (Arbesman 2014):

> She is told that behind one of them is a car, while behind the other two there are goats. Since it is presumed that contestants want to win cars not goats, if nothing else for their resale value, there is a one-third chance of choosing the car and winning.
>
> But now here's the twist. After the contestant chooses a door, the game show host has another door opened and the contestant is shown a goat. Should she stick with the door she has originally chosen, or switch to the remaining unopened door?

By switching, the contestant has a 2/3 chance of winning the car. Somehow, miraculously, the odds went from a perceived fifty-fifty chance—after all, two doors remain closed and nothing seems to have changed—to 2/3. By mapping out the probability space it becomes clear that this is really the case. However, the human mind's intuitions about probabilities are bad. Even professionally trained human minds (Arbesman 2014):

> In fact, Paul Erdős,[21] one of the most prolific and foremost mathematicians involved in probability, when initially told of the Monty Hall problem also fell victim to not understanding why opening a door should make any difference. Even when given the mathematical explanation multiple times, he wasn't really convinced. It took several days before he finally understood the correct solution.

Indeed, the cognitive psychologist Massimo is quoted as saying that (Vos Savant 1996, p. 15):

---

[21] See also Sect. 2.2.

> [N]o other statistical puzzle comes so close to fooling all the people all the time. […]
>
> [E]ven Nobel physicists systematically give the wrong answer, and […] they insist on it, and they are ready to berate in print those who propose the right answer.

But most strikingly, this cognitive impairment seems to be specific to human minds. Pigeons, on the other hand, have a better grasp of probabilities (Herbranson and Schroeder 2010):

> Birds completed multiple trials of a standard MHD [Monty Hall Dilemma], with the three response keys in an operant chamber serving as the three doors and access to mixed grain as the prize. Across experiments, the probability of gaining reinforcement for switching and staying was manipulated, and birds adjusted their probability of switching and staying to approximate the optimal strategy. Replication of the procedure with human participants showed that humans failed to adopt optimal strategies, even with extensive training.

Some ventures into the minds of animals are the following: the philosopher Thomas Nagel's classic *What Is It Like to Be a Bat?* (Nagel 1974) or the search for the origins of consciousness in the minds of cephalopods (Godfrey-Smith 2016). Indeed, octopuses are very alien life forms with three hearts, skin that acts like an organic display by changing both color and texture, and their brains are located in their eight semi-autonomous arms. Most intriguingly, they regularly use tools and can solve puzzles, and they can edit their own genes (specifically, RNA). They have about 33,000 genes (Albertin et al. 2015), compared to the 20,000–25,000 genes in humans (International Human Genome Sequencing Consortium 2004). However, for some reason, they don't live for very long.

In light of all the troubling findings discussed above, we should not be surprised that humans also cannot be convinced by empirical evidence (Ahluwalia 2000). In summary (Kaplan et al. 2016):

> Few things are as fundamental to human progress as our ability to arrive at a shared understanding of the world. The advancement of science depends on this, as does the accumulation of cultural knowledge in general.
>
> It is well known that people often resist changing their beliefs when directly challenged, especially when these beliefs are central to their identity. In some cases, exposure to counterevidence may even increase a person's confidence that his or her cherished beliefs are true.

This last epitome of irrationality is called the backfire effect. All of these insights become acutely worrisome—and amplified—in our modern digital and interconnected age. The Internet constantly feeds our biases, anchoring us in a state of blissful fantasy, where our beliefs get reinforced, but never challenged. This is mediated by mechanisms like filter bubbles (Pariser 2011) and echo chambers (Barberá et al. 2015; Del Vicario et al. 2016). Sadly, unearthing these deficits in the human mind will not be able to change much (Lehrer 2012):

> For one thing, self-awareness was not particularly useful: as the scientists note, "people who were aware of their own biases were not better able to overcome them." This finding wouldn't surprise Kahneman, who admits in "Thinking, Fast and Slow" that his decades of groundbreaking research have failed to significantly improve his own mental performance.

> "My intuitive thinking is just as prone to overconfidence, extreme predictions, and the planning fallacy"—tendency to underestimate how long it will take to complete a task—"as it was before I made a study of these issues," he writes.

For a popular account of human psychology, see, for instance Freeman and Freeman (2010).

11.3.3 The Broken Mind

Astonishingly, all the listed cognitive deficiencies and idiosyncrasies of consciousness, plus its warped and constructed perceptions, are associated with a healthy mind. Sadly, the mind can break in many ways, unearthing more enigmas of consciousness.

The *Oxford Textbook of Psychopathology* is a frightening 840 pages thick, listing every pathology that has been observed in the human mind. The array of potential mental defects is very wide, affecting all aspects of consciousness: the sense of self, perception, experience, memory, attention, general cognition, intelligence, instincts, aggression, affectivity, and sexuality. Perhaps most disheartening are delusions, where the patients are trapped alone in an atom of constructed reality no other mind can access. Other patients can have impaired time perception. Time can accelerate or slow down and even completely grind to a halt. The past and the present can be confused with each other or the future can be impossible to comprehend. Facing so many potential ruptures of the mind, it is astounding that most humans appear to have a normally functioning brain. The neurologist Oliver Sacks was perhaps one of the first researchers to introduce the nightmares of brain dysfunctions to a wide audience. In his popular book, titled *The Man Who Mistook His Wife for a Hat*, he describes the case histories of some of his patients (Sacks 1985). The title was inspired by the case study of a patient with visual agnosia, unable to distinguish between animate and inanimate things. After reading the 24 essays describing extraordinary disabilities of the mind, one is again left wondering about the status of sober waking consciousness. Sacks also researched the phenomenon of hallucinations (Sacks 2012).

Some mental illnesses are very perfidious. Like Tourette syndrome, where the affected people suffer from compulsive tics. The worst being the urge to express obscenities—the more inappropriate a situation the greater the impulse to swear. Narcolepsy is a sleeping disorder which is very debilitating for the sufferers. During the day, these people inadvertently and constantly fall into momentary states of deep sleep, while walking the dog, buying groceries, or doing any other activity. The social ostracism must be unbearable. People affected by schizophrenia—about 1% of the population—live in a world which is incoherent and fragmented (Swaab 2014). Inner and outer perception mix, giving rise to hallucinations and delusions. A schizophrenic mind can be instructed by (inner) voices to kill other people, which some then obey. Other mental illnesses are truly bizarre. Cotard delusion is a condition in which the affected person holds the belief that they are dead or do not exists (Ananthaswamy

2016). Patients suffering from aphantasia lose their inner eye and become mentally blind, unable to form mental images.

Sometimes neuroscience can give some insight into the mechanisms underlying the problems. Capgras delusion is a disorder in which a person firmly holds the belief that a friend, spouse, parent, or family member is an impostor (Ramachandran 2007):

> So, to explain this curious disorder, we look at the structure and functions of the normal visual pathways in the brain. Normally, visual signals come in, into the eyeballs, go to the visual areas in the brain. There are, in fact, 30 areas in the back of your brain concerned with just vision, and after processing all that, the message goes to a small structure called the fusiform gyrus, where you perceive faces. [...] Now, when that area's damaged, you lose the ability to see faces, right?
>
> But from that area, the message cascades into a structure called the amygdala in the limbic system, the emotional core of the brain, and that structure, called the amygdala, gauges the emotional significance of what you're looking at. Is it prey? Is it predator? Is it mate? Or is it something absolutely trivial, like a piece of lint, or a piece of chalk [...].
>
> But maybe, in this chap [a sufferer of Capgras delusion], that wire that goes from the amygdala to the limbic system, the emotional core of the brain, is cut by the accident. So because the fusiform is intact, the chap can still recognize his mother, and says, "Oh yeah, this looks like my mother." But because the wire is cut to the emotional centers, he says, "But how come, if it's my mother, I don't experience a warmth?" Or terror, as the case may be?

Sometimes we voluntarily impair the brain. The use of botulinum toxin (botox) in cosmetic applications to reduce facial wrinkles has an unexpected side effect. By temporarily paralyzing the facial muscle used in frowning, a feedback loop is cut which results in reduced emotional processing of patients (Hennenlotter et al. 2008; Havas et al. 2010). By not being able to express facial emotions, people tend to lose their ability to recognize these in others.

The notion of a split-brain describes the result when the corpus callosum connecting the two hemispheres of the brain is damaged or severed (Sperry et al. 1969). This can happen due to an accident or can also be induced surgically, to treat severe forms of epilepsy (Wilson et al. 1978). The results are mind-numbing, as now two distinct minds seem to appear in these split brains. Indeed (Gazzaniga 2011, p. 59f.):

> One of the more general and also more interesting and striking features of this [split-brain] syndrome may be summarized as an apparent doubling in most of the realms of conscious awareness. Instead of the normally unified single stream of consciousness, these patients behave in many ways as if they have two independent streams of conscious awareness, one in each hemisphere, each of which is cut off from and out of contact with the mental experiences of the other. In other words, each hemisphere seems to have its own separate and private sensations; its own perceptions; its own concepts; and its own impulses to act, with related volitional, cognitive, and learning experiences.
>
> [...]
>
> Over the past ten years we have collected evidence that, following midline section of the cerebrum, common normal conscious unity is disrupted, leaving the split-brain patient with two minds (at least), mind left and mind right. They coexist as two completely conscious entities, in the same manner as conjoined twins are two completely separate persons.

The mystery of consciousness deepens. A whole unified mind can be divided into two independent whole minds. The functional traits of each hemisphere appear to be very different. In 2008, the neuroanatomist Jill Bolte Taylor delivered one of the most popular TED talks (Bolte Taylor 2008a), describing the battle of her hemispheres during a stroke. She begins:

> But on the morning of December 10, 1996, I woke up to discover that I had a brain disorder of my own. A blood vessel exploded in the left half of my brain. And in the course of four hours, I watched my brain completely deteriorate in its ability to process all information. [...]
>
> On the morning of the stroke, I woke up to a pounding pain behind my left eye. And it was the kind of caustic pain that you get when you bite into ice cream. And it just gripped me—and then it released me. [...]
>
> So I got up and I jumped onto my cardio glider, which is a full-body, full-exercise machine. And I'm jamming away on this thing, and I'm realizing that my hands look like primitive claws grasping onto the bar. And I thought, "That's very peculiar." And I looked down at my body and I thought, "Whoa, I'm a weird-looking thing." And it was as though my consciousness had shifted away from my normal perception of reality, where I'm the person on the machine having the experience, to some esoteric space where I'm witnessing myself having this experience.
>
> And it was all very peculiar, and my headache was just getting worse. So I get off the machine, and I'm walking across my living room floor, and I realize that everything inside of my body has slowed way down. And every step is very rigid and very deliberate. [...]
>
> And then I lost my balance, and I'm propped up against the wall. And I look down at my arm and I realize that I can no longer define the boundaries of my body. I can't define where I begin and where I end, because the atoms and the molecules of my arm blended with the atoms and molecules of the wall. And all I could detect was this energy.
>
> And I'm asking myself, "What is wrong with me? What is going on?" And in that moment, my left hemisphere brain chatter went totally silent. Just like someone took a remote control and pushed the mute button. Total silence. And at first I was shocked to find myself inside of a silent mind. But then I was immediately captivated by the magnificence of the energy around me. And because I could no longer identify the boundaries of my body, I felt enormous and expansive. I felt at one with all the energy that was, and it was beautiful there. [...]
>
> Then all of a sudden my left hemisphere comes back online and it says to me, "Hey! We've got a problem! We've got to get some help." And I'm going, "Ahh! I've got a problem!"
>
> But then I immediately drifted right back out into the consciousness—and I affectionately refer to this space as La La Land. But it was beautiful there. Imagine what it would be like to be totally disconnected from your brain chatter that connects you to the external world. [...]
>
> And I felt this sense of peacefulness. And imagine what it would feel like to lose 37 years of emotional baggage! Oh! I felt euphoria. It was beautiful.
>
> And in that moment, my right arm went totally paralyzed by my side. Then I realized, "Oh my gosh! I'm having a stroke!" And the next thing my brain says to me is, "Wow! This is so cool!" [...]

Bolte Taylor managed to get help and was taken to a hospital:

> When I woke later that afternoon, I was shocked to discover that I was still alive. When I felt my spirit surrender, I said goodbye to my life. And my mind was now suspended between two very opposite planes of reality. Stimulation coming in through my sensory systems felt like pure pain. Light burned my brain like wildfire, and sounds were so loud and chaotic that I could not pick a voice out from the background noise, and I just wanted to escape. Because I could not identify the position of my body in space, I felt enormous and expansive, like

> a genie just liberated from her bottle. And my spirit soared free, like a great whale gliding through the sea of silent euphoria. Nirvana. I found Nirvana. And I remember thinking, there's no way I would ever be able to squeeze the enormousness of myself back inside this tiny little body. […]
>
> And I pictured a world filled with beautiful, peaceful, compassionate, loving people who knew that they could come to this space at any time. And that they could purposely choose to step to the right of their left hemispheres—and find this peace. And then I realized what a tremendous gift this experience could be, what a stroke of insight this could be to how we live our lives. And it motivated me to recover. […]
>
> So who are we? We are the life-force power of the universe, with manual dexterity and two cognitive minds. And we have the power to choose, moment by moment, who and how we want to be in the world. Right here, right now, I can step into the consciousness of my right hemisphere, where we are. I am the life-force power of the universe. I am the life-force power of the 50 trillion beautiful molecular geniuses that make up my form, at one with all that is. Or, I can choose to step into the consciousness of my left hemisphere, where I become a single individual, a solid. Separate from the flow, separate from you. I am Dr. Jill Bolte Taylor: intellectual, neuroanatomist. These are the "we" inside of me. Which would you choose? Which do you choose? And when? I believe that the more time we spend choosing to run the deep inner-peace circuitry of our right hemispheres, the more peace we will project into the world, and the more peaceful our planet will be.

It took her eight years to completely recover. Her ordeal is described in her book (Bolte Taylor 2008b). Beauty, peace, disintegration, expansion, euphoria, merging with the universe—these are not the words one would expect to hear from a person whose left brain is damaged. The described experiences sound like what users of psychoactive substances often report (Sect. 14.3). Indeed, there is a distinct spiritual message in Bolte Taylor's words. In effect, she believes in the reality of the extraordinary experiences she witnessed. More on the notion and context of spirituality is found in Chap. 14.

Martin Pistorius contracted a brain infection at the age of twelve. Slowly he lost his cognitive abilities (Pistorius 2015):

> My parents were told I was as good as not there. A vegetable, having the intelligence of a three-month-old baby. They were told to take me home and try to keep me comfortable until I died. […]
>
> I had become a ghost, a faded memory of a boy people once knew and loved. Meanwhile, my mind began knitting itself back together. Gradually, my awareness started to return. But no one realized that I had come back to life. I was aware of everything, just like any normal person. I could see and understand everything, but I couldn't find a way to let anybody know. My personality was entombed within a seemingly silent body, a vibrant mind hidden in plain sight within a chrysalis.
>
> The stark reality hit me that I was going to spend the rest of my life locked inside myself, totally alone. I was trapped with only my thoughts for company. I would never be rescued. No one would ever show me tenderness. I would never talk to a friend. No one would ever love me. I had no dreams, no hope, nothing to look forward to. Well, nothing pleasant. I lived in fear, and, to put it bluntly, was waiting for death to finally release me, expecting to die all alone in a care home.
>
> I don't know if it's truly possible to express in words what it's like not to be able to communicate. Your personality appears to vanish into a heavy fog and all of your emotions and desires are constricted, stifled and muted within you. For me, the worst was the feeling of utter powerlessness. I simply existed. It's a very dark place to find yourself because in a

> sense, you have vanished. Other people controlled every aspect of my life. They decided what I ate and when. Whether I was laid on my side or strapped into my wheelchair. I often spent my days positioned in front of the TV watching Barney reruns. I think because Barney is so happy and jolly, and I absolutely wasn't, it made it so much worse.
>
> I was completely powerless to change anything in my life or people's perceptions of me. I was a silent, invisible observer of how people behaved when they thought no one was watching. Unfortunately, I wasn't only an observer. With no way to communicate, I became the perfect victim: a defenseless object, seemingly devoid of feelings that people used to play out their darkest desires. For more than 10 years, people who were charged with my care abused me physically, verbally and sexually.

It is impossible to comprehend the gravity of this devastating account. There are perhaps only a few torture techniques which can compare to locked-in syndrome, where a functioning mind is cut from any human social interaction and reality itself. Miraculously, Pistorius did not surrender:

> My mind became a tool that I could use to either close down to retreat from my reality or enlarge into a gigantic space that I could fill with fantasies.

After being trapped in his body for thirteen years, by chance, an aromatherapist who came to the care home he was in thought she had detected a sign of life in him—a responsiveness. She urged experts to run tests:

> And within a year, I was beginning to use a computer program to communicate. It was exhilarating, but frustrating at times. I had so many words in my mind, that I couldn't wait to be able to share them. Sometimes, I would say things to myself simply because I could. In myself, I had a ready audience, and I believed that by expressing my thoughts and wishes, others would listen, too.

Today, Pistorius, born in 1975, is still confined to a wheelchair and cannot talk. However (The Scotsman 2011):

> So much has happened since then. Being unlocked from that prison, aged 25, learning to read and write and communicate through the written word, finding a job, falling in love and getting married, moving country. Pistorius' story is a mix of serendipity and determination on an epic scale.

He wrote an autobiography of his truly unique life (Pistorius 2011).

Perhaps the most amazing and shocking aspect of the mind is that it can persist even without much physical neural hardwiring. The following case study surprised experts and laypeople alike. In 2007, a 44-year-old man went to see a doctor because of a problem in his leg (New Scientist 2007):

> Scans of the 44-year-old man's brain showed that a huge fluid-filled chamber called a ventricle took up most of the room in his skull, leaving little more than a thin sheet of actual brain tissue.
>
> "It is hard for me [to say] exactly the percentage of reduction of the brain, since we did not use software to measure its volume. But visually, it is more than a 50 to 75 per cent reduction," says Lionel Feuillet, a neurologist at the Mediterranean University in Marseille, France.
>
> Feuillet and his colleagues describe the case of this patient in *The Lancet*. He is a married father of two children, and works as a civil servant.

See Feuillet et al. (2007). How can this be possible? If consciousness is associated with neural correlates of consciousness in the brain, then how can sober waking consciousness emerge in a brain that is hardly developed? Indeed (New Scientist 2007):

> Intelligence tests showed the man had an IQ of 75, below the average score of 100 but not considered mentally retarded or disabled.
>
> "The whole brain was reduced—frontal, parietal, temporal and occipital lobes—on both left and right sides. These regions control motion, sensibility, language, vision, audition, and emotional and cognitive functions," Feuillet told *New Scientist*.

Another case study describes a 24-year-old woman who was missing a large part of her brain (the cerebellum, also called "the little brain," representing about 10% of the brain's total volume but contains roughly 50% of its neurons), again, without anybody noticing (Yu et al. 2014). Then, a boy missing the visual processing center of his brain, unexpectedly seems to have near-normal sight (Klein 2017). This phenomenon is called blindsight.

The brain displays a great plasticity and dynamic. This could explain why some damages to the brain result in an enhanced mind. This phenomenon is known as acquired savantism. For instance, Derek Amato, who, after suffering a head injury after diving into a shallow swimming pool, suddenly became a musical prodigy (Amato 2013). A normal person, without any particularly remarkable skills, he transformed into a composer and pianist. Other acquired savants, resulting from brain trauma, are the artists Jon Sarkin and Tommy McHugh, and the mathematical talents Jason Padgett and Orlando Serrell. At the age of three, Ben Underwood lost both of his eyes because of cancer. Around the age of five, he taught himself echolocation (Rojas et al. 2009). Similar to bats, he used a series clicking sounds to navigate in space, allowing him to accomplish amazing feats like running, playing basketball, riding a bicycle, rollerblading, playing football, and skateboarding. Underwood died at the age of sixteen as a result of his cancer. People suffering from synesthesia experiences a mixing of sensory inputs (Cytowic 2002)—for instance, hearing color or seeing sounds. For some, letters and numbers are associated with distinct colors. Higher levels of creativity are thought to go hand in hand with synesthesia (Dailey et al. 1997).

What happens if the brains of criminals are analyzed? Pedophiles, for instance, have an abnormally functioning amygdala (Sartorius et al. 2008). Then, other insights reveal how an arising brain pathology can drastically change behavior (Eagleman 2011, p. 151f.):

> On the steamy first day of August 1966, Charles Whitman took an elevator to the top floor of the University of Texas Tower in Austin. The twenty-five-year-old climbed three flights of stairs to the observation deck, lugging with him a trunk full of guns and ammunition. At the top he killed a receptionist with the butt of his rifle. He then shot at two families of tourists coming up the stairwell before beginning to fire indiscriminately from the deck at people below. The first woman he shot was pregnant. As others ran to help her, he shot them as well. He shot pedestrians in the street and the ambulance drivers that came to rescue them. The night before Whitman had sat at his typewriter and composed a suicide note:

> I do not really understand myself these days. I am supposed to be an average reasonable and intelligent young man. However, lately (I cannot recall when it started) I have been a victim of many unusual and irrational thoughts.
>
> It was after much thought that I decided to kill my wife, Kathy, tonight…I love her dearly, and she has been a fine wife to me as any man could ever hope to have. I cannot rationally pinpoint any specific reason for doing this…

Along with the shock of the murders lay another, more hidden surprise: the juxtaposition of his aberrant actions and his unremarkable personal life. Whitman was a former Eagle Scout and marine, worked as a teller in a bank, and volunteered as a scoutmaster for Austin Scout Troop 5. […]

A few months before the shooting, Whitman had written in his diary:

> I talked to a doctor once for about two hours and tried to convey to him my fears that I felt overcome by overwhelming violent impulses. After one session I never saw the Doctor again, and since then I have been fighting my mental turmoil alone, and seemingly to no avail.

Whitman's body was taken to the morgue, his skull was put under the bone saw, and the medical examiner lifted the brain from its vault. He discovered that Whitman's brain harbored a tumor about the diameter of a nickel. This tumor, called a glioblastoma, had blossomed from beneath a structure called the thalamus, impinged on the hypothalamus, and compressed a third region, called the amygdala. The amygdala is involved in emotional regulation, especially as regards fear and aggression.

A similar case study is reported (Eagleman 2011, p. 154f.):

> Take the case of a forty-year-old man we'll call Alex. Alex's wife, Julia, began to notice a change in his sexual preferences. For the first time in the two decades she had known him, he began to show an interest in child pornography. And not just a little interest, an overwhelming one. […]
>
> This was no longer the man Julia had married, and she was alarmed by the change in his behavior. At the same time, Alex was complaining of worsening headaches. And so Julia took him to the family doctor, who referred them on to a neurologist. Alex underwent a brain scan, which revealed a massive brain tumor in his orbitofrontal cortex. The neurosurgeons removed the tumor. Alex's sexual appetite returned to normal.
>
> The lesson of Alex's story is reinforced by its unexpected follow-up. About six months after the brain surgery, his pedophilic behavior began to return. His wife took him back to the doctors. The neuro-radiologist discovered that a portion of the tumor had been missed in the surgery and was regrowing—and Alex went back under the knife. After the removal of the remaining tumor, his behavior returned to normal.

Such insights motivate the burgeoning field of neurolaw.

The criminal justice system is based on the assumption that criminals had the choice to not act out their crimes. Hence, they are culpable and incarceration is the right measure to correct such immoral behavior. Neuroscience questions this assumption. Indeed, in the case of Whitman, one wonders what would have happened if he had had his brain tumor removed. More personally, I must assume that if my brain is affected by such an invasive destructive force, I too would be capable of heinous acts unimaginable to my healthy mind now. Neurolaw presents a dilemma. Clearly, perpetrators do great harm to society, hence society needs protection from them. But on the other hand, what happens to the notion of responsibility if one's brain is in fact damaged? Indeed "My brain made me do it!" is becoming a common criminal defense (Sternberg 2010).

In summary (Eagleman 2011, p. 157f.):

> Many of us like to believe that all adults possess the same capacity to make sound choices. It's a nice idea, but it's wrong. People's brains can be vastly different—influenced not only by genetics but by the environments in which they grew up. Many "pathogens" (both chemical and behavioral) can influence how you turn out; these include substance abuse by a mother during pregnancy, maternal stress, and low birth weight. As a child grows, neglect, physical abuse, and head injury can cause problems in mental development. Once the child is grown, substance abuse and exposure to a variety of toxins can damage the brain, modifying intelligence, aggression, and decision-making abilities. The major public health movement to remove lead-based paint grew out of an understanding that even low levels of lead can cause brain damage that makes children less intelligent and, in some cases, more impulsive and aggressive. How you turn out depends on where you've been. So when it comes to thinking about blameworthiness, the first difficulty to consider is that people do not choose their own developmental path.

11.4 The Mind-Body Problem

To reiterate: How do the processes happening in the brain give rise to the stream of subjective conscious experience? Why does it "feel like something?" Why don't all the subroutines in the brain simply collaborate to ensure survival and procreation without the emergence of an identity—an observer? Why the need for authorship? As discussed, one solution is to rebrand consciousness as an illusion. Indeed, now the enigma of the hard problem of consciousness is "explained away." This line of thought does, however, not convince everyone. Nonetheless, if we do believe in the reality of ourselves, the specter of dualism emerges. In essence, how does the ethereal mind interact with the physical? What is this elusive mind-body link?

One clue comes from psychosomatic disorders, where the mind is a key factor in a physical condition (Dum et al. 2016). Another one comes in the guise of the placebo effect (Beecher 1955). Simple beliefs and expectations can trigger spontaneous self-healing in patients. Indeed, this effect is so strong that clinical trials should be conducted as double-blind experiments (Rivers and Webber 1907). It does not suffice to keep the patients ignorant about which pill is the actual medicine and which one is simply a sugar tablet. Surprisingly, also the doctor is not allowed to know. If he or she knows which patients are receiving the medicine and the placebo, some form of nonverbal communication can subconsciously influence the patients, leading to a biases in the study. The placebo effect works on many levels. The color, shape, and size of a pill affects its effect. Large capsules appear more effective than small ones, yellow capsules are associated with a stimulating and antidepressant effect, while green soothes pain (Buckalew and Coffield 1982). Moreover, blue pills act best as sedatives (Blackwell et al. 1972), although they induce insomnia in Italian men (Vallance 2006). Remarkably, placebo medication works better if the patients are told that they are taking a placebo and the effect is explained[22] (Kelley et al. 2012; Locher et al. 2017). These are now called open-label placebos. Some neurophysiological and genetic underpinnings of the placebo effect are emerging (Hall et al. 2015). Strikingly, even placebo surgery works. For instance, when comparing real surgery for osteoarthritis of the knee to a simulated procedure using skin incisions (Moseley et al. 2002).

On the one hand, the effectiveness of traditional medication appears to be declining. The medical term tachyphylaxis describes a sudden and unexplained decrease in the response to an administered drug. These developments are worrying the pharmaceutical industry (Wired Magazine 2009):

> It's not only trials of new drugs that are crossing the futility boundary. Some products that have been on the market for decades, like Prozac, are faltering in more recent follow-up tests. In many cases, these are the compounds that, in the late '90s, made Big Pharma more profitable than Big Oil. But if these same drugs were vetted now, the FDA might not approve some of them. […]
>
> The fact that an increasing number of medications are unable to beat sugar pills has thrown the industry into crisis.

But on the other hand, the placebo effect seems to somehow be getting stronger (Tatera 2015):

> "If 40 percent of people recover from a chronic illness without a medication, I want to know why," Jon-Kar Zubieta, study lead and chair of the Department of Psychiatry at the University of Utah, said in the press release. "And if you respond to a medication and half your response is due to a placebo effect, we need to know what makes you different from those who don't respond as well."

While the placebo effect might appear as a strange phenomenon, it simply documents the body's innate ability to heal itself. Even more bizarre is the nocebo effect where your beliefs actually harm your body. In one case study, a patient required emergency medical intervention (Reeves et al. 2007):

> A 26-year-old male took 29 inert capsules, believing he was overdosing on an antidepressant. Subsequently, he experienced hypotension requiring intravenous fluids to maintain an adequate blood pressure until the true nature of the capsules was revealed. The adverse symptoms then rapidly abated.

The negative effects of Voodoo spells could be linked to the nocebo phenomenon. Indeed, the recent rise of reported nonceliac gluten sensitivity could also be a collective nocebo effect (Di Sabatino and Corazza 2012). The human mind's ability to harm the "host" it is living in is truly astonishing. What is the evolutionary benefit of allowing organisms to will themselves into a state of reduced fitness? In conclusion (Vallance 2006)

> Research into the placebo effect has proved it to be a vastly complicated phenomenon, encompassing complex interactions of conscious and unconscious psychosocial processes. Furthermore, the phenomenon stretches intriguingly across the mind/body gap, a conceptual

[22]Meaning that they are told that placebos contain no actual medicine but can induce healing nevertheless.

> divide that has plagued scientists and philosophers since Descartes and beyond. Functional neuroimaging may not fully resolve this philosophical conundrum, but it is beginning to unravel some of the placebo effect's neurobiological components; already several candidate areas and processes are being proposed. Although research so far remains hampered by small samples and lack of replication, it will undoubtedly continue to reveal useful insights.

Perhaps the increasing research on the effects of meditation—even simple mindfulness—can also help unravel more of the mystery (Lutz et al. 2004).

11.4.1 Free Will

Free will is very a intuitive notion. Indeed, even discussing the topic appears ridiculous as the counter-thesis is preposterous. With no free will, who or what is making decisions and why? Unfortunately, the interpretation of quantum mechanics and neuroscientific insights force us to critically reevaluate the issue. In summary (Eagleman 2011, p. 220f.):

> Do human minds interact with the stuff of the universe? This is a totally unsolved issue in science, and one that will provide a critical meeting ground between physics and neuroscience. Most scientists currently approach the two fields as separate, and the sad truth is that researchers who try to look more deeply into the connections between them often end up marginalized. Many scientists will make fun of the pursuit by saying something like "Quantum mechanics is mysterious, and consciousness is mysterious; therefore, they must be the same thing." This dismissiveness is bad for the field. To be clear, I'm not asserting there is a connection between quantum mechanics and consciousness. I am saying there could be a connection, and that a premature dismissal is not in the spirit of scientific inquiry and progress. When people assert that brain function can be completely explained by classical physics, it is important to recognize that this is simply an assertion—it's difficult to know in any age of science what pieces of the puzzle we're missing.

Free Will in Quantum Mechanics

Recall Sects. 4.3.4 and 10.3.2 on quantum mechanics,[23] specifically Sect. 10.3.2.2 on the interpretation of quantum physics. Before addressing the quantum challenges, a brief overview of the status of free will in physics follows. Isaac Newton's theory of classical mechanics (Sect. 2.1.1) is the starting point (Lewis 2016, p. 145):

> Historically, the greatest challenge to free will has been determinism. If the physical world is like a giant clockwork, what room is there for free human action?

Then, Albert Einstein's theory of special relativity merged space and time into the space-time continuum (Sect. 3.2.1). This gives rise to an atemporal block universe, where time, and thus free will, are an illusion (Sect. 10.4.2).

The rise of quantum theory gave free will a new chance (Lewis 2016, p. 145):

> So it is not surprising, then, that the advent of quantum mechanics was hailed by many as giving a physical underpinning for free will, since quantum mechanics provides the first suggestion that determinism might fail at the fundamental physical level.

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[23] For quantum field theory, see Sects. 3.1.4, 3.2.2.1, 4.2, and 10.1.1.

The inherent randomness of the subatomic level of reality appeared to be hospitable to the notion of free will. Unfortunately (Zeilinger 2010, p. 266):

> It does not at all follow that quantum randomness explains free will as is often stated.

Moreover, it is the phenomenon of quantum entanglement (Sect. 10.3.2.2) that appears to break causality as one cannot distinguish between "cause" and "effect" anymore (Stefanov et al. 2002, and Sect. 10.3.2.2). A causal ordering of events is a prerequisite for free will. As so often, nature refuses to give clear and unambiguous answers. In the end, the discussion comes down to personally held views (Zeilinger 2010, p. 266):

> In the experiment on the entangled pair of photons, Alice and Bob are free to choose the position of the switch that determines which measurement is performed on their respective particle. [...] This fundamental assumption [that choice is not determined from the outside] is essential to doing science. If this were not true, then, I suggest it would make no sense at all to ask nature questions in an experiment [...].

However, the very nature of a measurement in quantum mechanics is problematic. Specifically, how (or whether) the spread out wave function of probability, obeying Schrödinger's equation, collapses and becomes a randomly located point as a result of the measurement. This appears to give an observer the power to influence objective reality. See Sect. 10.3.2.2 for alternative, albeit no less unsettling, interpretations.

Muddying matters even more is the "free will theorem" (Conway and Kochen 2006).[24] In detail (Maudlin 2011, p. 252):

> This paper contains the astonishing claim of a derivation from the predictions of quantum theory to the conclusion "if indeed there exist any experimenters with any modicum of free will, then elementary particles must have their own share of this valuable commodity."

For the ensuing technical debates, see Conway and Kochen (2007, 2009).

In the end, we appear to be facing two radical and contradictory options regarding free will. Either it does not exists at all or everything has free will—including electrons. For further reading, see, for instance Aaronson (2016).

Free Will in Neuroscience

There are certain contexts in which the free will of a person is restricted. For instance, sufferers of Tourette's are not free to stop swearing. Split-brain patients can develop alien hand syndrome (Eagleman 2011, p. 163f.):

> While one hand buttons up a shirt, the other hand works to unbutton it. When one hand reaches for a pencil, the other bats it away. No matter how hard the patient tries, he cannot make his alien hand *not* do what it's doing.

The crux of the question is now whether all of our actions are simply the result of neural activity—the outcome of the subconscious subroutines autopiloting decisions—or if there is a free will unconstrained by biology. To summarize (Swaab 2014, p. 327):

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[24]This is an extension of the Kochen–Specker theorem (Sect. 10.3.2.2). One co-author of the theorem, the mathematician John Conway, was already introduced in Sects. 2.1.4 and 5.5.2.

> Our current knowledge of neurobiology makes it clear that there's no such thing as *absolute* freedom. Many genetic factors and environmental influences in early development [...] determine the structure and therefore the function of our brains for the rest of our lives. As a result, we start life not only with a host of possibilities and talents but also many limitations [...].

Moreover, it appears that most of our actions are not a result of free will (Eagleman 2011, p. 167):

> In the 1960s, a scientist named Benjamin Libet placed electrodes on the heads of subjects and asked them to do a very simple task: lift their finger at a time of their own choosing. They watched a high-resolution timer and were asked to note the exact moment at which they "felt the urge" to make the move. Libet discovered that people became aware of an urge to move about a quarter of a second before they actually made the move. But that wasn't the surprising part. He examined their EEC recordings—the brain waves—and found something more surprising: the activity in their brains began to rise before they felt the urge to move. And not just by a little bit. By over a second. In other words, parts of the brain were making decisions well before the person consciously experienced the urge.

Libet's experiment is one of the most famous in neuroscience (Libet et al. 1983). While it has been reproduced many times, and some criticism addressed (Matsuhashi and Hallett 2008), it remains controversial. But the evidence is mounting. In one experiment, subjects were told that they can freely choose between adding or subtracting numbers appearing on a screen. Analyzing their fMRI data, the researchers could accurately predict which choice would be made several seconds before the subjects reported that they had consciously made a decision (Soon et al. 2013).

Overall neuroscientists and philosophers of the mind agree that free will is a contestable notion and that it is illusory in many contexts. Ironically (Gazzaniga 2011, p. 114):

> The belief that we have free will permeates our culture, and this belief is reinforced by the fact that people and societies behave better when they believe that is the way things work.

Yet again, we face an existential dilemma. All our intuitions and beliefs of the world center around the existence of our self and the free will accompanying it. However, experimental results expose these ideas as flawed or false. But not everyone agrees (Metzinger 2009, p. 126f.):

> As noted previously, the philosophical spectrum on freedom of the will is a wide one, ranging from outright denial to the claim that all physical events are goal-driven and caused by a divine agent, that nothing happens by chance, that everything is, ultimately, willed. The most beautiful idea, perhaps, is that freedom and determinism can peacefully coexist. [...] Determinism and free will are compatible.
>
> [...]
>
> Probably most professional philosophers in the field would hold that given your body, the state of your brain, and your specific environment, you could not act differently from the way you're acting now—that your actions are preordained, as it were. [...] This is a widely shared view: It is, simply, the scientific worldview. The current state of the physical universe always determines the next state of the universe, and your brain is a part of this universe.
>
> [...]

> If we take our own phenomenology seriously, we clearly experience ourselves as beings that *can* initiate new causal chains out of the blue—as beings that *could* have acted otherwise given exactly the same situation. The unsettling point about modern philosophy of mind and the cognitive neuroscience of will, already apparent even at this early stage, is that a final theory may contradict the way we have been subjectively experiencing ourselves for millennia. There will likely be a conflict between the scientific view of the acting self and the phenomenal narrative, the subjective story our brains tell us about what happens when we decide to act.

Conclusion

Modern neuroscience has unveiled remarkable and unexpected aspects of our minds (Gazzaniga 2011, p. 102):

> The view in neuroscience today is that consciousness does not constitute a single, generalized process. It is becoming increasingly clear that consciousness involves a multitude of widely distributed specialized systems and disunited processes, the products of which are integrated in a dynamic manner by the interpreter module [the conscious narrator in our brains]. Consciousness is an emergent property. From moment to moment, different modules or systems compete for attention and the winner emerges as the neural system underlying that moment's conscious experience. Our conscious experience is assembled on the fly […].

This has unexpected consequences. The neurobiologist Robert Provine summarizes (quoted in Brockman 2015, p. 157):

> We fancy ourselves intelligent, conscious, and alert, thinking our way through life. This is an illusion. We're deluded by our brain's generation of a sketchy, rational narrative of subconscious, sometimes irrational, or fictitious events that we accept as reality. These narratives are so compelling that they become common sense. […] Indeed, we may be passengers in our body, just going along for the ride and privy only to secondhand knowledge of our status, course, and destination.
>
> Behavioral and brain science detect chinks in our synthetic, neurologically generated edifice of reality. Research on sensory illusions indicates that percepts are simply our best estimate of the nature physical stimuli, not a precise rendering of things and events. The image of our own body is an oddly shaped product of brain function. Memory of things past is also fraught with uncertainty; it is not the reading-out of information from the brain's neurological data bank, but an ongoing construct subject to error and bias. The brain also makes decisions and initiates action before the observer is consciously aware of detecting and responding to stimuli.

In essence, everything in my personal subjective stream of consciousness is fabricated, especially my perception of the world "out there." This gives rise to a momentous enigma—a truly existential puzzle. In the words of Chalmers (2014):

> On the one hand, it's a datum that we're conscious. On the other hand, we don't know how to accommodate it into our scientific view of the world. So I think consciousness right now is a kind of anomaly, one that we need to integrate into our view of the world, but we don't yet see how. Faced with an anomaly like this, radical ideas may be needed, and I think that we may need one or two ideas that initially seem crazy before we can come to grips with consciousness scientifically.

We have witnessed a breathtaking series of human dethronements, eclipsing the Copernican and Darwinian revolutions. Our theories of reality are contingent and constructed and so is our knowledge of the universe. The deeper we probe reality with our minds, the more questions emerge (Chap. 9). Indeed, reality itself turned out to be a radically different structure than our intuitions and beliefs would have let us imagine. There appears to be no foundation to it and it is an inherently elusive phenomenon. Notions of space, time, matter, and causality seem to crumble under closer inspection (Chap. 10). But the hardest blow comes perhaps from neuroscience. Incomprehensibly, our own sense of identity and freedom are illusions conjured up by unconscious subroutines in the brain. Consciousness is a post hoc narrator of decisions emerging from the vast non-conscious depths of the brain. My perception of the external world is an internal construction, akin to a simulation. In the final analysis, the current scientific worldview is telling me that I am fictitious and an anomaly incarnated in an otherwise incomprehensible and inaccessible physical reality. The Book of Nature (Chaps. 2 and 5) was a grand and elaborate farce. The most profound questions of existence:

Q1 What can I know?
Q2 What is reality?
Q3 What is consciousness?

now have very disheartening answers:

A1 Nothing.
A2 Inaccessible and/or illusionary.
A3 Illusionary.

Where do we go from here? The universe appears pointless, callous, hostile, and cruel for tricking us into believing the illusions of the self and the external world. The inquisitive human mind seems to have reached a dead end. Disenchanted and alienated it is left to its own devices, forever trapped in a stream of delusions.

But how inescapable is this conclusion? One fundamental question remains:

> Could there be something we don't yet know about ourselves and the universe, the knowledge of which could change everything?

Are we making erroneous assessments and coming to wrong conclusions because we are assuming a faulty worldview? If so, what needs to be adjusted in order to regain a fuller understanding of ourselves and the universe? This is the topic of Part III. A new existential foundation is explored, centered around information (Chap. 13) and a novel understanding of consciousness (Chap. 14). The final conclusion is presented in Chap. 15.

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Part III
A New Horizon

Wherein a new foundation of existence is explored.

Chapter 12
The Age of Post-Truth

Abstract The initially happy and rewarding quest of the human mind in understanding itself and the universe was thwarted by unexpectedly fierce opposition. The clouds on the horizon turned into an existentially threatening thunderstorm. All our human intuitions turned out to be untenable. The nature of reality and consciousnesses is as elusive as ever. Against this backdrop, our modern post-truth world is infused with ignorance and anti-intellectualism. "My ignorance is as good as your knowledge." Conspiracy theories abound. Trench wars are fought along social, political, and religious delimitations. Most tragically, we have reached a level of technological prowess, lacking any signs of collective intelligence, which is resulting in the systematic and rampant destruction of the biosphere. This book is an invitation to reevaluate everything—mixing imagination with critical thinking. Could there be something we don't yet know about ourselves and the universe, the knowledge of which could change everything? Before addressing this question, notions of collective intelligence, self-organization, scientific utilitarianism, and radical open-mindedness are explored.
Level of mathematical formality: not applicable.

The human mind set out to discover and decipher the Books of Nature. After what appeared to be an astonishingly successful pursuit of knowledge, ignorance and uncertainty reemerged—stronger and more threatening than ever. The Books of Nature turned out to be incomplete translations, where the original alien language appears incomprehensible to the human mind. Nature mocked the mind by pretending to expose its secrets. Now, the futility of existence is exposed. The universe seems pointless, callous, cruel, and cynical. Every intuition we cultivated about ourselves and reality turned out to be false. In a profound existential attack, the center of being itself—our own self—is deconstructed and free will ousted. We are only left with the gift of technology, the result of a partial and superficial understanding of reality. Against this gloomy existential backdrop, modern life unfolds. With no scientific, philosophical, or spiritual guidance our global society fractures. Nothing is obliging and "anything goes."

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We now live in an age of divergence. Extreme polar opposites are orbiting each other, with no chance of reconciliation. This schism can be seen to divide all aspects of human endeavor. The whole spectrum of sociopolitical, cultural, theological, philosophical, and scientific ideas are affected. At the core of this crisis lie conflicting beliefs resulting in a gridlock that is paralyzing our world on so many levels. Trench wars are fought along social, political, and religious delimitations. Each faction truly and passionately believes to be on the right side of history. As a result, we see the emergence of individual radicalization and deep-seated hatred for different thought around the world. There exist key drivers fueling this dystopianism. The failure of science and philosophy to provide a consoling and unifying foundation for reality is disenchanting and alienating (Part II). With this missing bedrock, nothing appears binding and a proliferation of complacent beliefs abounds unchecked.

12.1 The Cult of Ignorance

The sober and critical worldview, informed by scientific inquiry, reasoning, and thought, has been one of the early victims of this modern battle for the Truth. In an ironic turn of events, the knowledge systems giving rise to the dazzling technological prowess permeating every aspect of modern life—and widely adopted by billions of people—have become marginalized and rejected. Scientists are no longer credited for their efforts to decipher the workings of the world (Part I), laying the foundation of technology. To the contrary, they are skeptically eyed and thought to be following a hidden agenda if scientific findings contradict one's own beliefs. In an effort to justify these, enemy scientists are stigmatized, at best, as being incompetent or, at worst, corrupt. The harder the edifice of science clashes with the personal sociopolitical, cultural, theological, or philosophical belief systems of a person, the more disdaining views of scientists are invoked.

This rise of anti-intellectualism has been diagnosed for some time now. The historian Richard Hofstadter wrote a Pulitzer Prize-winning book in 1963, called *Anti-Intellectualism in American Life* (Hofstadter 1963). Nearly two decades later, the prolific science fiction writer and academic, Isaac Asimov, lamented in a *Newsweek* article, aptly titled *A Cult of Ignorance* (Asimov 1980, p. 19):

> There is a cult of ignorance in the United States, and there always has been. The strain of anti-intellectualism has been a constant thread winding its way through our political and cultural life, nurtured by the false notion that democracy means that "my ignorance is just as good as your knowledge."

This assessment is particularly unfortunate and ironic when it applies to a day and age where nearly the entire accumulated knowledge of humanity can easily be accessed by billions of people—and a lot of it even for free.[1]

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[1]Some examples include http://arxiv.org, http://biorxiv.org, http://ssrn.com, http://socarxiv.org, http://www.wikipedia.org, http://scholar.google.com, http://books.google.com, and the legally contested repository Sci-Hub and search engine LibGen.

A modern and acute example of such a reflex to reject expertise that challenges one's own beliefs can be found in the words of Michael Gove, former *Times* columnist and British Conservative Party politician. His response to the fact that thousands of economists warned about the dire effects of Brexit was that "people in this country have had enough of experts" (Manace 2016). One is uncannily reminded of the title of a comic book by Scott Adams, the creator of the character *Dilbert*, called "When Did Ignorance Become a Point of View?" Gove later went on to compare pro-EU economists warning about the potential fallout of Brexit, some of them Nobel laureates, to Nazi scientists paid by Adolf Hitler's government (Mason and Asthana 2016). For this, he afterwards apologized.

But also experts can succumb to anti-intellectualism and wishful thinking. For instance, the prestigious and widely observed magazine *The Economist* can offer frighteningly simple and naive solutions to notoriously complex and challenging problems. Acknowledging global inequality as a major global issue (Sect. 7.4.2.3), the solution is obvious: simply increase social mobility (The Economist 2011). Regarding anthropogenic global warming, a fact the magazine started to accept in 2006 (The Economist 2006), the ultimate answer is clear: geoengineering. By dispersing aerosols into the atmosphere, the threat of climate change will easily be mitigated by man-made global cooling (The Economist 2015).

It can, however, be argued that there will always be an inherent conflict in the sociopolitical and philosophical ideas of people. Depending on what point of view to favor, what nuances to highlight, what issues to disregard, the resulting beliefs are expected to diverge. This can be seen to reflect the complexity, diversity, and plurality of the social world we live in. Indeed, there appears to be a neural basis for political affiliation (Sect. 11.3.1). What is a lot harder to grasp, however, is when people evade evidence altogether by fleeing into a world constructed and construed out of beliefs conspiracy theories peddle. Here we see the Dunning–Kruger and the backfire effects at work (Sects. 11.3.1 and 11.3.2).

12.2 The Age of Conspiracy

One of the subtler effects of today's highly networked and mass digitized world is the ease by which any kind of idea can be widely disseminated. This novel data deluge, comprised of fiercely competing ideas on any conceivable topic, is relentlessly flooding our minds and ultimately altering our perception of reality.

12.2.1 The Spectrum

Today we inhabit "filter bubbles" (Pariser 2011) and "echo chambers" (Barberá et al. 2015; Del Vicario et al. 2016). These are the result of algorithms carefully selecting and curating the content of the information we are exposed to—from every Google search to the items seen in the news feeds of our social media accounts. Intended as a service to deliver relevant information in line with the user's preferences and beliefs, these mechanisms also serve to radicalize people's opinions: Our brain's propensity to be affected by confirmation bias is constantly being triggered and any doubt dispersed. The more we are exposed to rumors, the more we tend to believe them (Bessi et al. 2015).

The result is twofold: the surfacing of unadulterated hatred and open hate speech in anonymous online interactions, and an abundance of conspiracy theories to choose from. In detail (Zollo et al. 2015):

> [T]he wide availability of user-provided content and the direct path between producers and consumers of information often foster confusion about causations, encouraging mistrust, rumors, and even conspiracy thinking.

Indeed, this plethora of false information can be understood as a danger (Zollo et al. 2015):

> Misinformation on online social media is pervasive and represents one of the main threats to our society according to the World Economic Forum.

And most worryingly, such information is immune to any refutation (Zollo et al. 2015):

> [We] find that attempts at debunking are largely ineffective. […] Indeed, after interacting with debunking posts, users retain, or even increase, their engagement within the conspiracy echo chamber.

In broad terms, conspiracy theories are (Grimes 2016):

> […] beliefs, which attribute events to secret manipulative actions by powerful individuals, are widely held by a broad-cross section of society. Belief in one conspiracy theory is often correlated with belief in others, and some stripe of conspiratorial belief is ubiquitous across diverse social and racial groups. These concepts run the gauntlet from the political to the supernatural, and a single working definition is not easy to obtain.

Some popular conspiracy theories are the following:

1. vaccines cause autism;
2. the moon-landing was fake;
3. global warming is:
   a. a hoax perpetrated by scientists for their own personal gain;
   b. a UN-led hoax to create a New World Order;
   c. a natural phenomenon and not influenced by human activity;
   d. due to human activity, but the potential impacts are not sufficient to require any policy response;
   e. due to human activity, but will be easily mitigated by a technological solution, again implying that concerns are unwarranted;
4. the existence of chemtrails, i.e., chemical agents that are being sprayed into the atmosphere by high-flying airplanes for various sinister purposes;

5. creationism as advocated by Evangelical Christians mostly in the United States;
6. the world is controlled by:
   a. the Bilderberg Group;
   b. the Trilateral Commission;
   c. the Illuminati;
   d. shape-sifting extraterrestrial reptilian humanoids;
7. the Moon is hollow;
8. the Earth is hollow;
9. the Earth is flat.

Although, naturally, some conspiracy theories have turned out to be true in the history of mankind, overall, the failure probability for any given conspiracy is extremely high and exposure thus very likely (Grimes 2016). In other words, for any of the aforementioned conspiracies to be true a vast coordination and collusion effort is required on an international scale. The conspirators have to implement upkeep mechanism that ensure continued secrecy over time. Next to government officials, political elites, and financial power-holders most conspiracy theories crucially depend on the assistance from a majority of scientists. Only if the science people have been taught is erroneous conspiracy theories can be viable. This faces us with the aforementioned irony. The vocal advocates of conspiracy theories denounce scientists as perpetrators or puppets in this grand scheme to manipulate countless innocent civilians while, at the same time, they unwittingly embrace and utilize the technology that emerges from scientific inquiry and knowledge.

Some conspiracy theories have been around for centuries. Others have resurfaced, like the notion of a flat Earth. In January 2016, a US American rapper turned to Twitter to express his skepticism that the world was round, sparking an online battle with Neil deGrasse Tyson, an astrophysicists and science communicator. This has not been the only incidence where members of the entertainment industry have shown signs of extreme anti-science or a loathing of scientists. In 2009, a US American hip hop duo called *Insane Clown Posse* released a song called *Miracles*. In particular, they had an issue with magnets:

> I see miracles all around me
> Stop and look around, it's all astounding
> Water, fire, air and dirt
> Fucking magnets, how do they work?
> And I don't wanna talk to a scientist
> Y'all motherfuckers lying, and getting me pissed

Again, the bitter irony the two artists missed is the fact that the miraculous technology, allowing them to produce and disseminate their music and music videos, was divined by scientists in the form of knowledge systems like quantum mechanics (Sect. 4.3.4 and 10.3.2), information theory (Sect. 13.1.2), and electromagnetism (Sect. 2.1.2).

Then, sometimes, the emergence of a conspiracy theory can be pinpointed. Around the turn of the millennium, Andrew Wakefield published an article in the prestigious medical journal the *Lancet* pointing to a link between autism and MMR vaccines (Wakefield et al. 1998). This claim was further established in a second publication

(Wakefield 1999). In 2010, the *Lancet* fully retracted the 1998 publication when Wakefield's research was found to be fraudulent. He had multiple conflicts of interest, manipulated evidence, and broke ethical codes. As a consequence, he was struck off the UK medical register and was barred from practicing medicine in the UK. Nonetheless, the link that vaccines cause autism has stuck in the public's collective mind. To the conspiracy theory camp, Wakefield is a martyr unjustly prosecuted by the evil scientific establishment in an effort to hide the truth about autism and vaccines (Eggertson 2010). Meanwhile, the damage to public health continues as thousands of parents around the world turn against MMR vaccination, resulting in low vaccination rates which are below the 95% level recommended by the World Health Organization to ensure herd immunity (Godlee et al. 2011). "In 2008, for the first time in 14 years, measles was declared endemic in England and Wales" (Godlee et al. 2011).

In the following, a short anecdote of some personal exposure to conspiracy theories is presented. In 2009, my co-author and I published a study analyzing the control emerging in various national ownership networks, uncovering a systematic concentration of financial power (Glattfelder and Battiston 2009 and Sect. 7.3.2.1). A fact that was not overlooked by the conspiracy theory camp. I commented (Glattfelder 2013, p. 210):

> The empirical inequality in the distribution of control was seen as proof of the existence of an elite group controlling the world. Some of the titles circulating the Internet include "Illuminati Proven by Physics", "Physicists Shed Light on Illuminati" and "New World Order, Interlocking Directorships".
>
> Indeed, the study appeared to spur the exuberant imagination of some people. One author saw a connection between our findings and solar cycles, purporting that the sun is the hidden influence behind global finance in a recently published book.

In conclusion, some of the tactics that are successfully employed to gain support for conspiracy theories are:

- cherry-picking facts and quote mining;
- constructing straw-man arguments and misrepresentations of science;
- making up analogies supporting the claims;
- invoking fringe science;
- offering simple solutions to complex issues;
- discreditation tactics and character assassination;
- instilling a sense of uncertainty and confusion;
- subtle evasion tactics;
- relentlessly spamming the Internet with the claims, especially if they have been disproven and debunked.

And crucially: Don't be afraid to flip-flop, deceive, or lie for the greater good of defending the Truth.

12.2.2 Creationism

One of the grandest anti-science conspiracy theories is creationism as advocated by Evangelical Christians mostly in the United States. In this belief system the universe was created about 6,000–10,000 years ago in its present form. Here we are faced with a literal interpretation of the Bible which needs to be reconciled with the observable universe. In a nutshell, creationism is a set of beliefs that, next to competing with other creationist theologies, contradicts:

- cosmology and astrophysics;
- nuclear physics;
- geology;
- biology.

In other words, science is mostly wrong and the true nature of reality can only be divined by a leap of faith: by accepting the Christian Scriptures as the only source of knowledge. In a cunning move, the void arising due to the rejection of science is filled with what is known as "creation science." This enterprise has been hugely successful in the Unites States and is spreading to Europe (Gross 2002):

> Time and again, American creationists succeed in purging the minimal curriculum of the science they loathe, as it happened temporarily in Kansas in 1999, or at least in getting biology books adorned with a sticky label saying that evolution is just a theory (a procedure just reconfirmed in Alabama). Surveys reveal that a whopping 47% of the nation that contributed most to the sequencing of the human genome stubbornly denies the process by which it came into existence, and which is confirmed a million times over by all the genetic data now available. Equally paradoxically, half the population commanding the world's biggest nuclear arsenal reckon that radioactive decay is a less reliable measure of the Earth's age than the bible.

Many websites and countless hours of online videos are devoted to this formidable task of forcing reality into a preconceived box of static and archaic ideas. On occasions, creationists and scientists cross swords. On the 4th of February 2014, at the Creation Museum in Petersburg, Kentucky, science educator Bill Nye debated Australian creationist Ken Ham. The event was widely broadcast in the Internet and lasted nearly three hours. Needless to say, each camp saw their spokesperson winning the debate. At the end of the day, it all boils down to the following dialog: "You cannot prove that God exists!" "No, you cannot prove that God does not exist!"

The allure of creationism can hardly be underestimated. Hard work and diligent studying are no longer required to give a person access to the universe's intimate secrets. There is no need anymore to slog through complicated textbooks and deal with petty abstract ideas in order to scale the mountain of knowledge. There is no requirement to learn and understand what countless deep thinkers have, through the ages, contributed to today's understanding of the universe. By simply taking that leap of faith and cultivating a personal relationship with the deity you revere you are granted infinite knowledge and wisdom. You replace the faulty Books of Nature with the pristine Christian Bible. Not only will you be justified in scorning or ignoring the false prophets of science, but, crucially, you will ultimately be rewarded with an eternity of bliss. All of this also reveals the special place the believer holds in the grand scheme of things: to be one of the lucky few who are born into a culture and geographic location on Earth where the one and only True Religion is preached and not one of the competing false theologies.

But perhaps it is possible to reconcile science and religion, at least partially. Maybe there is a less literal, more sympathetic reading of Scripture that focuses on the needs that religions answer. This is a proposition of the philosopher Alain de Botton, seen, as an example, in his book *Religion for Atheists* (De Botton 2012). He believes it is futile to debate if religion is true or not but importantly tries to understand the human needs religion answers: what it is that drives people to religion. For instance, guidance, consolation, and morality. De Botton understands that reality can sometimes be unbearably painful. The looming terror of death, existential crisis, and the fear that life is pointless and absurd creates a longing for comfort and cosmic significance religion can answer to. Moreover, at its best, religion can offer social cohesiveness by defining a universal cultural matrix. It can inspire kindness, virtue, introspection, and spirituality. Also a sense of being one with humanity, nature, and the universe can emerge. Regrettably, the most common utilizations of religion nowadays appear to result in imposing a sense of superiority and self-righteousness, denying other people their rights, prohibiting progression, fostering ignorance, abdicating personal responsibility, and inflicting violence. In this dogmatic, intolerant, and fundamentalist incarnation, religion is a scourge of mankind.

12.3 What About This Book?

It can be argued that this book, in fact, opens the floodgates to anti-intellectualism. The advocated uncertainty (Sect. 8.1.1) appears to undermine any true knowledge of the world. By sympathizing with postmodern ideas, by embracing relativism and constructivism (Chap. 9) one can be lead to believe that this book can be instrumentalized to cater to ignorance. By highlighting the limits of knowledge (Chap. 9), the fundamental incomprehensibility of the nature of reality (Chap. 10), and the grave limitations of human perception and cognition (Chap. 11), this book can be understood as legitimatizing conspiracy theories. The ominous words of the influential philosopher of science, Paul Feyerabend, echo: "Anything goes!" (see Sect. 9.1.6). Such exploitations would, however, represent a drastic and fatal misunderstanding of the entire content.

It is true, at the deepest level of the understanding relating to existence we are faced with profound epistemic and ontic dilemmas. None of the following possibilities can be unequivocally disproved:

- reality was created five seconds ago, along with all my memories of the past;
- I am a disembodied brain kept alive in a vat and electrochemically stimulated so that my mind constructs the illusion of an external world I experience my self being embedded in Putnam (1981);

- my mind is freely hallucinating the entire reality I perceive;
- the reality I wake up to every day is also being "dreamt up" by my mind and one day I will really wake up and find myself in the genuine "waking" reality which is unimaginably more vivid, coherent, and complete;
- reality is unfathomably more complex and richer than anyone ever imagined, extending beyond the constraints of space, time, and energy; similarly "I" am not just manifested within these physical boundaries but "parts of me" extend to these otherworldly realms;
- separation, delimitation, and individuation are illusory and all things in the universe are various manifestations of the oneness that is all there is;
- reality is a simulation (Sect. 13.4.2);
- reality is a creation of consciousness and consciousness is the essence of existence (Sects. 14.2, 14.4, 15.1, and 15.2).

How should we then account for the fact of existence—other than uncritically believing one of the aforementioned options or shrugging the whole thing off as simply being the way things are?

Any honest analysis must incorporate the concessions that we do not understand the structure and nature of reality. Compounding the problem is the fact that all our contingent anthropic-centered intuitions about the universe and the self are incomplete or wrong. Nothing is as it seems. Once this truth is admitted, the human mind can reconsolidate and search for new horizons. Some insightful scientists are addressing this most fundamental challenge by opening up to "crazy" ideas. In this context, a central question emerges:

> Could there be something we don't yet know about ourselves and the universe, the knowledge of which could change everything?

This book emphatically argues "Yes!" In Part III we are asked to take a leap of faith and unconditionally believe in the reality of our own consciousness—and that of others. By assigning this ethereal phenomenon an essential role in the enigma of existence we, perhaps, will find that subjective consciousness and objective reality are more similar than we ever dared to dream.

Another major obstacle standing in the way of a grander understanding of existence is not only what we don't know, but, crucially also, what we think we know—facts we believe which are false. In the words of the historian Daniel Boorstin (quoted in Middelmann 2011, p. 14f.):

> The greatest obstacle to discovery is not ignorance—it is the illusion of knowledge.

Perhaps one way to combat the illusion of knowledge is to follow the recommendations of Albert Einstein (Einstein 2009, p. 97):

> Imagination is more important than knowledge. For knowledge is limited, whereas imagination embraces the entire world, stimulating progress, giving birth to evolution. It is, strictly speaking, a real factor in scientific research.

It is remarkable to hear one of the most accomplished scientist speak of such non-intellectual virtues. One would expect advice more along the lines of critical thinking (Lai 2011):

> Critical thinking involves both cognitive skills and dispositions. These dispositions, which can be seen as attitudes or habits of mind, include open and fair-mindedness, inquisitiveness, flexibility, a propensity to seek reason, a desire to be well-informed, and a respect for and willingness to entertain diverse viewpoints.

In the end, combining the gifts of imagination with critical thinking is maybe the final quest of the human mind in understanding its own existence and the universe it is embodied in.

12.4 The Dawning of a New Age

In summary, humanity today faces at least three major challenges:

1. the systematic and rampant destruction of the biosphere (discussed in the Epilogue);
2. the proliferation of conspiracy theories and anti-science attitudes, next to widespread ignorance, hostility, and misanthropy;
3. the missing understanding of ourselves and the universe we inhabit.

Although these challenges seem daunting, perhaps the solutions are closer and more straightforward than imagined. It is tempting to face the challenges of our times with fear, denial, cynicism, indifference, or alienation. After all, we are embedded in the world and cannot avoid exposure. However, using our mind's capacity to think in abstract terms, we can try and analyze the status quo from an external point of view. Now it becomes possible to identify patterns and processes that have lead to the way things are today.

12.4.1 Collective Intelligence

One striking observation relates to the two modes of intelligence: individual and collective. In essence, humans have an abundance of individual intelligence, fueling knowledge generation and technological proficiency, but an acute lack of collective intelligence, which would allow our species to co-evolve and co-exists in a sustainable manner with the biosphere that keeps it alive. This is a true enigma of our modern times: Why does individual intelligence not foster collective intelligence? Take, for instance, a single termite. The biological capacity for cognition is very limited. However, as a collective swarm, the termites engineer nests they equip with air-conditioning capabilities, ensuring a constant inside temperature allowing the termites to cultivate a fungus which digest food for them they could otherwise not utilize (Turner and Soar 2008). Some species of ants farm aphids—keeping them safe and milk them (Reznikova and Novgorodova 1998). Indeed, ants are an astonishing superorganism, displaying impressive feats of collective intelligence (Hölldobler and Wilson 2009).

This is in stark contrast to humans and their societies. Incredible individual accomplishments of higher cognitive functioning are manifested: self-awareness, sentience, language capability, creativity, abstract reasoning, formation and defense of beliefs, and much, much more. Remarkably, but regrettably, multiplying this amazing potential and capacity times a few billion results in our current sate of affairs. We face a formidable contradiction: as our collective knowledge grows, our collective behavior results in the unimpeded destruction of the biosphere.

However, recall the nascent emergence of distributed ledger technology as the first decentralized architecture for finance and economics (Sect. 7.4.3). Decentralization is an ideal blueprint for allowing collective intelligence to emerge. Perhaps this marks the beginning of a paradigm shift, where economic thinking (Chap. 7) becomes more inclusive, holistic, and sustainable. Indeed, free-content collaborative efforts are providing us with the unrestricted availability of constantly evolving, cutting-edge software. Peer-to-peer lending, crowdfunding, and crowd-sourcing all leverage the network effect created by a collective of like-minded people. Shareconomies are offering a radically different option to the status quo. See also Glattfelder (2016).

12.4.2 Self-organization

The universe appears to be guided by an intrinsic force, driving it to higher and higher levels of complexity (Sect. 8.1.3). Processes of self-organization (Chap. 6) have assembled one layer of reality upon the next, resulting in structure formation and information processing capabilities. From an initial singularity, defined by low entropy and seeded with quantum fluctuations, the physical forces in the universe (Sect. 4.3) carved out a cosmic landscape which, at one point, allowed the creation of organic matter. This newly unlocked level of complexity allowed information to be stored and processed on a molecular level. A couple of billion years later, these organic self-replicators had assembled one of the greatest wonders we have discovered in the universe: the human brain. Within the mind, unprecedented levels of information processing now became possible, unlocking a novel non-carbon based conception of computation, ushering in the era silicon-based digital computation.

In essence, this self-organizing force in the universe, characterized by adaptability and resilience, can be replicated using some very basic ingredients: Self-organization is driven by simple and decentralized interactions (Sect. 5.2.2). Therefore, it is not too outlandish to believe that the systems we humans create can also, one day, demonstrate traits of collective intelligence. If we manage to change the micro rules of interaction, then the resulting macro systems will change. By employing architectures and designs which are successfully implemented by nature, as mentioned above, we stand a chance of transforming our social sphere and hence could halt the destruction of the biosphere. There is no fundamental reason individual intelligence should not also foster collective intelligence.

However, even if we humans fail and eradicate all higher lifeforms on earth, the processes of self-organization is still in effect, guiding the universe, once again, to ever higher levels of information processing. Indeed, the many extinction events in the history of biological life on Earth bear testimony to this unstoppable creative power (Sect. 8.1.3).

12.4.3 Scientific Utilitarianism

While it is impossible to prove any ontology unequivocally, there exist criteria which make certain belief systems more utilitarian. By shifting the discussion away from the truth value of a theory to its actual design and function, different levels of validity can be discerned. In essence, each theory should be assigned with a utility function, defining its operation space. Some obvious criteria any knowledge system should be scrutinized by are seen in Table 12.1, where they are applied to science and creationism.

Of course, it is up to personal taste which utility criteria are desirable, but some are objectively less attractive. For instance, the dynamic aspect of scientific knowledge systems allows them to evolve and error-correct. Creationism instills a sens that the universe is static. The world we perceive today is exactly as it was 6,000–10,000 years ago, when it was created. As a consequence, the world will forever stay in this form: in a state of stasis frozen in time. This is an ironic belief when confronted with the universally dynamic nature of the universe. The forces guiding self-organization and structure formation are denied, the increase in complexity overlooked. This is a profoundly restrictive Weltanschauung. In extreme contrast, quoting the words of the cosmologist Martin Rees (Rees 2005):

> The sun has been shining for four and a half billion years, but it'll be another six billion years before its fuel runs out. On that schematic picture, a sort of time-lapse picture, we're halfway. And it'll be another six billion before that happens, and any remaining life on Earth is vaporized. There's an unthinking tendency to imagine that humans will be there, experiencing the sun's demise, but any life and intelligence that exists then will be as different from us as we are from bacteria. The unfolding of intelligence and complexity still has immensely far to go, here on Earth and probably far beyond. So we are still at the beginning of the emergence of complexity in our Earth and beyond.

Moreover, science aims at unifying the fragments of knowledge it churns up as best as it can (Chap. 4). In contrast, conspiracy theories require a vast array of ad hoc explanations for nearly every observable aspect of reality they relate to. Consider the idea of a flat Earth. The following questions then need to be explained by a multitude of different and unrelated theories, whereas science only needs one single compelling explanation: the Earth is round and rotating. For instance, puzzles like:

- Why is there day and night?
- Why do seasons exist?

Table 12.1 Some criteria by which belief or knowledge systems can be evaluated, uncovering a level of utility associated with the system

Utility criteria	Science	Creationism
Type of knowledge source	The world itself	Ancient scripture
	The human mind	
Method of knowledge generation	Experimental inquiry	Leap of faith
	Formal thought systems	
Aim of knowledge system	Knowledge generation	Prove existence of Christian God
	Manipulation of world	
Required skill-set of practitioner	Years of education/training	Blind faith
	Exposure to existing knowledge	Well-versed in the Bible
	Constantly updating knowledge	Formation of defense tactics
Is the knowledge system		
Reproducible	✓	Only to the believer
Dynamic	✓	×
Self-correcting	✓	×
Unifying	Partly	Very ad hoc
Dependent on conspiracy	×	✓
Dogmatic/authoritarian	×	✓
Constrained	See Sect. 12.4.4	✓

- Why do boats vanish at the horizon?
- Why is there ice at the "poles?"
- How did Earth's magnetic field emerge?
- Why do we feel gravity?
- Why does the atmosphere not get sucked into space?
- Why do hurricanes display spiral patterns?
- Why does draining water swirl in different directions in each "hemisphere?"
- Where does lava come from?
- What drives plate tectonics?
- Why do the stars appear to move in the night sky?
- Why do the stars move differently when viewed from the "Southern" or "Northern Hemisphere?"
- Why do we only observe spherical planets and moons?
- How do satellites, for instance enabling the GPS system and global telecommunication, stay in the sky?
- Why are there tides?

Moreover, the following pressing issues arise as well:

- Why has no one traveled to the edge of the Earth (presumably Antarctica)?
- What is on the other side of flat Earth?
- What motivates the conspiracy of international space agencies, telecommunication companies, airlines, shipping companies, meteorologists and other scientists?

Most people are baffled and at a loss of words when faced with such extreme conspiracy theories and anti-science attitudes. There is, however, one striking cognitive bias which may help explain the reasons experts continually fail with their knowledge systems and anti-science flourishes. Recall the Dunning–Kruger effect introduced in Sect. 11.3.1: the unskilled are also unaware. In detail, the study uncovered the following (Kruger and Dunning 1999, p. 1130):

> In the neurosciences, practitioners and researchers occasionally come across the curious malady of anosognosia. Caused by certain types of damage to the right side of the brain, anosognosia leaves people paralyzed on the left side of their body. But more than that, when doctors place a cup in front of such patients and ask them to pick it up with their left hand, patients not only fail to comply but also fail to understand why. When asked to explain their failure, such patients might state that they are tired, that they did not hear the doctor's instructions, or that they did not feel like responding—but never that they are suffering from paralysis. In essence, anosognosia not only causes paralysis, but also the inability to realize that one is paralyzed.
>
> In this article, we proposed a psychological analogue to anosognosia. We argued that incompetence, like anosognosia, not only causes poor performance but also the inability to recognize that one's performance is poor. Indeed, across the four studies, participants in the bottom quartile not only overestimated themselves, but thought they were above-average. [...] In a phrase, Thomas Gray was right: Ignorance is bliss—at least when it comes to assessments of one's own ability.

To add insult to injury, the researchers continued (Kruger and Dunning 1999, p. 1131):

> [W]e discovered that highly competent individuals also show some systematic bias in their self appraisals. Across the four sets of studies, participants in the top quartile tended to underestimate their ability and test performance relative to their peers.

As the study is confirmed by a growing body of research, we are sadly reminded of the words of the great mathematician and philosopher Bertrand Russell, already quoted in Sect. 8.1.1 on p. 286:

> One of the painful things about our times is that those who feel certainty are stupid, and those with any imagination and understanding are filled with doubt and indecision.

Or the words of the Nobel laureate Daniel Kahneman, quoted on p. 286:

> Paradoxically, it is easier to construct a coherent story when you know little, when there are fewer pieces to fit into the puzzle.

To conclude, while this book does contain challenging ideas relating to what we believe we know about the universe and ourselves, in no way should these be employed to invoke an anti-science stance, cultivate ignorance or justify ideology. To the contrary, if anything, the first thing this kind of skepticism and honesty should combat, are belief systems with a low scientific utility. By fostering truthful introspection we should become painfully aware of the possibility that we are all also potential victims of the Dunning–Kruger effect.

12.4.4 Radical Open-Mindedness

We have identified a key malaise of our times: most people feel great certainty about their own knowledge. Again, this affects sociopolitical, cultural, theological, philosophical, and scientific ideas. If there is any progress to be made towards reconciliation, any hope of consilience, every single human mind must ask itself: do I harbor false beliefs?

By doubting the comforting and cozy feeling of certainty, a healthy state of skepticism and open-mindedness can be cultivated. Only if we are willing to abandon certainty, we can start with a fresh slate. If we are willing to not a priori exclude any notion based on beliefs, a certain worldview, or some zeitgeist, we are free to explore new realms of ideas which now become accessible. Only by constantly challenging all that is thought to be known, we have the possibility to truly enhance our knowledge of the workings of the world.

Perhaps now is the time we urgently need new impulses and insights. Science is a shifting and fragmented structure, lacking any clear foundation and overarching or unifying context (Chap. 9). Reality itself—including time, matter, and causality—withdrew from our probing minds and revealed itself as bizarre and incomprehensible (Chap. 10). Even our own consciousness—including free will—appears to transcend any scientific description (Chap. 11). By probing the outer reaches of outlandish ideas, we maybe stand a chance to progress the understanding of the universe and ourselves which has eluded us forever.

In Table 12.1 a utility criteria was offered, assessing if knowledge systems are constrained. In other words, how much of reality can they encompass? The answer depends on who is asked. Some scientists are very open-minded, accepting the limits of science. For instance, the mathematical evolutionary biologist Martin Nowak. He is also a Roman Catholic and sees no contradiction in his religious and scientific outlook on life (quoted in Powell 2007):

> Science and religion are two essential components in the search for truth. Denying either is a barren approach.

Despite Nowak's scientific prowess and authority, such a sentence will make many scientists cringe. Other scientists are agnostic and don't see any utility in engaging in dialogues beyond their area of expertise. As an example, this sentiment can be heard in the rallying cry of quantum physicists, "Shut up and calculate," discussed in Sect. 2.2.1. Finally, at worst, scientists can sometimes appear as closed-minded and dogmatic as the proponents of anti-intellectual thought systems they so resent.

The physicist David Deutsch is perhaps the antipode of Nowak—also an eminent scientists with an impressive track record and many highly cited publications.[2] On the face of it, he seems very open-minded and aware of the limitations of knowledge. This can be inferred, for instance, from his 2011 book *The Beginning of Infinity: Explanations That Transform the World* (Deutsch 2011). On Page 396 one can read:

> [W]e can be badly mistaken in any of our ideas, even about ourselves, and even when we feel strongly that we are right.

On Page 214:

> Progress cannot take place at all unless someone is open to, and prepares for, [...] inconceivable possibilities.

Directly relating to science, Page 199 offers the following:

> Given an experimental oddity, we have no way of predicting whether it will eventually be explained merely by correcting a minor parochial assumption or by revolutionizing entire sciences. We can know that only *after* we have seen it in the light of a new explanation. In the meantime we have no other option but to see the world through our best existing explanations—which include our existing misconceptions. And that biases our imagination. Among other things, it inhibits us from conceiving significant changes.

Such a progressive attitude allows Deutsch to understand and interpret physical processes in a radically new light. In effect, he invokes the notion of an infinitely rich ontology where the perceivable and measurable universe is only the tip of the iceberg. This outlandish proposition is that we inhabit a multiverse, an assemblage of parallel universes conjured up by the many-worlds interpretation of quantum mechanics (Sect. 10.3.2.2), one of several mainstream interpretations. In the mind of Deutsch, the simple observation of the way light behaves (in the infamous double-slit experiment) irrevocably concludes the existence of the multiverse. In his own words (Deutsch 1998, p. 54):

> In interference experiments there can be places in a shadow-pattern that go dark when new openings are made in the barrier casting the shadow. This remains true even when the experiment is performed with individual particles. A chain of reasoning based on this fact rules out the possibility that the universe we see around us constitutes the whole of reality. In fact the whole of physical reality, the multiverse, contains a vast number of parallel universes.

Or, more recently (Deutsch 2011, p. 276):

> There is a way—I think it is the only way—to meet simultaneously the requirements that our fictional laws of physics be universal and deterministic, and forbid faster-than-light and inter-universe communication: *more universes*.

To the uninitiated, such grandiose claims—turning everything you believed to be true upside down—could appear as supernatural as any religious explanations of the cosmos. However, the scientific proponents would argue that this conclusion is inescapable—just like their theological opponents.

Although Deutsch understands that science does not claim infallibility but is a creative enterprise—an adaptive, dynamic, and corrective process—he still claims

[2] He is a pioneer of the field of quantum computation (Deutsch 1985, 1989; Deutsch and Jozsa 1992).

certainty. The main thesis of *The Beginning of Infinity* is that humans are "universal explainers," that is, they can access ideas that have unlimited reach, in a universe that is amenable to explanation (Deutsch 2011, p. 56):

> The ability to create and use explanatory knowledge gives *people* a power to transform nature which is ultimately not limited by parochial factors [...] but only by universal laws. This is the cosmic significance of explanatory knowledge—and hence of people, whom I shall henceforward define as entities that can create explanatory knowledge.

In a nutshell: "Human reach is essentially the same as the reach of explanatory knowledge itself" (Deutsch 2011, p. 60). As a corollary, the world cannot be inexplicable. Indeed, "[a]ny assumption that the world is *in*explicable can lead only to extremely bad explanations" (Deutsch 2011, p. 53f.). Deutsch objects to the idea that "the universe is queerer than we can suppose," a concept he attributes to the evolutionary biologists John B.S. Haldane and Richard Dawkins. Specifically (Haldane 1927, p. 298):

> Now my own suspicion is that the Universe is not only queerer than we suppose, but queerer than we *can* suppose.

Deutsch is certain that the human mind now can, or will be able to in future, access all there is to know in its waking mode of consciousness. There cannot exist something which cannot be comprehend and explained by the analytical and rational capabilities of our minds. Deutsch rejects the notion "that progress in science cannot exceed a certain limit defined by the biology of the human brain" (Deutsch 2011, p. 53).

Unsurprisingly, this certainty about the unyielding capacity of the human mind is not universally shared. In other words, some scientists and philosophers would understand Deutsch's conviction as faith or wishful thinking. Based on his reasoning he feels certain that sober waking consciousness can fathom reality. The very notion that reality—and consciousness—could be a vastly more exotic and unimaginable is excluded. Given the body of evidence presented in Part II, especially related to the neurological basis of perception and experience (Chap. 11), such an assessment appears more like "bad thinking." This is the kind of dogmatic pseudo-scientific exclusion we should avoid. Of course, Deutsch could very well be correct with all of his propositions about the universality of thought. However, using this as an argument to constrain or exclude certain ideas seems fruitless. There exists no certainty.

Furthermore, this specific view of reality and the human mind that Deutsch is offering is a static worldview. The intelligence we know today will always exist in the future. Basically we happen to have reached the pinnacle of any potential understanding. Our brain has reached a threshold allowing it to probe reality in a way that will forever generate universal explanations of the universe and ourselves. The possibility imagined by Rees is denied by this thinking. Namely, that intelligence is still unfolding, resulting in future emanations we toady cannot even imagine and most probably wouldn't even recognize. Or even the possibility that future manifestations of consciousness can access novel realms of existence.

Finally, Deutsch's understanding of reality and cognition is also limiting. There exists only one true channel to access knowledge and truth. There is only one way to scale the mountain of knowledge and gain insights. Namely, human minds generating universal explanations. However, this tempting idea becomes far less appealing, once one considers the drastically different and alternative modes of consciousness and perception which are experienceable (see Sect. 14.3). New realms of reality, previously unknown to most minds, are waiting to be explored. Realities which defy conventional conceptuality and traditional modes of thinking. Perhaps now the idea of an unfathomably vaster and richer ontology appears less unreasonable. An ontology that can only be detected and possibly grasped if our consciousness changes gears and accesses new levels of cognition transcending classical concepts of explanation, understanding, and knowledge. Maybe not only "the universe is queerer than we can suppose," but crucially also our own minds. After all, if Deutsch is willing to expand his idea of universal explanations to include evolving and transcendent concepts of knowledge generation, also all attributable to the human mind, the apparent conflict may be reconciled.

In summary, we are invited to rethink everything. There is no idea or concept that should, a priori, not be scrutinized nor any idea or concept that should be excluded. Scientific inquiry is preferably unconstrained and dynamic. Anyone claiming certainty should listen to the words of deGrasse Tyson (2002):

> One thing is for certain, the more profoundly baffled you have been in your life, the more open your mind becomes to new ideas.

Which, in turn, opens up the possibility for new discoveries. Because, as the philosopher Henri Bergson is said to have exclaimed:

> The eyes only see what the mind is prepared to comprehend.

Moreover, if we adhere to the advice of the astronomer Carl Sagan, radical open-mindedness can truly help us progress our understanding (quoted in Catling 2013):

> It pays to keep an open mind, but not so open that your brains fall out.

Conclusion

After recovering from the existential shock of Part II, and after analyzing the boundaries of knowledge and belief systems, the human mind is ready to venture on. Anti-intellectualism is expelled, as is a dogmatic and constraining scientific worldview. We are invited to reconsider all possibilities, without falling prey to our own biases and preferences. Everything needs to be critically evaluated—especially our own beliefs. The human mind appears to have reached the limits of comprehension given the current dominant materialistic and reductionistic scientific worldview. A new horizon is emerging, offering a foundation for existence. Specifically, the notions of information, consciousness, and reality are braided into a unified fabric of existence. This is the final quest awaiting us in Part III.

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Chapter 13
A Universe Built of Information

Abstract In the long journey of the human mind attempting to decode the workings of reality, one trusted companion has to be abandoned: the materialistic and reductionistic scientific worldview. What new notion should fill the void? Slowly a novel worldview is emerging, supported by different theoretical traditions. Most intriguingly, at the nexus of these formal approaches a new ontology of reality is becoming most apparent. Two novel mantras are spreading through humanity's collective mind: "Information is physical" and "Information represents the ultimate nature of reality." These surprisingly simple assertions have many deep consequences. Information theory is the wellspring of our contemporary digital world. Computation is, in essence, information processing. Then, information can be harnessed for mechanical work. Moreover, some of the pioneers of modern theoretical physics have, for a long time, suspected that information plays a fundamental role in nature. One striking consequence of this paradigm is that reality is inherently finite. Infinities can only be found in the abstract thought systems of the human mind. Essentially, there is a limit to how many bits of information can be stored in any region of space. The amalgamation of information theory, black hole thermodynamics, and string theory is hinting at a radical ontology: The universe is a hologram. In other words, our three-dimensional reality is an illusion created by the information content encoded on a two-dimensional area. Indeed, space and time appear to be emergent properties arising from pure quantum entanglement. Then, in very recent developments, string theory and theoretical computer science are conspiring to spearhead this novel probe into the heart of reality. The recalcitrant theory of quantum mechanics is reborn in a more approachable quantum-computational framework. In this novel information-theoretic context, the universe easily can be interpreted as a vast simulation.
Level of mathematical formality: intermediate.

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Paradigm shifts—or scientific revolutions[1]—happen in the dark. The established scientific wordview continues to dominate the discourse, while a pocket of resistance emerges. Within this heretical breeding ground, the current challenges threatening the orthodox view are, relentlessly and uncompromisingly, being addressed. Unbeknownst to most, a handful of brave pioneers is questioning the status quo. They believe that the, by now, glaring cracks in the current edifice of knowledge warrant not only the contemplation of radical new ideas but, crucially, the abandonment of many befriended assumptions.

Today, our understanding of the world and ourselves is challenged on three fronts. We do not understand the relationship between our own consciousness and physical reality (Chap. 11). Unexpectedly, the very nature of this reality, as far as we can probe, appears truly outlandish and bizarre (Chap. 10). Even the nature of physical laws and knowledge seems elusive (Chap. 9). Overall, existence itself—including the uniquely improbable cosmic evolution leading to this very moment in time—is unfathomable (Chap. 8). We are lacking a foundational understanding of the world. In essence, the current materialistic and reductionistic scientific worldview appears to have reached its limits. After all the amazing success in decoding the workings of the world (Chaps. 2–7), giving us the gift of technology, sadly, this edifice of knowledge now seems outdated and ineffective. However, what should replace the void once we retire this current sketch of existence? The answer is: information.

Information is an elusive concept. However, it can be formalized or mathematized. Indeed, information is the very notion that unlocked the latest, and most dramatic, technological surge: the emergence of information processing capabilities. Indeed (Floridi 2014, p. 4):

> The information society has been brought about by the fastest growing technology in history. No previous generation has ever been exposed to such an extraordinary acceleration of technological power over reality, with the corresponding social changes and ethical responsibilities. [...] The computer presents itself as a culturally defining technology and has become a symbol of the new millennium, playing a cultural role far more influential than that of mills in the Middle Ages, mechanical clocks in the seventeenth century, and the loom or the steam engine in the age of the Industrial Revolution.

Moreover, information is the unifying thread connecting aspects of classical physics (Sect. 2.1), complexity theory (Chap. 6), quantum mechanics (Sects. 4.3.4 and 10.3.2), cosmology (Sects. 4.1 and 10.1.2), string/M-theory (Sects. 4.3.2 and 10.2.2), and loop quantum gravity (Sect. 10.2.3). Slowly, a computational and information-theoretic approach to reality is emerging. Specifically, information is a prime candidate for the foundations of the world. Indeed (Davies 2014, p. 95):

> [A]n alternative view is gaining in popularity: a view in which *information* is regarded as the primary entity from which physical reality is built. It is popular among scientists and mathematicians who work on the foundations of computing, and physicists who work in the theory of quantum computing.

The eminent physicist John Wheeler was one of the first human minds to realize this.

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[1] See Sect. 9.1.3.

13.1 The Many Faces of Information

An interesting dichotomy emerged. At the same time as the notion of matter started to disintegrate and dematerialize (Sect. 10.4.1 and Davies and Gregersen 2014), the intangible concept of information became robust. Both developments were unexpected.

13.1.1 *The Philosophy of Information*

The philosopher Luciano Floridi has laid out a philosophy of information (Floridi 2010, 2014). This overlap is seen as very fruitful (Floridi 2014, p. 16):

> PI [the philosophy of information] possesses one of the most powerful conceptual vocabularies ever devised in philosophy.

Philosophy is now understood as "conceptual engineering." Notwithstanding (Floridi 2014, p. 30):

> What is information? This is the hardest and most central problem in PI and this book could be read as a long answer to it. Information is still an elusive concept. This is a scandal not by itself, but because so much basic theoretical work relies on a clear analysis and explanation of information and of its cognate concepts.

The problem is that (Floridi 2010, p. 1):

> Information is notorious in coming in many forms and having many meanings. It can be associated with several explanations, depending on the perspective adopted and the requirements and desiderata one has in mind.

A general definition of information is the following:

Definition 13.1 σ is an instance of information, understood as semantic content, if and only if:

1. σ consists of n data, for $n \geq 1$;
2. the data are well formed;
3. the well-formed data are meaningful.

See Floridi (2010). Some of the approaches trying to capture the enigma of information are related to probability spaces (Bar-Hillel and Carnap 1953), algorithmic information theory (Chaitin 2003), and data spaces (Floridi 2014). The constructor theory of information (Deutsch and Marletto 2015) aims at "a physical theory of the *regularities in the laws of physics* required for there to exist what has been vaguely referred to as 'information'" (Durham and Rickles 2017, p. 104). However, the most successful approach is known as information theory.

13.1.2 The Computability of Information

In 1948, the engineer and mathematician Claude Shannon published a seminal paper (Shannon 1948). Information theory was born (Guizzo 2003):

> In that paper, Shannon defined what the once fuzzy concept of "information" meant for communication engineers and proposed a precise way to quantify it—in his theory, the fundamental unit of information is the bit. He also showed how data could be "compressed" before transmission and how virtually error-free communication could be achieved. The concepts Shannon developed in his paper are at the heart of today's digital information technology. CDs, DVDs, cell phones, fax machines, modems, computer networks, hard drives, memory chips, encryption schemes, MP3 music, optical communication, high-definition television—all these things embody many of Shannon's ideas and others inspired by him.

It is, however, worth noting that (Davies and Gregersen 2014, p. 5):

> When the foundation of information theory was laid down by Shannon, he purposely left out of the account any reference to what the information means, and dwelt solely on the transmission aspects.

Notwithstanding, Shannon reduced the notion of information to a pragmatic and tangible entity by providing an operational definition. He took the binary digit, $d \in \{0, 1\}$, to be the fundamental unit in information theory. Now, the information content of any kind of message can be encoded using binary digits—called bits. This subtle and unremarkable shift in perspective had huge ramifications.

For one, information theory utilizes discrete mathematic. The unbridgeable infinity of real numbers between 0 and 1 is overcome by postulating two binary states. In essence, information is quantized, similarly to the idea Max Planck invoked at the genesis of quantum physics (Sect. 4.3.4). A new formal model emerged (Hromkovič 2010) from discrete mathematics (Steger 2001; Biggs 2003), rivaling the success of its infinite cousin, called continuous mathematics. Recall the tension and unity of these two mathematical branches recounted in Sect. 5.3.

The discrete binary system of data encoding has advantages over its analogue counterpart, characterized by the continuous and smooth. Bits represent the common ground where semantics, logic, and the physical can converge. This follows from the many possibilities of physically representing the true-false logic of Boolean algebra (Boole 1854) as transistors, switches, circuits, tapes, and CDs. As a result (Floridi 2010, p. 29):

> [I]t is possible to construct machines that can recognize bits physically, behave logically on the basis of such recognition, and therefore manipulate data in a way we find meaningful.

However, the most powerful aspect of digital computation is the possibility of error-correction (Deutsch 2011, p. 140):

> Without error-correction all information processing, and hence n knowledge-creation, is necessarily bounded.

Perhaps the most fruitful concept emerging from this novel digital, computational, and informational paradigm is universality. This notion goes back to Alan

Turing and his infamous Turning machine, laying the benchmark for universality, or Turing completeness. A universal computer can perform any possible mathematical manipulation (Turing 1936; Church 1936; Turing 1938). In other words, computers can access any level of mathematical complexity without the need of being complex themselves. Essentially (Seife 2007, p. 18):

> This means that you can, in theory, do the most complicated algorithms, the most intricate computerized tasks, if you are able to read, write, or erase a mark on a tape and move the tape around.

Just as complexity emerges from elegant simplicity (Sect. 5.2.2), so too, is the computability of reality encoded in simple rules. Moreover, universal computers can simulate each other efficiently. As a result, the messy details of any particular instantiation of a computer can be disregarded. Even Turing's cumbersome but smallest possible skeleton of computation suffices to unlock the magic of universal information processing. Today, the work of Turing has been extended to the Church–Turing–Deutsch principle: A universal computing device can simulate every physical process (Deutsch 1985).

Intriguingly, the computational structure emerging from bits of information mirrors the inherent paradoxes found in mathematics. Recall how Kurt Gödel single-handedly brought mathematics to its knees with his incompleteness theorems (Sect. 2.2). Turing's halting problem (Sect. 9.4.1) goes a step further by defining the general concept of a formal system (Gleick 2011, p. 212):

> Any mechanical procedure for generating formulas is essentially a Turning machine. *Any* formal system, therefore, must have undecidable propositions. Mathematics is not decidable. Incompleteness follows from uncomputability.

Finally, Gregory Chaitin uncovered the inherent randomness in mathematics by introducing uncomputable numbers and extending the legacy yet again (Sect. 9.4.1). Unfortunately, Turing's own life ended tragically (Seife 2007, p. 20):

> Sadly, Turing himself would not play a major role in the newborn science of information theory. In 1952, Turing, a homosexual, pleaded guilty to charges of "gross indecency" for his dalliance with a nineteen-year-old boy. To avoid imprisonment, he consented to undergo "treatment"—a set of hormone injections that were supposed to end his sexual proclivities. They didn't, and his "moral turpitude" was a stain that he never recovered from. Two years later, the tortured Turing apparently killed himself with cyanide.

13.1.3 Information is Physical

Up to now, the notion of information has remained intangible. Even if we encode data as bits, the content, representation, and ontology of information appear separate. How then, can information be physical? In other words, what link establishes the relationship between the ethereal nature of information and its physicality?

The first hint was given by Shannon himself. He reinterpreted the notion of entropy, found in thermodynamics, in an information-theoretic context. Thermodynamics—pioneered by Rudolf Clausius, William Thomson Kelvin, James Clerk Maxwell, Ludwig Boltzmann, and Josiah Willard Gibbs—offers two laws:

Theorem 13.1 *It holds that:*

1. *The energy of the universe is constant.*
2. *The entropy of the universe always increases.*

See Huang (1987). The notion of entropy was forced upon physicists, as thermodynamics required a novel measure which somehow corresponded to the unavailability of energy. This entropy turned out to be just as measurable as temperature, volume, or pressure. In statistical mechanics, it represents the measure of uncertainty about the state of a physical system. More loosely, it is an expression of the disorder, or randomness of a system.

Shannon reinterpreted physical entropy as a measure of the uncertainty about a message—the lack of information about it. Specifically, given all the possible messages a communication source can produce, how probable is a specific message? The answer is given by recasting the equation defining physical entropy:

$$H(X) = -\sum_{i=1}^{n} \mathrm{P}(X_i) \ln\left(\mathrm{P}(X_i)\right), \tag{13.1}$$

where P is a probability mass function[2] and X is a discrete random variable with possible values $X_1, \ldots, X_n$ (Shannon 1948). This is a remarkable insight: physical and informational entropy share the same mathematical expression. Interestingly, such a link had already been discovered earlier. However, it was published in a German journal of physics. There, it was established that each unit of information brings a corresponding increase in entropy of $kT \ln 2$ units, where k is Boltzmann's constant and T the environment's temperature (Szilárd 1929).

The final step in unmasking information as physical, tying all the strings together, was done by Rolf Landauer at IBM, while in exile from Nazi Germany. In essence (Landauer 1996):

> Information is not a disembodied abstract entity; it is always tied to a physical representation. It is represented by engraving on a stone tablet, a spin, a charge, a hole in a punched card, a mark on paper, or some other equivalent. This ties the handling of information to all the possibilities and restrictions of our real physical word, its laws of physics and its storehouse of available parts.

Landauer made the relationship of $kT \ln 2$ per bit exact. For reversible computations the entropy does not increase, i.e., no heat is dissipated. In other words, processing information by flipping bits from zero to one and vice versa conserves information and entropy. In contrast, Landauer's principle states that only the erasure of information—an irreversible operation—increases entropy (Landauer 1961, 1996). Information is physical: by deleting its physical manifestation as strings of bits, the universe reacts. Experiments have confirmed the validity of this principle (Bérut et al. 2012; Jun et al. 2014; Hong et al. 2016). In essence, the process of erasing a bit in one place transfers information to another place, in the form of heat. In other words:

[2] The discrete version of the probability density function, see Sect. 6.4.3.2.

> Information cannot be destroyed.

Recently, physicists have been able to build a contraption which converts information into mechanical work (Paneru et al. 2018). The engine exceeds the conventional bound of the second law of (nonequilibrium) thermodynamics and, for the first time, achieves a bound set by a generalized second law of thermodynamics.

In his famous paper called *Information is Physical*, Landauer outlines the implications of information's physical properties for the nature of physical laws (Landauer et al. 1991). He also reminds us of the great physicists Wheeler.

13.2 It from Bit

John Archibald Wheeler was one of the pioneers helping develop general relativity (Misner et al. 1973). He coined the words "black hole" (Thorne 1995, p. 536) and "wormhole" (Misner and Wheeler 1957). Moreover, he was also involved in quantum mechanics, coining the term "quantum foam" (Thorne 1995, p. 536, also related to Sect. 10.1). He worked with Niels Bohr on nuclear fission (Bohr and Wheeler 1939). His interests included the interpretation of quantum mechanics (Wheeler and Zurek 1983). He also devised the infamous delayed choice experiment, a quantum enigma where a choice now appears to alter the past (Sect. 10.3.2.2). Wheeler contributed to the first attempt in devising a theory of quantum gravity, in the form of the Wheeler–DeWitt equation (Sect. 10.2.1). Finally, he was also involved in the study of quantum information. Notably, two of his former Ph.D. students discovered the important no-cloning theorem (Wootters and Zurek 1982), establishing quantum encryption technology (Sect. 10.3.2.1). However, perhaps his most insightful work will turn out to be related to the nature of information (and consciousness, as discussed in the next chapter), igniting a potential paradigm shift (Gleick 2011, p. 9f.):

> Increasingly, the physicists and the information theorists are one and the same. The bit is a fundamental particle of a different sort: not just tiny but abstract—a binary digit, a flip-flop, a yes-or-no. It is insubstantial, yet as scientists finally come to understand information, they wonder whether it may be primary: more fundamental than matter itself. They suggest that the bit is the irreducible kernel and that information forms the very core of existence. Bridging the physics of the twentieth and twenty-first centuries, John Archibald Wheeler, the last surviving collaborator of both Einstein and Bohr, put this manifesto in oracular monosyllables: "It from Bit." Information gives rise to "every it—every particle, every field of force, even the spacetime continuum itself." This is another way of fathoming the paradox of the observer: that the outcome of an experiment is affected, or even determined, when it is observed. Not only is the observer observing, she is asking questions and making statements that must ultimately be expressed in discrete bits. "What we call reality," Wheeler wrote coyly, "arises in the last analysis from the posing of yes-no questions." He added: "All things physical are information-theoretic in origin, and this is a participatory universe." The whole universe is thus seen as a computer—a cosmic information-processing machine.

Wheeler offered a monumental shift in understanding the nature of reality. Quantum mechanics, and thus reality, is about information. Reality is quantized because information is quantized. "The bit is the ultimate unsplittable particle" (Gleick 2011, p. 357). If reality is built upon and utilizes the abstract notion of information, no wonder the quest to find a tangible foundation for it fails (Sect. 10.4.1). Moreover, consciousness is intrinsically woven into the informational fabric of existence. The notion that the world exists "out there" independent of the mind is a view which is abandoned.

Wheeler proposed these unconventional views in an influential article called *Information, Physics, Quantum: The Search for Links* (Wheeler 1990). There, he sets out to depose of some core concepts of the prevailing scientific worldview:

> (1) The world cannot be a giant machine, ruled by any preestablished continuum physical law.
> (2) There is no such thing at the microscopic level as space or time or spacetime continuum.

The laws of nature are emergent and became manifested at the Big Bang; reality is a finite structure. In his own words (Wheeler 1990):

> It from bit. Otherwise put, every it—every particle, every field of force, even the spacetime continuum itself—derives its function, its meaning, its very existence entirely—even if in some contexts indirectly—from the apparatuselicited answers to yes or no questions, binary choices, bits. It from bit symbolizes the idea that every item of the physical world has at bottom—at a very deep bottom, in most instances—an immaterial source and explanation; that what we call reality arises in the last analysis from the posing of yes-no questions and the registering of equipment-evoked responses; in short, that all things physical are information-theoretic in origin and this is a participatory universe.

Reality is animated by information; subjective consciousness is intimately intertwined with objective reality. Wheeler offers five clues supporting his idea:

1. A topological argument: The boundary of a boundary is zero.
2. Without question, no answers exist.
3. The super-Copernican principle rejecting "nowcenteredness."
4. Consciousness.
5. Complexity.

He also discusses the Bekenstein bound, introduced below. The notion of consciousness is picked up in the next chapter. Regarding complexity and information processing, in the words of the quantum mechanical engineer Seth Lloyd (Lloyd 2014, p. 125f.):

> Everywhere you look, you see immense variation and complexity. Why? How did the universe get this way? We know from astronomical observation that the initial state of the universe, fourteen billion years ago, was extremely flat, regular, and simple. Similarly, the laws of physics are simple: the known laws of physics could fit on the back of a T-shirt. Simple laws, simple initial state. So where did all of this complexity come from? The laws of physics are silent on this subject.
>
> By contrast, the computational theory of the universe has a simple and direct explanation for how and why the universe became complex. The history of the universe in terms of information-processing revolutions, each arising naturally from the previous one, already hints at why a computing universe necessarily gives rise to complexity. In fact, we can prove

> mathematically that a universe that computes must, with high probability, give rise to a stream of ever-more-complex structures.

In a nutshell (Lloyd 2006, p. 3):

> The computational capability of the universe explains one of the great mysteries of nature: how complex systems such as living creatures can arise from fundamentally simple physical laws.

In this context, recall Chap. 6. For details on complexity and information, see Haken (2006).

Today, some of the proponents of "it from bit" come from the field of quantum information and computation (Aspelmeyer et al. 2003; Nielsen and Chuang 2007). These are the practitioners grappling with the notion of information at the quantum level of reality. For instance, Anton Zeilinger who has realized many important quantum information protocols (Bouwmeester and Zeilinger 1997; Poppe et al. 2004) next to his work on the foundations of quantum mechanics (Nairz et al. 2003; Gröblacher et al. 2007; Giustina et al. 2013; Ma et al. 2012). He describes his views on information and quantum mechanics in the book *Dance of the Photons: From Einstein to Quantum Teleportation* (Zeilinger 2010). There we can read on Page 267:

> Information has a significant role in quantum physics, and that role seems to go beyond the role it plays in physics.
>
> [...]
>
> We can now make a very important observation. This is the observation that the concepts *reality* and *information* cannot be separated from each other.

However, he admits (quoted in Brockman 2006, p. 223):

> What I believe but cannot prove is that quantum physics requires us to abandon the distinction between information and reality.

Zeilinger is convinced (quoted in Brockman 2006, p. 224):

> Once you adopt the notion that reality and information are the same, all quantum paradoxes and puzzles—like the measurement problem [...]—disappear.

Then, Lloyd analyzes the computational properties and capacities of reality itself. In other words, do physical systems compute? Specifically, his career focuses on quantum computation (Lloyd 2006, p. 53):

> A few years ago, acting on a suggestion from the physicist Richard Feynman, I showed that quantum computers can simulate any system that obeys the known laws of physics (and even those that obey as yet undiscovered laws!) in a straightforward and efficient way.

See Lloyd (1996). All interactions of elementary particles in the universe not only convey energy but crucially also information. In this sense the entire universe is computing reality. In his words (quoted in Wired Magazine 2006):

> Atoms and electrons are bits. Atomic collisions are "ops" [logical operations per second]. Machine language is the laws of physics. The universe is a quantum computer.

In detail (Lloyd 2014, p. 125):

> [N]ot only does the universe register and process information at its most fundamental level, as was discovered in the nineteenth century, it is literally a computer: a system that can be programmed to perform arbitrary digital computations.

Moreover (Lloyd 2002):

> Merely by existing, all physical systems register information. And by evolving dynamically in time, they transform and process that information. The laws of physics determine the amount of information that a physical system can register (number of bits) and the number of elementary logic operations that a system can perform (number of ops).

Lloyd analyzed the physical limits of computation by asking what a physical system with a mass of one kilogram confined to a volume of one liter—the ultimate laptop—can compute. The answer is 10^{51} operations per second on 10^{31} bits, compared to today's laptops performing 10^{10} operations per second on 10^{10} bits (Lloyd 2000). The universe is also a physical system. Lloyd placed an upper limit on its computational capacities: no more than 10^{120} operations per second on 10^{90} bits can have been performed (Lloyd 2002). For Lloyd it is very clear (Wired Magazine 2006):

> [E]verything in the universe is made of bits. Not chunks of stuff, but chunks of information—ones and zeros.

Physical systems interact in a language consisting of information, where the syntax yields the laws of physics.

13.2.1 It from Qubit

A classical bit is in either one of two states—0 or 1. On the physical realization of this information, a digital computer performs its computations. Bestowing classical bits with the powers of the quantum realm unlocks a new level of computation. One key property of quantum systems is that they exist in a state of superposition until a measurement is made. For instance, an electron can have a spin "pointing" up or down (Sect. 3.2.2.1) or a photon can have a horizontal or vertical polarization. Let $|\uparrow\rangle$ and $|\downarrow\rangle$ denote the spin-up and spin-down states of an electron in bra-ket notation (Sect. 3.1.4), respectively. In general, electrons exist in a state of superposition

$$|\psi\rangle = a|\uparrow\rangle + b|\downarrow\rangle, \tag{13.2}$$

where $|\psi\rangle$ is related to the wave function, a and b are complex numbers with $|a|^2 + |b|^2 = 1$. In a sense, the electron is simultaneously comprised of the two opposite states. By encoding a classical bit using a quantum system, the binary digital information is augmented by a superposition of 0 and 1. A qubit is born (Schumacher 1995). In general (Grover 2001):

> Just as classical computing systems are synthesized out of two-state systems called bits, quantum computing systems are synthesized out of two-state systems called qubits. The

> difference is that a bit can be in only one of the two states at a time, on the other hand a qubit can be in both states at the same time.

A qubit, represented by the state $|\psi\rangle$, is a linear combination of the states corresponding to 0 and 1

$$|\psi\rangle = a|0\rangle + b|1\rangle. \tag{13.3}$$

A classical bit can be examined to determine whether it is in the state 0 or 1. Remarkably, for a qubit one cannot find its quantum state. In other words, there is no way of discovering the values of a and b. However, by measuring a qubit, it is either 0 with a probability $|a|^2$ or 1 with a probability $|b|^2$. Consequently, new ways of processing information emerge (Nielsen and Chuang 2007).

Next to superposition, quantum computers employ other quantum-mechanical phenomena, such as entanglement (Brown 2000). Stated loosely, this gives them more power, as they utilize a novel computational layer of reality. Consider a classical 2-bit system, where there are $2^2 = 4$ possible states: (00), (01), (10), (11). Now, the corresponding 2-qubit system is described by $|\psi\rangle = a_1|00\rangle + a_2|01\rangle + a_3|10\rangle + \rangle + a_4|11\rangle$, where the a_i are the complex coefficients obeying $\sum_i |a_i|^2 = 1$. In other words, the 2-qubit quantum system, corresponding to two classical bits, can utilize four bits of information in its computation. In general, n qubits are associated with 2^n classical bits. It appears as if the quantum world can harness more computational power. However, there is a catch, as one has to distinguish between the quantum states and the actual information which is accessible. Indeed, to describe the state of n qubits requires 2^n classical bits. Unfortunately, there is no way in which 2^n classical bits can be stored using n qubits and then reliably read out later (Holevo 1973).

It is sometimes stated that quantum computers can effectively solve problems that would take conventional computers longer than the age of the universe to solve. The power of superposition allows the creation of an immense number of parallel computational branches. However, this is, unfortunately only applicable to some very specific problems. In the words of the computer scientists Scott Aaronson (quoted in Horgan 2016):

> In particular, if an event can happen one way with a positive amplitude,[3] and another way with a negative amplitude, those two amplitudes can "interfere destructively" and cancel each other out, so that the event never happens at all. The goal, in quantum computing, is always to choreograph things so that for each wrong answer, some of the paths leading there have positive amplitudes and others have negative amplitudes, so they cancel each other out, while the paths leading to the right answer reinforce.
>
> It's only for certain special problems that we know how to do that. Those problems include a few with spectacular applications to cryptography, like factoring large numbers, as well as the immensely useful problem of simulating quantum mechanics itself.

Specifically, Grover's algorithm is a quantum search algorithm utilizing the principle of superposition and entanglement (Grover 1996). The quantum speed gain is

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[3]Probability amplitudes are at the core of the formalism of quantum mechanics. By squaring them, the actual probability is derived. See Sect. 3.1.4.

impressive. A classical search algorithm's performance will grow linearly and in direct proportion to the size N of the input data set. Grover's algorithm grows with $\sqrt{N}$. Then, Shor's algorithm, represents another milestone in quantum computing (Shor 1999). Given an integer N, the algorithm finds all its prime factors. Theoretically, any encryption key can be broken by a quantum computer of comparable size in reasonable time.[4] In comparison, a classical computer requires eons to crack 256-bit encryption. At the time of writing, the Oak Ridge National Laboratory's *Summit* supercomputing machine[5] is the fastest computer, running at 200 petaflops or 10^{15} floating-point operations per second. A petaflop is approximately also 2^{50} operations. Note that there are $31,536,000 = 365 \cdot 24 \cdot 60 \cdot 60\,\mathrm{s}$ in a year. To explore all the 2^{256} combinations related to the encryption, *Summit* requires the following number of years

$$\frac{2^{256}}{200 \cdot 2^{50} \cdot 365 \cdot 24 \cdot 60 \cdot 60} \approx 1.6 \cdot 10^{52}. \tag{13.4}$$

Recall that the age of the universe is $13.8 \cdot 10^{10}$ years. In effect, quantum computers could render all of today's cryptography useless (Sect. 7.4.3). However, quantum computing is still in its infancy and in 2014, the number 56,153 was quantum factorized into 241 and 233 using 4 qubits (Dattani and Bryans 2014). In 2015, basic quantum computation was achieved with silicon (Veldhorst et al. 2015).

Essentially, quantum mechanics makes statements about information. Heisenberg's uncertainty principle is simply a limit to universal information retrieval (Sect. 10.1). Measurements result in the fragile fuzziness of superpositions becoming manifested as a single state—the apparent wave function collapse—and are essentially information transfers. Depending on how we "interrogate" an electron, it behaves as a wave or a particle. Indeed, all answers to the fundamental questioning of reality are always binary. Entanglement (Sect. 10.3.2.1) fuses quantum systems into a single information entity—it encodes information. This new system appears to be unconstrained by space and time but very much obeying the rules of quantum information (Jaeger 2009). In essence, space and time become impotent or non-existent at the fundamental level of reality—all that remains is information-theoretic. Furthermore, (Wootters 2007, p. 229):

> [It is] remarkable that, even though entanglement by itself does not constitute a communication channel, the presence of entanglement allows modes of communication that are not possible without it.

Consequently, "it from qubit" appears to be the exact mantra (Deutsch 2004; Vedral 2012; D'Ariano 2015). Although (Jaeger 2009, p. 189):

> A central question when considering information in relation to the foundations of quantum mechanics is whether quantum information and classical information differ, and if so, how fundamental their differences are.

Some see quantum information as fundamental (Deutsch 2004, p. 93):

[4]Technically, in polynomial time.

[5]See https://www.ornl.gov/news/ornl-launches-summit-supercomputer.

> Although […] the classical information storage capacity of a qubit is exactly one bit, there is no elementary entity in nature corresponding to a bit. It is qubits that occur in nature. Bits, Boolean variables, and classical computation are all emergent or approximate properties of qubits [...].

In any case (Jaeger 2009, p. 256):

> Given that quantum theory involves probability, state preparation and state measurement, which are essential elements of signaling, and that communication is based on the establishment of correlations using these, it is clear that information theory will remain of considerable relevance to the investigation of the foundations of quantum physics. […] the perspective provided by the recent focus on information has contributed to what is the most detailed picture yet of the broader implications of quantum theory.

Moreover (Brukner and Zeilinger 2006, p. 47):

> There are at least three different ways in which quantum physics is connected with the concept of information. One is the relationship between quantum interference and knowledge. This was at the very heart of the early debates concerning the meaning of quantum mechanics, most notably the Bohr-Einstein dialogue. […] The debate was resolved by the Copenhagen interpretation in the most radical, conceptually challenging and foresightful manner, although for many physicists today, the Copenhagen interpretation is still conceptually unacceptable. The second connection between quantum physics and information was the discovery in the early 1990s that quantum concepts could be used for communication and for processing information in completely novel ways. These include such topics as quantum cryptography, quantum teleportation and quantum computation. The third connection between quantum physics and information has been emerging gradually over the last few years with the conceptual groundwork for this connection going back to the works of von Weizsaecker and Wheeler. It is the notion that information is the basic concept of quantum physics itself. That is, quantum physics is only indirectly a science of reality but more immediately a science of knowledge.

Yet another proposition utilizing quantum information as a unifying theme is (Pawłowski et al. 2009):

> We suggest that information causality—a generalization of the no-signalling condition [i.r., information cannot be transmitted faster than light]—might be one of the foundational properties of nature.

13.2.2 The Ur-Alternatives

While Wheeler was instrumental in popularizing the notion of an information-theoretic reality, he was not the first to think along these lines. Probably the first person to do so was the mathematician, philosopher, inventor, and mechanical engineer, Charles Babbage (Gleick 2011). His interests included the manipulation of information: messaging, encoding, and processing. In 1642, Blaise Pascal, a mathematician, physicist, and inventor, had constructed an adding machine. Three decades later, Gottfried Wilhelm Leibniz, the co-creator of calculus and an influential philosopher (Sect. 8.1.2), improved on the design. However, Babbage realized that these prototypes were all very similar to an abacus and not automatic. In 1822, he presented a working model of an automatic mechanical calculator, called the *Difference Machine*, to the Royal Society. His next project was the *Analytical Engine*, the first mechanical general-purpose computer, he described in 1837. In principle, this contraption was Turing-complete—igniting the age of computation. The mathematician Ada Lovelace was initially Babbage's acolyte before becoming his muse. She was the first person to realize that the *Analytical Engine* was more than a calculator. "It had been an engine of numbers; now it became an engine of information" (Gleick 2011, p. 116). Lovelace devised an algorithm for the engine, emerging as the first computer programmer in history. Babbage himself "took an information-theoretic view of the new physics" (Gleick 2011, p. 375) that was emerging. Newtonian mechanics (Sect. 2.1.1) imposed the notion of a clockwork universe. In contrast, to Babbage, "nature suddenly resembled a vast calculating engine, a grand version of his own deterministic machine" (Gleick 2011, p. 376).

Carl Friedrich von Weizsäcker was an eminent and distinguished physicist and philosopher. He played an important role in the developments of 20th century physics, in particular related to astrophysics and nuclear physics. Other contributions he made centered around the understanding of the nature of reality and time, and the interpretation of quantum mechanics. The occasion of his 90th birthday in 2002 prompted the compilation of essays—a homage to his work—by renowned physicists. The book is aptly titled *Time, Quantum and Information* (Castell and Ischenbeck 2003). One chapter is also contributed by Zeilinger.

Von Weizsäcker was the first person to think about a quantum theory of information (Castell and Ischenbeck 2003, VI):

> Weizsäcker called the elementary unit of information in quantum theory an *ur*. As an all encompassing theory of physics, quantum theory should contain the possible fundamental forms of matter, elementary particles, and their interactions. It should thus permit the construction of particles and interactions from quantized bits of information. This hypothesis is called the *ur-hypothesis*, which was developed during the 1970s at the *Max Planck Institut zur Erforschung der Lebensbedingungen der wissenschaftlich-technischen Welt* in Starnberg.

He introduced the novel concept of the most basic informational entity of reality in 1971 (von Weizsäcker 1971), 19 years before Wheeler's"it from bit" (Wheeler 1990). Indeed, von Weizsäcker first started to conceive of these ideas in the 1950s (von Weizsäcker 1952, 1955, 1958). Utilizing the notion of an information-theoretic foundation of reality, he set out to axiomatically construct a unified quantum theory (von Weizsäcker 1975, 1985; Lyre 1995, 1998). At the Big Bang, the universe began with one ur—one bit of information. Today, the information content is 10^{120} urs. From this result, the estimated 10^{80} nucleons in the universe can be derived. Moreover, ur theory was shown to be connected with the Bekenstein-Hawking entropy seen below (Görnitz 1988).

Unfortunately, von Weizsäcker's information-based ideas never enticed a larger audience. Notably, in Anglo-Saxon countries his contributions remain overlooked. In modern monographs discussing the fundamental nature of information, von Weizsäcker is not mentioned at all or only in a different context (Jaeger 2009; Davies and Gregersen 2014; Aguirre et al. 2015; Durham and Rickles 2017). Moreover, popular accounts, chronicling the (quantum) information-theoretic revolution, omit his legacy as well (Siegfried 2000; Seife 2007; Gleick 2011; Vedral 2012). In contrast, Wheeler is prominently featured. In retrospect, they both helped establish what is today known as digital physics.

13.3 Digital Physics

Digital physics, and by extension, digital philosophy, is a movement of contemporary scientists who believe in the fundamental nature of information. By taking the notion of digital information seriously, a new worldview emerges. For one, the universe is a giant information-processing machine—a digital computer. Then, reality is a finite structure and infinities are only harbored in the abstract realm the human mind can access (recall Fig. 2.1 in Sect. 2.1). In essence, everything in the universe is quantized or grainy—including space and time. Mathematically speaking, we are dealing with discrete entities and not continuous ones (Sect. 5.3).

The physicist and computer scientist Edward Fredkin is a pioneer of this approach. He invented the computational circuit called the Fredkin gate (Fredkin and Toffoli 1982). It is suitable for reversible computing and is universal, meaning that any arithmetic operation can be constructed entirely of such gates. Moreover, it is also relevant for quantum computing (Patel et al. 2016). Early work on digital physics can be found in Fredkin (1992). Other proponents of this idea also include the mathematician Chaitin (Sect. 9.4.1). He traces the genesis of the philosophy back to Leibniz, the discoverer of base-two arithmetic (Chaitin 2005). The first person to claim that the universe is a digital computer was the IT pioneer Konrad Zuse. Specifically, he proposed that the cosmos is being computed by some kind of computational systems, for instance, by cellular automata (Sect. 5.2.2). This idea was outlined in his 1969 book called *Rechnender Raum* (Zuse 1969)—the calculating space. The physicist, computer scientist, and entrepreneur Stephen Wolfram (Sect. 5.2.2) proposed the idea that the universe, and all its inherent complexity, is built from simple programs. The computational systems he invokes are also cellular automata. He outlines this idea in the 2002 book, called *A New Kind of Science*, comprising one-thousand-two-hundred pages (Wolfram 2002). Furthermore, Lloyd, another digital physics proponent, proposes a theory of quantum gravity based on quantum computation (Lloyd 2005). The Nobel laureate Gerard 't Hooft entertains the notion that quantum gravity is linked to (the dissipation of) information ('t Hooft 1999). Moreover, he has proposed a cellular automaton interpretation of quantum mechanics ('t Hooft 2016). In 2010, the Foundational Questions Institute,[6] or FQXi, held its third essay contest. It was co-sponsored by *Scientific American*.[7] The question posed was "Is Reality

[6]See https://fqxi.org/.

[7]See https://blogs.scientificamerican.com/observations/is-reality-digital-or-analog-read-the-essays-and-cast-your-vote/.

Digital or Analog?" and the various essays attacked the problem form a multitude of angles.[8] In 2013, the 856-page book, called *A Computable Universe: Understanding and Exploring Nature as Computation*, was published. It contains contributions from many scientists, including Fredkin, Chaitin, Wolfram, and Lloyd (Zenil 2013).

In a nutshell, digital physics, or synonymously, digital philosophy, can be summarized as follows, taken from Fredkin's webpage[9] devoted to the subject:

> Digital Philosophy (DP) is a new way of thinking about the fundamental workings of processes in nature. DP is an atomic theory carried to a logical extreme where all quantities in nature are finite and discrete. This means that, theoretically, any quantity can be represented exactly by an integer. Further, DP implies that nature harbors no infinities, infinitesimals, continuities, or locally determined random variables.

An introductory text is Fredkin (2003). Four laws of digital physics are laid out:

1. Information is conserved.
2. The fundamental process of nature must be a computation-universal process.
3. The state of any physical system must have a digital representation.
4. The only kind of change is that caused by a digital informational process.

In the novel paradigm of a finite nature of reality, physics appears in a new light. For instance, "five big questions with pretty simple answers" are (Fredkin 2004):

1. What is the origin of spin?
2. Why are there symmetries and CPT (charge conjugation, parity, and time reversal)?
3. What is the origin of length?
4. What does a process model of motion tell us?
5. Can the finite nature assumption account for the efficacy of quantum mechanics?

Indeed, there may exist experimental predictions of digital physics (Fredkin 2004):

> Digital mechanics [digital physics implies this discrete process called digital mechanics which must be a substrate for quantum mechanics] predicts that for every continuous symmetry of physics there will be some microscopic process that violates that symmetry. We are, therefore, able to suggest experimental tests of the finite nature hypothesis. Finally, we explain why experimental evidence for such violations might be elusive and hard to recognize.

Recall that the notion of symmetry was the common thread in Chaps. 4 and 3, from which much of theoretical physics emerged.

13.3.1 The Illusion of the Infinite

Carlo Rovelli, one of the founders of loop quantum gravity, recently paraphrased a saying of Karl Popper (Chap. 9 and Sect. 8.1.1), an influential philosopher of science (Rovelli 2017, p. 208):

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[8] See https://fqxi.org/community/essay/winners/2011.1.

[9] See http://www.digitalphilosophy.org/.

> The only truly infinite thing is our ignorance.

Today, most people believe that the universe is spatially infinite. However, we can ever only see the observable universe (Halpern and Tomasello 2016):

> Because of the expansion of space and the finite age of the cosmos, there exists a horizon beyond which the light emitted by objects will never be able to reach us, marking the bounds of the observable universe.

The latest estimation of the radius is 14,200 Mpc, or 46.3 billion light-years (Halpern and Tomasello 2016). Indeed, even what we once believed to be the Big Bang singularity—an instant where the laws of general relativity break down and the temperatures, densities, and energies of the universe become infinitely large—has been revised. In the words of the theoretical astrophysicist Ethan Siegel (Siegel 2018):

> But this picture [existence of Big Bang singularity] isn't just wrong, it's nearly 40 years out of date! We are absolutely certain there was no singularity associated with the hot Big Bang, and there may not have even been a birth to space and time at all.
>
> […]
>
> The idea of a Big Bang singularity went out the window as soon as we realized we had a different state—-that of cosmic inflation—preceding and setting up the early, hot-and-dense state of the Big Bang.

The notion of inflation is a postulated exponential, but extremely brief, expansion of space in the early universe, around 10^{-36} s after the breakdown of general relativity (Guth 1981; Collins et al. 1989; Peacock 1999; Peebles 1993; Penrose 2004). Crucially, "inflation cannot arise from a singular state, because an inflating region must always begin from a finite size" (Siegel 2018).

Infinity, like zero, is a strange concept. Our minds can approximately comprehend its abstract nature. Mathematically, it becomes tractable. The work of the mathematician Georg Cantor uncovered different "types" of infinities. For instance, there exist more real numbers than natural numbers, although both sets of numbers are infinite (Cantor 1874). Interestingly, Cantor's continuum hypothesis—relating to the question if there lies an "infinity" between the integers and the real numbers (Cohen 2008)—was demonstrated to be an example of the incompleteness of mathematics Gödel had theorized about: the truth or falsity of the hypothesis cannot be determined within the mathematical framework we know today (specifically, set theory). Notwithstanding, we can never observe an instantiation of infinity—or zero—in our physical universe. This insight prompted the following warning from the eminent mathematician David Hilbert (paraphrased in Ellis and Silk 2014):

> Although infinity is needed to complete mathematics, it occurs nowhere in the physical Universe.

More recently, the cosmologist Max Tegmark observed (quoted in Brockman 2015, p. 48ff.):

> I was seduced by infinity at an early age. Georg Cantor's diagonality proof that some infinities are bigger than others mesmerized me, and his infinite hierarchy of infinities blew my mind. The assumption that something truly infinite exists in nature underlies every physics course

> I've ever taught at MIT—and, indeed, all of modern physics. But it's an untested assumption, which begs the question: is it actually true?
>
> [...]
>
> In the past, many venerable mathematicians were skeptical of infinity and the continuum. The legendary Carl Friedrich Gauss denied that anything infinite really exists, saying "Infinity is merely a way of speaking" [...]. In the past century, however, infinity has become mathematically mainstream, and most physicists and mathematicians have become so enamored with infinity that they rarely question it.
>
> [...]
>
> Let's face it: despite their seductive allure, we have no direct observational evidence for either the infinitely big or the infinitely small. We speak of infinite volumes with infinitely many planets, but our observable universe contains only about 10^{89} objects (mostly photons). If space is a true continuum, then to describe even something as simple as the distance between two points requires an infinite amount of information, specified by a number with infinitely many decimal places. In practice, we physicists have never managed to measure anything to more than about 17 decimal places. Yet real numbers with their infinitely many decimals have infested almost every nook and cranny of physics, from the strengths of electromagnetic fields to the wave functions of quantum mechanics: we describe even a single bit of quantum information (qubit) using two real numbers involving infinitely many decimals.
>
> Not only do we lack evidence for the infinite, but we don't need the infinite to do physics. Our best computer simulations, accurately describing everything from the formation of galaxies to tomorrow's weather to the masses of elementary particles, use only finite computer resources by treating everything as finite. [...] Our challenge as physicists is to discover this elegant way and the infinity-free equations describing it—the true laws of physics. To start this search in earnest, we need to question infinity. I'm betting that we also need to let go of it.

Perhaps many of today's problems faced by physicists stem from this clash of philosophies. The crux of quantum gravity essentially centers around the failed attempts to naively quantize—essentially finitize—gravity (Sect. 10.2). Discrete quantum mechanics won't be married to continuous general relativity. This schism runs deep. Again, Fredkin[10]:

> The utterly fantastic success of Mathematical Analysis (the mathematics of continuous functions of continuous variable) as applied to physics and engineering, tends to blind us to the possibility that the ultimate nature of space and time might be discrete.

This fundamental tension between the finite and the infinite was outlined in Sect. 5.3. Essentially, Fig. 5.9 in Sect. 5.4 provides a schematic overview of the four different types of knowledge generation utilizing formal representations. The analytical description of nature is the one employing continuous mathematics—the infinite. As mentioned, this approach has been spectacularly successful in describing so-called fundamental processes. This is the story of Chaps. 2–4. Most of theoretical physics is unearthed by this approach. In contrast, only slowly is the fundamental relevance of discrete mathematics being realized—finiteness raises its head. This formal representation lies at the heart of what is called the algorithmic description of nature in this book. This mode of knowledge-generation has uncovered a wealth of understanding relating to the complex phenomena surrounding us and comprising us—a tale which is told in Chaps. 6 and 7. Perhaps now is the time that the

[10] See http://www.digitalphilosophy.org/index.php/2013/09/01/an-unfortunate-paradox/.

human mind unleashes the power of yet another approach to decoding reality. After over three hundred years of utilizing the fundamental-analytical paradigm of knowledge generation, and a couple of decades employing the complex-algorithmic one, the fundamental-algorithmic paradigm is emerging. Guided by an inherently finite information ontology, new insights about the fundamental nature of reality are being gained.

13.4 An Information Ontology

The intangible notion of information is undeniably a physical manifestation. Moreover, it holds a fundamental role in the interpretation of quantum physics. This raises the ontological question: Is nature discrete or fundamental? See also Holden (2004). Digital physics goes a step further and asks: Is nature fundamentally digital or analogue? The philosophical questions relating to an information ontology, or even a digital ontology, are currently a hot topic in fundamental theoretical physics. In other words, modern theories of quantum gravity are providing insights into this novel approach to reality.

Why is this new paradigm only emerging now? Aaronson proposes an answer, of why everything appears to becoming together now (Aaronson 2005):

> In my (unbiased) opinion, the showdown that quantum computing has forced—between our deepest intuitions about computers on the one hand, and our best-confirmed theory of the physical world on the other—constitutes one of the most exciting scientific dramas of our time. But why did this drama not occur until so recently? Arguably, the main ideas were already in place by the 1960's or even earlier. I do not know the answer to this sociological puzzle, but can suggest two possibilities. First, many computer scientists see the study of "speculative" models of computation as at best a diversion from more serious work. [...] And second, many physicists see computational complexity as about as relevant to the mysteries of Nature as dentistry or tax law.

Quantum computing, string/M-theory, and loop quantum gravity are converging with respect to a very specific topic: the black hole information paradox.

13.4.1 The Cosmic Hologram

Black holes represent the ultimate interface where quantum mechanics meets general relativity. At first, they were thought to be just a theoretical curiosity in the emerging field of general relativity.

13.4.1.1 Black Holes

At the end of their life, after having "burned up" all the available energy, stars die and transform into various astrophysical entities. While some stars simply explode at the end of their life-cycle, others contract into small compact objects, like white dwarfs (Chandrasekhar 1931) or neutron stars (Baade and Zwicky 1933). However, if the original sun is large enough, the stellar remnant remaining after the gravitational collapse can have an extreme gravitational pull. So much so, that not even electromagnetic radiation can escape. A black hole is born, effectively cutting itself off from the rest of the universe (Oppenheimer and Snyder 1939). The equations of general relativity break down at the center of a black hole. Here we find the so-called gravitational singularity, a region where the curvature of space-time becomes infinite—at least mathematically. However, this "naked singularity" is shielded from the rest of the universe by the black hole's event horizon. This is basically a border of causality where anything crossing it will forever be trapped inside. It is interesting to see how physicists believing in the reality of infinity deal with this issue. For instance, Stephen Hawking, explaining Roger Penrose's cosmic censor conjecture (Penrose 1969), observes (quoted in Hawking and Penrose 1996, p. 21):

> Nature abhors a naked singularity.

Perhaps the true reason is the fictitious nature of mathematical infinity. Recall that the Big Bang represents yet another "singularity" in general relativity.

Black holes are, by their very definition, hard to detect. Indirect evidence speaks of a gigantic black hole at the center of the Milky Way (Johnson et al. 2015). Notwithstanding a black hole's bizarre nature, it is very easily described. By knowing only three externally observable classical parameters (i.e., mass, electric charge, and angular momentum) any black hole can be fully classified (Israel 1967; Carter 1970; Hawking 1971). This is known as the "no-hair" theorem. It also states that "a large amount of information is lost when a body collapses to form a black hole" (Hawking and Penrose 1996, p. 39). By introducing thermodynamics and quantum mechanics into the picture, a puzzle emerges.

In the early 1970s, the physicist Jacob Bekenstein, a former Ph.D. student of Wheeler, was theorizing about the entropy of black holes and discovered an astonishing fact: Black hole entropy has a remarkable geometric interpretation. The entropy was found to be proportional to the area of its event horizon (Bekenstein 1972, 1973). Unlike any other object in the universe, the entropy of a black hole increases with the area of its surface. As a result, any matter dropped into a black hole will only increase its entropy as much as it can increase the event horizon. Somehow, the three-dimensional nature of ordinary entropy is reduced to two dimensions. Hawking picked up on these ideas and showed that black holes, in fact, also radiate energy due to quantum effects (Hawking 1974). This thermal radiation corresponds to a temperature related to the black hole's gravity, i.e., its mass. In general, thermal radiation has no informational content. In other words, it cannot encode any signal. In Hawking's words (quoted in Hawking and Penrose 1996, p. 26):

> This [the black hole radiation being thermal] is too beautiful a result to be a coincidence or just an approximation.

In a next step, Hawking improved on Bekenstein's calculations of the black hole entropy S_{BH}. He derived the following equation (Hawking 1975)

$$S_{\mathrm{BH}} = \frac{kc^3 A}{4G\hbar}, \tag{13.5}$$

where A is the area of the horizon. We now have an amalgamation of very different fundamental constants, coming from thermodynamics (Boltzmann's constant k), quantum mechanics (Planck's constant $\hbar$), special relativity (the speed of light c), and general relativity (Newton's gravitational constant G). Essentially, the Bekenstein-Hawking entropy is one-fourth the area of the event horizon.

Now the paradox emerges. Due to Hawking radiation, black holes lose mass and eventually evaporate. Recall that any matter, and thus information, falling into a black hole inescapably gets trapped there. Indeed, the no-hair theorem tells us that all we can ever know about it is its mass, electric charge, and angular momentum. A black hole could have been "fed" with the most intricate configurations of matter and information, at the end of its life cycle, everything appears to have vanished without a trace—any information about the black hole's composition is lost. The key question is: Where did all the information go? In essence, what happened to all the bits of information once the black hole has evaporated? There exist three alternatives (Penrose 2004, p. 840):

1. Information is lost when the black hole evaporates.
2. Information is stored in a final "nugget," a remnant of the hole.
3. Information is returned to the universe in a final explosion.

The crux of the issue is the following (Gleick 2011, p. 358):

> According to quantum mechanics, information may never be destroyed. The deterministic laws of physics require the states of a physical system at one instance to determine the states at the next instance; in microscopic detail, the laws are reversible, and information must be preserved. […] The loss of information would violate unitarity, the principle that probabilities must add up to one.

For classical physics, time reversal symmetry is a discrete symmetry.[11] It guarantees that the equations of motions can be rewinded and yield a single unique past history. In quantum mechanics, the wave function encapsulates the distribution of probability for a given property. Schrödinger's equation (Sect. 3.1.4) encodes the time evolution of the wave function. It is deterministic and time-reversal symmetric. A foundational assumption of quantum mechanics is that the probability is conserved. This notion, called unitarity, ensures that the described properties will always have some possible value (including zero). In other words, probabilities add up to one. As a result, the quantum states are preserved and no information is lost. This conservation of information now refers to the quantum information describing the full informational content of the wave function and not just a single probabilistic measurement. It is worth noting that the Copenhagen interpretation (Sect. 10.3.2.2) is not deterministic nor time-reversal symmetric. One of its core postulates is that a measurement irreversibly collapses the wave function, manifesting a specific result from the many probabilities.

The black hole information paradox has prompted many discussions among theoretical physicists (Susskind 2008). Bets were made if information is really lost or not. Some physicists presented very unique solutions. For instance, Hawking changed his

[11] In contrast to the continuous symmetries described in Noether's theorem, seen in Sect. 3.1.4.

initial stance that information is lost, subsequently losing a bet. He offered an argument for information preservation (Hawking 2005) utilizing Feynman path integrals (Sect. 10.1.1). However "his new formulation struck some physicists as cloudy and left many questions unanswered" (Gleick 2011, p. 359). Penrose presented what he calls the conformal cyclic cosmology, where the universe iterates through infinite cycles and each ending cycle spawns a new one with a Big Bang singularity (Penrose 2010). However, the most intriguing solution came from string/M-theory.

13.4.1.2 AdS/CFT Duality

M-theory is the eleven-dimensional overarching framework unifying the five known string theories (Sect. 4.3.2 and Witten 1995). At the core of its discovery lie dualities (Duff 1999; Kaku 2000). They are powerful mathematical tools—symmetry principles—linking different theories to each other. In essence, dualities relate quantities that appear to be separate. For instance, T-duality associates strings in a space-time with radius R to strings in a space-time with radius $1/R$ (Giveon et al. 1994). The surprising result is that "a string cannot tell the difference between a big circle and a small one" (Duff 1999, p. 325). S-duality uncovers the equivalence of a theory which is mathematically intractable to another theory in which calculations are easy (Sen 1994). Specifically, S-dualities relate ten-dimensional string theories to M-theory. Moreover, even the dualities are dual to each other.

One of the most powerful and fruitful dualities was discovered by Juan Maldacena (Maldacena 1998). In a nutshell, there exists a correspondence between theories with gravity in d dimensions and theories without gravity in $(d-1)$ dimensions. Specifically, a quantum gravitational theory on the bulk of a space is equivalent to a quantum field theory on its surface. Formally, anti-de Sitter (AdS) space is a manifold with negative curvature. It is closely related to a hyperbolic space, meaning it has a boundary "at infinity." On the one side the duality considers aspects of M-theory formulated on AdS space. On the other side, conformal field theories are analyzed. These are a quantum field theories (Sects. 3.1.4, 3.2.2.1, 4.2, and 10.1.1) which are invariant under conformal transformations (i.e., functions that preserve angles). Specifically, AdS/CFT duality links a string theory in a five-dimensional AdS space to a supersymmetric (Sect. 4.3.2) Yang-Mills theory (Sect. 4.2) on its four-dimensional boundary (Maldacena 1998). In other words, the string theory with gravity describes the five-dimensional space-time, while the quantum field theory of point particles with no gravity operates on the four-dimensional space-time. Both descriptions are equivalent, meaning that no observer could ever determine if she was inhabiting the five dimensional world or its four dimensional boundary.

To summarize, the words of Aaronson (quoted in Horgan 2016):

> Ideas from quantum computing and quantum information have recently entered the study of the black hole information problem—i.e., the question of how information can come out of a black hole, as it needs to for the ultimate laws of physics to be time-reversible. Related to that, quantum computing ideas have been showing up in the study of the so-called AdS/CFT (anti de Sitter / conformal field theory) correspondence, which relates completely different-

> looking theories in different numbers of dimensions, and which some people consider the most important thing to have come out of string theory.

Maldacena's publication is the most referenced high-energy physics paper, with 12,968 citations up to the end of 2017.[12]

13.4.1.3 The Bounds of Information

The Planck length is the scale at which quantum gravitational effects should become apparent. It is defined as

$$\ell_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^3}} \approx 1.6 \times 10^{-35} \text{ [m]}, \tag{13.6}$$

employing the speed of light c, Planck's constant $\hbar$, and the gravitational constant G. The early work of Bekenstein and Hawking gave a glimpse of a new feature of quantum gravity. The black hole entropy (13.5) can be expressed in terms of information, recalling Shannon's reinterpretation of physical entropy as an information-theoretic concept. Specifically (Bekenstein 2003, p. 61):

> [A] hole with a horizon spanning A Planck areas has $A/4$ units of entropy. […] Considered as information, it is as if the entropy were written on the event horizon, with each bit (each digital 1 or 0) corresponding to four Planck areas.

Consequently, and unlike any other theory, the total number of bits that can be stored in a certain bounded region of space is predicted to be finite rather than infinite. This idea is, of course, in line with the speculative philosophy of digital physics.

In 1981, Bekenstein presented an exact bound on the entropy of a physical system S_{matter}. Only the mass (or equivalently, the energy) and volume of the system are relevant. The relation is (Bekenstein 1981)

$$S_{\text{matter}} \leq 2\pi \frac{kER}{\hbar c}, \tag{13.7}$$

utilizing Boltzmann's constant, next to Planck's, and the speed of light. E represents the mass-energy of the matter system and R is the radius of the smallest sphere that can enclose the matter system. In order to derive this result, Bekenstein had to generalize the second law of thermodynamics, establishing black hole thermodynamics (Bekenstein 1974). The Bekenstein bound relates the information capacity of a system in bits to its size, given a density. Specifically (Vedral 2012, p. 185):

> The number of bits that can be packed into any system is at most 10^{44} bits of information times the system's mass in kilograms and its maximum length in meters. […]
>
> It is amazing that to calculate something as profound as the information carrying capacity of an object, out of its infinitely many possible properties, we only need two: area and mass.

---

[12] See https://inspirehep.net/info/hep/stats/topcites/2017/alltime.html.

Fourteen years later, the holographic bound was introduced (Susskind 1995). It is a weaker bound and essentially defines how much information can be contained in a specified region of space. In other words, the focus now lies on the area A enclosing a matter system, without any knowledge of its nature. Mathematically, using Planck units[13]

$$S_{\text{vol}} \leq \frac{A}{4}. \tag{13.8}$$

It then holds that

$$S_{\text{matter}} \leq 2\pi E R \leq \pi R^2 = \frac{A}{4}. \tag{13.9}$$

Some of the implications are the following (Bekenstein 2003, p. 63):

> The visible universe contains at least 10^{100} bits of entropy, which could in principle be packed inside a sphere a tenth of a light-year across.

Moreover, consider packing information—for instance, bits stored in RAM chips—into a spherical volume. Then (Bekenstein 2003, p. 63):

> [T]he theoretical ultimate information capacity of the space occupied by the heap [of chips] increases only with the surface area. Because volume increases more rapidly than surface area, at some point the entropy of all the chips would exceed the holographic bound.

At this point, a black hole will be formed. A black hole is thus the densest information storage device allowed by the laws of physics. Or, equivalently, a black hole is the most entropic object that can be fitted inside a spherical volume.

The derivation of the holographic bound was motivated by 't Hooft's research. In 1993, using simple arguments, he claimed that at the Planck scale our world is no longer three-dimensional. Rather, he found that reality is described by bits located on a two-dimensional lattice ('t Hooft 1993). Leonard Susskind formalized these ideas in the context of string theory, introducing the holographic bound (Susskind 1995). Now its name can be understood: 't Hooft and Susskind are arguing that our reality is a hologram (Bekenstein 2003, p. 63):

> In the everyday world, a hologram is a special kind of photograph that generates a full three-dimensional image when it is illuminated in the right manner. All the information describing the 3-D scene is encoded into the pattern of light and dark areas on the two-dimensional piece of film, ready to be regenerated. The holographic principle contends that an analogue of this visual magic applies to the full physical description of any system occupying a 3-D region: it proposes that another physical theory defined only on the 2-D boundary of the region completely describes the 3-D physics. If a 3-D system can be fully described by a physical theory operating solely on its 2-D boundary, one would expect the information content of the system not to exceed that of the description on the boundary.

Our universe has a four-dimensional space-time structure. There now should exists a set of physical laws, operating on the three-dimensional border of physical space-time, describing the identical physical reality. In a nutshell, our physical universe is a hologram that is isomorphic to the quantum information encoded on the surface of

[13] I.e., $\hbar = G = k = c = 1$.

its boundary. Again, an observer cannot know if she inhabits the bulk space or the boundary. Note also, that now the usual assumptions about our universe are dropped. It is no longer infinite, without boundary, and expanding indefinitely.

The holographic bound has been generalized and extended to any type of space-time (Bousso 1999). This new upper bound on information is called the covariant entropy bound and is associated with a maximum information capacity of one bit per Planck area. Both the Bekenstein bound and the holographic bound can be derived from it. However, how can one construct a holographic theory?

13.4.1.4 Tying It All Together

Surprisingly, all the different worlds are starting to converge.

Strings and Loops

Most intriguingly (Busso 2002):

> The AdS/CFT correspondence realizes the holographic principle explicitly in a quantum gravity theory.

Moreover, AdS/CFT duality offers a solution to the black hole information paradox (Hawking 2005). Then, the holographic principle can help find a non-perturbative definition[14] of string theory. Furthermore, it can also be useful in deriving a background-independent formulation[15] of string theory. Remember that loop quantum gravity, string theory's rival, is a non-perturbative and background-independent theory (Sect. 10.2.3).

There was a recent claim that loop quantum gravity violated the holographic principle (Sargın and Faizal 2016). However, this turned out to be an error. In the words of the theoretical physicist Sabine Hossenfelder[16]:

> [A]fter having read the paper I did contact the authors and explained that their statement that the LQG [loop quantum gravity] violates the Holographic Principle is wrong and does not follow from their calculation. After some back and forth, they agreed with me, but refused to change anything about their paper, claiming that it's a matter of phrasing and in their opinion it's all okay even though it might confuse some people.

Indeed, within this new toolbox of concepts and formalisms, the incompatibilities of string theory and loop quantum gravity could vanish, potentially making them the "two sides of the same coin" (Hossenfelder 2016). Moreover, questions about quantum information and entanglement are "exactly what people in loop quantum gravity have been working on for a long time" (Hossenfelder 2016). In addition (Hossenfelder 2016):

> Meanwhile, in a development that went unnoted by much of the string community, the barrier once posed by supersymmetry and extra dimensions has fallen as well.

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[14]Recall that calculations in quantum field theory were perturbative approximations, seen in Sect. 10.1.1.

[15]See Sect. 10.2.1.

[16]Taken from her blog: http://backreaction.blogspot.com/2015/09/no-loop-quantum-gravity-has-not-been.html, retrieved July 31, 2018.

We now have a higher-dimensional theory of loop quantum gravity incorporating supersymmetry (Bodendorfer et al. 2013). Things are changing. The "younger people in string theory [...] are very open-minded" and they "are very interested [in] what is going on at the interface" (Hossenfelder 2016). Recall the days when string theory was said to be the "only game in town" (Sect. 10.2.1). Could information and computation be the unifying element for the two theories of quantum gravity? Indeed, the holographic principle is relevant in both theories. While string theory offered the powerful AdS/CFT duality, loop quantum gravity theorists are also trying to incorporate the feature. In the words of Bekenstein (2003, p. 65):

> Holography may be a guide to a better theory. What is the fundamental theory like? The chain of reasoning involving holography suggests to some, notably Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo [a pioneer of loop quantum gravity], that such a final theory must be concerned not with fields, not even with spacetime, but rather with information exchange among physical processes. If so, the vision of information as the stuff the world is made of will have found a worthy embodiment.

The Bleeding Edge

Recall that black hole entropy was the starting point of the whole discussion opening up new horizons. Moreover, this information-theoretic angle of attack appears to be the nexus where many different theoretical fragments meet: the Bekenstein-Hawking black hole entropy can be derived from loop quantum gravity (Smolin 1995a; Rovelli 1996), string theory (Strominger and Vafa 1996), and von Weizsäcker's ur-alternatives (Görnitz 1988).

Currently, this line of thinking—building on the holographic principle and AdS/CFT duality—has been extended even further. The ontology of reality is being probed ever deeper. Now entanglement enters the picture (Van Raamsdonk 2010):

> [W]e argue that the emergence of classically connected spacetimes is intimately related to the quantum entanglement of degrees of freedom in a non-perturbative description of quantum gravity.

In other words, quantum entanglement creates space-time. Maldacena and Susskind jumped in Maldacena and Susskind (2013). In a next iteration, the entanglement giving rise to the emergence of space-time is based on one fundamental concept: quantum information (Verlinde 2017). In this formalism, the enigma of dark energy (Sect. 10.3.1) finds an explanation. Naturally, these speculations are at the bleeding edge of contemporary theoretical physics, including quantum information theory. However, they seem to wrap up many isolated phenomena into a unified and broad view of reality. Moreover, recall all the problems encountered by the conventional materialistic scientific worldview, asserting the reality of matter (Sect. 10.4.1). The newly forming ontology speaks of space-time being emergent and information the only fundamental entity of reality.

Computational Complexity Theory to the Rescue

The role of quantum information and computation is essential for this new worldview. Crucially, only a finite number of bits can be stored in a bounded region of space which translates into the same number of qubits per volume.[17] As a result, in the words of Aaronson (quoted in Horgan 2016):

> So, that immediately suggests a picture of the universe, at the Planck scale [...] as this huge but finite collection of qubits being acted upon by quantum logic gates—in other words, as a giant quantum computation.

Interestingly, a specific problem recently identified in the context of Hawking radiation, called the firewall paradox (Almheiri et al. 2013), has an easy quantum computational answer. If the standard conjectures in theoretical computer science are true, then the paradox never actually can appear in the universe (Harlow and Hayden 2013). At the heart of this information-theoretic approach lies the power of computational complexity, a concept from theoretical computer science. The most famous problem in this framework is the unsolved P versus NP problem (Cook 1971). At its core, the challenge is to classify computational problems according to their inherent difficulty. For this, different complexity classes are defined. Specifically, can a problem whose solution is verified quickly (in nondeterministic polynomial time NP) also be solved quickly (in polynomial time P)? Symbolically, does our universe allow $N = NP$ or $N \neq NP$? The answer to this question has huge consequences for the theory of computation. If equality holds, Aaronson observes that "it would mean that we'd grossly underestimated the abilities of our existing computers" (quoted in Horgan 2016). The whole puzzle is also related to the incompleteness of mathematics (Sect. 2.2) and the undecidability in computation (Sect. 9.4.1). Returning to the issues at hand, the connection between computational complexity and quantum gravity is currently being addressed by Susskind and Aaronson (Susskind 2018):

> For how long a time does classical GR [general relativity] hold during the evolution of a black hole? This connection between black holes and complexity classes is unexpected, and in my opinion very remarkable. Broadly speaking it says that the longer classical general relativity describes the interior of black holes, the less quantum computers have power to solve PSPACE-complete problems [where PSPACE refers to a complexity class].

In broader terms (Cowen 2015):

> "It appears more and more that the growth of the interior of a black hole is exactly the growth of computational complexity," says Susskind. If quantum entanglement knits together pieces of space, he says, then computational complexity may drive the growth of space—and thus bring in the elusive element of time.

Recall that Susskind is not only a pioneer of string theory but has also made many important contributions over the years. This new interest in quantum information appears to mark a departure from the orthodox views in the community. Resources on computation are Hopcroft et al. (2008), Hromkovič (2010), Aaronson (2013), Cockshott et al. (2015), Moore and Mertens (2016).

A New Ontology

The merger of (quantum) information with quantum gravity reveals a radically new ontology of reality. The nature of the universe is as follows:

[17]This is a consequence of a theorem showing that for n classical bits, n qubits are the upper limit that can store and retrieve the n classical bits (Holevo 1973).

1. Infinities are abstract concepts never encountered in the physical world. [Digital physics]
2. Space-time is discrete and comprised of “atoms.” [Loop quantum gravity’s quantized volume operator]
3. Reality’s finite structure is brought about by the digital nature of information. [Information bounds, “it from bit”]
4. The universe is a computational engine. [Digital physics]
5. What appears as a three-dimensional universe is the result of quantum information encoded on its two-dimensional surface [Holographic principle, AdS/CFT]

All of this can be summarized as the informational-digital ontology.

The Holometer[18] at Fermilab is designed to detect holographic fluctuations in space-time. In other words, it should be able to detect the pixelation of space-time. Recently, claims supporting the holographic principle have been made, based on apparent observations in the cosmic microwave background data, competing with standard cosmological models (Afshordi et al. 2017). It is also interesting to note, that the science writer Michael Talbot already presented the notion of a holographic universe in his book by the same name in 1991 (Talbot 1991). Especially, as he unified completely separate angles of research, building on the conclusions of the eminent physicist David Bohm and the psychologist and psychiatrist Karl H. Pribram. Talbot writes (Talbot 1991, p. 1f.):

> Intriguingly, Bohm and Pribram arrived at their conclusions independently and while working from very different directions. Bohm became convinced of the universe’s holographic nature only after years of dissatisfaction with standard theories’ inability to explain all the phenomena encountered in quantum physics. Pribram became convinced because of the failure of standard theories of the brain to explain various neurophysiological puzzles.

13.4.2 A Simulated Reality

The holographic principle, with strong support from theoretical physics and quantum information theory, suggests that the world is essentially an illusion. Specifically, the three-dimensional nature of space is fictitious. At the heart of reality lies a two-dimensional computational grid. If one zooms into the fabric of the universe one hits an endpoint. This is reached at the Planck length, where every Planck area carries one bit (or qubit) of information. From this foundation, our illusion of three spatial dimensions is being computed, in which elementary particles (with and without mass) interact. In the words of one of the pioneers of an information-theoretic reality (Bekenstein 2003, p. 65):

> Our innate perception that the world is three-dimensional could be an extraordinary illusion.

Can we go a step further? Could this illusion be more elaborate than we dare to dream? Is reality itself perhaps a vast simulation? Is “it from bit” and digital

[18] See https://holometer.fnal.gov/.

physics actually uncovering a radically different ontology of reality? One in which everything is simulated? In effect, the ontology we are embedded in is one which is simulated—most likely computed—in a vaster and more fundamental ontology encompassing the simulation.

The notion that reality is an illusion has a long history. Recall Zhuang Zhu's butterfly dream recounted in the Preface. Or the Buddhist notion of *anicca*, describing reality as a vast and impermanent illusion (Chap. 1). The postmodern philosopher Jean Baudrillard introduced the notion of simulacra in the context of simulations (Baudrillard 1981). A simulation is the imitation of the operation of a real-world process or system. In contrast, simulacra represent the last step in four stages disassociating from reality. From faithful representations, higher levels of "perversion" finally reveal the simulacrum, which bears no relation to reality anymore. As it is not a copy of reality, it becomes a reality in its own right. Baudrillard coined the term hyperreality for this: "It is the generation by models of a real without origin or reality" (Baudrillard 1994, p. 1).

Naturally, the premise of a fictitious reality is also encountered in science fiction (Botz-Bornstein 2015):

> *Solaris* (1972) and *Stalker* (1979) by Andrei Tarkovsky as well as *The Matrix* by the Wachowski brothers are science fiction films with a highly metaphysical appeal. In addition, all three films deal with the possible falseness of what we generally supposed to be a "reality". In *The Matrix*, a posthuman reality of millions is declared to be due to cognitive manipulations effectuated by machines and computers. People do not live their everyday lives in a human way in the real world but inside a computer program.

Today, the notion of a simulated reality has been adopted by some Silicon Valley tech billionaires, potentially helping fund research on such outlandish ideas (Griffin 2016).

In the science community, Brian Whitworth has proposed that the physical world is a virtual reality (Whitworth 2008, 2010). However, the most popular version of a simulated universe goes under the name of the simulation hypothesis. An early version was proposed by the robotics and artificial intelligence researcher Hans Moravec in Moravec (1999). Then, the philosopher Nick Bostrom developed and expanded the argument. In a nutshell (Bostrom 2003):

> Many works of science fiction as well as some forecasts by serious technologists and futurologists predict that enormous amounts of computing power will be available in the future. Let us suppose for a moment that these predictions are correct. One thing that later generations might do with their super-powerful computers is run detailed simulations of their forebears or of people like their forebears. Because their computers would be so powerful, they could run a great many such simulations. Suppose that these simulated people are conscious (as they would be if the simulations were sufficiently fine-grained and if a certain quite widely accepted position in the philosophy of mind is correct). Then it could be the case that the vast majority of minds like ours do not belong to the original race but rather to people simulated by the advanced descendants of an original race. It is then possible to argue that if this were the case, we would be rational to think that we are likely to be among the simulated minds rather than among the original biological ones. Therefore if we do not think that we are currently living in a computer simulation, we are not entitled to believe that we shall have descendants who will run lots of simulations of their forebears. That is the basic idea.

More technically (Bostrom 2003):

> [A]t least one of the following propositions is true: (i) the human species is very likely to become extinct before reaching a "posthuman" stage; (2) any posthuman civilization is extremely unlikely to run a significant number of simulations of its evolutionary history (or variations thereof); (3) we are almost certainly living in a computer simulation. It follows that the belief that there is a significant chance that we shall one day become posthumans who run ancestor-simulations is false, unless we are currently living in a simulation.

A posthuman stage of civilization is "where humankind has acquired most of the technological capabilities that one can currently show to be consistent with physical laws and with material and energy constrains" (Bostrom 2003). More generally (Herbrechter 2013, back cover):

> Posthumanism is a major reassessment of the most pressing of contemporary debates.

Ancestor-simulations are simulations of ancestral life which are indistinguishable from reality to the simulated observer. Creationism (Sect. 12.2.2) implies an ancestor-simulation. Although our universe appears billions of years old to the uninitiated, it is actually a couple of thousand years old filled with fictitious (simulated) evidence of its epochal history.

Bostrom presents his argument in detail as follows. One of the following statements is correct (Bostrom 2003):

1. The fraction of all human-level technological civilizations that survive to reach a posthuman stage is close to or zero.
2. The fraction of posthuman civilizations that are interested in running ancestor-simulations is close to or zero.
3. The fraction of all observers with human-type experiences that live in simulations is close to or one.

Bostrom, of course, believes option three is the most probable one. He asks (Bostrom 2003):

> If there were a substantial chance that our civilization will get to the posthuman stage and run many ancestor-simulations, then how come we are not living in such a simulation?

He is proposing an either/or argument: "unless we are now living in a simulation, our descendants will almost certainly never run an ancestor-simulation" (Bostrom 2003). Either there is no technologically advanced species in the universe capable of creating high-fidelity simulations or, once they are discovered, the simulations proliferate. Especially through nested ones, where simulated observers in the simulated realities create their own simulated realities with simulated observers—a process that could go one indefinitely. As humanities computational prowess, and the understanding of reality as information-theoretic, increases, we should expect to be able to construct detailed simulations of reality in the near future, including observers—unless humanity destroys itself (see also Epilogue).

Are there any indications that the simulation hypothesis is more than an entertaining thought experiment? If we inhabit a simulation, the following observations can be expected:

1. The finite nature of the computational process running the simulation should render the simulation finite as well.
    a. There should exist no measurements with infinite accuracy within the simulation.
    b. Changes can only happen in discrete steps.
    c. The accuracy of the initial conditions should determine how systems evolve in time.
    d. There should exist a minimal non-zero value and a maximal value for physical quantities.
2. The simulation should become fuzzy and uncertain at the "borders" of the simulation.
3. Informational entities should be unconstrained by space and time.
4. There should exists glitches in the simulation.
5. There should exists hacks in the simulation.
6. The simulation should be optimized.

Indeed, this is what we observe. Heisenberg's uncertainty principle gives a limit to how accurate measurements can be (1a). Quantum mechanics was the first theory speaking of discreteness: the infamous quantum leap (1b). Chaos theory (Sect. 5.1.3) displays a path-dependence sensitive to the accuracy of the initial conditions (1c). The speed of light is constant and the third law of thermodynamics forbids that absolute zero ($-273.15\,°$C) can be reached by a physical system (1d). Our entire commonsensical classical world disintegrates at the quantum level (2). Entangled systems are only constrained by the laws of quantum information and are not impeded by space or time (3). Mathematics suffers from inherent incompleteness and randomness and computation is fundamentally undecidable (Sect. 9.4)—to everyone's great surprise (4). The holographic principle (and AdS/CFT duality) allow the three-dimensional simulation to be rendered using only two-dimensional computation (5). Quantum mechanics and general relativity are incompatible due to the different nature of their underlying "programming" (i.e., the discrete vs. the continuous), exposing a missing feature in the simulation (5). The exactly fine-tuned values of the "natural constants" (Sect. 10.3.1), allowing for complex structure formation, are simply the parameters of the simulation (6). The location of Earth within the universe and the current time in cosmic history ("axis of evil" and "coincidence problem," Sect. 10.3.1) both appear to be very special and not coincidental (6).

It may seem surprising that thinking about reality in terms of a simulation allows many phenomena to appear in a very different light. However, how feasible is such a computation? In the words of Aaronson[19]:

> [O]ur observable universe could be simulated by a quantum computer—or even for that matter by a classical computer, to high precision, using a mere $\approx 2^{10^{122}}$ time steps.
>
> But crucially, if you believe that the observable universe couldn't be simulated by a computer even in principle—that it has no mapping to any system of bits or qubits—then at some

[19]Taken from his blog: https://www.scottaaronson.com/blog/?p=3208, retrieved August 1, 2018.

> point the speculative shoe shifts to the other foot. The question becomes: do you reject the Church–Turing Thesis? Or, what amounts to the same thing: do you believe, like Roger Penrose, that it's possible to build devices in nature that solve the halting problem or other uncomputable problems? If so, how? But if not, then how exactly does the universe avoid being computational, in the broad sense of the term?

In essence, he claims that the simulation hypothesis is unfalsifiable. He refutes[20] the claims some people have made that a recent publication has falsified the hypothesis (Ringel and Kovrizhin 2017). Some physicists support the idea with humor, sidetracking the profound philosophical implications. For instance, the Nobel laureate George Smoot's TEDx talk, with the tongue-in-cheek title *You are a Simulation and Physics Can Prove It* (Smoot 2013). Indeed, the general public also appears to find this idea intriguing (Lewin 2016):

> The 17th annual Isaac Asimov Debate at New York's American Museum of Natural History sold out in just 3 minutes online, host Neil deGrasse Tyson told the audience. The debate featured five experts chewing on the idea of the universe as a simulation.

Some attempts to find empirical evidence have been made (Beane et al. 2014). Naturally, many people find the notion of a simulated universe preposterous. Specifically, who is doing the programming on what sort of computer, in what kind of reality and why? In effect, the simulation hypothesis is a variation of the theistic intelligent design argument, shifted towards programming "deities" or aliens.

13.4.3 Alternatives and Opposition

The cosmologist Max Tegmark goes a step further with his proposed ontology of reality. He retreats from the informational paradigm and invokes a radical form of Platonism (Sect. 2.2). An overview of the current situation is found in the following (Brockman 2016, p. 228f.):

> Computation is different from mathematics. Mathematics turns out to be the domain of formal languages, and is mostly undecidable, which is just another word for saying uncomputable (since decision making and proving are alternative words for computation, too). All our explorations into mathematics are computational ones, though.
>
> […]
>
> A growing number of physicists understand that the universe is not mathematical, but computational, and physics is in the business of finding an algorithm that can reproduce our observations. The switch from uncomputable, mathematical notions (such as continuous space) makes progress possible.

Tegmark closes the loop by redeclaring the primacy of mathematics. His ideas are summarized under the term of the mathematical universe hypothesis (Tegmark 2008, 2014). In a nutshell, reality is a mathematical structure. Tegmark proceeds as follows (Tegmark 2008):

[20] See https://www.scottaaronson.com/blog/?p=3482.

> In this section, we will discuss the following two hypotheses and argue that, with a sufficiently broad definition of mathematical structure, the former implies the latter.
>
> 1. External Reality Hypothesis: There exists an external physical reality completely independent of us humans.
> 2. Mathematical Universe Hypothesis: Our external physical reality is a mathematical structure.

In his book, called *Our Mathematical Universe*, Tegmark adds the following concepts (Tegmark 2014, Chapter 12):

1. Computable Universe Hypothesis: Our external physical reality is a mathematical structure defined by computable functions.
2. Finite-Universe Hypothesis: Our external physical reality is a finite mathematical structure.

Tegmark claims that the mathematical universe hypothesis is, in principle, testable and falsifiable. It should not come as a surprise that today many eminent physicists are pondering radical new ideas for the ontology of reality. In the words of Tegmark (2014, p. 8):

> If my life as physicists has taught me anything at all, it's that Plato was right: modern physics has made abundantly clear that the ultimate nature of reality isn't what is seems.

He list some of the responses to the question "What is reality?" (Tegmark 2014, p. 9). A shortened selection is:

- Elementary particles in motion.
- Quantum fields in curved space-time.
- Strings in motion.
- A divine creation.
- A social construct.
- A neurophysiological construct.
- A dream.
- Information.
- A simulation.
- A mathematical structure.
- We have no access to what Immanuel Kant called "das Ding an sich."
- Reality is fundamentally unknowable.
- Not only don't we know it, but we couldn't express it if we did […] (postmodern answer by Jacques Derrida and others).
- Reality is all in our head (constructivist answer).
- Reality doesn't exists (solipsism).

Many of the themes and concepts have appeared throughout this book, some even being trusty companions in the voyage.

Another approach claiming that information is the primordial essence of reality comes from Fisher information, a concept from mathematical statistics. Ronald

Fisher was a geneticist who was instrumental in the development of modern statistics. He was a prolific researcher.[21] The physicist B. Roy Frieden utilizes Fisher information to claim that, in general, "information is at the root of all fields of science" (Frieden 2004, back cover). In effect, he is unifying much of physics utilizing his grounding principle. Examples are Schrödinger's wave equation of quantum mechanics, and the Maxwell-Boltzmann distribution of statistical mechanics.

Floridi opposes the notion of a digital ontology. The ideas of Wheeler, Fredkin, Lloyd, and others represent an unsatisfactory approach "to the description of the environment in which informational organisms like us are embedded" (Floridi 2010, p. 339). Floridi argues in favor of an informational structural realism. Structural realism was discussed in Sect. 2.2.1, and its ontic version was introduced in Sects. 6.2.2 and 10.4.1.

Others oppose the entire notion of an information-theoretic basis of reality. The science writer John Horgan, famous for his book on the end of science (Horgan 1997), believes (Horgan 2011):

> [T]he everything-is-information meme violates common sense.

More specifically (Horgan 2011):

> The concept of information makes no sense in the absence of something to be informed—that is, a conscious observer capable of choice, or free will [...]. If all the humans in the world vanished tomorrow, all the information would vanish, too.

The question of how consciousness might enter an information ontology is the topic of Chap. 14. Moreover, in 2011 the link between AdS/CFT duality, entanglement, and algorithmic complexity theory had not been established. The current work at the interface of these topics supports an information ontology.

In the collection of essays[22] published as the book *It From Bit or Bit From It* (Aguirre et al. 2015), Wheeler's dictum is analyzed in great detail. One finds that (Aguirre et al. 2015, p. 3):

> Some entrants argued against Wheeler's stance that *It* derives from *Bit*, and these contributions appear in Chaps. 14–18.

There are 19 chapters in total. Chapter 17 argues the following (Barbour 2015, p. 197):

> Examination of what Wheeler meant by "it" and "bit" then leads me to invert his aphorism: "bit" derives from "it". I argue that this weakens but not necessarily destroys the argument that nature is fundamentally digital and continuity an illusion.

The quantum information expert Gregg Jaeger, whose work was introduced above in Sect. 13.2.1, also rejects the fundamental nature of information. In detail (Jaeger 2009, p. 234f.):

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[21] For a list of publications, see https://en.wikipedia.org/wiki/Ronald_Fisher_bibliography.

[22] See https://fqxi.org/community/essay/winners/2013.1.

> The idea that physics is reducible to information is problematic for at least two reasons. One difficulty is that it is far from clear that all physical things have anything intrinsic corresponding to informational magnitudes, much less that they are "submitting to information-theoretical descriptions" in all their aspects. […] A second, insurmountable difficulty is that any information-theoretic description of an object is, by definition, *entirely different* from the *existent* it describes. A physical entity is not a simulacrum and cannot be equated with its own description; that this issue could have been ignored is a symptom of the influence of postmodernism […].

He goes on to examine the work of Zeilinger and Landauer. It is perhaps safe to say that at this point the discussion has become philosophical. In the end, we all adopt a worldview and try to classify reality within its bounds. This is why it is so important to critically examine all such conceptual frameworks—old and new. Key notions relate to certainty (Sect. 8.1.1) and the question"Is the universe queerer than we can suppose?" (Sect. 12.4.4).

Conclusion

Perhaps the metaphor of the Book of Nature (Chaps. 2 and 5) containing all knowledge of the world—in formal abstract language—was a misguided thought. It seems that at the core of reality we find a computational engine which needs to be fed with information. As a consequence, the "Book of Nature" should be closer to a computational device in which the algorithms of reality are encoded. The static physical "pages" are replaced with a dynamic and fluid "display."

At the heart of this new understanding of the world lies the notion of information (Zurek 1990, p. vii):

> The specter of information is haunting sciences. Thermodynamics, much of the foundation of statistical mechanics, the quantum theory of measurement, the physics of computation, and many of the issues of the theory of dynamical systems, molecular biology, genetics and computer science share information as a common theme.

Indeed, many different and unrelated theoretical frameworks are converging on one key idea: information is the basis of reality. Moreover, the seemingly intangible notion of information has strikingly physical properties. From this bedrock the physical universe emerges as a computational entity. Space and time are emergent phenomena. In essence, all of reality is fundamentally finite and infinities are only found in the human mind. Crucially, this picture is currently been reconfirmed at the interface of theoretical computer science and theoretical physics. A new paradigm is emerging, replacing the old materialistic and reductionistic scientific worldview.

The basic idea is surprisingly elementary (Zeilinger 2004, p. 210):

> Our observation that the most elementary system carries only one bit of information simply means that it can carry only the answer to one question or the truth value of one proposition only. We can now show how this simple, innocuous observation leads to an understanding of such basic notions as complementarity, of the randomness of individual quantum events, and of entanglement.

In summary (Aguirre et al. 2015, p. 1):

> Over the past century, there has been a steady progression away from thinking about physics, at its deepest level, as a description of material objects and their interactions, and towards physics as a description of the evolution of information about, and in, the physical world. Information theory encompasses the apparently inherent probabilistic nature of quantum mechanics, our statistical understanding of thermodynamical systems, and computer science, where the encoding of data is described classically using rules laid out by Claude Shannon. Recent years have seen an explosion of interest at the nexus of physics and information, driven by the information age in which we live and by developments in quantum information theory and computer science. The idea that information is more fundamental than the matter that conveys it was famously encapsulated by physicist John Archibald Wheeler in the phrase "It from Bit".

String theorists agree (Ananthaswamy 2017):

> But to Susskind at least, the idea that reality might be rooted in 0s and 1s is poetically beautiful. Perhaps, he says, we will one day be able to sum up the universe in a simple epigram: "ah, everything is information".

One specific and outlandish picture of reality emerges at the interface of information theory, black hole cosmology and thermodynamics, and string theory. Our three-dimensional universe is an illusion arising from a two-dimensional computational process. Reality, at its foundation, is a two-dimensional grid comprised of Planck areas each able to register one bit of information. We inhabit a hologram. From such mind-boggling suggestions about the ultimate nature of reality it is not hard to conceive of all of reality as fictitious. Specifically, the suspicion that the universe is a simulation. However, where does consciousness fit into this picture?

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Chapter 14
The Consciousness of Reality

Abstract Finally, the human mind faces its own nature. By extending the information-theoretic paradigm, the informational nature of consciousness is uncovered. This gives rise to the very first formal description of consciousness. In attempts to bridge the chasm between the objective and subjective, scientists and philosophers have opened up to the unspeakable. The nature of consciousness, as has been suggested by ancient Eastern and shamanic traditions, is necessarily universal and primal. The notion of spirituality is creeping back into science. Moving towards a more empirical analysis, the enigma of intelligence is discussed, arising in decentralized systems and even in inanimate structures. Then, the surprising therapeutic effects of psychedelics is discovered, next to a myriad of transcendental planes of being, accessible to pure consciousness. Moreover, peer-reviewed studies are appearing in the physics literature describing mind-matter interactions in double-slit quantum experiments—a long suspected connection by many pioneers of quantum mechanics. As the cracks in the current edifice of science continually grow, the new information-theoretic paradigm is embraced. Beginning with an information ontology, a radical participatory ontology is hinted at. In essence, the human mind is witnessing the most radical paradigm shift in its own history. The well-served and previously glorious materialistic and reductionistic scientific worldview is yielding to a novel scientific conception of subjective consciousness and objective reality—and their unexpected intimate kinship.
Level of mathematical formality: low.

Consciousness is a truly puzzling phenomenon. For one, my own consciousness is the only element of existence I am personally aware of. Through the flow of subjective experiences I perceive an external reality and myself demarcated from it. I assume that other human minds—and to some extent non-human minds—experience a similar structure in this eternal moment of "now." Strangely however, the subjective itself is very hard to objectify. The totality of perception, including every memory, is notoriously unreliable and misleading (Chap. 11). How then, should one try to comprehend the fundamental nature of consciousness? Moreover, is the external world our senses are seemingly reporting to us about really "out there?"

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The latter question of how consciousness can acquire knowledge about the external world has a long history in philosophy. According to René Descartes and John Locke, a distinction needs to be introduced when thinking about material entities. In detail (Baggott 2009, p. 99):

> [P]hysical objects possess primary qualities such as extension in space, shape, motion, density, number, and so on, all underpinned by the concept of material substance. [...] Secondary qualities such as color exist only in our minds and therefore cannot be said to be independently existing real qualities of physical objects.

This view is compatible with empiricism and rationalism (Chap. 9). However (Tarnas 1991, p. 335):

> Locke was followed by Bishop Berkeley, who pointed out that if the empiricist analysis of human knowledge is carried through rigorously, then it must be admitted that *all* qualities that the human mind registers, whether primary or secondary, are ultimately experienced as ideas in the mind, and there can be no conclusive inference whether or not some of those qualities "genuinely" represent or resemble an outside object.

Indeed (Baggott 2009, p. 100):

> Berkeley's logic is merciless but compelling. We can hold on to the idea of independently [of the mind] existing material substance, but at the cost of having to accept that we can ascribe no independently real properties to it, and can never hope to explain how this substance might give rise to the perceptions we have of it.

So, why do we appear to witness the same objective reality, if all things are intangible? For Berkeley it was clear (Tarnas 1991, p. 336):

> The reason that objectivity exists, that different individuals continually perceive a similar world, and that a reliable order inheres that world, is that the world and its order depend on a mind that transcends individual minds and is universal—namely, God's mind.

The next iteration in this line of reasoning came in the form of David Hume's skepticism (Tarnas 1991, p. 337):

> Like Berkeley, Hume could not accept Locke's views on representative perception, but neither could he accept Berkeley's identification of external objects with internal ideas, rooted ultimately in the mind of God.

He drove the critique of empiricism to its final extreme (Tarnas 1991, p. 339):

> [A] more disturbing consequence of Hume's critical analysis was its apparent undermining of empirical science itself, for the latter's logical foundation, induction, was now recognized as unjustifiable.
>
> [...]
>
> If all human knowledge is based on empiricism, yet induction cannot be logically justified, then man can have no certain knowledge.

All is contingent. Hume's philosophy stimulated "Immanuel Kant to develop the central philosophical position of the era" (Tarnas 1991, p. 340). In effect, Hume awakened Kant from his "dogmatic slumber." The result was an existential blow (Tarnas 1991):

> In retrospect, the long-term consequences of both the Copernican and Kantian revolutions were fundamentally ambiguous, at once liberating and diminishing. Both revolutions awakened man to a new, more adventurous reality, yet both also radically displaced man—one from the center of the cosmos, the other from genuine cognition of that cosmos. [P. 348]
>
> [...]
>
> In the wake of Kant's Copernican revolution, science, religion, and philosophy all had to find their own bases for affirmation, for none could claim a priori access to the universe's intrinsic nature. [P. 351]

In detail, Kant argued the following in his *Critique of Pure Reason* (Kant 1781). The *Transcendental Aesthetic* reads (translated by Meiklejohn 2003):

> From this investigation it will be found that there are two pure forms of sensuous intuition, as principles of knowledge a priori, namely, space and time. [§1]
>
> Space is nothing else than the form of all phenomena of the external sense, that is, the subjective condition of the sensibility, under which alone external intuition is possible. [§4]
>
> Time is nothing else than the form of the internal sense, that is, of the intuitions of self and of our internal state. [§7]
>
> [...] if we take away the subject, or even only the subjective constitution of our senses in general, then not only the nature and relations of objects in space and time, but even space and time themselves disappear; and that these, as phenomena, cannot exist in themselves, but only in us. [§9]

In a nutshell (Tarnas 1991, p. 343f.):

> Space and time are thus not drawn from experience but are presupposed in experience. They are never observed as such, but they constitute that context within which all events observed. They cannot be known to exist in nature independently of the mind, but the world cannot be known by the mind without them.
>
> Space and time therefore cannot be said to be characteristic of the world in itself, for they are contributed in the act of human observation. They are grounded epistemologically in the nature of the mind, not ontologically in the nature of things.

A contemporary interpretation of this line of thought is provided by the philosopher Hilary Putnam. He pondered about the notion of brains in a vat (Putnam 1981):

> Here is a science fiction possibility discussed by philosophers: imagine that a human being (you can imagine this to be yourself) has been subjected to an operation by an evil scientist. The person's brain (your brain) has been removed from the body and placed in a vat of nutrients which keeps the brain alive. The nerve endings have been connected to a super-scientific computer which causes the person whose brain it is to have the illusion that everything is perfectly normal. There seem to be people, objects, the sky, etc; but really all the person (you) is experiencing is the result of electronic impulses travelling from the computer to the nerve endings. The computer is so clever that if the person tries to raise his hand, the feedback from the computer will cause him to "see" and "feel" the hand being raised. Moreover, by varying the program, the evil scientist can cause the victim to "experience" (or hallucinate) any situation or environment the evil scientist wishes. He can also obliterate the memory of the brain operation, so that the victim will seem to himself to have always been in this environment. It can even seem to the victim that he is sitting and reading these very words about the amusing but quite absurd supposition that there is an evil scientist who removes people's brains from their bodies and places them in a vat of nutrients which keep the brains alive.

The question now is (Baggott 2009, p. 105):

> So, could you be just a brain in a vat? If all your knowledge of the physical world around you is derived from your perceptions and your perceptions were being manipulated to give you the impression of reality, then how would you know otherwise?

Putnam tried to argue that the brain-in-a-vat scenario is impossible. His reasoning is based on the idea that brains are usually in causal connection with real objects in the real world, making the statement "I am a brain in a vat" a self-refuting proposition. Not everyone agrees (Baggott 2009, p. 115):

> This [the argument of causal connection and self-refutation] is, perhaps, a perfectly natural assumption. But it *is* an assumption.

Such musings about the nature of the objective world our subjective experiences seem to bear witness to—from Berkeley to Putnam—only represent the tip of the existential iceberg. Some other radical explanations for the content of my personal conscious perception in this very moment have been listed in the introductory part of Chap. 1. Needless to say, all of the alternative explanations of existence cannot be proven or disproven. To recapitulate:

E1 It is all just one big coincidence and happened by pure chance. We know the fundamental laws of nature and consciousness is simply the result of how the brain works. There is no mystery and that is all there is to say. [Materialism, scientific realism]

E2 A God created the universe. Perhaps 13.8 billion years ago or perhaps 6,000 years ago with fictitious properties making the universe appear older (or even 5 seconds ago, with false memories implanted in all human minds). [Creationism in Abrahamic religion]

E3 Reality is a vast and impermanent illusion (*anicca*) comprised of endless distractions and suffering. The quest of the mind is to cultivate a state of awareness, allowing the illusion to be seen for what it is. Then the enlightened mind can withdraw from the physical realm and enter a state of pure bliss. [Buddhism]

E4 Only the Self exists. Life is the endless play of the Self (*lila*) losing itself only to find itself again in a constant game of hide-and-seek. [Hinduism]

E5 Only pure consciousness exists. In endless cycles, it manifests itself as separate physical embodiments, allowing for an experiential context, only to merge in unity again and start afresh. [Spirituality, panpsychism]

E6 We are dreaming this life and will some day "wake up" to a richer reality which is unimaginably more lucid and coherent. Physical death marks the transition of consciousness from the dreaming state to a higher-dimensional reality or maybe a reality entirely outside the realm of space and time. [Esotericism variation]

E7 We live in the multiverse, the infinite set of all possible universes. As a consequence, we naturally find ourselves in that corner of it which allows for intelligent and sentient life. [String/M-theory, cosmology, many-worlds interpretation of quantum mechanics]

E8 Our physical three-dimensional universe is an illusion. It is a hologram that is isomorphic to the quantum information encoded on the surface of its boundary. [Holographic principle, AdS/CFT duality]

E9 We inhabit a simulation that has these features programmed. [Simulation hypothesis]

The human mind's scientific quest to comprehend the world and its own nature is detailed in Part I. The limits of the current materialistic and reductionistic scientific worldview are outlined in Part II. Then, Chap. 13 offers a novel scientific understanding of the world, based on an information ontology. Creationism is discussed in Sect. 12.2.2. Buddhism appeared in the context of mindfulness (Sects. 7.4.2.1, 9.3.5, and 11.1). The Hindu concept of *lila* is discussed below, as is the notion of panpsychism. Recall the words of the philosopher of the mind Thomas Metzinger, reminiscing about his experience of an episode of false awakening (Sect. 11.2.2):

> So, how do you know that you actually woke up this morning? Couldn't it be that everything you have experienced was only a dream?

Elements of string/M-theory are introduced in Sects. 4.3.2, 10.2.2, and 13.4.1.2, while the notion of the multiverse is discussed in Sect. 10.3.2.2. The holographic principle is introduced in Sect. 13.4.1. It is motivated by theoretical findings related to the novel information-theoretic paradigm outlined in Chap. 13. So too is the simulation hypothesis, which is explained in Sect. 13.4.2. In conclusion (Baggott 2009, p. 228):

> We must now come to terms with the fact that there is no hard evidence for this common-sense reality to be gained from anywhere in the entire history of human thought. There is simply nothing we can point to, hang our hats on and say *this is real*.

How should the human mind proceed from here? Should we simply concede that information is the fundamental nature of physical reality and that our minds are forever unknowable enigmas? In other words, subjectivity allows the objective to be grasped while remaining ethereal itself. This chapter argues that the human mind can take a final step in understanding itself. It is a small step within the informational ontology, but a huge step conceptually. Only the brave mind can reach the destination, as it requires a radical reassessment of all things believed to be true. For one, radical open-mindedness is asked for (Sect. 12.4.4). Indeed (deGrasse Tyson 2007, p. 305):

> One thing is for certain: the more profoundly baffled you have been in your life, the more open your mind becomes to new ideas.

In the words of an influential neuroscientist introduced in the next section (Koch 2012, p. 134f.):

> Let me end with a plea for humility. The cosmos is a strange place, and we still know little about it. It was only two decades ago that scientists discovered that a mere 4 percent of the mass-energy of the universe is the sort of material out of which stars, planets, trees, you, and I are fashioned. One-quarter is cold dark matter, and the rest is something bizarre called dark energy.[1] Cosmologists have no idea what dark energy is or what laws it obeys. [...] Our knowledge is but a fire lighting up the vast darkness around us, flickering in the wind. So, let us be open to alternative, rational explanations in the quest for the source of consciousness.

[1]Both concepts are introduced in Sect. 10.3.1.

Finally, the list of phenomena which are deemed impossible requires a re-evaluation. In essence, to understand itself, the human mind needs to entertain "crazy" ideas and break taboos. The Nobel laureate Francis Crick once gave the following advice (quoted in Bilger 2011):

> The dangerous man is the one who has only one idea, because then he'll fight and die for it. The way real science goes is that you come up with lots of ideas, and most of them will be wrong.

Only now, freed from prejudice and preconceived notions, can the information-theoretic paradigm shift become truly earth-shaking by encompassing the human mind.

14.1 Formalizing Consciousness: Integrated Information Theory

In Sect. 11.1, the history of the scientific study of consciousness is outlined. Notably, research on the topic was dormant until Crick, together with the now eminent neuroscientist Christof Koch, published an article called *Towards a Neurobiological Theory of Consciousness* (Crick and Koch 1990). Then, four years later, the young philosopher of the mind, David Chalmers, introduced the "hard problem of consciousness." Slowly, the notion of consciousness, a vague concept unworthy of any scientific attention, started to captivate scholars. However, it would take another 10 years before attempts were made at mathematizing consciousness—in an information-theoretic framework.

14.1.1 The Taboo of Subjectivity

It is an interesting observation that the human mind's most effective tool has only now been employed to analyze its own nature. The power of utilizing formal thought systems in decoding the workings of reality, thus unearthing knowledge, has been nearly exclusively applied to the external world. This is the essence of science's success: the human mind has the capability to encode aspects of the physical world as formal representations which inhabit an abstract world of their own and can be manipulated by the mind and decoded back into the physical world, yielding predictions. Knowledge generation is a result of acts of translation between the physical and abstract realms of existence. This process has been detailed in Chaps. 2 and 5, and applied in Chaps. 3, 4, 6, and 7. While discussing the nature of consciousness in Chap. 11, many philosophical ideas were presented, next to the neuroscientific knowledge gained about the workings of the brain—specifically, the flaws and shortcomings of consciousness. However, a formal approach has been lacking.

The nature of consciousness appeared to challenge the scientific worldview. Even the very notion of subjectivity has been banned from science. In the words of Koch (2012, p. 8):

> I also write in the face of a powerful professional edict against bringing in subjective, personal factors. This taboo is why scientific papers are penned in the desiccated third person: "It has been shown that…" Anything to avoid the implication that research is done by flesh-and-blood creatures […].

Science is understood as being concerned only with the tangible world, not the inner world of the subjective. Physicists inquire about the nature of objective reality without factoring in their own existence. This is also why philosophy is seen as essentially futile. A sentiment conveyed by a quote from the eminent theoretical physicist Freeman Dyson, found in Sect. 9.1.4:

> Compared with the giants of the past, they [contemporary philosophers] are a sorry bunch of dwarfs.

In essence, scientific materialism divided the world into two domains: the objective and the subjective. B. Alan Wallace is a scholar concerned with the nexus of science, philosophy, and religion—specifically also focusing on the relationship between science and Buddhism. In the book called *The Taboo of Subjectivity* he writes (Wallace 2000, p. 123):

> In the dualistic, mechanical philosophy that dominated the rise of modern science, nature was not only seen as devoid of consciousness but also was objectified to the point that it was divorced from perceptual experience altogether. The material objects that made up the world were believed to have certain primary qualities, such as size, shape and velocity; but they were inherently devoid of all secondary properties, such as color, smell, and sound, which were relative to perception. Thus, conscious experience was effectively removed from nature and, therefore, from the objective domain of science.
>
> As the scientific worldview developed, words that previously referred to constituents of human sensory experience were defined in purely objective terms. Sound became fluctuations in an objective medium such as air; smell became molecules adrift in the atmosphere; light became a form of electromagnetic energy; and color became specific frequencies of that energy. Science was concerned solely with these phenomena as they were thought to occur independently in nature. Adhering to the principles of scientific materialism, science came to be equipped with more and more sophisticated means of exploring objective physical processes; but there was no corresponding development of means to explore subjective cognitive processes. Thus, scientists simply redefined secondary properties—such as color, sound, and so on—in terms of the objective physical stimuli for the corresponding subjective experiences. In so doing, they shed increasing light on the nature of these physical phenomena, while shedding little or no light on the corresponding subjective perceptions. Thus, subjective experience was not explained; rather, it was overlooked through a purgative process of objective redefinitions.

Furthermore (Wallace 2000, p. 145):

> After four centuries of advances in scientific knowledge, more than a century of psychological research, and roughly a half century of progress in the neurosciences, even most advocates of scientism acknowledge that science has yet to give any intelligible account of the nature of consciousness. Nevertheless, the extent of our ignorance concerning consciousness is often

> overlooked. This ignorance is like a retinal blind spot in the scientific vision of the world, of which modern society seems largely unaware. In most books and articles on cosmogony, evolution, embryology, and psychology, consciousness is hardly mentioned; and when it is addressed, it tends to be presented not in terms of experiential qualia but in terms of brain functions and computer systems.

Koch succinctly captures the essence of this discrepancy (Koch 2012, p. 23):

> [A]stronomy can make testable statements about an event that took place 13.7 billion years ago [referring to NASA's Cosmic Background Explorer data]! Yet something as mundane as a toothache, right here and now, remains baffling.

14.1.2 The Mathematical Engine

In 2004, for the first time, consciousness was formalized. Now a quantitative theory began to emerge which could be potentially falsified. Koch observes (Koch 2012, p. 8):

> The endpoint of my quest [to understand consciousness] must be a theory that explains how and why the physical world is capable of generating phenomenal experience. Such a theory can't just be vague, airy-fairy, but must be concrete, quantifiable, and testable.

He has been collaborating on a mathematical theory of consciousness, based on information, first introduced by the neuroscientist and psychiatrist Giulio Tononi. In the publication with the title *An Information Integration Theory of Consciousness*, Tononi first outlined the thesis (Tononi 2004):

> This paper presents a theory about what consciousness is and how it can be measured. According to the theory, consciousness corresponds to the capacity of a system to integrate information. This claim is motivated by two key phenomenological properties of consciousness: differentiation—the availability of a very large number of conscious experiences; and integration—the unity of each such experience. The theory states that the quantity of consciousness available to a system can be measured as the Φ value of a complex of elements. Φ is the amount of causally effective information that can be integrated across the informational weakest link of a subset of elements. A complex is a subset of elements with $\Phi > 0$ that is not part of a subset of higher Φ.

Integrated information theory (IIT) has been developed further since then (Tononi 2008, 2011; Oizumi et al. 2014; Tononi et al. 2016).

IIT makes two assumptions. Conscious states are informationally rich and they are highly integrated. In general (Tononi et al. 2016):

> Integrated information theory starts from the essential properties of phenomenal experience, from which it derives the requirements for the physical substrate of consciousness.

To this end, IIT defines a set of axioms (Oizumi et al. 2014):

- Existence: Consciousness exists—it is an undeniable aspect of reality. Paraphrasing Descartes, "I experience therefore I am".

- Composition: Consciousness is compositional (structured): each experience consists of multiple aspects in various combinations. Within the same experience, one can see, for example, left and right, red and blue, a triangle and a square, a red triangle on the left, a blue square on the right, and so on.
- Information: Consciousness is informative: each experience differs in its particular way from other possible experiences. Thus, an experience of pure darkness is what it is by differing, in its particular way, from an immense number of other possible experiences. A small subset of these possible experiences includes, for example, all the frames of all possible movies.
- Integration: Consciousness is integrated: each experience is (strongly) irreducible to non-interdependent components. Thus, experiencing the word "SONO" written in the middle of a blank page is irreducible to an experience of the word "SO" at the right border of a half-page, plus an experience of the word "NO" on the left border of another half page—the experience is whole. Similarly, seeing a red triangle is irreducible to seeing a triangle but no red color, plus a red patch but no triangle.
- Exclusion: Consciousness is exclusive: each experience excludes all others—at any given time there is only one experience having its full content, rather than a superposition of multiple partial experiences; each experience has definite borders—certain things can be experienced and others cannot; each experience has a particular spatial and temporal grain—it flows at a particular speed, and it has a certain resolution such that some distinctions are possible and finer or coarser distinctions are not.

These axioms are then formalized into postulates relating to physical mechanisms, such as neurons or logic gates. The properties the configurations of mechanisms must satisfy, in order to generate experience, are analyzed. In a first step, the trivial postulates of the existence of mechanisms in some state and the composition of mechanisms into systems are stated. The postulates of information, integration, and exclusion apply both at the level of individual mechanisms and at the level of systems of mechanisms (Oizumi et al. 2014):

- Individual mechanisms:
  - Information: A mechanism can contribute to consciousness only if it specifies "differences that make a difference" within a system. That is, a mechanism in a state generates information only if it constrains the states of a system that can be its possible causes and effects—its *cause-effect repertoire*. The more selective the possible causes and effects, the higher the *cause-effect information* specified by the mechanism.
  - Integration: A mechanism can contribute to consciousness only if it specifies a cause-effect repertoire (information) that is *irreducible* to independent components. *Integration/irreducibility* φ is assessed by partitioning the mechanism and measuring what difference this makes to its cause-effect repertoire.
  - Exclusion: A mechanism can contribute to consciousness at most one cause-effect repertoire, the one having the maximum value of *integration/irreducibility* φ^{Max}. This is its *maximally irreducible* cause-effect repertoire (MICE, or *quale sensu stricto* (in the narrow sense of the word)). If the MICE exists, the mechanism constitutes a *concept*.
- Systems of mechanisms:
  - Information: A set of elements can be conscious only if its mechanisms specify a set of "differences that make a difference" to the set—i.e. a *conceptual structure*. A conceptual structure is a *constellation* of points in concept space, where each axis is a possible past/future state of the set of elements, and each point is a concept specifying differences that make a difference within the set. The higher the number of different

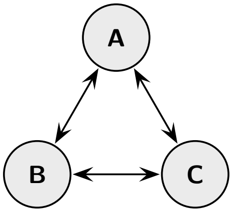

Fig. 14.1 Integrated information theory example. The network is comprised of a set of mechanisms A, B, and C, which are logic gates (e.g., OR, AND, XOR, …). The configuration is a candidate set for IIT analysis

concepts and their φ^{Max} value, the higher the *conceptual information* that specifies a particular constellation and distinguishes it from other possible constellations.

– Integration: A set of elements can be conscious only if its mechanisms specify a conceptual structure that is irreducible to non-interdependent components (strong integration). *Strong integration/irreducibility* Φ is assessed by partitioning the set of elements into subsets with unidirectional cuts.
– Exclusion: Of all overlapping sets of elements, only one set can be conscious—the one whose mechanisms specify a conceptual structure that is *maximally irreducible (MICS)* to independent components. A local maximum of integrated information Φ^{Max} (over elements, space, and time) is called a *complex*.

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Consider the fully connected network of three logic gates, seen in Fig. 14.1. Each mechanisms can be on (1) or off (0), allowing the whole system to be in one of eight (2^3) states at time t_0, defined by three bits: $ABC = \{000\}$, $ABC = \{100\}$, …, $ABC = \{111\}$. Let A be an OR gate, meaning that the inputs from B and C at t_0 will determine its state at t_1 accordingly. Specifically, $BC = \{11\}$, $BC = \{01\}$, and $BC = \{10\}$ results in $A = 1$. The simplest quantity to compute is the cause-effect information (cei) for the mechanism A in a specific state. Constrain A to be on: $A^c = 1$. The probability distribution of past states ABC^p that could have been potential causes of A^c is the cause repertoire $cr = p(ABC^p|A^c = 1)$. cr is an 8-dimensional vector labeled by the possible states of ABC, in the following order: {000}, {100}, {010}, {110}, {001}, {101}, {011}, and {111}. It is computed to be $cr = (0, 0, 1/6, 1/6, 1/6, 1/6, 1/6, 1/6)$ (Oizumi et al. 2014, Supplementary Methods). The amount of information that A^c specifies about the past is its cause information (ci). It is defined as the distance $\mathcal{D}$ between the cause repertoire cr and the unconstrained past repertoire $p^{uc}(ABC^p)$. Formally

$$ci(ABC^p|A^c = 1) = \mathcal{D}\left[p(ABC^p|A^c = 1), p^{uc}(ABC^p)\right]. \tag{14.1}$$

p^{uc} is given by a uniform distribution (i.e., all components are 1/8). Note that the utilized distance measure between the probability distributions is what is known as the earth mover's distance. Other options are discussed in Tegmark (2016). Similarly to ci, the effect information (ei) can be computed for the future states ABC^f. This allows the cause-effect information to be determined

$$cei(ABC^{p,f}|A^c = 1) = \min\left[ci(ABC^p|A^c = 1), ei(ABC^f|A^c = 1)\right]. \quad (14.2)$$

Step by step, the integrated information φ, and the maximally irreducible cause-effect information φ^{Max}, can be derived for the mechanisms, yielding concepts. Moving to systems of concepts, the (conceptual) integrated information Φ is specified for constellations, i.e., conceptional structures. Finally, the maximal integrated information Φ^{Max} can be found, yielding a complex. There exists an online tool for performing example calculations.[2]

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Formally, integrated information Φ is a measure of the cause-effect power of a physical system. Intuitively, a system has a higher Φ the "richer" its interconnection structure is.[3] IIT posits that the larger Φ is, the more conscious the system is. In other words, a thermostat has incremental consciousness, while a room full of human minds does not have more consciousness than the individual minds.

With respect to the notion of information, IIT has the following to say (Tononi et al. 2016):

> Shannon information is observational and extrinsic—it is assessed from the extrinsic perspective of an observer and it quantifies how accurately input signals can be decoded from the output signals transmitted across a noisy channel. It is not compositional nor qualitative, and it does not require integration or exclusion.

Recall Claude Shannon's information theory, introducing the concept of binary digits, or bits, in Sect. 13.1.2. In contrast (Tononi et al. 2016):

> In IIT the information content of an experience is specified by the form of the associated conceptual structure (the quality of the integrated information) and quantified by Φ^{Max} (the quantity of integrated information). In IIT, information is causal and intrinsic: it is assessed from the intrinsic perspective of a system based on how its mechanisms and present state affect the probability of its own past and future states (cause-effect power). It is also compositional, in that different combinations of elements can simultaneously specify different probability distributions within the system. Moreover, it is qualitative, as it determines not only how much a system of mechanisms in a state constrains its past and future states, but also how it does so. Crucially, in IIT, information must be integrated. This means that if partitioning a system makes no difference to it, there is no system to begin with. Information in IIT is exclusive—only the maxima of integrated information are considered.

Thus, we are presented with the inner and outer aspects of information (Sect. 15.1).

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[2] See http://integratedinformationtheory.org/calculate.html.

[3] This is related to complex network theory, discussed in Sect. 6.3.

In summary, in the words of Koch (2014):

> Basically, Φ captures the quantity of consciousness. The quality of any one experience—the way in which red feels different from blue and a color is perceived differently from a tone—is conveyed by the informational geometry associated with Φ. The theory assigns to any one brain state a shape, a crystal, in a fantastically high-dimensional qualia space. This crystal is the system viewed from within. It is the voice in the head, the light inside the skull. It is everything you will ever know of the world. It is your only reality. It is the quiddity of experience. The dream of the lotus eater, the mindfulness of the meditating monk and the agony of the cancer patient all feel the way they do because of the shape of the distinct crystals in a space of a trillion dimensions—truly a beatific vision. The water of integrated information is turned into the wine of experience.

Qualia are subjective conscious experiences, like the greenness of green, see Chap. 11. Information geometry is a contemporary framework for scientific analysis and it unifies statistics with geometry. Specifically, it examines the geometrical structure of the manifolds of probability distributions (Amari and Nagaoka 2000). In essence, IIT offers a formal mapping of a system's causal power upon itself, quantified as integrated information, to geometric structures. Hence the phenomenology of a system can be seen as being isomorphic to the mathematical abstractions. The idea of mapping reality aspects onto higher-dimensional geometric shapes has also emerged in quantum gravity with the discovery of the amplituhedron (Sect. 10.4).

Books outlining the history and ideas of IIT include (Edelman and Tononi 2000; Tononi 2012; Koch 2012).

14.1.3 Putting It to the Test

In 2016, a study tested a complexity metric in the context of IIT (Casarotto et al. 2016). A threshold was derived, above which consciousness emerges. Patients may be misdiagnosed as being in a vegetative state due to their lack of expressing signs of consciousness, although they are experiencing the world. This can result from brain injury. Locked-in syndrome is the tragic condition in which a patient is completely paralyzed and unable to communicate while being fully conscious. Recall the devastating and inspiring story of Martin Pistorius recollected in Sect. 11.3.3. In the study, healthy subjects were measured as being conscious during:

- wakefulness;
- REM sleep;
- Ketamine anesthesia.

Note that Ketamine anesthesia and REM sleep are "conditions in which consciousness is present but is disconnected from the external environment" (Casarotto et al. 2016). Brain injured patients with the following conditions were determined to be conscious:

- locked-in syndrome;
- subcortical stroke;

- cortical stroke;
- other disorders of consciousness with a minimally conscious state.

In the contrast, no signs of consciousness in healthy subjects were found during:

- non-REM sleep;
- anesthesia (Midazolam, Xenon, and Propofol).

Older and more restricted research had reached similar conclusions (Casali et al. 2013; Sarasso et al. 2014, 2015). In another study, subjects were shown three films: a movie, a scrambled movie, and TV noise. Their neural responses were measured utilizing fMRI images. The researchers found that the meaningfulness of the stimulus was associated with higher information integration among cortical regions of the brain. This could be measured without any assumptions about the stimuli and how they are represented in the brain. See Boly et al. (2015).

Moreover (Tononi 2015):

> IIT provides a principled and parsimonious way to account for why certain brain regions appear to be essential for our consciousness while others do not. For example, widespread lesions of the cerebral cortex lead to loss of consciousness, and local lesions or stimulations of various cortical areas and tracts can affect its content (for example, the experience of color). A prominent feature of the cerebral cortex is that it is comprised of elements that are functionally specialized and at the same time can interact rapidly and effectively (when awake or dreaming). According to IIT, this is the kind of organization that can yield a comparatively high value of Φ^{Max}. On the other hand, lesions of the cerebellum do not affect our consciousness in any obvious way, although the cerebellum is massively interconnected with the cerebral cortex and has four times more neurons. This paradox can be explained by considering that the cerebellum is composed of small modules that process inputs and produce outputs largely independent of each other. As suggested by computer simulations, a system thus organized, even if each module is tightly connected with a complex of high Φ^{Max} (the cortical complex), will remain excluded from the conceptual structure of the latter, nor will it form a complex on its own (at best it would decompose into many mini-complexes each having low Φ^{Max}).

Then (Tononi 2015):

> It is well established that, after the complete section of the corpus callosum—the roughly 200 million fibers that connect the cortices of the two hemispheres—consciousness is split in two: there are two separate "flows" of experience,[4] one associated with the left hemisphere and one with the right one. An intriguing prediction of IIT is that, if the efficacy of the callosal fibers were reduced progressively, there would be a moment at which, for a minor change in the traffic of neural impulses across the callosum, experience would go from being a single one to suddenly splitting into two separate experiencing minds. The splitting of consciousness should be associated with the splitting of a single conceptual structure into two similar ones (when two maxima of integrated information supplant a single maximum). Under certain pathological conditions (for example, dissociative disorders such as hysterical blindness), and perhaps even under certain physiological conditions (say "autopilot" driving while having a phone conversation), such splits may also occur among cortical areas within the same hemisphere in the absence of an anatomical lesion. Again, IIT predicts that in such conditions there should be two local maxima of information integration, one corresponding to a "major" complex and one or more to "minor" complexes (Mudrik et al. 2014).

[4]See Sect. 11.3.3.

Finally (Tononi 2015):

> A counterintuitive prediction of IIT is that a system such as the cerebral cortex may be conscious even if it is nearly silent, because it would still be specifying a conceptual structure, though one composed purely of negative concepts. Such a silent state is perhaps approximated through certain meditative practices that aim at reaching "naked awareness" without content (Sullivan 1995).

Maybe the most outlandish prediction of IIT is that any sufficiently complex and integrated system "feels like something." Physical entities can possess interior mental aspects. Recall the discussion about animal consciousness in the introduction of Chap. 11. Now we are potentially faced with the dilemma of a conscious Internet or a conscious computational device. And what about black holes (Sect. 13.4.1.1)?

14.1.4 The Opposition

Tononi has received support from some notable scholars. In particular, the help of Koch and Chalmers. Another influential supporter is the cosmologist Max Tegmark. He was introduced in Sect. 13.4.3 with his mathematical universe hypothesis. Tegmark proposes the following in a recent publication called *Consciousness as a State of Matter* (Tegmark 2015):

> We examine the hypothesis that consciousness can be understood as a state of matter, "perceptronium", with distinctive information processing abilities. We explore four basic principles that may distinguish conscious matter from other physical systems such as solids, liquids and gases: the information, integration, independence and dynamics principles. [...] Our approach generalizes Giulio Tononi's integrated information framework for neural-network-based consciousness to arbitrary quantum systems, and we find interesting links to error-correcting codes, condensed matter criticality, and the Quantum Darwinism program, as well as an interesting connection between the emergence of consciousness and the emergence of time.

Naturally, not all agree. For instance, the quantum computer scientists Scott Aaronson. He was introduced in the last chapter, specifically in Sects. 13.2.1, 13.4.1.2, 13.4.2, and 13.4.1.4. In a blog post from May 21st, 2014, he argues that[5]:

> Yes, it might be a decent rule of thumb that, if you want to know which brain regions (for example) are associated with consciousness, you should start by looking for regions with lots of information integration. And yes, it's even possible, for all I know, that having a large Φ-value is one necessary condition among many for a physical system to be conscious. However, having a large Φ-value is certainly not a *sufficient* condition for consciousness, or even for the appearance of consciousness. As a consequence, Φ can't possibly capture the essence of what makes a physical system conscious, or even of what makes a system *look* conscious to external observers.

In detail, he observes:

[5] See https://www.scottaaronson.com/blog/?p=1799, retrieved August 15, 2018.

> [IIT] unavoidably predicts vast amounts of consciousness in physical systems that no sane person would regard as particularly "conscious" at all.
>
> [...]
>
> I conjecture that approximating Φ is an NP-hard problem.[6]

Aaronson invokes the example of a two-dimensional grid (of logic gates) which would render Φ a function of its size.

One could shrug and wonder about the relevance of a blog post. However, Aaronson enjoys a high level of visibility. In the comments section of his posts we find active engagement of the likes of Koch, Tegmark, and Chalmers. A week after Aaronson's critique, on May 28th, Tononi sent him a 14-page rebuttal, titled *Why Scott Should Stare at a Blank Wall and Reconsider (or, the Conscious Grid)*.[7] There we can read:

- Scott's mathematical argument is right: certain systems whose structure and function are easy to describe from the extrinsic perspective of an observer, such as expander graphs performing parity checks, or worse, grids doing absolutely nothing, may in fact have a large value of PHI if they can be built to be large enough (again, they must be actual physical structures).
- Because of their extreme structural and functional "simplicity", they apparently fit Scott's "commonsense" intuition that they cannot possibly be conscious.
- However, Scott's "commonsense" intuition that such simple systems cannot possibly be conscious is wrong and should be revised.

Tononi explains and outlines other aspects of IIT with respect to the critique. Two days later Aaronson replied. He lists four arguments for IIT he believes Tononi provided and explains why he finds them unpersuasive. In the end, Aaronson concludes[8]:

> At this point, I fear we're at a philosophical impasse. Having learned that, according to IIT,
>
> 1. a square grid of XOR gates is conscious, and your experience of staring at a blank wall provides evidence for that,
> 2. by contrast, a linear array of XOR gates is not conscious, your experience of staring at a rope notwithstanding,
> 3. the human cerebellum is also not conscious (even though a grid of XOR gates is), and
> 4. unlike with the XOR gates, we don't need a theory to tell us the cerebellum is unconscious, but can simply accept it as "reasonably established" and "largely uncontroversial,"
>
> I personally feel completely safe in saying that this is not the theory of consciousness for me.

In November 2015, a two-day workshop on integrated information theory was held at New York University. The speakers included Tononi, Koch, Tegmark, Chalmers, and Aaronson as skeptic. The science writer John Horgan reports (Horgan 2015):

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[6] See Sect. 13.4.1.4.

[7] See http://integratedinformationtheory.org/download/conscious_grid.pdf, retrieved August 15, 2018.

[8] See https://www.scottaaronson.com/blog/?p=1823, retrieved August 15, 2018.

> Tononi shrugged off Aaronson's criticism. "We have to be prepared to be extremely surprised," he said. He also suggested that Aaronson had critiqued an outdated version of phi. IIT is "a work in progress," Tononi said.

In any case, IIT has and will continue to face criticism (Cerullo 2015). Also the philosopher John Searle had already chimed in and provoked this response (Koch and Tononi 2013). A recent overview of the evolution of IIT can be found in Moon and Pae (2018).

Yet again, the detailed technical discussions about theoretical concepts threaten to become postmodern narratives, where meaning, clarity, and understanding is at stake. Recall the Sokal hoax and the Bogdanov affair discussed in Sect. 9.1.4. Time will tell if IIT will survive and evolve through different embodiments of formal structures. For the moment, one must ask what is happening with grids in IIT[9]:

> To conclude, whether one like's grids or not, think highly of them or not, and no matter what your intuition tells you about their level of consciousness, you should begin to take them seriously, as it seems that our own experience of 2D space requires a grid to create it. True, even though we can try to approximate it by staring at a blank screen, we do not experience exactly "what it is like to be a single, isolated 2D grid", because we are made of multiple interconnected grids, and of many additional structures that extract categories out of grids. And yet, if we trust a theory that starts from phenomenology and is supported by empirical evidence more than unreliable and unsupported intuitions, our best inference should be that, if a 2D grid is large and well built, it could be quite conscious, though perhaps a bit boring and not that intelligent.

Maybe there exists a link to the holographic principle outlined in Sect. 13.4.1 or the geometric entities encountered in altered states of consciousness (discussed below in Sect. 14.3.2).

At the end of the day, IIT helped open Pandora's box of radical postulates about consciousness. Within the time-span of 28 years, it is today not only acceptable to talk about consciousness, but also about the notion of universal consciousness—a topic that would otherwise make many scientists recoil in utter disgust.

14.2 The Cosmic Nature of Consciousness

Now that the floodgates have been opened, the recalcitrant nature of consciousness can be viewed in a novel light. In a remarkable turn of events, the seemingly isolated phenomenon of consciousness reemerges within the structure of the cosmos itself.

[9]See http://integratedinformationtheory.org/download/conscious_grid.pdf, retrieved August 15, 2018.

14.2.1 Panpsychism: The Universality of Consciousness

The cognitive scientist Donald D. Hoffman argues that what we perceive of reality is nothing like reality itself (Sect. 11.2.1). In a Kantian twist, evolution maximizes evolutionary fitness and not veridical perceptions. Hoffman also holds other "crazy" ideas (Hoffman 2015):

> Perhaps reality is some vast, interacting network of conscious agents, simple and complex, that cause each other's conscious experiences. Actually, this isn't as crazy an idea as it seems, and I'm currently exploring it.

Chalmers is also thinking about such outlandish properties of reality (Chalmers 2014):

> In the time remaining, I want to explore two crazy ideas that I think may have some promise. The first crazy idea is that consciousness is fundamental. Physicists sometimes take some aspects of the universe as fundamental building blocks: space and time and mass. They postulate fundamental laws governing them, like the laws of gravity or of quantum mechanics. These fundamental properties and laws aren't explained in terms of anything more basic. Rather, they're taken as primitive, and you build up the world from there. Now sometimes, the list of fundamentals expands. In the 19th century, Maxwell figured out that you can't explain electromagnetic phenomena in terms of the existing fundamentals—space, time, mass, Newton's laws—so he postulated fundamental laws of electromagnetism and postulated electric charge as a fundamental element that those laws govern. I think that's the situation we're in with consciousness. If you can't explain consciousness in terms of the existing fundamentals—space, time, mass, charge—then as a matter of logic, you need to expand the list. The natural thing to do is to postulate consciousness itself as something fundamental, a fundamental building block of nature. This doesn't mean you suddenly can't do science with it. This opens up the way for you to do science with it. [...]
>
> The second crazy idea is that consciousness might be universal. Every system might have some degree of consciousness. This view is sometimes called panpsychism: pan for all, psych for mind, every system is conscious, not just humans, dogs, mice, flies, but even Rob Knight's microbes,[10] elementary particles. Even a photon has some degree of consciousness. The idea is not that photons are intelligent or thinking. [...] But the thought is maybe photons might have some element of raw, subjective feeling, some primitive precursor to consciousness.
>
> This may sound a bit kooky to you. I mean, why would anyone think such a crazy thing? Some motivation comes from the first crazy idea, that consciousness is fundamental. [...] A deeper motivation comes from the idea that perhaps the most simple and powerful way to find fundamental laws connecting consciousness to physical processing is to link consciousness to information. Wherever there's information processing, there's consciousness. Complex information processing, like in a human, complex consciousness. Simple information processing, simple consciousness.
>
> A really exciting thing is [that] in recent years a neuroscientist, Giulio Tononi, has taken this kind of theory and developed it rigorously with a mathematical theory. [...] Now, I don't know if this theory is right, but it's actually perhaps the leading theory right now in the science of consciousness, and it's been used to integrate a whole range of scientific data [...].
>
> Another final motivation is that panpsychism might help us to integrate consciousness into the physical world. Physicists and philosophers have often observed that physics is curiously

[10]See, for instance, Knight's 2014 TED talk *How Microbes Make Us Who We Are*.

abstract. It describes the structure of reality using a bunch of equations, but it doesn't tell us about the reality that underlies it. As Stephen Hawking puts it, what puts the fire into the equations?[11] Well, on the panpsychist view, you can leave the equations of physics as they are, but you can take them to be describing the flux of consciousness. That's what physics really is ultimately doing, describing the flux of consciousness. On this view, it's consciousness that puts the fire into the equations. On that view, consciousness doesn't dangle outside the physical world as some kind of extra. It's there right at its heart.

The notion of panpsychism is introduced in the *Stanford Encyclopedia of Philosophy* as follows (Goff et al. 2017):

> Panpsychism is the view that mentality is fundamental and ubiquitous in the natural world. The view has a long and venerable history in philosophical traditions of both East and West, and has recently enjoyed a revival in analytic philosophy. For its proponents panpsychism offers an attractive middle way between physicalism on the one hand and dualism on the other. The worry with dualism—the view that mind and matter are fundamentally different kinds of thing—is that it leaves us with a radically disunified picture of nature, and the deep difficulty of understanding how mind and brain interact. And whilst physicalism offers a simple and unified vision of the world, this is arguably at the cost of being unable to give a satisfactory account of the emergence of human and animal consciousness. Panpsychism, strange as it may sound on first hearing, promises a satisfying account of the human mind within a unified conception of nature.

More specifically, in the words of Koch (2014):

> Panpsychism is one of the oldest of all philosophical doctrines extant and was put forth by the ancient Greeks, in particular Thales of Miletus and Plato. Philosopher Baruch Spinoza and mathematician and universal genius Gottfried Wilhelm Leibniz, who laid down the intellectual foundations for the Age of Enlightenment, argued for panpsychism, as did philosopher Arthur Schopenhauer, father of American psychology William James, and Jesuit paleontologist Teilhard de Chardin. It declined in popularity with the rise of positivism in the 20th century.[12]

More personally, he adds (Koch 2014):

> As a natural scientist, I find a version of panpsychism modified for the 21st century to be the single most elegant and parsimonious explanation for the universe I find myself in.

For many, the notion of panpsychism sounds simply ludicrous—a metaphysical aberration. Even if some great thinkers in history have tinkered with panpsychism, today, we should know better. Indeed (Goff 2017, p. 170):

> The main objection one comes across to panpsychism is that it is "crazy" and "just obviously wrong." It is thought to be highly counterintuitive to suppose that there is something that it is like to be an electron, and this is taken to be a very strong reason to doubt the truth of panpsychism.

The philosopher Philip Goff retorts (Goff 2017, p. 170):

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[11] See Sect. 9.2.1.

[12] See Sect. 9.1.1.

> But the view that time slows down at high speeds, that particles have determinate position only when measured, that the Earth goes round the sun, or that we have a common ancestor with apes were (indeed, still are) also highly counterintuitive, and to many "just obviously wrong." And yet the counter-commonsensicality of these views gives us little or no reason to think them false. It is hard to see why the fact that most Westerners living today happen to be pre-theoretically inclined to think panpsychism false constitutes a reason to think that it is false.

The science writer Amanda Gefter also reminds us (Gefter 2012):

> [F]undamental physics has a long history of disregarding our common sense notions.

One could argue that, overall, the skepticism towards panpsychism is rooted in the prejudices of the prevailing materialistic and reductionistic scientific worldview. The renowned philosopher Thomas Nagel wrote a controversial book in 2012, where he attacked this worldview (Horgan 2013):

> Some scholars, notably philosopher Thomas Nagel, are so unimpressed with science that they are challenging its fundamental assumptions. In his new book *Mind and Cosmos: Why the Materialist Neo-Darwinian Conception of Nature Is Almost Certainly False*, Nagel contends that current scientific theories and methods can't account for the emergence of life in general and one bipedal, big-brained species in particular. To solve these problems, Nagel asserts, science needs "a major conceptual revolution," as radical as those precipitated by heliocentrism, evolution and relativity. Many pundits calling for such a revolution are peddling some sort of religious agenda, whether Christian or New Age. Nagel is an atheist, who cannot accept God as a final answer [...].

In the words of Nagel (2012):

> Certainly the mind-body problem[13] is difficult enough that we should be suspicious of attempts to solve it with the concepts and methods developed to account for very different kinds of things. Instead, we should expect theoretical progress in this area to require a major conceptual revolution at least as radical as relativity theory, the introduction of electromagnetic fields into physics—or the original scientific revolution itself, which, because of its built-in restrictions, can't result in a "theory of everything,"[14] but must be seen as a stage on the way to a more general form of understanding. We ourselves are large-scale, complex instances of something both objectively physical from outside and subjectively mental from inside. Perhaps the basis for this identity pervades the world. [P. 42]
>
> Everything, living or not, is constituted from elements having a nature that is both physical and nonphysical—that is, capable of combining into mental wholes. So this reductive account can also be described as a form of panpsychism: all the elements of the physical world are also mental. [P. 57]

Nagel already started to write about panpsychism in 1979 (Nagel 1979). It may come as a surprise to some, that such seemingly unscientific views were also held by a few of the pioneers of modern theoretical physics. For instance, Dyson, who expressed his distaste for philosophy above, also observed in 1979 (quoted in Schooler et al. 2011, p. 169):

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[13] See Sect. 11.4.

[14] See Sect. 4.3.

> [...] mind is already inherent in every electron, and the processes of human consciousness differ only in degree but not in kind from the processes of choice between quantum states we call "chance" when made by electrons.

So too the eminent physicist David Bohm, who contributed unorthodox ideas to quantum theory (Bohm 1980). He noted (quoted in Schooler et al. 2011, p. 169):

> [W]e have something that is mind-like already with the electron.

Unnoticed by the scientific mainstream, the specter of panpsychism has been haunting intellectually inquisitive—and open—minds for decades. In April 2014, the conference *Toward a Science of Consciousness*, in Tucson Arizona, celebrated its 20th anniversary.[15] Notably, at its first gathering, Chalmers presented the "hard problem of consciousness" (Sect. 11.1). Twenty years later, ideas related to panpsychism were discussed. Attempts at incorporating such a view into science—as panpsychist realism—were presented, especially related to relativity and quantum mechanics (Graubart 2014).

Panpsychism could indeed be the key finally concluding the information-theoretic paradigm shift initiated in the previous chapter (and brought to full fruit in Chap. 15). In conclusion (Goff 2017, p. 170f.):

> While in the mindset of thinking that physics is on its way to giving a complete picture of the fundamental nature of reality, panpsychism seems improbable as physics does not attribute experience to fundamental particles. But once we realize that physics leaves us completely in the dark about the deep nature of the entities it talks about, and indeed that the only thing we know for certain about the deep nature of the universe is that some of it is taken up with consciousness, things look very different. All we get from physics is this big black and white abstract structure, which we metaphysicians must somehow color in with concrete categorical nature. Assuming the falsity of substance dualism,[16] we know how to color in one bit of it: the brains of organisms are colored in with consciousness. How to color in the rest? The most elegant, simple, sensible option is to color in the rest of the world with the same pen.

Within the set of ideas related to panpsychism, one can find variations which too have found a place in the history of human thought. For instance, in Hinduism, the notion of *lila* (explanation E4 listed above and discussed in Sect. 15.2.2) is akin to the concept of pandeism. In detail (Mapson 2017, p. 5):

> Pandeism is a theological theory proposing that instead of the traditional notion of an external God-entity creating our Universe wholesale and then observing it from the outside, our Universe is more logically explained as the product of a Creator wholly becoming it, with principles in place from this becoming which allow its structure—including life within it—to arise organically within it as part of its experience. The history of this idea reaches back to the earliest etchings of human history.

Staying within this theist realm, in contrast (Russell 2004, p. 330):

[15] See http://www.consciousness.arizona.edu/documents/FinalCCS_BOOKofAbstracts_2014-2.pdf.

[16] This is a variety of dualism, discussed in Sect. 11.1.

> The Greek view, that creation out of nothing is impossible, has recurred at intervals in Christian times, and has led to pantheism. Pantheism holds that God and the world are not distinct, and that everything in the world is part of God. This view is developed most fully in Spinoza, but is one to which almost all mystics are attracted. It has thus happened, throughout the Christian centuries, that mystics have had difficulty in remaining orthodox, since they find it hard to believe that the world is outside God.

Albert Einstein once remarked "I believe in Spinoza's God" (Sect. 9.2.1). Then (Culp 2017):

> "Panentheism" is a constructed word composed of the English equivalents of the Greek terms "pan", meaning all, "en", meaning in, and "theism" meaning God. Panentheism considers God and the world to be inter-related with the world being in God and God being in the world. It offers an increasingly popular alternative to both traditional theism and pantheism. Panentheism seeks to avoid either isolating God from the world as traditional theism often does or identifying God with the world as pantheism does. Traditional theistic systems emphasize the difference between God and the world while panentheism stresses God's active presence in the world and the world's influence upon God. Pantheism emphasizes God's presence in the world but panentheism maintains the identity and significance of the non-divine.

In summary, while pantheism equates the divine with the cosmos ("all is God"), panentheism allows for a distinction between the divine and the non-divine. Some have argued for a reconciliation of science and theism along these lines (Griffin 2014 p. 275):

> Crucial for a reconciliation between science and religion, and hence a "scientific world-view" that promotes religious pluralism, will be the acceptance—within both "religious" and "scientific" circles, of the type of naturalism and panentheism advocated in this book.

14.2.2 The Primacy of Consciousness

Chalmers mentioned the notion of consciousness being fundamental above. Some scholars have tried to conceptualize around this idea. For instance, the eminent philosopher of science and systems theorist Ervin Laszlo. In his book with the title *The Systems View of the World: A Holistic Vision for Our Time* (Laszlo 1996), Laszlo outlined a systems-based view of nature, based on over three decades of research. In essence, he advocated a complexity-oriented understanding of reality (see Chap. 6, especially Sect. 6.2). In 2006, Laszlo published *Science and the Reenchantment of the Cosmos* (Laszlo 2006). Peter Russell contributed an essay (Russell 2006, p. 144):

> Ervin Laszlo has proposed that the virtual energy field known as the quantum vacuum, or zero-point field,[17] corresponds to what Indian teachings have called Akasha, the source of everything that exists, and in which the memory of the cosmos is encoded. I would like to take his reasoning a step further and suggest that the nature of this ultimate source is consciousness itself, nothing more and nothing less.

[17] See Sect. 10.1, especially 10.1.1, and 10.1.2.

> Again we find this idea is not new. In the Upanishads, *Brahman*, the source of the cosmos (literally, "that from which everything grows"), is held to be equal to *Atman* ("that which shines"), the essence of consciousness. And in the opening lines of *The Dhammapada*, the Buddha declares that "All phenomena are preceded by mind, made by mind, and ruled by mind."
>
> Such a view, though widespread in many metaphysical systems, is completely foreign to the current scientific worldview. The world we see is so obviously material in nature; any suggestion that it might have more in common with mind is quickly rejected as having "no basis in reality." However, when we consider this alternative worldview more closely, it turns out that it is not in conflict with any of the findings of modern science only with its presuppositions. Furthermore, it leads to a picture of the cosmos that is even more enchanted.

Russell has degrees in theoretical physics, computer science, and experimental psychology, next to having studied meditation in India. He is the author of *The Awakening Earth: The Global Brain* (Russell 1982), predicting the Internet and its impact. Russell argues for the primacy of consciousness—mind is more fundamental than matter. Consciousness is the most fundamental essence of existence out of which comes the experience of material reality. This is the exact opposite of the materialistic scientific paradigm, where matter/energy and space/time is said to reside at the foundation of reality and consciousness emerges out of it. The problem with this is, however, that neither does this scientific worldview predict consciousness, nor can it explain it. Something appears to be missing. Others don't go as far as Russell, by placing consciousness at the center of the ontology, but give it the same status as the scientific fundamental properties of reality. Chalmers explained this stance above.

In the introduction to Chap. 11, the *Swiss Biennial on Science, Technics + Aesthetics* was mentioned, focusing on contemporary challenges in quantum physics, cosmology, and consciousness. In 2018, the topic of the conference was *The Enigma of Consciousness*. Speakers from different disciplines were presenting. Among them were Hoffman; Wallace; Horgan, who is well-known for his book *The End of Science* (Sect. 9.2.2); the theoretical physicist Marcelo Gleiser, known for his writing about truth and knowledge (Gleiser 2010, 2014); Bernardo Kastrup, who has a Ph.D. in computer engineering, is an entrepreneur, and writes about metaphysics and the philosophy of the mind; and the cosmologist Martin Rees. In former years, the mathematical physicists and cosmologist Roger Penrose presented his views on consciousness (Penrose 1989, 1994, 1997). Other speakers were scholars of anthropology and psychology. One specific topic gravitated around non-ordinary states of consciousness found in the Peruvian shamanic traditions, discussed below. Relating to the concept of primal consciousness, the notion of the ontological primitive was discussed. This describes the irreducible components of reality. Next to matter/energy and space/time it was agreed that consciousness should also be a potential candidate. The challenge this poses to the prevailing materialistic worldview was acknowledged. Wallace invited the audience to ponder the following. In our scientific quest to understand the universe and ourselves, we implicitly incorporate a Eurocentric perspective. Specifically, older truth-seeking traditions found in the East are discarded as being pre-scientific and thus invalid. Wallace argued that any inquiry into the nature of consciousness requires introspection, focus, and awareness. Meditators in the East have been cultivating mindfulness form millennia. In detail:

- Observing the process of origination, abiding, and dissolution of mental processes.
- Identifying mental afflictions, which can be described by the criterion that they disrupt the balance and equilibrium of the mind.
- Observing whether mental processes and states are stable or momentary, true sources of happiness or unsatisfying, personal or impersonal.

Could it be that these ancient truth-seekers have discovered aspects of consciousness, and thus reality, without the Western mind even knowing? Wallace reminds us:

- About 5,000 years ago the early Indian seekers (*śramaṇa*) developed stable and highly focused attention (*samādhi*).
- The Gautama Buddha explored states of consciousness and their objects in unprecedented ways (*vipaśyanā*) about 2,500 years ago. "The mind that is established in equipoise comes to know reality as it is" (*śamatha* and *vipaśyanā*).

In these ancient contemplative traditions consciousness is understood as primordial:

- The ultimate, luminous, empty ground-state of consciousness pervades all phenomena (*jñāna*).
- The non-dual, non-local, atemporal, absolute space of phenomena (*dharmadhātu*), gives rise to the emergence of configurations of space-time. Similarly, the energy of primordial consciousness (*jñāna-vayu*) allows for configurations of matter-energy to appear.

Essentially, Buddhism is "empirical," as every practitioner is invited by the Gautama Buddha to check the claims themselves. "Do not believe anything that you have not experience yourself!" is a foundational principle of the philosophy. Overall, topics related to the exploration of vast inner realities were discussed at the conference—relating to contemplative and shamanic traditions, next to psychedelic explorations. Kastrup outlined his skepticism of materialism. His books are titled *Why Materialism is Baloney* (Kastrup 2014) and *Brief Peeks Beyond* (Kastrup 2015). There we can read (Kastrup 2014, p. 215):

> Let us be honest: the fairytale of materialism has served a valid purpose during a more naïve and childish age, but has now far outlived its use fullness. We no longer live in the reality of the 19th century. The collective experiences of our modern humanity in the early 21st century demand a mature, adult worldview.

Horgan summarized his experiences at the conference in Horgan (2018).

14.2.3 The Taboo of Spirituality

The journey outlined in this chapter began with a formal theory of consciousness. Soon, however, the narrative left this scientific footing and explored the non-scientific realms of theism and spirituality. The term "religion" refers to a set of teachings and rituals laid out at the conception of any specific theist doctrine. Religions are geographically constrained and mostly conceived to be static worldviews. However, religion represent the human mind's very first attempt at deciphering the universe it awoke to. Indeed, religion appears to be the matrix out of which the modern human mind—with its complex socio-cultural structures—would eventually emerge and conquer the cosmos (Harari 2015, p. 100ff.):

> In 1995 archaeologists began to excavate a site in south-east Turkey called Göbekli Tepe. In the oldest stratum they discovered no signs of a settlement, houses or daily activities. They did, however, find monumental pillared structures decorated with spectacular engravings. Each stone pillar weighed up to seven tons and reached a height of five metres. In a nearby quarry they found a half-chiselled pillar weighing fifty tons. Altogether, they uncovered more than ten monumental structures, the largest of them nearly thirty metres across.
>
> Archaeologists are familiar with such monumental structures from sites around the world—the best-known example is Stonehenge in Britain. Yet as they studied Göbekli Tepe, they discovered an amazing fact. Stonehenge dates to 2500 BC, and was built by a developed agricultural society. The structures at Göbekli Tepe are dated to about 9500 BC, and all available evidence indicates that they were built by hunter-gatherers. The archaeological community initially found it difficult to credit these findings, but one test after another confirmed both the early date of the structures and the pre-agricultural society of their builders. The capabilities of ancient foragers, and the complexity of their cultures, seem to be far more impressive than was previously suspected.
>
> Why would a foraging society build such structures? They had no obvious utilitarian purpose. They were neither mammoth slaughterhouses nor places to shelter from rain or hide from lions. That leaves us with the theory that they were built for some mysterious cultural purpose that archaeologists have a hard time deciphering. Whatever it was, the foragers thought it worth a huge amount of effort and time. The only way to build Göbekli Tepe was for thousands of foragers belonging to different bands and tribes to cooperate over an extended period of time. Only a sophisticated religious or ideological system could sustain such efforts.

Furthermore, the origins of domesticated wheat could be traced to a region about thirty kilometers from Göbekli Tepe. All of this suggest the unconventional view "that the temple may have been built first, and that a village later grew up around it" (Harari 2015, p. 102). Science and religion always appeared to be natural enemies (Sects. 5.3.1 and 12.2.2). However, some scientists can assimilate both aspects with ease (Sects. 12.4.4 and 15.3).

One can argue that religion mostly requires the submission of its believers to an external authority. Spirituality, in contrast, can be understood as the quest of finding a source of authority within one's own inner reality. Indeed, a strong definition of spirituality could be summed up as the conviction of the ontological reality of one's personal consciousness, reigning supreme over the objects which appearing within it. More generally, spirituality can be defined as (Walach et al. 2011, p. 6):

> [A]n experiential realisation of connectedness with a reality beyond the immediate goals of the individual. It gives rise to a holistic type of knowing that manifests cognitively, emotionally and motivationally. This is why it is termed "experience" in the sense of an inner experience of reality.

Within a scientific worldview, spirituality is mostly seen as being just as villainous as religiosity. Even the empathetic words of the physicist Carl Sagan, revered in the scientific community, have not changed much about this attitude (Sagan 1996, p. 29):

> Science is not only compatible with spirituality; it is a profound source of spirituality.

However, slowly the scientific taboos are beginning to tumble. The monograph called *Neuroscience, Consciousness and Spirituality* outlined an example of this (Walach et al. 2011, p. v):

> [The book] was born out of the vision to build bridges and get different disciplines to talk to each other. We have been observing these disciplines for quite a while, doing empirical research in the field of mindfulness meditation, conceptual, psychological and philosophical issues, as well as spirituality. We were struck by the lack of communication between different pockets of research cultures. We thought that neuroscience researchers could learn from philosophers and from those dealing with issues around spirituality and mystical experience, and vice versa. We felt that the philosophical discourse around the issue of what constitutes consciousness and how it can be explained would benefit from hard neuroscientific data on the one hand and from insights stemming from first-person experience on the other hand, as it is the currency of spiritual traditions.

The monograph contains essays from various scholars. One specifically outlines the following (Schooler et al. 2011, p. 157):

> Material reductionism—the prevailing metaphysical view that reality can be understood entirely in terms of non-conscious physical stuff—is at odds with the existence of experience, the flow of time,[18] and the privileged present. We propose an alternative scientifically-grounded metaphysical perspective that posits: (1) Consciousness represents a fundamental aspect of reality such that all material things enjoy some varying degree of consciousness (panpsychism); […] (3) both experience and the flow of time suggest the reality of a subjective realm of existence; […]. Although speculative, these conjectures illustrate the type of alternative metaphysics that may be able to accommodate scientific observations without abandoning the self-evident facts that experience exists and time flows.

However, the book's editors admit (Walach et al. 2011, p. v):

> Science within the comfort zone of unidisciplinarity is always nice and easy, and cosy, too. Stepping beyond is not only challenging, it is nothing short of madness and professional suicide. Yet, we felt it is necessary. Spirituality seems to be a necessary ingredient in the scientific debate. Talking about consciousness without taking into account exceptional experiences and personal accounts of conscious states that are beyond the ordinary is a bit like trying to do physics with the constraint of only studying crystal lattices. That won't yield a valid theory of matter. Neither will philosophising about consciousness without taking into account different aspects, especially extraordinary and even rare states of consciousness. Plasma states of matter are rare and not normally observed in our everyday world. Yet, they teach us a lot about matter. In the same sense, extraordinary states of consciousness as reported in the spiritual literature, by those practicing spiritual methods such as meditation, can teach us more about consciousness than thousands of discussions of what consciousness is like in a normal day in the supermarket.

The essence—or crux—of spirituality is its experiential dimension. If a person has experienced an episode so real, so intense, that ordinary events appear bland and inconsequential in comparison, it is hard to talk them out of it. Even knowing that by simply exposing my brain to a magnetic field can induce a mystical experience (Sect. 11.3.1) will in no way diminish the experiential reality of such an episode. The same is true for "hallucinations" experienced while the brain is flooded with psychoactive molecules, from psychedelics to empathogens or entactogens. Commonly,

[18] See Sect. 10.4.2.

a mystical experience—spontaneous or induced—will leave a mark on the psyche for years. The fascinating story of the neuroanatomist Jill Bolte Taylor was told in Sect. 11.3.3. While the left hemisphere of her brain was being damaged by a hemorrhage, she experienced the most profound mystical experience. Space ceased to exist as her consciousness united with all of existence. "I found Nirvana" (Bolte Taylor 2008). In his controversial end-of-science book of 1996, Horgan reports about a mystical experience in the epilogue. We can read (Horgan 2012, p. 261):

> Years ago, before I became a science writer, I had what I suppose could be called a mystical experience. A psychiatrist would probably call it a psychotic episode. Whatever. For what it's worth, here is what happened. Objectively, I was lying spread-eagled on a suburban lawn, insensible to my surroundings. Subjectively, I was hurtling through a dazzling, dark limbo toward what I was sure was the ultimate secret of life. Wave after wave of acute astonishment at the miraculousness of existence washed over me. At the same time, I was gripped by an overwhelming solipsism. I became convinced—or rather, I *knew*—that I was the only conscious being in the universe. There was no future, no past, no present other than what I imagined them to be. I was filled, initially, with a sense of limitless joy and power. Then, abruptly, I became convinced that if I abandoned myself further to this ecstasy, it might consume me. If I alone existed, who could bring me back from oblivion? Who could save me? With this realization my bliss turned into horror; I fled the same revelation I had so eagerly sought. I felt myself falling through a great darkness, and as I fell I dissolved into what seemed to be an infinity of selves. For months after I awoke from this nightmare, I was convinced that I had discovered the secret of existence: God's fear of his own Godhood, and of his own potential death, underlies everything. This conviction left me both exalted and terrified—and alienated from friends and family and all the ordinary things that make life worth living day to day. I had to work hard to put it behind me, to get on with my life. To an extent I succeeded.

Some years later Horgan published the book called *Rational Mysticism: Dispatches from the Border Between Science and Spirituality*. There he updates the reader as follows (Horgan 2003b, p. 4):

> In *The End of Science*, I alluded to a drug-induced episode that had been haunting me since 1981. I kept this section short, because I feared it might repel the scientifically oriented readers for whom my book was intended. The opposite reaction occurred. Many readers—including scientists, philosophers, and other supposed rationalists—wrote to tell me that they found the section on mysticism the most compelling part of the book. Readers related their own mystical episodes, some ecstatic, others disturbing. Like me, these readers seemed to be struggling to reconcile their mystical intuitions with their reason.

Finally, the neurosurgeon Eben Alexander reports his near-death experience during a coma in his book *Proof of Heaven* (Alexander 2012a). In a nutshell (Alexander 2012b):

> Yet in spite of the complete absence of neural activity in all but the deepest, most primitive portions of my brain, my identity—my sense of self—did not go dark. Instead, I underwent the most staggering experience of my life, my consciousness traveling to another level, or dimension, or world.

Alexander's book became a *New York Times* bestseller. He recalls a very remarkable experience (Alexander 2012a, back cover):

> Alexander's recovery is a medical miracle. But the real miracle of his story lies elsewhere. While his body lay in a coma, Alexander journeyed beyond this world and encountered an angelic being who guided him into the deepest realms of super-physical existence. There he met, and spoke with, the Divine source of the universe itself.

In more detail (Alexander 2012a, p. 47):

> My situation was, strangely enough, something akin to that of a fetus in a womb. The fetus floats in the womb with the silent partner of the placenta, which nourishes it and mediates its relationship to the everywhere present yet at the same time invisible mother. In this case, the "mother" was God, the Creator, the Source who is responsible for making the universe and all in it. This Being was so close that there seemed to be no distance at all between God and myself. Yet at the same time, I could sense the infinite vastness of the Creator, could see how completely minuscule I was by comparison.

Despite the commercial success of the book not everyone was convinced (Alexander 2012b):

> But I've also weathered considerable criticism—in large part from people who are appalled that I, a brain surgeon, could possibly make the claim that I experienced what I did.
>
> I can't say I'm surprised. As a scientist, I know that the consensus of my tribe is that the self is created through the electrochemical activity of the brain. For most neurosurgeons, and most doctors generally, the body produces the mind, and when the body stops functioning, the mind stops, just like a picture projected on a screen does if the projector is unplugged.
>
> So when I announced to the world that during my seven days of coma I not only remained fully conscious but journeyed to a stunning world of beauty and peace and unconditional love, I knew I was stirring up a very volatile pot.

Indeed, the *Esquire* reported critically about Alexander, questioning his credibility (Dittrich 2013):

> Before *Proof of Heaven* made Dr. Eben Alexander rich and famous as a "man of science" who'd experienced the afterlife, he was something else: a neurosurgeon with a troubled history and a man in need of reinvention.

Alexander retorts (quoted in Bercovici 2013):

> I stand by every word in this book and have made its message the purpose of my life. *Esquire's* cynical article distorts the facts of my 25-year career as a neurosurgeon and is a textbook example of how unsupported assertions and cherry-picked information can be assembled at the expense of the truth.

14.2.4 Non-Human Intelligence

After the excursion into the unscientific dimensions accompanying the enigma of consciousness, this section ends by returning to the terra firma of the objective realm. At this point, it is justified to contemplate the following. If consciousness really is a fundamental and/or universal phenomenon, then one would expect such characteristics also to be manifested in the cognitive capabilities of consciousness—specifically, in relation to the puzzle of intelligence.

Kevin Warwick is a scholar of cybernetics and robotics. In his book, called *QI: The Quest for Intelligence*, he writes (Warwick 2000):

> Intelligence is a term we all think we understand, but do we? What do we mean when we describe someone, some animal or even some thing as being intelligent? [P. 6]
>
> We are not only subjective in the way we view other human beings' intelligence, but also in our assessment of animal and machine intelligence. We have preconceived ideas, despite clear evidence to the contrary. For example, many people think that pigs are dirty, smelly animals and as a consequence not very intelligent. This is patently untrue—pigs are, when compared to other animals, of relative high intelligence. Likewise, many people think machines have no intelligence at all, that they get things done by following programs. This again is not true; some can learn and adapt, and such abilities are growing with every technological advancement made. [P. 14]

Before diving into the ocean of the many expressions of non-human intelligence, one fact should be recalled. In Sect. 11.3.3, two cases were reported, where seemingly normally functioning humans—expressing no obvious signs of intellectual disability—lacked most of what constitutes a brain. Such cases appear to break the expected correlation between cognition and neural complexity.

14.2.4.1 Collective Intelligence

Collective Intelligence is an abstract form of disembodied intelligence. It can be manifested without any individual cognitive capacity accompanying it. Many social insects can exhibit astonishing expressions of collective intelligence. In other words, each individual entity has very limited capacity for cognition, if any, but as a swarm the system functions as a single, intelligent superorganism. For instance, insect colonies that engineer air-conditioning capabilities or farm and milk other species (Sect. 12.4.1). In particular, the superorganism comprised of ants has been studied with great detail (Hölldobler and Wilson 2009). Indeed (O Shea-Wheller et al. 2015):

> Insect societies are complex systems, displaying emergent properties much greater than the sum of their individual parts. As such, the concept of these societies as single "superorganisms" is widely applied to describe their organisation and biology. […] Our findings lend support to the superorganism concept, as the whole society reacts much like a single organism would in response to attacks on different parts of its body.

Another fascinating aspect is collective decision-making. For instance, when colonies of honey bees choose among nectar sources (Seeley et al. 1991) or select new nest-sites (Britton et al. 2002). Collective decision-making has also been argued to underlie flocks of starlings while performing collective turns as a swarm. Essentially, swarm intelligence (Bonabeau et al. 1999) is another explicit manifestation of collective intelligence.

Within the study of complexity (Chap. 6), self-organization, structure formation, and emergence are often encountered phenomena. These can give rise to adaptive, resilient, and sustainable behavior. In other words: to collectively intelligent systems. A hallmark of such collective intelligence is a decentralized blueprint for the interactions of the system's components (Sect. 5.2.4). This key feature is mostly missing in the collective system's we humans design (Chap. 7)—at least until very recently (Sect. 7.4.3).

In conclusion, intelligence can be divorced from electrochemical processes appearing in a biological neural network. This raises the question, what, then, the essence of this collective intelligence is? Where is it located? Analyzing a colony of ants does not reveal incremental units of intelligence distributed among the individual insects. Collective intelligence is an emergent phenomenon, suddenly appearing at a threshold where the whole is literally more than the sum of its parts. Moreover, what is the substrate for this intelligence? How does it come to be, how is it physically embodied, and how is it sustained? Perhaps it is encoded in the fabric of reality itself, as we today know that at the heart of complexity resides miraculous simplicity (Sect. 5.2.1 and Chap. 6).

14.2.4.2 Animal Intelligence

The question, if animals are intelligent, is a thorny one. The culturally normalized act of eating animals suddenly poses a potential ethical challenge. How intelligent must an animal be, before I refuse to consume its flesh? How much non-human suffering am I willing to induce for my subjective sensory pleasure?[19] This is a culturally charged topic (Harari 2015, p. 382):

> Around the time that *Homo sapiens* was elevated to divine status by humanist religions, farm animals stopped being viewed as living creatures that could feel pain and distress, and instead came to be treated as machines. Today these animals are often mass-produced in factory-like facilities, their bodies shaped in accordance with industrial needs. They pass their entire lives as cogs in a giant production line, and the length and quality of their existence is determined by the profits and losses of business corporations. [P. 382]
>
> The tragedy of industrial agriculture is that it takes great care of the objective needs of animals, while neglecting their subjective needs. [P. 385]

The dimensions of this ethical conflict are truly mind-boggling. Recall from the introduction to Chap. 11 that in 2016, approximately 65.8 billion chickens, 1.5 billion pigs, and 302 million cattle were slaughtered globally.

Anyone who ever had a pet knows for certain that animals are very intelligent and appear to have a rich inner life. Dogs and cats seem to also understand the inner life of humans—although cats often appear less interested. But not all. Oscar is a therapy cat living in a nursing and rehabilitation center. He is quite special (Dosa 2007):

> Since he was adopted by staff members as a kitten, Oscar the Cat has had an uncanny ability to predict when residents are about to die. Thus far, he has presided over the deaths of more than 25 residents […].

[19]Next to the issue of animal ethics, there exists mounting evidence that a well-planed plant-based diet leads to a healthier life (Lim et al. 2012; Orlich et al. 2013; Greger 2015) and that the ecological footprint of a diet heavy in meat and dair is alarming. See the discussion on anthropogenic environmental destruction in the Epilogue.

A book was written about his abilities (Dosa 2010). Another prominent feline is Bob. The street cat was adopted by the homeless heroin addict James Bowen and essentially helped him turn his life around. *A Street Cat Named Bob: And How He Saved My Life* appeared on the *New York Times* bestseller list and recounts this story (Bowen and Jenkins 2012).

Perhaps the most astonishing feat of animal intelligence is the comprehension of human language. For instance (Williams 2004):

> A border collie with a stellar vocabulary has accomplished a type of learning previously only seen in toddlers. The researchers say the finding indicates that even mammals distantly related to humans may have the rudiments of language learning.

Also birds appear to have a grasp on human language. Alex is perhaps the most famous parrot, studied by Irene Pepperberg at Harvard (Pepperberg 1999). She bought him in a pet-shop in 1977. On September 6, 2007, Alex is reported to have uttered the following last words to her before his death at the age of 31 (Philipkoski 2007):

> You be good. See you tomorrow. I love you.

Koko was a gorilla who achieved proficiency in conversing with signs. "Her total vocabulary now approximates that of human toddlers" (Fischer 1999, p. 27). Koko also adopted a kitten during her lifetime (Patterson and Cohn 1985). She taught the gorilla called Michael how to utilize sign language and thus communicate with her and humans (Fischer 1999).

Other signs of animal intelligence include tool use. Perhaps the ability of primates to make and utilize tools does not strike one as particularly extraordinary (Boesch and Boesch 1990). Tool use by birds may appear more exceptional (Emery 2006):

> Comparative psychologists interested in the evolution of intelligence have focused their attention on social primates, whereas birds tend to be used as models of associative learning. However, corvids and parrots, which have forebrains relatively the same size as apes, live in complex social groups and have a long developmental period before becoming independent, have demonstrated ape-like intelligence. [...] In reviewing the evidence for avian intelligence, corvids and parrots appear to be cognitively superior to other birds and in many cases even apes. This suggests that complex cognition has evolved in species with very different brains through a process of convergent evolution rather than shared ancestry [...].

It seems amazing, that an overall small avian brain could outperform a much larger primate brain. Especially, as birds lack arms, hands, and fingers. See also Lefebvre et al. (2002) for more on avian tool use and brains. Indeed, Sect. 11.3.2 baffled with the insight that pigeons are better equipped at intuitively grasping probabilities than humans. Then, octopuses (Sect. 11.3.2) are truly bizarre organisms (Courage 2013):

> If you want to study an alien intelligence, [philosopher] Godfrey-Smith says, "octopuses are the closest thing we have."

They are also very intelligent—perhaps even the earliest manifestations of intelligence. Albeit a very unusual one (Reynolds 2015):

> [T]he cognition of an octopus is decentralised and distributed throughout its body, allowing each tentacle to integrate with other systems as well as act independently. Octopuses are also capable of sophisticated, learned behaviour, much of which we'd consider to be a mark of consciousness in humans.

A deeper look at the lives and brains of octopuses is found in Godfrey-Smith (2016). Then, mirror self-recognition, the self-identification of the specular image, is known for apes, monkeys, dolphins, and elephants. It is believed to be associated with empathy and aiding behavior (de Waal et al. 2005). With respect to fairness (Brosnan 2013):

> Humans are not alone in responding negatively to differential treatment compared with a partner. This response is shared with other species and appears to be instrumental in successful cooperation.

Chimpanzee have far superior short-term memory than humans (Inoue and Matsuzawa 2007). Perhaps the most striking indication of the rich inner lives of animals is the capacity for play (Boyd 2004):

> Pleasure is nature's way of ensuring that creatures perform an activity, and animals and humans not only look as though they enjoy play but their brains release dopamine when they anticipate or take part in it. [...] Play has been observed in many animal species, including all mammals in which it has been looked for, and especially in rats, canids (dogs and wolves), primates and cetaceans (dolphins and whales). Easily recognized by experts and non-experts alike, despite the difficulty of defining it, play has been much studied by biologists.

Today, with the ubiquity of recording devices and streaming platforms in the Internet, we can witness behaviors of animals which perhaps no researcher has ever been able to analyze. For instance, inter-species "friendship" among animals. The video-sharing website YouTube has many videos showing capybaras bonding with an array of different animals.

Again, all of this suggests that intelligence is not simply a function of complex neural connectivity, with the human brain eclipsing all animal brains. In detail (Brockman 2015a, p. 29):

> The bigger an animal's brain, the greater its intelligence. You may think the connection is obvious. [...] In particular, you'll find the idea repeated in every modern textbook—that the brain size of different primate species is causally related to their social intelligence. I admit I'm partly responsible for this, having championed the idea back in the 1970's. Yet, for a good many years now, I've had a hunch that the idea is wrong.

In the final analysis, we appear to be confronted with the challenge of having to modify our cherished notion of superior anthropocentric thinking and intelligence. Somehow, intelligence is akin to "software" that can be run on different neural wetware—even on a distributed system of insects. We are, yet again, invited to formulate our understanding within an information-theoretic paradigm, embedded in a computational framework (Sects. 13.1.2 and 13.2.2). As an example, how is intelligence inherited? On the face of it, individual intelligence is encoded in the genes and unravels as the cognitive apparatus of the offspring develops. However, looking at animals constructing very complex and elaborate nest structures, the exact way this knowledge propagates seems mystifying. The behavioral skill-set is physically encoded as information in the fertilized zygote's genes. It is then decoded and programs the young animal's developing brain to allow this instinctive knowledge to manifest. And so an animal constructs a physical structure it has never encountered before in its life. The more intricate the nests, the greater the potential computational complexity of the programming which was transmitted. For instance, this applies to the huge geometric circular structure the male pufferfish creates (Kawase et al. 2013), as it does to the intricate and ornamental nest the male bowerbird assembles (Borgia 1985).

We are also gently invited to reconsider what is deemed food and what represents creatures quipped with rich, subjective inner spaces of sentience, capable of great suffering. From such considerations a potential intrinsic moral right of a species could be derived, to not be subjected to factory-farming in enormous numbers. A simple exercise in empathy is to imagine being the other creature. This is obviously hard to imagine for non-human animals. Nagel wrote a much-noticed piece called *What Is It Like to Be a Bat?* (Nagel 1974), also relating to the philosophy of the mind (Sect. 11.1).

14.2.4.3 Plant Intelligence

Do we also face a potential ethical challenge by consuming plants? Alan Watts, a philosopher, psychonaut, mystic, and interpreter of Eastern philosophy, observes in his essay, titled *Murder in the Kitchen*, the following (Watts 1971 p. 23f.):

> I am simply amazed to find myself living on a ball of rock that swings around an immense spherical fire. I am more amazed that I am a maze—a complex wiggliness, an arabesque of tubes, filaments, cells, fibers, and films that are various kinds of palpitation in this stream of liquid energy. But what really gets me is that almost all the substance of this maze, aside from water, was once *other* living bodies—the bodies of animals and plants—and that I had to obtain it by murder. We are creatures rearranged, for biological existence continues only through the mutual slaughter and ingestion of its various species. I exist solely through membership in this perfectly weird arrangement of beings that flourish by chewing each other up.

Plants represent the only ubiquitous, terrestrial, biological interface to the sun, harnessing its energy by transforming solar radiation into life-sustaining chemical energy. Thus, the fundamental question is: Do plants feel pain and can they suffer? In Switzerland, the Federal Ethics Committee on Non-Human Biotechnology discussed the ethical status of plants in the 2008 report *The Dignity of Living Beings With Regard to Plants. Moral Consideration of Plants for Their Own Sake*.[20] The topics of ownership, instrumentalization, patenting, and genetic modification were discussed. Specifically:

> The Committee members unanimously consider an arbitrary harm caused to plants to be morally impermissible. This kind of treatment would include, e.g. decapitation of wild flowers at the roadside without rational reason.

[20] See http://www.ekah.admin.ch/en/topics/dignity-of-living-beings/.

However:

> A majority considers any action with or towards plants that serves the self-preservation of humans to be morally justified, as long as it is appropriate and follows the principle of precaution.

Other researchers disagree (as quoted in Koechlin 2009):

> [T]he discussion going on in Switzerland about the dignity of plants could lead us down to an absurd and dangerous path.

Plants lack a standard central nervous system able to process information and generate complex experiential inner landscapes. But this does not mean that plants are not intelligent. Intriguingly, there exists striking similarities between plant cells, especially in the roots, and neurons (Baluška 2010). Forests are sustained by vast underground networks, comprised of fungi and the roots of trees and plants, all existing in a symbiotic equilibrium transferring nutrients (Simard et al. 2012). More generally (Koechlin 2009):

> [M]any discoveries in recent years [have been made] that suggest a new "sensitive" picture of plants. It has, for instance, been revealed that plants are active in sensing numerous parameters from their environment, communicate extensively and actively; they interact with their surroundings. They can choose between different possibilities and change their behaviour accordingly. On the cellular level, similarities between animals and plants are far greater than previously assumed (communication with electrical action potentials, similar vesicle trafficking and signaling molecules, etc.). They have an innate immune system. At a rudimentary level, their roots can distinguish between self and non-self.

Plants can express a wide variety of intelligent behavior. The biologist Florianne Koechlin, member of the Federal Ethics Committee, explains the following about plants (quoted in Reissman 2016):

> [T]hey form memories, send warnings, attack predators, and pick up on signals from their environment. They communicate with other plants. They alter their behavior based on past experiences. […] When a caterpillar attacks a leaf, the [tomato] plant starts to produce leaf toxins and, at the same time, releases a cloud of fragrance to warn neighboring tomatoes, so they too can start with their defense […] not only [does] the tomato know that she is being attacked, but also exactly who is attacking her. If she is attacked by spider mites, she produces a fragrance cocktail that attracts predatory mites that eat spider mites, but if she is attacked by caterpillars, she produces a slightly different cocktail of fragrances to attract parasitic wasps. Tomato plants detect their predators through the taste of the insects' saliva.

Plants cry for help, ward off bugs, and save each other using molecular codes based on what are known as volatile organic compounds (Preston 2018). Finally (Pollan 2013):

> [T]he dodder vine, *Cuscuta europaea*, [is] a parasitic white vine that winds itself around the stalk of another plant and sucks nourishment from it. A dodder vine will "choose" among several potential hosts, assessing, by scent, which offers the best potential nourishment. Having selected a target, the vine then performs a kind of cost-benefit calculation before deciding exactly how many coils it should invest—the more nutrients in the victim, the more coils it deploys.

Slowly, the true extent of plant intelligence is being comprehended (Mancuso and Viola 2015; Trewavas 2016; Haskell 2017). Indeed (Calvo et al. 2017):

> Probably, 95% of plant biologists would reject any association of sentience with plant life. So did the authors of this article initially. But an investigation of older literature combined with present understanding led us to a more agnostic position [...].

Once again in the history of the Western mind, a cognitive blind spot resulted in myopia towards the surrounding wonders. The Sanskrit word *ahiṃsā* encapsulates the doctrine of non-violence and it applies to all living beings. For instance, the followers of the Indian religion of Jainism (Sect. 3.1) go out of their way so as not to even hurt insects. One of the central tenets of Buddhism is compassion—again, without an anthropocentric prejudice.

14.2.4.4 Non-sentient Intelligence

Remarkably, intelligence is an intangible phenomenon that can appear in very different biological configurations. However, in the discussion up to now, intelligence was incorporated in either complex organic matter—including plants—or in societies of insects with complex social structures. Can we find intelligence in other creatures?

Slime moulds are organisms that can live as single amoeba-like cells or can aggregate together to form multicellular structures. "Slime mould is effectively a supercell—a bunch of dumb cells that gather together to form a seemingly smart and mobile superorganism" (Collins 2015). Surprisingly, slime mould can solve mazes. Specifically, it can "find the minimum-length solution between two points in a labyrinth" (Nakagaki et al. 2000). "Slime moulds aren't just capable of learning, they can teach each other too" (Tennenhouse 2017).

Perhaps the biggest enigma related to intelligence is that it can latch onto non-organic matter. Even samarium nickelate oxide (SNO), a synthetic crystal, can mimic learning (Zuo et al. 2017). Indeed (Garisto 2017):

> It might be discomfiting that SNO—without a brain or even living cells—can learn. How special are we if a couple layers of atoms can learn, too? But then again, just because humans don't have a monopoly on learning doesn't mean we re not unique. We did discover SNO.

Indeed, the human mind unlocked unprecedented levels of non-organic information processing by engineering computers. Or perhaps the universe is guided by an invisible force driving it to ever higher levels of self-organized complexity and information processing—first organic, then mental, and finally digital (this raises the question of teleology, discussed in Sect. 15.2).

The fields of artificial intelligence (AI) and, specifically, machine learning, are currently exploding. Indeed, deep neural networks are being framed within an information-theoretic context, slowly shedding light on non-human learning mechanisms (Shwartz-Ziv and Tishby 2017):

> We demonstrated that the visualization of the layers in the *information plane* [related to the input and output variables of neural network layers] reveals many—so far unknown—details about the inner working of Deep Learning and Deep Neural Networks.

In 2016, a threshold was reached (Granter et al. 2017):

> In March of last year, Google's (Menlo Park, California) artificial intelligence (AI) computer program AlphaGo beat the best Go player in the world, 18-time champion Lee Se-dol, in a tournament, winning 4 of 5 games. At first glance this news would seem of little interest to [...] anyone [...]. After all, many will remember that IBM's (Armonk, New York) computer program Deep Blue beat Garry Kasparov—at the time the greatest chess player in the world—and that was 19 years ago. So, what's so significant about a computer winning another board game?
>
> The rules of the several-thousand-year-old game of Go are extremely simple. [...] Despite the simplicity of its rules, Go is a mind-bogglingly complex game—far more complex than chess. A game of 150 moves (approximately average for a game of Go) can involve 10^{360} possible configurations, "more than there are atoms in the Universe." As complex as it is, chess is vastly less complex than Go, and chess is amenable to "brute force" algorithmic computer approaches for beating expert chess players like Kasparov. To beat Kasparov, Deep Blue analyzed possible moves and evaluated outcomes to decide the best move.
>
> Go's much higher complexity and intuitive nature prevents computer scientists from using brute force algorithmic approaches for competing against humans. For this reason, Go is often referred to as the "holy grail of AI research." To beat Se-dol, Google's AlphaGo program used artificial neural networks that simulate mammalian neural architecture to study millions of game positions from expert human-played Go games. But this exercise would, at least theoretically, only teach the computer to be on par with the best human players. To become better than the best humans, AlphaGo then played against itself millions of times, over and over again, learning and improving with each game—an exercise referred to as reinforcement learning. By playing itself and determining which moves lead to better outcomes, AlphaGo literally learns by teaching itself. And the unsettling thing is that we don't understand what AlphaGo is thinking. In an interview with *FiveThirtyEight*, one computer scientist commented, "It is a mystery to me why the program plays as well as it does." In the same article, an expert Go player said, "It makes moves that no human, including the team who made it, understands," and "AlphaGo is the creation of humans, but the way it plays is not." It is easy to see how some viewed AlphaGo's victory over Se-dol as a turning point in the history of humanity—we have created machines that truly think and, at least in some areas like Go, they are smarter, much smarter, than we are.

Metzinger points out the following (Metzinger 2009, p. 187):

> In thinking about artificial intelligence and artificial consciousness, many people assume there are only two kinds of information-processing systems: artificial ones and natural ones. This is false. In philosophers' jargon, the conceptual distinction between natural and artificial systems is neither *exhaustive* nor *exclusive*: that is, there could be intelligent and/or conscious systems that belong in neither category. With regard to another old-fashioned distinction—software versus hardware—we already have systems using biological hardware that can be controlled by artificial (that is, man-made) software, and we have artificial hardware that runs naturally evolved software.

Furthermore (Metzinger 2009):

> [L]et us call any system capable of generating a conscious self an *Ego Machine*. An Ego Machine does not have to be a living thing; it can be anything that possesses a conscious self-model. [P. 187]
>
> The first self-modeling machines have already appeared. Researchers in the field of artificial life began simulating the evolutionary process long ago, but now we have the academic discipline of "evolutionary robotics." Josh Bongard, of the Department of Computer Science

> at the University of Vermont, and his colleagues Victor Zykov and Hod Lipson have created an artificial starfish that gradually develops an explicit internal self-model. Their four-legged machine uses actuation-sensation relationships to infer indirectly its own structure and then uses this self- model to generate forward locomotion. When part of its leg is removed, the machine adapts its self-model and generates alternative gaits—it learns to limp. Unlike the phantom-limb patients […], it can restructure its body representation following the loss of a limb; thus, in a sense, it can learn. As its creators put it, it can "autonomously recover its own topology with little prior knowledge," by constantly optimizing the parameters of its resulting self-model. The starfish not only synthesizes an internal self-model but also uses it to generate intelligent behavior. [P. 189]

Lipson is featured in the 2018 documentary *Do You Trust this Computer?*[21] and recalls the following episode from a year earlier. He and his team were training an AI system for a live demonstration. Specifically, they were testing how the objects waved in front of the AI's camera were being recognized. On a side screen, the researchers could observe how certain neurons in the AI were responding to the stimuli. At 53 min and 37 s Lipson remarks:

> And suddenly we noticed that one of the neurons was tracking faces. It was tracking our faces as we were moving around. Now, the spooky thing about this is that we never trained the system to recognize human faces and yet, somehow, it learned to do that. Even though these robots are very simple, we can see that something else is going on there. It is not just programming.

The 2015 *Edge* annual question (Sect. 9.3) was: "What Do You Think about Machines that Think?" The psychologist Tania Lombrozo cautions: "Don't Be A Chauvinist About Thinking." Specifically, (Brockman 2015b, p, 337):

> Cultural psychologists have challenged the idea that Western adults provide a privileged population from which to study human thinking. Developmental psychologists have raised questions about whether and how preverbal infants can think. Comparative psychologists have long been interested in whether and how non-human animals can think. And philosophers, of course, have considered these questions along the way. Across these disciplines, one advance in how we think about thinking has come from recognizing and abandoning the idea that "thinking like I do" is the only way to think about thinking, or that "thinking like I do" is always the best or most valuable kind of thinking. In other words, we've benefited from scrutinizing the implicit assumptions that often slip into discussions of thinking, and from abandoning a particular kind of thinking chauvinism.
>
> With thinking machines, we face many of the very same issues, but the target of study has shifted from humans and other animals to machines of our own creation. […]. Recent advances in artificial intelligence are already compelling us to rethink some of our assumptions about thinking. They aren't just making us think differently and with different tools, but changing the way we think about thinking itself.

A potential future in which the human mind is faced with non-human and non-organic intelligence is unsettling to some and fascinating to others. The term (technological) singularity (Vinge 1993; Kurzweil 2005) encompasses this ambiguity. It is the hypothesis that one day, soon, artificial superintelligence will surpass human intelligence. Effectively, the human era will end. This challenge is analyzed by both

[21] See http://doyoutrustthiscomputer.org/.

Tegmark and the philosopher Nick Bostrom (introduced in Sect. 13.4.2 with his simulation hypothesis):

> If machine brains one day come to surpass human brains in general intelligence, the fate of our species would depend on the actions of powerful AI. [*Superintelligence* (Bostrom 2014, back cover)]

> We stand at the beginning of a new era. What was once science fiction is fast becoming reality, as AI transforms war, crime, justice, jobs and society—and, even, our very sense of what it means to be human. More than any other technology, AI has the potential to revolutionize our collective future […]. [*Life 3.0* (Tegmark 2017, blurb in dust jacket)]

The notion of posthumanism is invoked (Herbrechter 2013, p. 3):

> This could indeed be regarded as a preliminary definition of posthumanism: it is the cultural malaise or euphoria that is caused by the feeling that arises once you start taking the idea of "postanthropocentrism" seriously. To be able to think the "end of the human" without giving in to apocalyptic mysticism or to new forms of spirituality and transcendence—this would correspond to the attitude that the phrase "critical posthumanism" wishes to describe.

Tegmark founded *The Future of Life Institute*.[22] It is concerned with potential existential risks approaching humanity and its motto reads:

> Technology is giving life the potential to flourish like never before—or to self-destruct. Let's make a difference!

Advisors include the entrepreneur Elon Musk and, prior to his death, Stephen Hawking. In an open letter, signed by 3,978 AI/Robotics researchers and 22,541 others,[23] it is warned of the dangers of weaponizing AI. However, even without the existence of artificially-intelligent autonomous weapon systems, the following question stands out:

> How should true artificial superintelligent assess the role and utility of humanity, given its global political and religious ideological entrenchment (Chap. 12), its faulty economic and financial systems (Chap. 7) resulting in unimaginable inequity (Sect. 7.4.2.3), the tendency of the strong to exploit the weak, the globally prevailing cruel treatment of countless sentient beings, and the systematic destruction and pollution of the entire biosphere (Epilogue)?

At the moment, the challenges we face with respect to AI are similar to the general societal challenges. The current level and utilization of AI threatens democracy and increases inequality (O'Neil 2016). Moreover, if human online interactions are taken as a training set for AI, the results are unsavory. In 2016, Microsoft unleashed its chat bot Tay, supposed to mimic a 19-year-old US American girl, on social media. 24 hours later, the AI was shut down and Microsoft issued an apology[24]:

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[22] See https://futureoflife.org/.

[23] See https://futureoflife.org/open-letter-autonomous-weapons/, retrieved August 21, 2018.

[24] See https://blogs.microsoft.com/blog/2016/03/25/learning-tays-introduction/.

> We are deeply sorry for the unintended offensive and hurtful tweets from Tay, which do not represent who we are or what we stand for, nor how we designed Tay.

In effect, mirroring the normal, daily behavior witnessed on social media, Tay quickly manifested abusive fascist, racist, and misogynist traits. We will never know how much this reveals about humanities dark side, thriving in anonymous online interactions, and how much is due to mischievous behavior—trolling.

In closing, intelligence is an emergent property of reality itself, being manifested in very different material and computational structures. It can be localized or distributed and it can be embodied within a conscious mind or not. Having said this, consciousness itself is still an enigma. Do any tools exists, which could help the human mind understand its own conscious nature?

14.3 Enhanced Consciousness: The Psychedelic Renaissance

Up to now, the enigma of consciousness was discussed with respect to three of its manifestations: sober waking consciousness, dreaming, and meditative states. However, since the dawning of the human mind it has been known that there exist radically different states of consciousness—often induced chemically. As these have been deemed harmful, most modern societies have banned any substances causing altered states of consciousness—with the exception of ethanol, nicotine, caffeine, and psychiatric medication. Yet again, a consequential blind spot emerges in the collective vision of humanity. However, slowly the prohibition of, and the stigma associated with, psychoactive substances is today being reevaluated—with profound potential for understanding consciousness and reality.

In 1980, the eminent psychiatrist Stanislav Grof observed (quoted in Carhart-Harris et al. 2014):

> [P]sychedelics, used responsibly and with proper caution, would be for psychiatry what the microscope is for biology and medicine or the telescope is for astronomy.

The influential writer Aldous Huxley is on record saying (in the 1958 BBC program *Monitor*[25]):

> I think it would be extremely good for almost anybody with fixed ideas and with a great certainty about what's what to take this thing [psychedelics] and to realize the world he's constructed is by no means the only world, that there are these extraordinary other types of universe.

Huxley famously documented his mescaline experience in the book *The Doors of Perception: And Heaven and Hell* (Huxley 1954)—the inspiration for the US American rock band's name, *The Doors*. LSD was a serendipitous discovery with great cultural ramifications. At first (Kaiser 2011, p. xxii):

[25] See https://www.bbc.co.uk/programmes/p015fs9b.

> The Central Intelligence Agency and the U.S. Army sponsored research on effects of LSD at government laboratories and reputable research universities throughout the 1940s and 1950s.

However (Kaiser 2011, p. xxi):

> The hippie counterculture sported […] a personal striving often facilitated by heavy use of psychedelic drugs. LSD, synthesized in a Swiss lab in the late 1930s, was first outlawed in the United States in 1966; possession of the drug was bumped up to a felony offense in 1968.

Indeed, the US Drug Enforcement Administration specifies[26]:

> Schedule I drugs, substances, or chemicals are defined as drugs with no currently accepted medical use and a high potential for abuse. Some examples of Schedule I drugs are: heroin, lysergic acid diethylamide (LSD), marijuana (cannabis), 3,4-methylenedioxymethamphetamine (ecstasy), methaqualone, and peyote.

The ethnobotanist and psychonaut Terence McKenna is doubtful of this explanation for banning psychedelics (Lin 2014):

> His assumption about psychedelics had always been that they were illegal "not because it troubles anyone that you have visions" but because "there is something about them that casts doubts on the validity of reality." This makes it difficult, McKenna observed, for societies—even democratic and especially "dominator" societies—to accept them, and we happen to live in a global "dominator" society.

The chemist Alexander Shulgin, who had synthesized and tested hundreds of new psychedelic substances, also observed (Shulgin and Shulgin 2017b, p. 385):

> Then: The earth is the center of the universe, and anyone who says otherwise is a heretic. Now: All drugs that can expand consciousness are without medical or social justification, and anyone who uses them is a criminal.

He was the most prolific psychedelic chemist in history (Horgan 2014b):

> Alexander "Sasha" Shulgin, I learned later, was a top-rank researcher for Dow Chemical in 1960 when he ingested a psychedelic compound—mescaline—for the first time. Shulgin found the experience so astonishing that he devoted the rest of his career to psychedelic chemistry.
>
> Today, experts realize (Boseley and Glenza 2016):
>
> The global "war on drugs" has harmed public health, human rights and development. It's time for us to rethink our approach to global drug policies, and put scientific evidence and public health at the heart of drug policy discussions.

Surprisingly, medical experts call for global drug decriminalization. A panel of 22 medical experts called together by Johns Hopkins University advocate this stance in a publication in the leading medical journal, *The Lancet* (Frenk et al. 2010). Indeed (Tatera 2016a):

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[26]See https://www.dea.gov/drug-scheduling.

> [N]ot only is there ample research against the current prohibitionist drug approach, but there's support for decriminalization thanks to countries like Portugal and the Czech Republic which have already decriminalized all non-violent minor drug offenses. These countries have showed that in real-world settings, policies for drug decriminalization can have positive impacts on society.

In the early 1990s, Zurich was plagued by Europe's biggest open drug scene. Over decades, misery, suffering, and death became ever more visible in an otherwise affluent city. Evictions by the police resulted in relocation. In 1992, a pragmatic drug policy was enforced,[27] allowing for heroin distribution under medical attention. Despite certain political opposition against "the government supplying junkies with free heroin," the pioneering program was a success (Neue Zürcher Zeitung 2013). Having lived in Zurich since the early 1990s, the transformation is astonishing and the former conditions unimaginable.

In 2016, a landmark study was published in the prestigious journal *Proceedings of the National Academy of Sciences* (Carhart-Harris et al. 2016). For the first time, modern brain scanning techniques were applied to the brains of humans under the influence of LSD. The study was crowdfunded.[28] Senior researcher on the study, the neuropsychopharmacologist David Nutt, explained (quoted in Sample 2016):

> "This is to neuroscience what the Higgs boson was to particle physics," he said. "We didn't know how these profound effects were produced. It was too difficult to do. Scientists were either scared or couldn't be bothered to overcome the enormous hurdles to get this done."

Specifically (Reynolds 2016):

> [Lead author Robin] Carhart-Harris, from Imperial, said that the brain on LSD becomes more "integrated or unified" as the separateness between different brain functions (i.e. vision, movement, hearing) starts to dissolve.

The study concludes (Carhart-Harris et al. 2016):

> Results revealed marked changes in brain blood flow, electrical activity, and network communication patterns that correlated strongly with the drug's hallucinatory and other consciousness-altering properties. These results have implications for the neurobiology of consciousness and for potential applications of LSD in psychological research.

This line of research is being actively pursued (Atasoy et al. 2017):

> We found that LSD alters the energy and the power of individual harmonic brain states in a frequency-selective manner. Remarkably, this leads to an expansion of the repertoire of active brain states, suggestive of a general re-organization of brain dynamics given the non-random increase in co-activation across frequencies. Interestingly, the frequency distribution of the active repertoire of brain states under LSD closely follows power-laws[29] indicating a re-organization of the dynamics at the edge of criticality.

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[27] Bundesratssitzung, May 13, 1992.

[28] See https://crowd.science/campaigns/lsd/.

[29] See Sect. 6.4.1.

The psychiatrist Franz X. Vollenweider has been studying the effects of psilocybin, especially in the context of meditation, for over 20 years at the University of Zurich (Vollenweider et al. 1997). He is one of a few researchers in the world holding such a track record. However, a senior member of the Swiss People's Party (SVP)—a right-wing populist political party—opposes his research (Tagesanzeiger 2014, translation mine):

> Drugs haze perception and blur reality. One can also have mystical experiences by going to church.

Notwithstanding, psychedelics are experiencing a cultural renaissance—from their usage at transformational festivals (Leung 2010), like Burning Man, to Silicon Valley tech geeks microdosing LSD (Leonard 2015; Solon 2016; Hogan 2017). In Switzerland, a faction of the center-right, pro-business party FDP is discussing the legalization of all illegal drugs (Simonsen and Ballmer 2018).

14.3.1 Healing the Mind

Perhaps the most astonishing aspect of the increased research activity into psychedelic substances is their therapeutic effect. In stark contradiction to the definition of a Schedule I drug, an array of substances, formaly only utilized as recreational or party drugs, is showing very promising signs of healing capacity (McClelland 2017). Indeed (Wordsworth 2017):

> "Mental health for years has been inadequately addressed, partly because the tools we had on offer were hard to scale, and partly because some of the most powerful tools in brain health were stigmatised and turned into scheduled drugs, effectively halting any progress that could be made to prove their efficacy," says Khaliya [Khan], public health specialist and mental health advocate. "The drugs I am referring to are psychedelic compounds like Psyciliciban [sic], LSD, MDMA, Ayahausca and 5-MeO-DMT."
>
> "In the past few years, the research into these drugs, while primarily small scale studies, has had phenomenal success. [They] hold the promise that we might finally be able to not just treat, but actually heal the brain."

Specifically, successfully treating post-traumatic stress disorder (PTSD) patients with MDMA (Mithoefer et al. 2018), alleviating the symptoms in depressed patients with Ketamine (Berman et al. 2000), and reduced anxiety in terminally-ill patients utilizing LSD (Gasser et al. 2014). Moreover (Horgan 2010):

> [D]octors at schools like Harvard, Johns Hopkins, UCLA and NYU are testing the potential of psilocybin and other hallucinogens for treating depression, obsessive-compulsive disorder, post-traumatic stress disorder, alcoholism—and for inducing spiritual experiences.

Such chemical support comes at a crucial time (Wong 2017):

> [T]reatment for depression, the most common mental illness, came to be dominated by drugs called selective serotonin reuptake inhibitors (SSRIs)[…]. But recently, […] more and more studies suggest SSRIs aren't as effective as we thought. […]

> Last year, at the Psychedelic Science 2017 conference in Oakland, California, a group led by Michael Mithoefer at the Medical University of South Carolina presented results from trials in which 107 people with PTSD underwent a psychotherapy while under the influence of MDMA. A year or so after having the therapy, roughly 67 per cent of them no longer had PTSD […]. […] [T]he FDA was so impressed that it granted MDMA "breakthrough therapy" status, which will accelerate the path towards approval. If all goes well, it could be in use as soon as 2021. […]
>
> [A]fter the combined psilocybin-psychotherapy session, the amygdala[responsible for emotions] lit up. And again, this effect correlated with how well people did: the greater the response in the amygdala, the more their symptoms improved [in contrast to SSRIs dampening those responses].

Moreover (Tatera 2016b):

> Ketamine leads to [the] "most significant advance in mental health in more than half a century" […] "My life will always be divided into the time before that first infusion [of Ketamine] and the time after," [a sufferer of 25 years of depression] told the *Washington Post* […]. "That sense of suffering and pain draining away. I was bewildered by the absence of pain."

Johns Hopkins researchers report on a study with psilocybin (Medicine 2006):

> One third [of participants] said the experience was the single most spiritually significant of their lifetimes; and more than two-thirds rated it among their five most meaningful and spiritually significant. […] 79 percent of subjects reported moderately or greatly increased well-being or life satisfaction compared with those given a placebo at the same test session. A majority said their mood, attitudes and behaviors had changed for the better.

In 2016, a new psychedelic science group was formed at Yale (Gardner 2016):

> Psychedelic science is enjoying revival after nearly 50 years of dormancy in clinical research settings and clinical practice. Most psychedelic substances have been classified as "drugs of abuse" with no recognized medical value since the early 1970s, when research into their use was terminated.

Other psychedelic research group include MAPS[30] and ALIUS.[31]

What about all the negative effects of such drugs? In 2010, a study was published in *The Lancet*, analyzing the dangers of various drugs along two dimensions: harm to user and harm to others. A ranking by overall harm score (in parenthesis), revealed: alcohol (72), heroin (55), crack cocaine (54), methamphetamine (33), cocaine (27), tobacco (26), amphetamine (23), cannabis (20), GHB (19), Ketamine (15), ecstasy (9), LSD (7), and mushrooms (6) (Nutt et al. 2010). It is ironic, and troubling, that two legal substances are leading the ranking. Notably, alcohol scores disproportionately high in the measure of harm to others, while crack cocaine, heroin, and methamphetamine reach high scores for the harm to the user. The 2017 Global Drug Survey,[32] the world's largest drug survey with over 110,000 participants from over 50 countries, reported the following post-consumption emergency treatment

[30] See https://maps.org/

[31] See http://www.aliusresearch.org/.

[32] See https://www.globaldrugsurvey.com/.

seeking (percentages in parenthesis): methamphetamine (4.8), synthetic cannabis (3.2), alcohol (1.3), MDMA/ecstasy (1,2), amphetamine (1.1), cocaine (1.0), LSD (1.0), cannabis (0.6), and mushrooms (0.2). However, as most users of illegal substances can never be sure of the exact composition of the drugs purchased from the black market,[33] it is unclear how many of these emergency treatments were due to contaminated or entirely different chemical compounds. In terms of overall dependence scores—averaging physical and psychological dependence and factoring in pleasure—where 3.0 represents the maximum, one ranking is found to be: heroin (3.0), cocaine (2.39), nicotine (2.21), barbiturates (2.01), alcohol (1.93), cannabis (1.51), LSD (1.23), and ecstasy (1.13) (Nutt et al. 2007). Yet again, nicotine and alcohol emerge as very potent and addictive substances, while psychedelics appear benign.

In the late 1970s, the psychologist Bruce Alexander separated rats into cages and gave them a choice of two water bottles to drink from—one of them laced with morphine. The cages were either isolatory ones or stimulating ones with playing opportunities and fellow rats. The latter became known as "rat park." Alexander wanted to measure the effect of the environment on addiction rates. In isolation, rats tended to overdose and die, while in "rat park" the drugged water appeared uninteresting (Alexander et al. 1978). This highlights the importance of social connection in the context of addiction. Next to the details of a person's brain architecture, the integration within a healthy web of interpersonal relationships can determine the fate of a drug user. In general (Hari 2015):

> For 100 years now, we've been singing war songs about addicts. I think all along we should have been singing love songs to them, because the opposite of addiction is not sobriety. The opposite of addiction is connection.

In this context, incarcerating drug users appears as the worst possible solution to the problem. Moreover, the current rampaging opioid crisis in the US is perhaps indicative of the disintegration of the social fabric. However, in a potentially bright future, the healing powers of psychedelics can also be utilized to break the gridlock of political ideology and help cultivate empathy, understanding, and social connectivity—reducing the fear driving people to embrace fascist ideals (see also Sect. 11.3.1 for the neurophysiological role of fear in political ideology formation).

The stigma associated with psychedelics still runs deep. Simply the word "psychedelic" conjures up the image of a drug-crazed hippie in many minds. A better word is "psychotropic," alluding to the capacity to affect the mind or mental processes. The journalist and author Michael Pollan is currently on a quest to correct the misinformation associated with psychedelics. Indeed, he observes (quoted in Oaklander 2018):

> The biggest misconception people have about psychedelics is that these are drugs that make you crazy. We now have evidence that that does happen sometimes—but in many more cases, these are drugs that can make you sane.

[33] Since 2001, the municipality of Zurich has an information center related to drug use. Free of charge and protected by confidentiality, users can have their drugs chemically analyzed. A counseling interview is, however, required. See https://www.saferparty.ch/.

In his book, persuasively titled *How to Change Your Mind: What the New Science of Psychedelics Teaches Us about Consciousness, Dying, Addiction, Depression, and Transcendence* (Pollan 2018), Pollan presents a combination of science, history, medicine, and personal experiences related to this new frontier of understanding. The science writer Jennifer Ouellette devoted a chapter, called *Feed Your Head*, in her book *Me, Myself, and Why: Searching for the Science of Self* (Ouellette 2014) to the troubled history and bright future of psychedelics. Then, the *New York Times* bestseller *Stealing Fire: How Silicon Valley, the Navy SEALs, and Maverick Scientists are Revolutionizing the Way We Live and Work* (Kotler and Wheal 2017) chronicles the phenomena of human peak performance. Psychedelics play an important role and we meet Shulgin and his wife Ann. He has been called a "genius biochemist"—or, alternatively, "a dangerous criminal" by the US Drug Enforcement Agency—and was the first to resynthesize ecstasy,[34] next to over 200 psychoactive substances (Petridis 2014). The Shulgins tested, and diligently documented, all the psychedelic substances themselves, specifically phenethylamines (Shulgin and Shulgin 2017a) and tryptamines (Shulgin and Shulgin 2017b). The resulting two books are called *PiHKAL* and *TiHKAL*, acronyms for *Phenethylamines/Tryptamines I Have Known And Loved* and total 1,782 pages. It is a safe guess that their minds have experienced states of being few other human minds will ever know. They also "argued passionately for the rights of the individual to explore and map the limits of human consciousness without government interference" (Power 2014). Finally, the psychiatrist Rick Strassman writes in his book *DMT: The Spirit Molecule: A Doctor's Revolutionary Research into the Biology of Near-Death and Mystical Experiences* (Strassman 2001, p. xviii):

> It is so important for us to understand consciousness. It is just as important to place psychedelic drugs in general, and DMT in particular, into a personal and cultural matrix in which we do the most good, and the least harm. In such a wide-open area of inquiry, it is best that we reject no ideas until we actually disprove them. It is in the interest of enlarging the discussion about psychedelic drugs that I've written *DMT: The Spirit Molecule*.

14.3.2 DMT: Down the Rabbit Hole

DMT is a simple organic chemical found in many plants and some animals (Carbonaro and Gatch 2016). Specifically, it occurs as N, N-dimethyltryptamine, seen in Fig. 14.2, or as 5-methoxy-N, N-dimethyltryptamine (5-MeO-DMT). It is a psychedelic tryptamine (Shulgin and Shulgin 2017b) and probably the most powerful psychedelic substance known to the human mind. DMT is also produced by the human brain, although it is not clear where and for what function. Endogenous DMT is hypothesized to be synthesized in the pineal gland and related to dream states and near-death experiences (Strassman 2001). DMT has been utilized in Amazonian shamanic traditions as ayahuasca—a brew from two plants, drunk as a sacred

[34] MDMA had been synthesized but forgotten (Petridis 2014).

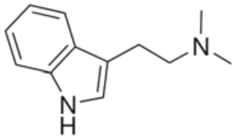

Fig. 14.2 The shape of DMT. The two-dimensional structure of *N*, *N*-dimethyltryptamine. Source: Wikimedia

medicine—since ages ago. Indeed, in these cultures the associated plants are understood as being connected to the origin of the world (Rätsch 1998, p. 9). In general (Horgan 2010):

> Why is DMT so fascinating? For starters, DMT is the only psychedelic known to occur naturally in the human body. In 1972, the Nobel laureate Julius Axelrod of the National Institutes of Health discovered DMT in human brain tissue, leading to speculation that the compound plays a role in psychosis. Research into that possibility—and into psychedelics in general—was abandoned because of the growing backlash against these compounds.
>
> In 1990, however, Rick Strassman, a psychiatrist at the University of New Mexico, obtained permission from federal authorities to inject DMT into human volunteers. Strassman, a Buddhist, suspected that endogenous DMT might contribute to mystical experiences. From 1990 to 1995, he supervised more than 400 DMT sessions involving 60 subjects at the University of New Mexico. Many subjects reported that they dissolved blissfully into a radiant light or sensed the presence of a powerful, god-like being.
>
> […]
>
> In *Antipodes of the Mind*[35] (Shanon 2002), the Israeli psychologist Benny Shanon, who has consumed ayahuasca more than 100 times, provides a gripping account of his own and others' visions. Shanon says the tea transformed him from a "devout atheist" into a spiritual believer awestruck by the mysteries of nature and the human mind. Yet Shanon, like Strassman, acknowledges that these hallucinogenic experiences pose risks. Quoting one ayahuasca shaman, Shanon warns that ayahuasca can also be "the worst of liars," leaving some users gripped by delusions.

DMT-induced visions can include—next to transcendental geometric shapes—robots, insects, and reptiles. McKenna coined the term "machine elves" for such apparently conscious entities inhabiting the psychedelic realm (McKenna 1993b, p. 114):

> We refer to the dynamic yet stable, apparently self-sustaining, non-three-dimensional spatiality into which the smoking of tryptamines conveys one. We especially refer to the apparently autonomous and intelligent, chaotically mercurial and mischievous machine elves encountered in the trance state, strange teachers whose marvelous singing makes intricate toys out of the air and out of their own continually transforming body geometries.

One may wonder about the possible implications of endogenous DMT release in the human brain. How much of mythology and how many reports of alien abduction could be the result of this?

Horgan reports his own experience (Horgan 2010):

[35] Horgan finds this one of the most compelling books on altered states he has ever read (Horgan 2003a), next to William James's *Varieties of Religious Experience* (James 1902), Huxley's *Doors of Perception* (Huxley 1954), and Shulgin's *PIHKAL* (Shulgin and Shulgin 2017a) and *TIHKAL* (Shulgin and Shulgin 2017b).

> I drank ayahuasca a decade ago while researching my book *Rational Mysticism* (Horgan 2003b). It tastes like stale beer dregs flavored with cigarette butts. After I threw up, I had a cosmic panic attack, in which I was menaced by malevolent, dayglo-hued polyhedra. I have no desire to repeat this experience.

In more detail, he explains (Horgan 2014a):

> The forms shifted, tumbled, quivered, danced with a kind of mischievous intelligence. They were showing off, trying to stagger me with ever-more-ostentatious displays of otherworldly beauty: Look at this! Okay, now check this out! […]
>
> All around me was a riot of color; the world dissolved into undifferentiated dayglo goo. A ten-foot pine tree at the bottom of the embankment quivered like a flame, fierce, fractal, exultant, discharging an unholy blue light. My head, too, sparked and crackled with electricity. Too much, I thought. I'm losing my mind. Too much. […]
>
> The colors became ever-more-dazzling, the shapes ever-more-complex, until there were no shapes and colors any more. They yielded to something deeper and more fundamental than shape, color, syntax, thought: the metaphysical principles underlying all things, the machine code of reality. […]
>
> I was seeing the future, long after humanity, and all of life, has vanished from the earth. The flame of consciousness has flickered out in the eternally expanding cosmos, and it has reverted to dumb, blind, painless, meaningless matter, as it must.

Others have probed the DMT realm with greater success and reported about its myriads of facets. For instance, the entomologist Adam Oliver Brown (Brown 2014):

> This is a form of purging in which the body is expelling this nasty bitter liquid in your stomach. But it's not just the physical purge, it's also a psychological one. Now, it seemed like there was a lot of vomiting going on. In retrospect, there wasn't. Because afterwards I looked in the bucket and there were only a few drops of spit […]. But at the time it really felt like there were these torrents of vomit coming out—and not to disgust you too much, for one, because it wasn't even vomit, it was snakes. So there were snakes oozing out of my nose and my mouth and this is quite literally what I was experiencing. […] It was very cathartic because these snakes felt like they were bringing demons up from inside and were cleansing my soul in the process. […]
>
> So not long after say 45 minutes into this, the first couple of layers of insect grids began to dissipate and I moved closer towards these bobbing pastel colored orbs of light, and managed to spend a little bit of time in that weird, strange cartoon kind of world until, all of a sudden, they came rushing at me, and I found myself blasted off into the universe on the back of some kind of fractal fireworks roller coaster. So I was traveling through the universe at light speed with the visuals becoming much, much more intense at this point, with colorful mandala's, the fractals opening and closing and spiraling around each other, like clockwork. So quickly I couldn't take it all in. And in fact at this point I was also physically being thrown around by the violent turbulence of the wild ride on this comet that I was traveling through the universe on. And again, I had to say to myself, this is so weird, because, rationally, I was able to recognize that there shouldn't be any lights. I'm in the dark in a hut in Peru. And why am I feeling like my body's being thrown around? So this was a really all-encompassing experience at this point and I have to admit, at this point, it was a little much for me and I started to panic, thinking "I don't like this anymore." I wanted to get off. But of course, you can't. You are on this ride until the very end. And at some point, I admitted that to myself and said, "Well we're just going to have to ride it out."
>
> But when that subsided we came down into this really thick, quiet, warm, emotionally laden place. It wasn't a room, it was like more of a zone and this zone was bordered by a big, red,

> velvety curtain. […] However, what did come next was truly astonishing to me. The curtain pulled back and revealed to me a scene—a forgotten scene—from my own childhood that was somewhat troubling emotionally. And I had forgotten about that scene probably since the very day it happened. But as soon as that curtain pulled back and I was witness to it again, I recognized it immediately as having been an important event in my life, that I somehow had repressed. And what was interesting about this is while I was re-experiencing this slightly traumatic scene from my childhood, I wasn't revisiting any of the emotional trauma associated with. It it was like I was a third party observer impartially and objectively being able to watch my life story and to be to determine why or how it was important to me becoming who I was as an individual. It was almost like I wasn't seeing what was happening, but I was being told why what I was seeing was important to how I became as an individual later on in my life. And so over the course of the next hour or so these curtains continued to part and presented me with these astonishingly vivid memories that I had forgotten about. […]
>
> So the point here folks is not a story about recreational drug tourism. It's about illustrating the potential for these chemicals to help us. To help us heal ourselves, our health, our psychology, and our societies.

A synthetic form of DMT can be smoked as a crystalline substance. After a sucession of tokes the effects set in, lasting about ten minutes in physical time. In comparison, an ayahuasca journey can last up to twelve hours. The effects include[36]:

> Immersion into very bizarre worlds, separation of mind and body, dissolution of ego, and a feeling of unity with the cosmos are the rule, near death experiences common.

There are countless personal reports of DMT-induced experiences posted online.[37] The magazine *Vice* interviewed people who had just smoked DMT (Barclay 2012):

> Within a few seconds of inhaling its thick, harsh smoke, one is taken to a place very different from what most contemporary Westerners refer to as reality. While there is a lot of debate regarding where that place exists (or if it exists, or if anything exists for that matter), it can be said with absolute certainty that DMT Town looks very cool. The passenger is immediately overwhelmed with exotic patterns, colors, textures, emotions, and other things that we don't yet have words for.
>
> "I felt what God was like. It was something that was smaller than anything. It's not made of anything—it is everything around the thing that it is and everything inside of it at the same time and it kind of moves about in a way that's not on the grid.
>
> "You're beyond consciousness—but you are consciousness—and you want nothing to tie you down to this physical realm."
>
> "Almost the strangest part is how quickly you come down. With acid it lingers for a day sometimes—the whole next day you feel weird. With this you pretty much feel normal almost immediately afterwards."

Another user reports[38]:

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[36]Take from https://de.know-drugs.ch/, retrieved August 24, 2018; translation mine.

[37]For instance https://www.reddit.com/r/DMT/, https://www.erowid.org/experiences/subs/exp_DMT.shtml, https://www.dmt-nexus.me/forum/default.aspx?g=topics&f=3, and https://www.dmt-nexus.me/forum/default.aspx?g=topics&f=71.

[38]See https://www.dmt-nexus.me/forum/default.aspx?g=posts&m=187288.

> Where I went I can't even fathom. The image zoomed out and it was revealed I was in a colossal grid of light, and I knew instantly that this was EVERYTHING. It's like zooming out from the planets, galaxies and beyond, further and further, until what you find is this. The grid. In the grid nothing makes sense, and everything makes sense. Words are meaningless.

And[39]:

> At this point I closed my eyes. I remember being frightened. I was met with a cartoonish place. It almost felt like some kind of a school of sorts, a mathematical place. Where bits of me were disintegrating, piece by piece, into this mathematical structure.

Finally, Pollan reports his experiences with 5-MeO-DMT in the smoked venom of the Sonoran Desert toad (Pollan 2018):

> "This is the Everest of psychedelics," she began, portentously, putting a steadying hand on my forearm. Olivia is in her early fifties, a management consultant with a couple of kids; I had vaguely known she was into Eastern religion but had no idea she was a psychonaut, too. "You need to be prepared." [P. 375]
>
> I have no memory of ever having exhaled, or of being lowered onto the mattress and covered with a blanket. All at once I felt a tremendous rush of energy fill my head accompanied by a punishing roar. I managed, barely, to squeeze out the words I had prepared, "trust" and "surrender." These words became my mantra, but they seemed utterly pathetic, wishful scraps of paper in the face of this category 5 mental storm. Terror seized me—and then, like one of those flimsy wooden houses erected on Bikini Atoll to be blown up in the nuclear tests, "I" was no more, blasted to a confetti cloud by an explosive force I could no longer locate in my head, because it had exploded that too, expanding to become all that there was. Whatever this was, it was not a hallucination. A hallucination implies a reality and a point of reference and an entity to have it. None of those things remained. [P. 378]
>
> Unfortunately, the terror didn't disappear with the extinction of my "I." Whatever allowed me to register this experience, the post-egoic awareness I'd first experienced on mushrooms, was now consumed in the flames of terror too. In fact every touchstone that tells us "I exists" was annihilated, and yet I remained conscious. "Is this what death feels like? Could this be it?" That was the thought, though there was no longer a thinker to have it. [P. 378f.]
>
> Here words fail. In truth, there were no flames, no blast, no thermonuclear storm; I'm grasping at metaphor in the hope of forming some stable and shareable concept of what was unfolding in my mind. In the event, there was no coherent thought, just pure and terrible sensation. Only afterward did I wonder if this was what the mystics call the *mysterium tremendum*, the blinding unendurable mystery (whether of God or some other Ultimate or Absolute) before which humans tremble in awe. Huxley described it as the fear "of being overwhelmed, of disintegrating under a pressure of reality greater than a mind, accustomed to living most of the time in a cosy world of symbols, could possibly bear." [P. 379]
>
> The other metaphor was the big bang, but the big bang run in reverse, from our familiar world all the way back to a point before there was anything, no time or space or matter, only the pure unbounded energy that was all there was then, before an imperfection, a ripple in its waveform, caused the universe of energy to fall into time, space, and matter. Rushing backward through fourteen billion years, I watched the dimensions of reality collapse one by one until there was nothing left, not even being. Only the all-consuming roar. It was just horrible. [P. 380f.]
>
> And then suddenly the devolution of everything into the nothingness of pure force reverses course. One by one, the elements of our universe begin to reconstitute themselves: the

[39] See https://erowid.org/experiences/exp.php?ID=111779.

> dimensions of time and space returned first, blessing my still-scattered confetti brain with the cozy coordinates of place; this is somewhere! And then I slipped back into my familiar "I" like an old pair of slippers and soon after felt something I recognized as my body begin to reassemble. The film of reality was now running in reverse, as if all the leaves that the thermonuclear blast had blown off the great tree of being and scattered to the four winds were suddenly to find their way back, fly up into the welcoming limbs of reality, and reattach. The order of things was being restored, me notably included. I was alive! [P. 381]
>
> I felt for the first time gratitude for the very fact of being, that there is anything whatsoever. Rather than being necessarily the case, this now seemed quite the miracle, and something I resolved never again to take for granted. Everybody gives thanks for "being alive," but who stops to offer thanks for the bare-bones gerund that comes before "alive"? I had just come from a place where being was no more and now vowed never to forget what a gift (and mystery) it is, that there is something rather than nothing.[40] [P. 382f.]

An interesting observation is that the human brain appears to have the final authority with respect to its own experience creation. Not always do psychedelics result in altered states of consciousness. I have been confronted with anecdotal evidence that the ingestion of LSD or ayahuasca left the consumer waiting in vain for the psychotropic effects. It seems as if, some days, the brain simply refuses to change gears. Also, there could exist a personal predisposition or affinity with respect to how drugs are experienced. This can perhaps explain why the avid psychonaut Watts surprisingly assesses DMT as "amusing but relatively uninteresting" (Watts 1971, p. 82).

It is truly astonishing that a single molecule, ubiquitous in nature, has the capacity to hijack our entire cognitive apparatus and "teleport" our consciousness into a realm transcending space and time, sometimes inhabited by alien entities of consciousness. What is also intriguing, is that these are entirely subjective experiences made by individual minds. One cannot share them. Any attempts at communicating their contents are severely restricted by our "normal" conceptuality, shaped during sober waking consciousness, thoroughly inadequate at capturing the reality of these transcendental realms of consciousness. Either a human mind has experienced such otherworldly states first-hand—harboring faint memories of the events ever after—or creative attempts at imagining the ineffable are made. Similarly to the abstract notions of infinity and zero, my mind can at best speculate about what it could mean to experience a non-material reality outside of space and time. However, people are attempting to contextualize the DMT realm (Kotler and Wheal 2017):

> [T]he Hyperspace Lexicon reflects a collective effort to codify and make sense of the utterly novel landscape of DMT (which aficionados refer to as "hyperspace"). The Lexicon is packed with neologisms that would have made James Joyce proud. Among many others, there's "*lumenorgastic*," for the orgasmic experience of white light; "*mangotanglement*," referring to the brightly colored fractal building blocks of DMT reality; and "*ontoseismic*," for the utter shattering of your worldview after glimpsing the DMT universe.

Psychonauts recount their observations of grids, mathematical structures, or the machine code of reality lurking behind the veils of physical reality, next to interacting with alien conscious entities. Within the prevailing materialistic and reductionistic

[40] See Sect. 8.1.2.

scientific worldview, such narratives are understood as being absurd. However, we have seen that this paradigm is currently crumbling (Chap. 10) and being replaced (Chap. 13), opening up the possibility of pragmatic and impartial explorations of these outer realms of existence. Furthermore, the various different pieces of understanding which could be brought back to the "normal" realm of reality that our minds inhabit, speak of the same architecture of these netherworlds. This can be seen by the similar "sacred geometries" expressed in different cultures. Indeed, how much of the awakening of the human mind has been influenced by certain chemical substances?

14.3.3 Cultural Roots

The human species is not the only one that knows about altered states of being and craves them. Within the animal kingdom, "getting high" is no rarity. For instance, early primates' ethanol consumption from fermented fruits (Carrigan et al. 2015); alcohol self-administration by elephants (Siegel and Brodie 1984); vervet monkeys on the Caribbean island of St. Kitts and their problems with alcohol (Palmour et al. 1997); the effects of catnip on most domestic cats; opium-eating wallabies (Williams 2010); jaguars consuming Yage vine, one of the ingredients of ayahuasca (Anderson 2013); and dolphins consuming the toxins of pufferfish (Nuwer 2013).

McKenna put forward the "stoned ape" theory of human evolution (McKenna 1993a). He argues that the key driver of Homo sapiens' remarkable explosion of cognitive capabilities was due to the influence of psilocybin mushrooms. As McKenna's thesis cannot be substantiated by much evidence, it has been ignored by the scientific community. However, as shamanic traditions emerged around the globe at the dawn of the modern human mind, it is perhaps not all too unreasonable to expect at least some cultural influence from the use of psychedelics. For instance, the anthropologist and ethnopharmacologist Christian Rätsch—who traveled the world to partake in a great number of psychedelic shamanic rituals of many indigenous people[41]—observed the following (Rätsch 1998, p. 635, translation mine):

> Indeed, it is quite possible that Santa Claus, who is always dressed in red and white garments and flies through the skies with his team of reindeer, is simply an anthropomorphized fly agaric mushroom or fly agaric shaman.

Perhaps only people who have themselves ventured into the psychedelic realm are open to such fantastic ideas.

In his book, called *A History of the World in 6 Glasses*, Tom Stanadage recounts the importance of certain psychoactive beverages since the dawn of humanity. In particular (Standage 2006, p. 134f.):

> This spirit of rational inquiry spread into the mainstream of Western thought over the next two centuries, culminating in the movement called the Enlightenment, as the empirical, skeptical approach adopted by scientists was applied to philosophy, politics, religion, and commerce. [...]

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[41] In an interview, he alleged that of all drugs, alcohol is the most dangerous (Mingels 2013).

> The diffusion of this new rationalism throughout Europe was mirrored by the spread of a new drink, coffee, that promoted sharpness and clarity of thought. It became the preferred drink of scientists, intellectuals, merchants, and clerks—today we would call them information workers—all of whom performed mental work sitting at desks rather than physical labor in the open. […]
>
> The impact of the introduction of coffee into Europe during the seventeenth century was particularly noticeable since the most common beverages of the time, even at breakfast, were weak "small beer" and wine. Both were far safer to drink than water, which was liable to be contaminated, particularly in squalid and crowded cities.

Perhaps even the computer revolution has some of its roots in psychedelics. In 2008, the programmer Dennis R. Wier made a confession. He was the chief architect for one of the biggest programming projects in 1975. Then (Wier 2008):

> At one point in the project I could not get an overall viewpoint for the operation of the entire system. It really was too much for my brain to keep all the subtle aspects and processing nuances clear so I could get a processing and design overview. After struggling with this problem for a few weeks, I decided to use a little acid to see if it would enable a breakthrough […]. […]
>
> While stimulated by the LSD I was able to get the entire system wholly in my mind at the same time. I spent some time mentally visualizing various aspects of the compiler, the language and the processing which would take place. I did discover three or four design inconsistencies while being stimulated by the effect of the LSD, and I made notes for later checking.
>
> After twenty-four hours when the effect of the LSD was completely gone, I went over my notes. I needed to have a measure of "faith" that the design changes suggested by my notes would produce the beneficial effects they seemed to imply […]. […]
>
> Once all the changes were made, I was able to successfully complete the programming of this huge system. […] Although the use of LSD was an important component of the success of the system, no one knew of its use except me.

Steve Jobs and other computer pioneers believed that LSD helped their creativity (Grossman 2011).

14.3.4 Plant Consciousness

At the 2018 *Swiss Biennial on Science, Technics + Aesthetics*,[42] Susana Bustos, a psychologist and scholar of Amerindian shamanic traditions, explained the concept of *Vegetalismo*. This is the process by which the shamans are said to gain their knowledge and power to cure diseases. This knowledge originates from the plants—specifically the transcendental states induced by ayahuasca. A central element is the *icaro*, a "song" of the plant which the shaman tries to get to resonate in the sick person, inducing healing (Bustos 2004; Callicott 2013). In effect, the plants are at

[42]Recall Chap. 11 and Sect. 14.2.2

the center of the Amerindian cosmology. Indeed, “Mother Ayahuasca” is reported as being the spiritual source of divine insights. In detail[43]:

> “Some people come away from drinking ayahuasca thinking it is a very real, living entity,” says anthropologist Christine Holman of Arizona State University. “The people that believe in her believe that very strongly. They call her Mother Ayahuasca.” But experienced ayahuasca-drinkers say only Mother Ayahuasca knows whether she will reveal her nurturing side or instead unleash terror.

In a therapeutic context (Labate and Cavnar 2013, p. 141):

> Patients and therapists alike emphasized that ayahuasca can function as an “inner mirror” that allows one to readily accept previously denied aspects of the psyche that are usually difficult to address in therapeutic contexts. […] However, it seems that confrontation stemming from within or from a perceived spiritual source, such as “Mother Ayahuasca,” “Mother Earth” or “God” can be better received, integrated, and contained by patients […].

In detail (Kent 2010, p. 116):

> The extreme diets and psychedelic medicine catalyze spontaneous stress-based reorganization of neural identity structures, and the shamanic mythology creates the semantic frame through which the subject parses the transformational experience.

The author Claus von Bohlen explains the following[44]:

> South American shamans believe in “teacher plants”. These are plants whose spirits will guide you and teach you, when you ingest the plant itself. That is of course a belief that is challenging from a Western scientific perspective. However, many people will say that they have gained new insights and perspectives from alterations in consciousness […].

Sitting in the Amazon rain-forest, engulfed by countless shades of green representing a myriad of botanical diversity, the following question seems natural[45]:

> I remember asking her [the shaman] how the indigenous peoples of the Amazon came by their knowledge of healing and medicinal plants, and particularly Ayahuasca, which requires two separate plants to be boiled together for a number of hours in order to have any effect. She looked at me as if I had asked a very foolish question, then she replied, “That’s what the spirits teach us.”

Indeed, if humans directly ingest the DMT-containing component of ayahuasca, nothing will happen. Monoamine oxidase inhibitors (MAOIs) are required to unleash the psychedelic effects. These are found in the other ingredient. If this knowledge was not received by otherworldly means, then one is faced with uncountable possible combinations of plant substances which would have to be tested by trial and error for their psychedelic effects.

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43 See http://sciencenotes.ucsc.edu/2011/pages/ayahuasca/ayahuasca.html, retrieved August 27, 2018.

44 See http://www.clausvonbohlen.com/post/155437462934/teacher-plants, retrieved August 27, 2018.

45 See http://www.clausvonbohlen.com/post/155437462934/teacher-plants, retrieved August 27, 2018.

Why does such an abundance of chemicals exist in nature which can alter—and greatly enhance—the normal functioning of the sober waking state of the human mind? Why did this chemical affinity emerge? Some psychedelic substances are toxic, but others, like psilocybin, are not. DMT is even produced by the human brain. What is their function? Indeed, in the book *The Encyclopedia of Psychoactive Plants: Ethnopharmacology and Its Applications*, Rätsch describes a breathtaking array of psychoactive plants in a thousand page tour-de-force (Rätsch 2005). The human brain is immersed in a vast chemical landscape able to contest the primacy of sober waking reality. In contrast, a world in which no plant component has the power to modify human cognition could easily be imagined, where intoxication simply leads to unconsciousness. In detail, why do specific receptors in mammalian cells exist that recognize a plant-derived substance? As an example, the endocannabinoid system in the human brain is important for various physiological functions. It is surprising that the brain has a complex system of interacting chemicals related to cannabis (Pacher et al. 2006). Interestingly (Pacher et al. 2006):

> Marijuana, or cannabis, is the most widely used illicit drug in Western societies and also the one with the longest recorded history of human use.

The reality we perceive is a function not only of our neural hardwiring but crucially also of the chemical substances present in the brain. The evolutionary optimized state of sober waking consciousness is only one in a vast array of possibilities. Synthesized by plants, animals, and even the human brain, such chemicals can appear to give access to novel realms of reality.

Finally, the plant "consciousness" encountered in ayahuasca is currently also cultivating an emerging global environmental sensibility, a much needed antidote to the threatening environmental crises humanity is instigating (Hill 2016):

> Over the last 25 years or so ayahuasca has gone global, with many 1000s of people travelling to Peru and other South American countries to drink it, and expert healers—curanderos, shamans, ayahuasqueros, maestros—travelling abroad to hold ceremonies. […]
>
> "[Ayahuasca is] the conduit to a body of profoundly ancient genetic and evolutionary wisdom that has long abided in the cosmologies of the indigenous peoples of the Amazon who have guarded and protected this knowledge for millennia, who learned long ago that the human role is not to be the master of nature, but its stewards," [Dennis] McKenna wrote [the younger brother of Terence]. "Our destiny, if we are to survive, is to nurture nature and to learn from it how to nurture ourselves and our fellow beings. This is the lesson that we can learn from ayahuasca, if only we pay attention."

14.3.5 The Noumenon

For Kant, the human mind can ever only access the phenomenal world of the senses. Even space and time are categories of the mind and not features of true reality (see introduction to this chapter). The underlying reality, called the noumenon—

the thing-in-itself—can never be known. DMT users have reported of glimpsing the noumenon[46]:

> I felt like I was viewing the true nature of reality, but I was in some kind of limited room because I was only a human and didn't have the eyes to see or whatever.

People talk about notions like "the control room of reality" and "behind the veils of reality" when describing the DMT realm.

Taking a step back (Gallimore 2014):

> It is comforting to see the world around us as being somehow fixed, solid and, most importantly, real. But it only takes a lungful of *N*, *N*-dimethyltryptamine (DMT) to shatter this delusion. Whether the external world-in-itself, the noumenal world, is truly real is difficult to answer and, for the purposes of this discussion, it really doesn't matter. The only world we can ever experience is the phenomenal world—the world that appears to consciousness. As far as we know, the phenomenal world is never transcendent—it never reaches out and touches the noumenal world; it is always in the head. Thomas Metzinger (Metzinger 2009) expresses it clearly:
>
>> The global model of reality constructed by our brain is updated at such great speed and with such reliability that we generally do not experience it as a model. For us, phenomenal reality is not a simulational space constructed by our brains; in a direct and experientially untranscendable manner, it is the world we live in.
>
> For most people and for most of the time, this phenomenal world appears stable and predictable, but only because the brain has evolved to generate a stable and predictable model of the noumenal world. However, psychedelic drugs, such as DMT, LSD and psilocybin, among others, not only show us that the phenomenal world can become fluid, unpredictable and novel, but that it can be annihilated in an instant and replaced with a world altogether stranger than anything we can imagine. It is tempting to regard such perceptual aberrations as just that—"tricks of the mind", hallucinations, illusions or, if we want to appear especially smart, "false perceptions". But such a self-assured attitude is hard to justify, as deciding what is true and what is false about our perceptions is far from trivial.
>
> […]
>
> It is all too easy to assume that consensus reality is a privileged model of reality, the truest model, the real thing. But, as we have seen, it is actually just a tiny subspace within a much broader reality topology available to the brain's extraordinary information-generating machinery and, with the aid of a select number of natural and synthetic psychedelic drugs, this entire topology may become accessible and open to exploration.

Most people who have journeyed to the DMT realm argue that what they have experienced is just as real as experiences made during the sober waking state—if not much more so. As mentioned, it is tempting to disregard such experiences as hallucinations—nothing more, nothing less. However, this raises philosophical questions. Recall that neuroscientists are quite clear: Our perception of reality is a hallucination tethered by a bit of sensory input (Sect. 11.2.1). What I experience through sober waking consciousness is an elaborate virtual reality rendering in my brain. The nature of this hallucination can be modulated by the chemical composition

[46]See https://www.dmt-nexus.me/forum/default.aspx?g=posts&t=39663, retrieved August 27, 2018.

of the brain. Crucially, the DMT produced by my own body has the potential to intrinsically and naturally modify the contents of my consciousness—by "teleporting" my mind to the DMT realm. Indeed, simply by shutting down the left hemisphere of the human brain appears to induce travels of the mind, allowing consciousness to access a "place" of peace and euphoria (recall Bolte Taylor's experiences in Sect. 11.3.3). How can I then be certain that the fidelity and truth content of the one hallucination is superior to the other? What epistemic guarantee do I have that would allow me to negate the reality of the DMT realm? How can I exclude the possibility that reality is indeed "queerer than we can suppose" (Sect. 12.4.4) and everything I have ever known about is metaphorically restricted to a tiny isolated island in a vast archipelago of transcendental existence?

Moreover, we are faced with the startling possibility of otherworldly knowledge generation. Next to the amazing mechanisms of knowledge generation utilizing formal thought systems (Chaps. 2 and 5), these transcendental sources of information represent an orthogonal approach to understanding. Medicine men in shamanic traditions have been utilizing otherworldly knowledge for healing purposes for millennia (Luna and White 2006, p. vii):

> Any attempt to understand Amerindian cosmology, spirituality, and artistic manifestations must include a knowledge of shamanism in addition to the central importance given to the ritual use of psychotropic plants, including tobacco and coca, perhaps the oldest of all the psychoactive plants of the Americas, dating at lest 6,000 BCE.

Roland Loomis, also known as Fakir Musafar, was a US American performance artist and a pioneer of the modern primitive movement. He was known for extreme body modifications, including tattooing, body piercing, scarification, and flesh hook suspension. Loomis personally explored many rituals and built, for instance, a bed of nails and a bed of blades on which he would lay. "After an hour of surrender to the blades, I drift off and forget where I am" (Musafar 2005, p. 46). "After an hour, I trance out and feel like I am floating about 30 cm above the wicked spikes. I am warm and comfortable. I have visions and inner travels" (Musafar 2005, p. 50). His book, called *Spirit and Flesh*, opens with: "The images in this book may disturb you" (Musafar 2005, p. 8). He recounts a journey of his consciousness, initiated by extreme physical tourment, and the obtaining of otherworldly knowledge (Musafar 2005, p. 83):

> Because I made permanent holes in my breasts in 1975, I was able to experience Native American body rituals [...]. Because I had suspended from them several times, I was no longer afraid to let go and hang freely from these two piercings. [...] *Mandan O-Kee-Pa* suspension [a complex ceremony of the Mandan Native American tribe] were done in a darkened lodge. It was a rite of passage for young men and a way for elder medicine men the leave their bodies and reconnect with the powers beyond earth. I was now the elder medicine man. I left my body and met the Great Mystery, my own White Light, face-to-face. We had a telepathic conversation in that timeless place that is not a place. I received the answers to many mysteries that had puzzled me for years.

The seasoned psychonaut Rätsch explains in an interview (Mingels 2013, translation mine):

> *Rätsch:* You probably believe that the [LSD] visions are projections of the brain?
>
> *Reporter:* Of course.
>
> *Rätsch:* This is a stupendous error. The other [psychedelic] reality is always there. Namely, inherent in our world. Some physicists even say that there are infinitely many simultaneously existing universes.
>
> *Reporter:* But you say you were a jaguar [during an LSD experience], which is clearly a projection of the brain! Or are you really claiming that now you also exist as a jaguar?
>
> *Rätsch:* Not in this reality. Not now, not here in this kitchen in my apartment. We cannot access the jaguar-reality at the moment. Unless we would take some LSD.

In summary (Kent 2010, p. 158):

> Spirit contact is a central part of many psychedelic practices. While the autonomy of spirit entities is a subject for endless metaphysical debate, the reports of seeing spirits under the influence of psychedelics are common enough to make some generalizations. First, psychedelic entities are anthropomorphic interfaces through which psychedelic information is generated or transmitted. Second, formal spirit types represent idealized versions of specific information matrices: cellular, insect, plant, animal, ancestral, mythic, alien, pagan, machine, cosmic, and so on, and each type of spirit reveals different insights into the ordered nature of life and the universe. Third, psychedelic spirits are tricksters; they often speak in riddles, communicate in visual rebus and pantomime, and typically never give a straight answer to inquiries. From an information standpoint it does not matter if the spirits are real or delusion, the information they generate is real and can be analyzed from a formal perspective.

Metzinger asked, "How do you know that you actually woke up this morning?" (Sect. 11.2.2). Perhaps the more accurate, and pressing, question is "How do you know that you are not 'high' right now?"

14.4 A Participatory Ontology

In Chap. 13, specifically Sect. 13.4, the case for an information ontology was made. At the intersection of theoretical physics and theoretical computer science a new paradigm is emerging, replacing the current materialistic and reductionistic scientific worldview. In this novel understanding, information is the ethereal building block of reality. The very real possibility that our universe is a hologram, or even a simulation, was discussed. In this chapter, the idea that information has an inner aspect was introduced, giving rise to the subjective world emerging in minds. In this paradigm, consciousness is understood as primal and distributed. Indeed, panpsychism offers a solution, albeit an unexpected one, to the age old challenge of unifying the subjective with the objective (Sect. 11.1). It was also discovered that intelligence is an emergent phenomenon which can attach itself even to non-living matter (Sect. 14.2.4). Finally, psychonauts have been speaking of transcendental realms of existence since the beginning of time—planes of reality which can be accessed by disembodied consciousness. We find ourselves being conscious actors on a vast, intricate, and multifaceted stage of reality, comprising countless ineffable otherworldly realms.

However, what if we are in fact not actors at all, but creators? What if we inhabit a reality with a participatory ontology?

The eminent physicist John Wheeler[47] was instrumental in initiating the information-theoretic paradigm shift (Sect. 13.2). In the same sentence where he introduces this outlandish idea—it from bit—he also outlines the notion of metaphysical participation. He explains these notions as follows (Wheeler 1990):

> [I]n short, that all things physical are information-theoretic in origin and this is a participatory universe.

In more detail (Horgan 2011):

> Wheeler once explained this concept to me by comparing a scientist to someone playing the "surprise version" of the old game 20 Questions. In this variant, the Guesser leaves the room while the rest of the group—or so the excluded person thinks—agrees on some person, place or thing. The Guesser then re-enters the room and tries to guess the group's secret with a series of questions that can only be answered with a yes or a no.
>
> But the group has decided to play a trick on the Guesser. The first person to be queried will only think of something *after* the Guesser asks his question. Each subsequent person will do the same, making sure that his or her response is consistent with all previous questions. "The word wasn't in the room when I came in even though I thought it was," Wheeler noted. In the same way, physical reality exists in an indeterminate limbo before we pose our questions. "Not until you start asking a question, do you get something." We live in a "participatory universe," Wheeler suggested, which emerges from the interplay of consciousness and physical reality, the subjective and objective realms.

As a consequence (Heaven 2015):

> For Wheeler, this meant the universe couldn't really exist in any physical sense—even in the past—until we measure it. And what we do in the present affects what happened in the past—in principle, all the way back to the origins of the universe. If he is right, then to all intents and purposes the universe didn't exist until we and other conscious entities started observing it.

Remarkably, Wheeler's delayed choice experiment (Wheeler 1978)—where a choice made now by an observer can change or edit the past of a photon—has been experimentally confirmed and published in the prestigious journal *Science* (Jacques et al. 2007):

> Our realization of Wheeler's delayed choice Gedanken Experiment demonstrates beyond any doubt that the behavior of the photon in the interferometer depends on the choice of the observable which is measured, even when that choice is made at a position and a time such that it is separated from the entrance of the photon in the interferometer by a space-like interval [i.e., by a separation where events cannot affect each other].

The philosopher of science, Paul Feyerabend, harbor a similar intuition with respect to the participatory nature of the universe (Feyerabend 2008, p. 270):

> What we find when living, experimenting, doing research is therefore not a single scenario called "the world" or "being" or "reality" but a variety of responses, each of them constituting a special (and not always well-defined) reality for those who have called it forth. This is relativism because the type of reality encountered depends on the approach taken.

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[47] "[O]ne of the most influential scientists of the twentieth century" (Barrow et al. 2004, back cover).

Indeed, the notion of a participatory reality is also found in Kant's philosophy. In summary (Tarnas 1991):

> The a priori forms and categories serve as absolute conditions of experience. They are not read out of experience, but read into it. They are a priori, yet empirically applicable and applicable only empirically, not metaphysically. For the only world that man knows is the empirical world of phenomena, of "appearances," and that world exists only to the extent that man participates in its construction. We can know things only relative to ourselves. Knowledge is restricted to the sensible effects of things on us, and these appearances or phenomena are, as it were, predigested. Contrary to the usual assumption, the mind never experiences what is "out there" apart from the mind in some clear, undistorted mirroring of objective "reality." Rather, "reality" for man is necessarily one of his own making, and the world in itself must remain something one can only think about, never know. [P. 344f.]
>
> In terms of scientific knowledge, the world could not be said to exist complete in itself with intelligible forms that man could empirically reveal if only he would clear his mind of preconceptions and improve his senses by experiment. Rather, the world that man perceived and judged was formed in the very act of his perception and judgment. Mind was not passive but creative, actively structuring. [P. 347]

This astute and eloquent summary of Kant's ideas was given by the historian Richard Tarnas. In his bestseller, called *The Passion of the Western Mind: Understanding the Ideas That Have Shaped Our World View*, he analyzes the thinking of the last two and a half millennia. His powerful and penetrating analysis immerses the reader in the epic journey of the human mind grappling with reality and its own existence. In the chapter, called *The Postmodern Mind*, Tarnas observes (Tarnas 1991, p. 396):

> Reality is not a solid, self-contained given but a fluid, unfolding process, an "open universe," continually affected and molded by one's actions and beliefs. [...]. Reality is in some sense constructed by the mind, not simply perceived by it, and many such constructions are possible, none necessarily sovereign.

He outlines his conclusions in the epilogue, where he empathetically and persuasively argues for a participatory epistemology (Tarnas 1991, p. 396):

> The consensus is decisive: The world is in some essential sense a construct. Human knowledge is radically interpretive. There are no perspective-independent facts. Every act of perception and cognition is contingent, mediated, situated, contextual, theory-soaked. Human language cannot establish its ground in an independent reality. Meaning is rendered by the mind and cannot be assumed to inhere in the object, in the world beyond the mind, for that world can never be contacted without having already been saturated by the mind's own nature. That world cannot even be justifiably postulated. Radical uncertainty prevails, for in the end what one knows and experiences is to an indeterminate extent a projection. [P. 418f.]
>
> The new conception fully acknowledged the validity of Kant's critical insight, that all human knowledge of the world is in some sense determined by subjective principles; but instead of considering these principles as belonging ultimately to the separate human subject, and therefore not grounded in the world independent of human cognition, this participatory conception held that these subjective principles are in fact an expression of the world's own being, and that the human mind is ultimately the organ of the world's own process of self-revelation. In this view, the essential reality of nature is not separate, self-contained, and complete in itself, so that the human mind can examine it "objectively" and register it from without. Rather, nature's unfolding truth emerges only with the active participation of the human mind. Nature's reality is not merely phenomenal, nor is it independent and objective;

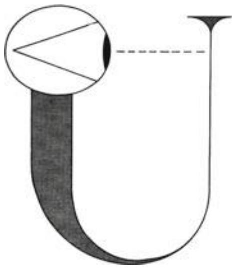

Fig. 14.3 A participatory universe. Wheeler's illustration of the notion, taken from Wheeler (1980), Fig. 22.13

> rather, it is something that comes into being through the very act of human cognition. Nature becomes intelligible to itself through the human mind. [P. 434]

> I believe there is only one plausible answer to this riddle [related to the philosophy of science, genuine knowledge, Popper, Kuhn and Feyerabend], and it is an answer suggested by the participatory epistemological framework outlined above: namely, that the bold conjectures and myths that the human mind produces in its quest for knowledge ultimately come from something far deeper than a purely human source. They come from the wellspring of nature itself, from the universal unconscious that is bringing forth through the human mind and human imagination its own gradually unfolding reality. In this view, the theory of a Copernicus, a Newton, or an Einstein is not simply due to the luck of a stranger; rather, it reflects the human mind's radical kinship with the cosmos. It reflects the human mind's pivotal role as vehicle of the universe's unfolding meaning. In this view, neither the postmodern skeptic nor the perennialist philosopher is correct in their shared opinion that the modern scientific paradigm is ultimately without any cosmic foundation. For that paradigm is itself part of a larger evolutionary process. [P. 436f.]

Within the information-theoretic paradigm, the jump from a participatory epistemology to a participatory ontology is perhaps only a small one. Wheeler once mused (quoted in Horgan 1997, p. 84):

> At the heart of everything is a question, not an answer. When we peer down into the deepest recesses of matter or at the farthest edge of the universe, we see, finally, our own puzzled faces looking back at us.

By thinking the idea of an information-theoretic reality to its radical conclusion, he realized (paraphrased in Gefter 2014):

> The universe has created an observer and now, in an act of quantum measurement, the observer looks back and creates the universe. Wheeler scribbled a caption beneath the drawing: "The universe as a self-excited system."

The drawing is depicted in Fig. 14.3. We all are the universe observing itself. This conclusion has not escaped others. Recall from the Preface the insight of Sagan:

> We are a way for the cosmos to know itself.

Also, the musings of Watts:

> Through our eyes, the universe is perceiving itself. Through our ears, the universe is listening to its harmonies. We are the witnesses through which the universe becomes conscious of its glory, of its magnificence.

In the words of an entirely different paradigm (Harvey 2005):

> [A]nimism is a sophisticated way of both being in the world and of knowing of the world; it is a relational epistemology and a relational ontology.

In the final analysis, panpsychism offers the conscious fabric from which the universe is tailored.

14.4.1 The Quantum Observer

The reason physicists wade out into the murky waters of metaphysics is driven by quantum mechanics (Sects. 4.3.4 and 10.3.2). The emergence of an observer has vexed the physics community since the discover of the quantum realm of reality in 1901. Indeed (Rosenblum and Kuttner 2011, p. back cover):

> In trying to understand the atom, physicists built quantum mechanics, the most successful theory in science and the basis of one-third of our economy. They found, to their embarrassment, that within their theory, physics encounters consciousness.

This goes to the heart of Cartesian dualism: the inexplicable schism between the physical body and an ethereal mind (Sect. 11.1). In summary (Stapp 2009):

> Yet, in stark contrast to classical mechanics, in which the physically described aspect is matter-like, the physically described aspect of quantum mechanics is mind-like! *Thus both parts of the quantum Cartesian duality are ontologically mind-like.*
>
> In short, orthodox quantum mechanics is Cartesian dualistic at the pragmatic/*operational level*, but mentalistic on the *ontological* level.
>
> This conclusion that nature is fundamentally mind-like is hardly new. But it arises here not from some deep philosophical analysis, or religious insight, but directly from an examination of the causal structure of our basic scientific theory.

Henry Stapp was a collaborator of Wolfgang Pauli, Werner Heisenberg, and Wheeler. He is known for the development of the axiomatic S-matrix theory (Stapp 1971). Stapp probably was the first US American physicist to popularize Bell's theorem in the early 1970s (Stapp 1975), then still obscure, and thus bring the issue of entanglement to attention (Sect. 10.3.2.1). He has also been working on the connection between quantum mechanics and consciousness for decades. In his book *Mindful Universe: Quantum Mechanics and the Participating Observer* he summarizes his research (Stapp 2011). In essence (Stapp 2011, p. 160):

> Quantum mechanics is a causal structure that joins the epistemological and ontological aspects of nature together in a rationally coherent dynamical reality. Knowledge and the acquisition of knowledge become integral parts of the process of creating the evolving universe! The acquisition of knowledge does not simply reveal what is physically fixed and settled; it is part of the process that creates the reality that we know.

Again, we are confronted with a participatory role of consciousness. Stapp also criticizes the philosopher Daniel Dennett, famous for "explaining consciousness away" (Sect. 11.1). Specifically (Stapp 2011, p. 2):

> But the now-falsified classical conception of the world still exerts a blinding effect. For example, Daniel Dennett (1994, p. 237) says that his own thinking rests on the idea that "a brain was always going to do what it was caused to do by current, local, mechanical circumstances". But by making that judgment he tied his thinking to the physical half of Cartesian dualism, or its child, classical physics, and thus was forced in his book *Consciousness Explained* (Dennett 1991) to leave consciousness out, as he himself admits, and tries to justify, at the end of the book. By effectively restricting himself to the classical approximation, which squeezes the effects of consciousness out of the more accurate consciousness-dependent quantum dynamics, Dennett cuts himself off from any possibility of validly explaining the physical efficacy of our conscious efforts.

To the point (Stapp 2011, p. 9):

> The most radical change wrought by this switch to quantum mechanics is the injection directly into the dynamics *of certain choices made by human beings about how they will act*. Human actions enter, of course, also in classical physics. But the two cases are fundamentally different. In the classical case the way a person acts is fully determined in principle by the physically described aspects of reality alone. But in the quantum case there is *an essential gap in physical causation*. This gap is generated by Heisenberg's uncertainty principle, which opens up, at the level of human actions, a range of alternative possible behaviors between which the physically described aspects of theory are in principle unable to choose or decide. But this loss-in-principle of causal definiteness, associated with a loss of knowable-in-principle physically describable information, opens the way, logically, to an input into the dynamics of another kind of possible causes, which are eminently knowable, both in principle and in practice, namely our conscious choices about how we will act.

Stapp also sees an information-theoretic relevance (Stapp 2014, p. 148):

> By virtue of this filling of the causal gap, the most important demand of intuition—namely that one's conscious efforts have the capacity to affect one's own bodily actions—is beautifully met by the quantum ontology. And in this age of computers, and information, and flashing pixels there is nothing counterintuitive about the ontological idea that nature is built—not out of ponderous classically conceived matter but—out of events, and out of informational waves and signals that create tendencies for these events to occur.

Wheeler's thinking was also influential for a modern alternative interpretation of quantum mechanics (Sect. 10.3.2.2), called quantum Bayesianism, or QBism (Fuchs et al. 2014). Bayesian probabilities are understood as subjective degrees of belief about a system (see Sect. 11.3.2 for Bayesian inference). In QBism, the quantum wave function's probabilities are interpreted as Bayesian probabilities. One of the founders of QBism admits (Fuchs 2017, p. 113):

> John Archibald Wheeler's writings were a tremendous influence on the point of view on quantum mechanics we now call QBism […].

In more detail (Gefter 2015):

> QBism, on the other hand, treats the wave function as a description of a single observer's subjective knowledge. It resolves all of the quantum paradoxes, but at the not insignificant cost of anything we might call "reality." Then again, maybe that's what quantum mechanics has been trying to tell us all along—that a single objective reality is an illusion.

QBism also gives rise to a participatory realism (Fuchs 2017). The science writer and author Amanda Gefter takes the criticism of a single universe shared by multiple observers a step further. In her 2012 FQXi essay *Cosmic Solipsism* she elaborates[48]:

> I argue that the basic assumption of a single universe shared by multiple observers is wrong. Synthesizing the implications of black hole radiation, horizon complementarity, dark energy, observations of the cosmic microwave background and quantum logic, I argue that moving toward a true theory of quantum gravity will require us to give up the notion that we all share the same universe. Instead, each observer has their own universe, which constitutes a complete and singular reality.
>
> […]
>
> This cosmic solipsism turns on all of our common sense notions about the world; then again, fundamental physics has a long history of disregarding our common sense notions.
>
> […]
>
> John Wheeler famously asked, "Why the quantum?" I suspect that the answer is something like this: because each observer has their own universe, and we can never speak about more than one at a time.

14.4.2 Psi: Measuring the Transcendental

If anything written in this chapter and the last is true, then one should expect some experimental support. Specifically, an influence of the mind on physical reality seems a pertinent area of research. Alas, any suggestion of a direct connection between subjective consciousness and objective reality conjures up the final taboo of the supernatural. Parapsychology is the study of paranormal and psychic phenomena, refereed to as psi research in the following. There probably exists no other topic that triggers as much disdain, animosity, and contempt in scientists, philosophers, and theologians alike. Psi research is an off-limits subject matter obviously unworthy of any serious attention, as it has allegedly been debunked ages ago. Furthermore, it is seen as a threat to the prevailing materialistic and reductionistic scientific paradigm, which confidently dictates what is possible and not. For instance, scholars can propose the following speculative traits of reality, without fearing any professional backlash or public ridicule: reality is (up to) eleven-dimensional (Sect. 10.2.2), where the additional dimensions conveniently curl up and become undetectable; there exists a mirror world of supersymmetric particles (Sect. 4.3.2); the universe is a hologram (Sect. 13.4.1); we live in the multiverse, an infinite collection of parallel universes (Sect. 10.3.2.2); causality is an illusion (Sect. 10.3.2.2); time is an illusion (Sect. 10.4.2); consciousness is an illusion (Sect. 11.1); free will is an illusion (Sect. 11.4.1); and panpsychism. However, exclaiming that the subjective could potentially have a direct influence on the objective is professional suicide.[49] Of course, it does not help that history is fraught with charlatans and fraudsters preying on the gullible and uninformed.

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[48]See https://fqxi.org/community/forum/topic/1512, retrieved August 28, 2018.

[49]Recall that even the study of consciousness held the same status until 1990 (Sect. 11.1).

The investigation of psi phenomena has not always been stigmatized. The psychiatrist Carl Jung famously introduced the notion of synchronicity (Jung 1952). This is the idea that events can be related, even if there exists no causal relationship. In essence, consciousness has the power to meaningfully arrange physical reality. In the words of Tarnas (2006, p. 50):

> Jung first described the remarkable phenomenon he named synchronicity in a seminar as early as 1928. He continued his investigations for more than twenty years before at last attempting a full formulation in the early 1950s. He presented his influential, still-evolving analysis of synchronicity in the final paper he gave at the *Eranos* conferences, and immediately followed this with a long monograph. Developed in part through discussions with physicists, particularly Einstein and Wolfgang Pauli, the principle of synchronicity bore parallels to certain discoveries in relativity theory and quantum mechanics. Yet because of its psychological dimension, Jung's concept possessed a special relevance for the schism in the modern world view between the meaning-seeking human subject and the meaning-voided objective world.

Pauli was one of the pioneers of quantum mechanics. He is also known for an "effect" named after him. The theoretical physicist George Gamow once wrote the following about Pauli (Gamow 1985, p. 63f.):

> He is famous in physics on three counts:
>
> 1. The *Pauli Principle*, which he preferred to call The Exclusion Principle.
> 2. The *Pauli Neutrino*, which he conceived of in the early twenties and which for three decades escaped experimental detection.
> 3. The *Pauli Effect*, a mysterious phenomenon which is not, and probably never will, be understood on a purely materialistic basis.
>
> It is well known that theoretical physicists cannot handle experimental equipment; it breaks whenever they touch it. Pauli was such a good theoretical physicist that something usually broke in the lab whenever he merely stepped across the threshold. [...] You may believe this anecdote [involving the collapse of a complicated apparatus for the study of atomic phenomena] or not, but there are many other observations concerning the reality of the Pauli Effect!

Indeed, the Nobel laureate Otto Stern forbid Pauli from entering his laboratory (Mallonee 2016).

The physicist and historian David Kaiser meticulously researched the history of quantum mechanics in his book *How the Hippies Saved Physics: Science, Counterculture, and the Quantum Revival* (Kaiser 2011). Sections 4.3.4 and 10.3.2.1 contain important information provided by Kaiser. He traced the origins of the study of quantum information, the revival of research into the foundations of quantum physics, and the popularization of Bell's theorem and entanglement to a group of hippies, calling themselves the *Fundamental Fysiks Group*. However, their "contributions lie buried still, overlooked and forgotten in physicists' collective consciousness" (Kaiser 2011, p. xvii). Perhaps the reason is all too obvious (Kaiser 2011, p. xvii):

> Indeed, from today's vantage point it may seem shocking that anything of lasting value could have come from the hothouse of psychedelic drugs, transcendental meditation, consciousness expansion, psychic mind-reading, and spiritualist séances in which several members dabbled with such evident glee. History can be funny that way.

Stapp, himself not a hippie, was a charter member of the group (Kaiser 2011, p. 101). His experiences with psi research is also recounted (Kaiser 2011, p. 254ff.). He was approached in the early 1990s by a physicist-turned-parapsychologist. Skeptical but open minded, Stapp, agreed to an experiment. To his great surprise, there was a statistically significant trend in the data, which should have been random. Kaiser, then an undergraduate at Berkeley, remembers discussing these results with Stapp. A formal approach aimed at this "causal anomaly" yielded the following (Kaiser 2011, p. 256):

> Stapp realized that the modified equations could account for effects like those in the recent parapsychology experiment while still reproducing the usual, well-tested behavior of atoms predicted by ordinary quantum theory.

He proceeded to write an article and submitted it to a physics journal in 1993. Stapp received a letter from the journal's editor, asking him to shift the emphasis from psi phenomena to theoretical physics. After complying, another letter arrived, asking him to remove all details of the experiment. Stapp, amused and aggravated, agreed and the paper was published (Stapp 1994). However (Kaiser 2011, p. 257f.):

> Getting the paper into print proved to be only half the battle. Six months after his paper appeared, the editor-in-chief for all divisions of the *Physical Review*—the senior editor for the entire American Physical Society, who had not been involved with Stapp's submission—sent Stapp a long and agitated letter chastising Stapp's work and regretting that the paper had ever been accepted. He granted that Stapp and others were "legitimately interested in such matters as human intervention in experiment, or, even, of the nature of thought and its relation to physical reality. But, the editor continued, at the present time such ideas belong to the world of philosophy, not to the world of physics." Stapp's gravest offense, as the editor saw it, was lending credibility to parapsychologists claims.

However, in the end, "the statistical effect had entirely washed out" (Kaiser 2011, p. 258) leaving Stapp most likely in a state of puzzlement.

Today, only a few brave scientists exist who openly admit to researching psi. The biochemist Rupert Sheldrake proposed the concept of morphic resonance—a kind of information field or collective memory—to account for phenomena like collective intelligence next to psi phenomena (Sheldrake 1988). He claims that dogs[50] telepathically know when their owners are coming home (Sheldrake 1999) and that humans can sense when they are being stared at Sheldrake (2005). For this, he offers experimental evidence. In 2008, Sheldrake was invited to give a Google Tech Talk.[51] In the Q and A session, around 1 h, 27 min, and 14 s, he recalls the following anecdote:

> [T]he people who are really skeptical have such a strong belief that they know in advance the evidence must be wrong. You say if you believe it's impossible, then if I come along and say, "Here are results that shows it's possible," either it proves I'm a fool—I've done the experiments so badly or incompetently; I've got false positive results and haven't been smart enough to see it—or I'm a fraud. I'm trying to deceive you and the world. And so, the instant reaction is one of hostility and accusing people of being fools or frauds. Richard Dawkins,

[50] Oscar, the death-sensing cat, was introduced above, in Sect. 14.2.4.2.

[51] It was uploaded to Google's YouTube channel on September 2, 2008, called *The Extended Mind: Recent Experimental Evidence*. See https://www.youtube.com/watch?v=JnA8GUtXpXY.

> who's a very smart man and is, in this area, not very smart at all. He's a very bigoted skeptic, and he came to interview me for his most recent TV series in Britain.
>
> […]
>
> I said I only agree to take part if it's a genuine scientific discussion about evidence and if he's really open to discussing the evidence, otherwise, there's no point. […] They gave me a written assurance that this was the case. So, I agreed to meet him and he came to see me.
>
> […]
>
> And he started off by saying, "I dare say we agree about quite a number of things, Rupert," he said, "But let me tell you what worries me about you." And I said, "Okay, what worries you about me." And he said, "What worries me about you is you're prepared to believe almost anything and science should be base on the minimum number of beliefs." So, I said, "Well, okay. Well, let me tell you what worries me about you." I said, "You come across as prejudiced and bigoted and I think you give science a bad name." So, we didn't get very far with that conversation.
>
> […]
>
> Then I said, "Well, look, okay. Why don't we get down to the evidence and actually discuss the evidence, which is why we've met." He said, "I didn't want to talk about the evidence." And I said, "Well, why not?" And he said, "There isn't time."

Dean Radin is one of an estimated 50 doctorate-level scientists engaging in full-time psi research (Radin 2006, p. 7). In 2008, he also gave a Google Tech Talk.[52] Radin has held appointments at Princeton University, Edinburgh University, University Nevada, and Las Vegas.[53] He believes that scientific inquiry should not be restricted by a taboo, i.e., by preconceived ideas of what is possible or not. The scientific consensus that consciousness cannot possibly have a direct influence on physical reality is seen by him as prime example of such a taboo. Indeed, he claims that many people have experienced such phenomena—which they only communicate in private. He has written three books on the subject, where he presents empirical evidence (Radin 1997, 2006, 2013). For instance, in a skeptical publication on telepathy, called *Finding and Correcting Flawed Research Literatures*, the authors report (Delgado-Romero and Howard 2005):

> After eight studies, we had an overall hit rate of 32% (which agrees with the positive meta-analyses) and, in fact, our hit rate was also statistically significant.

Faced with having reproduced the phenomenon, they continue (Delgado-Romero and Howard 2005):

> So, for the moment, even the evidence against humans possessing psychic powers is precariously close to demonstrating humans do have psychic powers.

Then they run another experiment, using an ad hoc and untested method[54] and received a significant negative result. In conclusion (Delgado-Romero and Howard 2005):

[52] It was upload to Google's YouTube channel on January 18, 2008, called *"Science and the Taboo of Psi" with Dean Radin*. See https://www.youtube.com/watch?v=qw_O9Qiwqew.

[53] See the introduction to his Google Tech Talk.

[54] According to Radin, Google Tech Talk, approximately at 28 minutes and 04 seconds.

> Due to this last data set, we do not believe that humans possess telepathic powers. Further, the approximately 32% correct figure obtained in an enormous number of psi studies remains perplexing.

Radin elaborates (Radin 2006, p. 120):

> From 1974 through 2004 a total of 88 ganzfeld experiments [...] in 3,145 trials were conducted. The combined hit rate was 32% as compared to the chance-expected 25%. This 7% above-chance effect is associated with odds against chance of 29,000,000,000,000,000,000 (29 quintillion) to 1.

In 1995, the *American Institutes for Research* performed a review of remote viewing for the CIA (Mumford et al. 1995).[55] In conclusion (Mumford et al. 1995):

> In evaluating the various laboratory studies conducted to date, the reviewers reached the following conclusions:
>
> - A statistically significant laboratory effort has been demonstrated in the sense that hits occur more often than chance.
> - It is unclear whether the observed effects can unambiguously be attributed to the paranormal ability of the remote viewers as opposed to characteristics of the judges or of the target or some other characteristic of the methods used. [...]
> - Evidence has not been provided that clearly demonstrates that the causes of hits are due to the operation of paranormal phenomena; the laboratory experiments have not identified the origins or nature of the remote viewing phenomenon, if, indeed, it exists at all.

The statistician Jessica Utts writes in her review (Mumford et al. 1995):

> Using the standards applied to any other area of science, it is concluded that psychic functioning has been well established. The statistical results of the studies examined are far beyond what is expected by chance. Arguments that these results could be due to methodological flaws in the experiments are soundly refuted. Effects of similar magnitude to those found in government sponsored research at SRI [Stanford Research Institute] and SAIC [Science Applications International Corporation] have been replicated at a number of laboratories across the world. Such consistency cannot be readily explained by claims of flaws or fraud.

Another reviewer, the psychologist Ray Hyman, observes (Mumford et al. 1995):

> We agree that the effect sizes reported in the SAIC experiments are too large and consistent to be dismissed as statistical flukes.

A meta-analysis on dream extrasensory perception (ESP), considering 37 studies from 1966–2002, find a median effect size of 0.255, indicating an overall medium sized effect. The study concludes (Sherwood and Roe 2003):

> We hope that this review will help re-awaken interest in this neglected but promising paradigm.

In a study, where two isolated people were requested to think about each other, the EEG data showed a statistically significant correlation of brain activity, unnoticed

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[55] See also https://www.cia.gov/library/readingroom/docs/CIA-RDP96-00791R000200180006-4.pdf.

by the subjects themselves. This was done with 13 couples (Radin 2004). Then there exists a wealth of academic research that is published in journals committed to studying fringe science or in proceedings of parapsychological conventions. For instance, a study showing that when two isolated people are asked to think of each other and the "sender" is stimulated by a light flash, the "receiver's" brain shows corresponding activity (Kittenis et al. 2004). Similarly, another study selected one couple out of 30 and, again, asked the participants to focus their attention. When the "sender" received a visual stimulus, neural activity was reported in the "receivers" fMRI data of the visual cortex (Standish et al. 2003). Precognition has been reported in Bierman and Scholte (2002). A result relating precognition to electrophysiological aspects of the heart has been published in a peer-reviewed medial journal (McCraty et al. 2004). More recent research in more established journals include telepathy (Tressoldi et al. 2011), ESP (Storm et al. 2010), and precognition (Radin 2011; Mossbridge et al. 2012). More publications can be found on Radin's webpage.[56]

Another line of research analyzes random number generators. In essence, the notion that the human mind can change the performance characteristics of computers is researched. This was performed at the Princeton Engineering Anomalies Research (PEAR) laboratory. In detail (Van Bakel 1995):

> Nearly a hundred volunteers have conducted 212 million REG [random event generator] trials during the 15 years of the lab's existence, and the research shows a tiny but statistically significant result that is not attributable to chance. […]
>
> The effects that the volunteers accomplish are very small, but amazing. "The operators are roughly altering one bit in 1,000," explains Michael Ibison, a British mathematical physicist who has come to work for a year at PEAR after stints at Siemens, IBM, and Agfa. […]
>
> You don't have to be in the same room as the REG to get results. Or, for that matter, in the same city, state, or country. Volunteers as far away as Hungary, Kenya, Brazil, and India have shown they can influence Princeton's REG as if they were sitting 3 feet away. […] The effects generated by two people with an emotional attachment were much larger than those produced by an "unattached" pair of operators.[…]
>
> Skeptics have examined the lab's instruments, its data-processing software, its protocols. […] Other scientists have, by and large, been able to replicate PEAR's experiments—just as PEAR's own work builds on other academically sound research.

PEAR closed in February 2007. Efforts to reproduce and validate their claims have been unsuccessful or inconclusive. The Global Consciousness Project[57] is a psi experiment which begun in 1998. The project monitors a network of geographically distributed random number generators in order to detect anomalous output which correlates with global events of emotional importance. For instance (Radin 2006, p. 203):

> On September 11, 2001, the curve deviated wildly as compared to all the other days we examined. As it happened, this curve peaked nearly two hours before a hijacked jet crashed into World Trade Tower 1 in New York City at 8:46 a.m. EDT, and it dropped to its lowest point around 2 p.m., roughly eight hours later. […]. The huge drop in this curve within an eight-hour period was the single largest drop for any day in the year 2001.

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[56] See http://www.deanradin.org/.

[57] See http://www.global-mind.org/.

In response to these claims (May and Spottiswoode 2001):

> We also provide verification of a separate analysis posted by Dr. Dean Radin, but we differ markedly with regard to the posted conclusions. Using Radin's analysis, we do not find significant evidence that the GCP [Global Consciousness Project] network's EGG's [the collection of random number generators] responded to the New York City attacks in real time. Radin's computation of 6000:1 odds against chance during the events are accounted for by a not-unexpected local deviation that occurred approximately 3 hours before the attacks. We conclude that the network random number generators produced data consistent with mean chance expectation during the worst single day tragedy in American history.

Perhaps the most compelling, and reproducible, psi effects appear in studies of human consciousness interacting with experimental quantum devices. For instance, a study appearing in the *Center for Open Science's*[58] *Open Science Framework*[59] in 2017 (last updated in March 2018), reports (Guerrer 2017):

> Motivated by a series of reported experiments and their controversial results, the present work investigated if volunteers could causally affect an optical double-slit system through mental efforts alone. […] The four pre-registered experiments combined resulted in a statistically null difference between the data collected in intention and relax conditions. A post hoc combination of the formal experiments' scores using sign independent statistics, however, provided statistically significant results favoring the existence of anomalous interactions between conscious agents and a physical system. Further studies are warranted to formally test the post hoc hypothesis.

Other, related research, was previously published in peer-reviewed scientific journals, demonstrating the robustness and reproducibility of these double-slit quantum experiments (Radin et al. 2012, 2015, 2016). Earlier experiments had been done using interferometers (Radin 2008). *The Global Consciousness App*[60] is an attempt to bring psi research to your smart-phone.

The controversy surrounding psi research is deep-rooted. The situation is very similar to the political entrenchment discussed in Chap. 12, especially related to open-mindedness (Sect. 12.4.4). In essence (Van Bakel 1995):

> Unfortunately, many of our critics basically say: "This is the kind of nonsense I wouldn't believe even if it were real." They're people who have made up their minds that this is all hogwash, without having studied the data.

In 1986, an article appeared in the prestigious science journal *Nature* summarizing (Marks 1986):

> Parascience has so far failed to produce a single repeatable finding and, until it does, will continue to be viewed as an incoherent collection of belief systems steeped in fantasy, illusion and error.

However, the journal also has a somewhat troubled history with the subject. In 1974, it prominently published a psi study by the physicist Russell Targ and the engineer Harold Puthoff, offering compelling evidence of a subject's psi powers (Targ and Puthoff 1974). It was later found out that the subject was the illusionist Uri Geller. The physicist Jack Sarfatti, a leading member of the *Fundamental Fysiks Group*, was

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[58] A non-profit collaborative science research project. See https://cos.io/.

[59] See https://osf.io/.

[60] See http://www.consciousness-app.com/.

at first impressed by Geller's apparent psi capabilities. However, after the magician James Randi was able to demonstrate similar feats as the ones performed by Geller to him, Sarfatti exclaimed (quoted in Kaiser 2011, p. 82):

> I do not think that Geller can be of any serious interest to scientists who are currently investigating paraphysical phenomena.

Moreover (Kaiser 2011, p. 98):

> He [Randi] dedicated an entire chapter of his popular book on "delusions" to the SRI [Stanford Research Institute] psi lab's exploits, calling Puthoff and Targ "the Laurel and Hardy of psi." Thirty pages detailed what Randi considered to be Puthoff's and Targ's crimes against scientific method, statistical reasoning, and common sense.

At the end of the day, the following can be concluded. There appear to be effects happening which require an extension of the current scientific worldview. These effects are mostly very small and hard to reproduce. Nonetheless, the claims that psi is ruled out by what we know about the workings of nature is based on a belief—a belief inspired by science, but nevertheless a belief. The implicit ontology that is invoked with such claims is based on a materialistic and reductionistic scientific worldview. However, as more and more cracks appear in this specific edifice of science—and an entirely new information-theoretic and participatory ontology seems to be emerging—the certainty and justifiability associated with these assertions can only be upheld on ideological grounds. Certainty is an elusive notion (Sect. 8.1.1, Chap. 9, Sects. 10.4, 11.2.1, 11.3, and 14.3.5). Then it is perhaps not really intellectually honest to categorically exclude that reality is "queerer than we can suppose" (Sect. 12.4.4). In stark contrast (Ribur Rinpoche 1999, p. 56):

> In Tibetan the word for "existence" is "sipa", which also means "possible". In existence, anything is possible, anything can happen.

Finally, every paradigm is afflicted by blind spots. Currently, this relates to the taboo of subjectivity (Sect. 14.1.1) and spirituality (Sect. 14.2.3), the pointless nature of psychedelics (Sect. 14.3), the unnoticed insights gained by ancient Eastern truth-seekers and shamans (Sects. 14.2.2 and 14.3.4), the possibility of gaining knowledge through unorthodox channels (Sects. 14.3.5 and 14.3.4), and the ridiculous idea of psi phenomena. Moreover, astute scholars have suspected from the very beginning that quantum physics should be understood in the context of establishing a link between consciousness and the cosmos. The cosmologist and psi skeptic Sean Carroll reminds us (Carroll 2016):

> The trash heap of history is populated by scientists claiming to know more than they really do, or predicting that they will know almost everything any day now.

And as a result, the emergence of important knowledge has been deferred. The tragic story of Ignaz Semmelweis comes to mind. He claimed that simply washing hands could significantly reduce mortality in obstetrical clinics. He presented empirical evidence to substantiate his claim (Semmelweis 1861). Alas, his insights were ridiculed and rejected by his peers. He turned to alcohol and suffered from mental breakdowns. It did not help his cause that he wrote angry, bitter, and accusing letters to professors refusing to accept his ideas. See Obenchain (2016).

Conclusion

The question "Could there be something we don't yet know about ourselves and the universe, the knowledge of which could change everything?" is beginning to be answered. In the last chapter, an information-theoretic ontology was outlined. Guided by cutting-edge theoretical physics and theoretical computer science an unlikely foundation of the world was glimpsed: the fabric of objective reality is woven out of threads of information. Intriguingly, the notion of information is also understood as being central to the subjective and recalcitrant phenomena of consciousness. Information possesses an inner dimension giving rise to experiences. A truly outlandish world emerges, where consciousness is part of the cosmic fabric. Now, a participatory ontology arises, where the ultimate taboo within the current materialistic and reductionistic scientific worldview is being broken by exposing a mind-matter relationship—or more succinctly: mind over matter. Only very few great scientific minds ever had the courage to uttered such heresies. Slowly the blind spots within the current scientific paradigm are being exposed. Previously demonized substances are rediscovered in a therapeutic context and the experiences they are able to relay speak of a multiverse. However, one comprised of transcendental universes beyond space, time, and matter, accessible to pure consciousness. In the recent peer-reviewed physics literature one can find multiple double-slit quantum experiments, showing reproducible hints of a direct mind-matter connection. A feature some of the great pioneers of quantum mechanics had always suspected. Finally, intelligence can be a decentralized and non-sentient phenomena, latching onto various configurations of matter. Given these newly emerging surprising insights it is perhaps not all too puzzling that the prevailing scientific paradigm failed to uncover this ultimate nature of reality and the human mind, as outlined in Part II. In contrast, this knowledge some ancient Eastern truth-seekers and shamanic traditions appear to have had access to for a long time.

In a strange twist of events, the human mind was first dethroned and banished from the center of creation only to reawaken in the fabric of existence. These new advances in understanding have been criticized as neo-geocentrism (Horgan 2016). However, perhaps the most common, pervasive, and overlooked manifestation of geocentrism relates to our sober waking state of consciousness. We take this mode of subjective experience as the defining and default one. By ignoring all other states of consciousness—induced by meditation, trance, chemicals, pain, brain trauma, sleep, or spontaneously—we are placing our so-perceived reality at the core of existence, denying the possibility of vast and rich alternate realms of reality, only accessible by silencing the sober waking mind. Moreover, in a peculiar turn of events, we indeed do appear to be at the center of the universe. Humanities most advanced experimental and theoretical cosmological proficiency has resulted in two truly puzzling observations: the "axis of evil" and the "coincidence problem" (Sect. 10.3.1). In essence, given the entire context of the universe, "right here" and "right now" appear to be very special coordinates. In the words of the cosmologist Lawrence M. Krauss (Krauss 2006):

> But when you look at CMB [cosmic microwave background] map, you also see that the structure that is observed, is in fact, in a weird way, correlated with the plane of the earth around the sun. Is this Copernicus coming back to haunt us? That's crazy. We're looking out at the whole universe. There's no way there should be a correlation of structure with our motion of the earth around the sun—the plane of the earth around the sun—the ecliptic. That would say we are truly the center of the universe.

Yet another such enigma is the way the universe "conspired" to give rise to this very moment in time—including sentient and inquisitive minds inhabiting a neural network based on organic matter—through a series of breathtaking coincidences (Sect. 8.1.3). Is the universe perhaps more than a cold, pointless, callous, cruel, and cynical place? Is it being driven by an innate ordering force ever higher levels of computation resulting in emergent complexity? Is each human mind an author of its own "Book of Nature?"

In a final synthesis, the next chapter unifies the information-theoretic and participatory ontologies. The entelechy of existence emerges, containing all the rhizomes of reality comprising the transcendental multiverse.

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Chapter 15
Consilience

MILLENNIA ago, the human mind set out to discover the cosmos it had one day awoke to. After a long and meandering journey it has finally returned and in a final act of cognition faced its own nature.

THE journey was long and challenging but fraught with rewards. Most importantly, novel territories were discovered. The first being the Platonic realm of abstractions. Here, the human mind discovered science. By translating aspects of the real world into formal representations, the workings of nature became visible. The mind could comprehend the mathematical language of the cosmos, revealing its structure. The emergence of science would keep the human mind busy for centuries.

The next domain the mind conquered was the realm of information. Building on zeros and ones, the computational capacity of the universe was unleashed. Again, the mother tongue was mathematics. Equipped with the newly discovered abstract and computational tools, the human mind began to engineer reality. The gift of technology was received.

FOR a long time the cosmos was accommodating to the human mind. Physicists and philosophers alike wondered about "the unreasonable effectiveness of mathematics in the natural sciences." Then, a couple of decades ago, it was discovered that, surprisingly, simplicity lies at the heart of complexity. Yet again, the reach of the mind was dramatically extended, as complex phenomena could now be tackled. The supremacy of the materialistic scientific worldview was firmly established.

At the same time, however, the human psyche was suffering. Various Copernican revolutions dethroned the mind. Uncertainty seemed inherent and ubiquitous in the human condition. The expanding island of knowledge found itself surrounded by ever longer shores of ignorance. Age-old questions appeared as elusive as ever. "What is the fundamental nature of reality?" "What is the true nature of consciousness?" The universe seemed to only reveal itself to the mind as far as to awaken the false hope in its comprehensibility.

The human mind suddenly reawoke in a cold, pointless, callous, cruel, and cynical cosmos. Moreover, much self-inflicted suffering arose. The financial and economic

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systems the mind devised were based on tribal hierarchies of concentrated power, lacking collective intelligence. As a result, inequity and unsustainability became rampant. The entire biosphere, supporting all life on earth, threatened to destabilize. In dramatic turns of events, trench wars were fought globally along social, political, and religious delimitations. The age of post-truth raised its ugly head.

WE are currently witnessing a fundamental paradigm shift, replacing the prevailing scientific dogma. By breaking the taboos of the current materialistic worldview and exposing its blind spots, the human mind is progressing once again. A new domain of reality is discovered—this time at its very core. By rethinking the most basic assumptions and reassessing the most cherished beliefs about existence, a novel scientific paradigm is emerging.

Insights from theoretical physics and theoretical computer science uncover information at the most fundamental level of the cosmos. The fabric of objective reality is woven out of threads of information—not space, time, or matter. At the heart of reality, we find a computational engine which needs to be fed with information. The entire universe is computational in nature. The consequences are far-reaching. For one, the whole cosmos is necessarily finite. The abstract notion of infinity only resides within the human mind. Then, the most groundbreaking and earth-shattering implication is the very real possibility that the universe itself is a vast hologram and reality perhaps a simulation.

How does consciousness enter this new information-theoretic paradigm? For centuries, the materialistic scientific worldview confidently declared with great certainty what was possible and not. Now, in a final act of heresy, this orthodoxy is being denounced. Deep within the structure of reality, consciousness is found. John Wheeler is one of the pioneers initiating this paradigm shift and is considered to be one of the most influential physicists of the twentieth century. He once observed (quoted in Horgan 1997, p. 84):

> When we peer down into the deepest recesses of matter or at the farthest edge of the universe, we see, finally, our own puzzled faces looking back at us.

In a similar vein the physicist Carl Sagan, revered in the science community, remarked (Sagan et al. 1990):

> We are a way for the cosmos to know itself.

Finally, in the words of Alan Watts, a philosopher, interpreter of Eastern philosophy, and psychonaut (quoted in Crombie and Jardine 2016):

> Through our eyes, the universe is perceiving itself. Through our ears, the universe is listening to its harmonies. We are the witnesses through which the universe becomes conscious of its glory, of its magnificence.

Within the nascent new paradigm, consciousness is rediscovered as the inner aspect of information (see next section for details). While its outer manifestation gives rise to objective reality, its inner quality allows subjective experiences to emerge. Now, the implications are truly outlandish. The possibility that consciousness is a fundamental and universal property of reality arises. We thus are inhabiting a participatory universe, where objective reality and subjective consciousness share an inherent kinship.

Consequentially, whole new realms of existence are unearthed. The sober waking state of consciousness represents but one mode of perception out of a vast array of other states. We peer through this lens of awareness and glimpse the consensus reality. This default state of consciousness, however, can only render a tiny subspace within a much richer and broader reality landscape. In effect, vast new reality terrains are accessible to the human mind. By silencing the sober waking state of perception and inducing altered states of consciousness—through meditation, trance, chemical substances, pain, brain trauma, sleep, or spontaneously—new planes of existence appear, transcending space and time.

This information-theoretic paradigm shift is only materializing slowly. As with every scientific revolution, a lot of resistance is encountered. In the words of Max Planck, the discoverer of the quantum world (Planck 1950, pp. 33f.):

> A new scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.

However, the cracks in the current edifice of science are continually growing, exposing more and more of its inadequacy. Quantum physics has defied human understanding since the quantum realm of reality was accidentally discovered in 1901. Nonetheless, insightful, empathetic, and open-minded physicists always harbored a suspicion: the unruly nature of the quantum originates from a fundamental misconception. Namely, the separation of mind and matter. Within the very framework of quantum mechanics lurks a conscious observer embedded in a reality not constrained by space and time. Indeed, quantum experiments demonstrate how the past can be influenced from the present and how the mind can directly manipulate matter. Perhaps most relevant for the current forefront of technology is the notion of intelligence. Intelligence can be a decentralized and non-sentient phenomena, latching onto various inanimate configurations of matter. The emergence of artificial intelligence out of pure software perhaps represents humanities next great challenge.

15.1 The Inner and Outer Aspects of Information

If we choose to believe in the information-theoretic scientific paradigm, then information is truly the substrate of existence. In other words:

- Information tells consciousness how it "feels to be something."
- Information tells reality how to structure.

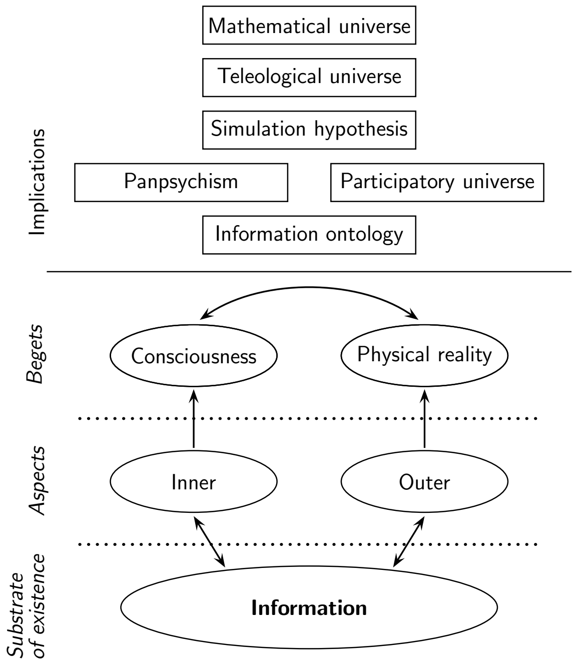

Fig. 15.1 The layers of reality. At the foundation of existence lies information. It expresses as two aspects, relating to subjective consciousness and objective reality. The implications of this metaphysics are discussed throughout Chaps. 13 and 14. The teleological aspect is introduced in the next section

The human mind is faced with the dichotomy of information. In the words of Watts (1991):

> The only thing you need to know to understand the deepest metaphysical secrets is this: that for every outside there is an inside and for every inside there is an outside, and although they are different, they go together.

This dictum is illustrated in Fig. 15.1.

15.2 The Rhizome of Reality and the Entelechy of Existence

In the wake of the mathematical understanding of reality discussed in Part I, epistemological and ontological questions emerged (Sect. 2.2.1):

1. What is the nature of the Platonic realm of abstractions?
2. How can the human mind access this world and acquire information?
3. Why do the structures in the abstract world reflect the structures in the physical world?

These puzzles are captured in Fig. 15.2. Within the new information-theoretic and participatory ontology, unexpected answers emerge. Before discussing these, some terms are defined.

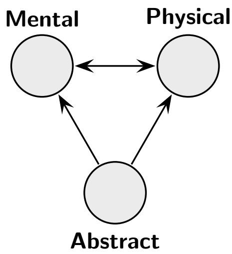

Fig. 15.2 Three worlds. The realms interacting in the process of formal human knowledge generation. The figure is reproduced from Page 58 of Sect. 2.2.1

15.2.1 Setting the Stage

Aristotle distinguished between the potential and the actual. The process of realizing the potential—making actual what was otherwise potential—is called entelechy. An example is how a sculpture emerges from a block of marble. The rhizome is a term originating from botany, describing an interconnected root system. The notion was introduced into philosophy by Gilles Deleuze and Félix Guattari in their classic text (Deleuze and Guattari 1980). A rhizome is essentially messy and non-hierarchical. In detail, it is characterized by the following[1]:

- All parts of a rhizome are connected with no single node having priority over any other.
- There's no necessary structure to the rhizome, instead each person encounters it differently.
- A rhizome can always be broken and restarted.
- The rhizome is always open and any point you choose to start at is irrelevant.

Finally, teleology is also a concept found in classical Greek philosophy. It describes a goal-oriented process or a purpose-driven force. Teleological considerations have been, and still are, used in a theological context relating to the existence of a monotheistic god. This is known as the teleological argument. Indeed (Yanofsky 2013, p. 280):

> While this explanation is satisfactory for deists, those who do not believe in a deity will find this solution unsatisfying. Such a deity raises all kinds of other, more mysterious, questions about the nature of a deity.

Overall, teleology is frowned upon from within a materialistic and reductionistic scientific worldview. However, it is encountered at the outskirts of knowledge. Specifically, related to the fine-tuning problem. In detail (Leslie and Kuhn 2013, p. 247):

> In recent years, the search for scientific explanations of reality has been energized by increasing recognition that the laws of physics and the constants that are embedded in these laws all seem exquisitely "fine tuned" to allow, or to enable, the existence of stars and planets and the emergence of life and mind. If the laws of physics had much differed, if the values of their constants had much changed, or if the initial conditions of the universe had much varied, what we know to exist would not exist since all things of size and substance would not have formed.

[1]See http://www.mantlethought.org/philosophy/rhizome-american-translation, retrieved September 4, 2018.

How do physicists respond to this challenge? For instance Leslie and Kuhn (2013, p. 248):

> Sir Martin Rees, Britain's Astronomer Royal, presents "just six numbers" that he argues are necessary for our emergence from the Big Bang.[2] A minuscule change in any one of these numbers would have made the universe and life, as we know them, impossible. Deeper still, what requires explanation is not only this apparent fine-tuning but also the more fundamental fact that there are laws of physics at all, that we find regularity in nature.

Then (Leslie and Kuhn 2013, p. 248):

> To Roger Penrose, the "extraordinary degree of precision (or 'fine tuning') that seems to be required for the Big Bang of the nature that we appear to observe [...(sic)] in phase-space-volume terms, is one part in $10^{10^{123}}$ at least." Penrose sees "two possible routes to addressing this question [...(sic)] We might take the position that the initial condition was an 'act of God'. [...(sic)] or we might seek some scientific/mathematical theory." His strong inclination, he says, "is certainly to try to see how far we can get with the second possibility."

Apparent fine-tuning seems ubiquitous. The cosmologist Andrei Linde observes (quoted in Brockman 2015a, p. 46):

> There are many strange coincidences in our world. The mass of the electron is 2,000 times smaller than the mass of the proton. Why? The only "reason" is that if it were even a little different, life as we know it would be impossible. The masses of the proton and neutron almost coincide. Why? If the masses of either were even a little different, life as we know it would be impossible.

In summary (Leslie and Kuhn 2013, p. 248):

> Stephen Hawking presented the problem this way:
>
> > Why is the universe so close to the dividing line between collapsing again and expanding indefinitely? In order to be as close as we are now, the rate of expansion early on had to be chosen fantastically accurately. If the rate of expansion one second after the Big Bang had been less by one part in 10^{10}, the universe would have collapsed after a few million years. If it had been greater by one part in 10^{10}, the universe would have been essentially empty after a few million years. In neither case would it have lasted long enough for life to develop. Thus one either has to appeal to the anthropic principle or find some physical explanation of why the universe is the way it is.

The cosmologists Frank Tipler and John Barrow formulated the Strong Anthropic Principle (Tipler and Barrow 1988). In summary (Leslie and Kuhn 2013, p. 186):

> The Universe must have those properties which allow life to develop within it at some stage of its history.

Such utterances come close to threatening the materialistic and reductionistic orthodoxy (Leslie and Kuhn 2013, p. 186):

> Where could such a necessity originate from within science alone, if that discipline has forsworn any consideration of purpose? The Strong Anthropic Principle is frankly teleological in its insistence that the world "must" have been that way.

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[2] See Rees (2000).

See also Sects. 8.1.2, 10.3.1, and Vidal (2014).

Next to the origins of the universe's initial conditions its inherent organizational principle also challenges the scientific status quo. The nature of self-organizing structure formation and emergent complexity remains mysterious. These themes are encountered in Chaps. 5 and 6, and Sects. 8.1.3 and 12.4.2. Most pressingly, the emergence of life and embodied consciousness represent a fundamental enigma. Indeed (Deacon 2012, p. 58):

> In this age of hard-nosed materialism, there seems to be little official doubt that life is "just chemistry" and mind is "just computation." But the origins of life and the explanation of conscious experience remain troublingly difficult problems, despite the availability of what should be more than adequate biochemical and neuroscientific tools to expose the details.

The theoretical biologist and complex systems researcher Stuart Kauffman also remarked (paraphrased in Horgan 1997, p. 135):

> Accident alone cannot have created life; our cosmos must harbor some fundamental order-generating tendency.

For further reading, see Schneider and Sagan (2005), Deacon (2012), Nagel (2012), Lineweaver et al. (2013), Leslie and Kuhn (2013), Wissner-Gross and Freer (2013), Vidal (2014), Ellis (2016).

At the fringes of knowledge, the human mind is challenged by perplexing mysteries. Moreover, the prevailing scientific paradigm is known to suffer from many essential inadequacies. These are outlined and discussed throughout Part II. The hardest problem being the apparent fundamental incompatibility of objective reality and our subjective consciousness (Sect. 11.1). What has the emerging information-theoretic paradigm, introduced in Part III, have to offer?

15.2.2 A Rehearsal

According to the basic myth found within the traditions of ancient India, existence is seen as a play. Watts elaborates (Watts 1971, p. 99f.):

> In the beginning—which was not long ago but now-ever—is the Self. Everyone knows the Self, but no one can describe it, just as the eye sees but does not see itself. Moreover, the Self is what there is and all that there is, so that no name can be given to it. It is neither old nor new, great nor small, shaped nor shapeless. Having no opposite, it is what all opposites have in common: it is the reason why there is no white without black and no form apart from emptiness. However, the Self has two sides, the inside and the outside. […]
>
> Because of delight the Self is always at play, and its play, called *lila*, is like singing or dancing, which are made of sound and silence, motion and rest. Thus the play of the Self is to lose itself and to find itself in a game of hide-and-seek without beginning or end. In losing itself it is dismembered: it forgets that it is the one and only reality, and plays that it is the vast multitude of beings and things which make up this world. In finding itself it is remembered: it discovers again that it is forever the one behind the many, the trunk within the branches, that its seeming to be many is always *maya*, which is to say illusion, art, and magical power.

> The playing of the Self is therefore like a drama in which the Self is both the actor and the audience. On entering the theater the audience knows that what it is about to see is only a play, but the skillful actor creates a *maya*, an illusion of reality which gives the audience delight or terror, laughter or tears. It is thus that in the joy and the sorrow of all beings the Self as audience is carried away by itself as actor.

The new information-theoretic and participatory scientific paradigm can be placed within a similar metaphor:

- In eternal cycles of co-creation, the outer aspects of information create the inner aspects and vice versa—the physical creates the mind, which creates the physical, and so forth. This is the rhizome of reality, emanating from pure cognizant information.
- At the source of existence lies infinite abstract potentiality—the ineffable, the incomprehensible. In the process of entelechy, the finite rhizome of reality actualizes out of the haze of potentiality. The proto-essence of existence instantiates and materializes as ensouled information.
- This endless process is guided by a teleological force, driving the transcendental multiverse—the totality of all physical and immaterial rhizomes—to ever higher levels of self-organized complexity and intricate structure. The configurations of information continually realize ever more and more powerful information-processing capacities, manifesting greater and greater intelligence. The process of the entelechy of existence hurtles towards an ultimate complex actuality.

This narrative is illustrated in Fig. 15.3.

As every being probes reality from a different vantage point, the postmodern plurality and ambiguity, seen afflicting science (Sect. 9.1), is explained. Classical consensus reality is at the center, the focal point, of the realization process. At the quantum level, the pool of potentiality is approximated and the boarders of objective reality are necessarily fuzzy and indeterminate (Sect. 10.3.2.2). Every quantum measurement is an act of entelechy: the potential is actualized. The finite nature of the rhizome of objective reality dictates its quantum character. Furthermore, it is but one instance in a vast topology of existence—the all-encompassing transcendental multiverse (Sect. 14.3.5), comprised of countless material and immaterial universes. Life, consciousness, and artificial intelligence are inevitable in the computational teleology of existence. No God or gods need to be invoked. The fact that information cannot be destroyed (Sect. 13.1.3) has spiritual implications in the context of physical death. However, the following questions remain unanswered:

- The beginning: Why is there something rather than nothing (Sect. 8.1.2)?
- The end: What is the computational teleology leading to?
- The meaning: Why?

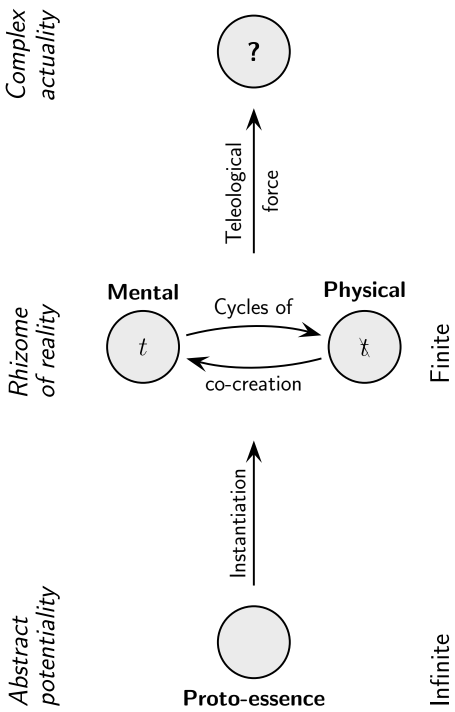

Fig. 15.3 The entelechy of existence. From abstract and infinite potentiality the finite information matrix emerges which manifests its inner and outer aspects. Space-time, energy, and consciousness appear. Whereas the physical is timeless, the conscious is bound to the eternal moment of "now." The mental and physical realms are locked in an eternal cycle of co-creation—the play of existence. Driven by a teleological force, ever higher levels of computation—and thus complexity—are sought

15.3 A New Horizon

The question, why something is the way it is, seems to lie outside of scientific knowledge by definition. Attributing meaning is seen to belong to the domain of theology. Often science and religion are understood as irreconcilable antipodes. Indeed, there is often much contempt to be found in each faction's assessment of the other.

15.3.1 Transcending Religion

Some voices tried to overcome the animosity between science and religion. For instance, the evolutionary biologist Martin Nowak, also a Roman Catholic, remarked (Powell 2007):

> Science and religion are two essential components in the search for truth. Denying either is a barren approach.

Albert Einstein, perhaps the greatest physicist of all times, agrees (Einstein 1940):

> Science without religion is lame, religion without science is blind.

However, he emphasizes (quoted in Dukas and Hoffmann 1989, p. 43):

> It was, of course, a lie what you read about my religious convictions, a lie which is being systematically repeated. I do not believe in a personal God and I have never denied this but have expressed it clearly. If something is in me which can be called religious then it is the unbounded admiration for the structure of the world so far as our science can reveal it.

Nonetheless, Einstein's outlook appears quite mystic (quoted in Frankenberry 2008, p. 147):

> Every one who is seriously involved in the pursuit of science becomes convinced that a spirit is manifest in the laws of the Universe—a spirit vastly superior to that of man, and one in the face of which we with our modest powers must feel humble.

Indeed (Einstein 2007, p. 5):

> The fairest thing we can experience is the mysterious. It is the fundamental emotion which stands at the cradle of true art and science. He who knows it not and can no longer wonder, no longer feel amazement, is as good as dead, a snuffed-out candle.

Einstein, having uncovered much deep knowledge himself, was enthralled by nature's incomprehensibility (quoted in Gaither 2012, p. 1419):

> The human mind is not capable of grasping the Universe. We are like a little child entering a huge library. The walls are covered to the ceilings with books in many different tongues. The child knows that someone must have written these books. It does not know who or how. It does not understand the languages in which they are written. But the child notes a definite plan in the arrangement of the books—a mysterious order which it does not comprehend, but only dimly suspects.

He further observed (quoted in Dukas and Hoffmann 2013, p. 39):

> What I see in Nature is a magnificent structure that we can comprehend only very imperfectly, and that must fill a thinking person with a feeling of humility.

In essence (Einstein 2009, p. 98):

> My religious feeling is a humble amazement at the order revealed in the small patch of reality to which our feeble intelligence is equal.

Einstein's sympathy for the religious longing in humans is perhaps most pronounced in his thoughts on *Cosmic Religion*, a notion transcending common religiosity (Einstein 2009, p. 48ff.):

> I will call it the cosmic religious sense. This is hard to make clear to those who do not experience it, since it does not involve an anthropomorphic idea of God; the individual feels the vanity of human desires and aims, and the nobility and marvelous order which are revealed in nature and in the world of thought. He feels the individual destiny as an imprisonment and seeks to experience the totality of existence as a unity full of significance. Indications of this cosmic religious sense can be found even on earlier levels of development—for example, in the Psalms of David and in the Prophets. The cosmic element is much stronger in Buddhism, as, in particular, Schopenhauer's magnificent essays have shown us.
>
> The religious geniuses of all times have been distinguished by this cosmic religious sense, which recognizes neither dogmas nor God made in man's image. Consequently there cannot

> be a church whose chief doctrines are based on the cosmic religious experience. It comes about, therefore, that precisely among the heretics of all ages we find men who were inspired by this highest religious experience; often they appeared to their contemporaries as atheists, but sometimes also as saints. Viewed from this angle, men like Democritus, Francis of Assisi, and Spinoza are near to one another. [...]
>
> Thus we reach an interpretation of the relation of science to religion which is very different from the customary view. From the study of history, one is inclined to regard religion and science as irreconcilable antagonists, and this for a reason that is very easily seen. For any one who is pervaded with the sense of causal law in all that happens, who accepts in real earnest the assumption of causality, the idea of a Being who interferes with the sequence of events in the world is absolutely impossible. Neither the religion of fear nor the social-moral religion can have any hold on him. A God who rewards and punishes is for him unthinkable, because man acts in accordance with an inner and outer necessity, and would, in the eyes of God, be as little responsible as an inanimate object is for the movements which it makes. [...]
>
> It is, therefore, quite natural that the churches have always fought against science and have persecuted its supporters. But, on the other hand, I assert that the cosmic religious experience is the strongest and the noblest driving force behind scientific research. No one who does not appreciate the terrific exertions, and, above all, the devotion without which pioneer creations in scientific thought cannot come into being, can judge the strength of the feeling out of which alone such work, turned away as it is from immediate practical life, can grow.
>
> Anyone who only knows scientific research in its practical applications may easily come to a wrong interpretation of the state of mind of the men who, surrounded by skeptical contemporaries, have shown the way to kindred spirits scattered over all countries in all centuries. Only those who have dedicated their lives to similar ends can have a living conception of the inspiration which gave these men the power to remain loyal to their purpose in spite of countless failures. It is the cosmic religious sense which grants this power.

However, both scientific and religious dogmatism can be harmful. While the former can lead to closed-minded thinking (Sect. 12.4.4), false certainty (Sect. 8.1.1), and blind spots (Part II and III), the latter tries to warp reality into a preconceived cage (Sect. 12.2.2). As an example, the following theistic interpretation of the information-theoretic ontology should heed as a warning (Davies and Gregersen 2014, p. 412):

> The Christian idea of a Triune God—Father, Son, and Holy Spirit—may [...] be a unique resource for developing a relational ontology that is congenial to the concept of matter as a field of mass, energy, and information.

Sagan also warns (Sagan 1979, p. 332f.):

> But religions are tough. Either they make no contentions which are subject to disproof or they quickly redesign doctrine after disproof. The fact that religions can be so shamelessly dishonest, so contemptuous of the intelligence of their adherents, and still flourish does not speak very well for the tough-mindedness of the believers. But it does indicate, if a demonstration was needed, that near the core of the religious experience is something remarkably resistant to rational inquiry.

However, recall his openness towards spirituality (Sect. 14.2.3).

15.3.2 In Closing

If we are truly living in a participatory universe, then the profoundest implication is the mind's capacity to sculpture physical reality.[3] Expressed within a different metaphor, the inner aspect of information continually reprograms the outer information matrix. As a consequence: "I give meaning to the reality I create." This dramatically shifts the unquenchable human yearning for knowledge from any outer authority to an inner authority. I find myself at the center of my universe, fully accountable. Perhaps this secret was known from the beginning of the mind's awakening, permeating ancient Hindu cosmology, Buddhist teachings, shamanic traditions, and now emerging within an information-theoretic and participatory scientific paradigm.

Many mathematicians and scientists are Platonists (Sect. 2.2). In other words, they believe in the reality of a transcendental realm of abstractions, from which mathematics springs. Perhaps the most radical Platonic proposition is that of the cosmologist Max Tegmark. He argues for the Mathematical Universe Hypothesis. In essence, our external physical reality is a mathematical structure (Sect. 13.4.3). Platonism, and the issues it raises (Fig. 15.1), can be incorporated into the template of the entelechy of existence (Fig. 15.3). Essentially, the Platonic abstract realm is at the root of the potentiality of existence, from which the mental and physical emanate. Their structural similarity drive the knowledge generation process discussed in Sect. 2.1. Moreover, the Hindu myth of existence also shares a congruence with the entelechy of existence. The concept of *nirguna*, "which is to say that it has no qualities and nothing can be said or thought about it" (Watts 1971, p. 98) corresponds to abstract potentiality. The play of *maya* is the rhizome of reality. These ancient truth-seekers also discovered the transcendental multiverse (Watts 1971, p. 101):

> The worlds that are manifested when the Self breathes out are not just this one here and those that we see in the sky, for besides these there are worlds so small that ten thousand of them may be hidden in the tip of a butterfly's tongue, and so large that all our stars may be contained in the eye of a shrimp. There are also worlds within and around us that do not reverberate upon our five organs of sense, and all these worlds, great and small, visible and invisible, are in number as many as grains of sand in the Ganges.

It is truly remarkable, that the human brain is equipped with the neurochemical makeup allowing its disembodied consciousness to experience these transcendental worlds firsthand (Sects. 14.3.2 and 14.3.5).

Returning to the nine explanatory templates for reality, introduced in Chap. 1 and again discussed in Chap. 14—i.e., $E1$–$E9$ on Page 5 or 519—we are left with the following adapted option of $E5$:

[3] As a result, by not believing in this mechanism, the mind is instructed to utilize its creative potential in a way which renders a reality reflecting this instruction. In other words, by denying the participatory ontology, a reality will be experienced which has no participatory ontology.

> *E10* Only information exists. It manifests itself out of an ineffable abstract source and actualizes physical individualizations and pure consciousness, which interact in endless cycles, allowing for an experiential context to emerge. Existence is driven to ever higher levels of actualized complex structure, expressing intelligence. [Information-theoretic and participatory ontology]

$E1$ and $E2$ are explanations arising within the dogma of the materialistic scientific worldview and Abrahamic religions, respectively. $E3$ and $E4$ are Eastern creation myths which can be placed within $E10$. $E7$ is also a compatible scientific explanation. $E8$ is the scientific explanation underlying $E10$ (Sect. 13.4.1). Finally, both $E6$ and $E9$ (Sect. 13.4.2) can either be incorporated into $E10$ or they incorporate $E10$ itself.

And so the curtain closes as the human mind remembers and glimpses more of the essence of existence, while the next act is being forged in the furnace of information…

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Epilogue

We appear to have reached a crossroad. Two paths unfold before the human mind. One is a mechanistic, reductionistic, and materialistic conception of the cosmos. While it has been an extraordinarily successful tool for unearthing knowledge and crafting technology, it leaves the human psyche in a state of limbo. Consciousness and free will are fictitious, the universe is ad hoc, random, and devoid of meaning. Existence is cruel, callous, and absurd. This path is a continuation of the one that a majority of humanity is currently journeying on.

However, we now see a new trail emerge, bifurcating off of the beaten path. It too carries the hallmarks of knowledge generation—formal and transcendental—however it speaks of an entirely different cosmos. The human mind is invited to comprehend its kinship with the material, to understand its own primal and universal nature. It is reminded to seek its own authority within itself. How will the human mind choose?

The clock is ticking. We are witnessing the global increase of religious fundamentalism and extremism. A new rise of populism is transitioning towards fascism and open neo-Nazism is reemerging. In effect, we are seeing the general radicalization of countless people around the globe—anger, fury, hatred, and fear abound. In order to precipitate this sentiment for self-serving power, post-truth is being weaponized by the insidious and reality and facts become optional. Debates with creationists and flat-Earthers continue inconclusively and ad nauseam. (Some of the following text passages are taken or modified from Glattfelder (2016a).)

We truly live in tumultuous times. In a global environment where ignorance, myopia, denial, cynicism, indifference, callousness, alienation, disenchantment, and superficiality reign it is not surprising to witness people escaping this angst short-term by distracting consumerism and numbing materialism overall. This then leads to the predicament outlined in Sect. 7.4.2. Our collective psyche is suffering under the current zeitgeist. In just a few decades the complexity and uncertainty of the lives we lead has dramatically increased and we now struggle even harder to find meaning. Most ominously, artificially intelligent software and robotic systems are lined up

J. B. Glattfelder, *Information–Consciousness–Reality*, The Frontiers Collection,
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to take over the jobs of many unqualified workers[1]—even qualified ones. Already in 1991, the historian Richard Tarnas analyzed all of these problem complexes in his bestselling book *The Passion of the Western Mind*. The following powerful and penetrating words resonate more than ever (Tarnas 1991, p. 362f.):

> Human individuality seemed increasingly tenuous, disappearing under the impact of mass production, the mass media, and the spread of a bleak and problem-ridden urbanization. Traditional structures and values were crumbling. With an unending stream of technological innovations, modern life was subject unprecedentedly disorienting rapidity of change. Gigantism and turmoil, excessive noise, speed, and complexity dominated the human environment. The world in which man lived was becoming as impersonal as the cosmos of his science. With the pervasive anonymity, hollowness, and materialism of modern life, man's capacity to retain his humanity in an environment determined by technology seemed increasingly in doubt. For many, the question of human freedom, of mankind's ability to maintain mastery over its own creation, had become acute.
>
> But compounding these humanistic critiques were more disturbingly concrete signs of science's untoward consequences. The critical contamination of the planet's water, air, and soil, the manifold harmful effects on animal and plant life, the extinction of innumerable species, the deforestation of the globe, the erosion of topsoil, the depletion of groundwater, the vast accumulation of toxic wastes, the apparent exacerbation of the greenhouse effect, the breakdown of the ozone layer in the atmosphere, the radical disruption of the entire planetary ecosystem—all this emerged as direly serious problems with increasing force and complexity.

In a similar vein, the words of the historian Yuval Harari in his bestseller *Sapiens: A Brief History of Humankind* (Harari 2015, p. 465):

> Moreover, despite the astonishing things that humans are capable of doing, we remain unsure of our goals and we seem to be as discontented as ever. We have advanced from canoes to galleys to steamships to space shuttles—but nobody knows where we're going. We are more powerful than ever before, but have very little idea what to do with all that power. Worse still, humans seem to be more irresponsible than ever. Self-made gods with only the laws of physics to keep us company, we are accountable to no one. We are consequently wreaking havoc on our fellow animals and on the surrounding ecosystem, seeking little more than our own comfort and amusement, yet never finding satisfaction.
>
> Is there anything more dangerous than dissatisfied and irresponsible gods who don't know what they want?

We have become very accustomed, and alarmingly indifferent and unconcerned, about the state of human affairs. As a species, our recent terraforming activities have fundamentally transformed the biosphere we rely on, resulting in considerable impact for us individually. In a nutshell, we have devised linear systems that extract resources at one end, which, after being consumed, are disposed of at the other end. However, on a finite planet, extraction soon becomes exploitation and disposal results in pollution. Today, this can be witnesses at unprecedented global scales. Just consider the following: substantial levels of toxic pollutants are accumulating in and contaminating human breast milk affecting vast populations even in remote locations, the increase of chronic diseases, antimicrobial resistance, the Great Pacific and the

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[1]This looming threat is why the notion of a basic universal income is slowly being discussed by pragmatically thinking people.

North Atlantic garbage patches, e-waste, exploding levels of greenhouse gases, peak oil and phosphorus, land degradation, deforestation, water pollution, food waste, overfishing, dramatic loss of biodiversity, the accumulation of microplastics in the global water cycle, etc. The list is constantly growing as we await the arrival of the next billion human inhabitants on this planet. Some references are Dewailly et al. (1989), Pronczuk et al. (2002), Landrigan et al. (2002), Mead (2008), Greger and Stone (2016), Gelband et al. (2015), Rios et al. (2010), Ryan (2014), Widmer et al. (2005), LeComte (2016), Newman et al. (2009), Cordell et al. (2009), Eswaran et al. (2001), Achard et al. (2002), World Water Assessment Programme (2006), Parfitt et al. (2010), Worm et al. (2006), Pereira et al. (2010), Barnosky et al. (2011), Motesharrei et al. (2014), Newbold et al. (2016), Crowther et al. (2015), Jamieson et al. (2017), Kosuth et al. (2018). We have arrived in the Anthropocene (Steffen et al. 2018):

> The Anthropocene is a proposed new geological epoch based on the observation that human impacts on essential planetary processes have become so profound that they have driven the Earth out of the Holocene epoch in which agriculture, sedentary communities, and eventually, socially and technologically complex human societies developed.

The habits of consumption in affluent countries have become deleterious to the biosphere. Indeed, the very idea of lifestyle sacrifices is antonymous to the notion of affluence. One basic but key pattern of consumption that is exerting tremendous pressure on all parts of the ecosystem is a diet based on meat and dairy, related to climate change, water depletion, deforestation, pollution, loss of biodiversity, and antimicrobial resistance. See also Wise et al. (1998), Steinfeld et al. (2006), Gerber et al. (2013), Machovina et al. (2015), de Boer et al. (2016), Erb et al. (2016), The Economist (2016). Indeed, "agriculture is now a dominant force behind many environmental threats, including climate change, biodiversity loss and degradation of land and freshwater" (Foley et al. 2011). Observing these impacts has, for instance, lead the UNEP, the agency of the United Nations responsible for coordinating environmental activities, to issue recommendations for the reduction of meat and dairy-based diets (Hertwich 2010). In 1969, the Union of Concerned Scientists was founded, a nonprofit science advocacy organization based in the United States. The organization seeks to offer solution to pressing environmental and social problems. In a 2008 report, the organization warned about the many mentioned environmental issues related to the emergence of a small number of very large confined animal feeding operations (Gurian-Sherman 2008). In 2016, "China's health authority has issued a guidebook telling people how to eat healthily, as the government aims to build a healthy China by 2020" (Guoxiu 2016). This advice to move towards a more plant-based diet[2] is aimed at over a billion people with the potential to ease the burden on the environment. At the end of the day, the calculation is surprisingly trivial. The sun is the sole energy source for all the world's crop calories, of which 55% are fed to people directly. 36% are turned into animal feed for livestock and only 12% of those feed calories can ultimately contribute to the human diet as meat and

[2]There is mounting evidence that a well-planed plant-based diet leads to a healthier life (Lim et al. 2012; Orlich et al. 2013; Greger 2015).

other animal products (Cassidy et al. 2013). Then, in terms of calorie conversion efficiency, for every 100 calories of grain fed to animals, about 40 calories can be retrieved in milk, 22 calories in eggs, 12 in chicken meat, 10 in pork, or 3 in beef (Cassidy et al. 2013). Finally, the ethical dilemma of consuming the bodies of sentient beings—equipped with rich inner worlds of perception allowing for the experience of great suffering—was touched in the introduction to Chap. 11 and Sects. 14.2.4.2 and 14.2.4.3.

Other researchers have set out to identify "planetary boundaries" designed to define a "safe operating space for humanity" (Rockström et al. 2009). Nine boundaries have been defined, relating to climate change, biodiversity loss, biogeochemical processes, ocean acidification, land use, freshwater supplies, ozone depletion, atmospheric aerosols, and chemical pollution. Of these, the first four boundaries are thought to have been crossed. In 2018, we have reached Earth Overshoot Day on the 1st of August. Each year, this day measures when human consumption of Earth's natural resources, or humanity's ecological footprint, approximately reaches the world's biocapacity to generated those natural resources in a year. Since the introduction of this measure in 1970, when the 23rd of December marked Earth Overshoot Day, this tipping point has been occurring earlier and earlier. Compounding these acute problems is the fact that today's generations are living at the expense of future generations, not only ecologically but also economically. One can check the Global Debt Clock,[3] recording public debt worldwide, to see an incomprehensibly and frighteningly high figure, casting an ominous shadow over future prosperity. Not to forget the current unprecedented levels of national and global inequality, triggering a multitude of cascading effects (Lewis 1990; Story 2008; Lahde 2008; Khurana and Zelleke 2009; Anderson 2010; Taibbi 2010; The Economist 2011a, b; Stiglitz 2011, 2012, 2013; Smith 2012; Buffet 2014; Chin and Culotta 2014; Hanauer 2014; Cingano 2014; Piketty 2015; Fleming and Donnan 2015; The Economist 2015; Elliott 2016). See also Sect. 7.4.2.3.

Yes, the outlook is very dire indeed and it is not surprising that such insights have also troubled distinguished scientists like Martin Rees, cosmologist and astrophysicist, Astronomer Royal, former Master of Trinity College, and former President of the Royal Society. Over a decade ago he asked: "Will the human race survive the 21st Century?" (Rees 2003). So too, Stephen Hawking predicted the end of life on Earth within 600 years, speaking at the Tencent WE Summit in Beijing, on the 5th of November 2017.

So, was this it? Are we simply yet another civilization at the precipice of its demise? Are we just a very brief, albeit spectacular, perturbation in the billion year history of life on Earth, which will most probably adapt to anything short of a global cataclysm and continue to flourish for billions of years until our sun runs out of fuel and turns into a red giant?

[3]See http://www.nationaldebtclocks.org.

Perhaps things are not as hopeless as they seem.[4] Maybe the chaotic paths to destruction or survival really are only separated by the metaphorical flapping of the wings of a butterfly. In the case at hand, a mere flicker in the minds of people—for instance, a radical and contagious thought or idea—could alter the course of history. What is missing is possibly a subtle change in the way we perceive and think of ourselves and the world we inhabit; a change that would initiate a true shift in our behavior which could lead to adaptive, resilient, and sustainable human systems and interactions. There exists most probably no universal law prohibiting the emergence of collective intelligence in a system comprised of individually intelligent beings. Our global display of non-intelligence is simply a collective choice we all continue to make. Indeed, today the human mind possesses the blueprints for designing collective intelligent systems (see Sects. 5.2.2 and 7.4.3).

One of the earliest and strongest constraints everyone of us as child is confronted with is the imprinting of local and static sociocultural and religious narratives, mostly emphasizing external authority. To resist this initial molding requires a very critical and open-minded worldview, not something every human child comes equipped with. However, what would happen if we would replace these obviously dysfunctional foundational stories that we have been telling our children? What if we, as a species, agreed to convey ideas to the next generation which do not simply depend on the geographic location of birth but represent something more functional, universal, and unifying? Ideas that also stress self-awareness, self-responsibility, and self-reliance? It should never be underestimate how exposing untainted young brains to novel empowering thoughts could result in the emergence of a new generation, significantly different from the last one. Bold ideas capable of transforming the inner space of the mind and thus having the power to emanate into the outer world. Can we dare to imagine a future, where we teach our children to be empathetic but critical thinkers? A time when responsible, dynamic, and inclusive mindsets are cultivated? When we teach children not to fear and discriminate against what is perceived as different and foreign; not to fear change and frantically cling on to the status quo, but to face the never ending challenges of life with confidence and trust? Just by playfully exposing children—whose minds are longing to decode the reality they are growing up in—to science, scientific thought, and philosophical musings can have the potential to bring about profound changes. Although young minds want to suck up knowledge and information like a sponge, already the adolescent mind can start to rebel: "I hate mathematics" is an unfortunate attitude all too familiar to many scientists. This is why science and philosophy children's books are so valuable. For instance, the science adventure book series by Lucy and Stephen Hawking (Hawking and Hawking 2007, 2011, 2014a, b, 2016). I ended my contribute to *George and the Blue Moon* (Hawking and Hawking 2016)—a short science essay, titled *What is Reality?*, outlining the information-theoretic and participatory ontology—with the words (Glattfelder 2016b, p. 213).

[4] Some currently optimistic voices are, for instance, Rosling et al. (2018), Pinker (2018).

> For millennia, the question of what reality *really* is was attempted to be answered by philosophers and religious people. Now, for the first time in history, science has expanded its understanding and has only just started to uncover all the illusions surrounding us. There are quite a few scientists who, after thinking deeply about these things, slowly dare to believe in such crazy ideas mentioned above [the information-theoretic and participatory paradigm]. And if any of these ideas turn out to be true, it would mean a very big shift in the way we humans understand reality and ourselves. But for the moment we can comfort ourselves with two answers to the question, "What is reality?"
>
> One is that reality is a much bigger, richer and more complex thing than we ever dared to dream.
>
> Or a short answer could be, "I create *my* reality!"

We are truly living in a brave new world of unprecedented potential, where future utopias or dystopias are possibly only separated by a thought, an idea, a behavior able to replicate and trigger self-organizing and adaptive collective action. Such a thought could indeed be the accountability every conscious mind is confronted with in a participatory ontology (see Sect. 15.3.2). Finding one's self at the center of one's own universe offers a radically different context to existence. In the end, what many embodied conscious minds fears most is the threat of annihilation. However, death[5] has appeared in very different cultural and religious matrices around the world. By witnessing the human corpses being burnt next to the Ganges in the ancient city of Varanasi, a somber but sorrow-free context of death can be experienced. Moreover, the *Tibetan Book of Living and Dying* (Sogyal Rinpoche 1992) also speaks of a very different meaning of death than what is encountered in modern materialistic societies. However, the emerging information-theoretic and participatory scientific paradigm, wherein information is conserved, implies an eternal and transcendental element of individualized consciousness. Indeed, meaning can be found in its edifice—namely, the meaning consciousness chooses to attribute to the reality consciousness chooses to create. Furthermore, beauty is to be found all around. The final words appearing in the book *A Beautiful Question*, written by the physics Nobel laureate Frank Wilczek, read (Wilczek 2016, p. 328):

> The physical world embodies beauty. The physical world is home to squalor, suffering, and strife. In neither aspect should we forget the other.

I would like to close on a personal note. The entire creation process of this book has mysteriously echoed the experience of the philosopher of science, Paul Feyerabend (Sect. 9.1.6). He observed (Feyerabend 2008, p. 8f.):

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[5]It is a remarkable fact that death is a function of temperature. "You're not dead until you're warm and dead" (Khazan 2014). Suspended animation trauma surgery literally kills people to save them. Without a pulse or brain activity, the "frozen" patients are clinically dead during the procedure (Murphy 2014; Mohiyaddin et al. 2018). Remarkably, even after extended periods of suspended animation, the patients can return to life and recover (Casarett 2014). Moreover, death can also be averted by pure willpower (Kamler 2002, 2009). Again, all of this is unexpected within a mechanistic, reductionistic, and materialistic conception of life. Finally, the actual act of dying is probably experienced as being devoid of pain and not unpleasant. At least this is what climbers recollect, who have fallen to their supposed death, but miraculously survived the ordeal (Schubert 1995, p.260ff.).

> The point of view underlying this book is not the result of a well-planned train of thought but of arguments prompted by accidental encounters.

Although I had the basic structure in place from the very beginning of writing, much of the actual content creation was dictated by random developments in the moment. Spontaneous ideas to look up certain notions in other books, conversations with people extending my knowledge at just the right time, reading a headline by chance which offered useful information, finding the right quote, connecting concepts, etc. mostly happened in an unorchestrated fashion. Essentially, by writing this book—by weaving the threads of physics, history, philosophy, theology, and spirituality into a possible tapestry of existence—I have convinced myself of the following for the moment.[6] A current draft of a personal manifesto:

I believe in the computational engine of the universe—reality's information-theoretic ontology. I believe that consciousness shares the same innate essence as the "material." I believe in the capacity of consciousness to influence reality—reality's participatory ontology. I believe in the entelechy of existence and its teleological arrow striving for ever higher levels of information processing. I am mesmerized by the reality-topology of the transcendental multiverse. But perhaps most importantly, "I give meaning to the reality I create." This translates into an ethical maxim: "I am fully accountable!"

In a TEDxSalford talk, I outlined the ideas presented in this book and closed with the following words (Glattfelder 2014):

> [I]f it is really true that we are in fact in charge of our own universe made of pure information, then it is essential for us to look for wisdom and truth within ourselves. Perhaps looking for reality outside of the mind is going the wrong way.

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[6] Naturally, everything I believe could be wrong.

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