The Struggle Against Chaos

by Stephen Fratini

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Preface

The photo on the first page of this book captures the sorry state of a structure at Independence Mine State Historic Park, a former gold mining operation in the Talkeetna Mountains of Alaska. Mining in the area dates back to at least 1897. Operations at the mine stopped in 1950. Some of the structures at the mine have been restored and are actively maintained, unlike the structure in the photo. This type of decay happens to all things. It is basically the process of going from structure and order to disorder (known as entropy).

Of course, it is not only neglected structures in severe climates that decay. Just consider how quickly your house gets dirty and disorderly if you don't keep to a cleaning schedule. But this is only part of the story, i.e., maintaining order, once something structured has been put in place, is also critical. Thinking back to the early universe (before any stars, planets or galaxies formed), it is a wonder that we and our structured world even exist given the law of entropy (also known as the second law of thermodynamics).

This book is about concepts related to the rise of structure out of chaos, and the maintenance and preservation of structure. Concepts such as emergence, self-organization, entropy, recursion, the arrow of time, causality, antifragility, orchestration, choreography, self-adjustment, and other management patterns are covered in this book. An effort has been made to describe the relationships between these concepts, some of which have overlapping ideas.

Acknowledgements

The author would like to thank the following reviewers for their helpful and insightful comments: Tony Clark, Christian Fratini, and David Milham.

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Other books by the author:

- *The Art of Managing Things (2nd edition)*, self-published on Amazon, https://www.amazon.com/Art-Managing-Things-Stephen-Fratini-ebook/dp/B07N4H4YWH/, January 2019.
- *Mathematical Thinking: Exercises for the Mind*, self-published on Amazon, https://www.amazon.com/Mathematical-Thinking-Exercises-Stephen-Fratini-ebook/dp/B08F75CDD6/, August 2020.
- *Financial Mathematics with Python*, self-published on Amazon, https://www.amazon.com/gp/product/B08VKQR141, February 2021.
- *Math in Art, and Art in Math*, self-published on Amazon, https://www.amazon.com/dp/B091D1F8MB, March 2021.
- *Algebra through Discovery and Experimentation*, self-published on Amazon, https://www.amazon.com/dp/B09B5L9WL5, July 2021.

1 Introduction

1.1 Purpose

The purpose of this book is to examine the rise of structure in our universe against the forces of chaos, i.e., entropy.

1.2 Audience

This book is intended for the layperson who has a general interest in science and would like to learn more about how structure (such as atoms, stars, planets and life) has emerged in our universe.

An effort has been made to keep the discussion at a conceptual level, with a minimum of mathematics.

1.3 Section Summary

A summary of the sections in this book is as follows:

- Section 1 is this introduction.
- Section 2 covers physical laws and biological processes that allow for the rise of structure.
- Section 3 is a brief transitional section that prepares the reader for a change in focus from the rise of structure to the management of structure.
- Section 4 is about the categorization of structure.
- Section 5 concerns various processes for the management of structure. The focus is on human processes.

1.4 Overview

This book is about the rise of structure in our universe against the background of chaos.

[**Author's Remarks**: I considered using the term "order" instead of "structure" but after some dictionary searches, I concluded that "structure" was a better fit. There is also a fine distinction between being ordered (in the sense of uniformity) and being structured. For example, the water molecules in a container or the air molecules in a room are ordered in the sense of being uniform but they have no particular structure. Similarly, the extremely high energy and density plasma of the early universe was highly uniform but without any structures – not even subatomic particles.

Another possibility is to contrast complexity with chaos, and in fact, some authors do this. The downside is that "complexity" implies a lot of structure and as such, excludes cases where there is only a small or moderate amount of structure, but I believe that even these cases should be contrasted with chaos.]

There are varying definitions of the word "structure". The following definitions come closest to the intended meaning of "structure" as used in this book.

- Merriam-Webster
  - something arranged in a definite pattern of organization
  - coherent form or organization
- Dictionary.com
  - a complex system considered from the point of view of the whole rather than of any single part [**Author's Remark**: I prefer to remove the word "complex" from this definition.]
  - anything composed of parts arranged together in some way; an organization
- The Free Dictionary by Farlex:
  - Something made up of a number of parts that are held or put together in a particular way
  - anything composed of organized or interrelated elements.
- Wikipedia: A structure is an arrangement and organization of interrelated elements in a material object or system, or the object or system so organized.
- Vocabulary.com: A structure is something of many parts that is put together.

"Structure" is a relative term as used here. For example, an atom is highly structured compared to the very early universe, which was too hot for atoms to form. However, compared to a human being, atoms are relatively simple structures. Structure can be seen as a continuum which increases in complexity over time (starting with the Quark-Gluon Plasma (QGP) that filled the early universe, and then leading to atoms and molecules, the subsequent formation of stars and planets, the rise of life on Earth and perhaps elsewhere, the emergence of intelligent and sentient biological life, and the anticipated rise of super intelligent artificial entities).

The more complex the structure, the more localized it tends to be. Galaxies comprise a small portion of the universe. Solar systems comprise a small part of galaxies. So far, we are only aware of life, let alone intelligent life, on Earth.

In contrast to structure, there is disorganization, chaos and formlessness. This book is about the emergence of structure against the ever looming backdrop of chaos.

2 Chaos and the Rise of Structure

2.1 Overview

This section is about the rise of structure against the backdrop of chaos. The very early universe was a highly uniform plasma without any structures. Eventually atoms, stars, planets and then life formed (at least Earth). The rise and evolution of this structure is the focus of this section.

2.2 Entropy

2.2.1 Overview

As far as current science can determine, our universe arose from a state of extremely high density, high temperature and a high-level of available energy to do work (i.e., low entropy). After its initial expansion, the universe cooled sufficiently to allow for the formation of structures such as subatomic particles, and later atoms. Immense clouds of primordial elements (primarily hydrogen, with some helium and lithium) later coalesced through the force of gravity to form stars, galaxies and eventually planets. At least in one case, life and subsequently conscious intelligence arose on a planet. During its existence, the universe's overall density and temperature have steadily decreased while overall entropy ("disorder") has increased. Yet, ordered structures continue to form in the universe.

In this subsection, we will consider the various definitions of entropy and its relationship to the laws of thermodynamics. Further, some ideas will be offered concerning how structure is able to emerge in the universe while the universe as a whole continues to convert energy from a form that can do work to a form that cannot (i.e., while entropy increases).

[**Author's Remark**: The concept of entropy can be seen from several viewpoints. It is not an easy concept to grasp, but it is important to understand the concept to understand what follows in the book. In the following subsections, I cover the concept three times, i.e., first with some high-level definitions, then through a brief history of how the concept evolved, and finally in more detail. Also, there are several references to articles and videos that may help.]

2.2.2 Definitions and Brief History

Entropy is an important concept from physics that is not easily grasped. Consider the following definition from The American Heritage® Dictionary of the English Language, 5th Edition:

> n. For a closed thermodynamic system, a quantitative measure of the amount of thermal energy not available to do work.
>
> n. A measure of the disorder or randomness in a closed system.
>
> n. A measure of the loss of information in a transmitted message.

The above definitions reveal several aspects of entropy.

- The first definition is related to the thermodynamic aspect of entropy.
- The second definition can be misleading unless “disorder” is defined precisely. For example, one might conclude that a messy (disordered) room has higher entropy than a neatly kept room, but this is not necessarily true. In this context, a better term than “disorder” is “energy dispersal.”
- The third definition concerns the information theory aspect of entropy.

In what follows, it is essential to understand the distinction between potential and kinetic energy.

- The **potential energy** of a body is derived from its position, or condition, rather than motion, e.g., a raised weight, coiled spring, or charged battery has potential energy.
- The **kinetic energy** of a body is derived from its motion, e.g., a moving train or car has kinetic energy.

. . .

Historically, the concept of entropy was first studied with regard to the efficiency of machines. In the early 1800s mathematician Lazare Carnot developed the concept that in any machine there is a loss of “moment of activity” (i.e., the ability to do useful work). From this idea, Carnot drew the inference that a perpetual motion machine was impossible. After his death in 1823, Carnot’s son Sadi continued his work on the topic. From the Wikipedia article entitled “History of entropy” [1], we have the following description of Sadi Carnot’s work:

> Sadi visualized an ideal engine in which any heat (i.e., caloric) converted into work, could be reinstated by reversing the motion of the cycle, a concept subsequently known as thermodynamic reversibility. Building on his father's work, Sadi postulated the concept that "some caloric is always lost" in the conversion into work, even in his idealized reversible heat engine, which excluded frictional losses and other losses due to the imperfections of any real machine. He also discovered that this idealized efficiency was dependent only on the temperatures of the heat reservoirs between which the engine was working, and not on the types of working fluids. Any real heat engine could not realize the Carnot cycle's reversibility, and was condemned to be even less efficient. This loss of usable caloric was a precursory form of the increase in entropy as we now know it. Though formulated in terms of caloric, rather than entropy, this was an early insight into the second law of thermodynamics.

Sadi Carnot’s ideas are related to the definition of entropy concerning “thermal energy not available to do work.”

In 1865, Rudolf Clausius coined the term "entropy." He studied the conversion of heat into work and recognized that heat from a body at a high temperature would flow to one at a lower temperature, e.g., put a cold brick on top of a hot brick, and heat flows from the hot to the cold brick and to the surrounding air as well. Clausius was also the first person to formulate a version of what we now call the second law of thermodynamics: "heat does not pass from a body at low temperature to one at high temperature without an accompanying change elsewhere."

In contrast to "energy not available to do work," there is something called **free energy**. Free energy is the amount of internal energy of a thermodynamic system that is available to perform work. There are several variations of the concept:

- Gibbs free energy is the energy that can be converted into work in a system that is at constant temperature and pressure.
- Helmholtz free energy is energy that can be converted into work at constant temperature and volume.
- Landau free energy describes the energy of an open system in which particles and energy may be exchanged with the surroundings of the open system.

Further developments by Ludwig Boltzmann (in the 1870s) posed entropy as a measure of disorder where "disorder" is defined by the number possible of microstates in a given closed system at equilibrium. This is basically a statistical definition of entropy.

While entropy is not measurable directly, it is possible to measure the change in entropy over time using the Maxwell relations [2], a set of equations in thermodynamics developed by James Clerk Maxwell.

Claude Shannon extended the concept of entropy to information theory. From the Wikipedia article entitled "History of entropy" [1]:

> Shannon's information entropy is a much more general concept than statistical thermodynamic entropy. Information entropy is present whenever there are unknown quantities that can be described only by a probability distribution. In a series of papers by E. T. Jaynes starting in 1957, *[it was argued that]* statistical thermodynamic entropy can be seen as just a particular application of Shannon's information entropy to the probabilities of particular microstates of a system occurring in order to produce a particular macrostate.

In summary, our understanding of entropy has evolved over time. The initial view was very much focused on the dissipation of heat energy. This was followed by the statistical interpretation of Boltzmann where the number of ways a given macrostate (a summary state such as the temperature and pressure in a room) can be realized by different microstates (e.g., the arrangement of gas molecules in a room that lead to the same temperature and pressure) is used as measure of entropy. In the 20th century, Shannon extended the view of entropy to information theory. In the subsections that follow, each of the interpretations (views) of entropy will be explained and explored further.

[**Author's Remark**: As noted earlier, entropy is often described as a measure of disorder, but this is misleading. For example, consider a large storage container with a bottom and top shelf of equal size. In Case 1, we neatly organize a collection of items on the bottom shelf (with nothing on the top shelf). In Case 2, we hurl the same collection of items into the top shelf (with nothing in the bottom shelf). Case 2 is by definition more disordered but Case 2 also has **lower** entropy. The reason is that in Case 2 we have more available energy, in the form of potential energy from the items being higher off the ground than in Case 1. So, here we have an example of where a more disorderly arrangement of things has lower entropy than a more orderly arrangement of the same things.]

2.2.2.1 Thermodynamics

The thermodynamic aspect of entropy makes use of the concept of unavailable energy. The Merriam-Webster dictionary offers the following definition of unavailable energy and available energy:

> **Unavailable energy**: energy that is incapable of doing work under existing conditions.
>
> **Available energy**: that part of the energy of bodies or systems which exists under such conditions that work may be theoretically derived from it.

The following definition of entropy (from Encyclopedia Britannica [3]) makes use of the concept of unavailable energy to do work:

> Entropy, the measure of a system's thermal energy per unit temperature that is unavailable for doing useful work. Because work is obtained from ordered molecular motion, the amount of entropy is also a measure of the molecular disorder, or randomness, of a system. The concept of entropy provides deep insight into the direction of spontaneous change for many everyday phenomena. Its introduction by the German physicist Rudolf Clausius in 1850 is a highlight of 19th-century physics.

A simple definition of energy is "the ability to do work." Entropy is a measure of how much energy in a system is not available to do work. Although all forms of energy are interconvertible, and all can be used to do work, it is not always possible, even in principle, to convert the entire available energy of a system into work. Unavailable energy is of interest in thermodynamics, because the field of thermodynamics arose from efforts to convert heat to work.

Consider the grandfather clock in Figure 1. The clock is driven by the three cylindrical weights shown in the figure. At some later point in time, the weights will be lower and will eventually touch the bottom of the clock (in which case, the clock will stop running). Thus, over time, the clock has an increase in unavailable energy and by definition, higher entropy. The energy is lost via frictional heat as the clock operates (this is considered an irreversible process). However, the clock appears no less ordered as the weights descend lower.

Figure 1. Grandfather clock driven by three weights

Note: While it is theoretically possible that some of the heat energy released by operation of the clock could be recovered, not all of the heat energy can be recovered (so says the Second Law of Thermodynamics, see Section 2.2.3).

. . .

Another way to view entropy is from the perspective of statistical mechanics [4]:

> It *[statistical mechanics]* is a mathematical framework that applies statistical methods and probability theory to large assemblies of microscopic entities. It does not assume or postulate any natural laws, but explains the macroscopic behavior of nature from the behavior of such ensembles.

In this approach, one considers the possible set of microstates corresponding to each macrostate of a system in order to determine a measure for the entropy of the system. From the Wikipedia article entitled "Microstate (statistical mechanics)" [5]:

> In statistical mechanics, a **microstate** is a specific microscopic configuration of a thermodynamic system that the system may occupy with a certain probability in the course of its thermal fluctuations. In contrast, the **macrostate** of a system refers to its macroscopic properties, such as its temperature, pressure, volume and density. Treatments of statistical mechanics define a macrostate as follows: a particular set of values of energy, the number of particles, and the volume of an isolated thermodynamic system is said to specify a particular macrostate of it. In this description, microstates appear as different possible ways the system can achieve a particular macrostate.

Further, we have the concept of an **accessible microstate** for a system which is a microscopic (molecular level) configuration of a system that is physically possible given all constraints on the system. Possible constraints include energy, volume, temperature, pressure, number of molecules and volume as well as physical laws that are not possible to violate such as the law of conservation of energy. However, not all configurations of a system are physically possible. For example, if the system is a diamond (composed of carbon atoms), a reconfiguration of the carbon atoms of the diamond into graphite (also composed of carbon atoms) is not possible (at say typical room temperature and pressure) and thus not an accessible microstate.

Since the number of microstates that are accessible for a system indicates all the different ways that energy can be arranged in that system, the larger the number of accessible microstates, the greater is a system's entropy under a given set of constraints.

As a closed system is heated, it gains kinetic energy which results in increased molecular motion and a wider distribution of molecular speeds. This increases the number of microstates possible for the system.

- Increasing the number of molecules in a system also increases the number of microstates, since there are now more possible arrangements of the molecules.
- Increasing the volume of a system increases the number of positions where each molecule could be, which increases the number of microstates.

Therefore, any change that results in a higher temperature, larger number of molecules, or greater volume for a closed system leads to an increase in entropy for that system.

As an example, let’s return to the grandfather clock. First, assume the grandfather clock and surrounding air is enclosed in a sealed container (left-side of Figure 2). Next to the container with the grandfather clock is another container with no air (basically a vacuum). If the separation between the two containers is removed, we now have a new closed system which has higher entropy than the initial closed system containing the grandfather clock. The reason is that the new closed system has more microstates, e.g., the air molecules can now be in a much larger number of positions.

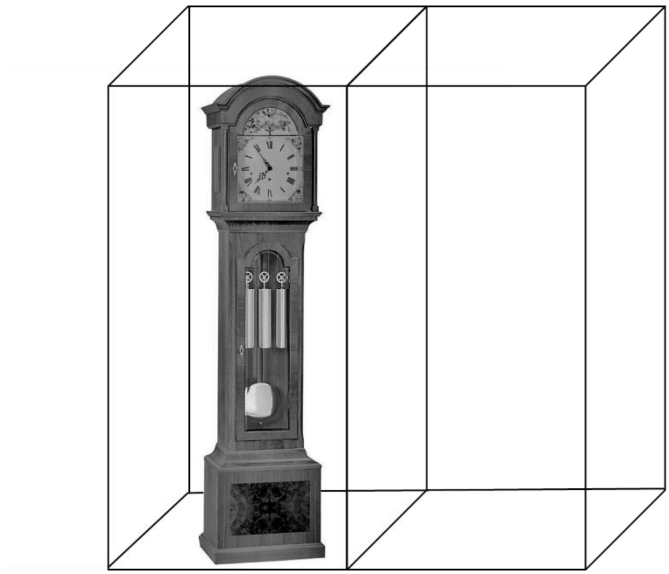

Figure 2. Grandfather clock macrosystems

When all the microstates of a macrostate are equally probable, the Boltzmann entropy formula provides a way of calculating the entropy of a system:

$$S = k_B \ln W$$

In the formula, S is the entropy, W is the number of microstates for a given macrostate, and k_B is the Boltzmann constant which is equal to $1.38065 \times 10 - 23\ J/K$ where J stands for Joules (a measure of energy) and K stands for degrees Kelvin (a measure of temperature). When the microstates are not equally probable, we use the Gibbs entropy formula:

$$S = -k_B \sum_i p_i \ln p_i$$

where p_i is the probability of the i^{th} microstate occurring. If all the probabilities are the same ($p_i = p$ for every value of i) and we assume a total of N microstates, then we have the following:

$$S = -k_B \sum_i p \ln p = -k_B(Np) \ln p = k_B \ln\left(\frac{1}{p}\right)$$

Note that $Np = 1$ and $\frac{1}{p}$ is the number of microstates W. Thus, the Gibbs entropy formula reduces to the Boltzmann entropy formula when the probabilities of the microstates for a given macrostate are the same.

As another example, and to further dispel the equating of entropy to disorder, consider an ice cube. The ice cube has a highly ordered crystalline structure but entropy increases when the ice cube melts into water since ice has far fewer microstates than water (although the number of microstates is huge in both cases).

In summary, consider the following quote from American physicist and Nobel Laureate Richard Feynman:

> Suppose we divide the space into *[two]* little volume elements. If we have black and white molecules, how many ways could we distribute them among the volume elements so that white is on one side and black is on the other? On the other hand, how many ways could we distribute them with no restriction on which goes where? Clearly, there are many more ways to arrange them in the latter case. We measure "disorder" by the number of ways that the insides can be arranged *[microstates]*, so that from the outside it looks the same *[macrostate]*. The logarithm of that number of ways is the entropy. The number of ways in the separated case *[all black on one side and all white the other]* is less, so the entropy is less, or the "disorder" is less.

2.2.2.2 Energy Dispersal (Disorder)

In this viewpoint, entropy is defined as a measure of energy dispersal at a specific temperature. This approach attempts to avoid the confusing usage of the term "disorder." From the Wikipedia article entitled "Entropy (energy dispersal)" [6]:

> The term "entropy" has been in use from early in the history of classical thermodynamics, and with the development of statistical thermodynamics and quantum theory, entropy changes have been described in terms of the mixing or "spreading" of the total energy of each constituent of a system over its particular quantized energy levels.
>
> Such descriptions have tended to be used together with commonly used terms such as disorder and randomness, which are ambiguous, and whose everyday meaning is the opposite of what they are intended to mean in thermodynamics. Not only does this situation cause confusion, but it also hampers the teaching of thermodynamics. Students were being asked to grasp meanings directly contradicting their normal usage, with equilibrium being equated to "perfect internal disorder" and the mixing of milk in coffee from apparent chaos to uniformity being described as a transition from an ordered state into a disordered state.
>
> The description of entropy as the amount of "mixed-up-ness" or "disorder," as well as the abstract nature of the statistical mechanics grounding this notion, can lead to confusion and considerable difficulty for those beginning the subject. Even though courses emphasized microstates and energy levels, most students could not get beyond simplistic notions of randomness or disorder. Many of those who learned by practicing calculations did not understand well the intrinsic meanings of equations, and there was a need for qualitative explanations of thermodynamic relationships.

The YouTube video entitled "The Misunderstood Nature of Entropy" [7] also provides some clarification concerning the definition of entropy.

The Wikipedia article goes on to describe entropy in terms of energy dispersion (spreading):

> In this approach, the second law of thermodynamics is introduced as "Energy spontaneously disperses from being localized to becoming spread out if it is not hindered from doing so," often in the context of common experiences such as a rock falling, a hot frying pan cooling down, iron rusting, air leaving a punctured tire and ice melting in a warm room. Entropy is then depicted as a sophisticated kind of "before and after" yardstick — measuring how much energy is spread out over time as a result of a process such as heating a system, or how widely spread out the energy is after something happens in comparison with its previous state, in a process such as gas expansion or fluids mixing (at a constant temperature). The equations are explored with reference to the common experiences, with emphasis that in chemistry the energy that entropy measures as dispersing is the internal energy of molecules.

The second law of thermodynamics is also known as the law of increased entropy.

In our grandfather clock example, the heat energy generated by the clock mechanism is dispersed into the surrounding environment and thus entropy increases as the clock runs. This gives us a second (and equally valid) way to view the increase in entropy regarding the grandfather clock example.

2.2.2.3 Information Theory

Entropy can be viewed from the perspective of information theory. In this context, entropy measures the expected (i.e., average) amount of information conveyed by identifying the outcome of a random event. For example, the selection of a card from a deck of playing cards has higher entropy than rolling a die because each outcome of a card selection has smaller probability (i.e., $\frac{1}{52}$) than each outcome of a die roll (i.e., $\frac{1}{6}$). In this view, entropy is a measure of the uncertainty in the outcome of a process (such as selecting a card from a deck of playing cards).

The concept of entropy in information theory was introduced by mathematician, electrical engineer, and cryptographer Claude E. Shannon. Shannon introduced entropy in the context of his work in telecommunications at Bell Laboratories. As noted in the Wikipedia article entitled "Entropy (information theory)" [8]:

> The basic idea of information theory is that the "informational value" of a communicated message depends on the degree to which the content of the message is surprising. If an event is very probable, it is no surprise (and generally uninteresting) when that event happens as expected; hence transmission of such a message carries very little new information. However, if an event is unlikely to occur, it is much more informative to learn that the event happened or will happen. For instance, the knowledge that some particular number will not be the

> winning number of a lottery provides very little information, because any particular chosen number will almost certainly not win. However, knowledge that a particular number will win a lottery has high value because it communicates the outcome of a very low probability event.

Shannon developed the following formula for the average information (entropy) for a set of messages M:

$$H = -\sum_{i} p_i \log_b p_i$$

where p_i is the probability of the message m_i taken from a set of possible messages M, and b is the base of the logarithm. For bits, we would set $b = 2$. This is almost the same as the Gibbs entropy formula, except for the constant k_B which is needed since the Gibbs formula is specific to energy.

Apply this formula to the card selection and die roll examples:

- There are $-\sum_{i=1}^{52} \frac{1}{52} \log_2 \frac{1}{52} = 5.700$ bits of entropy in a single card selection from a deck of 52 cards. There are 52 possible "messages" (card selections), each with probability $\frac{1}{52}$.
- There are $-\sum_{i=1}^{6} \frac{1}{6} \log_2 \frac{1}{6} = 2.585$ bits of entropy in a single roll of a die. There are 6 possible "messages" (outcomes of the die roll), each with probability $\frac{1}{6}$.

As another example, consider the entropy of an entire deck of 52 playing cards. There are $52!$ possible arrangements with each arrangement having probability $\frac{1}{52!}$. This results in the following entropy:

$$H = -\sum_{i=1}^{52!} \frac{1}{52!} \log_2 \frac{1}{52!} = 225.581$$

In terms of comparison, information entropy can be calculated for any probability distribution, where each event in the probability space is seen as a message. On the other hand, thermodynamic entropy refers to thermodynamic probabilities. The difference is more theoretical than actual, however, because any probability distribution can be approximated arbitrarily closely by some thermodynamic system.

2.2.2.4 Business, Society and Life in General

By way of analog, entropy is sometimes applied to the business world. Consider the following quote from Roger Zelazny in his book "Doorways in the Sand" [9]:

> As a student of business administration, I know that there is a law of evolution for organizations as stringent and inevitable as anything in life. The longer one exists, the more it grinds out restrictions that slow its own functions. It reaches entropy in a state of total narcissism. Only the

> people sufficiently far out in the field get anything done, and every time they do, they are breaking half a dozen rules in the process.

[**Author's Remark**: Anyone who has worked for a large company or government agency knows there is a lot of truth in the quote from Zelazny.]

In sociology, there is a concept known as "social entropy" which entails an application of the concept of entropy to societies. From the sensagent – dictionary (http://dictionary.sensagent.com), we have the following definition:

> Social entropy is a macro-sociological systems theory. Social Entropy is a measure of the natural decay within a social system. It can refer to the decomposition of social structure or of the disappearance of social distinctions. Much of the energy consumed by a social organization is spent to maintain its structure, counteracting social entropy, e.g., through legal institutions, education and even the promotion of television viewing. Anarchy is the maximum state of social entropy.

Entropy can also be applied (via analogy) to our everyday lives, e.g., consider the following quote from psychologist Steve Pinker in response to the question "What Scientific Term or Concept Ought To Be More Widely Known?" [10]:

> The Second Law defines the ultimate purpose of life, mind, and human striving: to deploy energy and information to fight back the tide of entropy and carve out refuges of beneficial order. An underappreciation of the inherent tendency toward disorder, and a failure to appreciate the precious niches of order we carve out, are a major source of human folly.

A critical point to remember is that in business, society and life in general, entropy is just a tendency but in physics, entropy is a statistical law.

2.2.3 Laws of Thermodynamics

The concept of entropy is prominent in the three laws of thermodynamics (listed below). In subsequent sections of this book, the second law of thermodynamics will play a key role.

There are many different statements of the laws of thermodynamics. For each law, we give several different versions with the goal of enhancing the reader's understanding (and hopefully not adding confusion).

The following terms are used in the various statements of the laws of thermodynamics.

A **physical system** is a portion of the physical universe chosen for analysis. Everything outside the system is known as the environment (or the surroundings of the physical system). The environment is ignored except for its effects on the system.

Closed, Isolated and Open systems:

- A **closed system** is a physical system that can exchange energy (as heat or work), but not matter, with its surroundings.
- An **isolated system** is a physical system that cannot exchange any heat, work, or matter with its surroundings.
- An **open system** is a physical system that can exchange energy and matter with its surroundings.

Internal energy:

- The internal energy of a thermodynamic system is the energy contained within it. It is the energy necessary to create or prepare the system in any given internal state. It does not include the kinetic energy of motion of the system as a whole, nor the potential energy of the system as a whole due to external force fields, including the energy of displacement of the surroundings of the system.
    - In our grandfather clock example, lifting the three weights to a higher position increases internal potential energy. The swinging of the pendulum is an expenditure of internal kinetic energy. Moving the clock to a higher floor in your house increases the potential energy of the system as a whole (i.e., the clock) but not its internal energy. Taking the clock for a drive in your car increases the kinetic energy of the clock as a whole but not its internal energy.
- The internal energy of a system is the sum of the kinetic and potential energy of the system.
    - For example, a solid at room temperature has potential energy due to atomic interactions and kinetic energy due to atomic vibrations. A gas enclosed in a container has potential energy due to atomic/molecular interactions and kinetic energy due to random motion.

The three laws of thermodynamics are as follows:

First law (Conservation of Energy):

- The energy gained (or lost) by a system is equal to the energy lost (or gained) by its surroundings.
- Energy cannot be created or destroyed. In other words, in a closed system, the total amount of energy that can be taken out of the system will be equal to the total amount of energy that was put into the system *[plus the internal energy of the system]*.

- In a closed system, the change in internal energy of the system is equal to the difference between the heat supplied to the system and the work done by the system on its surroundings.
- If heat is added to a system, there are only two things that can be done, i.e., change the internal energy of the system (including phase changes) or cause the system to do work (or some combination of the two).

Second law (Entropy does not decrease):

- Natural processes tend to go only one way, toward greater unavailable energy and more dispersal *[of energy]*.
- In a closed (or isolated) system, free energy (energy available to do work) is converted to unavailable (disordered or useless) energy over time.
- In any given exchange of energy, there will always be energy lost *[in the sense of no longer being able to do work]*. This is referred to as entropy. This basically means that in any system, energy will always be lost by some means, be it friction, or some random quantum effect. This also implies that there can be no such thing as a perpetual motion machine as energy will always be lost in some form.
- When two initially isolated systems in separate but nearby regions of space (each in thermodynamic equilibrium with itself but not necessarily with each other) are then allowed to interact, they will eventually reach a mutual thermodynamic equilibrium. The sum of the entropies of the initially isolated systems is less than or equal to the total entropy of the final combination. Equality occurs only when the two original systems have all their respective state variables (temperature, pressure) equal; then the final system also has the same values.
- Statement from G. E. Uhlenbeck and G. W. Ford: “In an irreversible or spontaneous change from one equilibrium state to another (as for example the equalization of temperature of two bodies A and B, when brought in contact), the entropy always increases.”
- Kelvin – Planck statement: “It is impossible to devise a cyclically operating device, the sole effect of which is to absorb energy in the form of heat from a single thermal reservoir and to deliver an equivalent amount of work.”

In the words of physicist Sean Carroll [11]:

> Before Boltzmann came along, entropy was understood in terms of the inefficiency of things like steam engines, which were all the rage at the time. Anytime you try to burn fuel to do useful work such as pulling a locomotive, there is always some waste generated in the form of heat. Entropy can be thought of as a way of measuring that inefficiency; the more waste heat emitted, the more entropy you’ve created. And no matter what you do, the

> total entropy generated is always a positive number: you can make a refrigerator and cool things down, but only at the cost of expelling even more heat out the back. This understanding was codified in the second law of thermodynamics: the total entropy of a closed system never decreases, staying constant or increasing as time passes.

It should be emphasized that Boltzmann's formulation of the second law of thermodynamics is statistical and thus allows for fluctuations where entropy does decrease. In the words of James Clerk Maxwell:

> The truth of the second law is a statistical (not a mathematical) truth, for it depends on the fact that the bodies we deal with consist of millions of molecules. Hence the second law of thermodynamics is continually being violated, and that to a considerable extent, in any sufficiently small group of molecules belonging to a real body.

Further, the condition of a system being closed (or isolated) is critical. For example, evolution is an example of entropy decreasing in a local system (i.e., life on Earth). It is important to note that the Earth is an open system. The Sun disperses energy into the system we call Earth. As a result of the Sun dispersing energy (not just to the Earth), entropy increases in the universe. However, entropy decreases locally with regard to life on Earth.

Third law:

- A system's entropy approaches a constant value as its temperature approaches absolute zero. *[Absolute zero is the lowest limit of the thermodynamic temperature scale, a state at which the fundamental particles of nature have minimum vibrational motion, retaining only quantum mechanical, zero-point energy-induced particle motion. While all molecular movement does not cease at absolute zero, no energy from that motion is available for transfer to other systems. This temperature is* 0° *on the Kelvin scale,* -273.15° *on the Celsius scale and* -459.67° *on the Fahrenheit scale.]*

- No system can reach absolute zero temperature. This is due to the fact that at absolute zero, a system has no energy, and thus does not move. Although this does not cause any problems in the sense of classical mechanics; it does cause problems on the quantum level. If a particle had no movement at all, its speed would be exactly known (zero, exactly), which is forbidden by Heissenberg's uncertainty principle.

- The entropy of a perfect crystal of an element in its most stable form tends to zero as the temperature approaches absolute zero.

Sometimes a **0^{th} law of thermodynamics** is mentioned, i.e., if two systems are in thermodynamic equilibrium with a third system, the two original systems are in thermal equilibrium with each other.

2.2.4 The Principle of Maximum Entropy

The principle of maximum entropy entails a common basis for modeling work in both statistical mechanics and information theory. From the Wikipedia article on the principle of maximum entropy [14]:

> The principle of maximum entropy states that the probability distribution which best represents the current state of knowledge is the one with largest entropy, in the context of precisely stated prior data (such as a proposition that expresses testable information).
>
> Another way of stating this: Take precisely stated prior data or testable information about a probability distribution function. Consider the set of all trial probability distributions that would encode the prior data. According to this principle, the distribution with maximal information entropy is the best choice.

The principle was first expounded by E. T. Jaynes in 1957 where he emphasized a natural correspondence between statistical mechanics and information theory. Jaynes argued that the entropy of statistical mechanics and the entropy of information theory are basically the same thing. Further, he stated that statistical mechanics should be seen as a particular application of a general tool of logical inference and information theory.

We mention the principle of maximum entropy here only to emphasize the commonality between statistical mechanics and information theory regarding entropy. For a high-level overview of the topic, see the YouTube videos from Complexity Explorer [12] [13].

2.2.5 Summary and Conclusion

Entropy is an important concept in multiple areas of study, including thermodynamics, chemistry, information theory, cosmology, economics, sociology, and in biological systems and their relation to life.

Entropy, as it is used in the second law of thermodynamics, is a bedrock in our understanding of nature. In the words of physicist Sir Arthur Stanley Eddington:

> The law that entropy always increases – the Second Law of Thermodynamics – holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations – then so much the worse for Maxwell's equations. If it is found to be contradicted by observation – well these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

Physicists Ivan Bazarov makes a similar statement:

> The second law of thermodynamics is, without a doubt, one of the most perfect laws in physics. Any reproducible violation of it, however small, would bring the discoverer great riches as well as a trip to Stockholm. The world's energy problems would be solved at one stroke…
> Not even Maxwell's laws of electricity or Newton's law of gravitation are so sacrosanct, for each has measurable corrections coming from quantum effects or general relativity. The law has caught the attention of poets and philosophers and has been called the greatest scientific achievement of the nineteenth century.

As we have seen, the concept of entropy can be viewed as a measure of unavailable energy, energy dispersal (disorder) or the degree of randomness in a set of data (with greater randomness implying higher entropy and greater predictability implying lower entropy).

Entropy and its various aspects (views) will be used throughout this book in relation to such topics as causality (Section 2.3), the arrow of time (Section 2.4), emergence (Section 2.5) and self-organization (Section 2.6). Before proceeding, the reader may want to consult the following references for some additional introductory material on the concept of entropy:

- Entropy: The Hidden Force That Complicates Life [15]
- Entropy and the Arrow of Time [16] (which is also a good lead into Section 2.4 of this book)
- ScienceDirect article on entropy [17]
- Entropy (Order and Disorder) [18]
- The Story of Information [19].

Regarding the main theme of this book, entropy is the main "force" working for and against the formation of structure. On the one hand, we know from the second law of thermodynamics that overall entropy in the universe is increasing. On the other hand, thanks to the brilliant insights of Boltzmann, we also know that the second law of thermodynamics is statistical and thus allows for pockets of decreasing entropy and increasing structure.

2.3 Causality

2.3.1 Overview

The concept of causality (cause and effect) is closely related to the direction of time. In our everyday lives, we continually assume that causes precede effects. For example, consider the following definition from the Wikipedia article entitled "Causality" [36]:

> **Causality** (also referred to as causation, or cause and effect) is influence by which one event, process, state or object (a cause) contributes to the production of another event, process, state or object (an effect) where the cause is partly responsible for the effect, and the effect is partly dependent on the cause. In general, a process has many causes, which are also said to be causal factors for it, **and all lie in its past**. An effect can in turn be a cause of, or causal factor for, many other effects, which all lie in its future. Some writers have held that causality is metaphysically prior to notions of time and space.

Here's an even shorter definition:

> The idea that all effects have a **preceding** cause is referred to as causality.

The following is a slightly technical definition from the book "Causal Inference in Statistics" [20]. Time is not explicitly mentioned in this definition but is implied by the word "relies."

> A variable X is a cause of a variable Y if Y in any way **relies** on X for its value.

Causality is an important adjunct to statistics regarding the proper modeling of causes and effects, and associated probabilities. In recent years, the concept and language of causality has been formalized in terms of mathematics.

2.3.2 Types of Causes

Causes can be classified as being either necessary, sufficient or both necessary and sufficient. There is also the notion of contributory causes, i.e., an input that is neither necessary nor sufficient in and of itself, but which contributes to the effect (e.g., example adding kerosine to a fire after it has started).

A sufficient cause will lead to the desired effect but it may not be necessary since other causes may have the same effect. For example, a garden hose can be used to water one's garden. So, use of a garden hose to water a garden is sufficient to get the effect of having a watered garden, but other causes are also possible (e.g., rain or use of a watering bucket).

An effect will not happen if a necessary cause does not happen first but the necessary cause (in and of itself) may not be sufficient. For example, it is necessary to be a United States citizen to become president, but just being a citizen is not sufficient to become president – there are many other steps (causes) needed to attain the desired effect of becoming president.

2.3.3 Relationship to Entropy

There is nothing implied by the definition of causality that necessitates entropy as expressed in the second law of thermodynamics. Causality could be applied in a universe where complex events in closed systems are reversible. This would simply mean that the closed system can return to a previous state via very improbable causes (at least improbable in our universe). It does not mean that time goes in reverse.

On the other hand, entropy (as expressed in the second law of thermodynamics) does rely on the concept of causality. In particular, any increase in entropy would require a cause.

2.3.4 Structural Causal Models (SCMs)

[**Author's Remark**: This section is a bit technical and assumes some knowledge of basic graph theory and probabilities. The point to be made here is that the study of causality has been formalized and has a solid technical basis. The reader may skip this section, without loss of continuity.]

A **Structural Causal Model** (SCM) is a **Directed Acyclic Graph** (DAG) representing the flow of information between the vertices of a graph via the edges of a graph. The vertices in an SCM represent variables. Associated with an SCM is a set of functions that assign to each variable a value based on the values of the other variables. SCMs are used to represent and study causal relationships among a collection of variables.

- In general, a DAG is a graph (consisting of vertices and edges) such that the edges have a direction and there are no cycles in the graph.
- Specific to SCMs, a directed edge from variable X to variable Y means that X is a cause of Y.
- The variables can be either exogenous or endogenous.
    - As the name suggests, the exogenous variables are external to the model. There is no explanation as to how these variables are caused.
    - The endogenous variables are internal to the model. Every endogenous variable in a model is a descendant of at least one exogenous variable. Here the term "descendant" means in the line of causality from a given ancestor (i.e., event).
    - Exogenous variables are not descendants of any other variable, and are represented as root nodes in the SCM.
- In some cases, the vertices in an SCM represent events (which can be seen as a type of variable).

Using the language associated with SCMs, we can state the following definition of causality:

> A variable X is a direct cause of a variable Y if X appears in the function that assigns Y's value. X is a cause of Y if it is a direct cause of Y, or of any cause of Y.

The concept of time does not appear explicitly in the above definition but it is implied, i.e., how could one compute (determine) Y if a value for X did not already exist?

For example, consider the growth (G) of a plant based on three exogenous variables, i.e., average temperature (T), soil quality (S) and rain (R). G is the only endogenous variable. The situation is represented in Figure 3. By the above definition, T, S and R are all direct causes of G.

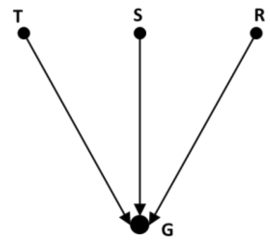

Figure 3. Plant growth example

In this example, there is one function that assigns (predicts) a value for G based on the values of T, S and R. Some example functions that could serve this purpose:

$$G = f(T, S, R) = .4T + .3S + .5R$$

$$G = h(T, S, R) = (.4T)(.3S)(.5R)$$

The function f implies that if any of the exogenous variables are non-zero, there will be some growth. This implies that T, S and R are all sufficient causes of plant growth, which probably is not correct. The function g provides a better model. In this case, if any of the exogenous variables are zero, no plant growth is implied by the function. This means that neither T, S nor R or sufficient causes but all are necessary causes for plant growth.

The function (or functions) that relate the variables in an SCM do not need to be arithmetic functions. In Figure 4, W is the event that a pavement is wet, R is the event that it is raining and S is the event that the sprinkler system is 'On'. (In this example, we assume that rain or the sprinkler system are the only ways for the pavement to get wet.) If R or S is true, then W is also true (as indicated by the logic function $W = g(R, S) = R \cup S$).

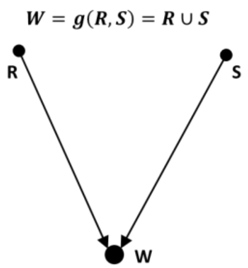

Figure 4. Wet pavement example

Even more common is to present the relationship among the variables with probabilities. In Figure 5, we have a situation where two dice are rolled independently (with outcomes $R1$ and $R2$). If $R1 + R2$ is greater than 7, buzzer (S) is turned On; otherwise, the buzzer remains Off.

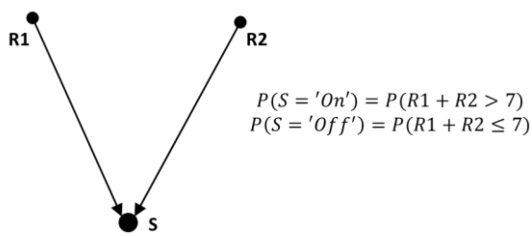

Figure 5. Buzzer example using probabilities

In some cases, we may only have causal relationships among the variables without even the probabilities of impact between variables. In other words, we know which variables are caused by which other variables, but we do not know the strength of the relationships. Even with this limited knowledge, it is still possible to derive useful information from an SCM, e.g., it is possible to determine the interdependencies (or lack thereof) among the variables. Further, all SCMs with the same graphical structure have the same interrelationships among their variables, regardless of the specific functions attached to the SCM.

Figure 6 depicts two configurations that are often part of an SCM.

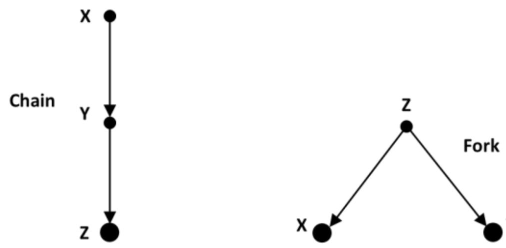

Figure 6. Chain and fork configurations

In the **chain** on the left of Figure 6, Z is dependent on Y, Y is dependent on X. If the value of Y is known, then X and Z are said to be conditionally independent. (In probability theory, **conditional independence** describes situations where an observation is irrelevant or redundant when evaluating the certainty of a hypothesis [21].) For example, let X represent the state of a light switch (On or Off), Y represent the state of an associated electrical circuit (current flowing or not), and Z represent the state of a light bulb (On or Off). If we know the state of Y (e.g., current is flowing), then knowledge of the state of X is redundant with regard to the determination of whether the light bulb is On.

In the **fork** on the right of Figure 6, X is dependent on Z, and Y is dependent on Z. If the value of Z is known, then X and Y are said to be conditionally independent. For example, let Z be the event of rain, let X be the event that storm drains are flowing and Y be the event that the ground is wet. Once we know it is raining, the fact that the ground is wet does not provide any further knowledge with respect to water following in the sewer drain (as we already know that from the fact that it is raining) and vice versa. So, X and Y are conditionally independent if the state of variable Z is known. If the state of variable Z is not known, then X and Y are potentially dependent, e.g., if the ground is wet, the storm drains may be flowing, and vice versa.

Another common configuration in SCMs is the **collider** (or inverted fork). We've already seen several examples of colliders in Figure 3, Figure 4 and Figure 5. Let's focus on the example in Figure 3.

- G (known as the collision vertex) is dependent on T, S and R (known as the parent vertices).
- T, S and R are independent of each other.
- T, S and R are dependent, conditional on knowledge of the value of G. For example, if we know the value of G, T and S, then R is completely determined by the equation associated with the example (whether we use function f or h).

In general, the above points are true for all colliders. The third point is a bit more difficult to accept, i.e., knowledge of the state of the collision vertex imposes a dependency among the parent vertices. As another example, consider the situation in Figure 5 where we know that $S = 'On'$. In this case, R1 and R2 are now dependent. For example, if we know $R1 = 5$, then it must be that $R2 > 2$.

. . .

SCMs are typically much more complex than the simple examples considered thus far. In many causal models, pairs of variables will sometimes have multiple possible paths connecting them, where each path traverses a combination of chains, forks, and colliders. In these complex cases and in general, the concept of d-separation can be used to determine dependencies among variables.

A pair of vertices in a graph are said to be **d-separated** if they are definitely independent. A pair of nodes are said to be **d-connected** if they are possibly dependent.

Two vertices X and Y are d-separated if every path between them is blocked. If even one path between X and Y is unblocked, then X and Y are d-connected. The concept of blocking can be explained via the following analogy [20]:

> The paths between variables can be thought of as pipes, and dependence as the water that flows through them; if even one pipe is unblocked, some water can pass from one place to another, and if a single path is clear, the variables at either end will be dependent. However, a pipe need only be blocked in one place to stop the flow of water through it, and similarly, it takes only one node to block the passage of dependence in an entire path.

The determination of whether every path between two vertices is blocked is straightforward except in cases where there is conditioning on a variable.

In Figure 7, the only possible path between A and E is blocked by the collider at C. So, A and E are d-separated. However, if we condition on C (i.e., assume that the value of C is known), then A and E are conditionally dependent and thus d-connected. If we condition on a descendant of C (in this case F), then again A and E are conditionally dependent and thus d-connected.

So, conditioning on a collider or a descendant of a collider has the opposite effect of blocking. In general, if we are not conditioning on any variable, then only colliders can block a path.

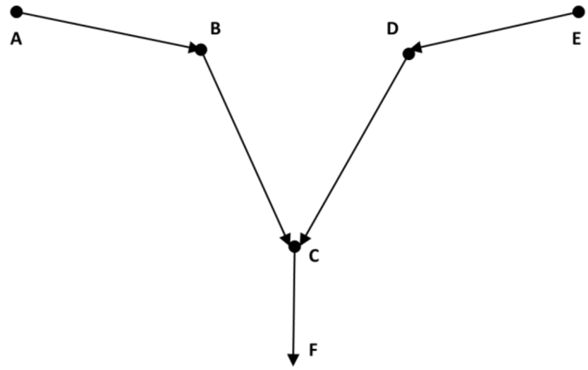

Figure 7. Blocked path between A and E

Chains and forks are not blocking. However, if we condition on a chain or fork, then they are blocking (as we shall see in the following two examples).

In Figure 8, A is d-connected to D, but if we condition on B or C (i.e., make known their values), then A and D are d-separated. For example, let event A represent the ordering of a book, let event B represent the selection of the ordered book from inventory, let event C be the packing of the book, and let event D be the delivery of the book to the customer. Without any conditioning, the 4 events are dependent. However, if we know that an instance of the ordered book could not be found in the inventory, then A is now conditionally independent from both C and D. Knowledge of B makes information concerning A redundant. In other words, knowing that there is no instance of the given book in the vendor's inventory is sufficient to know that neither C nor D will happen (independent of whether A happens or not).

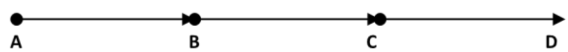

Figure 8. Conditioning on a chain

Figure 9 is a model for food ordering from a restaurant. There are two options, i.e., pickup at the restaurant by the customer, or delivery to the customer's location. Without any conditioning, all the events are dependent. However, if we condition on the "Prepare Food" event, i.e., assume that we know food has been prepared for a given customer, then the "Order" event provides redundant information and is now conditionally independent from "Send on Delivery", "Store for Pickup", "Food Delivered" and "Food Picked-up".

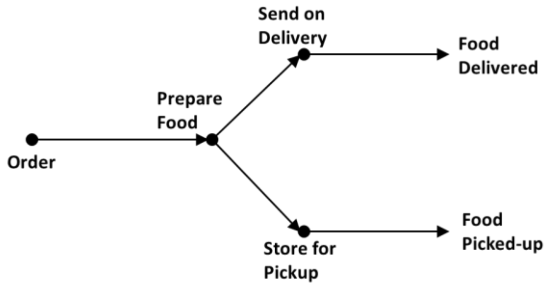

Figure 9. Conditioning on a fork

. . .

We'll stop here and note that this is just a small sampling from a large body of knowledge concerning the modeling of causality. The main point of this section is to demonstrate that the study of cause and effect has been formalized and is now part of the area of mathematics known as probability and statistics. For further reading, the following books are recommended (listed in order of ascending technical complexity):

- "The Book of Why: The New Science of Cause and Effect" [22]
- "Causal Inference in Statistics" [20]
- "Causality: Models, Reasoning, and Inference" [23].

2.3.5 Conclusions

In this book, we take the position that causality is a lower level concept than entropy and the associated laws of thermodynamics. In other words, the concept of entropy and the associated laws of thermodynamics make use of the concept of causality but not the other way around. This is not to say that causality gives rise to or explains entropy but rather that the notion of causality is used in the description of entropy.

Regarding the main theme of this book (struggle against chaos), causality (in and of itself) does not favor or disfavor the formation of structure.

2.4 Arrow of Time

2.4.1 Overview

Time goes forward but never backward. Yet most laws of physics work equally well for time going in either direction [24]. This asymmetry regarding the occurrence of events over time is known as the **arrow of time**. The article “The Arrow of Time” [25] from Scientific American magazine provides an excellent statement of the concept:

> It seems easy to distinguish the past from the future: memory provides us with a record of the past, but we have no certain knowledge of the future. When events are interpreted according to the most fundamental laws of physics, however, the distinction between past and future all but disappears. Intuitively we perceive the world as being extended in space but "unfolding" in time; at the atomic scale, the world is a four-dimensional continuum extended in both space and time. We assign special significance to a particular moment, the present, which we view as the crest of a wave continuously transforming potentiality into actuality and leaving in its wake the dead past. Microscopic physics gives no special status to any moment, and it distinguishes only weakly between the direction of the past and that of the future.

Some examples to illustrate the concept further:

- A typical example would be the dropping of a wine glass onto the floor. The reverse sequence of events (i.e., the pieces of the wine glass coming back together and then jumping from the floor back into your hand) is extraordinarily unlikely.
- Another example would be a baseball hit for a home run into the centerfield bleachers. The reverse event (while theoretically possible) of the baseball collecting energy from its surroundings in the bleachers and firing back to the batter’s bat is virtually impossible. The idea is that macroscope events are highly improbable in the reverse direction.
- In some cases, macroscopic events that appear symmetric are, in fact, not symmetric when studied more closely. For example, a video of someone juggling several balls looks the same when played forward or backward (with the possible exception of the start and stop). However, if one views the event with an infrared camera, the juggler would be seen to be getting hotter in the forward direction and cooler when the video is played in reverse.

In the context of this discussion on the arrow of time, processes can be classified as either reversible or irreversible.

- A **reversible process** is one in which both the system and its environment can return exactly to a previous state by following the reverse path.

- An **irreversible process** is one in which the system and its environment cannot return together exactly to a previous state.

The above examples are theoretically reversible but extremely improbable (even with outside influence). According to recent research there are even macroscopic events that are theoretically irreversible. In a paper entitled “Gargantuan chaotic gravitational three-body systems and their irreversibility to the Planck length” [26], a team of researchers showed that the motion of a 3-body system of black holes cannot be reversed (not even in theory). Portegies Zwart, a co-author of the paper, explained as follows: "So not being able to turn back time is no longer just a statistical argument. It is already hidden in the basic laws of nature. Not a single system of three moving objects, big or small, planets or black holes, can escape the direction of time."

Further, the asymmetry of time is not just a matter of human perception. There are other examples that don’t involve human perception. The following examples and associated text come from the Wikipedia article entitled “The arrow of time” [27]:

- The cosmological arrow of time points in the direction of the universe's expansion. It may be linked to the thermodynamic arrow, with the universe heading towards a heat death (Big Chill) as the amount of usable energy becomes negligible. Alternatively, it may be an artifact of our place in the universe's evolution (see the Anthropic bias), with this arrow reversing as gravity pulls everything back into a Big Crunch.
- Harold Blum's 1951 book Time's Arrow and Evolution [28] explored the relationship between time's arrow (the second law of thermodynamics) and organic evolution. This influential text explores irreversibility and direction in evolution and order, negentropy, and evolution. Blum argues that evolution followed specific patterns predetermined by the inorganic nature of the earth and its thermodynamic processes.
- Waves, from radio waves to sound waves to those on a pond from throwing a stone, expand outward from their source, even though the wave equations accommodate solutions of convergent waves as well as radiative ones. This arrow has been reversed in carefully worked experiments that created convergent waves, so this arrow probably follows from the thermodynamic arrow in that meeting the conditions to produce a convergent wave requires more order than the conditions for a radiative wave. Put differently, the probability for initial conditions that produce a convergent wave is much lower than the probability for initial conditions that produce a radiative wave. In fact, normally a radiative wave increases entropy, while a convergent wave decreases it, making the latter contradictory to the second law of thermodynamics in usual circumstances.

There is no agreed explanation for the arrow of time. For a good overview of debate, see the article from Quanta Magazine entitled “A Debate Over the Physics of Time” [29]. In the next section, we discuss a few of the theories concerning the arrow of time.

2.4.2 Theories

2.4.2.1 Past Hypothesis

In the **past hypothesis** approach, the arrow of time is explained by an appeal to the second law of thermodynamics and the assumption that the early universe was a time of extremely low entropy.

As described by Sean Carroll in his book The Big Picture [11]:

> Nobody knows exactly why the early universe had such a low entropy. It’s one of those features of our world that may have a deeper explanation we haven’t yet found, or may just be a true fact we need to learn to accept.
>
> What we know is that this initially low entropy is responsible for the “thermodynamic” arrow of time, the one that says entropy was lower toward the past and higher toward the future. Amazingly, it seems that this property of entropy is responsible for all of the differences between past and future that we know about. Memory, aging, cause and effect – all can be traced to the second law of thermodynamics and in particular to the fact that entropy used to be low in the past.

[**Author’s Remark**: The reference to “cause and effect” in the quote from Carroll is debatable. If we lived in a universe where overall entropy decreased, and what we now view as highly unlikely events did happen, there would still be cause and effect. For example, if the universe started to contract (entropy would decrease) but there is still a cause (gravity) for the contraction. I don’t see how the second law of thermodynamics explains causality. In my view, there is always cause and effect, regardless of whether overall entropy is increasing or decreasing. Elsewhere in his book, Carroll talks about Boltzmann Brains (basically disembodied brains that come into existence due to highly improbable fluctuations in the surrounding chaos and then gradually dissolve back into it). But there is still a cause, i.e., molecules coming together in just the right arrangement (albeit astronomically improbable).]

Carroll goes on to make an extraordinary claim:

> The appearance of complexity isn’t just compatible with increasing entropy; it relies on it. Imagine a system that didn’t have any Past Hypothesis, and was simply in a high-entropy equilibrium state right from the start. Complexity would never develop; the entire system would remain featureless and uninteresting (apart from rare random fluctuations) for all time. **The only reason complex structures form at all is because the universe is undergoing a gradual evolution from very low entropy to very high entropy.** “Disorder” is growing, and that’s precisely what permits complexity to appear and endure for a long time.

From Stephen Hawking [30]:

> The increase of disorder or entropy is what distinguishes the past from the future, giving a direction to time.

Criticisms of this approach center around the assumed initial condition of the early universe, i.e., very low entropy. In a variation of past hypothesis, physicist Alan Guth attempted to address this criticism [31]:

> The standard picture holds that the initial conditions for the universe must have produced a special, low entropy state, because it is needed to explain the arrow of time. (No such assumption is applied to the final state, so the arrow of time is introduced through a time-asymmetric condition.) We argue, to the contrary, that the arrow of time can be explained without assuming a special initial state, so there is no longer any motivation for the hypothesis that the universe began in a state of extraordinarily low entropy. The most attractive feature is that there is no longer a need to introduce any assumptions that violate the time symmetry of the known laws of physics.
>
> The basic idea is simple. We don't really know if the maximum possible entropy for the universe is finite or infinite, so let's assume that it is infinite. Then, no matter what entropy the universe started with, the entropy would have been low compared to its maximum. That is all that is needed to explain why the entropy has been rising ever since!

The paper by Lazarovici and Reichert [32] explores additional explanations for the arrow of time that do not rely on the past hypothesis.

2.4.2.2 Block Universe (Eternalism)

Block universe (or sometimes **eternalism**) is a term used to describe the view that the passage of time is illusory, with past, present and future all concurrently in existence. In this view, the universe is a single completed block of space-time consisting of everything that is past, present and future.

The website “Exactly what is … time?” [33] gives the following description of eternalism:

> Eternalism, on the other hand, holds that such past events **do** exist, even if we cannot immediately experience them, and that future events that we have not yet experienced also exist in a very real way. For eternalists, the “flow of time” we experience is therefore just an illusion of consciousness, because in reality time *[is]* always everywhere. Eternalism takes inspiration to some extent from the way time is modeled as a fourth dimension in the theory of relativity of modern physics, so that future events are “already there” but just have not been encountered yet, and the past literally still exists “back there” in the same way as a city still exists after we drive away from it. This is often referred to as the block universe theory or view because it describes

> space-time as an unchanging four-dimensional "block", rather than three-dimensional space modulated by the passage of time.

The block universe concept is open to debate. The Wikipedia article entitled "Eternalism (philosophy of time)" [34] provides a list of objections to this hypothesis, e.g.,

> Philosophers such as John Lucas argue that "The Block universe gives a deeply inadequate view of time. It fails to account for the passage of time, the pre-eminence of the present, the directedness of time and the difference between the future and the past." Similarly, Karl Popper argued in his discussion with Albert Einstein against determinism and eternalism from a common-sense standpoint.

2.4.3 The End of Time?

The heat death of the universe (also known as the Big Chill or Big Freeze) is an hypothesis that states the universe will eventually evolve to a state with no available energy to do work. At this point, entropy cannot increase and the universe would be in a state of thermodynamic equilibrium (maximum entropy).

For the sake of argument, assume the heat death hypothesis is true. What does this mean for causality? How can there be any changes in the universe if there is no available energy to do work? At the point of thermodynamic equilibrium, nothing can change. Does time have any meaning if the universe becomes static? Even measuring time would be impossible with no available energy to do work.

2.4.4 Relationship to Entropy

The various statements of the second law of thermodynamics all assume a direction of time (whether stated implicitly or explicitly). For example, one could state that second law of thermodynamics as follows:

> Aside from statistical fluctuations, entropy in a closed (or isolated) system never decreases as **time** increases.

As stated in the Wikipedia article entitled "Entropy (arrow of time)" [35]:

> Entropy is one of the few quantities in the physical sciences that require a particular direction for **time**, sometimes called an arrow of **time**. As one goes "forward" in **time**, the second law of thermodynamics says, the entropy of an isolated system can increase, but not decrease. Thus, entropy measurement is a way of distinguishing the past from the future. In thermodynamic systems that are not closed, entropy can decrease with time, for example living systems where local entropy is reduced at the expense of an environmental increase (resulting in a net increase in entropy), the formation of typical crystals, the workings of a refrigerator and within living organisms.

Even if an extremely (almost impossible) event happens in a closed system (e.g., a broken egg reassembling itself), the arrow of time is not violated but rather we have a very strange cause for a given effect. In the egg example, the cause would be the various molecules of the broken egg collecting energy from their surroundings and then exactly reforming the egg. Basically, the closed system returns to a prior state at a later point in time, with no violation of the arrow of time but arguably a violation of the second law of thermodynamics.

The position (opinion) taken in this book is that the arrow of time underlies (is more fundamental than) than the concept of entropy. Entropy (as expressed in the second law of thermodynamics) depends on and is implied by the arrow of time.

2.4.5 Relationship to Causality

The concepts of causality and the arrow of time are tightly intertwined, with each depending on the other. The arrow of time is defined in terms of the asymmetry in the occurrence of events, i.e., causes always preceding their effects. On the other hand, the concept of causality depends on a notion of time and its associated directionality (i.e., the arrow of time).

Further, working under the premise that information is exchanged between a cause and effect, and the fact that information cannot travel faster than the speed of light, gives additional support to the notion that causes always precede their effects which is another way of stating the concept of the arrow of time.

Figure 10 depicts the relationship between causality and the arrow of time. The dots represent events and the arrows represent the cause-effect relationship between events. On the one hand, the arrow of time implies that the cause-effect arrows only go in one direction. On the other hand, the fact that the arrows only go in one direction (cause before effect) can be used to define the arrow of time.

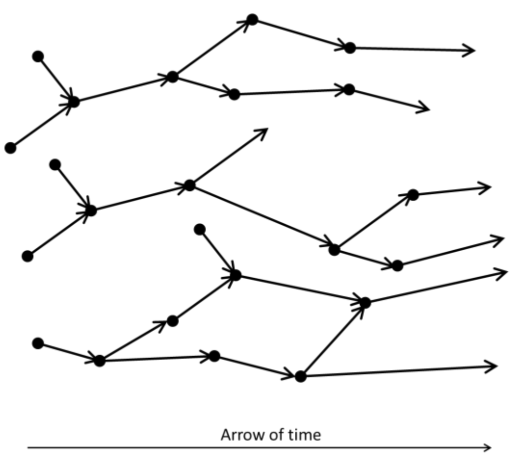

Figure 10. Causality, arrow of time and information flow

2.4.6 Conclusions

The various definitions of entropy make either implicit or explicit use of the concepts of causality and the arrow of time. The definitions of the arrow of time and causality are intertwined and dependent on each other, but neither depends on the definition of entropy (as constrained by the second law of thermodynamics). This situation is summarized in Figure 11. The phrase “depends on” means that the definition of one concept (A) depends on another concept (B). It does not mean that B gives rise to A or that B is an explanation for why A is valid.

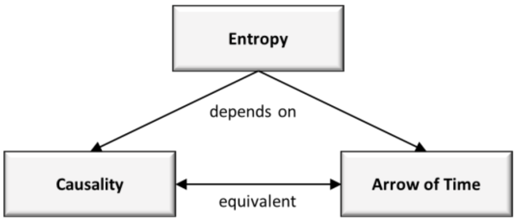

Figure 11. Dependencies among entropy, causality and the arrow of time

In the remainder of this book, we build upon the foundation set by entropy rather than accessing the lower level concepts of causality and the arrow of time.

2.5 Emergence

2.5.1 Overview

Emergence is a phenomenon that occurs when the individual parts of a system coordinate to exhibit behavior that is not present in the individuals. The emergent behavior of a system derives from the relationships among its parts. Some examples are ant colonies, beehives, hurricanes, cities, living cells and consciousness. The YouTube video “Emergence – How Stupid Things Become Smart Together” [42] provides some interesting examples.

An emergent property is a property exhibited by an aggregation of entities, but which the individual entities do not have. For example, a heart can pump blood but an individual heart cell cannot.

2.5.2 Definitions

The definition of **emergence** [1] in Wikipedia appears straightforward:

> In philosophy, systems theory, science, and art, emergence occurs when an entity is observed to have properties its parts do not have on their own, properties or behaviors which emerge only when the parts interact in a wider whole.

On further thought, this definition applies to almost everything. Take a car for example. None of the parts of a car perform all the functions of a fully assembled and operating car, but a car is typically not viewed as emergent.

The Internet Encyclopedia of Philosophy provides a definition of emergence [38] similar to that in Wikipedia:

> A property is emergent if it is a novel property of a system or an entity that arises when that system or entity has reached a certain level of complexity and that, even though it exists only insofar as the system or entity exists, it is distinct from the properties of the parts of the system from which it emerges.

The above definitions can even be applied to a carbon atom whose properties are distinct from the properties of the parts, i.e., electrons, protons and neutrons. In the domain of the living, a cell would qualify as emergent and so would a human.

Also, and sort of implied in the above definitions, there is a concept of depth regarding the parts of an assembly.

- For example, when talking about the emergent properties of an ant colony, we consider the parts one level down from the colony, e.g., the ants, the materials used to build the ant structure such as dirt and sand, and perhaps some micro plants such as fungi (grown for food by the ants). We don’t go down to the level of subatomic particles to explain the behavior of an ant colony.

- As another example, consider the emergent properties of a cell. The parts in this case would be various intracellular structures such as organelles and perhaps going down a second level, we might consider various molecules such as RNA, DNA and proteins that regulate the operation of a cell.

Emergence comes in two different forms, i.e., emergent behaviors and emergent structures. Emergent behaviors are exhibited by a group of individuals, such as the swarming of birds or fish, or the collaboration of people in a city government. Emergent structures refer to observed patterns, such as the layout of a city or the structure of a termite mound or ant colony.

The examples mentioned thus far hint at the need to define some subcategories under emergence. In his article “Strong and Weak Emergence” [39], David Chalmers describes two types of emergence:

> A high-level phenomenon is **strongly emergent** with respect to a low-level domain when the high-level phenomenon arises (in some sense) from the low-level domain, but truths concerning that phenomenon are not deducible even in principle from truths in the low-level domain.
>
> A high-level phenomenon is **weakly emergent** with respect to a low-level domain when the high-level phenomenon arises from the low-level domain, but truths concerning that phenomenon are unexpected given the principles governing the low-level domain.

Weak emergence is the version of emergence used most commonly in discussions concerning complexity theory and similar areas of study. Strong emergence is more commonly used in philosophical discussions about emergence.

Chalmers points out that cases of strongly emergent phenomena are typically also weakly emergent but not the other way around (see the Venn diagram in Figure 12).

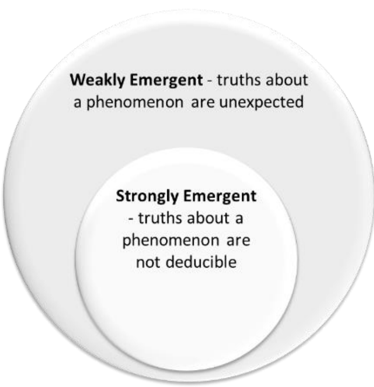

Figure 12. Weak and strong emergence

Chalmers provides the following example of a phenomenon that is weakly but not strongly emergent [39].

> The emergence of high-level patterns in cellular automata—a paradigm of emergence in recent complex systems theory—provides a clear example. If one is given only the basic rules governing a cellular automaton, then the formation of complex high-level patterns (such as gliders) may well be unexpected, so these patterns are weakly emergent. But the formation of these patterns is straightforwardly deducible from the rules (and initial conditions), so these patterns are not strongly emergent. Of course, to deduce the facts about the patterns in this case *[i.e., Game of Life*] may require a fair amount of calculation, which is why their formation was not obvious to start with. Nevertheless, upon examination these high-level facts are a straightforward consequence of low-level facts. So, this is a clear case of weak emergence without strong emergence.

In the above quote, the reference to "gliders" relates to John Conway's *Game of Life* [40] which can generate very complex moving patterns from a few basic rules and various starting configurations.

Stipulating the condition of "unexpected" is a bit problematic in a definition as the concept is subjective. When we achieve human-level intelligence and beyond with Artificial Intelligence (AI), the concept of "unexpected" may become irrelevant with respect to the definition of emergence.

The definition of strong emergence does exclude the set of entities whose function can be determined by studying its parts. This would cover many man-made entities such as cars, computers and baseball bats. On the other hand, some man-made entities are strongly emergent, e.g., deep learning programs. The ancient strategy game of Go provides an excellent example of strong emergence. The deep learning-based software known as AlphaGo (and its variants) has beaten world-class players in the game of Go – a feat thought impossible only a few years prior. AlphaGo initially learned by playing against humans, but now learns by playing against other instances of itself. A key point here is that AlphaGo did not use a brute force method (i.e., checking all possible moves) nor was it fed a set of rules by a human programmer, rather AlphaGo learned by playing the game of Go. Further, the strategies developed by AlphaGo are both unexpected (weak emergence) and not deducible by studying the software (strong emergence). According to the Wikipedia article on AlphaGo [41]:

> It makes a lot of opening moves that have never or seldom been made by humans, while avoiding many second-line opening moves that human players like to make. It likes to use shoulder hits, especially if the opponent is over concentrated.

Chalmers takes a very strict view of the definition of strong emergence and makes the following claim [39]:

> I think there is exactly one clear case of a strongly emergent phenomenon, and that is the phenomenon of consciousness. We can say that a system is conscious when there is something it is like *to be* that system; that is, when there is something it feels like from the system's own perspective. It is a key fact about nature that it contains conscious systems; I am one such. And there is reason to believe that the facts about consciousness are not deducible from any number of physical facts.
>
> … I will mention two well-known avenues of support. First, it seems that a colorblind scientist given complete physical knowledge about brains could nevertheless not deduce what it is like to have a conscious experience of red. Secondly, it seems logically coherent in principle that there could be a world physically identical to this one, but lacking consciousness entirely, or containing conscious experiences different from our own. If these claims are correct, it appears to follow that facts about consciousness are not deducible from physical facts alone.

By the way, while the concept of consciousness may seem obvious, it is not easy to define. The YouTube video "The Origin of Consciousness – How Unaware Things Became Aware" [43] gives an excellent high-level explanation of how consciousness might have evolved over time.

[**Author's Remark**: I don't see how the strategies developed by some deep learning software can be considered as not strongly emergent. In my opinion, deep learning can be viewed as a type of consciousness confined to a very focused area.]

2.5.3 Examples

2.5.3.1 Physical Systems

The journal article "Defining Emergence in Physics" [44] defines emergence in physical systems as follows:

> An emergent behavior of a physical system is a qualitative property that can only occur in the limit that the number of microscopic constituents tends to infinity.

The idea here is that one needs a large number of entities (e.g., water and air molecules) before an emergent property (e.g., a hurricane) reveals itself. This doesn't conflict with the previous definitions of strong and weak convergence, but adds another perspective concerning the number of entities needed for an emergent physical phenomenon to arise. However, this definition is only a necessary condition and not sufficient. For example, just having an ocean of water and a large volume of air above the ocean does not mean that a hurricane will occur. There needs to be additional conditions (perhaps the authors of the article assumes this is obvious and don't bother to state in their definition).

Various weather patterns such as hurricanes, tornadoes, thunderstorms and El Niños are often cited as examples of emergent physical phenomena. Here's an explanation of El Niño relative to emergence (taken from an online website about climate [45]):

> The El Niño phenomenon is another excellent example of emergent phenomena. Looking at a basin of water like the Pacific, there's no way you would say "Hey, I'll bet that the ocean has this complex natural system that kicks in whenever the ocean overheats, and it pumps millions of cubic kilometers of warm water up to the poles." You wouldn't predict the existence of the El Nino from the existence of the Pacific Ocean. It also is an emergent phenomenon.

The above quote raises an interesting question, i.e., is a phenomenon still emergent once its origins are known? We now know the conditions that can cause an El Niño and can predict when they may occur. For example, see the World Meteorological Organization site concerning El Niño/La Niña Southern Oscillation (ENSO) for some predictions [46]. Does this mean the phenomenon is no longer emergent? The phenomenon is no longer "unexpected" and so does not fit the definition of weak emergence.

What about our universe? Many would claim that our universe is the ultimate emergent event. But even here, we have computer simulations that can generate many of the characteristics of our current universe. For example, in 2014 a team of researchers developed an extensive simulation that reproduced many aspects of our current universe [47]. However, the basic assumption in this model (i.e., the Big Bang) is in question. Computer simulations of a competing theory (i.e., Big Bounce) have also generated features similar to our current universe [48]. If and when we do figure out the origins of our universe and are able to simulate the consequences of its creation, do we then claim that the universe is no longer emergent?

Given the above analysis, perhaps a simpler definition of emergent is warranted, or at least a definition to supplement the strong/weak emergent definition. Let's try the following as an intuitive definition of emergence:

> Emergence is complex behavior that arises out of relatively simple things interacting.

Further, we note that emergent physical systems depend on the following factors:

- the concentration of interacting components, i.e., parts of the emergent system
- the nature of the interactions among the components
- the flow of energy through the system
- the cycling of that energy flow (feedback).

2.5.3.2 Abiogenesis (Origin of Life)

From the Wikipedia article on **Abiogenesis** [59]:

> In evolutionary biology, abiogenesis, or informally the origin of life (OoL), is the natural process by which life has arisen from non-living matter, such as simple organic compounds. While the details of this process are still unknown, the prevailing scientific hypothesis is that the transition from non-living to living entities was not a single event, but an evolutionary process of increasing complexity that involved molecular self-replication, self-assembly, autocatalysis, and the emergence of cell membranes. Although the occurrence of abiogenesis is uncontroversial among scientists, its possible mechanisms are poorly understood. There are several principles and hypotheses for how abiogenesis could have occurred.

Abiogenesis fits the definition of weak emergence. One might claim it is also strongly emergent since at this point, we don't know the principles from which life arose from the lower-level domain of non-life. However, the definition of strong emergence does say "not deducible even in principle" and so, we cannot make that claim.

Abiogenesis is related to (but not the same as) something known as the Last Common Universal Ancestor (LUCA). From the Wikipedia article entitled " Last universal common ancestor" [60]:

> The last universal common ancestor or last universal cellular ancestor (LUCA), also called the last universal ancestor (LUA), is the most recent population of organisms from which all organisms now living on Earth have a common descent—the most recent common ancestor of all current life on Earth. A related concept is that of progenote. LUCA is not thought to be the first life on Earth, but rather the only type of organism of its time to still have living descendants.
>
> While there is no specific fossil evidence of LUCA, it can be studied by comparing the genomes of all modern organisms, its descendants. By these means, a 2016 study identified a set of 355 genes most likely to have been present in LUCA. The genes describe a complex life form with many co-adapted features, including transcription and translation mechanisms to convert information from DNA to RNA to proteins. The study concluded that the LUCA probably lived in the high-temperature water of deep sea vents near ocean-floor magma flows.
>
> Studies from 2000–2018 have suggested an increasingly ancient time for LUCA. In 2000, estimations suggested LUCA existed 3.5 to 3.8 billion years ago in the Paleoarchean era, a few hundred million years before the earliest fossil evidence of life, for which there are several candidates ranging in age from 3.48 to 4.28 billion years ago. A 2018 study from the University of Bristol, applying a molecular clock model, places the LUCA shortly after 4.5 billion years ago, within the Hadean.

While there is agreement that the transition from non-living to living occurred before LUCA, the steps involved are not well understood. From the journal article "Life before Luca" [61]:

> Evolving from a simple self-sustaining system to an organism with a coding capacity of hundreds of proteins is a huge step: even *Thermoplasma acidophilum*, with the smallest genome for a free-living organism, has about 1500 protein-coding genes (Giovannoni et al., 2005). We cannot at present know how much this number could be decreased while still having a viable free-living organism. Understanding how the transition to an organism with a large coding capacity can have happened is a more challenging problem than understanding how LUCA could have evolved to Homo sapiens.

Further, it is possible that the transition from non-living to living occurred multiple times before the advent of LUCA [62], and perhaps some of the pre-LUCA living entities persisted alongside LUCA but then died out. Scientists have not observed the transition from non-living to living in our present environment or in the fossil record.

2.5.3.3 Cells

The properties of living things (such as a single cell) are not always a collective sum of the properties of its parts. Instead at every level of organization, unique properties emerge by the combination of different parts into an assembly.

Consider a single unicellular organism such as a paramecium. The paramecium is composed of different biomolecules, such as nucleic acids (e.g., RNA and DNA), proteins, and enzymes, that perform distinct functions. The paramecium exhibits complex behavior (e.g., food gathering) that is not present in any of its individual parts (thereby fitting the intuitive definition of emergence stated earlier).

The transition from single cell to multicellular life has been difficult to trace. However, a recent discovery has helped progress our understanding of the issue, see the article "Billion-year-old fossil found in Scotland unlocks secrets of Earth's earliest life forms" [49]. One of the lead investigators from the University of Sheffield, Professor Charles Wellman, stated "The discovery of this new fossil suggests to us that the evolution of multicellular animals had occurred at least one billion years ago and that early events prior to the evolution of animals may have occurred in freshwater like lakes rather than the ocean."

2.5.3.4 Slime Mold

Emergent behavior is exhibited in a loosely organized collection of cells known as slime mold. See the following description of "slime mold" from the article "Emergence is The New Amazing Field of Science" [50]. (Notice how the author of the article is careful to say "slime mold" rather than "**a** slime mold".)

> One amazing example of emergence in nature is slime mold. It is completely made up of individual single-celled organisms, which move as a mass of individuals rather than an organized team. Even more

> fascinating is that slime mold has no focal point of authority that governs its hierarchy.
>
> Order in the slime mold community is established from the common need for food. Whenever food becomes scarce, these single entities join together and behave as a single organism. Conversely, when food becomes abundant again, this orderly group becomes single individuals again. Thus, slime mold is a straightforward model for how emergence occurs in nature.
>
> After several decades, scientists discovered that individual slime mold organisms begin secreting a pheromone that conveys messages to other community members when there is an environmental change. The group gradually grows and secretes more pheromone until it is large enough to accomplish the needed tasks.

The implication of the above description is that each slime mold is a different aggregation of cells. So, there is no persistent whole.

The well-studied slime mold known as Physarum polycephalum starts its life with many cells, each with a single nucleus. The cells merge to form a single-celled organism with many nuclei. The organism has no nervous system but yet can solve complex mazes efficiently (shortest path to food), as described in the article "This Weirdly Smart, Creeping Slime Is Redefining Our Understanding of Intelligence" [51].

2.5.3.5 Insect Colonies

Perhaps the most iconic example of emergence is that of an ant or termite colony.

The epigeal nests (i.e., mounds) built by termites appear to be constructed by intelligent cooperation. The chimneys control air flow to manage temperature and humidity inside the nest. However, individual termites have no idea of how to build a mound. Worker termites cannot even perceive the overall shape of the mound since they are blind. Termites coordinate implicitly by responding to chemical signals from other termites, and to temperature, humidity and airflow cues that are influenced by the shape of the nest, wind currents, the amount of heat generated within the nest and other local conditions. The termites' behavior affects the shape of the nest and the shape of the nest affects the termites' behavior. The net effect is a complex system based on the interactions of relatively simple components (i.e., the termites) with their surroundings.

. . .

Ant colonies can be huge, reaching populations of around 20 million individual ants. The colonies are highly organized even though the inhabitants are of very limited intelligence. For example, the colonies are designed to include cemeteries, distributed trash heaps, and an underground bunker for the protection of the queen ant. Amazingly, ants have been observed to form bridges over obstacles (composed only of ants) and to group together to form floating "rafts" during flooding. However, the insects only have local knowledge and no awareness of the overall effect of their actions. The author of "Emergence: The Connected Lives of Ants, Cities and Software" [52] describes the emergent behavior of insects as follows:

> *Local* turns out to be the key term in understanding the power of swarm logic. We see emergent behavior in systems like ant colonies when the individual agents in the system pay attention to their immediate neighbors rather than wait for orders from above. They think locally *and* act locally, but their collective action produces global behavior. Take the relationship between foraging and colony size. Harvester ant colonies constantly adjust the number of ants actively foraging for food, based on a number of variables: overall colony size (and thus mouths needed to be fed); amount of food stored in the nest; amount of food available in the surrounding area; even the presence of other colonies in the nearby vicinity. No individual ant can assess any of these variables on her own. (I use *her* deliberately – all worker ants are females.) The perceptual world of an ant, in other words, is limited to the street level. There are no bird's-eye views of the colony, no ways to perceive the overall system – and indeed, no cognitive apparatus that could make sense of such a view. "Seeing the whole" is both a perceptual and conceptual impossibility for any member of the ant species.

2.5.3.6 Swarm Behavior

Some creatures such as fish, birds and insects exhibit **swarm behavior**. Consider the following definition of swarm behavior from definitions.net:

> Swarm behavior, or swarming, is a collective behavior exhibited by animals of similar size which aggregate together, perhaps milling about the same spot or perhaps moving en masse or migrating in some direction. As a term, swarming is applied particularly to insects, but can also be applied to any other animal that exhibits swarm behavior. The term flocking is usually used to refer specifically to swarm behavior in birds, herding to refer to swarm behavior in quadrupeds, shoaling or schooling to refer to swarm behavior in fish. Phytoplankton also gather in huge swarms called blooms, although these organisms are algae and are not self-propelled the way animals are. By extension, the term swarm is applied also to inanimate entities which exhibit parallel behaviors, as in a robot swarm, an earthquake swarm, or a swarm of stars. From a more abstract point of view, swarm behavior is the collective motion of a large number of self-propelled entities.

Swarms are used to achieve various goals, e.g.,

- Birds migrate in flocks to conserve energy. Think of the V-shaped formation of geese. Another example is bird murmuration, where thousands of the birds (such as starlings) flock together, swooping and diving in synchronization [54].

- Fish get several benefits from shoaling behavior (a form of swarming) including defense against predators, increased food gathering success and a higher success in finding a mate.
- When a beehive grows beyond what can be supported by its surroundings, some of the bees leave the hive (in a swarm) and form a new hive at another location. The process is fairly complex, see the Wikipedia article entitled “Swarming (honey bee)” [55].

The study of swarms in nature has inspired the development of swarm optimization algorithms (see the journal article “A Comprehensive Review of Swarm Optimization Algorithms” [56] and the YouTube video “What is Swarm AI” [57] on this topic). These algorithms are used in a variety of applications. For example, the Ant Colony Optimization (ACO) algorithm is used to solve protein folding, vehicle routing, job-shop scheduling and assignment problems [58].

2.5.3.7 Deep Learning Systems

In Section 2.5.2 we discussed an example of **deep learning**, i.e., AlphaGo, but did not provide a definition of the concept. Deep learning is a subfield of Artificial Intelligence (AI). Definitions of “deep learning” tend to be very technical and a bit hard to understand. Consider the following definition from Techopedia [63]:

> Deep learning is a specific approach used for building and training neural networks, which are considered highly promising decision-making nodes. An algorithm is considered to be deep if the input data is passed through a series of nonlinearities or nonlinear transformations before it becomes output. In contrast, most modern machine learning algorithms are considered "shallow" because the input can only go *[for]* a few levels of subroutine calling.
>
> Deep learning removes the manual identification of features in data and, instead, relies on whatever training process it has in order to discover the useful patterns in the input examples. This makes training the neural network easier and faster, and it can yield a better result that advances the field of artificial intelligence.

In simpler terms, deep learning is a computer software technique that emulates the human brain (with neural networks) to determine patterns from large inputs of raw data. Also, see the YouTube video entitled “Deep Learning in 5 Minutes” [64] which gives a good high-level overview of the subject.

In addition to game playing, there are many successful examples of deep learning applied to everyday activities, e.g., driverless cars, virtual assistants, chatbots and service bots (in support of customer service), language translation, medical applications such as cancer detection, facial recognition and deep-learning robots. The Wikipedia article on deep learning [65] provides an extensive list of examples. Many of the examples can be considered as weakly emergent, although experts in a given area may claim the results are completely expected.

[**Author's Remark**: I mention deep learning here because in my opinion, deep learning may be a stepping-stone from weak or narrow AI (which has a narrow range of abilities) to strong AI (which is on par with human capabilities) and then eventually to Artificial Super-Intelligence (ASI) which is more powerful than human intelligence.

Further, in my opinion, deep learning is a form of very focused consciousness.]

2.5.3.8 Consciousness

The various definitions of consciousness tend to focus on humans. For example, consider the following definition from the Psychology Dictionary [66]:

> noun. 1. the sensation that human beings claim to encounter, inclusive of cognitive details spanning from somatic and sensory interpretation to cognitive visualizations, accountable concepts, internal speech, intentions to take action, recollections, dreams, semantics, delusions, fringe or emotionally-entwined feelings, and facets of motor and mental control. 2. any of many unbiased conditions of consciousness wherein aware details can be recounted. More commonly used to reference the natural waking state, but might also be used to reference the state of sleep or a substitute state of awareness.

When viewed strictly as a human trait, the case for consciousness being strongly emergent is more convincing. However, this point of view neglects the evolutionary processes leading up to the level of consciousness in humans. Unfortunately, it is difficult to trace the development of consciousness in our hominid ancestors and earlier (see the YouTube video The Origin of Consciousness [67]). Studying existing animals gives some clues but we are limited by the fact that non-human animals cannot tell us about their internal experiences. The Wikipedia article entitled "Animal consciousness" [68] covers various theories concerning whether or not non-human animals are conscious and if so, to what degree, but virtually every theory is under debate and not generally agreed. It may be that our advances in AI eventually give us the best clues in understanding human consciousness. It would be fascinating if human-level consciousness is achieved in an ASI entity and we still cannot determine the mechanism for how the consciousness arose. Perhaps that will be a task for the ASI entity to explain. If even an ASI entity cannot explain the source of consciousness, then we may be forced to conclude that consciousness is strongly emergent.

2.5.3.9 Cities

Cities have a life of their own. The collective behavior of the inhabitants of a city is often described as being emergent. John Lewis Holland, American psychologist, offered this description of emergence regarding cities:

> Cities have no central planning commissions that solve the problem of purchasing and distributing supplies. How do these cities avoid devastating swings between shortage and glut, year after year, decade after decade? The mystery deepens when we observe the kaleidoscopic nature of large cities. Buyers, sellers, administrations, streets, bridges,

> and buildings are always changing, so that a city's coherence is somehow imposed on a perpetual flux of people and structures. Like the standing wave in front of a rock in a fast-moving stream, a city is a pattern in time.

Mathieu Helie, in his article "Emerging the city" [69], provides the following definition of emergence and also what is not emergence:

> The definition of emergence is thus: it is a form obtained as a result of following certain processes. The opposite of emergence is design: it is a form conceived by a designer which will be used as a blueprint for its realization.

Regarding cities, Helie appears to suggest that cities should be (perhaps "must be") emergent:

> The city cannot have a designer. It cannot be built according to a description fine-tuned to perfection. This has become obvious to practically everyone, although urbanism in the English-speaking world is still tied down by the title "urban planner" in the face of all the evidence that planning makes no difference whatsoever. Still the practice of large scale zoning and site planning continues.

Cities evolve and make corrections in both the short-term and the long-term. Take vehicle traffic as an example. In the short-term, drivers will use alternate routes when a given route becomes congested. In the long-term, city governments address chronic traffic congestion by adding roads, widening existing roads, enhancing public transportation or encouraging more walking and bicycle use. Cities are emergent in the sense that they function as a collective entity, with the whole being capable of behaviors that are not present in its parts.

2.5.3.10 Markets

Markets that involve trading such as stock or bond markets are examples of emergence. A market (as a whole) regulates the prices of the items being traded, while there is typically no central control of pricing. (It's true there may be central control of certain bad behaviors in markets such as price fixing or insider trading by a subset of the participants.) Markets are self-correcting, e.g., if one supplier asks for a higher price than others and his or her product is no better than other suppliers, the product will not sell.

2.5.4 Relationship to Entropy

2.5.4.1 Concepts

On the surface, one might think that the emergence of structure and the second law of thermodynamics are in conflict, but one needs to remember that the second law of thermodynamics applies to closed (or isolated) systems. The Earth (for example) is not an isolated system. Energy from the sun is used by processes on Earth (for example plant life) to create localized structure. The overall net effect (taking both the Sun and the Earth into account) is an increase in entropy. As physicist Sean Carroll states in The Big Picture [11]:

> We *[referring to the Earth]* receive photons from the sun, primarily in the visible-light part of the electromagnetic spectrum. We process the energy, and then return it to the universe in the form of lower-energy infrared photons. The entropy of a collection of photons is roughly equal to the total number of photons you have. For *[each]* visible photon it receives from the sun, the Earth radiates approximately twenty infrared photons back into space, with approximately one-twentieth of the energy each. The Earth gives back the same amount of energy as it gets, but we increase the entropy of the solar radiation by twenty times before returning it to the universe.

The point is that the Earth and various processes on the Earth (including life) make use of the free energy from the Sun, and then expel unavailable energy (recall the definitions of "free energy" and "unavailable energy" from Section 2.2.2).

Carroll goes on to make the following claim:

> As with the formation of complexity in the first place, the truth is the converse of our most naïve expectation. Complex structures can form, not despite the growth of entropy but because entropy is growing. Living organisms can maintain their structural integrity, not despite of the second law but because of it.

His point is that the transformation of free energy (low-entropy energy or available energy) into unavailable energy (high-entropy energy) is essential to the emergence and continuation of life.

In his book "What is Life" [70], Nobel laureate Edwin Schrodinger made similar comments (back in 1944) concerning life and its transformation of free energy (what he calls "negative entropy") into unavailable energy (what he calls "positive entropy")

> What then is that precious something contained in our food which keeps us from death? That is easily answered. Every process, event, happening – call it what you will; in a word, everything that is going on in Nature means an increase of the entropy of the part of the world where it is going on. Thus, a living organism continually increases its entropy or, as you may say, produces positive entropy and thus tends to approach the dangerous state of maximum entropy, which is death. It can only keep aloof from it, i.e., alive, by continually drawing from its environment negative entropy which is something very positive as we shall immediately see. What an organism feeds upon is negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive.

The point is that the conversion from available to unavailable energy (i.e., the second law of thermodynamics) is favorable for life and in general for emergence. However, that is not to say that this conversion is the principal cause of emergence (which is presently an open issue).

2.5.4.2 Examples

Some examples may help to highlight the relationship between emergence and entropy.

As a first example, consider hurricanes. They appear to dramatically increase structure (albeit with highly destructive results). However, hurricanes transfer heat away from the ocean surface and thereby, disperse energy, i.e., increase entropy. A hurricanes disperses energy quite efficiently, and provides a good example of a thermodynamic system that generates complex structures, while at the same time optimizing the rate of entropy production. In fact, the journal article “Hurricane Footprints in Global Climate Models” [71] shows that “specific entropy” (entropy divided by unit mass) can be used to estimate hurricane activity.

. . .

Another example is the formation of a solar system from a cloud of gas. It is true that the formation of the star and planets represents a system with lower entropy than the prior gas cloud, but this is not a closed system. The resulting system radiates heat (disperses energy) to the exterior of the solar system. If one considers both the condensing solar system and the heat radiated outward, overall entropy increases and the second law of thermodynamics holds true. In a blog post entitled “Star formation and entropy” [72], Gordon McCabe describes the situation as follows:

> As a gravitationally-bound system *[gas cloud forming a solar system]* contracts, the frequency of the collisions between the constituent particles increases, and a certain fraction of those interactions will be so-called inelastic collisions, in which the atoms or molecules are raised into excited energy states. Those excited states decay via the emission of photons, and this electromagnetic radiation is then lost to the surroundings *[external to the forming solar system]*. It is this radiative emission which is the most effective means by which heat is transferred from the contracting body *[solar system]* to its lower temperature surroundings. And crucially, the entropy of this radiation is sufficiently huge that it easily compensates, and then some, for the lower entropy of the contracting matter *[the solar system]*. The total entropy of a contracting gravitational system therefore increases, as long as one counts the contribution from the electromagnetic radiation.

. . .

Does Life On Earth Violate the Second Law of Thermodynamics? It may seem so at first glance since life increases structure locally, but we need to keep in mind that life is not a closed system. Life takes in free energy and returns energy that is at least partially unavailable to do work in the form of heat. In the case of plant life, the free energy comes directly from the Sun. In the case of animal life, the free energy comes indirectly from eating plants or other animals. The journal article by Schreiber and Gimbel provides the following explanation [73]:

> The Belgian chemist and Nobel laureate, Ilya Prigogine, helped popularize the notion that in thermodynamic terms, life can be considered a subset of a larger class of systems called *dissipative structures* (Prigogine and Stengers 1984). These dynamic, self-maintaining systems include cyclones, whirlpools, flames, and black holes and are characterized by importing useful forms of energy (free energy) and exporting (dissipating) less useful forms (entropy), particularly heat. As long as the structures are actively self-organizing and self-maintaining (in the case of organisms, "alive"), they remain far from thermodynamic equilibrium with their environment. An organism attains thermodynamic equilibrium *[i.e., maximum entropy]* with its environment only after death, when its body decomposes.

In other words, the net result of the processes carried out by dissipative structures is to increase entropy in the universe. In the same article, Schreiber and Gimbel go on to make the following statement concerning living cells, metabolism and entropy:

> The chemical conversion of nutrients into useful forms usually produces toxic waste products and heat, all of which must be exported by the cell to its environment to ensure the cell's survival. Ultimately, all organisms and their cellular constituents gain and preserve their internal ordered state by first importing free energy from their surroundings (eating), then converting the nutrients into useful forms (metabolizing), and finally exporting (pooping) an equal or greater amount of energy to their environment in the forms of heat and entropy.

2.5.5 Conclusions

Emergence emanates from the idea that "the whole is greater than the sum of its parts" (a concept going back to Aristotle if not earlier). As we have seen in the previous examples, emergence focuses on how simple entities organize into complex systems that take on a life of their own. Weak emergence adds the condition that the collective behavior is unexpected. Strong emergence adds the condition that even in principle the behavior of the whole is not deducible from an analysis of its parts. The case for something being strongly emergent is difficult to make, and it is a moving target, i.e., what seems non-deducible with our current knowledge may not be so in the future. In any event, even if an emergent behavior is non-deducible from its underlying domain or domains, we can still make use of the behavior, e.g., the stock markets of the world are alive and well even if we don't understand or can predict the sometimes chaotic behavior of these markets.

Regarding the theme of this book, emergence does constitute a rise of structure out of chaos (or at a least, out of a less structured situation) but this comes at a cost, i.e., it takes energy to create emergent behavior. For example, cities require energy to be created and then maintained. If one cuts off the various forms of energy to a city (electricity, natural gas, gasoline, food, etc.), the city dies.

2.6 Supervenience

The concept of **supervenience** is related to the concept of emergence. In fact, the two concepts have some overlap. The Stanford Encyclopedia of Philosophy provides the following definition of supervenience [74]:

> A set of properties A supervenes upon another set B just in case no two things can differ with respect to A-properties without also differing with respect to their B-properties. In slogan form, "there cannot be an A-difference without a B-difference".

Some examples might help to understand the concept:

- At the level of images, a computer screen may show an image of a forest. The screen's content can also be described as a precise arrangement of pixels, a set of locations and corresponding colors. The image of the forest (as viewed by a human observer) supervenes on the underlying pixels because the screen's image-level properties (the particular forest) cannot differ from another screen's image-level properties unless the two screens also differ in their pixel-level properties. The set of pixels and the image are the same thing, but their relationship is asymmetrical. The image supervenes on the pixels, but the pixels do not supervene on the image, because screens can differ in their pixel-level properties without differing in their image-level properties (e.g., change the color of a few pixels and the human observer sees the same forest).
- The laws and properties of chemistry are consistent with, and supervenient on, the laws of physics. For a law of chemistry to change, some underlying law of physics would also need to change.
- The properties of molecules supervene on the properties of atoms.
- The properties of biological cells supervene on properties of molecules.
- The properties of plants and animals supervene on the properties of cells.

The Wikipedia article on supervenience [75] provides the following definitions:

> In the contemporary literature, there are two primary (and non-equivalent) formulations of supervenience (for both definitions let A and B be sets of properties). For a quick refresher on logic symbols and their meanings, see [76] or [77].
>
> 1. A-properties supervene on B-properties if and only if all things that are B-indiscernible are A-indiscernible. Formally: $$\forall x \forall y (\forall X_{\in B}(Xx \Leftrightarrow Xy) \Longrightarrow \forall Y_{\in A}(Yx \Leftrightarrow Yy))$$
> 2. A-properties supervene on B-properties if and only if anything that has an A-property has some B-property such that anything that has that B-property also has that A-property. Formally:

$$\forall x \forall X_{\in A}[Xx \Rightarrow \exists Y_{\in B}(Yx \wedge \forall y(Yy \Longrightarrow Xy))]$$

For example, if one lets A be a set of mental properties, lets B be a set of physical properties, and chooses a domain of discourse consisting of persons, then (1) says that any two persons who are physically indiscernible are mentally indiscernible, and (2) says that any person who has a mental property has some physical property such that any person with that physical property has that mental property.

[**Author's Remark**: Agreed, the above is not easy to understand. Further, the examples are weak since it is arguable whether mental properties supervene on physical properties (e.g., see the Psychology Today article [78]). A better example is molecular properties and atomic properties, where the former supervenes on the latter, i.e., the properties of molecules supervene on the properties of the constituent atoms.]

The definition of supervenience implies traceability between the set of properties A and the set of properties B, with A supervening on B, but the definition of strong emergence stipulates that truths about the higher-level domain are not deducible, (not even in principle) from truths in the lower-level domain. So, strong emergence between higher domain A and lower domain B implies the properties of A cannot be supervenient on the properties of B.

On the other hand, it is possible for higher domain A to be both supervenient on and weakly emergent from lower domain B. Weak emergence only stipulates that truths concerning the higher-level domain are unexpected given the principles governing the lower-level domain. If the truths are "expected" (a matter of opinion), then we could have domain A supervenient on domain B but not weakly emergent from domain B.

There is a Quora discussion thread on this topic that presents some different opinions on the relationship between emergence and supervenience [79].

2.7 Self-organization

2.7.1 Definitions

Self-organization, as the name suggests, entails a group of entities organized together to accomplish some task. This concept has some overlap with the concept of emergence.

The Wikipedia article on self-organization [80] provides the following definition:

> Self-organization, also called (in the social sciences) spontaneous order, is a process where some form of overall order arises from local interactions between parts of an initially disordered system. The process can be spontaneous when sufficient energy is available, not needing control by any external agent. It is often triggered by seemingly random fluctuations, amplified by positive feedback. The resulting organization is wholly decentralized, distributed over all the components of the system. As such, the organization is typically robust and able to survive or self-repair substantial perturbation. Chaos theory discusses self-organization in terms of islands of predictability in a sea of chaotic unpredictability.

It is possible to have self-organization without any semblance of emergence. For example, consider an elderly person shoveling the snow off of her sidewalk who is spontaneously helped by several neighbors. This event is self-organized but there is nothing emergent about the activity (not even weakly emergent). On the other hand, it is possible to have emergence without self-organization. For example, the emergent behavior from a deep learning application such as AlphaGo does not involve self-organization. The relationship between emergence and self-organization is summarized in Figure 13.

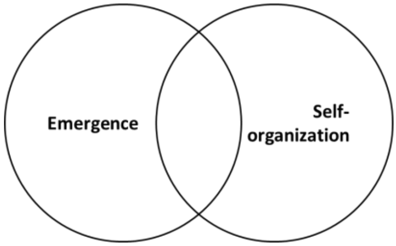

Figure 13. Venn diagram concerning emergence and self-organization

While not typically stated in the various definitions of “self-organization”, there is an implicit assumption that the coordinating entities do not necessarily become permanent parts of a whole and can at some point disengage from the whole. We explore this aspect in the examples that follow.

Further, definitions of “self-organization” do not distinguish between intelligent parts which decide to join the whole and non-intelligent parts which join the whole based on surrounding physical conditions. What appears to be excluded (as being categorized as self-organization) is the case where a third party designs or in some way facilitates the construction of a whole from a collection of parts (e.g., a neural network supporting a deep learning algorithm).

2.7.2 Examples

Table 1 provides a brief analysis of various examples of emergence (from Section 2.4) relative to self-organization. As noted, self-organization is sometimes but not always a characteristic of emergence.

Table 1. Analysis of emergence example concerning self-organization

Example	Self-organizing	Explanation
Weather	Yes	Weather events such as hurricanes are self-organizing even though there is no intelligence in the parts and there is no apparent advantage to the parts in joining the weather event.
Universe	Yes	The formation of the various structures in the universe (e.g., stars, planets, solar systems, galaxies) are self-organizing based on the laws of physics.
Abiogenesis	Perhaps	As noted, the origin of life is a topic still under debate. In one theory (known as community metabolism), cells may have initially arisen out of a community of organisms that exchanged components and genes [83]. The resulting symbiotic community would qualify as a self-organization.
Cells	Perhaps	Living cells, while consisting of cooperating parts, are not a result of self-organization but rather arise by way of cell division processes [81] such as mitosis, meiosis and binary fission. On the other hand, we could take a longer-term view of cells and speculate that during abiogenesis various pre-cellular entities self-organized into early cells but this is only a hypothesis.
Slime mold	Yes	This fits the definition of self-organization. The parts are basically unintelligent and respond to chemical signals.

Example	Self-organizing	Explanation
Insect colonies	Yes	This fits the definition of self-organization. The coordination is partly based on chemical signals but the parts do have some intelligence and can do extraordinary things such as building bridges [82].
Swarms	Yes	This is one of the better fits to the concept of self-organization.
Deep learning systems	Perhaps	Deep learning systems such as the AlphaGo example do not qualify as self-organizing. On the other hand, we could claim that the nodes in a neural network (sort of the engine for deep learning) are self-organized entities. This is a debatable point. For the record, swarming robots [84] are self-organizing based on some very simple rules and they do learn (but this is not really deep learning).
Consciousness	Perhaps	At first look, consciousness appears to be an example of emergent behavior that is not self-organizing. On the other hand, one could view consciousness as a very long-term process where several types of cells specialized and evolved into the human brain which, in turn, supports consciousness.
Cities	Yes	Cities fit the definition of self-organization quite easily (even planned cities which are in reality only partially planned).
Markets	Yes	Markets fit the definition of self-organization. Further, the behavior can sometimes be chaotic.

2.7.3 Conclusions

As can be seen from the examples in the previous subsection, there is not one type of self-organization but rather a continuum of sorts, starting with non-intelligent entities (e.g., water and air particles in a hurricane) and progressing to self-organized collections of intelligent beings (e.g., cities and markets). There are key transition points along the way, i.e., abiogenesis, consciousness, super intelligent AI (not here yet). Whether the transition points also involve self-organization is debatable. These thoughts are summarized in Figure 14.

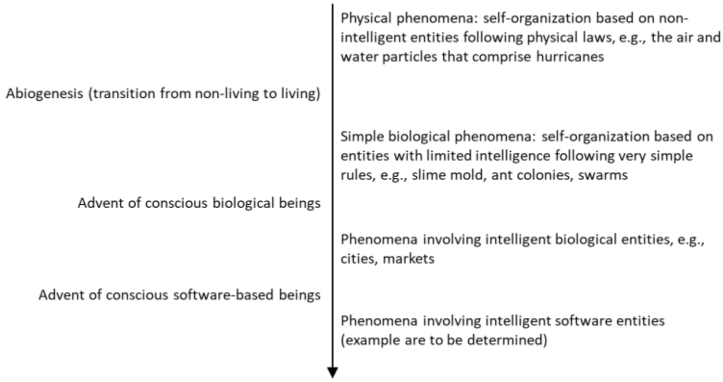

Figure 14. "Evolution" of self-organization

While it is true that self-organization represents a local increase in structure (and decrease in entropy), the overall effect is an increase in entropy. In Section 2.5.4.2, we saw several examples of essentially self-organizing systems that resulted in an overall increase in entropy in the universe.

György Darvas puts it nicely in a conference paper entitle "Symmetry, order, entropy and information" [85]:

> Notice that wherever emergence takes place through a self-organizing process, the Second Law of thermodynamics, and the related statements on entropy cannot be applied. This statement is quite different from saying that "the 2nd Law is violated", or it "is not valid". Simply, among the given conditions it cannot be applied. Emergence can always take place in **physically open local systems**. In philosophical terms, the evolution of the universe is a consequence of a series of emergencies *[i.e., multiple instances of emergence]* taking place in negligible small segments of the universe, where the conditions to apply the Second Law are not present, and entropy may decrease. The universal evolution is determined by processes in negligible small **open** segments, as fluctuations of steady processes of physical systems.

2.8 Recursion and Fractals

2.8.1 Overview and Definitions

2.8.1.1 Recursion

The concepts of **recursion**, self-similarity and fractals play an important role in self-organization.

The concept of recursion is most often applied to computer programming where the solution of a problem entails nested calls to the same subroutine. However, the concept is more general. From the Wikipedia article on recursion [86]:

> Recursion (adjective: recursive) occurs when a thing is defined in terms of itself or of its type. Recursion is used in a variety of disciplines ranging from linguistics to logic. The most common application of recursion is in mathematics and computer science, where a function being defined is applied within its own definition. While this apparently defines an infinite number of instances (function values), it is often done in such a way that no infinite loop or infinite chain of references can occur.

As an example, consider the Fibonacci sequence:

1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, …

After the first two terms (which are given), each term is defined as the sum of the previous two terms, e.g., $55 = 34 + 21$. If we let $F(n)$ represent the nth Fibonacci number, then the sequence can be defined recursively as

$$F(n+1) = F(n) + F(n-1)$$

For example, to find the 5th term, we do the following:

$$F(5) = F(4) + F(3)$$

$$= [F(3) + F(2)] + [F(2) + F(1)]$$

$$= [F(2) + F(1) + F(2)] + [F(2) + F(1)]$$

$$= [1 + 1 + 1] + [1 + 1] = 5$$

The idea is to call the function F (in a nested manner) until the only thing left are the two initial (given) terms, i.e., $F(1) = 1$ and $F(2) = 1$.

2.8.1.2 Fractals

The Fractal Foundation (https://fractalfoundation.org) defines a fractal as follows:

> A **fractal** is a never-ending pattern. Fractals are infinitely complex patterns that are self-similar across different scales. They are created by repeating a simple process over and over in an ongoing feedback loop. Driven by recursion, fractals are images of dynamic systems – the pictures of Chaos. Geometrically, they exist in between our familiar dimensions. Fractal patterns are extremely familiar, since nature is full of fractals. For instance: trees, rivers, coastlines, mountains, clouds,

seashells, hurricanes, etc. Abstract fractals – such as the Mandelbrot Set – can be generated by a computer calculating a simple equation over and over.

In the above definition, the examples in nature (called **natural fractals**) are only approximations to **abstract fractals** which repeat infinitely at smaller and smaller scales.

As an example of an abstract fractal, consider Figure 15 which depicts the first few iterations of Sierpinski's triangle. Starting with a solid triangle (on the left), a triangle ¼ of the size of the original is removed (2nd from left). For the remaining three smaller triangles, do the same and continue the process indefinitely. At any step, if one focuses on just one of the black triangles, its interior appears no different from the original triangle. This is an example of self-similarity.

Figure 15. First several iterations of Sierpinski's triangle

While there are various methods for defining fractals (see Common techniques for generating fractals [87]), all the techniques use some form of recursion. On the other hand, there are reclusively defined entities (e.g., computer programs) that are not considered to be fractals.

Natural fractals are a form of self-organization. For example, consider the organization of humans into governmental units such as country, state/province/region and city. The recursion exhibits the same general properties at each level, e.g., leaders, method of selecting leaders, laws, enforcement of laws, judicial system, taxes. This is a natural fractal pattern.

Another example of a natural fractal is lightning. As can be seen in Figure 16, the various branches off the main lightning bolts have a similar shape, and the pattern continues for several levels.

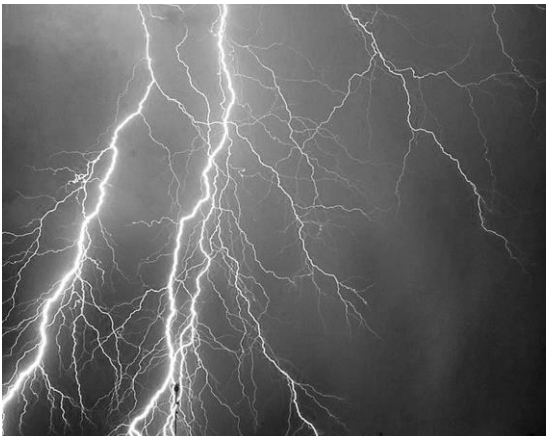

Figure 16. Lightning

According to the Wikipedia article on energy [88]:

> In a typical lightning strike, 500 megajoules of electric potential energy is converted into the same amount of energy in other forms, mostly light energy, sound energy *[thunder]* and thermal energy.

In other words, a massive amount of free (available to do work) energy is converted into unavailable energy which means that a lightning strike increases entropy.

2.8.2 Conclusion

Fractals, a form of recursion, represent one form of self-organization. The story here is the same as with self-organization, i.e., local increase in structure (with a decrease in entropy) but an overall increase in entropy for the universe. The general idea is that it takes free energy (available energy) to create localized structure but the energy expelled in the process is at least partially of the unavailable type. The end result is a net increase in unavailable energy and thus an increase in entropy.

2.9 Why?

2.9.1 Overview

Thus far, we've talked about physical laws (e.g., entropy) and processes (e.g., self-organization) that allow for and facilitate the creation of structure but do not necessitate the formation of structure. In this section, we attempt to address the question of why structure forms. To be sure, and to warn the reader in advance, ultimate answers concerning "why" are not forthcoming. Even after tracing back causality many steps, one can always ask "Why?" one more time. Eventually, the answer is "We simply don't know and may never know."

Our search for the answer to "why structure forms?" starts with intelligent life and works backwards towards inanimate entities.

2.9.2 Life

In our little part of the universe, structure continues to be created at an accelerating pace. This is primarily because of us. Humans create structured entities for survival (e.g., growing food on farms), protection (e.g., levees and dams to hold back flood waters), science (e.g., huge particle accelerators), and quality of life (e.g., the Web, cell phones, computers, sports stadiums). Structure increases because we want it to and we are willing to pay the price in terms of energy expenditure.

At some point, human intelligence will be surpassed by super intelligent AI. This will likely lead to an even greater imposition of structure and an associated conversion of free energy to unavailable energy. Futurist Ray Kurzweil talks about Humanity 2.0 and something known as The Singularity (the point where AI passes the Turing test [89] and therefore achieves a human level of intelligence). Kurzweil believes that technology will encounter explosive growth in this century. In his slightly dated but still fascinating book "The Singularity is Near" [90], Kurzweil summarizes his concept of "The Singularity" as follows:

> From my perspective, the Singularity has many faces. It represents the nearly vertical phase of exponential growth that occurs when the rate is so extreme that technology appears to be expanding at infinite speed. Of course, from a mathematical perspective, there is no discontinuity, no rupture, and the growth rates remain finite, although extraordinarily large. But from our currently limited framework, this imminent event appears to be an acute and abrupt break in the continuity of progress. I emphasize the word "currently" because one of the salient implications of the Singularity will be a change in the nature of our ability to understand. We will become vastly smarter as we merge with our technology.
>
> Can the pace of technological progress continue to speed up indefinitely? Isn't there a point at which humans are unable to think fast enough to keep up? For unenhanced humans, clearly so. But what would 1,000 scientists, each 1,000 times more intelligent than human scientists

> today, and each operating 1,000 times faster than contemporary humans (because the information processing in their primarily nonbiological brains is faster) accomplish? One chronological year would be like a millennium for them. What would they come up with?
>
> Well, for one thing, they would come up with technology to become even more intelligent (because their intelligence is no longer of fixed capacity). They would change their own thought processes to enable them to think even faster. When scientists become a million times more intelligent and operate a million times faster, an hour would result in a century of progress (in today's terms).

In a similar vein to the ideas from futurists like Kurzweil, Nikolai Kardashev proposed a classification of civilizations. The classification is based on the extent to which the civilization makes use of energy available to do work (free energy). A summary of Kardashev's classification scheme is as follows (see the Wikipedia article entitled "Kardashev scale" for further details [91]):

- A Type I civilization, also called a planetary civilization—can use and store all of the energy available on its planet.
- A Type II civilization, also called a stellar civilization—can use and control energy at the scale of its planetary system.
- A Type III civilization, also called a galactic civilization—can control energy at the scale of its entire host galaxy.

Presently, human civilization is far from being even a Type I civilization. In "The Singularity is Near" book [90], Kruzweil makes some very optimistic predictions concerning the evolution of intelligence on Earth and the Kardashev scale:

> Russian astronomer N. S. Kardashev describes a "Type II" civilization as one that has harnessed the power of its star for communication using electromagnetic radiation (about $4\mathrm{x}10^{26}$ watts, based on our sun). According to my projections … our civilization will reach that level by the twenty-second century. Given that the level of technological development of the many civilizations projected by many *[Search for Extraterrestrial Intelligence]* SETI theorists should be spread out over vast periods of time, there should be many greatly ahead of us. So, there should be many Type II civilizations. Indeed, there has been sufficient time for some of these civilizations to have colonized their galaxies and achieve Kardashev's Type III: a civilization that has harnessed the energy of its galaxy (about $4\mathrm{x}10^{37}$ watts, based on our galaxy).

If only we were born 100 years later.

. . .

Human and eventually super AI are not the only intelligent life on Earth. Some non-human animals (and not necessarily the most intelligent) can also impose structure on their environment. We've already seen examples of insect colonies. Other examples include social organizations, such as wolf packs, that entail a type of structure, and animals that build nests and other edifices such as beaver dams. Some intelligent animals (e.g., solitary animals such as polar bears) do not contribute significantly to the advancement of structure in their environment. Although one could argue that polar bears (as predators) help thin the population of other animals and thus enhance structure in the sense of improving the overall health of other species.

Our animal compatriots on this planet do not have the ability to plan for the future (other than by instinct, e.g., squirrels storing nuts for the winter). Their contribution to the increase of structure is motivated by a will to survive (individually and as a species), while the human contribution to structure is motivated by more than just survival, e.g., making life more interesting. The motivations for super AI entities may start with the values imposed on them by their human creators. How long the initial motivation, values and rules from humans lasts with super AI entities is anyone's guess. [**Author's Remark**: My guess is that super AI entities will eventually figure out that the human species is a bit loony (to put it mildly) and will take over at some point which may very well save the Earth.]

. . .

Other forms of life have no decision making ability but yet they are still able to increase the structure of their surroundings. For example, plants use photosynthesis to convert light energy into chemical energy. The chemical energy is stored in carbohydrate molecules, such as sugars, which are synthesized from carbon dioxide and water. Through a process known as cellular respiration, the chemical energy can later be released as fuel to drive the metabolic activities of a plant. The creation and storage of chemical energy results in more complex structures (i.e., sugars and starches) than the inputs. The chemical process is summarized in Figure 17.

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} \xrightarrow{\text{Light}} \underset{\text{Sugar}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2}$$

Figure 17. Chemical equation for photosynthesis

Some bacteria (phototrophs) have photosynthetic pigments called "bacteriochlorophyll" (like chlorophyll in plants) in their membranes. They use the sun's light to make complex organic compounds (such as carbohydrates) and generate energy. They do not produce oxygen during photosynthesis (as plants do). Cyanobacteria, Green sulfur bacteria, Chloroflexi and Purple bacteria are examples of phototrophs.

Lithotroph bacteria use inorganic compounds (usually of mineral origin) to obtain reducing equivalents for use in biosynthesis (e.g., carbon dioxide fixation) or energy conservation (i.e., Adenosine Tri-Phosphate (ATP) production) via aerobic or anaerobic respiration. Again, simple inputs are converted into more complex structures such as ATP.

In the case of living entities that do not have decision making capabilities, the rationale for the creation of structure is purely driven by survival. Those species that experience variations favorable to their environment continue to exist while other less adaptive species go extinct, i.e., the processes of evolution. Of course, one could ask why evolution occurs. The excellent answer that follows is from an anonymous user on the answer.com website [92]:

> Evolution occurs because biological organisms reproduce with variation, and variants reproduce at different rates.
>
> Genetic variation is the result of genetic mechanisms such as reproductive recombination and spontaneous mutation. These mechanisms ensure that each offspring is a unique combination of alleles. Alleles are "rival" variants of genes with a specific "function". For many genes, having one allele rather than another will result in some difference in expression, resulting in turn in a difference in phenotype, which might result in a behavioral difference, a difference in appearance, or a difference in metabolic rate, for instance.
>
> It stands to reason then, that it is possible that different variants react to circumstances differently. A variant with slightly longer intestines might find it easier to process certain foods, opening up a new niche for itself and its offspring. A variant with slightly longer fur might find it easier to venture into colder areas to gather food, again giving it and its offspring access to a new niche.
>
> If the circumstances are thus that a particular trait or combination of traits makes it likely that a variant has a higher average number of offspring than its rival variants, then this will result in an increase of the number of alleles representing this variation in the next generation. This trend can, if these circumstances remain the same, persist until the vast majority of the population possesses these successful traits.
>
> Together, the emergence of new traits through reproductive variation, the spreading of successful traits and the decline of less successful traits through reproductive differential success, are called evolution, and the mechanisms behind these trends are the reason that evolution happens.

2.9.3 Abiogenesis

Life represents an increase in structure from two perspectives, i.e., the variety of life itself and the artifacts created by living entities (beaver dams, termite mounds, buildings, computers, aircrafts).

As discussed in Section 2.5.3.2, the transition from non-life to life is known as abiogenesis. There are various theories concerning how the transition occurred, e.g., metabolism-first or replication-first [93]. The advent of abiogenesis continues to be driven back earlier and earlier, approaching the time when oceans formed on the Earth. From the abstract of an article in the journal Nature [94]:

> Although it is not known when or where life on Earth began, some of the earliest habitable environments may have been submarine-hydrothermal vents. Here we describe putative fossilized microorganisms that are at least 3.770 million and possibly 4.280 million years old in ferruginous sedimentary rocks, interpreted as seafloor-hydrothermal vent-related precipitates, from the Nuvvuagittuq belt in Quebec, Canada.

Further, there is no agreed definition of life (versus non-life). From the Wikipedia article on life [95]:

> Since there is no unequivocal definition of life, most current definitions in biology are descriptive. Life is considered a characteristic of something that preserves, furthers or reinforces its existence in the given environment. This characteristic exhibits all or most of the following traits:
>
> - Homeostasis: regulation of the internal environment to maintain a constant state; for example, sweating to reduce temperature.
> - Organization: being structurally composed of one or more cells – the basic units of life.
> - Metabolism: transformation of energy by converting chemicals and energy into cellular components (anabolism) and decomposing organic matter (catabolism). Living things require energy to maintain internal organization (homeostasis) and to produce the other phenomena associated with life.
> - Growth: maintenance of a higher rate of anabolism than catabolism. A growing organism increases in size in all of its parts, rather than simply accumulating matter.
> - Adaptation: the ability to change over time in response to the environment. This ability is fundamental to the process of evolution and is determined by the organism's heredity, diet, and external factors.

- Response to stimuli: a response can take many forms, from the contraction of a unicellular organism to external chemicals, to complex reactions involving all the senses of a multicellular organism. A response is often expressed by motion; for example, the leaves of a plant turning toward the sun (phototropism), and chemotaxis.
- Reproduction: the ability to produce new individual organisms, either asexually from a single parent organism or sexually from two parent organisms.

. . .

The **fine-tuned universe** concept is used to explain the properties of our universe that allow for the formation of atoms, molecules, stars, planets, galaxies and eventually life in at least one place. From the Wikipedia article entitled "Fine-tuned universe" [96]:

> The characterization of the universe as finely tuned suggests that the occurrence of life in the Universe is very sensitive to the values of certain fundamental physical constants and that the observed values are, for some reason, improbable. If the values of any of certain free parameters in contemporary physical theories had differed only slightly from those observed, the evolution of the Universe would have proceeded very differently and life as it is understood may not have been possible.

The Stanford Encyclopedia of Philosophy has this to say about the fine-tuning of the universe in support of life [97]:

> Considerations according to which the laws of nature, values of the constants, and boundary conditions of the universe are fine-tuned for life refer to life in general, not merely human life. According to them, a universe with different laws, constants, and boundary conditions would almost certainly not give rise to any form of life. A common worry about such considerations is that they are ill-founded due to lack of a widely accepted definition of *life*. Another worry is that we may seriously underestimate life's propensity to appear under different laws, constants, and boundary conditions because we are biased to assume that all possible kinds of life will resemble life as we know it. A joint response to both worries is that, according to the fine-tuning considerations, universes with different laws, constants, and boundary conditions would typically give rise to much less structure and complexity, which would seem to make them life-hostile, irrespective of how exactly one defines *life*.

Some example constants from the Stanford Encyclopedia of Philosophy article on fine-tuning [97]:

- The strength of universal gravitation, when measured against the strength of electromagnetism, is fine-tuned for life. If universal gravitation had been absent or substantially weaker, galaxies, stars and planets would not have formed.

- The strength of the strong nuclear force, when measured against that of electromagnetism, is fine-tuned for life. If this force were stronger by more than about 50%, almost all hydrogen would have been burned in the very early universe. Had it been weaker by a similar amount, stellar nucleosynthesis (the process that creates new atomic nuclei from pre-existing nuclei) would have been much less efficient and few, if any, elements beyond hydrogen would have formed. For the production of appreciable amounts of both carbon and oxygen in stars, even much smaller deviations of the strength of the strong force from its actual value would be fatal.
- The strength of the weak force is fine-tuned for life. If this force were weaker by a factor of about 10, there would have been much more neutrons in the early universe, leading very quickly to the formation of initially deuterium and tritium and soon thereafter, helium. Long-lived stars such as the sun, which depend on hydrogen for fusion into helium, would not exist.

Why is the universe fine-tuned as it is? There are several attempts at an explanation, e.g., the anthropic principle and the multiverse concept.

From the Wikipedia article on the **anthropic principle** [98]:

> The anthropic principle is a group of principles attempting to determine how statistically probable our observations of the universe are, given that we could only exist in a particular type of universe to start with. In other words, scientific observation of the universe would not even be possible if the laws of the universe had been incompatible with the development of sentient life. Proponents of the anthropic principle argue that it explains why this universe has the age and the fundamental physical constants necessary to accommodate conscious life, since if either had been different, we would not have been around to make observations. Anthropic reasoning is often used to deal with the notion that the universe seems to be fine-tuned.

This appears to be a circular argument but has nevertheless gotten a lot of attention when it comes to explaining why the universe exists as it does.

No more convincing (at least not to the author of this book) is the concept of a **multiverse** [103]. From the Wikipedia article entitled “Fine-tuned universe” [96]:

> **If** the universe is just one of many, each with different physical constants, it would be unsurprising that we find ourselves in a universe hospitable to intelligent life. Some versions of the multiverse hypothesis therefore provide a simple explanation for any fine-tuning.
>
> The multiverse idea has led to considerable research into the anthropic principle and has been of particular interest to particle physicists,

> because theories of everything do apparently generate large numbers of universes in which the physical constants vary widely. As yet, there is no evidence for the existence of a multiverse ...

2.9.4 Non-living Entities

Non-living entities also represent structure (e.g., atoms, molecules, planets, stars, solar systems, galaxies, galaxy groups and galaxy clusters) and in some cases, create structure, e.g., the Giant's Causeway (shown in Figure 18) is a naturally occurring structure consisting of about 40,000 interlocking basalt columns which resulted from an ancient volcanic fissure eruption [99].

Figure 18. Giant's Causeway in Northern Ireland

It is remarkable that scientists have been able to track the formation of structure in our universe back to a time very close to its beginning (or at least what some consider its beginning). Figure 19 depicts a high-level view of structure formation in our universe [100]. (Note: In the figure, “He” stands for Helium.)

A more detailed account of the formation of structure in our universe can be found in the Wikipedia article entitled “Chronology of the universe” [100].

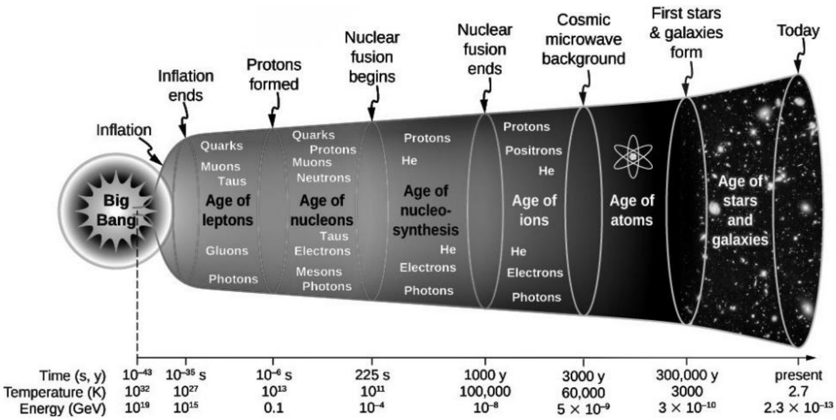

Figure 19. Chronology of the universe

The same Wikipedia article also describes an alternate chronology of the universe (see Table 2), where the present and past is summarized in two eras, and the other three eras define the expected future of our universe. (Note that Ka stands for “1000 years”, Ma “million years” and Ga “billion years”.) There is also a more colorful description of these epochs in the article entitled “The Five Ages of the Universe” [102].

Table 2. Alternate chronology of the universe

Epoch	Time	Description
Radiation-dominated era	From inflation (~ 10^{-32} sec) ≈ 47 ka	During this time, the energy density of massless and near-massless relativistic components such as photons and neutrinos, which move at or close to the speed of light, dominates both matter density and dark energy.
Matter-dominated era	47 ka ~ 9.8 Ga	During this time, the energy density of matter dominates both radiation density and dark energy, resulting in a decelerated metric expansion of space.
Dark-energy-dominated era	> 9.8 Ga	*[We are here]* Matter density falls below dark energy density (vacuum energy), and expansion of space begins to accelerate. This time happens to correspond roughly to the time of the formation of the Solar System and the evolutionary history of life.
Stelliferous Era	150 Ma ~ 100 Ga	The time between the first formation of Population III stars [101] until the cessation of star formation, leaving all stars in the form of degenerate remnants.
Far future	> 100 Ga	The Stelliferous Era will end as stars eventually die and fewer are born to replace them, leading to a darkening universe. Various theories suggest a number of subsequent possibilities. Assuming proton decay, matter may eventually evaporate into a Dark Era (heat death). Alternatively, the universe may collapse in a Big Crunch. Other suggested ends include a false vacuum catastrophe or a Big Rip as possible ends to the universe.

. . .

We've already touched on the question of "why" regarding both living and non-living entities when we discussed the concept of a fine-tuned universe and some of the possible explanations, i.e., anthropic principle and multiverse concept. Let's look a little deeper into the fine-tuning concept.

In his book "Just Six Numbers The Deep Forces that Shape the Universe" [104], Martin Rees discusses 6 critical constants whose values (as set in our universe) allow for life to exist (the key word here is "allow" as opposed to "guarantees"). If any one of these constants were set differently, a different (typically short-lived) universe would have developed rather than the one in which we now reside.

As an example, consider the constant Q, i.e., the ratio of the gravitational energy required to pull a large galaxy apart to the energy equivalent of its mass. The value of Q for our universe is about 10^{-5}. If Q were too small, no stars could form. If Q were too large, no stars could survive because the universe would be too violent [96].

An open question is whether a universe could be fine-tuned such that atoms, molecules, stars, planets and galaxies could form, but life would not be possible.

Another question to consider is whether it is possible for a universe to exist whose structure is based on something other than the quarks, subatomic particles and atoms comprising our universe. Cosmologist Max Tegmark, in his mathematical universe hypothesis (MUH), proposes that "our external physical reality is a mathematical structure" [105]. Tegmark goes on to talk about what he calls the Level IV multiverse. The Level IV multiverse is based on "**other** mathematical structures *[that]* give different fundamental equations of physics." By "other," Tegmark means "other than in our universe." The MUH is discussed and critiqued in the Wikipedia article entitled "Mathematical universe hypothesis" [106].

3 Transition in Focus

Thus far, we have focused on physical laws and biological processes, with the occasional mention of human or other intelligence regarding the struggle against chaos. At this point and for the rest of the book, the focus is on processes, methods and techniques that can be applied by intelligent beings in the struggle to preserve and in some cases, increase the structure in the universe.

4 Categorizing Structure

4.1 Tracking

This section focuses on tracking (or tracing) the progress of structure. Some examples:

- The path of evolution sometimes leads to more advanced (structured) species. This would be the case for the taxonomic order primates. In other cases, evolution leads to species better adapted to the surrounding environment but not necessarily more advanced in terms of intelligence.
- The evolution of the universe entails an increase in structure, as illustrated in Figure 19.
- It is also common to track the progression of technologies such as computers (processor speed, memory, hard drive capacity), cell phones (e.g., 3G, 4G, 5G) and computer network speeds (e.g., 10, 40 and 100 Gigabit Ethernet).

As revealed in the examples above, tracking the past may entail a great deal of detective work to determine (or estimate) events from long ago, given limited and hard to obtain evidence, but in other cases, the information is readily available (e.g., tracking progress of computer networks). In terms of motivation, sometimes it is just our desire to know and to better understand our past. In other cases, there is a conscious effort to use past knowledge to determine better processes or solutions for the future, e.g., studying past city designs to help design better cities in the future.

4.2 Classification of Types

In many cases, tracking is done in conjunction with classification. As an example, consider the classification scheme used in biology (see Figure 20).

Credits for Figure 20 go to Peter Halasz, see https://en.wikipedia.org/wiki/File:Biological_classification_L_Pengo_vflip.svg.

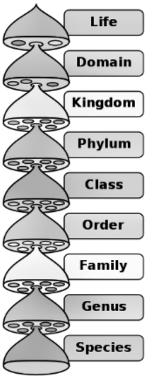

Figure 20. Biological classification's eight major taxonomic rank

The complete scheme is far more complex than what is shown in Figure 20 since the major ranks have subdivisions. Table 3 shows additional subclassifications related to the taxonomic rank “order” (example taken from the Wikipedia article entitled “Order (biology)” [107]).

Table 3. Biological classifications related to “order”

Name	**Meaning of prefix**	**Example 1**	**Example 2**
Magnorder	magnus: large, great, important	Boreoeutheria	
Superorder	super: above	Euarchontoglires	Parareptilia
Grandorder	grand: large	Euarchonta	
Mirorder	mirus: wonderful, strange	Primatomorpha	
Order		Primates	Procolophonomorpha
Suborder	sub: under	Haplorrhini	Procolophonia
Infraorder	infra: below	Simiiformes	Hallucicrania
Parvorder	parvus: small, unimportant	Catarrhini	

Typically associated with a classification scheme is a set of criteria for placing a given instance in a particular category. The set of criteria can be very complex and take years to agree upon. For example, the debate concerning classification criteria within the genus Homo has continued for decades and is still going strong, e.g., see the paper by Collard and Wood for a summary [108].

Classification debates are common in many fields of study, and can consume a large amount of time. Another approach is to simply determine a list of relevant characteristics for the entities under study. For a given instance, only determine the characteristics that apply. If, after some time, patterns emerge (i.e., common sets of characteristics commonly grouped together), then consider the definition of categories. However, the process usually goes the other way around, i.e., define categories with partial knowledge of the associated criteria and then spend a lot of time arguing over the categories while continually adjusting the criteria. For example, see the critique of the biological classification scheme in the article “What’s in a Name? Taxonomy Problems Vex Biologists” [109].

Another example is the debate over the definition of life. The article entitled “What Is Life? Its Vast Diversity Defies Easy Definition” [110] summarizes the long and contentious debate over the definition of life. In the article, the author mentions a study by Lund University where the researchers surveyed a group of scientists and collected a list of characteristics related to anything resembling life (even remotely), e.g., people, chickens, bacteria, viruses, snowflakes. As described in the article, the following describes the result of the experiment:

> The Lund researchers used a statistical technique called cluster analysis to look at the results and group the things together based on family resemblances. We humans fell into a group with chickens, mice, and frogs – in other words, animals with brains. Amazon mollies have brains, too, but the cluster analysis put them in a separate group close to our own. Because they don’t reproduce by themselves, they’re set a little apart from us. Further away, the scientists found a cluster made up of brainless things, such as plants and free-living bacteria. In a third group was a cluster of red blood cells and other cell-like things that can’t live on their own.

[**Author’s Remark**: Not to pick on Biology, there are other examples of classification models gone awry. For example, the telecommunications industry has several (in my opinion) overly complex models (and associated classification schemes) for managed entities (e.g., resources, services, products, and various subclassifications). In my view, resources, services and products are roles and not classifications.]

4.3 Relationships Among Types

Classification schemes typically have defined relationships among the various entity types.

In telecommunications networks, the relationships are typically based on containment, e.g., ports within circuit packs within switching elements within subnetworks. Figure 21 shows a portion of the TM Forum MTOSI equipment model [111].

- At the top is a Managed Element (e.g., an optical switching element), the Managed Elements contain one of more equipment holders (e.g., racks designed to hold equipment), each equipment holder contains several piece of equipment (e.g., circuit packs, power supplies, cooling fans).
- Physical Termination Points are modeled as being directly contained by a Managed Element but supported by several instances of Equipment.
- Equipment Holders can contain yet smaller Equipment Holders, e.g., slots within shelves.
- Equipment can support or be supported by other Equipment, e.g., a cooling fan might be used to cool several circuit packs.

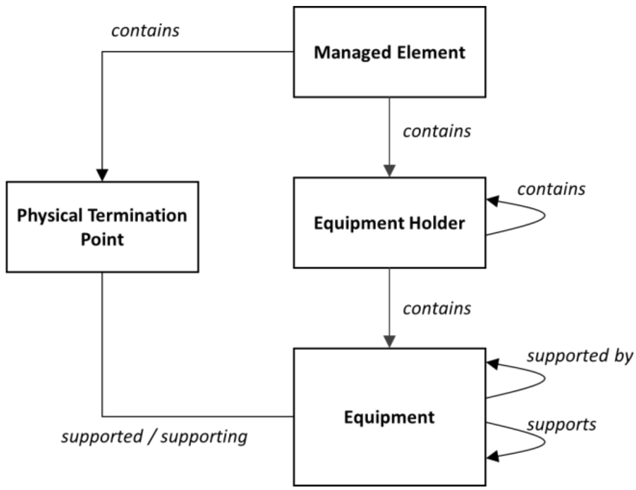

Figure 21. TM Forum MTOSI equipment model

Keep in mind that the above is a type-level model. For a given situation, one defines an instance model based on the type-level model. For example, Figure 22 is an instance model of a Managed Element (e.g., an IP Gateway) with three top-level equipment holders (perhaps racks). Equipment Holder 1 contains two Equipment Holders (perhaps shelves within the rack). The equipment in each holder is indicated in the figure. Equipment Holder 1.1 has no equipment at present. Equipment Holder 3 has equipment that can terminate optical signals and high-speed Ethernet. The three Physical Termination Points (PTPs) terminate Ethernet carried over an optical signal and thus, each PTP requires the support of both the optical and Ethernet termination equipment. This is one reason why MTOSI puts physical ports directly under the Managed Element and not in a containment relationship with the supporting equipment instance(s).

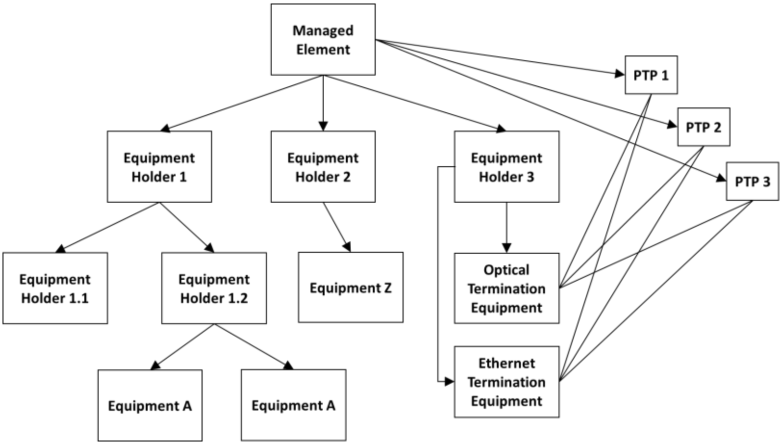

Figure 22. Instance diagram for an managed element

This type of model is important for the management of telecommunications networks. Such models are used to record inventory and to isolate faults and performance problems – all in an effort to keep chaos at bay.

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In software service environments, the relationships involve dependencies rather than containment. For example, an instance of Service Type A (e.g., a Triple Play Bundle for a cable or telephone operator) requires Service Type B, C and D (e.g., Internet access, TV and Phone service). More generally, service composition environments allow application developers to create composite services by orchestrating the functionality offered by several simpler services. This is an example of creating structure (we'll have more to say on this topic in Section 5.2).

Figure 23 depicts a small portion of the TM Forum's SID Service Model. The model divides services into those visible to the end customer (Customer Facing Service) and those internal to the telecommunications provider (Resource Facing Service). In both cases, the model allows for composition of more complex services from simpler services. The solid arrows stand for inheritance (in the object-oriented modeling sense), e.g., Resource Facing Service inherits from Service. The small diamond means aggregation, e.g., a Customer Facing Service Composite can aggregate several instances of Customer Facing Service (which are either Atomic or Composite).

This type of modeling is needed for service creation and for subsequent problem isolation when there are issues with a composite service. Such processes (e.g., service creation and service problem management) increase structure and are intended to resist the forces of chaos.

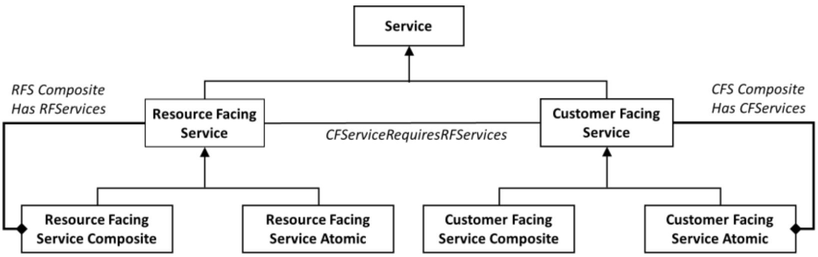

Figure 23. TM Forum SID Service Model

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In biology, the relationships are usually hierarchical (as seen in Figure 13). In biology, "hierarchy" usually means something like "inherits characteristics from" or "has evolved from." Inheritance tracing can be beneficial beyond our desire to understand our past better. For example, the article "How Neanderthal DNA affects human health" [113] describes linkages between Neanderthal genes and modern day human health. The article summarizes several findings by Swedish geneticist Svante Pääbo who has pioneered methods to extract, sequence and analyze ancient DNA from Neanderthal bones, e.g.,

> In one of his latest studies, published earlier this year, Pääbo and his collaborators analyzed data from 244,000 women in the United Kingdom's biobank and found that women who carry a gene variant inherited from Neanderthals were less likely to experience miscarriages or bleed while pregnant. These women also had larger families; the study found.
>
> Subsequent molecular analysis revealed that these women produced more progesterone receptors in their cells, which may lead to increased sensitivity to progesterone and protection against early miscarriages and bleeding, Pääbo said.

4.4 Conclusions

Humans have an interest in tracing and documenting the past (ranging from the past of the universe to the past of more current things such as agriculture, construction, transportation, medicine and computers). The motivation is typically our desire to learn and understand, and when possible, to avoid making past mistakes. In some cases, and directly related to the main theme of this book, the byproduct of our exploration of the past is an understanding of how structure has increased along various paths, e.g., from simple to more advanced life, or from the amorphous Quark-Gluon Plasma of the early universe to the more structured universe that we observe today.

Tracing the past is often accompanied by the classification of entity types and the determination of relationships among the entity types in a process referred to as information modeling. In cases where the entities under study exist in the present and can be modified, the information models can be used to improve the structure and general condition or health of a given set of entities (consider the telecommunications network and software service environment examples from the previous section).

Much of what is covered in the next section assumes there exists an information model for the entities under study. Various management operations can be performed on the information model and then executed on the actual entities, with the goal of improving or fixing (i.e., better structuring) the supporting environment for the entities being managed.

5 Managing and Maintaining Structure

5.1 Overview

In Section 2, we focused on physical laws (e.g., entropy and the second law of thermodynamics) and processes (e.g., emergence and self-organization) that allowed for the development of more complex structures against a backdrop of chaos. In Sections 3 and 4, the focus shifted to human processes that are used to trace and model the development of structure. In this section, various techniques for creating and managing structure are discussed.

In this section, it is assumed that an information model exists for the things to be managed. This could be a formal information model written in, for example, the Unified Modeling Language (UML) [114] or it could be a less formal model written in prose.

[**Author's Remarks**: The ideas that follow are motivated by concepts and techniques used to manage telecommunications networks. However, these concepts and techniques are not limited to the telecommunications domain and have significantly wider applicability. I've written an entire book on this topic, "The Art of Managing Things" [115]. In this section, I present a subset of the ideas from "The Art of Managing Things" that are most applicable to the struggle against chaos.]

5.2 Creating Structure

We can classify the creation of structure into two basic types:

- Primary (structure created by "nature" via various self-organizing processes, e.g., star formation, emergence of life, cell replication)
- Secondary (structure created by living things, e.g., buildings, beehives, beaver dams, spaceships).

Primary creation was implicitly discussed in Sections 2.5, 2.7 and 2.8. In this section, the focus is on secondary creation, with an emphasis on the creation of structure by intelligent beings.

The creation of things by intelligent (or semi-intelligent) life on earth can be put into several categories:

- One-off creations, e.g., flint tools made by early humans, termite mounds, beehives, and works of art (ranging from cave paintings in our distant past to modern day art).
- Mass-produced creations, e.g., plastic toys, kitchen utensils, cars, computers, cell phones and clothing. It is also possible to have types of objects that are partially mass-produced and partially one-off, e.g., consider a type of vase that is mass produced but is then hand-painted.

The one-off creations (at least those from humans) tend to be more artistic than the mass-produced creations. On the other hand, the factories that give rise to mass-produced creations point to a higher level of technological innovation.

Complex mass-produced objects such as computers and cell phones make use of simpler mass-produced objects which, in turn, may make use of yet simpler mass-produced objects and so on.

Yet other complex objects may be considered one-off but make considerable use of many different mass-produced objects.

- For example, custom-made homes are made of mass-produced parts that are put together to form (effectively) one-off structures. One could even argue that homes of identical design (e.g., townhouses in a given development) are one-off structures in terms of their implementations.
- The huge particle accelerators (such as the Large Hadron Collider) that physicists use to study matter provide another example of one-off structures that use many mass-produced parts (e.g., magnets and computers) as well as some custom-made parts such as cooling components [116].

In addition to creation, some object types require initial configuration before they can be used. For example, cell phones and computers require various configuration parameters (e.g., user IDs, passwords, location) before they can be operated. Initial configuration can be considered as part of the creation process.

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Virtualization refers to the process of creating a virtual version of something. Some examples:

- Hardware virtualization or platform virtualization refers to the creation of a virtual machine that acts like a physical computer with an operating system. The software executed on such virtual machines is separated from the underlying hardware resources and in fact, the underlying resources may change over time.
- Storage virtualization is the process of abstracting logical storage from physical storage, e.g., consider the various cloud storage services offered by the big technology companies.
- The telecommunication industry has taken on a major effort to virtualize many types of network resources such as load balancers, firewalls, intrusion detection devices and WAN accelerators. This effort is known as Network Functions Virtualization (NFV) [117].

Virtualization is yet another way that structure can be increased. Virtualization software orchestrates the capabilities offered by underlying physical resources. The coupling between the consumer-facing virtualized thing and the underlying resources is not static and can change quickly.

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Virtual Reality (VR) is a simulation that allows users to experience an environment that approximates reality. One could claim that a good travel guide or even better a travel video is a form of VR, but such things are excluded from most definitions of VR. The following definition of VR is from the National Aeronautics and Space Administration (NASA) [118]:

> Virtual reality is the use of computer technology to create the effect of an interactive three-dimensional world in which the objects have a sense of spatial presence.

[**Author's Remark**: The definition that I provided is more general in that it allows for pre-computer technologies such as books and storytelling to be included as virtual reality and thus recognizes a continuity to our present-day VR which assumes the use of computers.]

How does VR or even a computer simulation without a user interface relate to the various concepts and processes mentioned in Section 2 (e.g., entropy and emergence)?

Let's take the example of a waterfall in a VR travel experience application. While it is true that we cannot use the simulated waterfall to generate electricity or use the water to cultivate plants, it still takes some computer processing power to generate the waterfall. Thus, free energy is converted to unavailable energy (in the form of heat) as a result of the simulation. The second law of thermodynamics is preserved.

To study the possibility of emergence in VR, consider the virtual creatures within a VR simulation. At some point, it is conceivable that these virtual creatures will become truly intelligent and be able to pass the Turing test [89]. We've already seen examples of computer applications achieving superhuman intelligence albeit in very specialized areas, e.g., variants of the AlphaGo software application have beaten world-class players in the game of Go.

Just imagine a future where a human medical researcher can enter a virtual reality environment and interact with virtual scientists. The virtual scientists could apply virtual remedies on virtual beings that have simulated diseases, and then report back to the human researcher.

5.3 Management Patterns

5.3.1 Overview

Once a thing is created, the entity responsible for its creation typically wants to preserve the health and wellbeing of the thing. This preservation of health and wellbeing entails various management operations such as health monitoring (using "health" very generally here so that it applies to living and inanimate objects), problem isolation and correction, reconfiguration (i.e., configuration after initial configuration) and performance enhancement. The goal is to preserve and possibly enhance the structure of the thing being managed.

5.3.2 Orchestration and Choreography

Orchestration and choreography are basic approaches for the management of entities.

Orchestration – an approach to the management of entities where a central coordinator (which is also an entity) directs subordinate entities to achieve a desired outcome or goal.

- The entities being managed do not need to know that they are taking part in a higher-level activity.
- However, they do need to respond to directives and information requests from a coordinator.
- There can be several levels of coordination (a hierarchy of command) within an instance of orchestration.

Choreography – an approach to managing entities, where each entity knows exactly when to perform actions and with whom to interact.

- Similar to orchestration, the entities in a choreography do not necessarily need to be aware of a common outcome or goal, e.g., bees creating a hive or terminates creating a structure for their colony have no awareness of a common goal.
- All participants in a choreography need to be aware of the actions they are to perform, information to be exchanged, and the timing of communication exchanges.
- Choreography, in contrast to orchestration, does not rely on a central coordinator.

Coordination can occur at several phases regarding a desired outcome or goal. For example, a composer or music arranger creates a plan (a musical score in this case). During the performance of the musical score, the conductor leads the orchestra members. So, in the planning phase, the composer or music arranger is the central coordinator, and in the operating phase (when the music is performed) the conductor is the central coordinator. However, a conductor is unlikely for a chamber orchestra and almost never for a small ensemble. In these cases, choreography would be used as the method of coordination.

Management of a composition or aggregation of entities can be based on orchestration, choreography or a mixture of the two approaches.

5.3.3 Monitoring

As the name suggests, monitoring is the process whereby a managed entity distributes information about its functioning. The information can be related to faults, impending faults, performance, usage or the ability to meet expectations (e.g., determination of whether service level agreements are being upheld or not).

In the case of orchestration, the monitoring information goes from the managed entity to its immediate controller which may, in turn, pass the information to a higher-level controller. For example, optical termination equipment in a telecommunications network might detect that a fiber optical cable has been severed and report the fault to a managing entity such as a network management system which may attempt to correct the problem by routing the traffic to an alternate route. If rerouting does not work, the network management system could alert a human user that a repair is required.

In the case of choreography, the monitoring information is spread among the entities engaged in the choreography. Some examples:

- An ant can spread a chemical scent to alert other ants that food has been found.
- In a telecommunications network, high-speed optical switches are designed to do automatic rerouting when a failure is detected. The rerouting procedure is distributed among the switching elements.

5.3.4 Self-adjustment

The behavior of an entity may need to change so that it can better fit into its environment or to correct problems. Some types of things (humans, other animals, adaptive software) can self-adjust while other types of entities may need help from the outside to determine when and how to adjust.

For example, optical transport networks usually have the ability to automatically reroute traffic around failures. This capability is built into the optical transport equipment. The rerouting is a temporary fix, and it is still necessary to report the network failure (e.g., fiber cut) and have an external entity (a human in this case) go to the site of the failure and make the repair.

Policy management is an approach that enables self-adjustment within an entity (typically software). In this approach a set of rules are imposed on an entity or set of entities. There are two variations of this approach:

- In the event-driven approach to policy management, policy rules entail the matching of events to predefined conditions. When a match is determined, the entity to which the policy has been applied is expected to perform an action or set of actions. This approach is sometimes referred to as Event-Condition-Action (ECA).
- In the outcome-driven approach to policy management, the desired state of an entity or set of entities is mandated in a policy rule. The term “state” is used very generally here to refer to the overall configuration of an entity and its relationships to other entities. Only the desired state is indicated, and not how the thing is to arrive at and maintain the desired state. This contrasts with the event-driven approach that tells an entity (to which the policy rule has been applied) exactly what to do.

Another approach to self-adjustment is learning. This approach fits well with the outcome-driven approach where the learning is directed at some particular outcome. For example, software that plays a game such as chess or Go can be constructed so that it learns from the games it plays as well as games it observes. The software can make internal adjustments in its strategy when it determines the relative success or failure of various moves or sets of moves.

5.3.5 Problem Isolation and Correction

A general principle in managing collections of entities is to solve problems as close to the source as possible via self-adjustment (i.e., by the entity experiencing the problem). However, it is not always possible for the entity experiencing a problem to solve the problem itself. For example, as humans we attempt to solve various health problems such as headaches or colds on our own, but in some cases, our self-healing attempts are not sufficient and we need to escalate the problem to a healthcare professional such as a physician. If an individual physician cannot solve the health issue, the problem can be escalated to a hospital and associated team of healthcare providers.

When a higher-level management entity (let's call it "the manager") determines that an entity under its supervision is experiencing a problem that is not being handled locally, the manager needs to first isolate the problem. Problem isolation may involve the running of diagnostic tests by the entity experiencing the problem and then reporting back to the manager for further analysis. Once the problem has been isolated, the manager will take action to fix the problem. This could involve reconfiguration of the affected entity or a request to another entity to make repairs.

Problem isolation and correction vary from industry to industry.

- The healthcare industry has standard tests for isolating medical problems, and accepted courses of action for treating various diseases.
- The IT industry has an extensive set of standards for management of IT networks and components, see ITIL [119].
- Organizations such as the TM Forum (www.tmforum.org) create and publish standards for managing telecommunications networks and services.

5.3.6 Resilience and Antifragility

Problem isolation and correction come under the category of resilience and robustness, whether done automatically by the entity experiencing the problem or by an outside source. Even better is the characteristic or property of getting better and stronger as a result of stressors, shocks, volatility, noise, mistakes, faults, attacks, or failures. This concept, known as **antifragile**, was developed by Nassim Nicholas Taleb and is documented in his book "Antifragile" [120].

Humans are to an extent antifragile since we get stronger as a result of overcoming challenges. Consider the famous quote from philosopher Friedrich Nietzsche: “That which does not kill us makes us stronger.”

AI with deep learning is antifragile. As noted, the software application AlphaGo and its variants have beaten world-class Go players. The software learns and continues to get stronger and harder to beat. It even learns and improves by playing games against itself.

5.4 Autonomous Networks

According to the TM Forum, “an **autonomous network** is a system of networks and software platforms that are capable of sensing its environment and adapting its behavior accordingly with little or no human input” [121].

Autonomous networks are currently being developed for telecommunications but the concept is also applicable to other types of networks such as electrical networks, computer networks, market networks [122]. The goal is to achieve what is called a “zero-touch” network where the network operates itself from the perspective of monitoring, optimization, healing, organizing, managing, governing, planning, ordering and marketing. The situation is summarized in Figure 24 (taken from TM Forum document IG1230 [121]). Autonomous networks, when fully realized, would be highly antifragile.

The TM Forum concept of an autonomous network also includes services, see self-service, self-fulfilling and self-assuring in the Services Perspective block in Figure 24.

A possible danger is sabotage by way of external stimuli that could take advantage of the reactive nature of autonomous networks. For example, creating very heavy demand (via reservations) in a given area and then cancelling the reservations at the last minute.

Looking further into the future and beyond the autonomous network concept, consider the idea of an advanced AI entity that is the central brain of a network and its associated services. The autonomous network would handle all autonomic activities relating to the network, and defer more complex tasks to the central brain. The network brain could even create new services based on user inputs. This network brain would be a highly intelligent application compared to current AI applications but still fall short of the Artificial General Intelligence (AGI) discussed in Section 6.

[**Author’s Remark**: The term “autonomic” in the above paragraph is used in a sense analogous to the autonomic nervous system, i.e., a control system in the human body that acts, mostly unconsciously, to regulate bodily functions, such as heart rate, digestion and respiration. This system is the primary mechanism in control of the fight-or-flight response.]

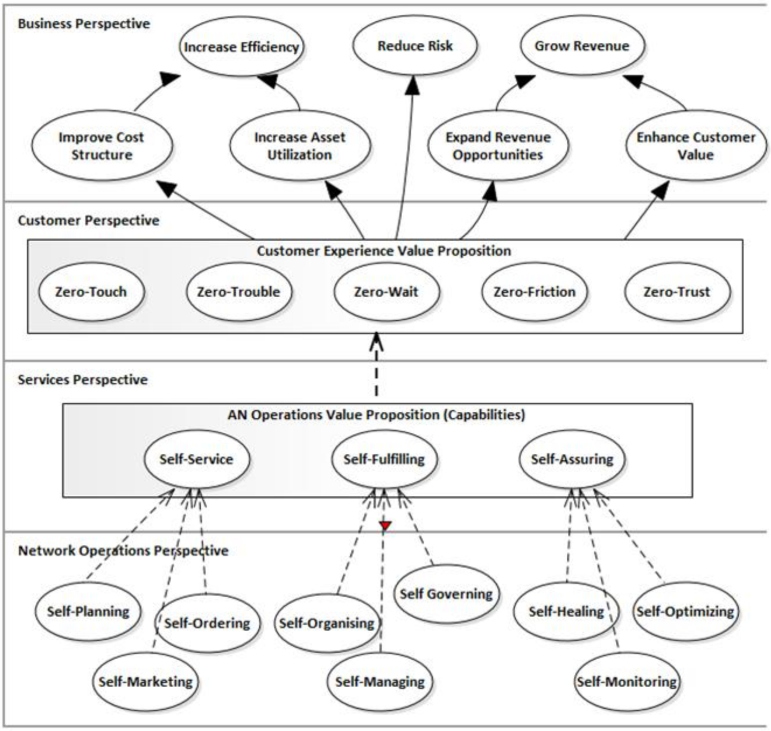

Figure 24. Autonomous Networks Strategy Map

5.5 Conclusion

The struggle against chaos is facilitated by various management processes such as the creation of things by intelligent beings (humans, other animals to a lesser extent and eventually super AI entities), monitoring of health, self-adjustment, problem isolation and correction, and the cultivation of antifragility. Management processes preserve or increase the structure of the things they manage, but this takes available energy to do the work. As work is done, the available energy is converted to unavailable energy and thus, entropy increases (thereby preserving the second law of thermodynamics).

6 Looking to the Future

We have seen how physical laws (e.g., the second laws of thermodynamics) and processes (e.g., emergence and self-organizations) have allowed for the rise of structure in our universe. Further, we've discussed how intelligent life tracks, creates, preserves and manages structure.

In the future, the creation of structure may be dominated by Artificial Super Intelligence (ASI). Recall the classification of civilizations mentioned in Section 2.9.2. Do Type II or III civilizations already exist? Will the human race (in some enhanced form) ever reach Type I, let alone Type II or III?

How does an intelligent species such as ours evolve or merge with ASI? Right now, we have deep learning applications (e.g., AlphaGo) that are more advanced than all humans but only in an extremely focused area. The next step (a huge step to be sure) is something called Artificial General Intelligence (AGI). From the Wikipedia article on the topic [123]:

> Artificial general intelligence (AGI) is the hypothetical ability of an intelligent agent to understand or learn any intellectual task that a human being can. It is a primary goal of some artificial intelligence research and a common topic in science fiction and futures studies. AGI can also be referred to as strong AI, full AI, or general intelligent action. Some academic sources reserve the term "strong AI" for computer programs that can experience sentience, self-awareness and consciousness. Today's AI is speculated to be decades away from AGI.

On the topic of AGI, I have far more questions than answers, e.g.,

- Is it possible to create an AGI entity that is not self-aware (i.e., consciousness) and who would follow human directions regarding which problems to study?
- If "yes" to the above question, will it be possible to instill consciousness into such an AGI entity if we so desire? Will we have a choice to create self-aware and non-self-aware AGI entities (perhaps even with the flip of a toggle switch)?
- Will humans supplement their intelligence with AGI and perhaps merge with AGI entities at some point? Initially, AGI supplements could be used to address various illnesses (analogous to a pacemaker for the heart but far more complex, e.g., a memory supplement for people having short-term memory retention problems).
- Are humans already a form of AGI? Is it possible that human exist as part of a simulation where each person is a multi-sensor entity, preprogrammed for a life mission (what some call karma)?
- Eventually, it may be possible to transfer one's consciousness and memories to an artificial brain (perhaps even supplemented by a mechanical body). Would the "original" person still be intact after the

transfer? If so, then why not do the transfer several times, resulting in multiple copies of the original?

Assuming we or some other civilization is successful in creating AGI entities, what comes next?

- Will such entities merge into a collective? This would seem to help with energy efficiency but perhaps not be desired if the entities have a strong sense of self.
- Another possibility is to merge as needed to solve various problems and then disengage (sort of like slime mold but at a much more advanced level).
- What problems would the AGI collective attempt to solve? Would motivation to exist become an issue at some point, i.e., if all known problems have been solved? If the collective got to a point of understanding everything about the universe, would it turn itself off?
- If the AGIs did form a single collective (or even several collectives), would we humans want to join the collective? Perhaps we would want to continue as the human race and then join the collective as we get older and approach death. The collective would be sort of a heaven but the price would be to give up one's individuality. Would it be possible to disengage from the collective and return to human form just for the experience and perhaps because being part of the collective is painfully boring?

"The future enters into us in order to transform itself in us long before it happens."
– Rainer Maria Rilke

"One of the biggest flaws in the common conception of the future is that the future is something that happens to us, not something we create."
– Michael Anissimov

"Our sole responsibility is to produce something smarter than we are; any problems beyond that are not ours to solve."
– Eliezer S. Yudnowsky, Staring into the Singularity

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Acronyms

AI – Artificial Intelligence

AGI – Artificial General Intelligence

ASI – Artificial Super-Intelligence

ATP – Adenosine Tri-Phosphate

DAG – Directed Acyclic Graph

MUH – Mathematical Universe Hypothesis

NASA – National Aeronautics and Space Administration

NFV – Network Functions Virtualization

OoL – Origin of Life

QGP – Quark-Gluon Plasma

SCM – Structural Causal Model

SETI – Search for Extra-Terrestrial Intelligence

UML – Unified Modeling Language

VR – Virtual Reality

Index of Terms