7 misconceptions in the foundations of physics

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Assumptions of Physics

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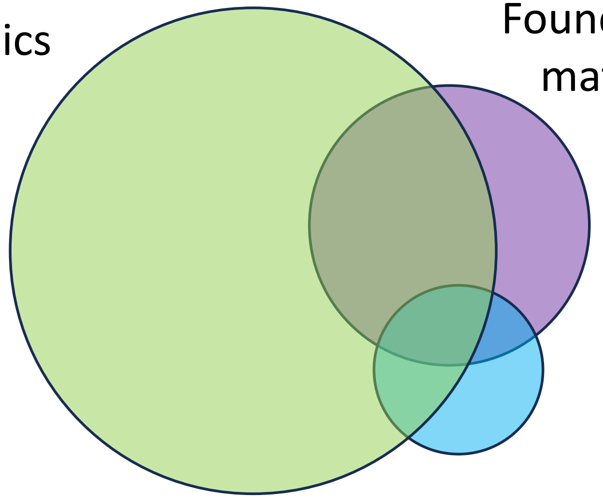
Aims to identify a handful of physical starting points from which the basic laws can be rigorously derived.



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Assumptions of Physics

1.

To understand quantum mechanics, we need the right “interpretation”

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Measurement (projection)

$\psi_I \rightarrow$ Measurement $\rightarrow m_1, m_2, m_3, \ldots$

$\xrightarrow{p_1} \psi_{m_1}$

$\xrightarrow{p_2} \psi_{m_2}$

$\xrightarrow{p_3} \psi_{m_3}$

…

Interpretation

$? \rightarrow$ Time evolution ? $\rightarrow ?$

Time evolution (unitary operation)

$\psi_I \rightarrow$ Time evolution Δt $\rightarrow \psi_O$

To understand quantum mechanics, we need a full account of what happens during a measurement

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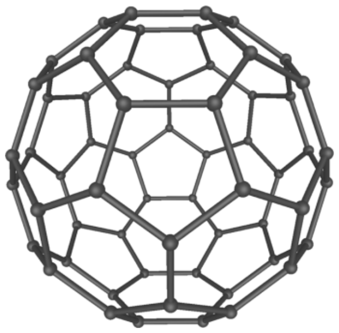

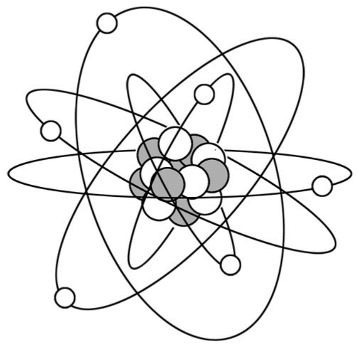

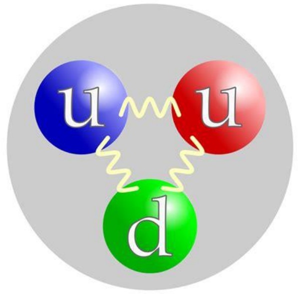

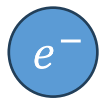

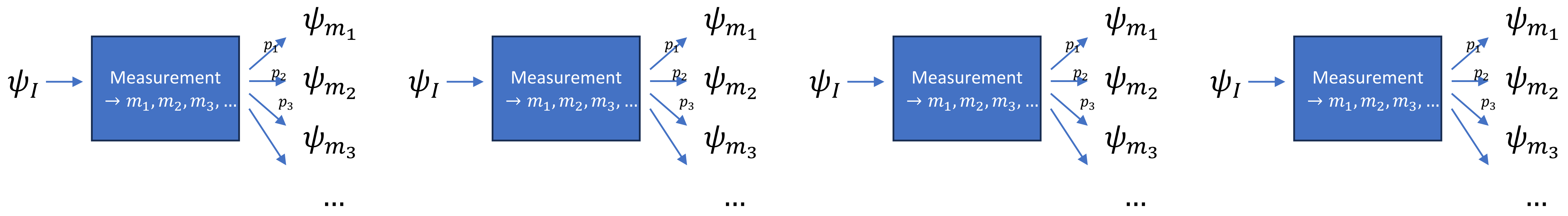

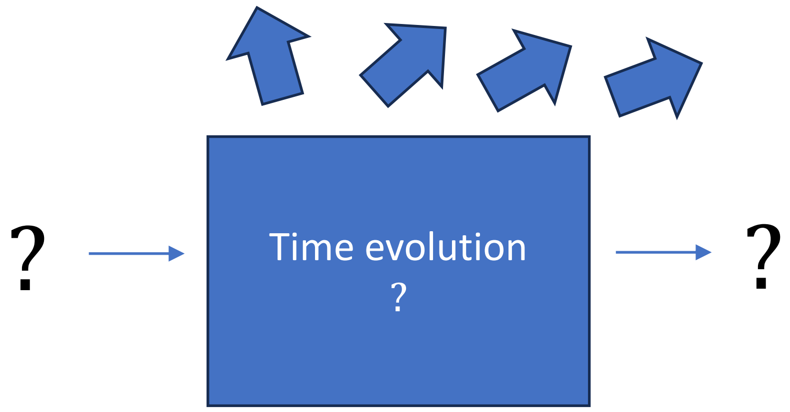

Unlikely we have one true mechanism, and we need to explain why all these different mechanisms look the same. Why so much focus on this?

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2.

Explanations must be about mechanisms

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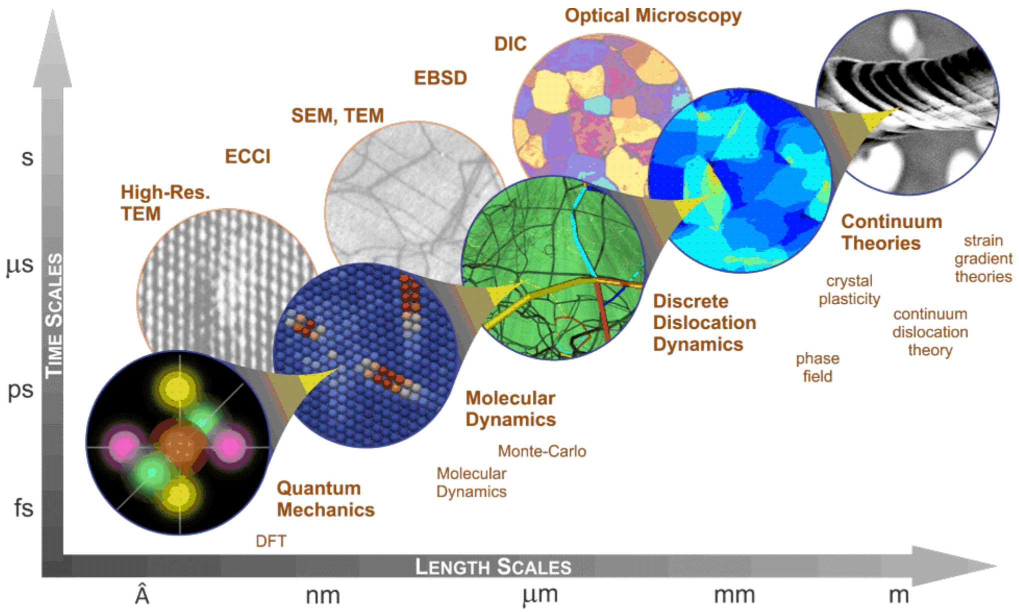
Physics explains the behavior of a physical system in terms of the behavior of the constituents



In a fundamental theory, objects cannot be further decomposed

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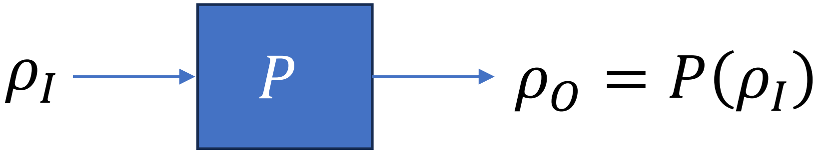
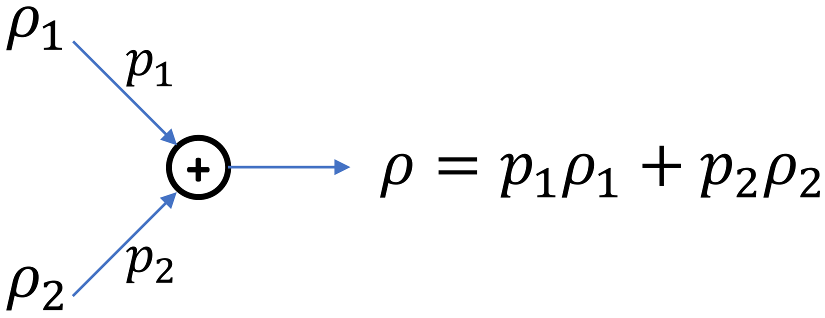
Any process (deterministic or stochastic) will take a statistical ensemble as input and return a statistical ensemble as output

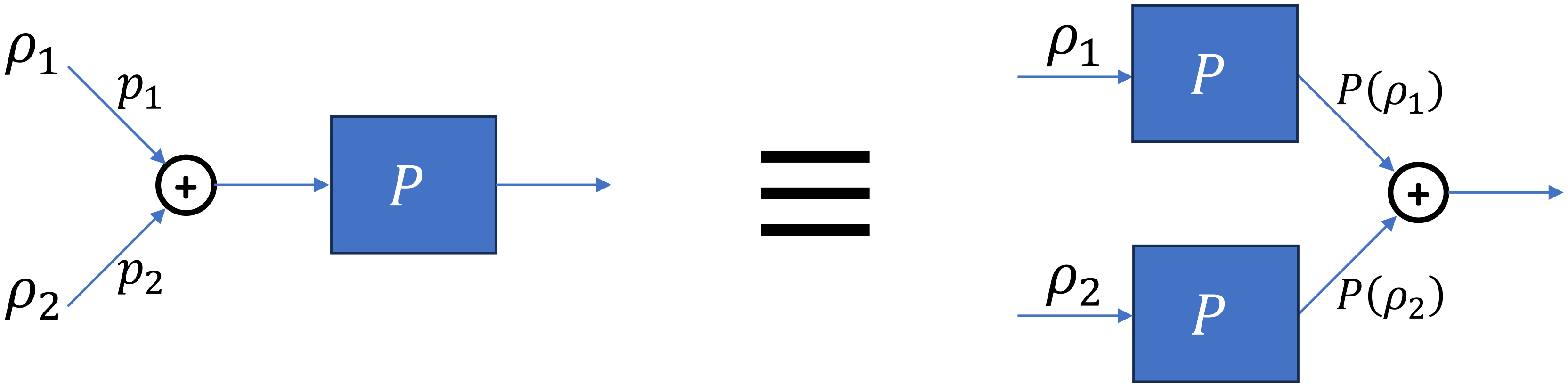


Statistical ensembles can be mixed



The output of a mixture must be equal to the mixture of the outputs (i.e. linear in probability)

$$P(p_1\rho_1 + p_2\rho_2) = p_1 P(\rho_1) + p_2 P(\rho_2)$$



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Deterministic and reversible

$$\rho_I \longrightarrow \boxed{P} \xrightarrow{\rho_O} \boxed{P^{-1}} \longrightarrow \rho_I$$

Conserves probability and allows an “inverse”

⇒ Unitary operation

Measurement

$$\rho_I \longrightarrow \boxed{P} \xrightarrow{\rho_O} \boxed{P} \longrightarrow \rho_O$$

Must be repeatable

⇒ Projection

The difference in behavior is intrinsic to the definitions of deterministic/reversible process and measurement. Any processes that approximately satisfy the requirements will do.

Why aren’t these types of explanations more prominent?

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3.

The laws of physics are the laws of the universe

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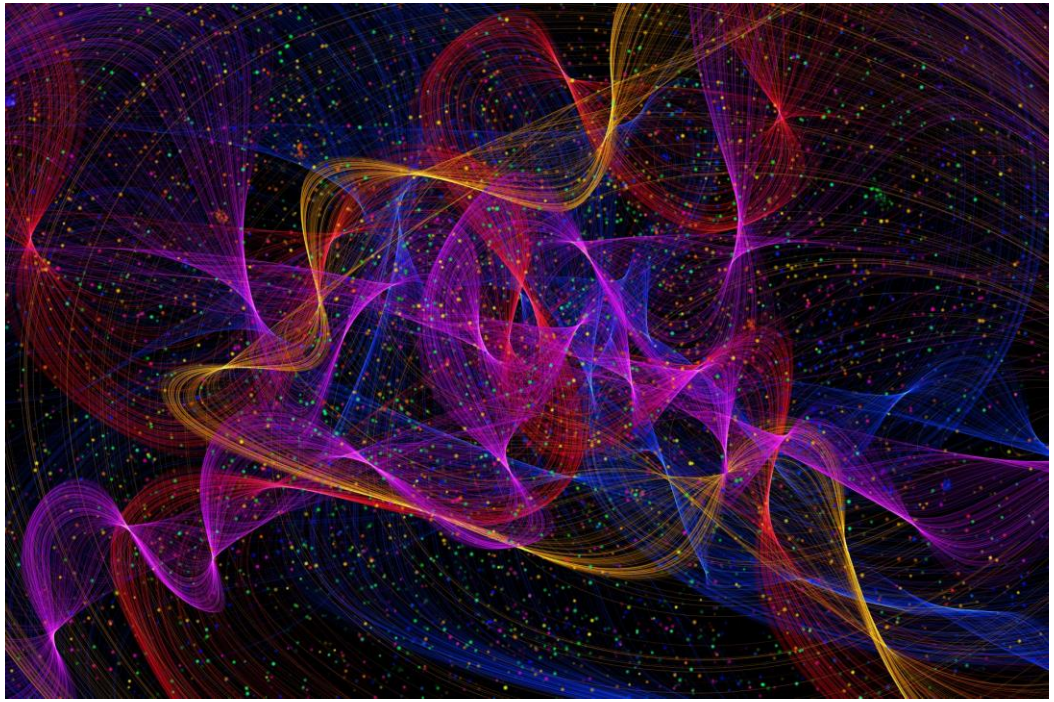
The goal of physics is to understand what are the ultimate constituents of the universe and how they behave. The mathematical objects represent real entities in the world.



Before, we implicitly assumed that physics produces approximate models of what is empirically accessible

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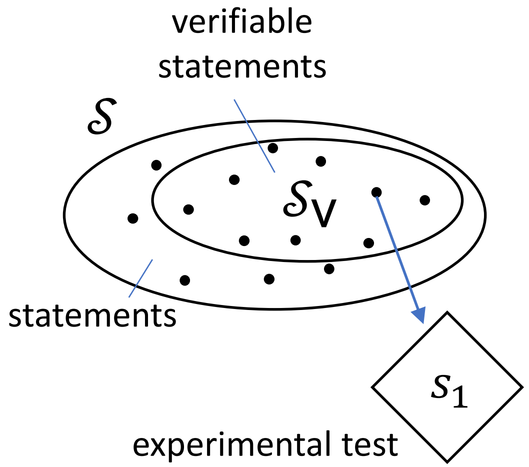
Verifiable statements: assertions that can be experimentally verified in a finite time



s_1	Test Result
T	SUCCESS (in finite time)
F	FAILURE (in finite time)
	UNDEFINED

Examples:

The mass of the photon is less than 10^{-13} eV

If I take 2 ± 0.01 Kg of Sodium-24 and wait 15 ± 0.01 hours there will be only 1 ± 0.01 Kg left

Counterexamples:

It is immoral to kill one person to save ten (not universal and/or evidence-based)

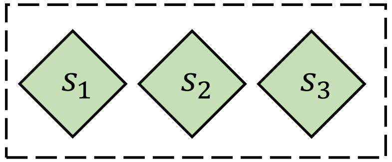
The number 4 is prime (not evidence-based)

The mass of the photon is exactly 0 eV (not verifiable due to infinite precision)

Logic of verifiable statements recovers fundamental mathematical structures (i.e. topologies and σ-algebras): all math used in physics built upon them

Finite conjunction (logical AND)

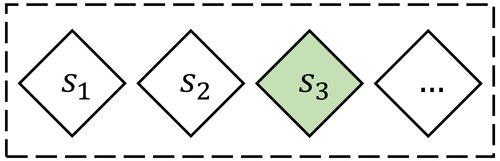
$\bigwedge_{i=i}^{n} s_i$



All tests must succeed

Countable disjunction (logical OR)

$\bigvee_{i=1}^{\infty} s_i$



One successful test is sufficient

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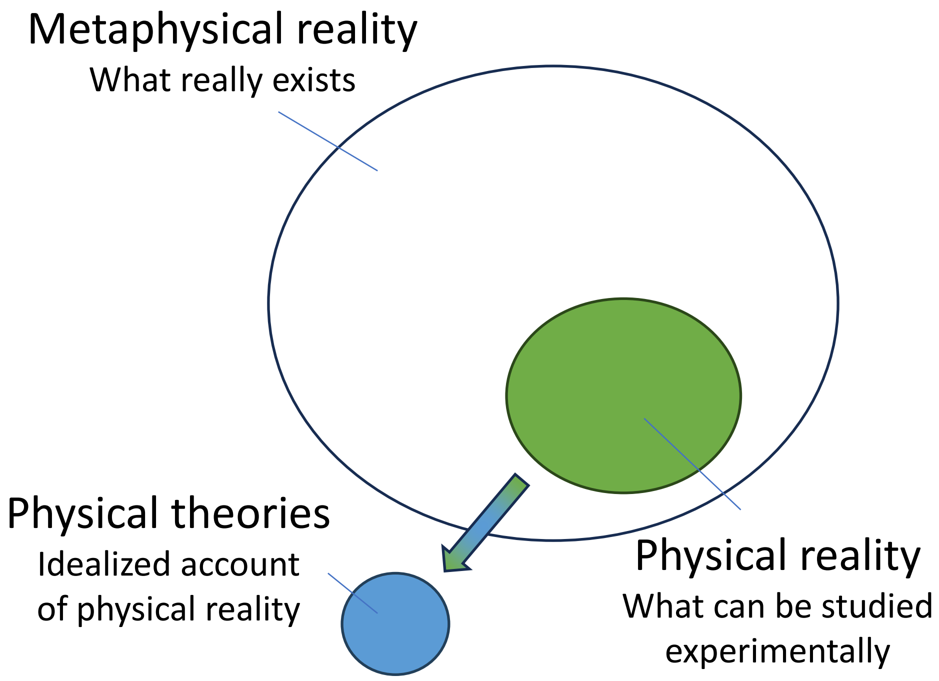
Fundamental mathematical structures capture experimental verifiability. Use of real valued quantities is equivalent to a set of highly idealized assumptions on experimentally verifiable statements.



"Correct viewpoint" because it is fruitful

Physical theories are models based on idealized verifiable statements

$\Rightarrow$

Correct mathematical structures.

The most basic mathematical structures can be derived through simple reasoning about empirical models. All this could have been developed/understood a hundred years ago. Why wasn't it?

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4.

The laws of physics are found experimentally

(not by reasoning)

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Assumptions of Physics

The laws of physics are found experimentally, not by “reasoning”. The idea that we can sit and think and determine scientific truth is preposterous.

Galileo found out that objects fall at the same rate through experimentation, not reasoning!

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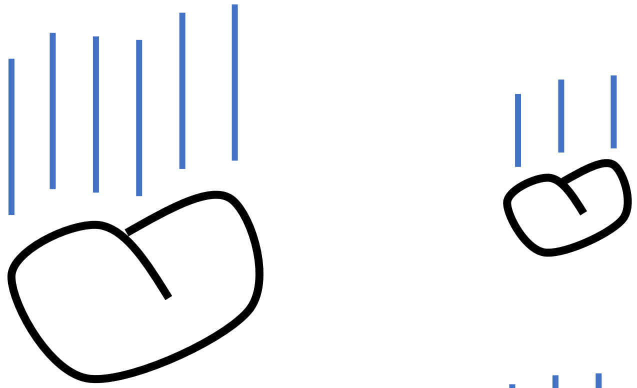
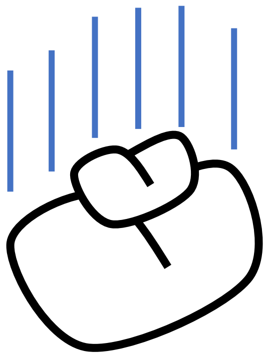
Assumptions of Physics

Suppose heavier objects fall faster than lighter ones



Suppose we connect a heavier object with a lighter



The slower object will slow the faster object and vice-versa:
the combined object will fall more slowly than the heavier part

However, the combined object is heavier than the heavier part,
so it must move faster. But this leads to a contradiction!

Heavier objects cannot fall faster than lighter ones!
We reach a stronger conclusion by arguing!

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SALV. Quando dunque noi avessimo due mobili, le naturali velocità de i quali fussero ineguali, è manifesto che se noi congiugnessimo il più tardo col più veloce, questo dal più tardo sarebbe in parte ritardato, ed il tardo in parte velocitato dall'altro più veloce. Non concorrete voi meco in quest'opinione?

SIMP. Parmi che così debba indubitabilmente seguire.

SALV. Ma se questo è, ed è insieme vero che una pietra grande si muova, per esempio, con otto gradi di velocità, ed una minore con quattro, adunque, congiugnendole amendue insieme, il composto di loro si moverà con velocità minore di otto gradi: ma le due pietre, congiunte insieme, fanno una pietra maggiore che quella prima, che si moveva con otto gradi di velocità: adunque questa maggiore si muove men velocemente che la minore; che è contro alla vostra supposizione. Vedete dunque come dal suppor che 'l mobile più grave si muova più velocemente del men grave, io vi concludo, il più grave muoversi men velocemente.

SALV. Then if we had two objects, whose natural velocities were different, it's clear that if we connected the slower with the faster, the slower would slow the faster and the faster would speed the slower. Wouldn't you agree?

SIMP. It seems it must follow.

SALV. But if that's so, and that the big stone moves, for example, with eight units of speed, and the smaller with four, connecting them, the composed system will move with a speed slower than eight units: but the two stones, connected together, will make a bigger stone than the first, that moved with eight units of speed: therefore this bigger one moves slower than the smaller; which is against your supposition. You see, then, how from supposing that the heavier object moves faster then the lighter, I can conclude that the heavier moves more slowly.

That's exactly what Galileo argued!

Can we find other lines of reasoning to justify other physical ideas?

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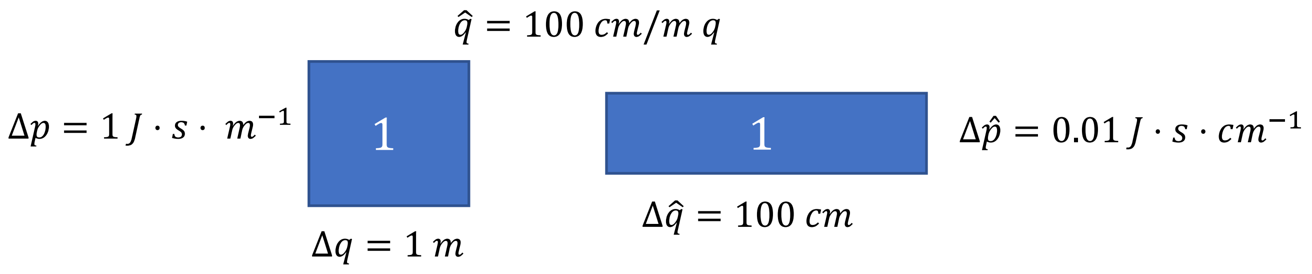
In classical mechanics, states are defined by position and conjugate momentum. Why?

In statistical mechanics, the count of configurations is given by areas of position and conjugate momentum.

Conjugate momentum is expressed in inverse units of position: product of position and momentum does not depend choice of frame. The count of states is frame invariant!



Suppose we require the count of states to be invariant ⇒ states must be described by conjugate pairs like position and conjugate momentum

⇒ classical states must be defined by position and conjugate momentum because this is the only way that we can define state count, entropy, probability densities, determinism and reversibility, information, … in a way that it is objective, the same for all.

Looking at the math closely, we can find conceptual reasons for a lot of physics… so why isn't this done more?

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5.

Mathematical details are for mathematicians to worry about

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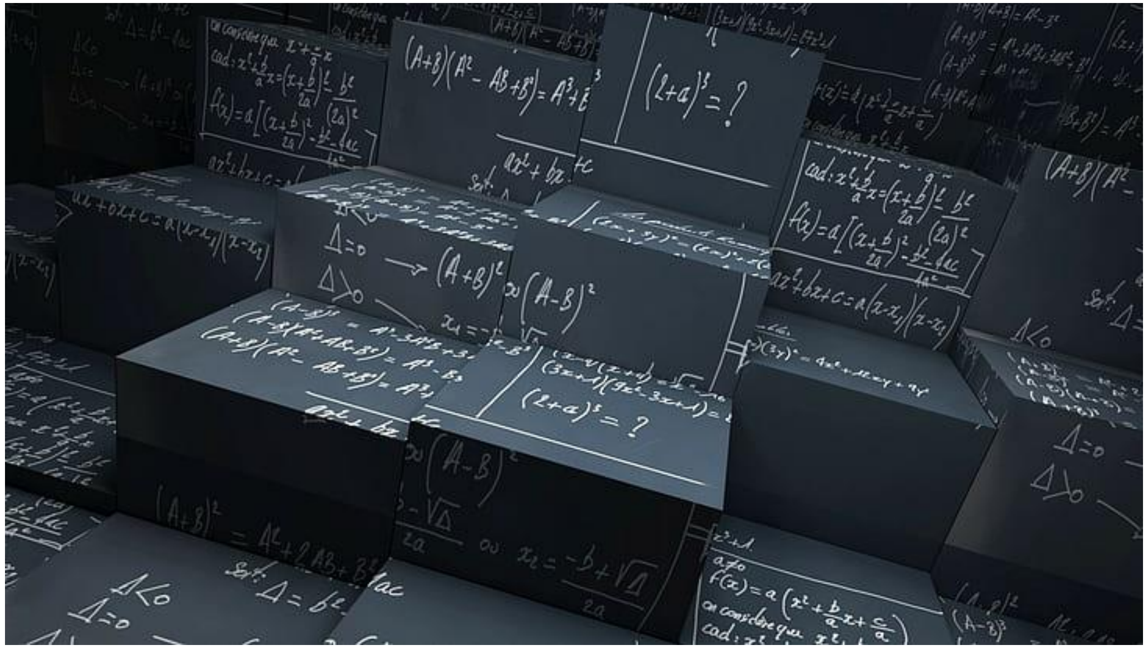
Mathematics is full of technicalities that are uninteresting to the physics. It’s the job of the mathematician to find the correct formal framework and fix the details.



In the same way that the mechanical engineer, electronics engineer, software engineer, … will fix the details of the experimental setup

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Assumptions of Physics

But the mathematics is not just a tool for calculation: it is the language we use to formalize our physical models. How can mathematicians, who are typically not trained in physics, know what the correct features of our physical models are?

In quantum mechanics

State ⇒ ray in a Hilbert space

$$\psi \in P[\mathcal{H}]$$

Observable ⇒ Hermitian operator

$$O : \mathcal{H} \to \mathcal{H}$$

Unbounded operators cannot be defined on the whole Hilbert space ⇒ There exists some state for which some quantity (e.g. position, momentum, energy, number of particles, …) is infinite or not defined!

$$E[X|\psi] = +\infty$$

Physically untenable. Mathematical details ARE physically important! Why don't we have part of the physics community specifically working on developing physically and mathematically sound tools?

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Assumptions of Physics

6.

There is only one correct way to do mathematics

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In the same way that there are correct laws of physics, there is correct math. Mathematicians discover the correct structures, organize them, so they will be able to take prototype theories from us physicists and give us the correct structure.

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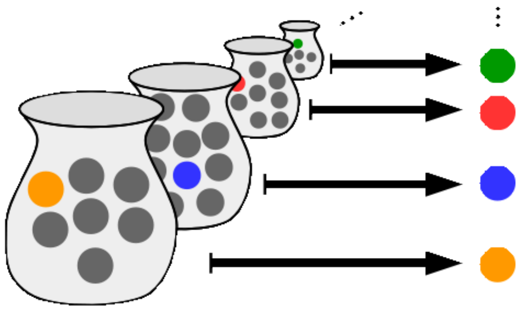
In reality: mathematics is based on axioms and definitions chosen based on specific goals (of mathematicians).



Axiom of Choice

Accept

Reject

What can be formally defined

Existence of objects that cannot be written down with finitely many symbols

E.g. well-ordering of the reals

What can be computed

Non-existence of objects useful in physics

E.g. the real numbers

In physics we care about what can be experimentally identified. Not only is there more than one correct way to do mathematics, the one physicists are interested in may not be one that mathematicians care about!

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7.

A theory of everything is the right foundation for physics

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A theory of everything will tell us what happens during measurements (1), in terms of some mechanism (2) describing the most fundamental objects of the universe (3). Since the correct theory is determined experimentally (4), we should focus on building rough prototypes. In the end, the mathematical detail is irrelevant (5) and mathematicians will later find the correct formulation (6).

What should the foundations of physics be about?

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Assumptions of Physics

Foundations of mathematics

Define the basic objects and rules (e.g. mathematical logic, set theory) used to do mathematics. Give a formal framework for what can be achieved in mathematics (e.g. proof theory).

⇒ Limits on mathematics: every formal system that is complex enough to describe the natural numbers will contain statements that are not provable.

Foundations of computer science

Define the basic objects and rules used to perform computation (e.g. theory of computation, information theory). Give a formal framework for what can be achieved by a computer (e.g. complexity theory).

⇒ Limits on computer science: no general algorithm exists to determine whether a program will terminate or not

Foundations of physics?

Define the basic objects and rules used to characterize physical systems. Give a formal framework for what can be achieved through experimentation.

⇒ Limits on physics?

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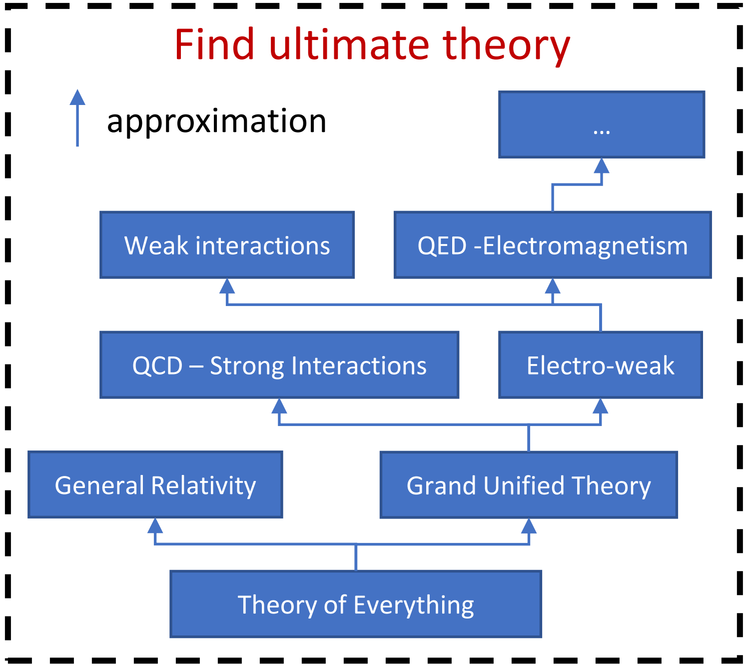
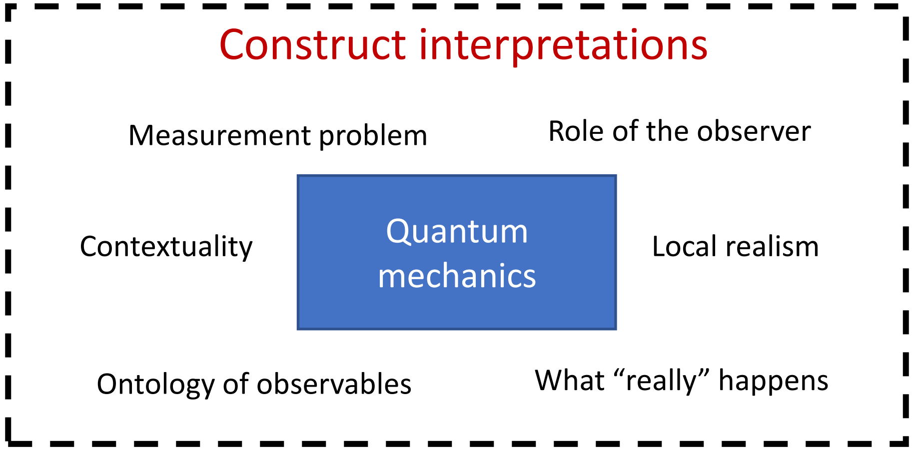
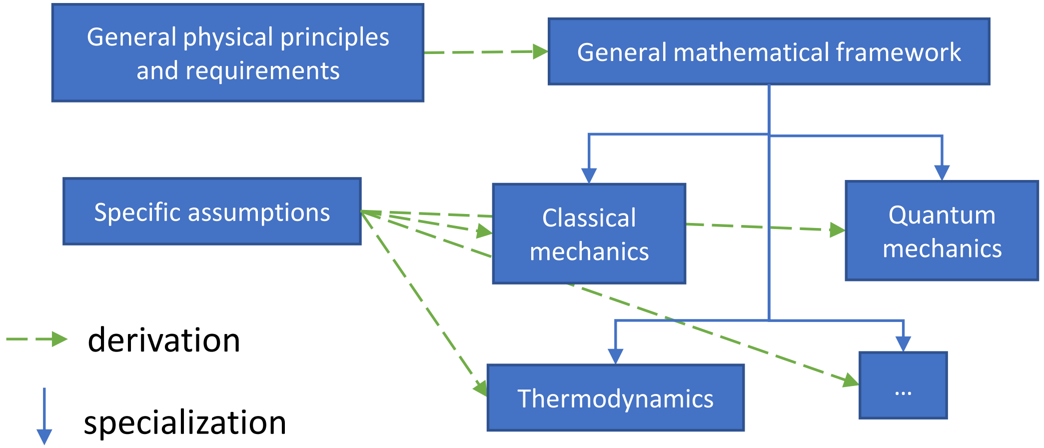
Typical approaches





Our approach

Find a minimal set of physical assumptions from which to rigorously rederive the laws



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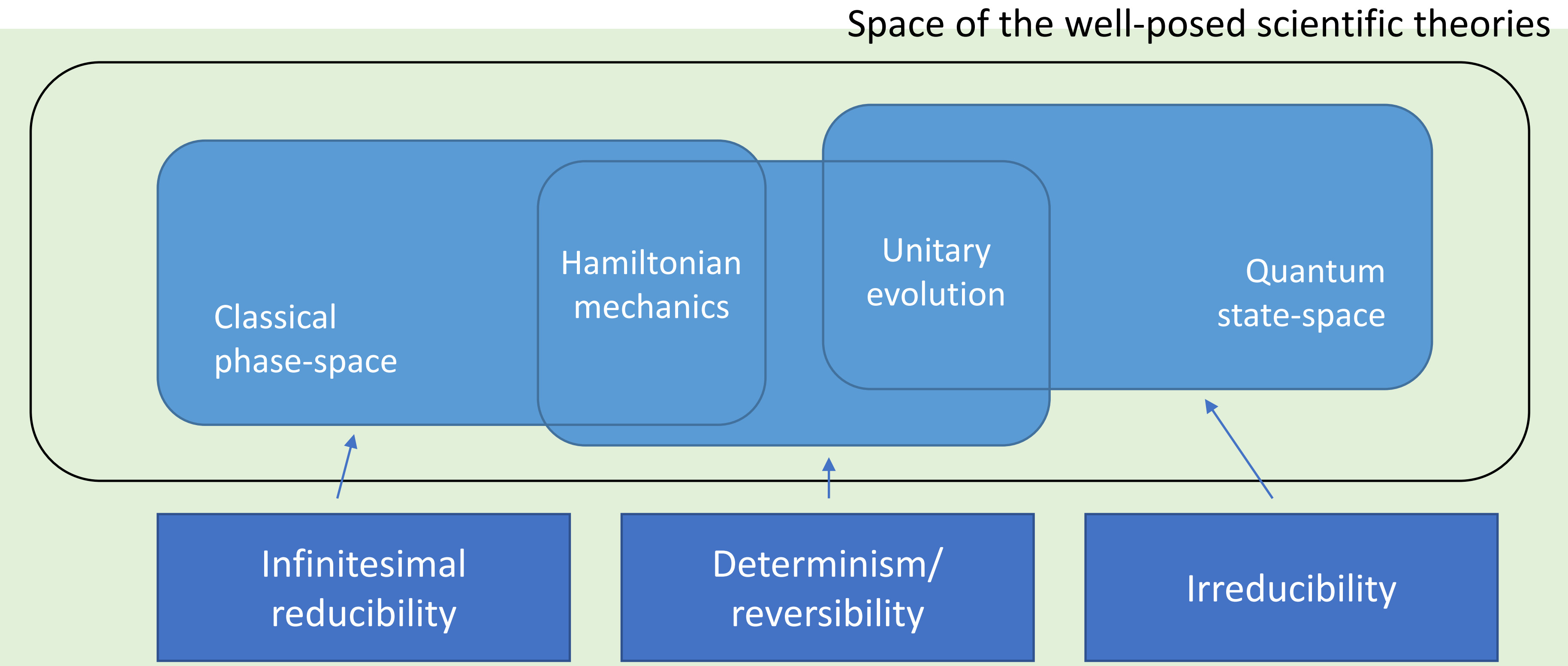

Physical theories

Specializations of the general theory under the different assumptions

Assumptions

States and processes

Information granularity

Experimental verifiability

General theory

Basic requirements and definitions valid in all theories

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We can give physics a more mathematically precise, conceptually consistent and physically meaningful foundation if we overcome these misconceptions

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