What is Space? From Newton-Leibniz debate to Einstein

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Why do we do physics?

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Plato vs. Isocrates: Two Schools, Two Visions

Isocrates – School of Practice (393 BCE) *"Let's be practical!"*
Plato – "The Academy" (387 BCE) *"Let's seek the truth!"*

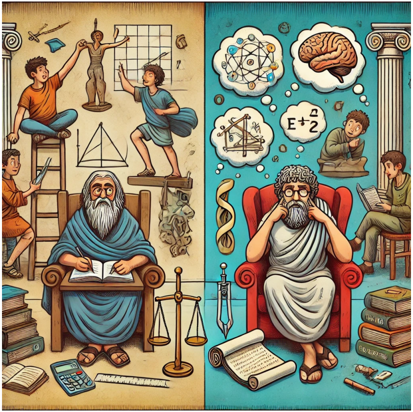


Figure: Isocrates' School vs. Plato's Academy

Isocrates' School:

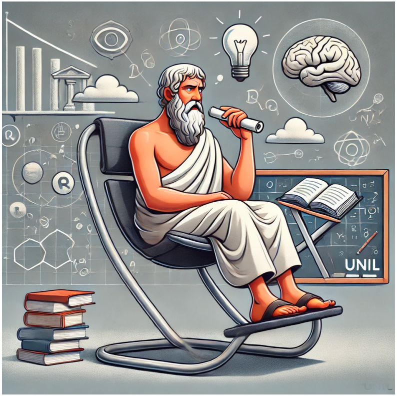
- Practical and concrete teaching
- Goal: Prepare young people for responsibilities in society

Figure: Isocrates' School

The Two Schools: Isocrates vs Plato

Plato's School (Academy):

- Discussions on big questions: "What is matter made of?" "What is space?" "What is time?"
- Invention of the word *philosophy* for this way of posing problems



The Role of Philosophy in Physics

The role of philosophy in Physics:

- **General Philosophy of Science**: The analysis and development of scientific methodology.
- **Philosophy of Physics**: Examining the foundations of physical theories.

What happens if we ignore philosophy?

Without Philosophy, Science Wanders in the Dark

Without Philosophy of Science: Lack of clear methodology $\rightarrow$ *"Science without philosophy of science wanders in the dark."*

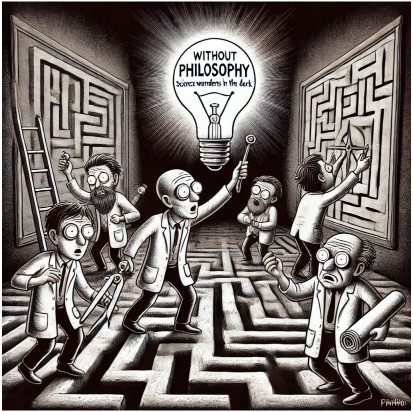


Figure: Without philosophy, science wanders in the dark.

The Role of Philosophy in Physical Theories

- **Without Philosophy of Physics:** Stagnation in physics $\rightarrow$ trapped in the "ideology" of current theories, without conceptual advances.

"A knowledge of the historical and philosophical context provides this kind of independence from the prejudices of one's era, from which most scientists suffer. This independence, created by philosophical insight, is—in my opinion—what distinguishes a mere craftsman or specialist from a true seeker of truth."

– Albert Einstein

Questions in Philosophy of Physics

Examples of fundamental questions:

- What is space? Is it an entity or a relation?
  (This is a question we will analyze in this lecture.)
- Is the passage of time an illusion or a fundamental reality?
- Is the world deterministic or indeterministic?
- What is the nature of physical laws? Are they fundamental or emergent?

What is Space?

The goal of this lecture: Show how asking conceptual questions is crucial for the advancement of physics.

Example: What is Space?

- What is space? Is it an independent entity or a relation between objects?
- What ontological role does the concept of space play in a physical theory?
- Does Newton's absolute space have physical reality, or is it simply a mathematical abstraction?

Space as an **Entity**

Space as an entity:

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- It exists where there are no entities in the universe.
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Interesting questions to ask:

- Why did Newton introduce an absolute space in his theory?
- Can we construct a dynamical theory without using an absolute space in its formulation?

Space as a **Relation**

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Examples of relations:

- For Descartes: "**touchness**" or "**contingency**" relations.
- For Leibniz: **distance** relations (e.g. ratios of distances).

Newton's substantivalism vs. Leibniz's relationalism

Two *metaphysical positions* toward space:

- **Substantivalism (e.g. Newton)**: Space exists independently of matter
- **Relationism (e.g. Leibniz)**: Space only emerges as a set relations between objects

Absolute motion vs Relative motion

The two manners of understanding **space** imply two manners of understanding **motion**:

- **Absolute motion**:
  - If space is an **entity**, motion can be defined as going from one part of space to another.
  - E.g., as defined by Newton.

Absolute motion vs Relative motion

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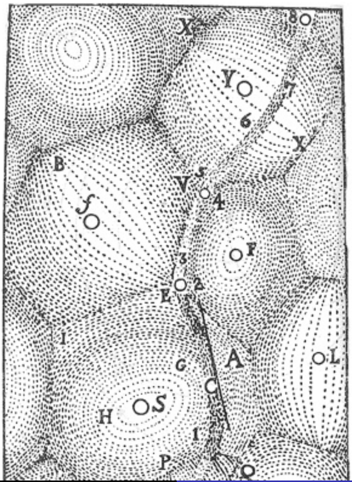
- **Absolute motion**:
  - If space is an **entity**, motion can be defined as going from one part of space to another.
  - E.g., as defined by Newton.
- **Relational motion**:
  - If space is a **relation**, motion can only be defined according to the relations between physical entities that define relational space.

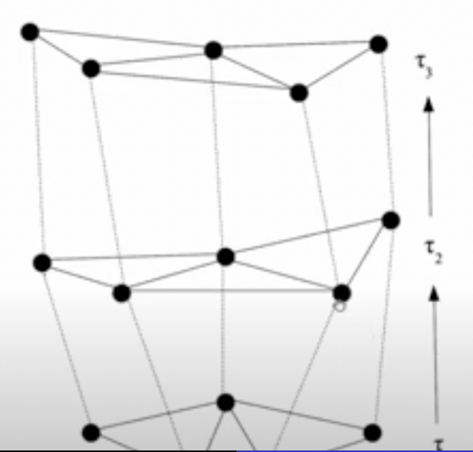
Descartes on Motion

- Motion is going from the **contiguity** of one object to the **contiguity** of another.



Leibniz on Motion

- Motion is the change of **spatial relations** between physical entities (e.g., change of distance ratios between physical entities).



Leibniz's shift arguments

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- Principle of sufficient reason (PSR): "There out to be a sufficient reason why things should be so, and not otherwise"
- Principle of identity of indiscernibles(PII): "To suppose things indiscernible is to suppose the same thing under two names"

Absolute space as a surplus structure?

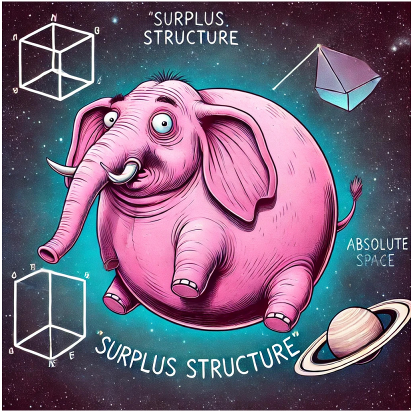

Figure: Absolute space as a surplus structure?

Static Shift Argument

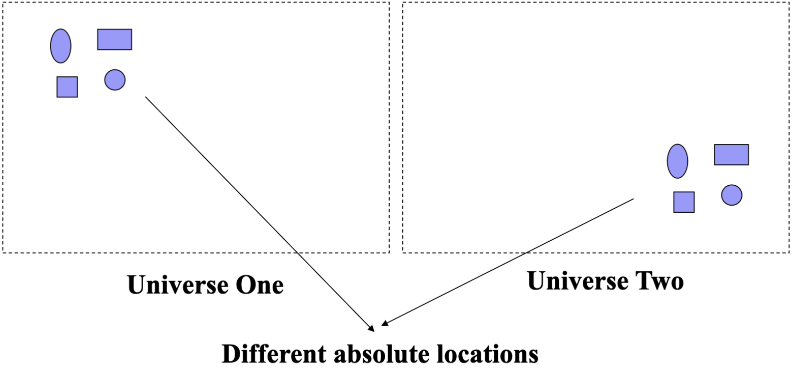

Figure: Leibniz's Static shift argument

Kinematic Shift argument

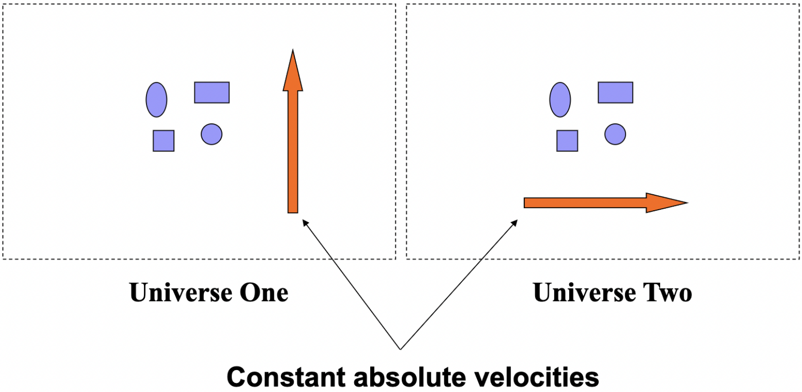

Figure: Leibniz's Kinematic shift argument

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- For a theory of absolute space (Newtonian theory for example): The two unviverses are not identical because the position in absolute space is different in the two universes.
- Leibniz's debate with Newton: Newton is committed to more structure than required by classical mechanics. **How would Newton reply to that?**

Dynamics and Relationalism

- Newton will justify the suprlus structure of absolute space by its role it plays in explaining dynamics, more precisely in explaining physical effects of acceleration
- Newton needed absolute space for the foundations of dynamics.
- F=ma becomes ill-defined without an absolute notion of acceleration.

Dynamics and Relationalism

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- Newton needed absolute space for the foundations of dynamics.
- F=ma becomes ill-defined without an absolute notion of acceleration.
- Challenge for a relationalist approach to dynamics: One should redefine all motions relationally, including accelerations.

Leibniz's Argument Against Absolute Space

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- While addressing the metaphysical status of absolute space, he overlooked its physical necessity for defining dynamics.
- The door remains open for relationalists, hinting at the need for **Machian relationalism**

Mach and relationalism

Figure: Mach (1838-1916)

- **Mach's Perspective**: Local inertial effects arise from relative motion with the universe's matter distribution, not absolute motion in an absolute space.

Machian Relationalism

- **No Absolute Space**: Motion and inertia have meaning only in relation to other bodies.
- **Relativity of Inertia**: The inertial frame is determined by the mass distribution of the universe, not by a background space.
- **Against surplus structure**: Physical laws should be formulated without referring to unobservable entities (like absolute space).

Machian Relationalism

- **No Absolute Space**: Motion and inertia have meaning only in relation to other bodies.
- **Relativity of Inertia**: The inertial frame is determined by the mass distribution of the universe, not by a background space.
- **Against surplus structure**: Physical laws should be formulated without referring to unobservable entities (like absolute space).
- Anticipates Einstein's search for a theory where spacetime structure *is linked to matter* (general relativity).

From Newton to Einstein

"It required a severe struggle (For Newton) to arrive at the concept of independent and absolute space, indispensible for the developement of theory... Newton's decision was, in the contemporary state of science, the only possible one, and particularly the only fruitful one. But the subsequent developement of the problems, proceeding in a roundabout way which no one could then possibly foresee, has shown that the resistance of Leibniz and Huygens, intuitively well-founded but supported by inadequate arguments, was actually justified... it has required no less strenuous exertions subsequently to overcome this concept (of absolute space)" (A. Einstein (1954) Preface to concepts of space)

From Newton to Einstein

"Newton, forgive me; you found the only way which, in your age, was just about possible for a man of highest thought and creative power."

- **Problem with absolute space**: It is unobservable surplus structure.
- **Einstein's move**: Reinterpret inertia and gravity without appealing to an absolute backdrop.
- **Guiding idea**: Equivalence Principle — locally, inertia and gravity are the same phenomenon.

What Einstein Questioned

- Newton took inertial effects to reflect absolute space.
- Einstein: inertial effects reflect properties of a physical field, not a background arena.
- Goal: Formulate mechanics so that inertial structure arises from interactions, not from absolute space.

Equivalence Principle: Inertia = Gravity (locally)

- In a small freely falling lab, gravity disappears: all bodies fall alike.
- No local experiment can distinguish uniform acceleration from a uniform gravitational field.
- **Moral**: What we call "gravitational force" is tied to the choice of frame; locally one can find an inertial frame.

Metric Field = Gravitational Field

- Spacetime is equipped with a metric $g_{\mu\nu}$ read by rods and clocks.
- Free motion follows **geodesics** of $g_{\mu\nu}$ (no forces needed).
- What was "gravity" becomes geometry: curvature, not a pull through space.

Dynamics: Matter $\to$ Curvature

- Einstein equations: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$.
- Matter–energy determines the metric; the metric determines inertial motion.
- Inertial effects are explained as local physical interactions with the gravitational (metric) field.

Removing Surplus Structure

- **Before**: Inertia referenced an unobservable absolute space.
- **After**: Inertia arises from the state of the metric field sourced by matter–energy.
- **Net effect**: Background absolutism is replaced by a dynamical spacetime.

Einstein and Mach: How Far?

- **Machian spirit**: Inertial structure should depend on the mass distribution.
- **GR outcome**: Often compatible (e.g., frame dragging shows matter influences local inertia).
- **But not total**: GR admits solutions with little or no matter (e.g., near-empty spacetimes), so it is only partly Machian.

Takeaway

- Equivalence Principle unifies inertia and gravity locally.
- Metric = gravitational field; free motion = geodesics.
- Dynamics: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$ ties geometry to matter.
- **Conceptual shift**: From absolute space to dynamical spacetime explaining inertial effects physically.

Summary

We have illustrated the role of a philosophical debate in the conceptual advancement of physical theories. **Without** a philosophical debate, physical theories **stagnate** in the 'ideology' of current theories. Here is a summary of the conceptual development in the theory of dynamics since Newton, thanks to the philosophical debate on the nature of space:

- **Newton (17th century)**:
  - Introduced absolute space in his theory.
  - Defended absolute space due to its necessity in formulating *dynamics*: The physical effects of acceleration cannot be explained solely by relative motion (*bucket argument*).

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- **Newton (17th century)**:
  - Introduced absolute space in his theory.
  - Defended absolute space due to its necessity in formulating *dynamics*: The physical effects of acceleration cannot be explained solely by relative motion (*bucket argument*).
- **Leibniz's Response (17th century)**:
  - Leibniz's *shift* argument criticized Newton's redundant structure.
  - Defended the principle of the identity of indiscernibles (PII).
  - Although philosophically sound, Leibniz lacked a dynamic theory to support his arguments.

Summary

- **Mach's Contribution (19th century)**:
  - 300 years later, Mach provided a relational explanation of inertial effects.
  - Argued that inertial effects are due to relative motion with respect **to the distribution of matter in the universe**, and **not** to absolute space.
- **Einstein (1916)**:
  - Eliminated absolute space and replaced its effects with local interactions with the gravitational field, thus removing the redundant structure of an "absolute space."
  - It is a local theory and our best theory of classical dynamics. **Is there a redundant structure in general relativity?** This remains an open question in the philosophy of physics. (And could be a good essay question)

Space and Time: An Invitation

I hope this lecture sparked your curiosity.

Ready to dive deeper into the philosophy of space and time?

Projects related to Philosophy of Space and Time

Section 8: Philosophy of Space and Time

8.1 The Nature of Space and Time: Substantivalism, Relationalism, and Super-Substantivalism

8.2 The Direction of Time

8.3 Time Reversal and Time-Reversal Invariance

8.4 Space-Time in General Relativity