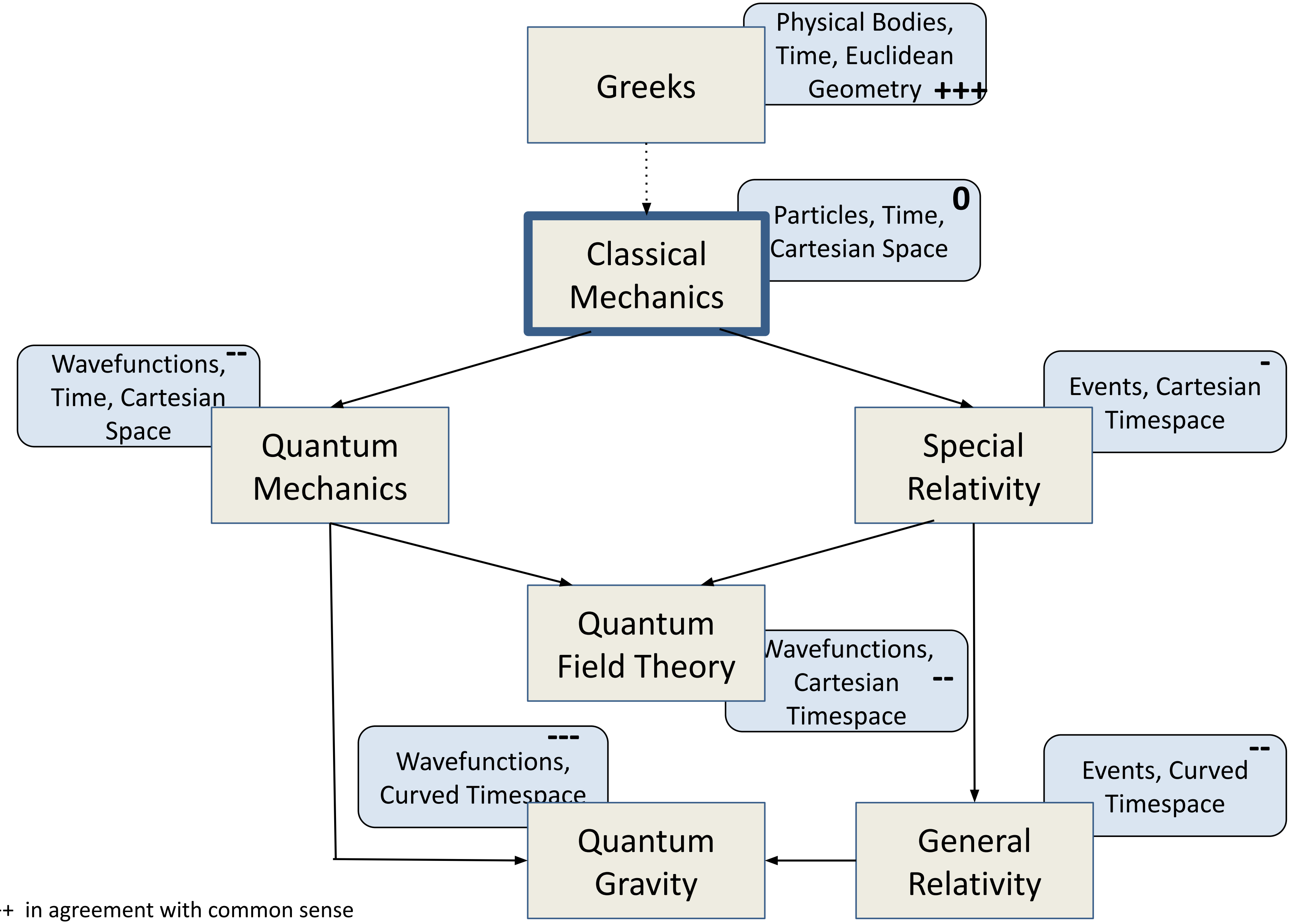
A Roadmap of Physics

Johannes Siedersleben, Oxford, July 2022

- A Roadmap of Physics
- The Greeks
- Classical Mechanics
- Special Relativity
- General Relativity
- Quantum Mechanics
- Quantum Field Theory and Quantum Gravity
- Some Books

A Roadmap of Physics (part of it)



+++ in agreement with common sense

--- in disagreement with common sense

The Greeks (some of them)

- **Anaximander (610 – 547)** is the founder of natural science, the first to think scientifically, according to Carlo Rovelli.

- **Democrit (460 – 370)** invented a theory of atoms without providing any evidence.

- **Aristotle (384 –322)** got it all wrong. His idea was that of objects tending to come to a rest.

- **Euclid (365 – 300)** amazing, compiled (most of) Greek geometry. Valid and virtually flawless to this day. Still THE pattern of mathematics.

- **Aristarchos of Samos (310 – 240)** computed the size of the moon using trigonometry.

- **Archimedes (287 – 212)** found the law of the lever, invented hydrostatics, anticipated modern calculus, and did a lot more. Considered the leading scientist of antiquity.

- **Eratosthenes (276 – 194)** computed the circumference of the Earth (using trigonometry).

Classical Mechanics

- **What's the Problem:** How do particles move in a field (spring, gravitational field, electric field, magnetic field, …) and how do particles affect the field?

- **Principle of Least Action (amazing, this principle rules the world!)**
  - The *Lagrangian* defines the effort caused per unit of time
  - The *action* is the accumulated amount of effort over time
  - The principle says: Every system minimizes the action □ Equations of Motion *(Euler-Lagrange, Hamiltonian)*

- **Principle of Relativity** (sic): Speed is relative and symmetric (you cannot tell which train is moving). There is no absolute rest *(Galileo Transformation)*

- **Consequences:**
  - Conservation of Momentum (*Newton's Laws*)
  - Conservation of Energy (*Energy = the Hamiltonian*)
  - Conservation of Information (*Theorem of Gibbs-Liouville)*

Special Relativity

- **What's the Problem?**
  - Given two observers A and A' travelling on a straight line at a high constant relative speed, what observations would they agree on?

- **Principles of Least Action, of Relativity** still hold.

- **Principle of Nonrelativity** (sic): The speed of light is the same for all observers.

- **What Einstein discovered or did in a few months**:
  - The *Lorentz-Transformation* transforms the observations of A into those of A‘ and vice versa.
  - A and A‘ would agree on *events* (= light beams, proper time)
  - He rewrote classical mechanics by replacing time t with proper time τ. Maxwell's equations happened to be Lorentz-invariant.

- **Consequences:**
  - Conservation laws still hold
  - Time dilation, length contraction, order of events shuffled
  - Equivalence of mass and energy

General Relativity

- **What’s the Problem?**
  - Given two observers A and A' travelling on a curved line at a high non-constant relative speed, what observations would they agree on?
  - Gravity not taken into account by special relativity.

- **Principles of Least Action, of Relativity, of Nonrelativity** still hold.

- **A New Principle**: Inertia and gravity are indistinguishable (elevator, ISS, see next slide)

- **What Einstein did single-handedly in 10 years**:
  - He used tensor calculus to transform the observations of A into those of A‘ and vice versa.
  - He rewrote special relativity (and thus classical mechanics) by replacing the Lorentz-Transformation with his calculus.

- **Consequences:**
  - Conservation laws still hold.
  - Space is curved, what appears as gravity is a centrifugal force caused by that curvature. Gravity does not occur in space, but space itself is gravity.

A Note on Trains, Elevators, and Spaceships

- **Train**
  - You cannot tell which train is moving.
  - You cannot measure speed without looking out of the window.

- **Elevator**
  - Inside an elevator, you cannot tell gravitational force from acceleration/deceleration
  - Inertia and gravitation are indistinguishable.

- **Spaceships, or: Why do astronauts float?**
  - Gravity amounts to 99.7% of what it is on the ground at 10 km altitude (aeroplane), 89% at 400 km (ISS) and 2% at 35.786 km (geostationary satellites).
  - The ISS orbits the Earth 15.6 times per day, a geostationary satellite exactly once. The speed is such that the centrifugal force compensates exactly the remaining gravity (89% or 2% resp.).
  - Astronauts cannot distinguish between gravity and centrifugal force (= acceleration). Their levitation is mostly due to centrifugal force.

Quantum Mechanics

- **What’s the Problem?**
  - Particles smaller than the wavelength of light behave strangely. How to interpret the double slit experiment?

- **What the Quantum people did in over 10 years**:
  - Replacing particles with wave functions (□ “Hilbert Space”)
  - Replacing the Hamiltonian with a “unitary operator”
  - Replacing observable values (e.g. position, momentum) with “Hermitian operators”, the *Observables* of Quantum Mechanics.
  - Rewriting the equations of motion in the new terms.

- **Consequences:**
  - The *Hamiltonian Equation* becomes the *Schrödinger Equation*
  - Conservation laws still hold, in particular the conservation of information (this is what is behind "unitary").
  - **New**: Heisenberg’s uncertainty principle tells us to what extent two observables are exclusive.
  - **New**: Entanglement (unfathomable, interpretation still being debated)

Quantum Field Theory and Quantum Gravity

- **What's the Problem?**
  - How to unify the divergent theories of quantum mechanics and relativity?

- **Quantum Field Theory**
  - Dirac's equation (1928) unifies Quantum Mechanics and Special Relativity.

- **Quantum Gravity**
  - This is the attempt to unify Quantum Mechanics and General Relativity (String Theory, Loop Theory, …).
  - Applies to Cosmology, Black Holes and all the rest
  - Under construction, highly debated

Some Books (1)

Albert Einstein

On Special and General Relativity (G, M)

Carlo Rovelli

Anaximander (G)
Seven Lectures on Physics (G)
Helgoland (G)
General Relativity: The Essentials (MM)

Leonard Susskind

Classical Mechanics (MM)
Quantum Mechanics (MM)
Special Relativity and Field Theory (MM)
General Relativity (MM)
The Black Holes War (C, G)
The Cosmic Landscape (C, G)
The Stanford Lectures (Website, MM)

Richard Feynman

The Character of Physical Law (G)
Lectures of Physics, I – IV (MM)

G	General public
C	Cosmology
M	Little maths
MM	A great deal of maths
MMM	For professionals only

Some Books (2)

Brian Green
The Hidden Reality (C, G)

David Deutsch
The Fabric of Reality (C, G)
The Beginning of Infinity (C, G)

Max Tegmark
Our Mathematical Universe (C, G)

Lawrence Krauss
A Universe from Nothing (C, G)

Frank Wilczek
Ten Keys to Reality (G)

Lee Smolin
The Trouble with Physics (G)

Tom Lancaster, Stephen Blundell
Quantum Field Theory for the Gifted Amateur (MM)

Roger Penrose
The Road to Reality (MMM)

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Some Variables and Functions

Abbreviation	Formula	Dimension	Long Name
x		m	position
m		kg	mass
t		s	time
v	x dot	m/s	velocity
a	x dot dot	m/s^2	acceleration
F	m * a	kg * m / s^2	force
p	m * v	kg * m / s	momentum
T(v)	m * v^2 / 2		kinetic energy in terms of v
T(p)	p^2 / (2 * m)		kinetic energy in terms of p
V(x)			potential energy depending on the field
L(x, v)	T(v) - V(x)		a typical Lagrangian
H(x, p)	T(p) + V(x)		a typical Hamiltonian