What Happens at Shorter Distances?

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Different disciplines for different scales – cars

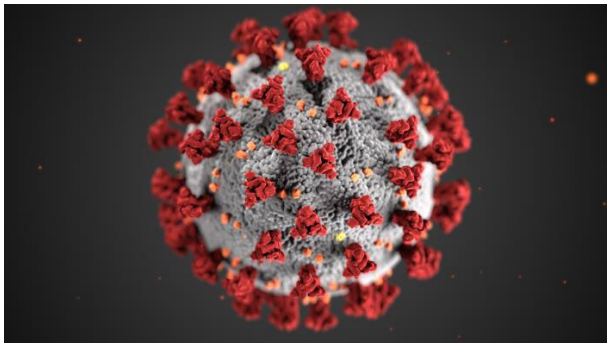
- Building an engine

- Driving a car

- Traffic control

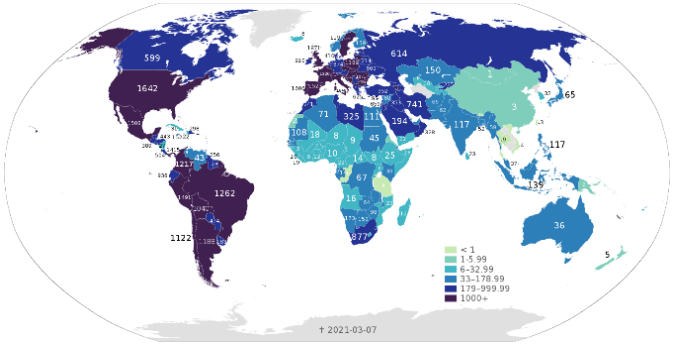
Different disciplines for different scales – COVID-19

- Details of the virus



- Transmission between individuals

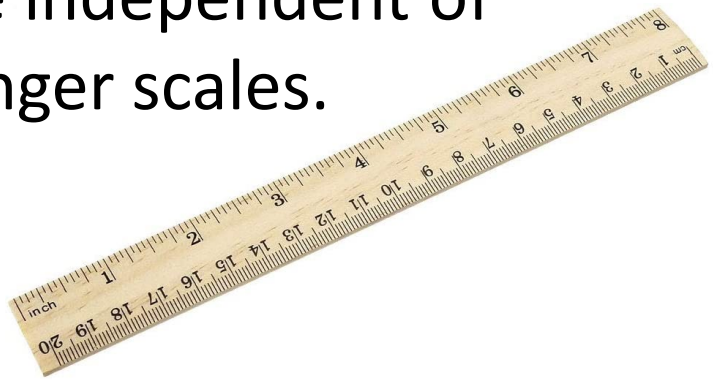
- Spreading of the pandemic



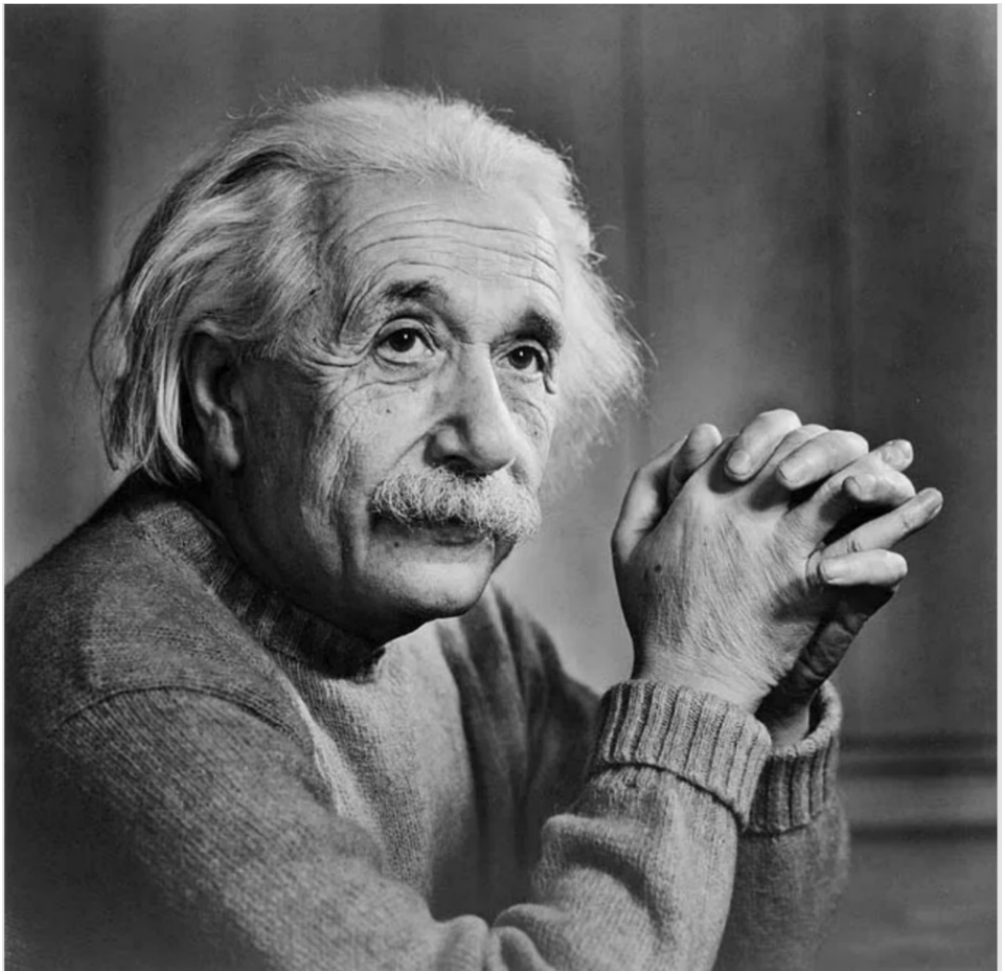
Separation of scales

Nature has a hierarchical structure.

Phenomena at one length scale are independent of most of the details at shorter or longer scales.



- No need to understand simultaneously all the details at all scales. Study Nature one scale at a time.
- Otherwise, it would have been impossible to understand Nature.
- Nature is kind to us – it did not have to be so simple.

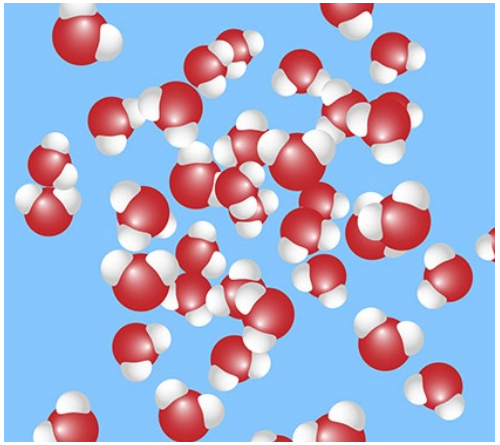


Subtle is the Lord, but malicious He is not.

– Albert Einstein (April 1921)

Separation of scales – Hydrodynamics

- Water molecules



- Flow of water

Separation of scales – Reductionism

Over the past centuries, scientific research has progressed in a two-way approach

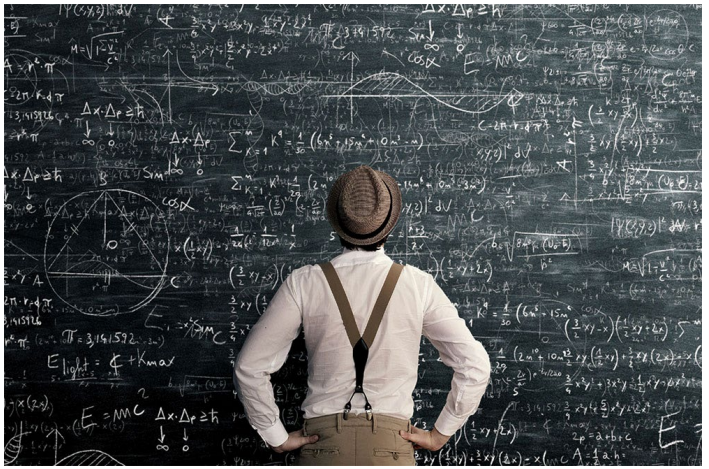
- Gradually uncovering deeper and more fundamental laws of Nature at shorter length scale
- Using these laws to learn about new phenomena at longer length scales

We refer to the description at long distances as an effective description. It is approximate, but effective.

Separation of scales – Reductionism

Progress happens in the two directions.

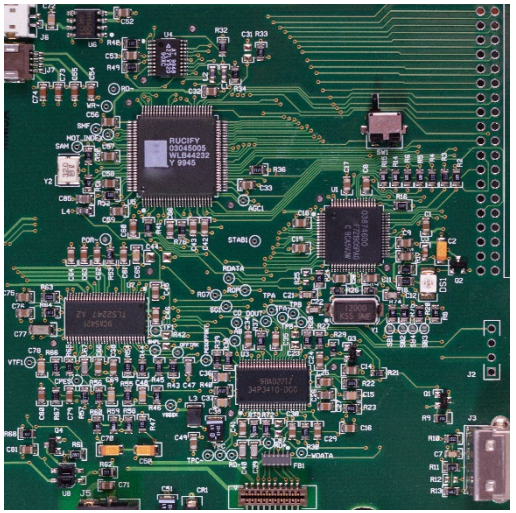
- The long-distance (macroscopic), effective description gives us clues motivating the search for the more fundamental (microscopic) rules.
- The short-distance (microscopic) theory is used to derive long-distance phenomena
  - Tests of our short-distance understanding
  - Finding new phenomena



Beauty of science

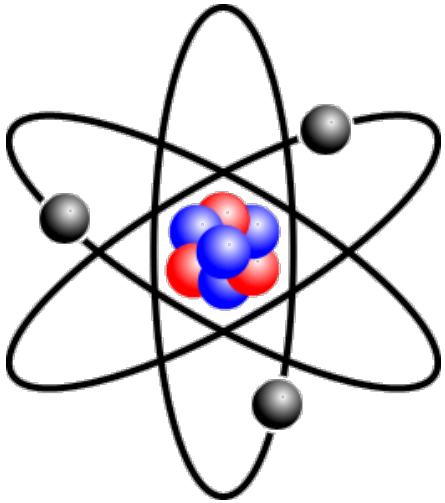
- Simple underlying laws
- Rich and complicated consequences
- These are not independent lines of research. There is an interesting interplay between them.

- And of course, there are technological applications.



Condensed Matter Physics and Chemistry – properties of materials

- Atoms and their quantum behavior at 10^{-10} meters

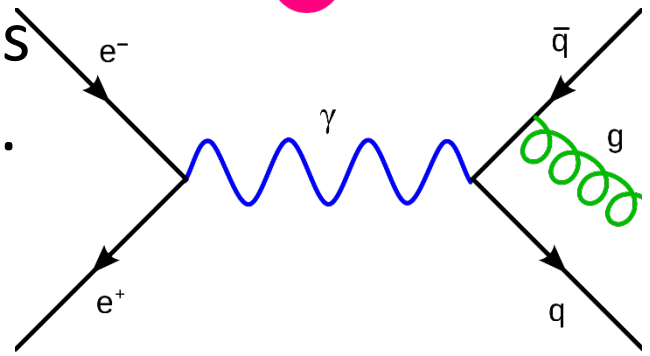


- Huge number of different materials exhibiting interesting and useful properties

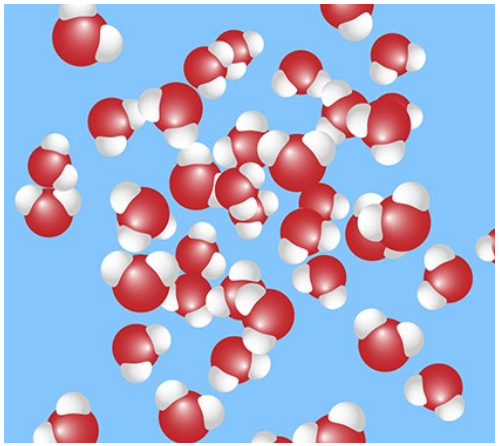
High Energy Physics – matter and forces

- Still unknown description at shorter distances, $\leq 10^{-18}$ meters

- The Standard Model of Particle Physics describes electrons, quarks, photons… At distances $\geq 10^{-18}$ meters



- Very good understanding between $10^{-18}m$ and $10^{-10}m$. (At larger distances, we follow Condensed Matter Physics and chemistry to find all the matter around us.)

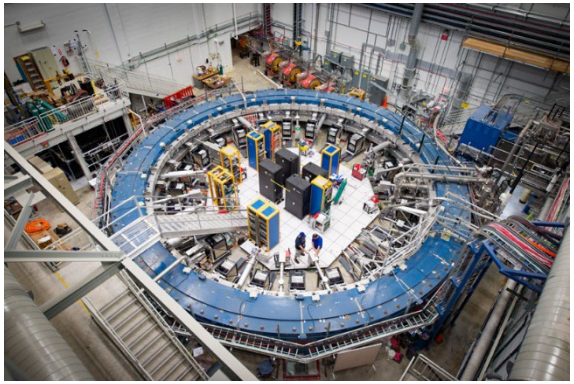


High Energy Physics – matter and forces

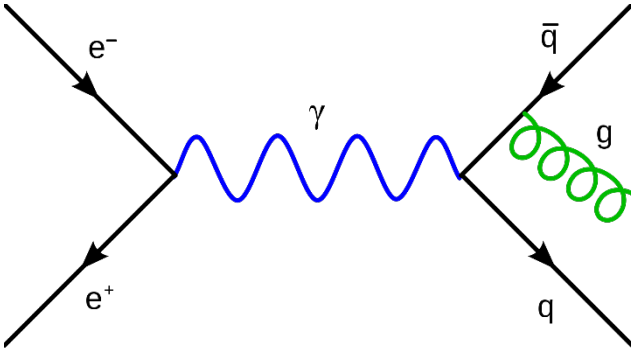
- Still unknown description at shorter distances, $\leq 10^{-18}\ m$
- Need better resolution

- Higher energy accelerators – Large Hadron Collider (LHC) and future colliders

- Precision measurements at relatively longer distances



Condensed Matter Physics and High Energy Physics



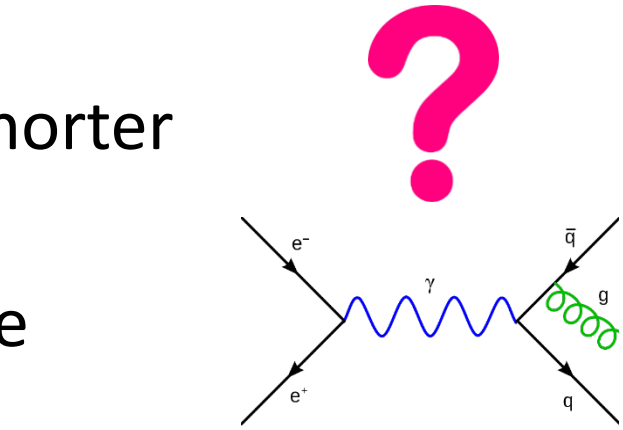
- The primary goal of CMP is to find new phenomena by using the known laws at distances $\geq 10^{-10}m$.
- The primary goal of HEP is to uncover new laws of Nature at short distances $\leq 10^{-18}m$.
- Surprisingly, these two disciplines are formulated using the same mathematical language.

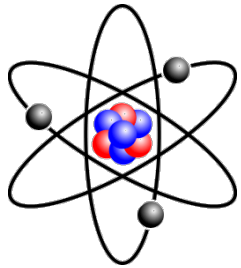
There's a school of philosophy of science associated in particular with the name of Thomas Kuhn, that sees the development of science – particularly of physics – as a series of paradigm shifts in which our point of view changes so radically that we can barely understand the theories of earlier times. I don't believe it for a minute. I think our successful theories always survive, as Newtonian mechanics has, and as I'm sure the Standard Model will survive, as approximations.

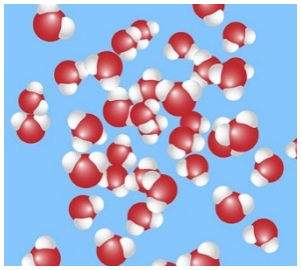
– Steven Weinberg (January 2021)

Summary of phenomena and scales

- String theory $10^{-35}m$
- Still unknown description at shorter distances
- The Standard Model of Particle Physics $10^{-18}m$
- Atoms, molecules $10^{-10}m$
- All the matter around us

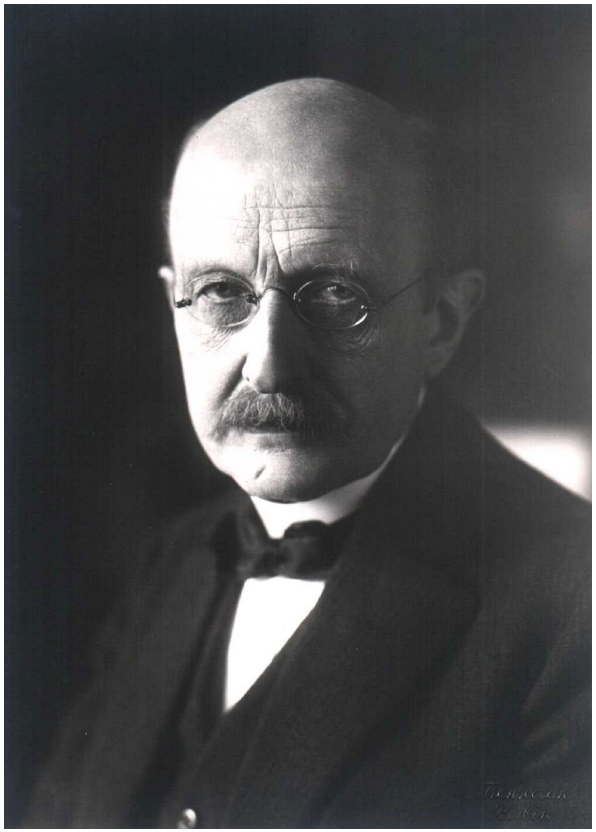






The biggest conceptual question

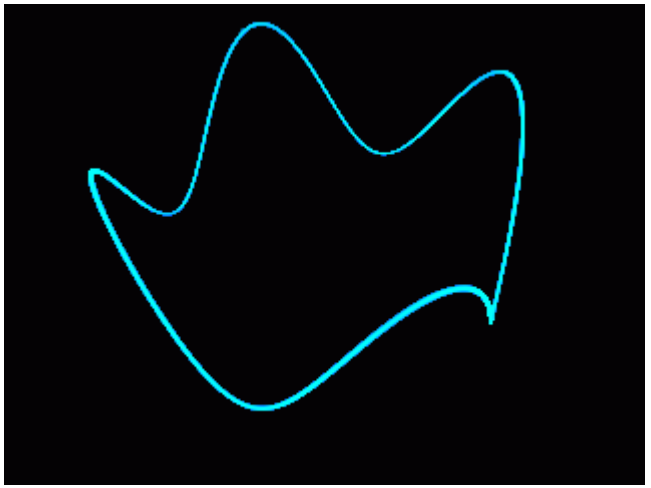
- Combine quantum mechanics and general relativity (gravity)
- Quantum gravity is most relevant at the Planck scale – the basic scale of Nature
  - 10^{-35} meters
  - 10^{-43} seconds
- Should address the structure of the Universe when it was 10^{-43} seconds old – origin of the Universe



Max Planck
1858-1947

String Theory

- Ambitious attempt to find a comprehensive theory of Nature
  - Elementary particles
  - Forces
  - Space and time



- Enormous challenges
  - We do not yet have a conceptual formulation of the theory. We do not know the underlying principles.
  - We still lack direct experimental confirmation of the theory.

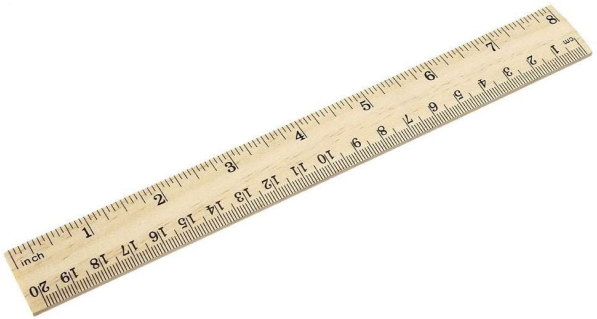
String Theory

Extremely promising

- Has the necessary ingredients to describe Nature
  - Quantum mechanics
  - Gravity (General Relativity)
  - Forces and particles of the kind we observe
- Miraculous and surprising consistency
- Deep intellectual structure
  - Many surprising connections between seemingly distinct branches of physics and mathematics
  - Many unexpected implications

What is space?

- Intuitive notion



- String theory provides mechanisms that make space an emergent concept.
- The notion of space is not fundamental. It emerges as an approximate notion at long distances.

What is space? Waves in the ocean

- The surface of the water looks like a two-dimensional curved sheet.
- Looking closer, there is no clear surface. It is an approximate illusion.
- An effective, macroscopic theory controlling the shape of that surface – Hydrodynamics.

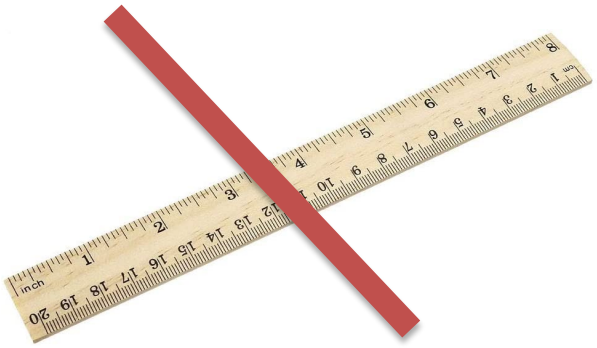
What is space? Waves in the ocean

The analogy:

- The surface of the water ⇒ Emergent space
- Hydrodynamics ⇒ General Relativity
- The water and air molecules ⇒ String Theory

What is space?

- If space is indeed emergent, then there is an ultimate shortest distance – the Planck scale, 10^{-35} meters.
- The notion of space makes no sense at shorter distances. The notion of distance ceases to make sense there.
- It is meaningless to ask: “What are the laws of Nature at shorter distances?”



What is time?

- Vague intuitive notion
- Physics is about time evolution
  - Making predictions about experiments and later verifying them
  - Causality
- Einstein's theory of relativity mixes space and time. Therefore, if space is emergent, it is likely that time is also emergent.

What is time?

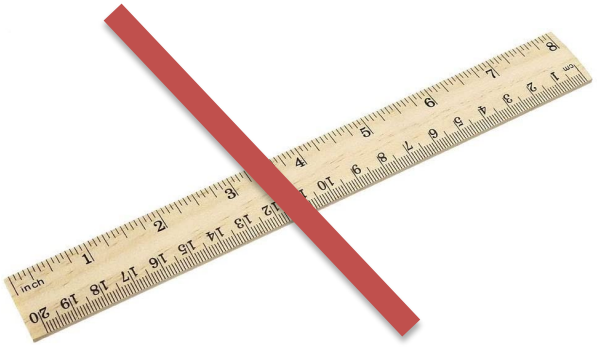
It is suggested that the notion of time is not fundamental. It emerges as an approximate notion at long times.

It is meaningless to ask "What happened before the Universe was 10^{-43} seconds old?"

Understanding how time emerges will also clarify the creation of the Universe – the notion of time did not make sense "before creation."

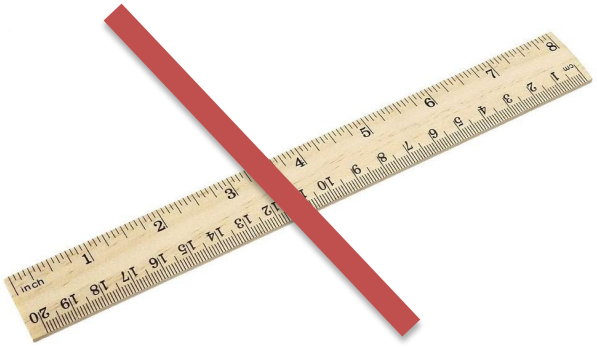
Emergent space and time

- If space and time are indeed emergent, then there is an ultimate shortest distance and shortest time – the Planck scale (10^{-35} meters, 10^{-43} seconds).
  - The notions of space, time, and distance cease to make sense there.
  - We can no longer ask: "What happens at shorter distances or at shorter times?"



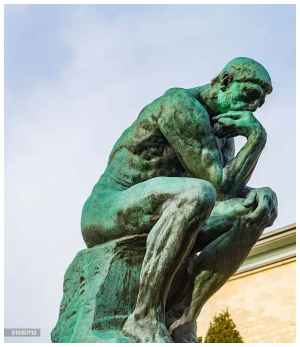
Emergent space and time

- Understanding the laws of Nature all the way down to the Planck scale will end the reductionist pursuit to find a deeper truth that underlies it at shorter distances – there are no shorter distances.



Summary

- Separation of scales
  - Nature is kind to us – can understand Nature one scale at a time.
  - Going to shorter distances to find deeper truth
  - Using this deeper truth to understand phenomena at longer distances – Reductionism
  - It did not have to be so simple.
  - Why is it so simple?



Summary

Physics at different scales

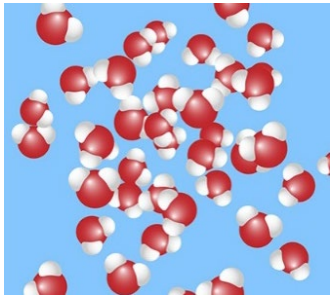
- Large scale physics (did not discuss here)
  - Cosmology
  - Astrophysics
  - Geophysics

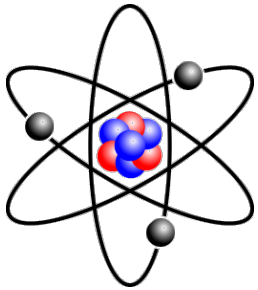
- Materials around us

Summary

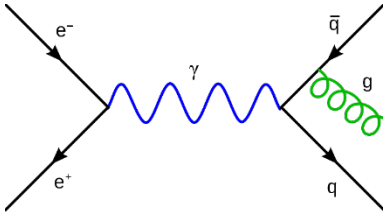
Physics at different scales

- Quantum theory, atoms, molecules, etc.





- The Standard Model of particle physics, electrons, quarks, Higgs, etc.



- ?
- Quantum gravity, string theory…

Summary

- Quantum gravity, string theory
  - Emergent space and time
  - If this turns out to be the case, end of reductionism – no shorter distances, no deeper truth.
  - We can no longer ask: “What Happens at Shorter Distances?”
  - Ultimate theory

- But it will not be the end of science, as there will still be many interesting phenomena that follow from it.

Thank you