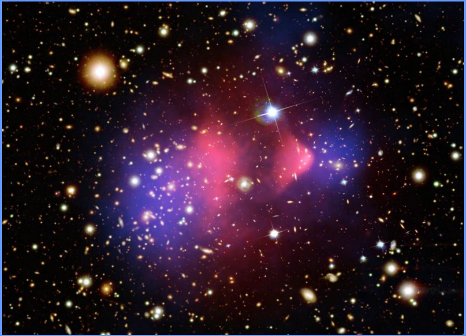
Unsolved Mysteries of Fundamental Physics



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By **fundamental physics**, I mean the search for a small set of laws which *in principle* determine everything we can calculate about the universe.

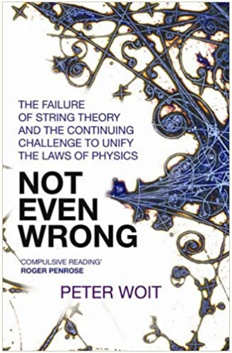
By 1980 we had one equation that could do a pretty good job:

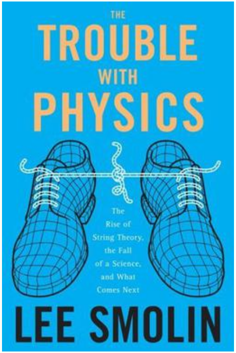
$$W = \overbrace{\int_{k<\Lambda} [Dg][DA][D\psi][D\Phi] \exp}^{\text{quantum mechanics}} \left\{ i \overbrace{\int d^4x \sqrt{-g}}^{\text{spacetime}} \left[\overbrace{\frac{m_p^2}{2} R}^{\text{gravity}} \right.\right.$$

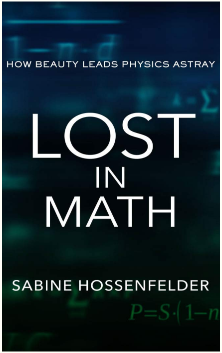
$$\left.\left. \underbrace{-\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu}}_{\text{other forces}} + \underbrace{i\bar{\psi}^i \gamma^\mu D_\mu \psi^i + \left(\bar{\psi}^i_L V_{ij} \Phi \psi^j_R + \text{h.c.} \right)}_{\text{matter}} \underbrace{- |D_\mu \Phi|^2 - V(\Phi)}_{\text{Higgs}} \right] \right\}$$

But some cracks were visible. Some have been fixed, but others have widened!

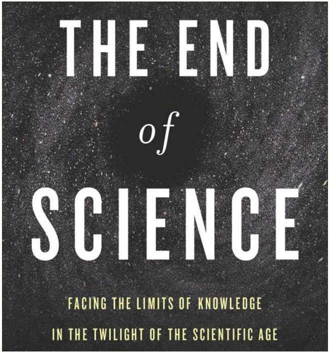
The lack of progress since 1980 has been troubling.







Some are even predicting the “end of science”.

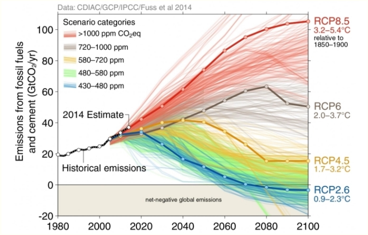


But that’s going too far: fundamental physics is just a small part of physics, which is a small part of science.

Science is just getting started, *unless* we manage to destroy our civilization.

The great thing about fundamental physics is that *it can wait*.

If you're an ambitious youngster, there are many urgent problems we *need* to solve.



There's also a lot of great "non-fundamental" physics to do!

But fundamental physics is still interesting. What do we know, and what are the mysteries?

The most fundamental mystery:

WHY?

Some say that science does not tell us *why* things happen, just *what* happens. There's some truth to that.

And yet science often moves forward by asking "why?"

Q: Why is the sky blue?

A: More than light of other colors, blue light is scattered in all directions by the Earth’s atmosphere.

Q: Why is blue light scattered more?

A: Because blue light has a shorter wavelength than most other visible light.

Q: Why does blue light have a shorter wavelength?

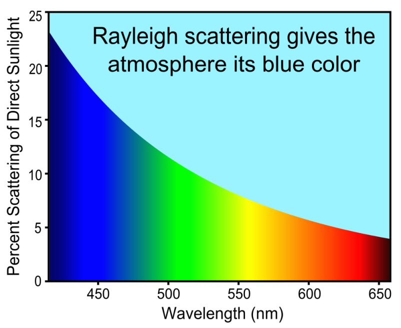
A: No reason: we just call visible light with short wavelengths "blue".

Q: But why does light with short wavelengths *look* blue?

A: Umm, err... that's not a physics question.

Q: So why does light with short wavelengths scatter more?

A: It's a general fact: almost any sort of wave scatters off small particles with an intensity proportional to 1/wavelength^4.



Q: Why 1/wavelength^4?

A: Now that's a good question!

I won't do the calculation here, but Lord Rayleigh showed this in 1871.

It relies on the fact that space is 3-dimensional. If space were 2-dimensional, the intensity would go like 1/wavelength^3.

Q: Why is space 3-dimensional?

A: Nobody knows. That’s too hard for us now!

There are many questions in physics that seem *too hard* for us now:

Q: Why is space 3-dimensional?

Q: Why is time 1-dimensional?

Q: Are there any truly fundamental laws, or only succession of better and better approximate laws?

Q: What are the fundamental laws, if they exist?

But some questions that looked too hard were actually answered!

Q: Why is time so different from space?

A: Because the distance between two points in spacetime is

$$\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2 - (\Delta t)^2}$$

The minus sign here explains most of the differences between space and time!

This is Einstein's theory of "special relativity".

It's hard to guess which questions we'll answer next, but it helps to know where we stand now.

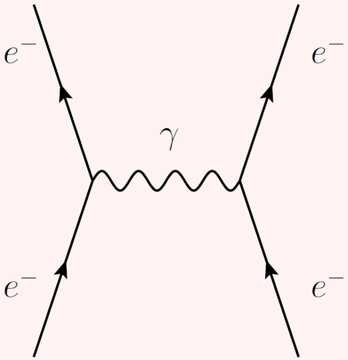
Our best theories of fundamental physics today:

STANDARD MODEL	**GENERAL RELATIVITY**
Electromagnetic Force Weak Force Strong Force	Gravity

The Standard Model describes all the forces *except* gravity.

General relativity describes gravity.

The Standard Model describes *matter* and *forces* using quantum mechanics.



There are particles that carry forces:

electromagnetism	γ (photon)
weak force	W, Z
strong force	g (gluon)

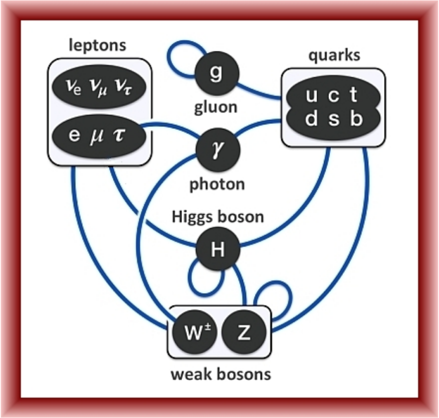
and particles that constitute matter:

	leptons	quarks
1st generation	e, ν_e	d, u
2nd generation	μ, ν_μ	s, c
3rd generation	τ, ν_τ	b, t

There is also one more:

H (Higgs boson)

They interact in various ways:



The strengths of their various interactions are described by 25 numbers. 22 involve the Higgs boson!

The most obvious mysteries seem very hard to solve.

Q: Why are there 3 forces?

Q: Why does each generation include 2 leptons and 2 quarks?

Q: Why are there 3 generations of matter particles?

Q: Why do the 25 numbers in the Standard Model have the values they do?

Some theories, like “Grand Unified Theories” offer plausible answers to the first two questions.

The third seems harder, and the fourth even harder.

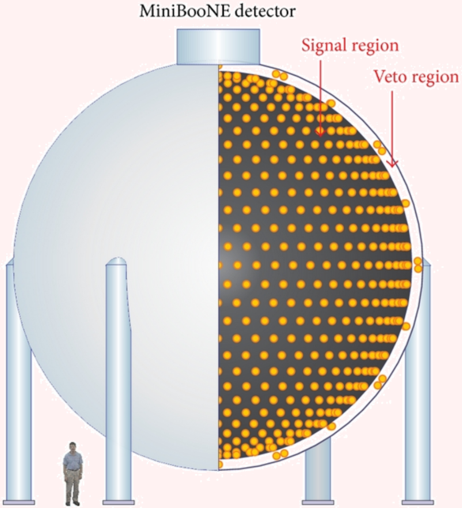
It seems easier to make progress on other puzzles.

Q: What's up with neutrinos?

Once we thought they were massless. Now we know they have masses and the 3 kinds can turn into each other. People had to fix the Standard Model.

We can do this by saying neutrinos interact with the Higgs boson. 7 of the 25 numbers in the Standard Model provide the details.

But we're not sure this is right!



MiniBooNE: 800 tons of mineral oil in a tank bombarded with muon neutrinos from a distance of 500 meters... for 16 years.

At MiniBooNE and an earlier experiment, muon neutrinos seemed to be turning into electron neutrinos too fast to be explained by the Standard Model!

To settle the question: MicroBooNE, with 170 tons of liquid argon!

So far, MicroBooNE has *not* seen muon neutrinos turning into electron neutrinos too fast.

General relativity says that freely falling objects trace out paths in spacetime that are “as straight as possible’, but matter curves spacetime according to Einstein’s equation.

Here is Einstein’s equation:

Given any small ball of freely falling test particles initially at rest relative to each other, the rate at which its volume starts to shrink is proportional to: the energy density at the center of the ball, plus the sum of the pressures in all three directions.

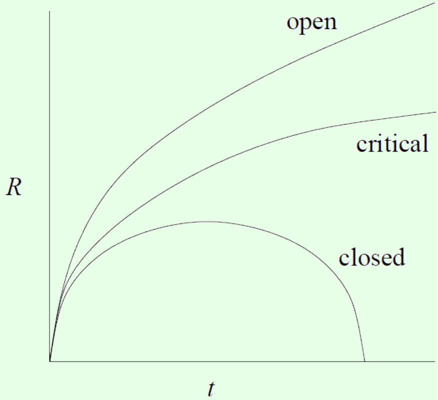
More precisely:

$$\left.\frac{\ddot{V}}{V}\right|_{t=0} = -\frac{1}{2}(\rho + P_x + P_y + P_z)$$

From this one can understand why masses attract, and also understand:

- black holes
- gravitational waves
- the Big Bang

If the pressure in intergalactic space is almost zero, there are 3 possibilites for how the Universe expands:



However, *none matches what we see.* It seems the universe is expanding faster and faster!

Q: What is making the expansion of the universe accelerate? Does the vacuum have pressure? If so, why? If not, what is responsible for this apparent effect?

The most popular option is this: *the vacuum has negative pressure but positive density*. To get the accelerated expansion we see, we need a density of 7×10^{-27} kilograms per cubic meter.

This theory is often called **"dark energy"**, though "invisible tension" would be better.

Gravity holds many other mysteries which seem hard to solve:

Q: How can we reconcile general relativity and the Standard Model?

Q: What really happened at the Big Bang?

Q: What happens to stuff that falls into black holes?

Q: What’s the ultimate fate of the Universe?

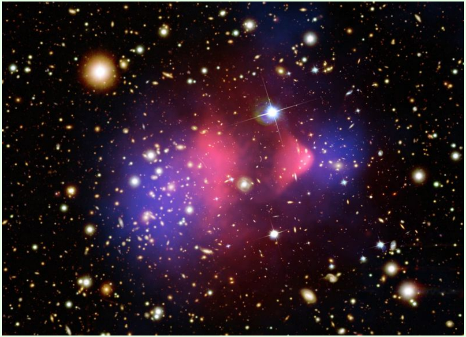
Q: Why is the future so different than the past?

It seems easier to make progress on other problems!

Q: Why don't galaxies or early hot gas in the Universe behave as we would expect? Why do we seem to need some new kind of invisible matter—**"dark matter"**—or a new theory of gravity?

- Galaxies rotate faster than we would expect.
- In the early universe, galaxies formed faster than we would expect.
- Fluctuations in the hot gas of the very early universe are more lumpy than we would expect.

Astrophysicists are learning a lot about these things... so this is a mystery with many clues!



SUMMARY

Don't hold your breath. Don't pay much attention to

- cool-sounding theories without experimental evidence
- surprising experimental results (until confirmed)

Stay tuned for news about

- neutrino oscillations
- dark energy
- dark matter

These are mysteries where we keep finding new clues, which touch on the questions:

- what makes things have mass?
- what makes spacetime bend?