VISIONS FOR THE FUTURE OF PHYSICS

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In earlier versions of this talk I discussed how physicists can help with the great challenge of our age: the Anthropocene.

We need to take responsibility for our effect on the planet.

But right now we're massively distracted by other things, like AI and the rapid decline of USA. I don't know the best ways for physicists to help with these. Mainly by being intelligent, critical and courageous?

Please think about it.

Physics is just one part of the good life. But now I'll just talk about physics.

The 20th century was the century of “fundamental” physics: the search for a small set of universal laws governing the whole physical world.

Progress in fundamental physics slowed down after 1980. We’re now in a new era. But we haven’t fully absorbed this fact.

Let’s look at a timeline, focused on the Standard Model and general relativity, showing:

- experimental discoveries that were later accounted for by theories
- theoretical predictions that were later confirmed by experiment
- experiments that confirmed theoretical predictions
- experimental discoveries that are still not fully accounted for by theories.

1897 – 1920

1897 — electrons are discovered.
1905 — the photon is predicted.
1905 — matter is made of atoms.
1905 — space and time are unified: special relativity.
1911 — every atom is found to contain a much smaller nucleus.
1915 — the bending of spacetime by gravity is predicted: general relativity.
1916 — gravitational radiation is predicted.
1919 — the bending of spacetime by gravity is found.

1920 – 1940

1922 — the expansion of the universe is predicted.
1923 — the photon is found.
1925 — the universe is predicted to be governed by linear algebra: quantum mechanics.
1926 — the expansion of the universe is found.
1930 — the 1st neutrino is predicted.
1932 — antimatter is discovered.
1932 — the neutron is discovered.
1933 — evidence for dark matter is discovered.
1937 — the 2nd heavy lepton is discovered (the muon).

1940 – 1960

1948 — special relativity, electrodynamics and quantum mechanics are unified: quantum electrodynamics

1956 — the 1st neutrino is found.

1956 — violation of P symmetry is found: right is different from left.

1960 – 1980

1962 — the 2nd neutrino is discovered.
1963 — the first 3 quarks are predicted.
1964 — violation of CP symmetry is found.
1968 — theory of electromagnetism and the weak force:
the W, Z and Higgs bosons are predicted.
1970 — the 4th quark is predicted.
1973 —the 5th and 6th quarks are predicted.
1973 — theory of the strong force: gluons are predicted.
1974 — the 4th quark is found.
1977 — the 5th quark is found.
1975 — the 3rd heavy lepton is discovered (the tau).
1979 — gluons are found.

1980 – 2000

1981 — gravitational radiation is found.
1984 — the W and Z bosons are found.
1995 — the 6th quark is found, completing the 3 generations of quarks.
1998 — neutrino oscillations are discovered.
1998 — the accelerating expansion of the universe is discovered.

2000 – 2025

2000 — the 3rd neutrino is found, completing the 3 generations of leptons.
2012 — the Higgs boson is found, completing the Standard Model.

Some big challenges remain, including:

- dark matter
- the accelerating expansion of the universe
- inflation?
- mathematical inconsistencies in the Standard Model?
- reconciling the Standard Model and general relativity

What should we do about the slow progress in fundamental physics?

Don’t be nostalgic. If something isn’t working well, try something else.

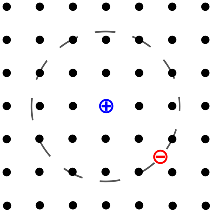
Today, there are more exciting things to do than fundamental physics.

Most branches of theoretical physics are thriving: we have a long way to go in *using* our knowledge of fundamental laws.

For example, we can now theoretically and *experimentally* explore marvelous things such as:

Excitons: something orbiting nothing

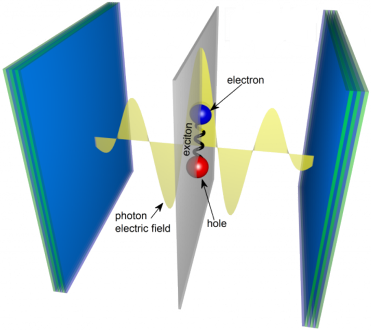
When you knock an electron off an atom in a crystal, it leaves a hole. The electron has a negative charge. The hole acts like it has a positive charge. So they attract!



The electron and hole can orbit each other. Then together they form a quasiparticle called an "exciton".

Polaritons: a blend of light and matter

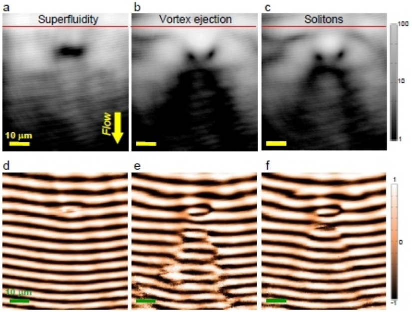
When you bounce light back and forth between mirrors, and put a crystal inside that easily forms excitons, the photons can form quantum superpositions with the excitons!



These photon-exciton superpositions act like particles in their own right, called "polaritons".

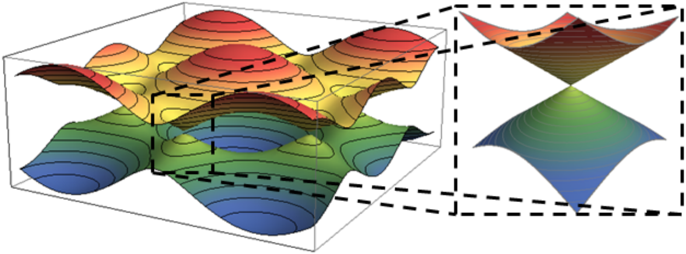
Polaritons: “liquid light”

Polaritons can form a fluid! This can be a superfluid, or a normal fluid that creates vortices as it passes an obstacle...



... or even a shock wave, a “sonic boom”, as it passes an obstacle at supersonic speed!

Artificial special relativity



This shows the energy E of electrons moving in a sheet of graphene as a function of their momentum (p_x, p_y). At certain points this looks like a lightcone in energy-momentum space. That's what we expect for a massless particle in special relativity!

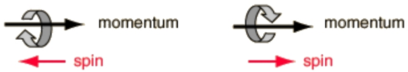
Whenever we get an energy-momentum relation that looks like

$$E^2 = p_x^2 + p_y^2$$

after some change in coordinates, this is called a Dirac cone. A Dirac cone gives physics that mimics massless relativistic particles in 2d space! This happens in graphene.

The same phenomenon happens in some 3d materials:

• Electrons act like massless spin-$\frac{1}{2}$ particles in Dirac semimetals such as sodium bismuthide.
• They act like *chiral* massless spin-$\frac{1}{2}$ particles in Weyl semimetals such as tantalum arsenide.



Artificial universes with 2 time dimensions

We can create "hyperbolic metamaterials" where light moves in waves like

$$\exp(i(\vec{p} \cdot \vec{x} - Et))$$

where we have approximately

$$E^2 = p_x^2 + p_y^2 - p_z^2$$

Thus, light behaves roughly as if there were *two dimensions of space and two dimensions of time!*

In a universe with 2 space and 2 time dimensions, the electromagnetic 4-potential A obeys

$$\left(\frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2}\right) A = J$$

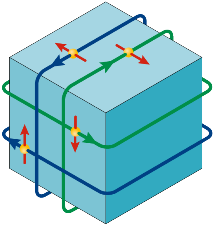
in Lorentz gauge, where J is the 4-current.

This equation is symmetric under the group $\mathrm{SO}(2,2)$, which is in some ways more interesting than the usual Lorentz group $\mathrm{SO}(3,1)$, because it's the 'split form' of $\mathrm{SO}(4,\mathbb{C})$.

This equation also has a symmetry that switches the space and time dimensions!

$$(x, y, z, t) \mapsto (z, t, x, y)$$

Topological matter



The simplest kind of 3-dimensional topological insulator is insulating on the inside — but its surface conducts electricity! Electrons on the surface have their spin locked at right angles to their momentum, so there are two kinds.

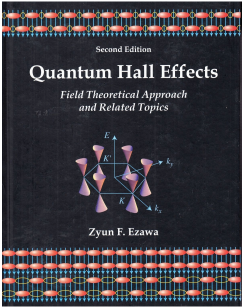
Most known 3d topological insulators are bismuth compounds, like bismuth antimonide.

More generally, topological matter has terms in its Hamiltonian density that give topological invariants when integrated over a manifold without boundary.

When the system *does* have a boundary, these terms tend to create “edge states” that live on the boundary.

Topological matter involves a huge amount of interesting math.

For example, the quantum Hall effect — where electrons move on a 2d surface in a magnetic field — winds up involving solitons, Chern classes, the Berry phase, noncommutative geometry, Kac–Moody algebras, K-theory... and more!



You can also learn these techniques and apply them to something new.

Active matter

"Active matter" is made of many agents that consume energy in order to move. Examples include flocks of birds, self-organizing bio-polymers such as microtubules, and swarms of nanobots or other self-propelled particles.

Active matter makes us study the statistical mechanics of systems that *lack conservation of energy* and *break time reversal symmetry*.

At the fundamental level energy is conserved, and the system has time reversal symmetry. These principles fail only because we have deliberately *neglected details* — as in a particle with friction.

New worlds

In fundamental physics we find powerful principles, like Lagrangian mechanics and Noether's theorem. We should never forget them!

But now we can create and study physical systems that are *approximately* described by *new* laws. This opens up ***thousands of new worlds to explore.***

These new approximate laws may *violate* the principles we've learned. That's okay. We can figure out how to reconcile this fact with how those principles hold at the fundamental level.

And these new worlds are not separate. They all fit together in our marvelous universe. It's our job to understand how.