VISIONS FOR THE FUTURE OF PHYSICS



JOHN BAEZ Annual Basic Research Community for Physics Symposium November 5, 2021

20th century physics:

Huge progress in the search for fundamental laws — up to about 1980.

Physicists faced huge responsibilities: nuclear weapons.

21 century physics:

Huge progress in applying fundamental laws. Physicists face huge responsibilities: the Anthropocene. The 20th century was the century of "fundamental" physics: the search for a small set of universal laws governing the whole physical world.

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Progress in fundamental physics slowed down after 1980. 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 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.

- 1922 the expansion of the universe is predicted.
- 1923 the photon is found.
- 1926 the expansion of the universe is found.
- 1927 the universe is predicted to be governed by linear algebra: quantum mechanics.
- 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).

- 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.

- 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 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:

dark matter the accelerating expansion of the universe inflation? neutrino oscillations? mathematical inconsistencies in the Standard Model? reconciling the Standard Model and general relativity What should we do about the slow progress in fundamental physics?

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

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

For example, in condensed matter physics we can theoretically and *experimentally* explore marvelous things such as: For example, in condensed matter physics we can theoretically and *experimentally* explore marvelous things such as:

Artificial special relativity



Dirac points, Weyl semimetals, Majorana fermions,...

Artificial universes with 2 time dimensions

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

$$\exp(i(\vec{k}\cdot\vec{x}-\omega t))$$

where we approximately have

$$\omega^2 = k_x^2 + k_y^2 - k_z^2$$

Then light behaves roughly as if there were two dimensions of space and two dimensions of time!

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So far most work has been done on classifying the 'topological phases', where nothing interesting happens locally. This already involves beautiful math, e.g. higher categories. But this is just the start!

So, there's no shortage of exciting things for physicists to do.

But what should we be doing? Let's look around....

We have left the Holocene and entered a new epoch, the Anthropocene, when the biosphere is rapidly changing due to human activities. Global warming is just *part* of this process.





Carbon Dioxide Information Analysis Center

Carbon Dioxide Variations



Antarctic ice cores and other data - Global Warming Art



Reconstruction of temperature from 73 different records — Marcott *et al.*



PIOMAS data, art by Andy Lee Robinson

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8-9 times as much phosphorus is flowing into oceans than the natural background rate.

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Consider having fewer children, or adopting. In the US each child adds \sim 9400 tonnes of CO₂ to the air.

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- 2) Use physics to help solve practical problems.
- 3) Be creative: have brand new ideas.

1) The numbers are important. To keep global warming below 2°C by 2100, it's likely that we will need *negative carbon emissions*:



But how much?

We are now putting 38 gigatonnes of CO_2 into the air each year.

To keep global warming below 2° C by 2100, we will probably need to remove about 10 gigatonnes of CO₂ from the air each year by 2050, and double that by 2100.

How could we do this? Some proposed solutions just aren't big enough: *the numbers matter*!

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For example: make plastics from CO_2 in the air? We make about 360 megatonnes of plastic per year — not nearly enough to make a difference!

We could pull down over 10 gigatonnes of CO₂ per year this way:

1 gigatonne by planting trees,

1.5 gigatonnes by better forest management,

3 gigatonnes by better agricultural practices,

5.2 gigatonnes by biofuels with carbon capture.

This is not enough to cancel the 38 gigatonnes we're dumping into the air each year now. *Together with reducing emissions* it could be enough!

But beware: governments are using dreams of future negative carbon emissions to avoid taking action now.

Condensed matter physics and physical chemistry for...

better batteries better solar cells

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Nuclear physics for...

better fission reactors better fusion reactors

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better solar cells

Nuclear physics for...

better fission reactors better fusion reactors

Fluid dynamics and atmospheric physics for...

weather/climate prediction

geoengineering

... and much more!

3) We also need *brand new ideas* to adapt to the Anthropocene.

In general, we have been pretending that:

the Earth is essentially infinite our effect on the biosphere is negligible exponential growth is a normal condition.

Acting as if these were true inevitably brought us to a point where they *stopped* being true!

Our simplified picture:



Our simplified picture neglects "waste", until it causes trouble:



In nature there is no waste, only more resources:



Take a walk in the woods and you'll see!

To understand ecosystems, ultimately will be to understand networks. — B. C. Patten and M. Witkamp



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But please — make up your own new ideas!