THEORETICAL PHYSICS IN THE 21ST CENTURY

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SUSTAINABILITY WEEK 2021

ETH ZURICH

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.

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 – 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.
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).

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 – 2020

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?

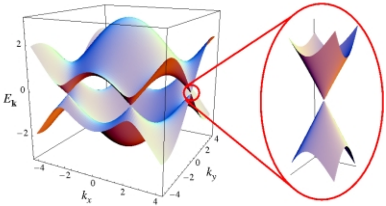
Don’t be nostalgic. If something isn’t working well, try something else.

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, 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

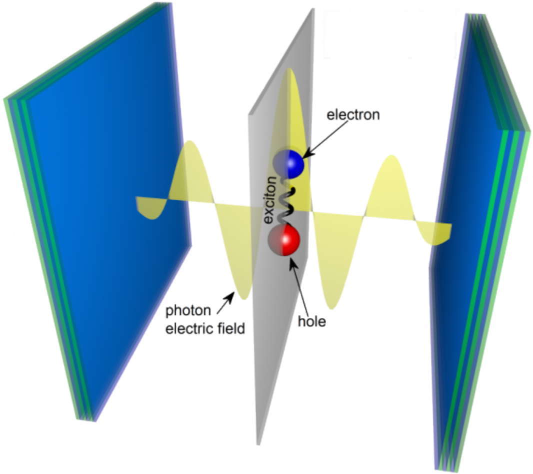
$$\exp(i(\vec{k} \cdot \vec{x} - \omega t))$$

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!*

Polaritons: particles that blend matter and light

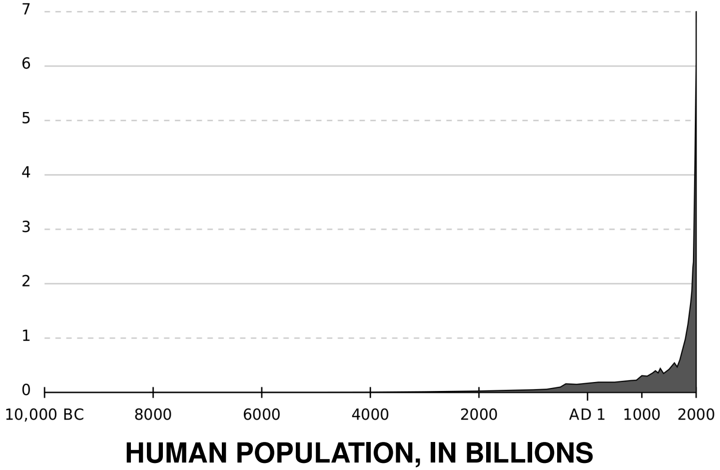


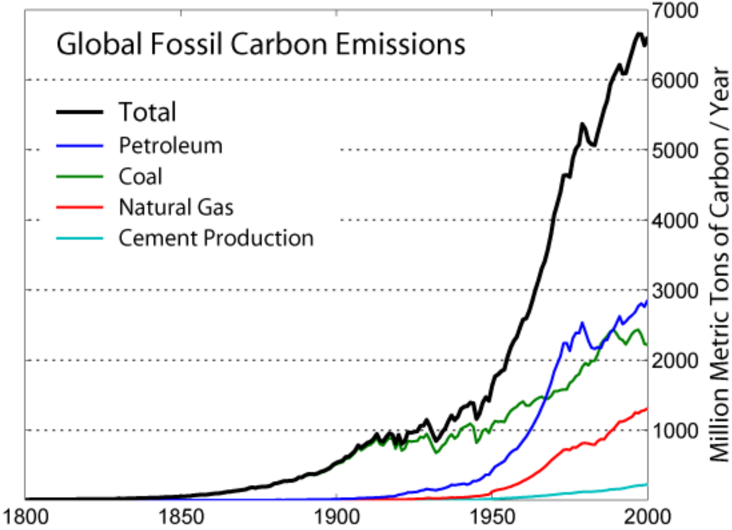
Polaritons can even form “liquid light”!

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

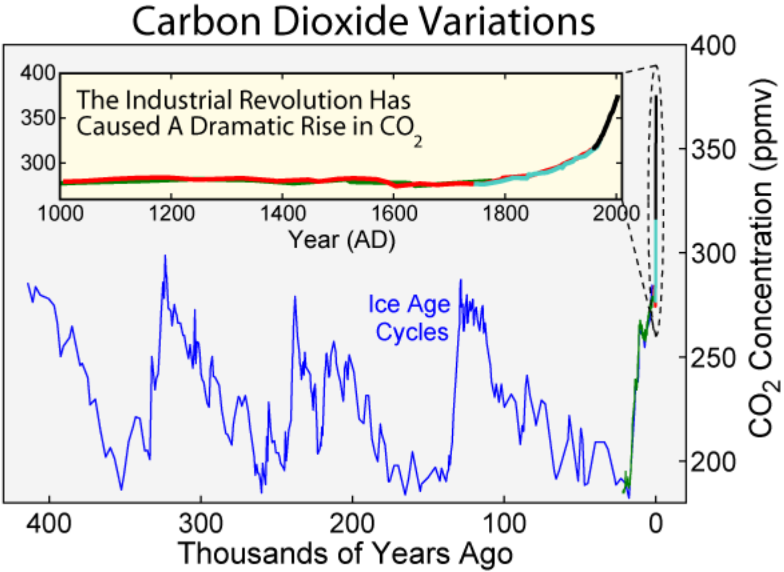
But what *should* we be doing? Let’s look around....

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.

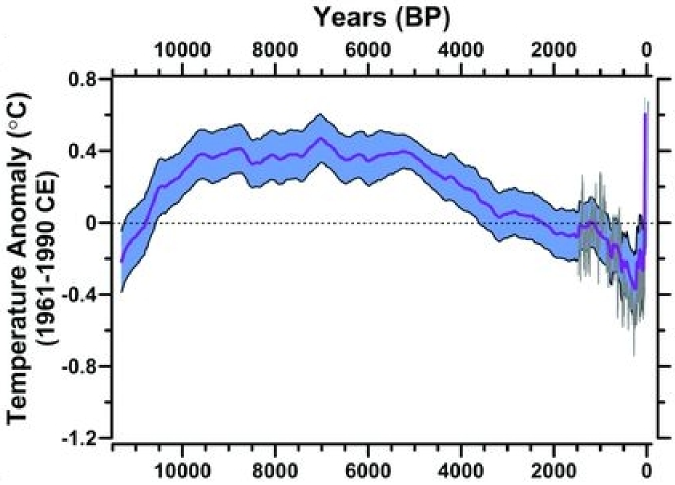




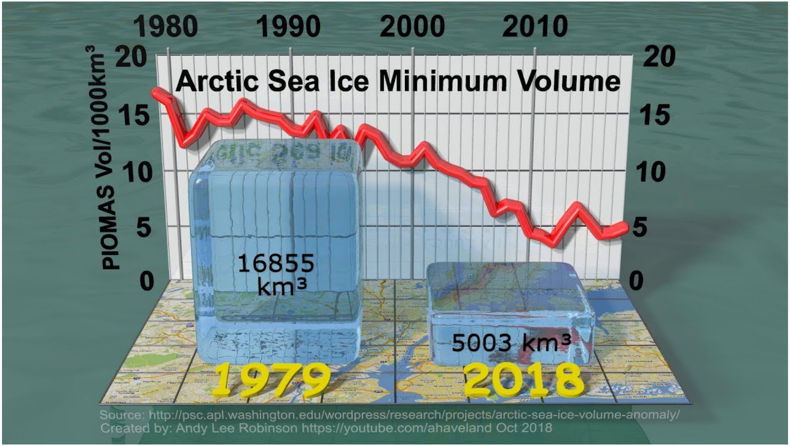
Carbon Dioxide Information Analysis Center



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

WE DOMINATE THE BIOSPHERE

About 1/4 of all chemical energy produced by plants is now used by humans.

The biomass of farmed mammals is 14 times that of wild mammals.

The biomass of farmed birds is 2.5 times that of wild birds.

Populations of large ocean fish have declined 90% since 1950.

The rate of species going extinct is 100-1000 times the usual background rate.

Humans now take more nitrogen from the atmosphere and convert it into nitrates than all other processes combined.

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

In view of all this, what should theoretical physicists do?

Like everyone else, we should do our part to curb global warming.

US citizens emit 16 tonnes of carbon dioxide per year on average; Swiss just 4.2. But we can all do more:

- Stop flying to conferences. By not flying from Los Angeles to Zürich I saved 3.5 tonnes of carbon dioxide.
- Eat less meat. Switching from a high-meat diet to a vegan diet can cut your CO_2 emissions about 1.5 tonnes per year.
- Consider having fewer children, or adopting. In the US each child adds $\sim$9400 tonnes of CO_2 to the air.

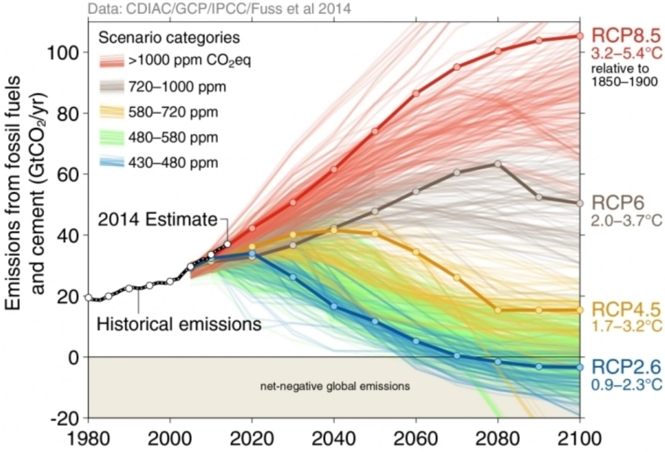
But what what special things can *theoretical physicists* do?

1) Learn more about the problems and solutions—and tell everyone! *You are better than average at understanding numbers!*

2) Use physics to help solve 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 CO_2 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!*

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 CO_2 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, but *together with reducing emissions* it could be enough!

2) What can physicists can do to help solve the climate crisis?
Many things!

Condensed matter physics and physical chemistry for...

better batteries

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!

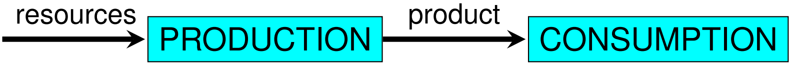
3) We also need *brand new ideas* to adapt to the Anthropocene.

In general, we have been pretending that:

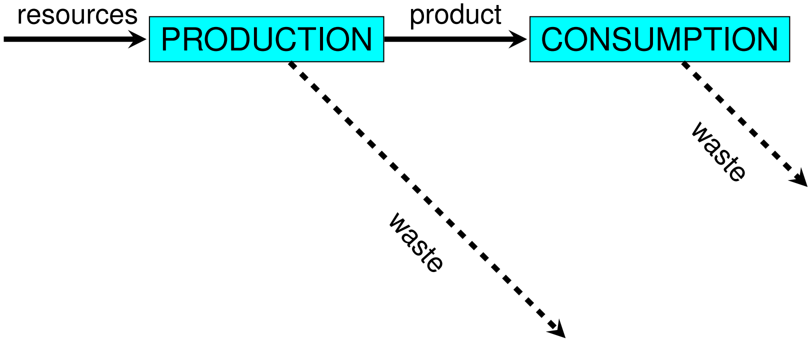
> the Earth is essentially infinite
>
> our effect on the biosphere is negligible
>
> exponential growth is a normal condition.

Acting as if these are true inevitably brings us to a point where they *stop* being true.

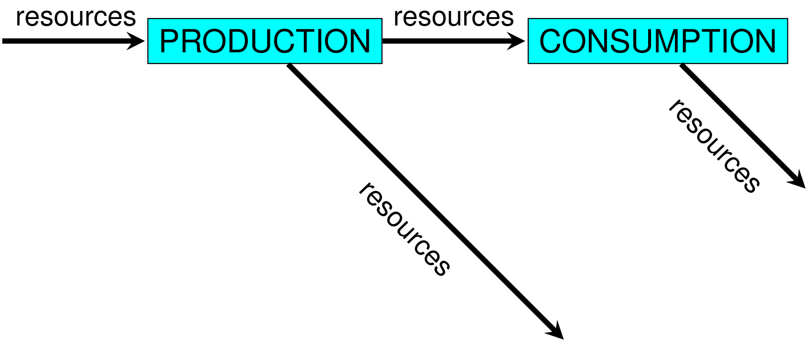
Our simplified picture:



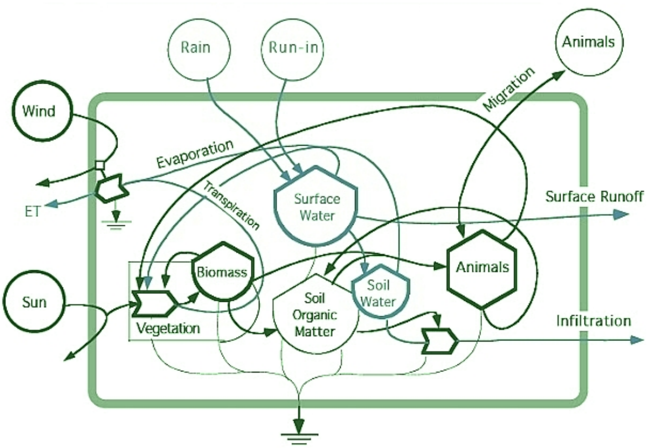
Our simplified picture neglects “waste”, until it causes trouble:



In nature there is no waste, only more resources:



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



We need to think about the physics of networks!

Here's some work along those lines:

tinyurl.com/networksbaez

But also find your own *brand new ideas.*