What is science?

(And why should you care?)

Dr. Kristian Harder,
Particle Physics Department,
Rutherford Appleton Laboratory

UKRI Science and Technology Facilities Council

About me

Dr. Kristian Harder, particle physicist

physics degree from Hamburg University, 1998
- emphasis topics particle physics and analytic philosophy

PhD Hamburg University/DESY, 2002:
- analysis of collider experiment data,
- simulation studies of future experiments

Fermi National Accelerator Laboratory, USA, 2002–2006:
- operation+upgrades of collider experiments,
- precision data analysis

Rutherford Appleton Laboratory, 2006–:
- electronics for experiments
- (data analysis)
- (science communication)

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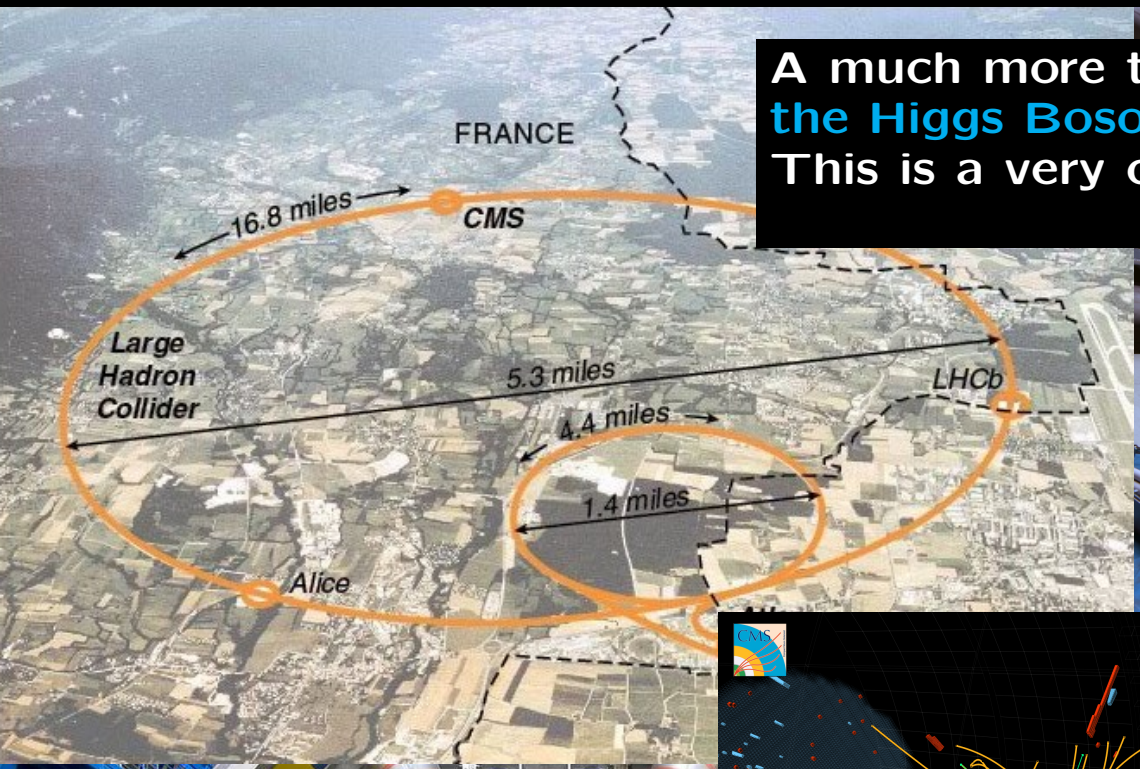
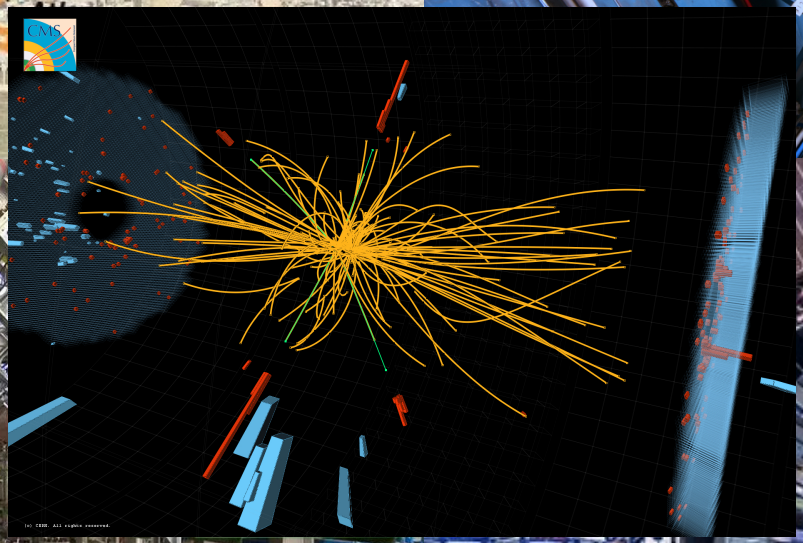
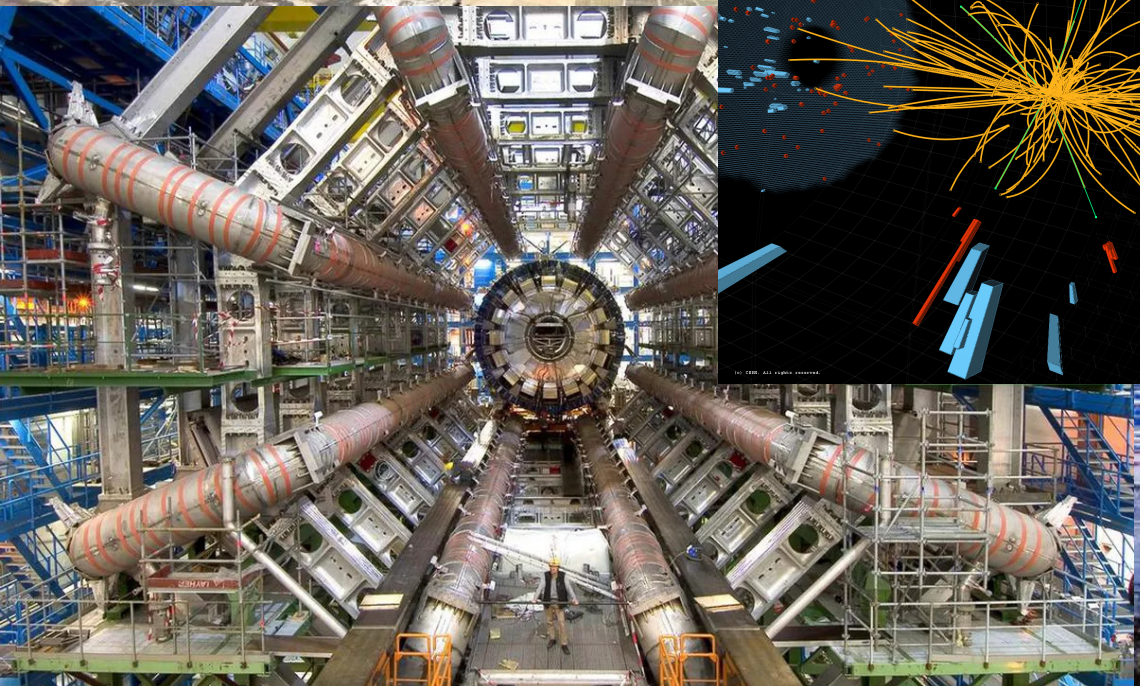
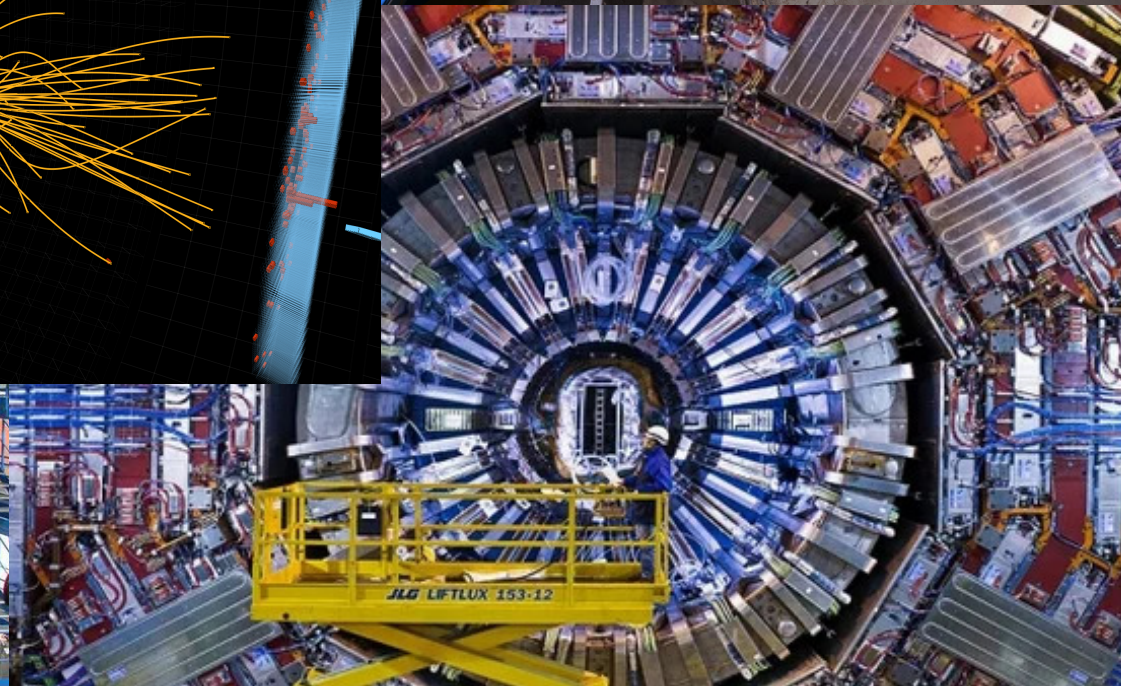
an unusual topic!

A much more typical theme for me to talk about:
the Higgs Boson discovery at the Large Hadron Collider!
This is a very complex scientific topic.









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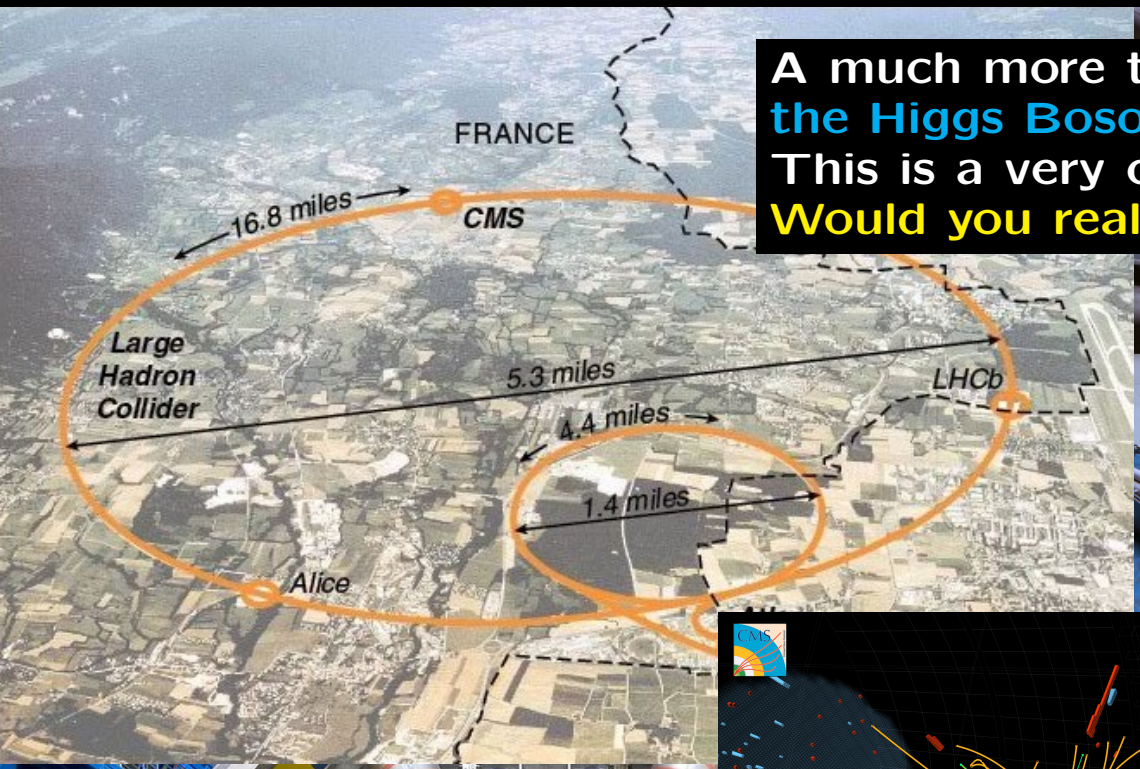
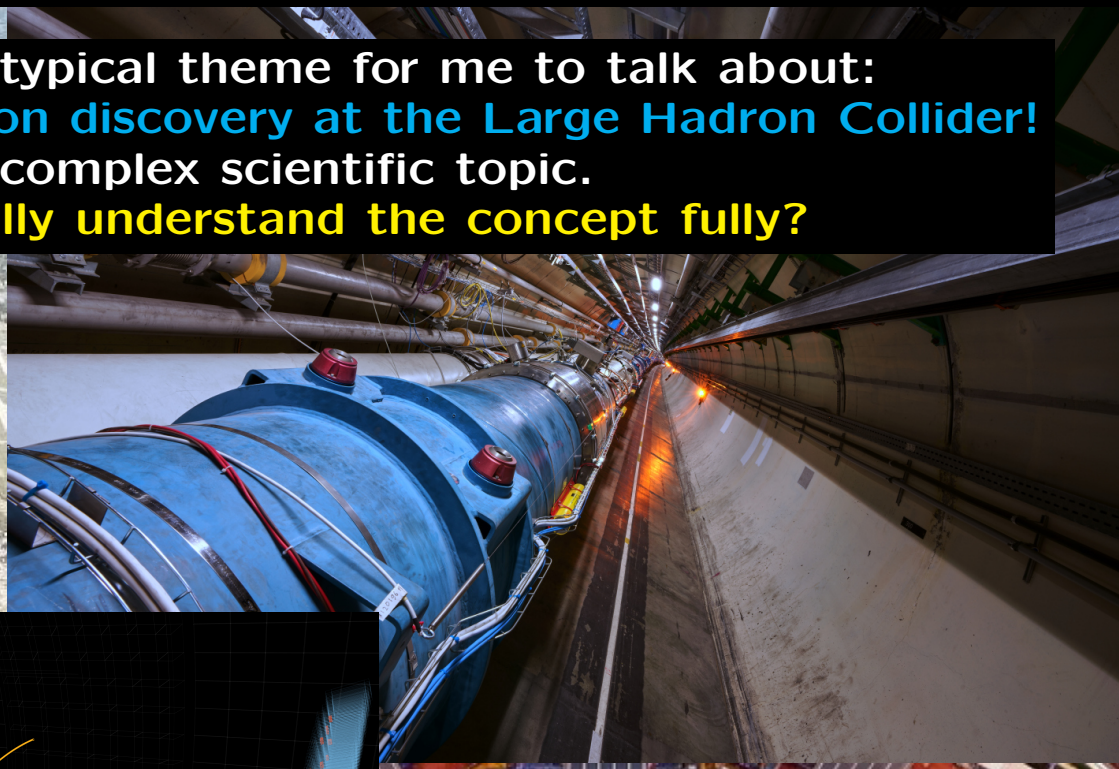
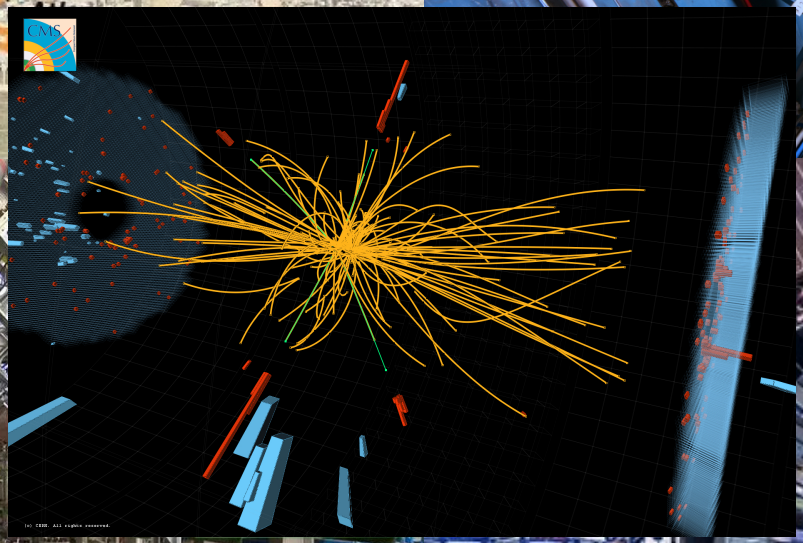
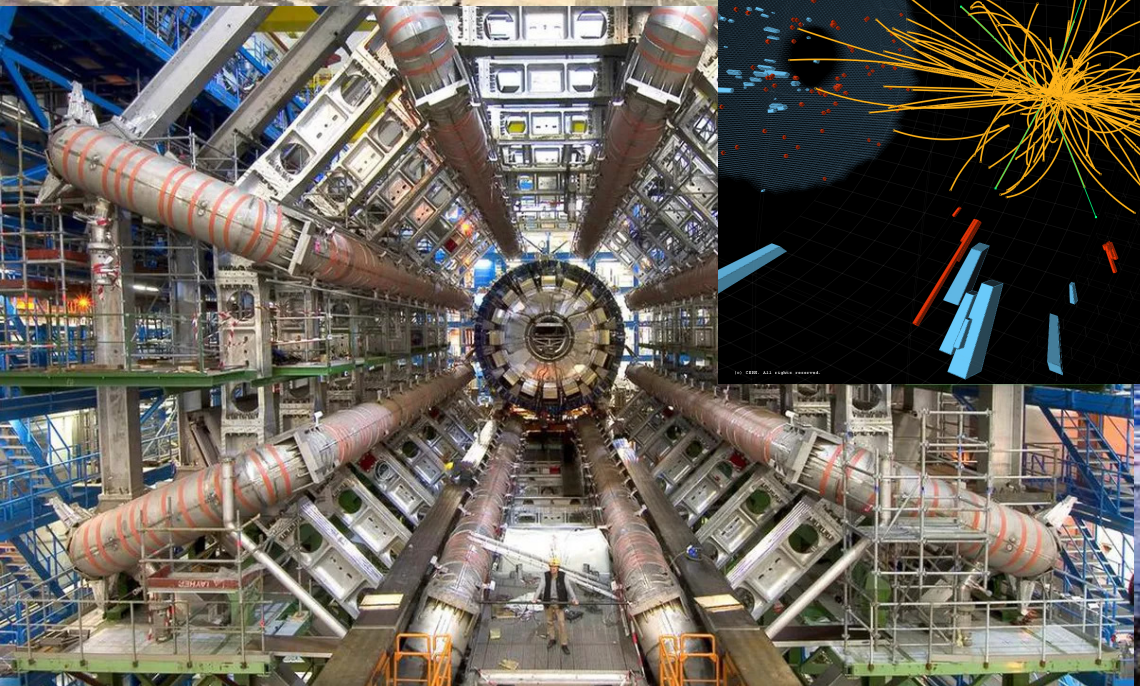
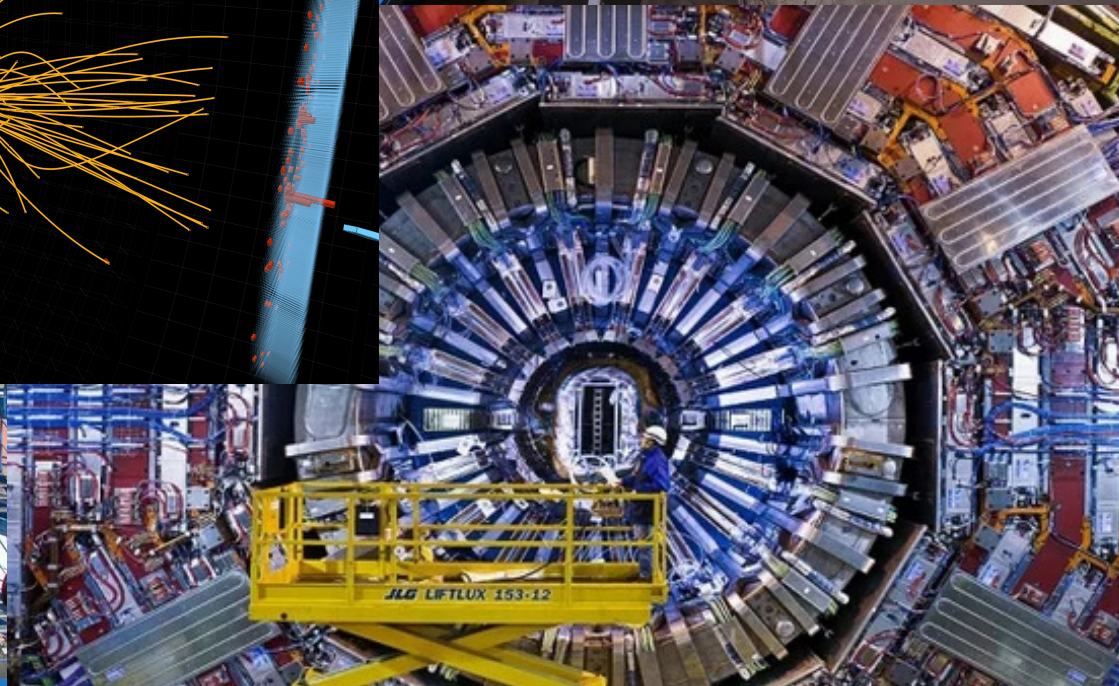
Would you really understand the concept fully?











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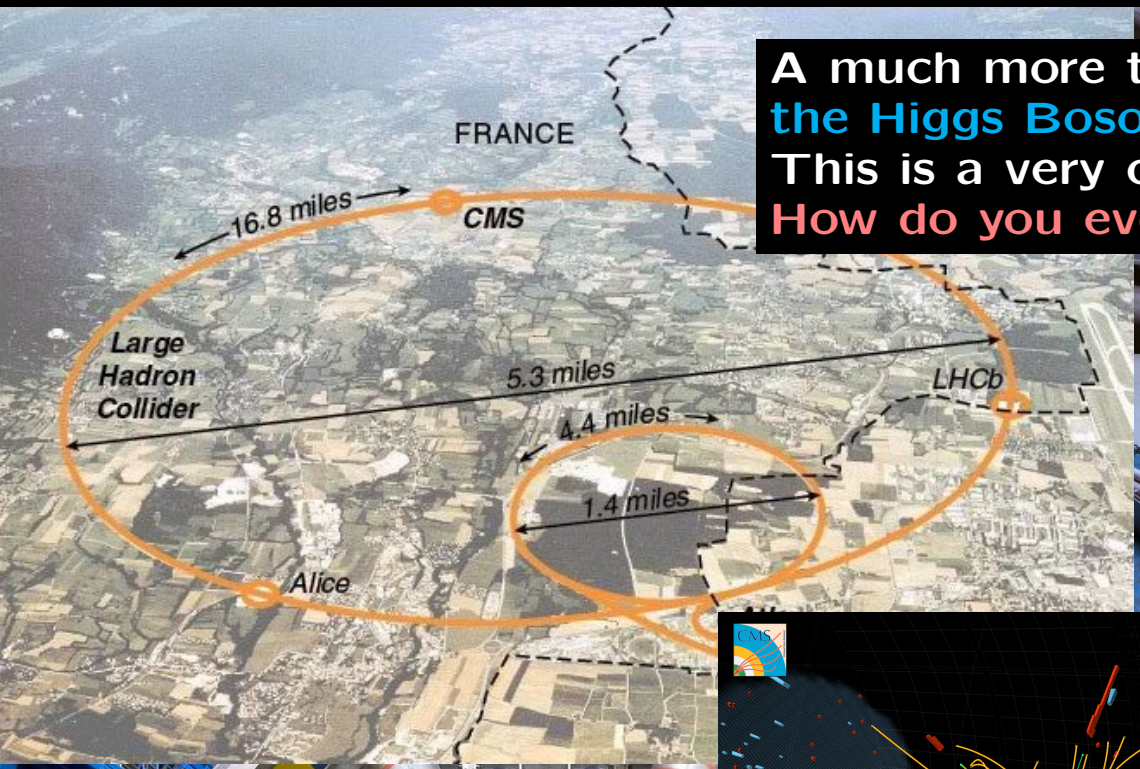
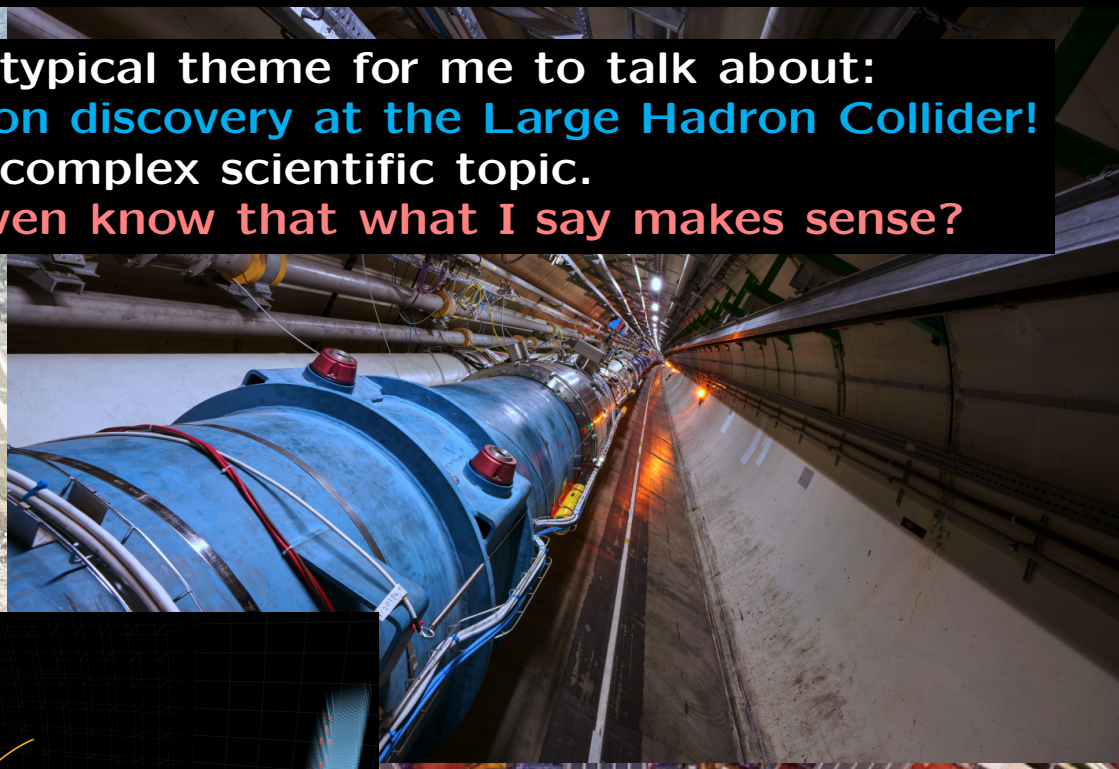
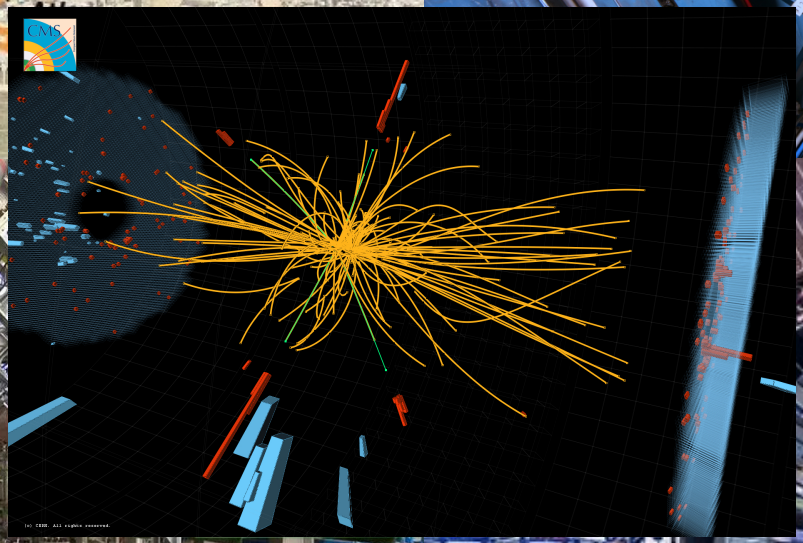
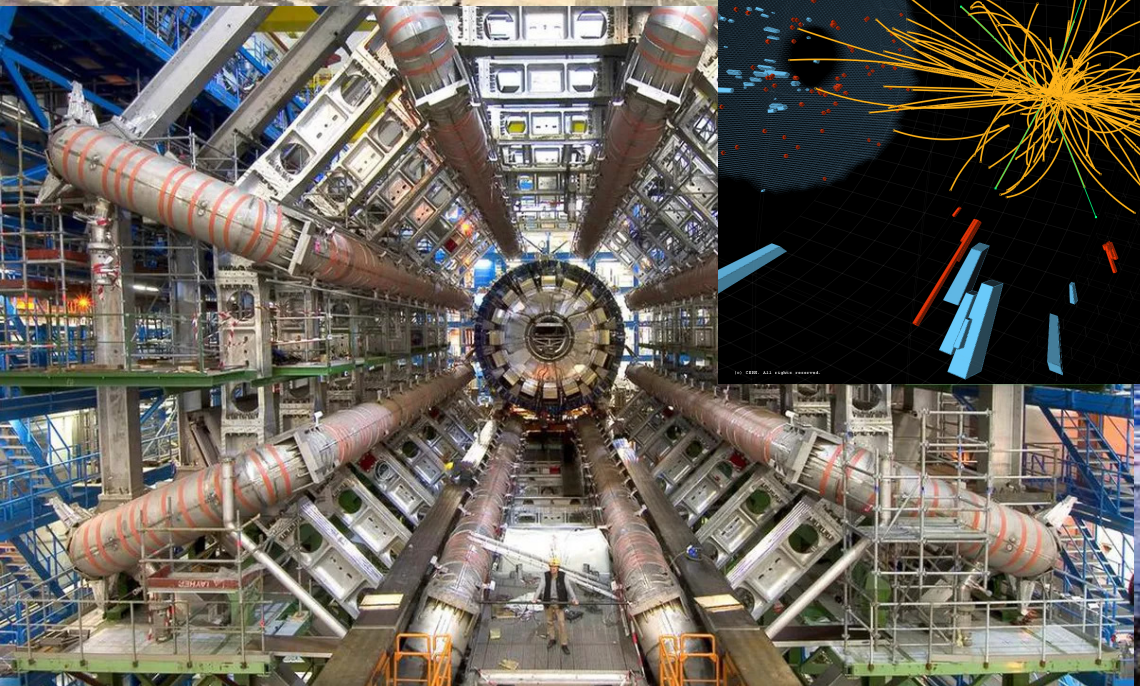
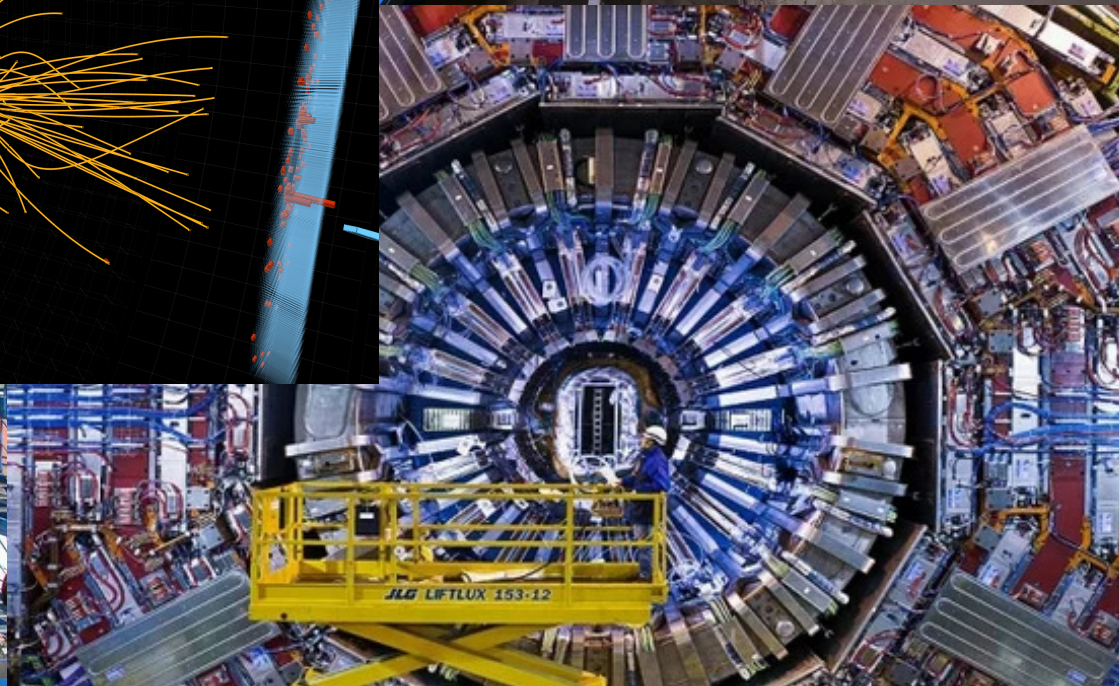
How do you even know that what I say makes sense?











trust the scientists?

With respect to particle physics, people tend to trust the experts:

- no strong commercial or political interest
- long consistent history over decades
- openness about incomplete or conflicting results
- not much at stake for the general public

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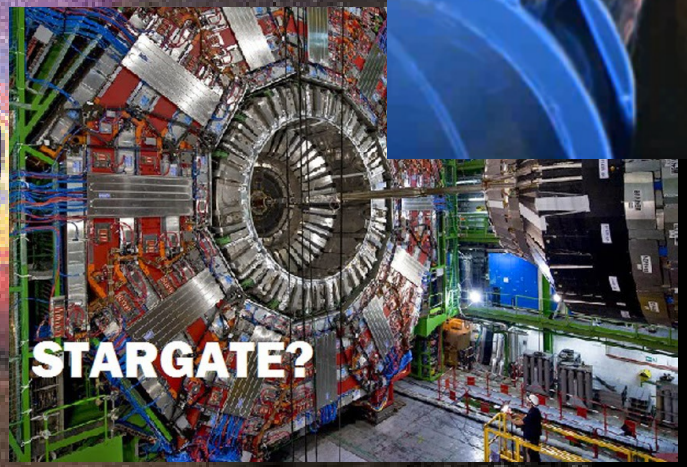
...even though we do have our share of conspiracy theories!

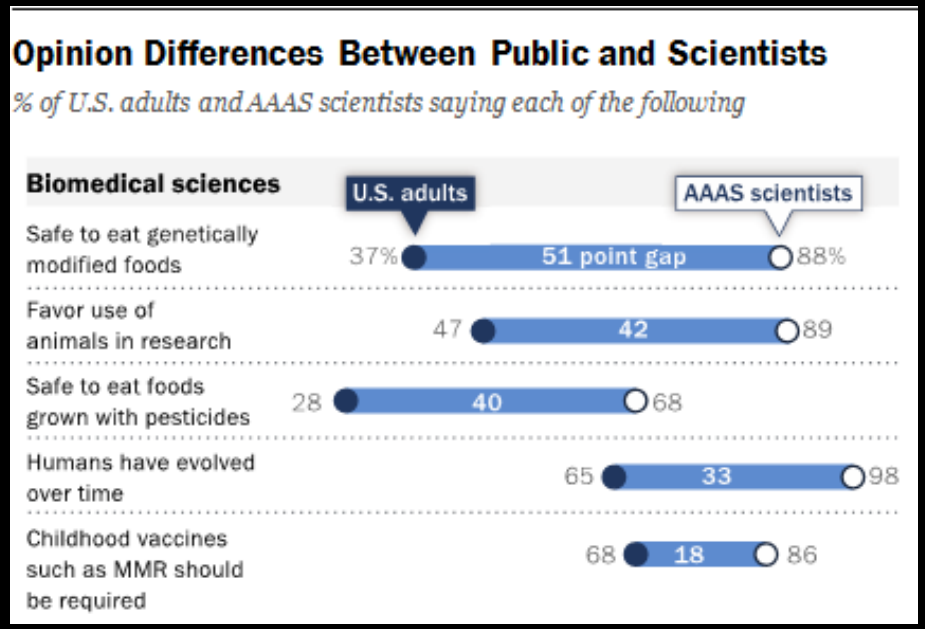


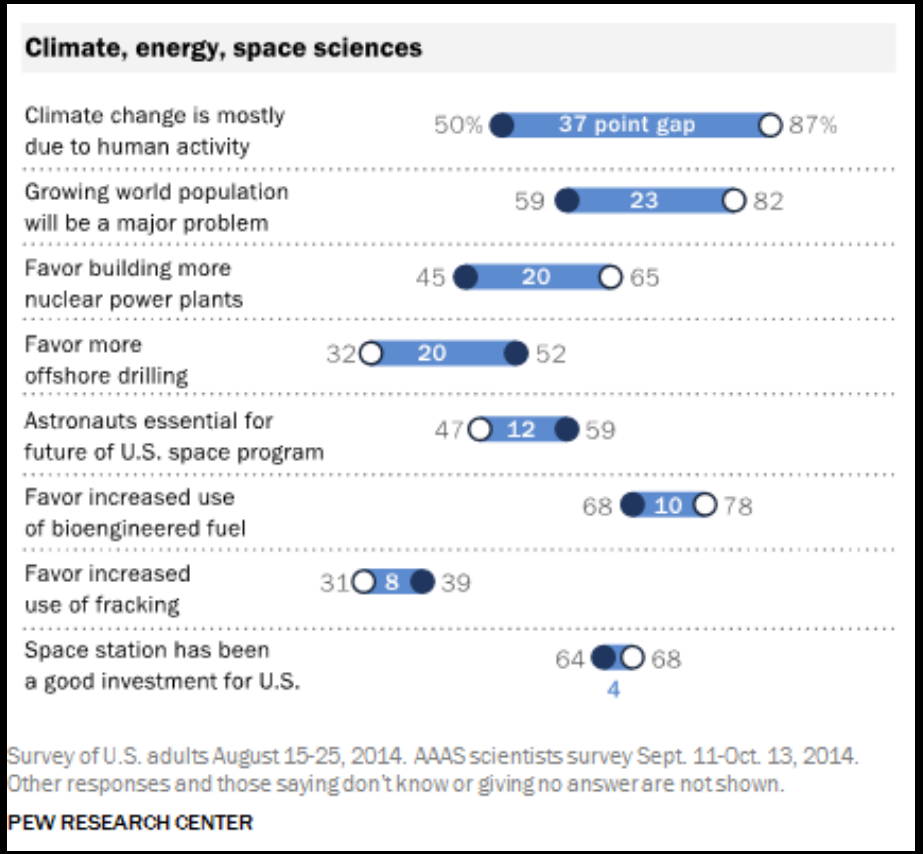
trust the scientists?

Topics of high impact, more general interest, political or commercial stakes:

Pew Research Center polls found big discrepancies between what scientists say and public opinion.

Limited trust in scientists?





Note: poll includes scientists of all disciplines — not all of them have actual expertise in the field being asked about

scientists

scientists

So who or what are scientists?

Scientists are not some secretive elite society with access to undisclosed sources of information.

Scientists

- are normal people trained to uncover new knowledge using specific methods
- tend to scrutinize their own and other scientists' results thoroughly
- need time to obtain and check results

pseudoscience

Generally, scientists are honourable people
who follow rigorous procedures
to make their results as reliable as possible.
However, not everything claiming to be science is trustworthy:

- pseudoscience, not following procedures to ensure a valid outcome
- attempts to influence science for political or personal gain,
- and in very rare cases even fraud and malice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Editorials

Wakefield's article linking MMR vaccine and autism was fraudulent

BMJ 2011 ; 342 doi: https://doi.org/10.1136/bmj.c7452 (Published 06 January 2011)
Cite this as: *BMJ* 2011;342:c7452

Fiona Godlee, editor in chief,Jane Smith, deputy editor,Harvey Marcovitch, associate editor

[1] *BMJ, London, UK*

Correspondence to: F Godlee fgodlee@bmj.com

Clear evidence of falsification of data should now close the door on this damaging vaccine scar

"Science is at once the most questioning and . . . sceptical of activities and also the most trusting," said Ar
1989. "It is intensely sceptical about the possibility of error, but totally trusting about the possibility of frau
implied a link between the measles, mumps, and rubella (MMR) vaccine and a "new syndrome" of autism a

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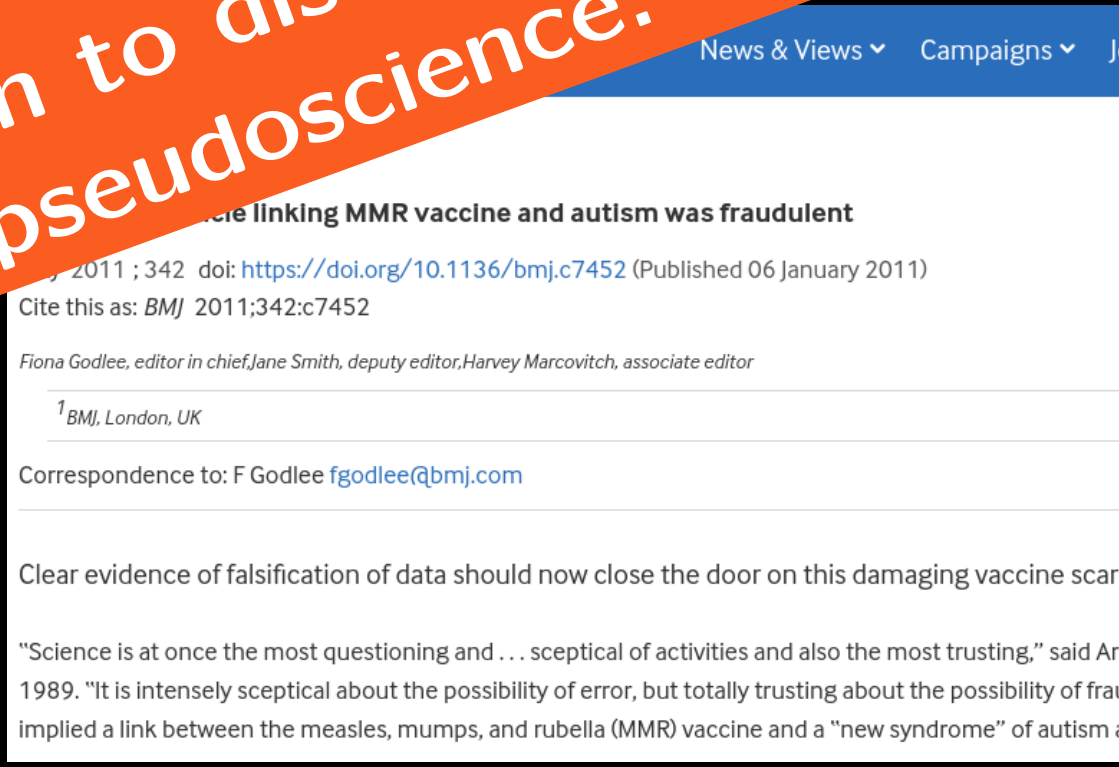
This undermines trust in real experts!
We need to learn to distinguish science from pseudoscience.



aim for today

The best way for you to distinguish real science from pseudo–science is not to look at individual results, but to understand the scientific method.

The aim is to help you understand

- which claims can be trusted and which ones can't,
- why we need to keep politicians/lobbyists/policymakers away as much as we can

and why should you care?

Science is very important for all of us!

Science can help us survive

- as individuals (medical research, material science etc)
- as a civilization (climate science, planetary exploration etc)

Science can make our lives better

- application in technology (energy, IT, transportation, media)
- agriculture, food production

We need to identify and strengthen good science for this to pan out.
Being here today shows that you do care — thank you!

➡ So let's have a look at how science works.

what is science

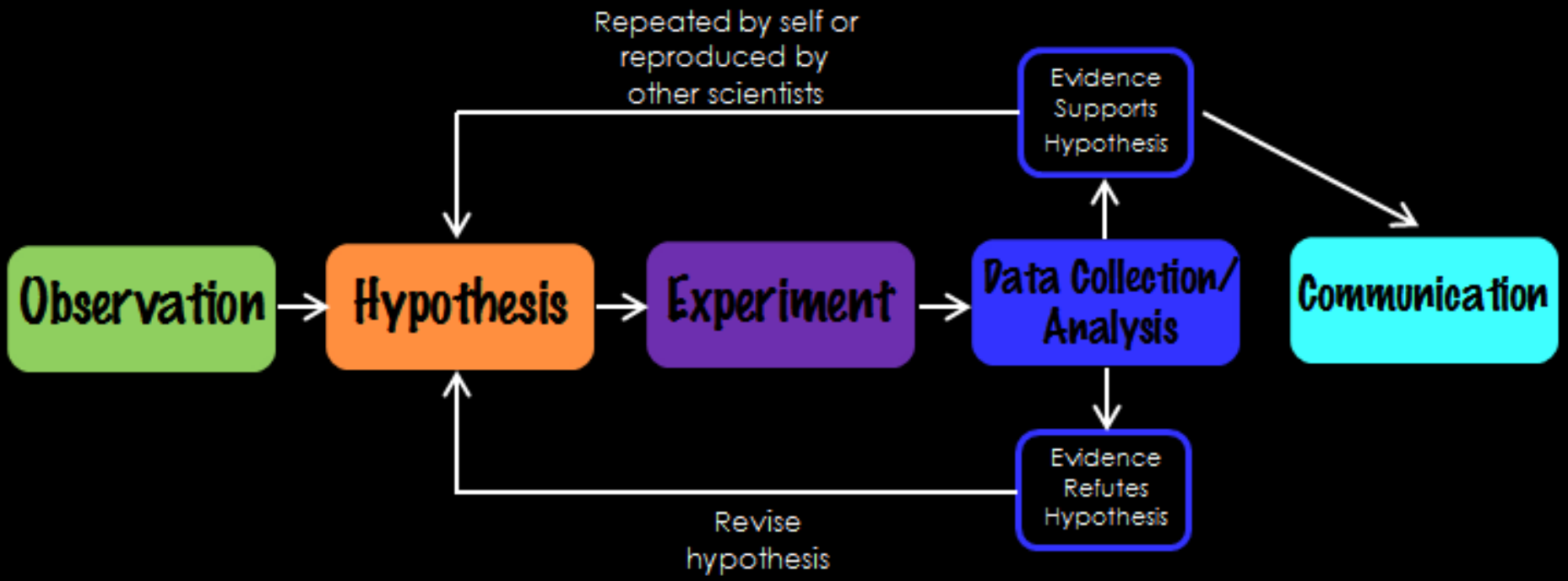
definition of science (Encyclopaedia Britannica):

"Science, any system of knowledge that is concerned with the physical world and its phenomena and that entails unbiased observations and systematic experimentation. In general, a science involves a pursuit of knowledge covering general truths or the operations of fundamental laws."
"Observing the natural world and paying attention to its patterns has been part of human history from the very beginning. However, studying nature to understand it purely for its own sake seems to have had its start among the pre-Socratic philosophers of the 6th century BCE, such as Thales and Anaximander."

the scientific method

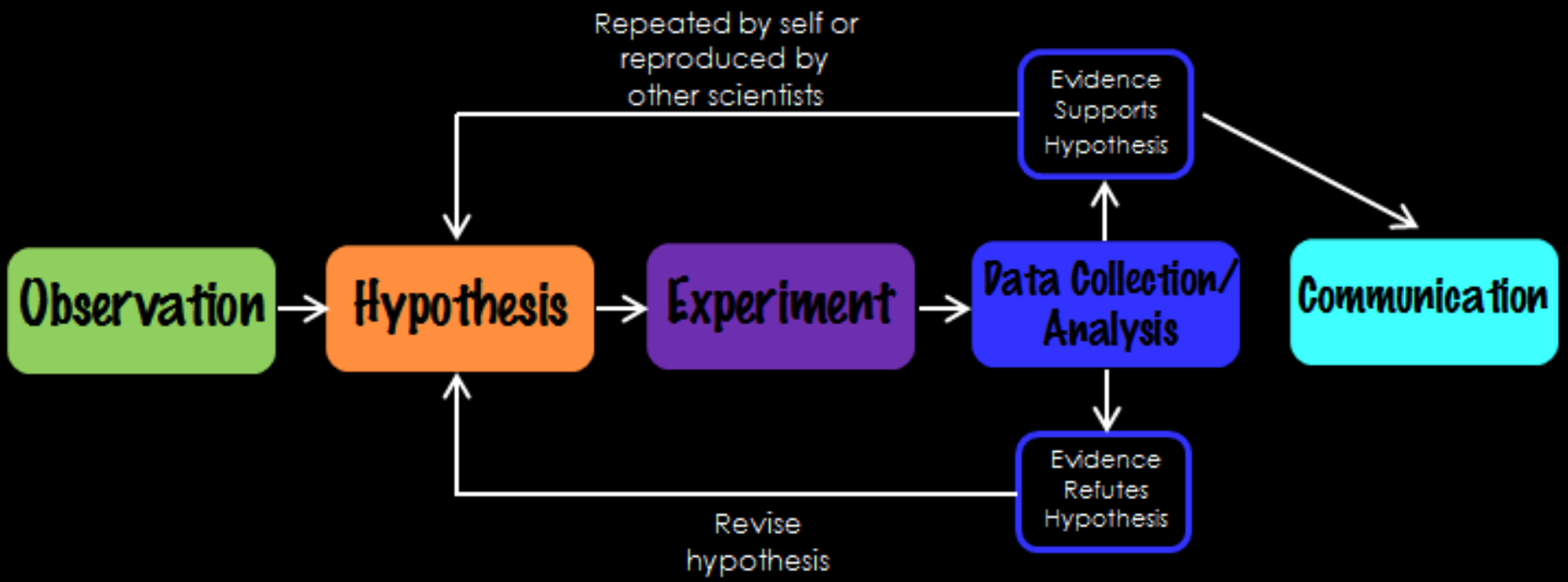
core of what science is about:
"unbiased observations and systematic experimentation"

Various steps taken in ancient Egypt, Greece, Arabia towards formalising this
Modern interpretation of the scientific method formed in 17th century:
Francis Bacon, René Descartes, Galileo Galilei, Isaac Newton



the scientific method

crucial aspects of the scientific method:



- testable predictions
- replicability
- peer review

Science is predominantly defined through its methods, not through a particular set of results.

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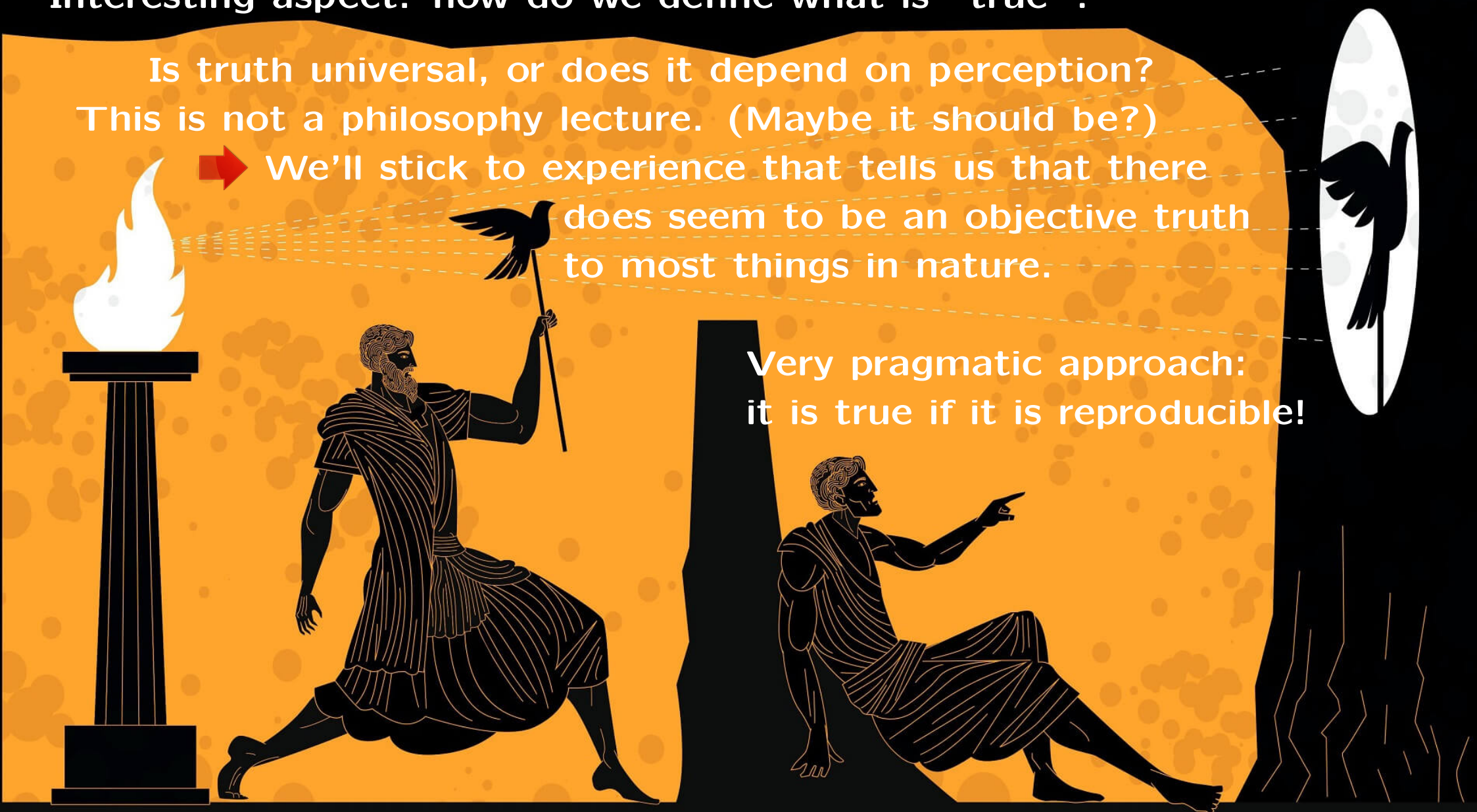
theory of science

Theory of science is an entire discipline of philosophy.
Interesting aspect: how do we define what is “true”?

Is truth universal, or does it depend on perception?
This is not a philosophy lecture. (Maybe it should be?)

➡ We’ll stick to experience that tells us that there does seem to be an objective truth to most things in nature.

Very pragmatic approach:
it is true if it is reproducible!



scientific method: justification

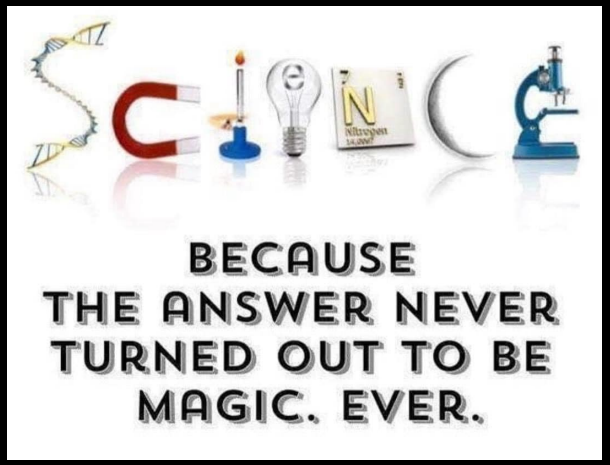
There is no fundamental reason why the scientific method works.

Alternative realities are imaginable where

- experiments never give the same result when repeated,
- negotiation with a higher intelligence affects results.

And yet, science is not just a belief system!

We use the scientific method because thousands of years of experience show that it works.



Items designed based on scientific principles (computers, antibiotics, cars, etc etc) work predictably and reliably.

theories

Mostly discussed test of individual hypotheses so far.
Individual measurements or experiments are rarely without context!

Sets of experiments lead to the derivation of general principles —
a consistent and underlying explanation for what we observe.

This is called a theory.

- Ideally, we should make observations first
  and then construct a theory framework explaining them.
  — Inductive method
- More often, we have a preconceived theory
  and try to confirm/falsify predictions derived from it.
  — Deductive method

Both approaches are valid!

Occam's razor

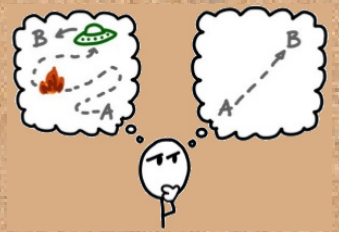
One of our principles is to keep the explanation as simple as possible.
When you flip a coin it ends up heads or tails a similar number of times because

a) the motion is random and the coin is symmetric

b) there are hidden magnets spread all over earth that monitor and control coin motion to ensure coin-tossing is always fair

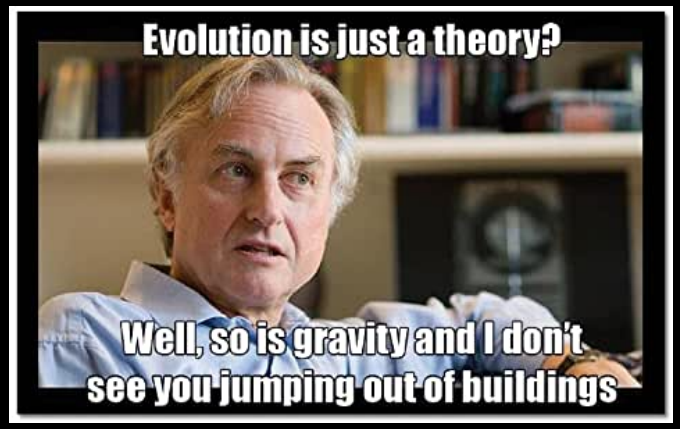
Which do you think is more likely?

- We try to find the simplest theory that accounts for all observations



it's not "just a theory"

A theory is the ultimate outcome of science! This is often misunderstood:



"theory of evolution" does not mean "evolution is just a theory".
"theory of gravity" does not mean "gravity is just a theory".

Both evolution and gravity are directly observed facts.
The theory of evolution/gravity is our best explanation for how it works.

Even if the theory of gravity has still lots of open questions,
this does not mean we doubt the existence of gravity.
It just means we haven't fully understood the underlying mechanism yet.

proving a theory

When can we conclude a topic is fully understood?
How can we prove that our theory is correct?

We can't!
It is fundamentally impossible to prove a theory right,
we can only prove it wrong.

- Despite passing all experimental tests so far, the next one could fail.
- Even if this theory explains all observations, so could others.

That means that science will never be "done".

paradigms

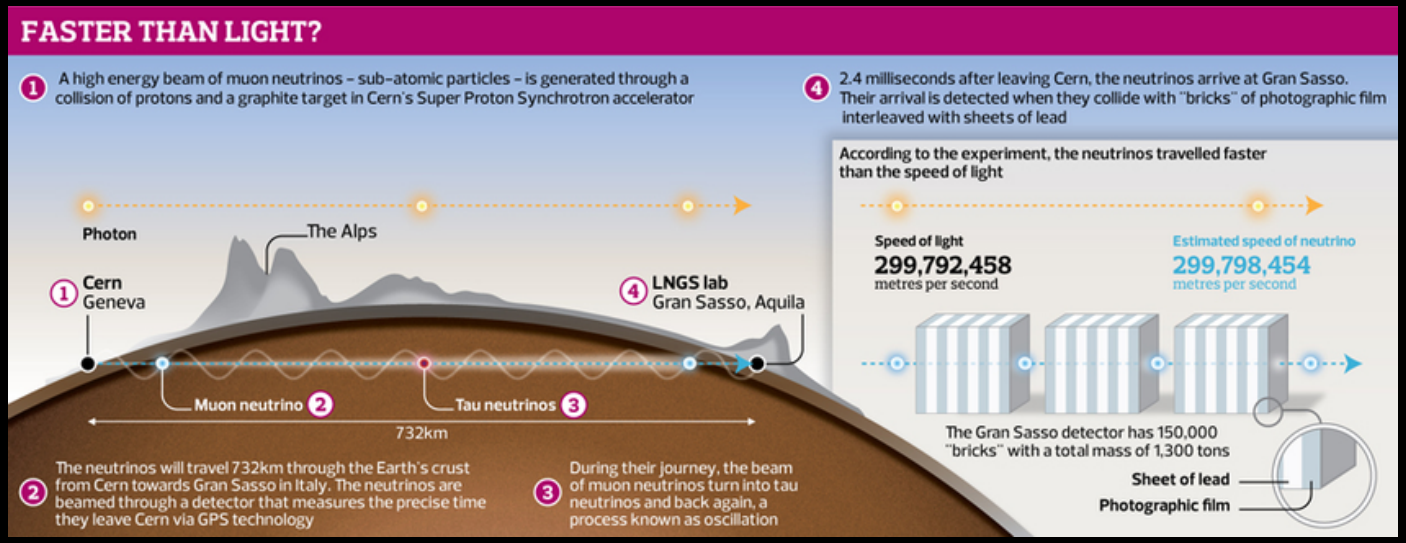
Once we have a theory that has withstood all tests for a while, it becomes a paradigm.

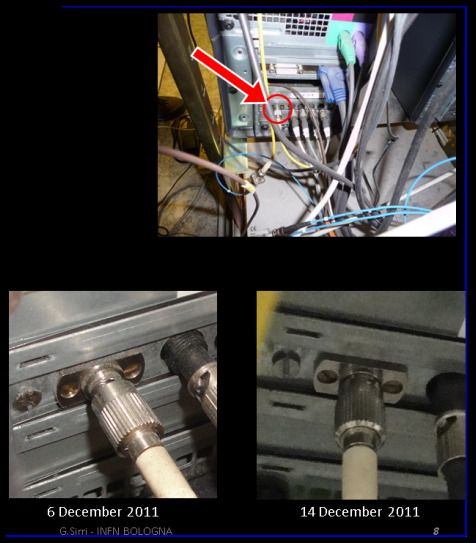
Incompatible observations are met with extra scepticism at that stage.
Very strong evidence is needed to trigger a paradigm shift.

Example paradigm shifts in physics:

- geocentric cosmology → heliocentric cosmology
- classical physics → quantum physics

Example of a failed challenge to a paradigm: faster than light neutrinos!





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how not to get it wrong

measurements in advanced science are difficult!

simple example:
are coin tosses really random?
➡ throw 100 times, count heads/tails

Now imagine doing this in darkness,
having to feel which side is up!

How often do you get this right?
Will the errors be random?
Or will they distort your result?

Your result will be less reliable,
but it might still be good enough —
need to figure out your measurement precision!

measurement precision

Most measurements have limited precision.
Often enough the actual value of the measurement is useless without good knowledge of its uncertainty.
The value of a measurement alone does not tell you much.

"My sofa is about 1 metre high."
"Well, my staircase is 1.02 metres wide."
"Will the sofa fit through it or not?"

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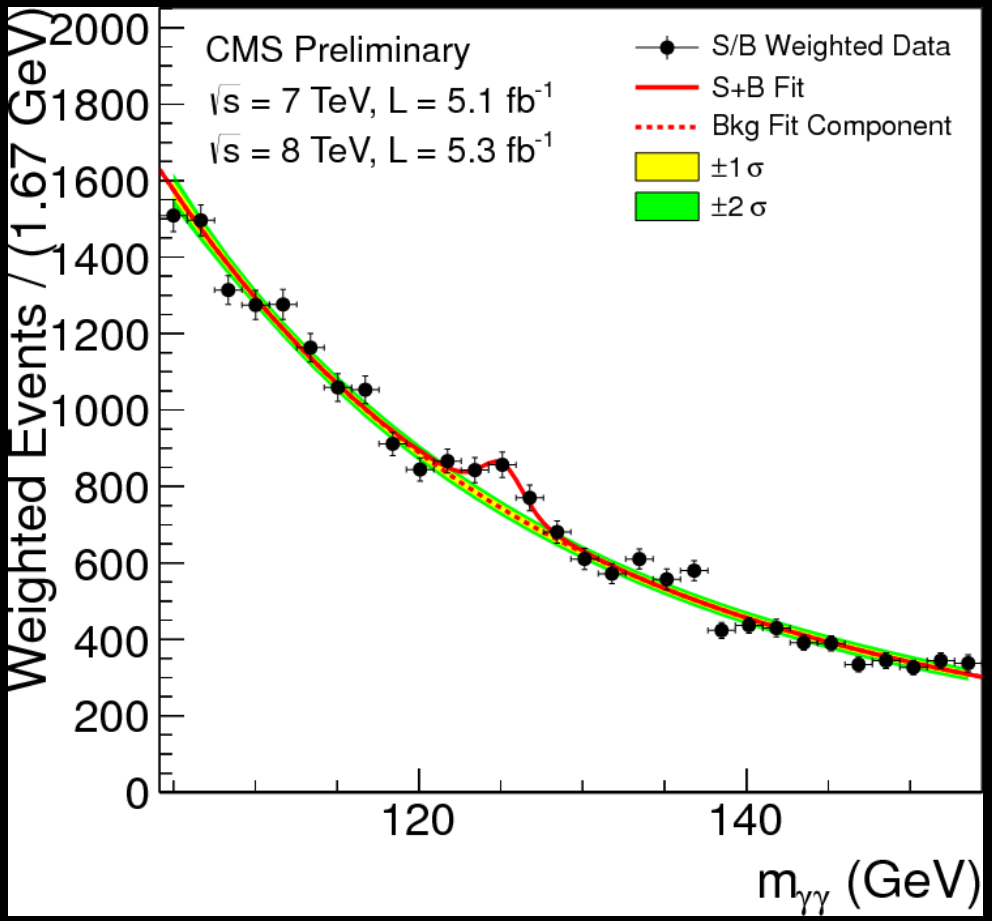
Different types of uncertainties:

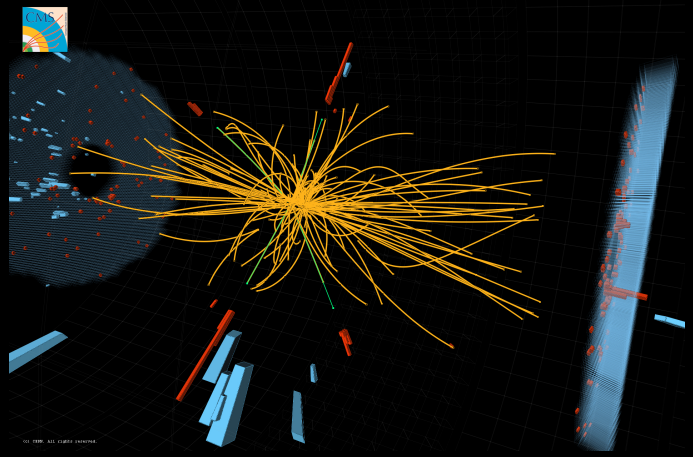
- random measurement errors
  - I measured three times, always within a cm or so
- systematic uncertainties
  - the handrail
  - moving around the corner

measurement precision

determining the uncertainty of a measurement tends to be a lot more difficult than performing the actual measurement!



CMS Collaboration, $H \to \gamma\gamma$, 2012

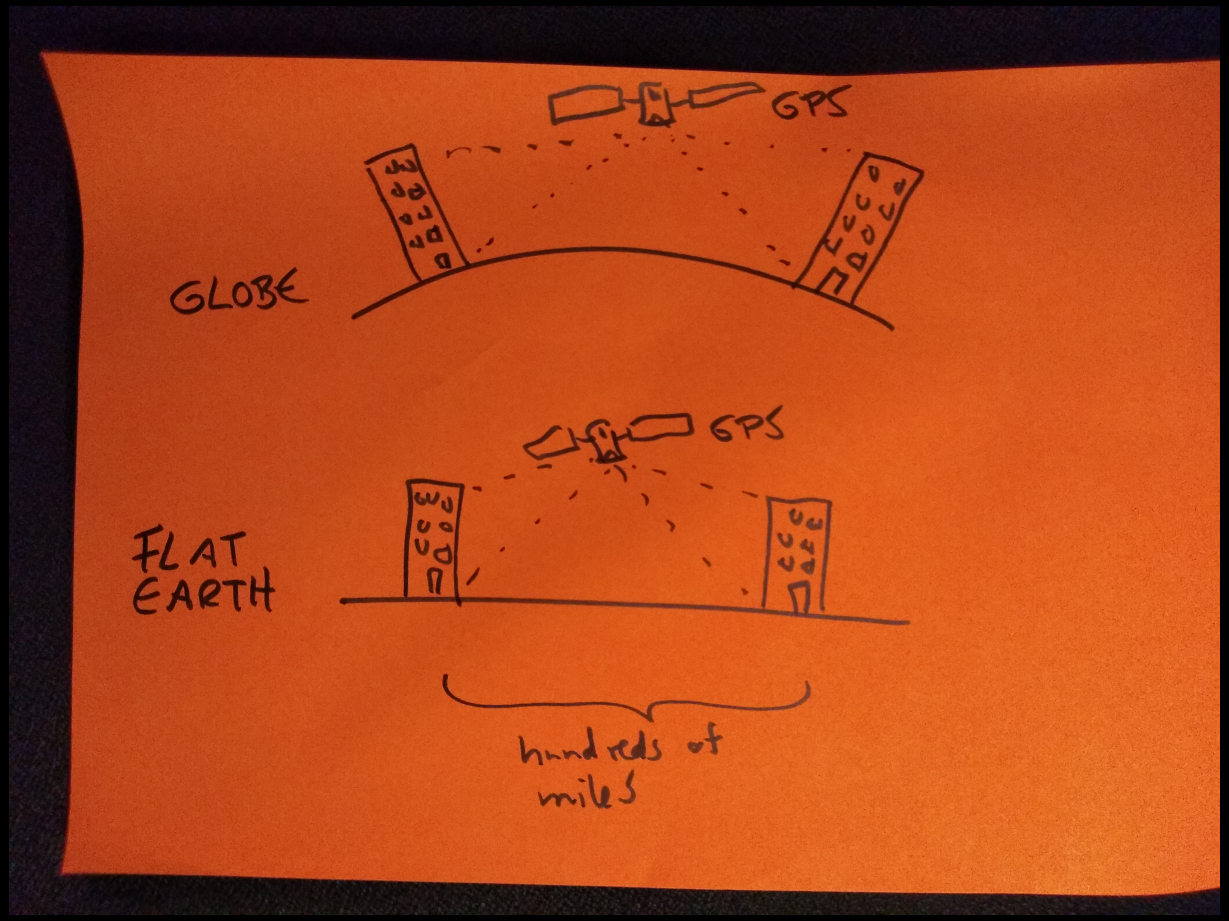


Look at candidates for Higgs bosons in LHC collisions
Broad distribution: background
Small peak: more candidates found than expected from background!
But is this within normal fluctuations?
Or is it definitely real?

biases and other errors

Unexpected effects can mess up an experiment completely!

- see “faster than light” neutrinos earlier
- or this example from a Flat Earth documentary:



Measure distance between skyscrapers in different cities at top and bottom.

Flat Earth: expect same distance

Globe: expect top measurement larger

result: same distance!

why?

That’s why we have thorough peer review!

pseudoscience

Not everything sold as science is actually science!
Pseudoscience is disguised as science,
but does not adhere to scientific methods

- results and claims are at best questionable, or entirely invalid

Why is pseudoscience so prevalent?

- cognitive biases (confirmation bias, traditions, etc)
- strong desire to find meaning, connections, control, hope
- lack of trust in mainstream society
- Dunning-Kruger effect
- "inverted snobbery about educational privilege" (The Guardian)
- lack of education

pseudoscience

A specific example: homeopathy, representative of alternative medicine

Homeopathy uses solutions of active ingredients
that are diluted to much less than a single atom

Homeopathy is clearly ineffective:

- proposed mechanism contradicts scientific principles
- clinical studies consistently demonstrate lack of effectiveness

However, practitioners and patients claim it works! How so?

This is in part a communication issue.
"It doesn't work" actually means "it works no better than a placebo".
The placebo effect is real.

Due to the placebo effect it is impossible for a practitioner to distinguish whether homeopathy itself has an effect,
only controlled trials can do that.

pseudoscience

CRAZY PHENOMENON	IF IT WORKED, COMPANIES WOULD BE USING IT TO MAKE A KILLING IN...	ARE THEY?
REMOTE VIEWING	OIL PROSPECTING	
DOWSING		
AURAS	HEALTH CARE COST REDUCTION	
HOMEOPATHY		
REMOTE PRAYER		
ASTROLOGY	FINANCIAL/BUSINESS PLANNING	
TAROT		
CRYSTAL ENERGY	REGULAR ENERGY	
CURSES, HEXES	THE MILITARY	
RELATIVITY	GPS DEVICES	✓
QUANTUM ELECTRODYNAMICS	SEMICONDUCTOR CIRCUIT DESIGN	✓

distinction by actual economic impact?

xkcd.com

pseudoscience

A Rough Guide to

SPOTTING BAD SCIENCE

Being able to evaluate the evidence behind a scientific claim is important. Being able to recognise bad science reporting, or faults in scientific studies, is equally important. These 12 points will help you separate the science from the pseudoscience.

1. SENSATIONALISED HEADLINES

Article headlines are commonly designed to entice viewers into clicking on and reading the article. At times, they can over-simplify the findings of scientific research. At worst, they sensationalise and misrepresent them.

2. MISINTERPRETED RESULTS

News articles can distort or misinterpret the findings of research for the sake of a good story, whether intentionally or otherwise. If possible, try to read the original research, rather than relying on the article based on it for information.

3. CONFLICTS OF INTEREST

Many companies will employ scientists to carry out and publish research - whilst this doesn't necessarily invalidate the research, it should be analysed with this in mind. Research can also be misrepresented for personal or financial gain.

7. UNREPRESENTATIVE SAMPLES USED

In human trials, subjects are selected that are representative of a larger population. If the sample is different from the population as a whole, then the conclusions from the trial may be biased towards a particular outcome.

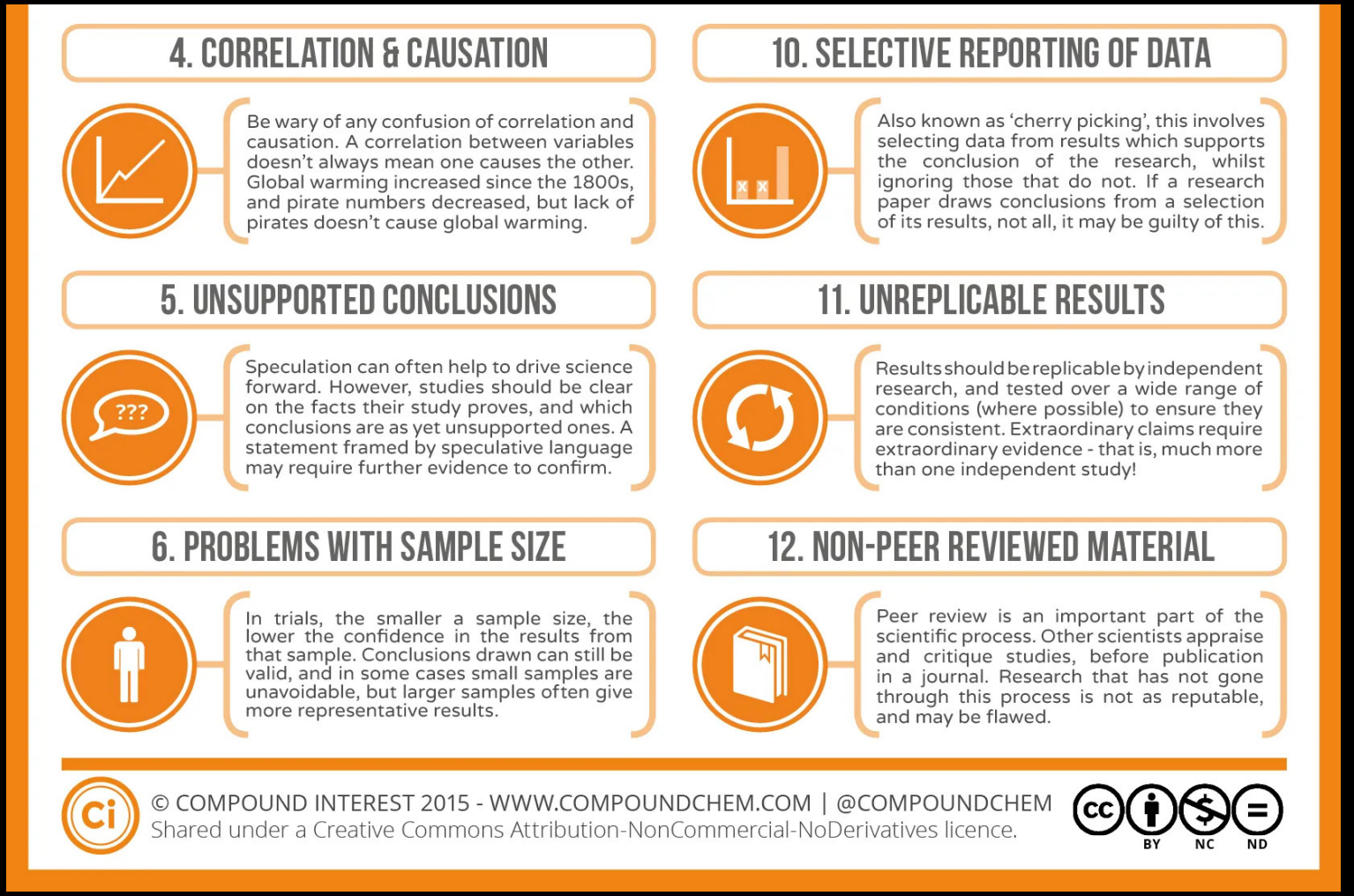
8. NO CONTROL GROUP USED

In clinical trials, results from test subjects should be compared to a 'control group' not given the substance being tested. Groups should also be allocated randomly. In general experiments, a control test should be used where all variables are controlled.

9. NO BLIND TESTING USED

To try and prevent bias, subjects should not know if they are in the test or the control group. In 'double blind' testing, even researchers don't know which group subjects are in until after testing. Note, blind testing isn't always feasible, or ethical.

pseudoscience



4. CORRELATION & CAUSATION

Be wary of any confusion of correlation and causation. A correlation between variables doesn't always mean one causes the other. Global warming increased since the 1800s, and pirate numbers decreased, but lack of pirates doesn't cause global warming.

5. UNSUPPORTED CONCLUSIONS

Speculation can often help to drive science forward. However, studies should be clear on the facts their study proves, and which conclusions are as yet unsupported ones. A statement framed by speculative language may require further evidence to confirm.

6. PROBLEMS WITH SAMPLE SIZE

In trials, the smaller a sample size, the lower the confidence in the results from that sample. Conclusions drawn can still be valid, and in some cases small samples are unavoidable, but larger samples often give more representative results.

10. SELECTIVE REPORTING OF DATA

Also known as 'cherry picking', this involves selecting data from results which supports the conclusion of the research, whilst ignoring those that do not. If a research paper draws conclusions from a selection of its results, not all, it may be guilty of this.

11. UNREPLICABLE RESULTS

Results should be replicable by independent research, and tested over a wide range of conditions (where possible) to ensure they are consistent. Extraordinary claims require extraordinary evidence - that is, much more than one independent study!

12. NON-PEER REVIEWED MATERIAL

Peer review is an important part of the scientific process. Other scientists appraise and critique studies, before publication in a journal. Research that has not gone through this process is not as reputable, and may be flawed.

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limits of science

We discussed pseudoscience because it infringes on actual science.
The scientific method is universal.

Is there anything not accessible to science?
Does science have limits at all?
What is its scope?

"You cannot prove love"

limits of science

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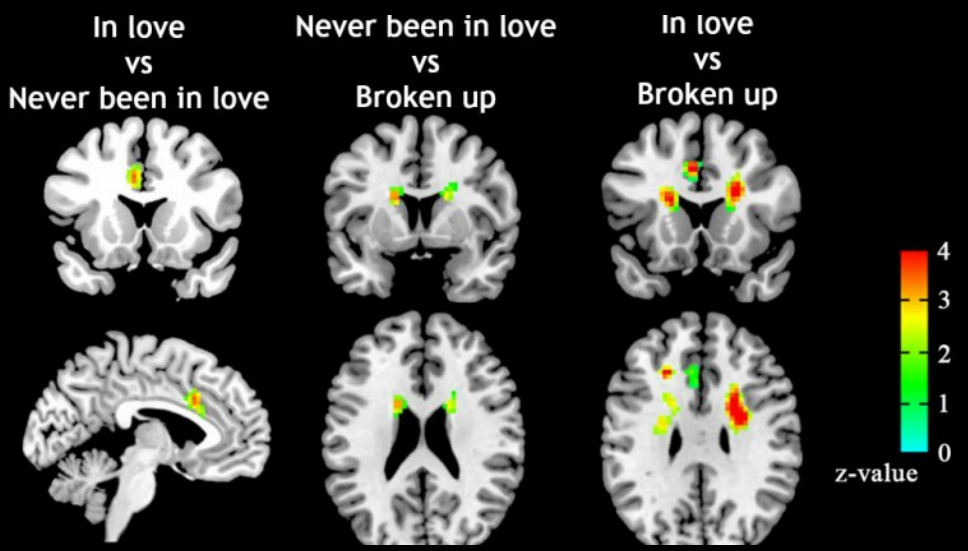
Does science have limits at all?
What is its scope?

"You cannot prove love" ... except, we can! (But do we want to?)



fMRI scans of students at Southwest University in China

limits of science

We discussed pseudoscience because it infringes on actual science.
The scientific method is universal.

Is there anything not accessible to science?
Does science have limits at all?
What is its scope?

All statements about reality are accessible to scientific scrutiny in principle. That includes human emotions and religious concepts.
However, there are ethical limits to science:

- established ones such as medical experiments on humans
- evolving ones such as medical experiments on animals

concluding remarks

This was quite a journey through many aspects of science!

Science is an exceptionally powerful tool.

Understanding the principles behind science is important for everyone.
Understanding the language of science is too ("theory", "ineffective").

Being a scientist is not so much about accumulating a lot of knowledge.
It's more about learning to obtain answers using a specific process.

This process is robust and trustworthy, but nobody is perfect.

What science has achieved for us is absolutely amazing. We should celebrate what has been achieved and support science in going beyond.