Energy; the process of science

Astronomy 101
Syracuse University, Fall 2020
Walter Freeman

October 8, 2020

We saw last time that Newton's two big ideas let us predict the motion of all the planets.

Newton's second law

$F = ma$ or $a = F/m$

Tells us the size of the acceleration created by any force

Gravitation

$$F_g = \frac{G m_A m_B}{r^2}$$

Tells us how big the gravitational force is between two objects A and B whose centers are a distance r apart

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Kepler knew that there were underlying causes of his laws, but he wasn't good enough at math to discover them. Can we do better than Kepler? Can we find *general principles of physics* that give us insight without needing hard math?

The conservation of energy

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Energy comes in two kinds:

- Kinetic energy: the motion of objects
  - Heat, light, and sound energy are technically kinds of kinetic energy, but we usually call them by those names instead
- Potential energy: objects are in a place where they are attracted to each other
  - If I let them go, they'll move toward each other
  - *Potential* to become kinetic energy
  - Chemical energy is a kind of potential energy
  - The one we really care about is *gravitational potential energy*

The big idea: conservation of energy

Energy can never be created or destroyed.
It can only be changed from one form to another.

A pendulum swings back and forth: it converts gravitational potential energy to kinetic energy and back again.

This perspective is universal: all forces just convert energy from one sort into another

A short history of some energy:

- Hydrogen in the sun fuses into helium
- Hot gas emits light
- Light shines on the ocean, heating it
- Seawater evaporates and rises, then falls as rain
- Rivers run downhill
- Falling water turns a turbine
- Turbine turns coils of wire in generator
- Electric current ionizes gas
- Recombination of gas ions emits light

- Nuclear energy $\rightarrow$ thermal energy
- Thermal energy $\rightarrow$ light
- Light $\rightarrow$ thermal energy
- Thermal energy $\rightarrow$ gravitational pot. energy
- Gravitational PE $\rightarrow$ kinetic energy and sound
- Kinetic energy in water $\rightarrow$ KE in turbine
- Kinetic energy $\rightarrow$ electric energy
- Electric energy $\rightarrow$ chemical potential energy
- Chemical PE $\rightarrow$ light

A pendulum, revisited

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... what happens to its *total* energy?

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D: Let's try it and find out!

E: Let's try it with a really big wrecking ball!

Conservation of energy, in general

Conservation of energy is *the biggest idea in science.*

Even if you can't track precisely how something moves, you can figure out a *lot* just from tracking the flow of energy.

I can calculate very easily, for instance:

- ... how long my laptop will run on its battery (chemical -¿ electrical)
- ... how much it will heat up as it does a calculation (electrical -¿ heat)
- ... how many Clif Bars I need to eat to climb a mountain (chemical -¿ gravitational potential)
- ... how much uranium a reactor must fission to power Syracuse (nuclear potential -¿ electrical -¿ other things)

Conservation of energy, for the Sun

One question we had for a long time: *how old are the Earth and the Sun?*

Maybe the source of the Sun's energy is the gravitational energy of the gas that makes it up!

- The matter in the Sun collapses under its own gravity
- As it "falls" it converts that gravitational potential energy into heat
- That heat is converted into light (we'll learn how in a few weeks)
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But we can work out how long this could sustain the Sun:

- We know the rate that the Sun converts heat into light ("how many joules per year")
- We know how much gravitational potential energy the Sun has
- Do some math:

$$\text{(lifespan of Sun in years)} = \frac{\text{(amount of potential energy, in joules)}}{\text{(rate of using energy, in joules per year)}}$$

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The answer: a few hundred thousand years.
This can't be why the Sun shines!

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What [they] have given us we must guard and try to keep alive with all our strength if humanity is not to lose its dignity, the security of its existence, and its joy in living.

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Tell your son to stop trying to fill your head with science, for to fill your heart with love is enough!

–Richard Feynman, 1981

The nature of science

The discoveries of Kepler, Galileo, and Newton did more than explain the solar system.

They merged disciplines that had been separate since the time of Ptolemy:

Natural philosophy

- "What is the truth of nature?"
- Focus on careful logic and reasoning
- Uses models and mathematics sometimes, but not too concerned with their precision
- More concerned with logic and thought than careful observation of nature itself

Greco-Egyptian astronomy

- Asks the question "How do things up there move?"
- Focus on detailed measurement and calculation
- Uses experiments when possible to measure things of interest (size of Earth)
- Builds models and uses mathematics
- Attempts to explain the details of observed motions in the sky

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- Concerned with the search for Truth
- Focus on careful logic and reasoning
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Greco-Egyptian astronomy

- Concerned with predicting motion of the sky
- Focus on detailed measurement
- Uses experiments when possible to measure things of interest (size of Earth)
- Builds models and uses mathematics to determine their predictions

Modern science

- Seeking Truth *through* precise predictions
- Models (often mathematical) are seen *as* what is true
- They must match precise measurements of what happens in Nature
- Design experiments to measure exactly what we want
- Careful logic and reasoning involved to interpret observations, get predictions from models, and avoid errors

The scientific method

- "Huh, that is interesting – I wonder how it works?"
- Develop a *model*: a picture that explains as much as you can
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7. Body of supporting evidence grows
8. Continually seek to expand the *scope* of the model with more observations

Properties of science

Broad properties of science:

- **Empiricism:** the ultimate authority is what we measure about the world around us, not what we think.
- It is vitally important that the conclusions we *claim* come from our data actually do
- There's a whole field of math dedicated to data analysis: *statistics*. It has to be done honestly and well!

- **Self-skepticism:** someone making a scientific claim should actively search for things that might prove themselves wrong
- Potentially refuting arguments/evidence are a *good* thing

- **Universality:** the laws of nature apply in all places and times, and to all things (including humans)
- Since the laws of nature are universal, they form a coherent whole
- Any new finding must find its place within the framework of preexisting measurements and principles
- Very rarely previously-accepted things get overturned; more often they are *extended*

- **Objectivity:** scientific ideas, or the evaluation of them, should be independent of any particular human perspective
- Science is not about *you* (whoever you are)
- Criticism of other people's ideas isn't about them, either

Properties of science, in our story

Science – as a means of seeking truth – has a few fundamental properties:

- **Empiricism:** the ultimate authority is what we measure about the world around us, not what we think.
- The new scientific approach to mechanics started with the observations of the planets from Uraniborg, observations made by Galileo and Newton, and then built from there
- This is different from the old Greek natural philosophy, that valued *pure thought* over the dirty work of *measuring things*

- **Self-skepticism:** someone making a scientific claim should actively search for things that might prove themselves wrong
- Kepler was convinced planetary orbits were circles and tried *very hard* to make circular orbits work... until the data convinced him otherwise
- Tycho did *not* do this: when he observed a lack of stellar parallax, he didn't consider the possibility that the stars might just be very far (250,000 AU) away

Properties of science, in our story

Science – as a means of seeking truth – has a few fundamental properties:

- **Universality:** the laws of nature apply in all places and times, and to all things (including humans)
- Newton's big idea: $F = ma$ explains all motion, in space and on Earth, in the same way
- This was different from the previous belief that matter on Earth worked one way, and matter in space worked a different way

- **Objectivity:** scientific ideas, or the evaluation of them, should be independent of any particular human perspective
- Earth was no longer given a privileged place or special rules
- Just because Galileo threatened a dominant religious/political paradigm doesn't make him wrong!

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Science doesn't attempt to answer everything, only:

- "What is the Universe made of?"
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What we learn from science *does* influence our answers, though!

Principles that come from these:

Empiricism: A model is only valid within the realm of data against which it has been checked.

- Precision: is the law of gravity valid to one part in a billion? One part in a trillion?
  - "Equivalence" (all objects fall at the same rate in a vacuum): holds to one part in 10^{17}
  - Universal gravitation: **Not quite true in regions of strong gravity!**
  - Conservation of energy: seems absolutely solid, from fragments of an atom to black holes
- Scope and scale: Is Newtonian mechanics valid for very fast things? Things as large as a galaxy? Things as small as an atom?
  - Very fast things: **not quite**, since close to the speed of light space and time get mixed up
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- Universality helps with this, but we have to be careful
  - We don't need to drop every rock off a cliff to understand projectile motion...
  - ... but it's hard to know exactly what limits we have to probe

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Self-skepticism: It's the duty of the claimer to search for experiments that they can do to possibly prove themselves wrong.

- "Neutrinos faster than light"
- The caution of LIGO after their Nobel Prize-winning discovery

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- The most powerful evidence for an idea is an experiment that will produce something unexpected if you're right, but can conclusively disprove your idea if you're wrong
- In 1917 Einstein proposed a radical new way of thinking about gravity
- ... and calculated from it two things, one of which could be tested the next time there was an eclipse
- If Einstein was wrong, we'd know it immediately.

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- These experiments need to be as diverse as possible: this is hard, since you have to check things you're not familiar with

Science: a powerful, corruptible tool

This synergistic enterprise has been behind a vast amount of progress for humanity in the last 350 years.

As with anything powerful, this process can be corrupted.

Your second paper will involve analyzing an incident where it has been.

Let's look at how that can happen.

Common fallacies

During this process, please freely discuss your own examples.

I'd like to spend much of the time today "off script" – talking about your examples, rather than my slides.

I'll also be steering clear of any topics that are "hot-button". Feel free to write about these in your papers! But I won't be using them as examples here: climate change, creationism, vaccination, drug laws...

Two notes

"Scientific integrity" is not a reference to the usual sort of integrity – to being a good, honest person.

It is possible to do horrible things in the process of research, but do research that is well-grounded and draws correct conclusions.

It is also possible to be an honest, diligent scientist and make mistakes, and come to incorrect conclusions because of flaws in the application of the scientific process. (I have done this myself.)

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There is a difference between a flawed process of science and simply being wrong. Everyone makes errors.

The scientific process has safeguards in place to avoid those errors from spreading too far, and we bypass those safeguards at our peril.

There is a difference between a flawed process of science and being a terrible person, too. We aren't talking about experiments that hurt their subjects, either.

Measurement bias

One example of how this goes wrong: **measurement bias.**

Using limited, biased data will give you a biased result – whether accidentally or intentionally

Example: the "fifth force", a proposed modification to gravity

- People in the 1980's uncovered evidence that gravity might depend on the type of matter
- They made careful measurements from the top of a tower that seemed to confirm this
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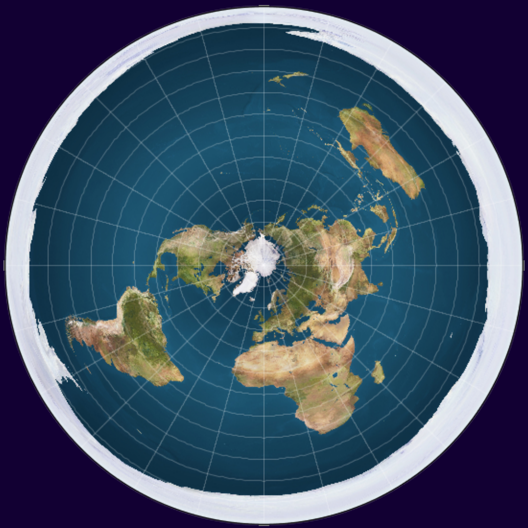
- Nobody meant to deceive anyone here

Examples



PeteSvarrior, for the Flat Earth Wiki; cc-by-sa.

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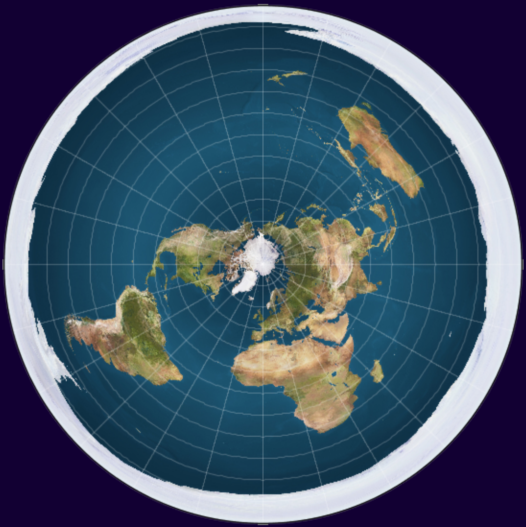


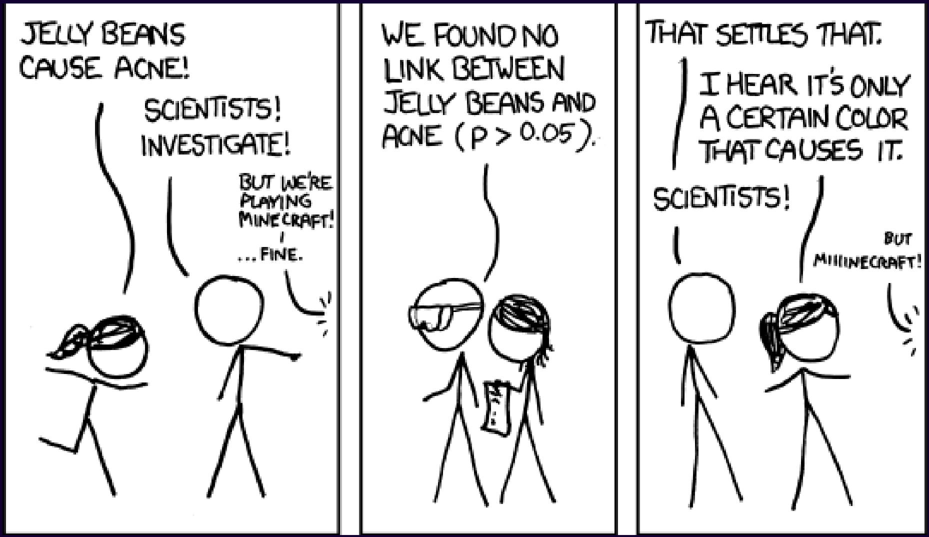
PeteSvarrior, for the Flat Earth Wiki; cc-by-sa.

Here's a map of a flat earth from the Flat Earth Wiki (ugh).

The distances are more or less right for the Northern Hemisphere...

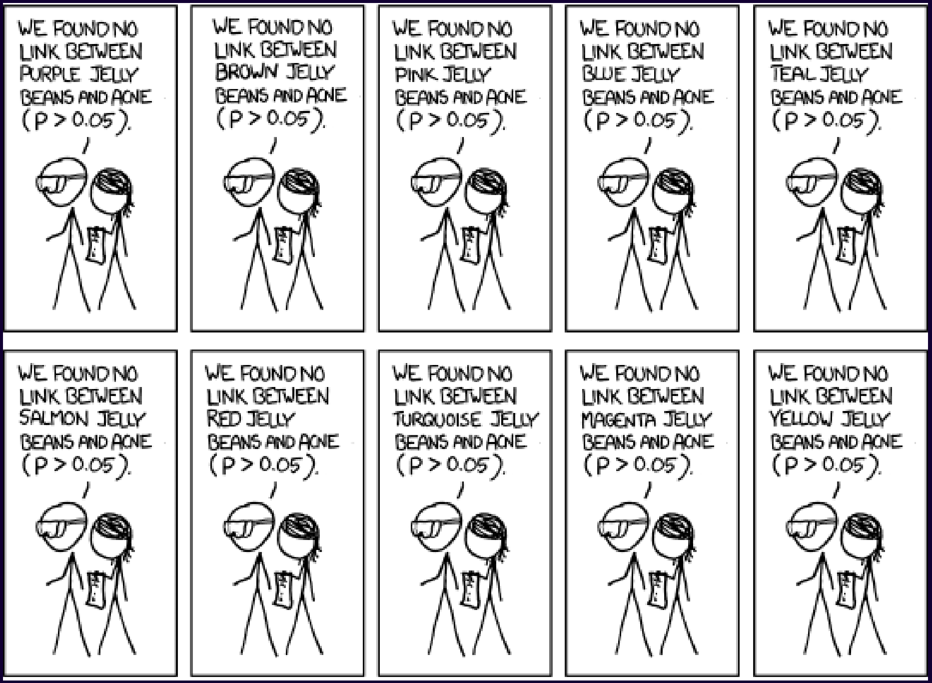
They're completely absurd for the Southern Hemisphere!

Clearly no Flat Earthers asked any Argentinians how far it was to New Zealand...



$p > 0.05$: "whatever we found, there's more than a 5% chance that it is just a coincidence"

Cherry-picking, examples: reporting bias



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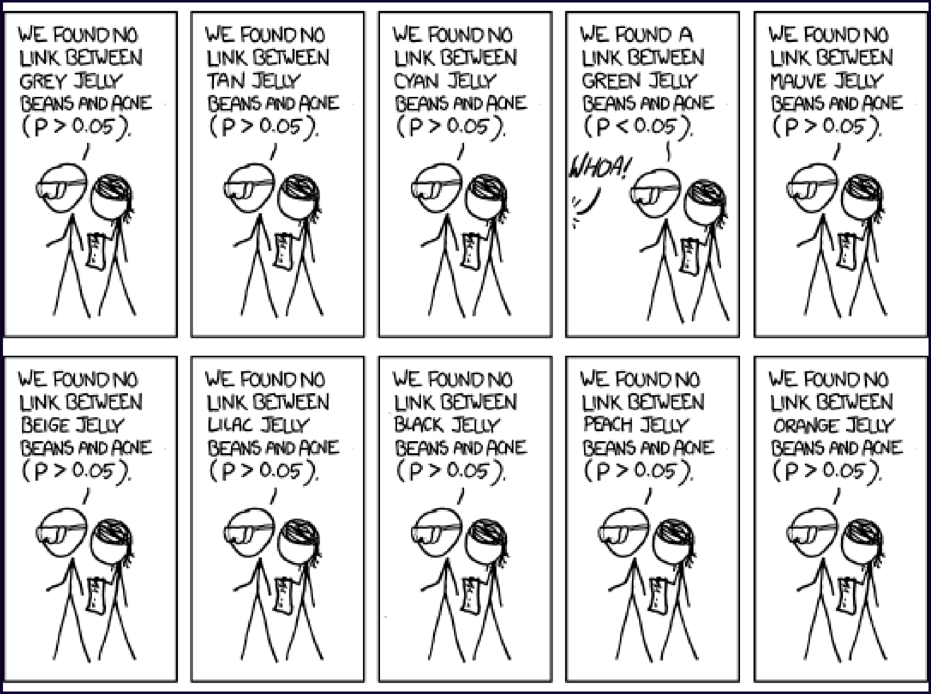

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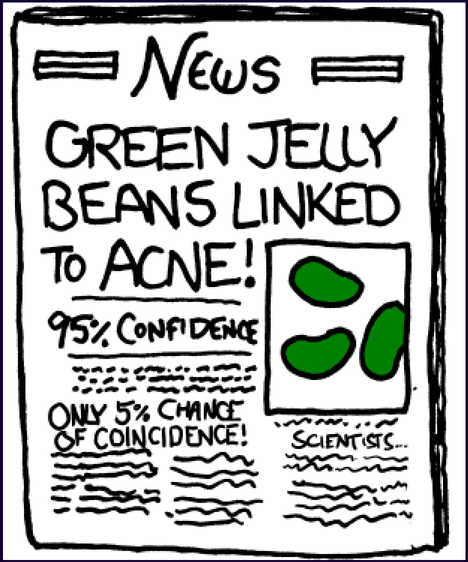

xkcd #882, by Randall Munroe: cc-by-nc.

Laundering data through statistics: dangerous!

Reporting only an interesting/profitable/exciting piece of data, and ignoring the rest, leads to flawed conclusions!

This is particularly worrying in medical research.

Do you have any favorite examples of biased data causing flawed conclusions?

Common fallacies: ad hominem arguments

An ad hominem argument is one that condemns someone else's argument because of *who* they are, not the content of their logic.

A few types (paraphrased):

Conspiracy-type reasoning (false allegations of ulterior motives):

- "NASA faked the moon landings because they wanted to cover up the fact that their rockets didn't work"
- "The anti-smoking campaign is there to make money, and also something something Nazis" (`http://www.smokingaloud.com`)
- "They just *say* that fluoride helps dental health but it's really a Communist plot"

Arguments based on status or identity:

- "That person is an esteemed expert; we must trust them without question!"
  - Four out of five dentists recommend such-and-such brand of toothpaste...
- "That person is a nobody; how could they have any good ideas?"
- "That person is a member of race/religion/gender/political party XYZ, how could they have anything right to say?"

Ad hominem arguments

Ad hominem (Latin: "against the person") arguments fail the scientific standard of *objectivity*: claims should be evaluated based on data and logic, not on who is making them.

False claims of ulterior motives are a common sort of *ad hominem* attack.

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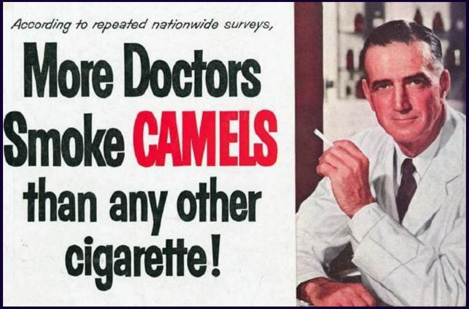
... and using "argument from authority" is the reverse: well, if these doctors say that they smoke Camels, they must be safe... right?

Sometimes deliberately deceptive people really *do* have ulterior motives. This can be a warning sign that someone is being deceptive...



Do you have any favorite examples of arguments from authority or arguments *ad hominem*?

Ignoring refuting evidence

Self-skepticism is a hallmark of sound science. Good scientists report:

- Any experimental evidence that might conflict with their proposal
- All of the possible flaws that *they* thought of in their claim
  - ... and how they considered them
- Any tests that anyone *else* could do to try to disprove them
- All the things that make them uncertain about their result
- The limits of their conclusions

Most good scientific writing spends much of its time doing the above. You should only try to convince other people you are right once you have tried very hard, yet failed, to prove yourself wrong.

Any claimant that spends most of their time talking *up* their conclusions is likely suspect.

Ignoring potentially refuting evidence

Ignoring or failing to search for refuting evidence is a common trait of faulty scientific process. This can either be:

- Ignoring refuting evidence altogether, even if it's widely known
- Dismissing refuting evidence out of hand, without considering it in any real way
- Failing to think of potentially refuting evidence and search for it

Do you have any favorite examples of flawed scientific claims that fail to address potentially refuting evidence?

https://wiki.tfes.org/Flat_Earth_-_Frequently_Asked_Questions

Manufacturing a controversy

We've discussed some of the common features of people *advancing scientific claims* incorrectly, negligently, or dishonestly.

Sometimes dishonest people aren't trying to *advance* something they know to be false, though.

They're more interested in convincing people to *reject* something that is true.

To do that, they only need to create doubt. This is commonly done by *manufacturing a controversy*.

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(This is a common tactic to erode trust in *anything*, not just science – common in politics and negative advertising)

Manufacturing a controversy

Do you have any favorite examples of manufactured controversies?

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Consider again the tobacco industry:

- “Secondhand smoke doesn’t cause health problems; those studies are wrong”
- “Are you really sure that secondhand smoke causes health problems? Maybe it was building ventilation!”

One of these is a far easier sell than the other!

The industry’s strategy does not require winning the debates it manufactures. It is enough to foster and perpetuate the illusion of controversy in order to muddy the waters around scientific findings that threaten the industry. Thus it offers reassurance to smokers, helping them to rationalize and repress their health concerns. Furthermore, claims of “not proven” resonate with friendly or naive journalists and governments, and provide an excuse for not taking strong governmental or societal action against tobacco.

–Yussuf Saloojee and Elif Dagli, ”Tobacco industry tactics for resisting public policy on health” Bull. World Health Organ. 78(7): Genebra, July 2000.

Sensationalism

Two things are both true:

- Some scientific findings can dramatically change our lives and our perspective on the world, and are compelling and exciting
- Whether a scientific claim is true or not doesn't depend on whether it's exciting or not (objectivity)

Scientists thus have twin duties:

- They should engage with society in sharing the excitement and interest of their findings. Science communication is vital (and many of us are bad at it; the astronomers do better than the physicists!)
- They should separate this excitement from the task of evaluating the validity of claims

Sensationalism

Beware of any sort of scientific claim that conflates the evidence that it is true with why you should be excited by it, or that seems to be hyped by its claimant.

Good scientists do hold press conferences, because many discoveries are exciting!

But these happen only in the context of:

- a vast amount of self-skepticism applied to their results first
- objective, sober presentation of the *evidence* for their conclusions

Science vs. pseudoscience

Often people adopt the trappings of science to give nonscientific ideas a veneer of validity. This is called “pseudoscience” – fake science.

Science

- Universal models
- Natural principles
- Testable predictions
- Not anthropocentric
- Replicable results
- Self-skepticism

Pseudoscience

- Singular events
- Supernatural explanations
- Untestable predictions
- Different rules for people
- Results defy replication
- Self-promotion