From mechanics to science

Physics 211
Syracuse University, Physics 211 Spring 2019
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February 26, 2019

Announcements

Upcoming schedule:

- Tuesday, February 26 (today): office hours 3-5 PM in the Physics Clinic
- Wednesday, February 27: HW4 due in recitation. Begin work on HW5 in recitation.
- Thursday, February 28: One new small topic; mostly review/practice
- Friday, March 1: Group Exam 2. Office hours 11-1 PM in the Physics Clinic
- Sunday, March 3: Review in Stolkin Auditorium, 1-4 PM
- Monday, March 4: office hours 1-3 PM
- Tuesday, March 5: Review in class; office hours 3-5 PM
- Wednesday, March 6: Come to recitation prepared with questions; review there
- **Thursday, March 7: Exam 2 in class.**
- Friday, March 8: **No recitation** (we'll be grading): enjoy your spring break!

Classical mechanics in context

Newton's laws give us a recipe for understanding how forces connect to motion.

- All objects have an acceleration $\vec{a}$ related to the forces acting on them: $\vec{a} = \sum \vec{F}/m$.
- Sometimes we have information about the forces on objects:
  - Gravity, friction, electricity...
- Sometimes we have information about objects' acceleration from *constraints*:
  - Ropes stay the same length
  - Objects don't move through one another
- We can use Newton's second law to learn about forces if we know acceleration, or vice versa

Today we'll take a look at three things:

- How can we extend this to systems that can't be solved using our kinematics?

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- How can we extend this to systems that can't be solved using our kinematics?
- What was the historical and philosophical context of the discovery of classical mechanics?
- What can we learn about how science goes right (and wrong) from this story?

Numerical mechanics

Most of the time, the forces on objects depend in a complicated way on their position, velocity, and time. This poses a problem:

- The force diagram constantly changes, and it depends on $\vec{x}(t)$, which we don't know
- We can't use constant-acceleration kinematics, and we don't even know the acceleration until we've solved the whole problem

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The Euler algorithm

But we can pretend that the acceleration is close *enough* to constant in small little chunks of time Δt, and do the following:

Repeat many times:

1. Draw a force diagram and calculate $\vec{a} = \sum \vec{F}/m$
2. Update the velocity: $\vec{v}_f = \vec{v}_0 + \vec{a}\Delta t$
3. Update the position: $\vec{x}_f = \vec{x}_0 + \vec{v}\Delta t + \frac{1}{2}\vec{a}(\Delta t)^2$

You need a computer to do this – maybe a human computer, but we have electronic ones now too...

Terminal velocity

We usually ignore air resistance, but we don't have to with this new tool:

- The force from drag is just $\vec{F}_d = -\gamma \vec{v} v$
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Doing physics calculations by computer is increasingly becoming far more important than doing them with a pencil.

If you're interested in learning more about computer simulations in physics, come talk to me!

The history of natural philosophy

To understand the scientific revolution in perspective, we need to take a tour through the history of both astronomy and natural philosophy.

In ancient Greece, astronomy was thought of as separate from (and lesser than) natural philosophy.

- **Astronomy:** How can I predict where Mars will be in the sky a month from now?
  - Concerned with mundane tasks like getting sailors home safe and predicting horoscopes
  - Not a proper pursuit for the *truly* enlightened, since you had to get your hands dirty with data

- **Natural philosophy:** What is the underlying, transcendent Truth of nature?

While astronomers had to do some natural philosophy, and while natural philosophers had to mess with data a bit, there was still a divide.

Greek natural philosophy

The preeminent Greek natural philosopher was Aristotle. He believed that:

- There are separate laws of nature for things in space and things on Earth
- All things in space are perfect spheres and move in perfect circles around the Earth (because the gods made them do that)
- All things on Earth can undergo two kinds of motion:
  - Natural motion: Material things fall (heavy things fall faster); all things come to rest
  - Unnatural motion (often translated "violent motion"): motion caused by external force (usually with intent)
  - Unnatural motion ceases as soon as the force is removed: if $\vec{F} = 0$, then $\vec{v} \to 0$!

A few properties of ancient thought that were very different from ours:

- Aristotle put great importance on "cause" and intent; we don't give people a special role in the laws of physics
- He did *not* believe that detailed examination or measurement was necessary to uncover Truth

Greco-Egyptian astronomy

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Ptolemy used the things he “knew” from Aristotle, and modified them in awkward ways to make them fit his observations:

- The Earth is at the center of everything
- All the planets go in circular orbits around a point not quite where the Earth is
- All the planets move in circular patterns around their circular orbits (called “epicycles”)
  - This last was required to predict retrograde motion

Ptolemy’s model made remarkably accurate predictions. There were some errors, which were fixed up centuries later by the Muslim astronomers that passed down his work and honed the

What's in the middle?

In the 1500's Copernicus proposed that instead the Sun was at the center, and the planets went around it in circles.

This explained retrograde motion without epicycles, but actually *didn't* predict the positions of the planets well. There was an odd preface, added by the publisher (paraphrased):
"This is unusual. But it is just mathematics; it should be judged on whether or not it makes accurate predictions; this is separate from whether it contains actual philosophical truth!"

In the next century or so, two things happened:

- Galileo saw things through a telescope that showed that the Earth *couldn't* be at the center
- Tycho Brahe and his assistants Sophie and Kepler made very precise measurements of the motions of the planets

Kepler and Newton

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  - The Sun at the center
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- He knew how precise his data were
- *No* arrangement of circular orbits fit the data:
- Mars' position always had an error of at least 1/8 of a degree

Eventually he realized that if the orbits were *ellipses*, he could fit the data perfectly.

He didn't know *why* the planets moved in ellipses, but he now had a model. (He wasn't good enough at mathematics to figure out the "why".)

Kepler and Newton

Newton was.

Kepler's observation that the planets moved in elliptical orbits was a perfect playground:

- The only meaningful force in space is gravity
- He realized that $\vec{F} = m\vec{a}$ together with $F_g = \frac{GMm}{r^2}$ could explain elliptical orbits
- ... and $\vec{F} = m\vec{a}$ could explain terrestrial motion, too!

(Getting from $\frac{GMm}{r^2} = ma$ to elliptical orbits required Newton's mathematical skill, but we have a computer...)

Properties of science

As we saw before, science – as a means of seeking truth about nature – 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 observations: planet motion, Newton's pendulums, falling objects...

- **Self-skepticism:** someone making a scientific claim should actively search for things that might prove themselves wrong
- Kepler was convinced planetary orbits were circles... until the data convinced him otherwise

- **Universality:** the laws of nature apply in all places and times, and to all things (including humans)
- Newton was able to explain *all* motion with one set of principles, in space and on Earth

- **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

Principles that come from these:

These things are difficult and many honest scientists (meaning: anyone who talks about the natural world) slip up. These principles are safeguards to protect us from being too convinced of things that are not true. But it is possible to be a good, honest scientist, and make mistakes.

Of course, it is also possible to be dishonest: to intentionally warp the process of science to convince people of things that are not true.

Principles that come from these:

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!**
- 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
  - Very large things: Yes, things as large as galaxies and beyond (but this requires dark matter)
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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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- 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

How does this go wrong?

One example of how this goes wrong: **cherry-picking.**

A strict definition: **Using limited, biased data that will give you a biased result**, accidentally or intentionally

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

- People in the 1980's uncovered evidence that the law of gravity might depend on the type of matter
- They made some very careful measurements from the top of a tower that seemed to confirm this
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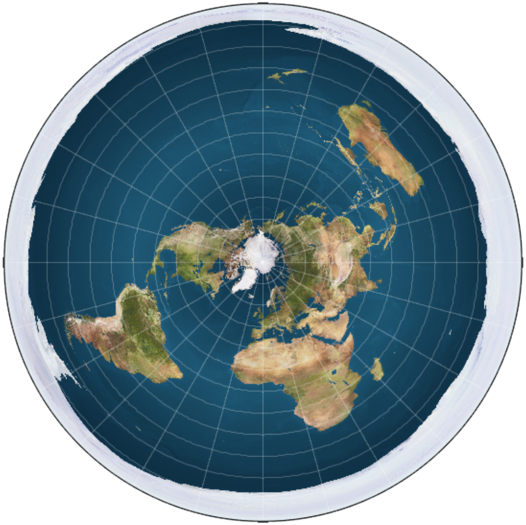
- Once this was realized and corrected, the signal went away
- Nobody meant to deceive anyone here

Cherry-picking, examples



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...

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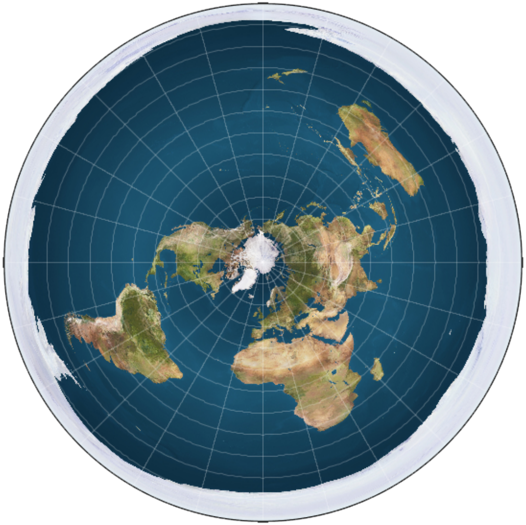

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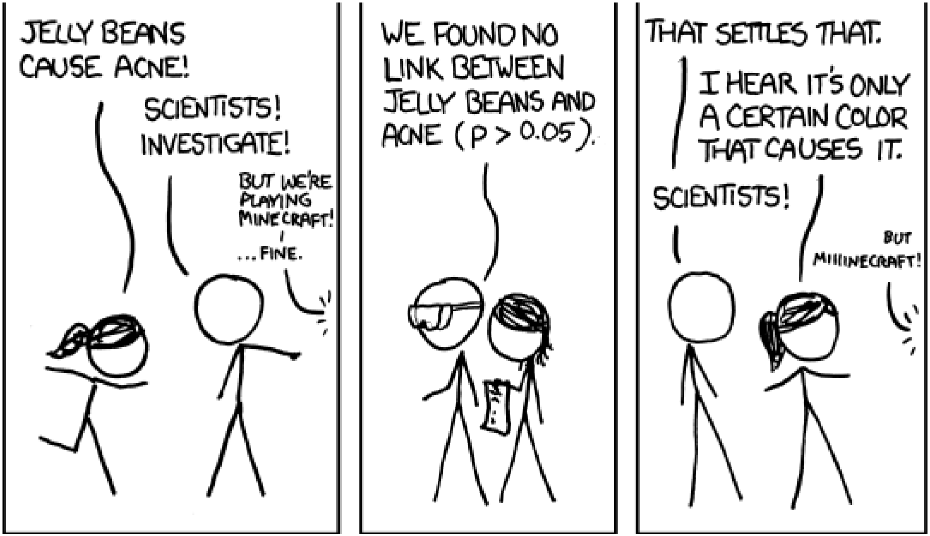
They're completely absurd for the Southern Hemisphere!

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

Cherry-picking, examples: reporting bias



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

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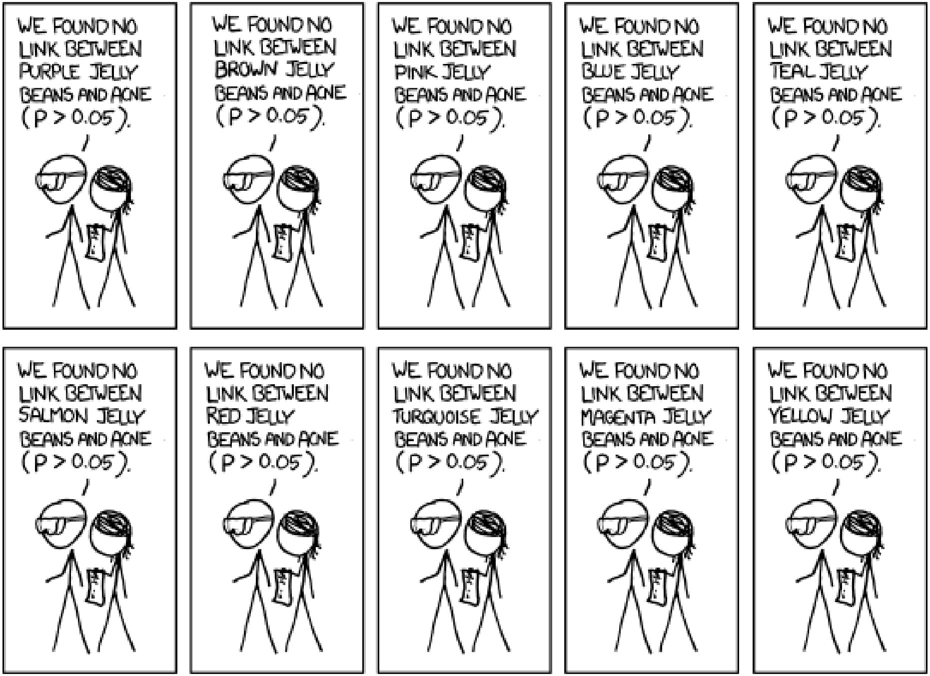

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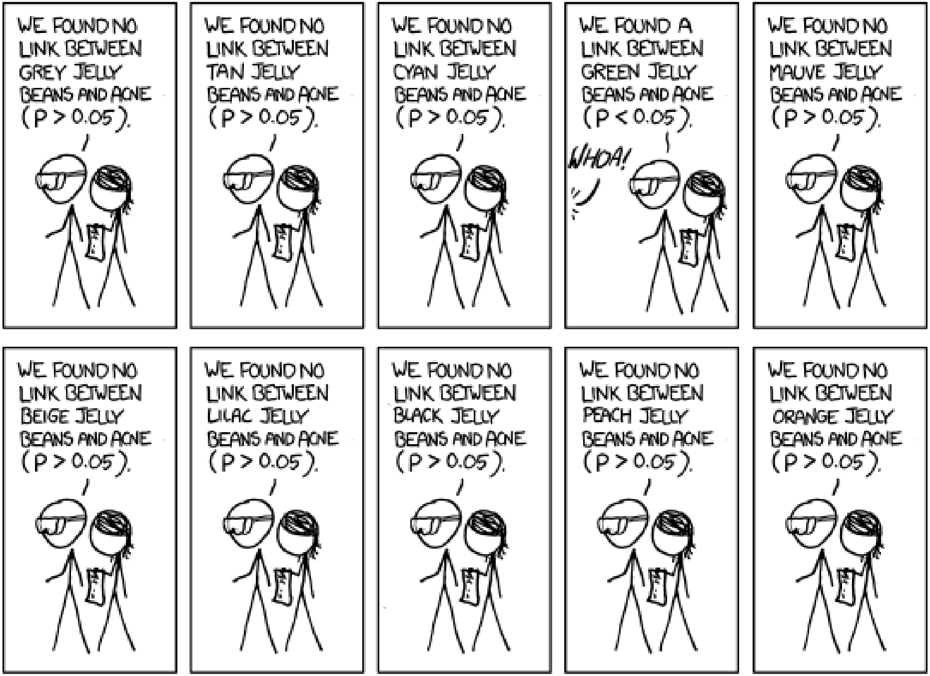

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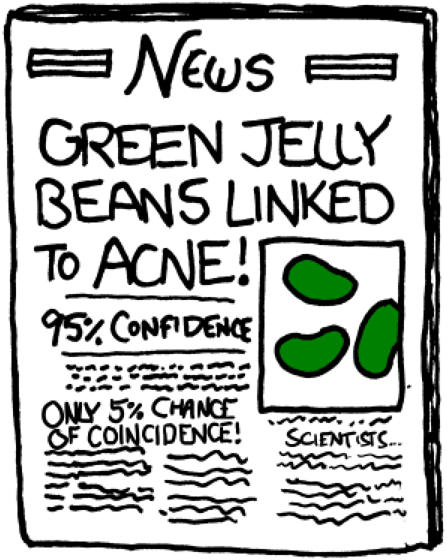

xkcd #882, by Randall Munroe: cc-by-nc.

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.

A look back at Aristotle

A reminder: Aristotle's mechanics claims:

- Falling objects fall at a rate proportional to their weight divided by the "density" of the thing they fall through
- "Forced" objects move at a rate proportional to the effort used to move them, divided by the resistance
  - Modern language: velocity = power / drag (this is correct!)
- Objects undergoing forced motion stop moving when the force is taken away

These things are *not wrong.* They're just limited in scope.
All these claims are *correct* for an object moving at terminal velocity!

Aristotle as accidental cherry-picker

Recall the principles above:

- A model is only as universal as the data it's checked against
- It's the duty of the model-builder to try to falsify their own model
- A universal description of motion needs to be checked in all sorts of ways

... but Aristotle considered only objects moving at terminal velocity!

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What might prompt skepticism that Aristotle's claims are not a universal description of motion?

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- Data only based on one narrow regime (high resistance/terminal velocity)

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What might he have done instead?

- Explored regimes of both high and low "resistance", conducting experiments to create the latter
- Explored motion shortly after a force was applied to an object, rather than only after a long time (when drag was dominant)

Recognizing this sort of thing in a modern context

In the modern era, people cherry-picking data (accidentally or deliberately) often:

- **Ignore potentially refuting evidence** instead of honestly examining it, focusing only on arguments *for* their claims
- **Focus only on a narrow scope of observations** but try to draw broad claims from them
- **Use a biased sample**, ignoring inconvenient things like puddles
- **"Launder data" through statistics**, rather than incorporating both positive and negative results