

Part 1: The Sky; History of Astronomy; How Science Works

- Tuesday, January 17 Reading: Chapters 1 & 2.1, Appendix A
 - Introduction, syllabus, class rules; units, scales,
 - rotation of the Earth, time zones, constellations; tour – where we go in the course
- Thursday, January 19 Reading: Chapters 2, 3 HW 1 assigned
 - The sky: Rotation of Earth, seasons, phases, eclipses
- Tuesday, January 24 Reading: Chapter 4-1, 4-2, 4-3
 - History of Astronomy: Greeks, Copernicus, Tycho, Kepler
- Thursday, January 26 Reading: Chapter 4-4, 4-5
 - History of Astronomy: Galileo, Newton
- Tuesday, January 31 Reading: “Windows on science” sections or
– How science works “How do we know?” sections in Chapters 1, 2, 3, 4
- Thursday, February 2 Reading: Chapter 5 HW 1 due
 - The nature of light, telescopes, spectra
- Monday, February 6 Help session from 4 — 6 PM in RLM 4.102
- Tuesday, February 7 Exam 1

HW1 help session:
Wed., Feb. 1, 4 – 6 PM
in Welch 3.502

Review: Newton's Law of Gravitation Explains Tides

The Earth and its oceans both fall toward the Moon because the Moon pulls on the Earth gravitationally. Important: The Earth falls freely through space.

The ocean on the side that faces the Moon is nearer to the Moon, so the Moon pulls harder on that ocean than on the Earth. Result: The ocean on the side that faces the Moon falls toward the Moon faster than the Earth does. So it falls away from the Earth. It makes a bulge – a high tide – that faces the Moon.

On the other side of the Earth, the opposite happens: the Moon pulls harder on the Earth than on the far-side water. So the Earth falls away from the far-side water and leaves behind a bulge – a high tide – that faces away from the Moon.



The rotation of the Earth carries you past two high tides and two low tides every day.

Because Earth rotates, the tidal bulge is dragged slightly ahead of the Moon. As a result, the rotation of the Earth slows down and the orbit of the Moon expands.

Review: Mass and Weight

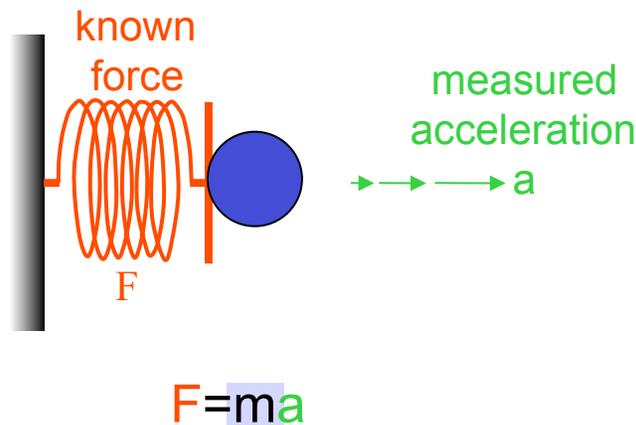
Mass

m

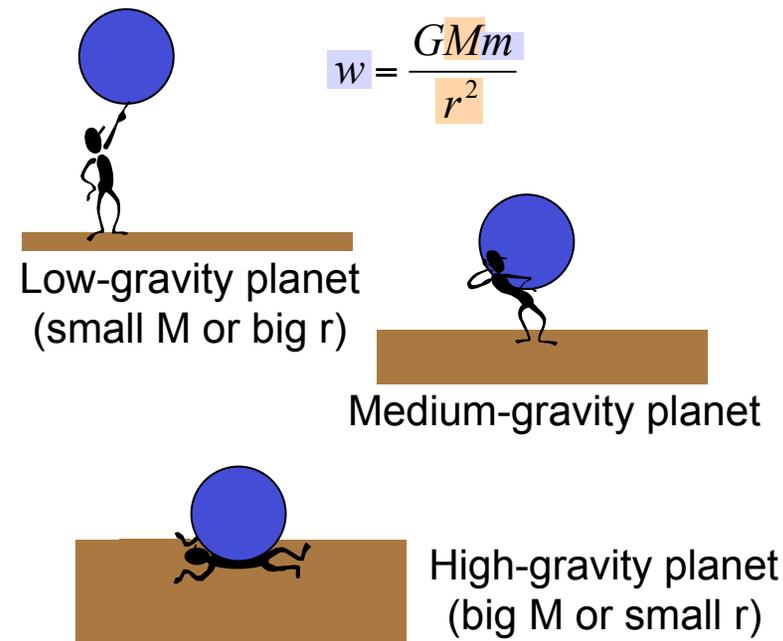
Weight

w

Mass is a measure of “how much stuff” you have.



Weight is the amount of force needed to keep an object from falling in a particular gravitational field



The mass of an object is the same everywhere.

Weight depends on where you are.

Review: Four Kinds of Forces

1. Gravity – holds you to the Earth, holds planets in orbits, etc.
2. Electromagnetic Force – holds your body and other objects together
3. Strong Nuclear Force – holds atomic nuclei together
4. Weak Nuclear Force – is involved in some radioactive decays

Gravity is the weakest force.

Put two protons 1 mm apart:

- They attract each other gravitationally.
- They repel each other electrically.
- Electrical repulsion is 10^{40} times stronger than gravitational attraction.

You are attracted gravitationally by the person sitting next to you.

But you are attracted 5 billion times more strongly by the Earth.

How Science Works



The Universe is full of magical things patiently waiting for our wits to grow sharper.

Eden Phillpotts

How Science Works

Philosophers

Religious Evangelists

Politicians

Salespeople

Scientists

Crackpots

all sound very sure of their beliefs.

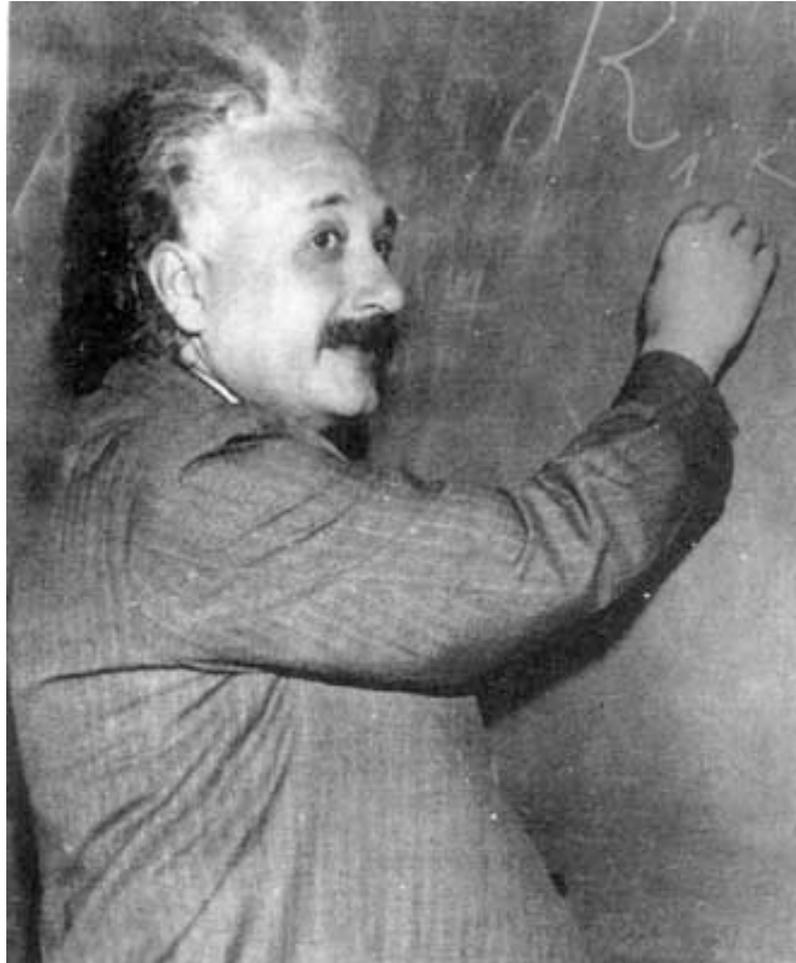
Why should we believe one sort of “knowledge” over any other?

How Science Works

The last 2 lectures were not just a history of how astronomical problems got solved. **They traced the development of our “scientific method”**. This lecture reviews this subject to give you a better feeling for how science works and why it is successful in helping us to discover new things.

*Imagine that you are watching a complicated game — like chess. You know nothing about it. Nothing makes sense. Players move pieces, but you don't know what they are trying to accomplish. You don't even know how they are allowed to move the pieces. In other words, **you don't know the rules of the game. In fact, you are not sure that there are any rules.** But gradually, as you watch, you notice patterns. There are only a few different kinds of pieces. All pieces of the same kind move the same way. Different kinds move different ways. Soon you have deduced the simplest rules: how pieces are allowed to move. But it takes a lot longer to figure out the goal of the game.*

Science is similar. We observe how nature behaves, and we try to figure out the rules of the game. They are called **physical laws**. With them, we can describe simply a lot of behavior that looks complicated. And we can use the laws to discover things that are useful or interesting. These include more physical laws.



Everything should be made as simple as possible, but not simpler.

Albert Einstein

The Scientific Method: Ask Nature

The scientific method is a three-step process

1. Observe the phenomenon that you are studying in as many ways as possible. In some cases, the only thing that you can do is observe nature. Astronomers are usually in this situation, because they cannot get their hands on the objects that they study. Or you may be able to carry out experiments that clarify how nature behaves.

2. Look for regularities. Form a hypothesis about what is happening. For example, the hypothesis may be a candidate physical law. The aim is that the hypothesis be more general than the specific examples of nature's behavior that it was designed to explain.

3. Test the hypothesis. Use it to make predictions. Make experiments to test the predictions.

If the hypothesis fails even one test, then you have proved that it is wrong.

Fixing it may require just a small change or it may require a completely different approach.

If it passes the test, our confidence in it is increased. But it is impossible to prove the hypothesis completely. We can never try all possible experiments, and so we can never be sure that we tested the hypothesis at its weakest point. But if it passes enough tests, we get so confident in it that for all practical purposes we treat it as proved.

Natural Laws

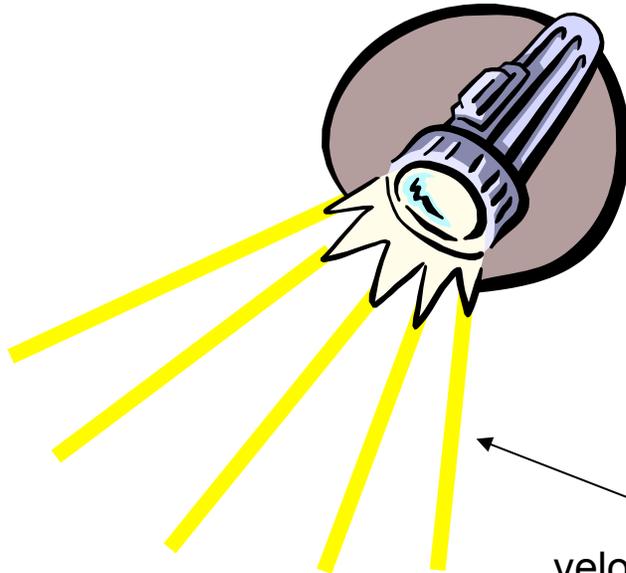
The simplest and most fundamental generalizations about nature, after they have been well tested, are called **natural laws**.

Examples

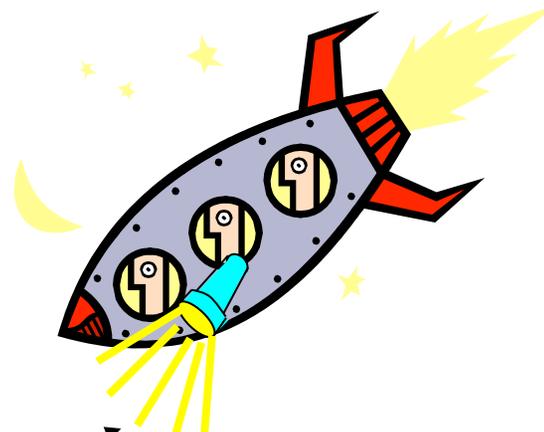
Newton's laws of motion and the equation of universal gravitation

Einstein's statement that the speed of light is a constant independent of the observer;
nothing can travel faster than light

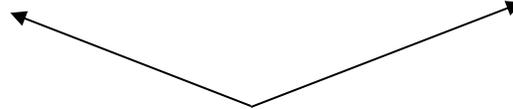
velocity = speed of Earth



velocity = 1/10 speed of light



velocity = speed of light



Theories

A **theory** or a **paradigm** is a collection of beliefs and techniques that summarizes our understanding of a subject. It is a self-consistent set of rules and principles. It applies to a wide variety of circumstances. A theory is usually much more elaborate than an individual hypothesis or natural law. A theory is built out of the results of testing and combining many hypotheses, techniques, and observations into a coherent picture.

For example, we have a **theory of gravity** that includes the work of Newton and Einstein. Newton's law of gravity is a special case of Einstein's more general theory.

We have a **theory of stellar structure** — how stars form, what they are like at every stage of their evolution, how they evolve, and how they die. **Many different kinds of scientific results are combined to construct it**, including natural laws (Newtonian gravity, ...), **more restricted theories** (the physics of hot gases, the physics of nuclear reactions, ...), specific calculations (put together all the equations that describe a star and calculate what it must be like, ...), and **observations** (compare the results of these calculations with a variety of observations and refine the theory until it agrees with the real world.)

THE CHARACTER OF
PHYSICAL LAW

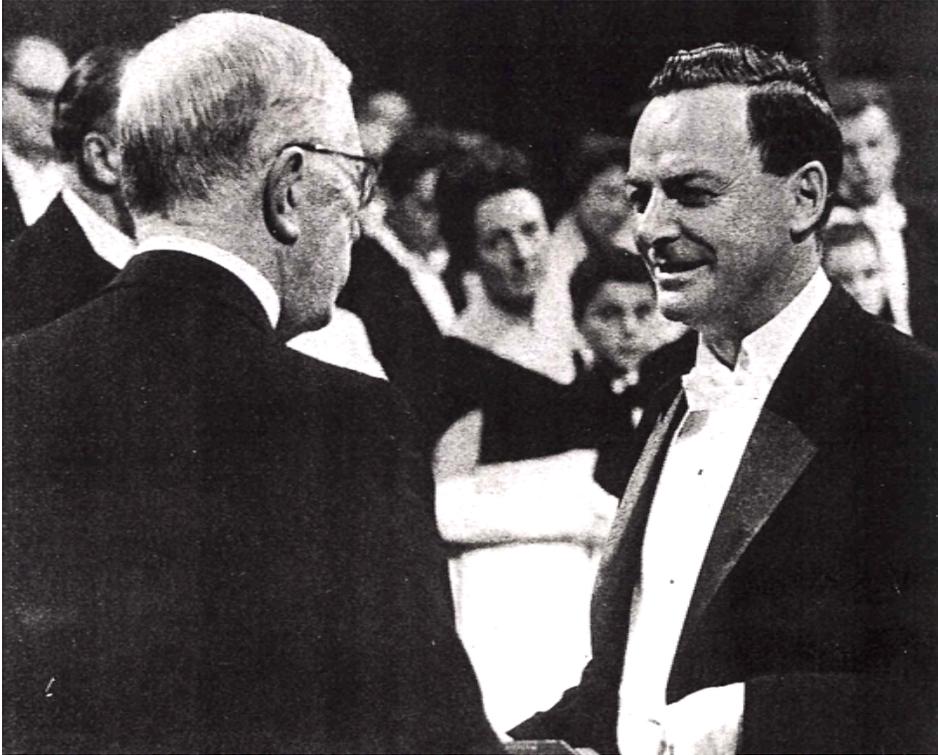
RICHARD FEYNMAN



THE M.I.T. PRESS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS, AND LONDON, ENGLAND

Richard Feynman



Receiving the 1965 Nobel Prize in Physics
from King Gustav VI Adolf of Sweden

Richard Feynman



“It is odd, but on the infrequent occasions when I have been called upon in a formal place to play the bongo drums, the introducer never seems to find it necessary to mention that I also do theoretical physics.”



Three Important Characteristics

Richard Feynman

The Test of Science is its Ability to Predict

A scientific theory must make **specific predictions** that can be **tested**. Quoting Feynman: “Experiment is the *sole judge* of scientific truth”. A theory is useful only if it is more general than the specific results that gave rise to it.

Scientific Results Must be Repeatable

Anyone who understands an experiment or an observation and has the resources to repeat it **should get the same answer**. If not, the theory is on “thin ice” and had better quickly provide an explanation.

The Language of Science is Mathematics

A scientific theory should make predictions that are quantitative and precise. **Agreement with observations must be quantitative and precise**, according to established rules about the accuracy of observations and the accuracy to which the theory is developed. A sensible yardstick for measuring progress is the improved accuracy to which the theory agrees with observations.

The Language of Science is Mathematics

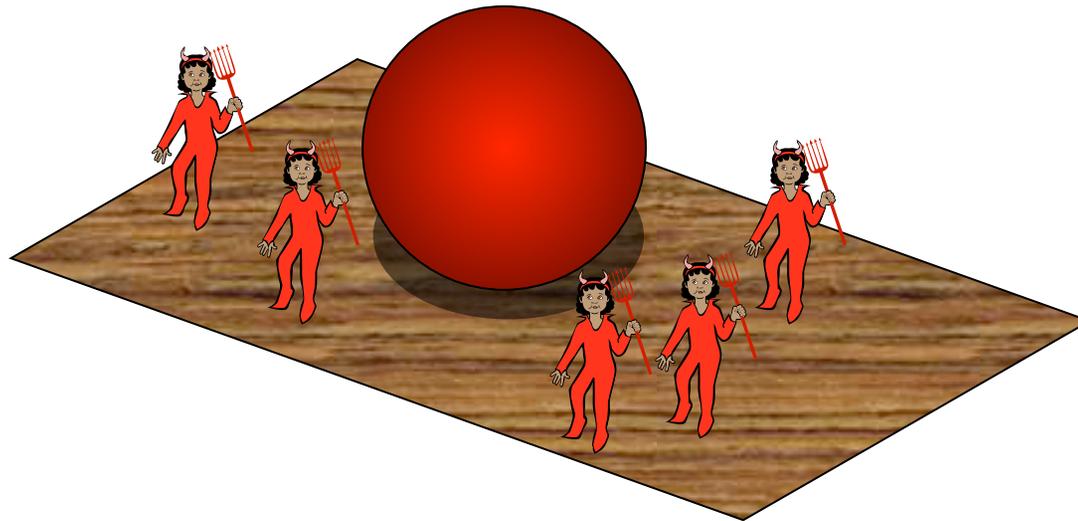
The natural language in which to state a theory is mathematics. Underlying principles can be stated in words. Other “languages” may be useful, too, like geometrical concepts and pictures. But you have to be able to get numbers out of a theory, or you can’t test it. Nobody can build a rocket that will get you to the Moon unless a lot of physics and a lot of engineering are carried out accurately and correctly.

One of the most profound things that we have learned about nature is that so many physical laws can be expressed in terms of simple mathematics.

The Parable of the Little Demons

(From Barrow 1988, *The World Within The World*, Oxford: Clarendon Press, 19)

You and Faustus have developed a difference of opinion regarding the nature of friction. You believe that a rolling ball is stopped by friction. But Faustus wants to persuade you that it is really stopped by a hoard of cunning little demons:



The Parable of the Little Demons

You: I don't believe in demons.

Faustus: I do.

Y: Anyway, I don't see how demons can make friction.

F: They just stand in front of things and push to stop them from moving.

Y: I can't see any demons even on the roughest table.

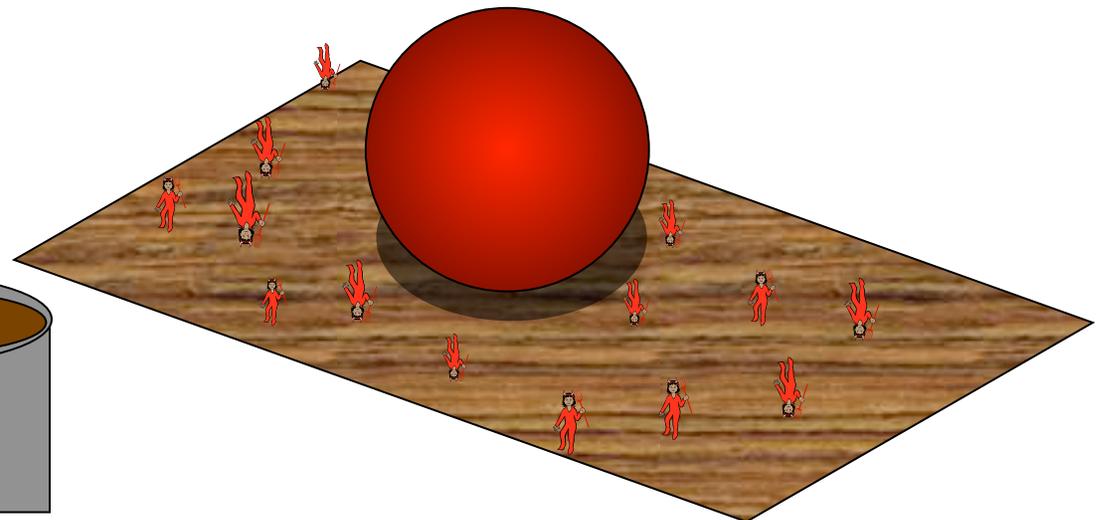
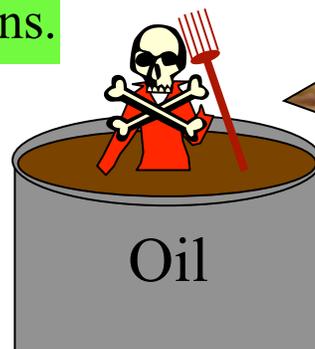
F: They are too small, almost transparent.

Y: But there is more friction on rough surfaces.

F: More demons.

Y: Oil helps.

F: Oil drowns demons.



The Parable of the Little Demons

Y: If I polish the table, there is less friction and the ball rolls farther.

F: You are wiping the demons off; there are fewer to push.

Y: A heavier ball experiences more friction.

F: More demons push it and it crushes their bones more.

Y: If I put a rough brick on the table I can push against friction with more and more force, up to a limit, and the block stays still, with friction just balancing my push.

F: Of course, the demons push just hard enough to stop you from moving the brick, but there is a limit to their strength beyond which they collapse.

Y: But when I push hard enough and get the brick moving there is friction that drags the brick as it moves along.

F: Yes, once they have collapsed the demons are crushed by the brick. It is their cracking bones that oppose the sliding.

The Parable of the Little Demons

Y: I cannot feel them.

F: Rub your finger along the table.

Y: Friction follows definite laws. For example, experiment shows that a brick sliding on a table is dragged by friction with a force independent of velocity.

F: Of course, the same number of demons to crush, however fast you run over them.

Y: If I slide a brick along the table again and again, the friction is the same each time. Demons would be crushed in the first trip.

F: Yes, but they multiply incredibly fast.

Y: There are other laws of friction: for example, the drag is proportional to the pressure holding the surfaces together.

F: The demons live in the pores of the surface: more pressure makes more of them rush out to push and be crushed. Demons act in just the right way to push and drag with the forces you find in your experiments ...

The Parable of the Little Demons

... and so on.

Faustus's idea is a viable way to develop systematic laws. Whenever you put forward a "law" of friction, he proposes a rule of demonic sociology.

In the context of the above dialogue, the two proposals are indistinguishable.

One seems "scientific" whereas the other (demons, hopefully) appears crazy because of other connotations that are outside the context of this dialogue.

This parable is quoted from Barrow, J. 1988, *The World Within The World* (Oxford: Clarendon Press), p. 19

The Parable of the Little Demons

What's wrong with this "theory"?

The demon theory illustrates a lot of what is wrong with pseudosciences:

- **It is not quantitative.** You cannot calculate quantitatively whether the claims are consistent with observations.
- **It is not predictive.** Every time you mention a new aspect of friction, Faustus adds to his theory a new property of demons that "explains" the phenomenon. But you never have enough information to use the theory to predict a new phenomenon that you can look for. In particular, you cannot identify an experiment that would distinguish the demon theory from its alternative. As long as Faustus says, "Demons act in just the right way to explain what you find in your experiments," his theory is not falsifiable.
Theories that are not falsifiable are not scientific.
- **It comes with unwanted mental "baggage"** — the term "demon" has connotations that can get the theory into trouble.

Other Ways to Recognize Pseudoscience

- The phenomena that gave rise to the theory are unreliable.
E. g., demonstrations of telepathy
- You cannot repeat the observations that gave rise to the theory.
E. g., “Little green men in a flying saucer picked me up and took me to Venus, but I’m special: they won’t appear for you.” Or: Only the originator of the theory is allowed to have control of the environment when the experiment is done. E. g., Blondlot's N-waves.
- The theory makes no contact with other well established science.
- Unprofessional lack of rigor is very suspicious. Examples: lack of statistical rigor, lack of “control samples” that are expected not to show the effect. Also: secretiveness, vagueness, ...
- Demonstrable inconsistencies or failures are indisputable disproofs (but they are nevertheless often ignored).

The Parable of the Little Demons

Can We Fix This Theory?

- We complained that it is not quantitative. OK, let's measure friction more carefully. Let's figure out how strong the demons have to be, and let's write an equation that describes this strength as quantitatively as anyone wants.
- We complained that it is not predictive. We complained that Faustus adds a new property of demons to his theory every time he needs to account for a new observation. No problem. Faustus doesn't know enough about friction. Let's give him a chance to observe it further – to study demon society in enough detail so that he can commit himself to a list of demon properties. They will include equations. And let's give him a chance to make predictions that we can check. After all, Rome — and theories — are not built in a day.
- The demon theory comes with unwanted mental baggage. Faustus may say: "You don't know as much about demons as you think. I will tell you all about demons. See above."

The Parable of the Little Demons

Can We Fix This Theory?

- Faustus will find that he needs to make a few other changes, too:
 - Demons are immortal.
 - Demons are incredibly strong. Friction does not crush them, they just push back.
 - The harder you push, the harder they push.
Remember: experiment will show exactly how strong they are.
 - And demons are tiny. You can't see them even in a microscope.

Now can Faustus make a scientific theory of demons?

The answer is “yes!”

The Parable of the Little Demons

Can Faustus Make a Scientific Theory of Demons?

Yes!

But for all practical purposes, the demon theory is now identical to the conventional theory that friction is caused by atoms in one surface rubbing against atoms in the other. That is, **the demons now have essentially the same properties as atoms.**

“Demon” is just a label. Labels are not fundamental, only the properties of the thing being labeled are fundamental. Substitute “atom” for “demon” and you recover the conventional theory of friction with no undesirable connotations.

Moral

Don't confuse yourself into thinking that labels mean something important. Don't assume that you understand something because you remember its name.

The Parable of the Little Demons

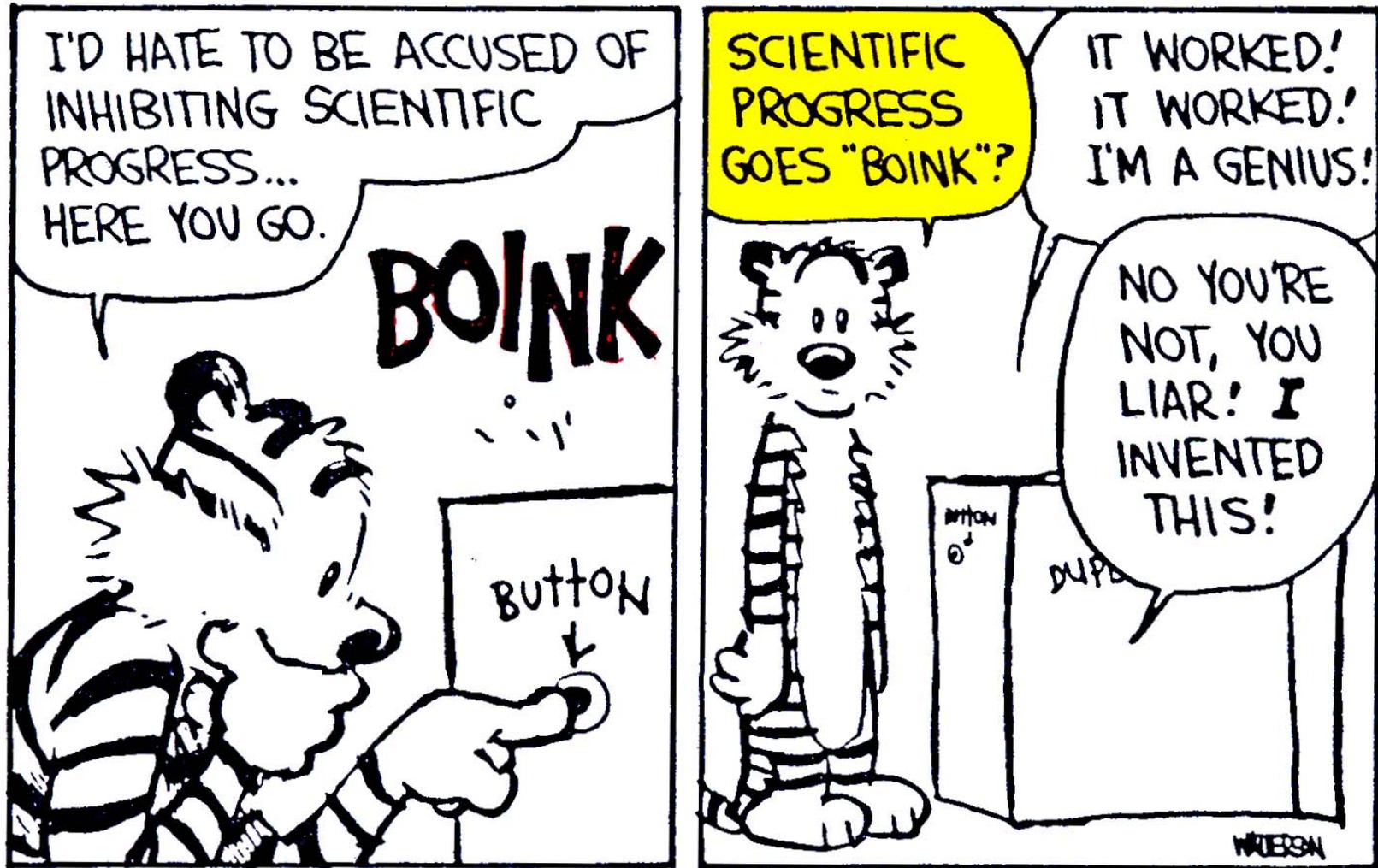
Ghostly Concepts at the Boundaries of Knowledge

Our parable illustrates one more thing about science:

At the frontiers of knowledge, the concepts and things that we deal with are very uncertain:

- We know that atoms exist: we study them in great detail and can see them in the most powerful microscopes.
- We know that subatomic particles (like protons and electrons) exist: they are too small to be seen, but we can detect them and study them in detail.
- Subatomic particles are thought to be made of still smaller pieces called quarks. The properties of quarks are inferred indirectly. No quark has ever been detected. Do quarks exist? Or are they just conceptual tricks (like Faustus's demons) that let us describe nature without understanding her?
- Are quarks more substantial than demons?

Sometimes Scientific Progress Goes “BOINK”



Scientists are (more or less) human and sometimes make mistakes.



Discoveries often proceed more speedily through the action of envy, competitiveness, and anger than through the pure-minded search for truth.

Allen Walker Read
Quoted in a *New Yorker* Profile
September 4, 1989



For a successful technology, reality must take precedence over public relations*, for Nature cannot be fooled.

Richard P. Feynman

*or: production schedules, or greed, or wishful thinking.

The Structure of Scientific Revolutions

Thomas S. Kuhn, University of Chicago Press, 1970

Paradigm

A paradigm is a body of beliefs that a scientific community accepts as the foundation for its subject. It includes laws of nature, theories, experimental techniques, and experimental results.

The acquisition of a paradigm and the sophisticated research that it permits transforms the unguided study of nature into a science. Ever since antiquity, one field of study after another has crossed this divide between its prehistory and its history as a science.

- Astronomy made the transition in antiquity. Economics became a science during the 1900s.
- Most behavioral fields have not yet become sciences.

Normal science is research within the framework of a paradigm.

Most people spend most of their time doing normal science.

Normal science is very efficient at producing results:

- It provides a running start: Fundamentals are assumed, not recreated by every investigator.
- It provides a filter: “It suggests which experiments would be worth performing and which, because they are directed to secondary [phenomena], would not.”
- It suggests technically and conceptually sophisticated observations and theoretical calculations that would never be conceived without the guidance of the paradigm.

The price of efficiency is rigidity and blindness to new ideas.

The Road to Revolution

Discovery begins with awareness of anomaly.

Normal science is very efficient at revealing anomaly:

1. The paradigm tells us exactly what is expected.
2. “Normal science leads to a detail of information and to a precision of the observation-theory match that could be achieved in no other way.”
3. “The scientist must know *with precision* what he should expect to be able to recognize that something has gone wrong.”

When Anomaly Turns Into Revolution



At the moment physics is terribly confused. Anyway, it is too difficult for me, and I wish I had been a movie comedian or something of the sort and had never heard of physics.

Wolfgang Pauli

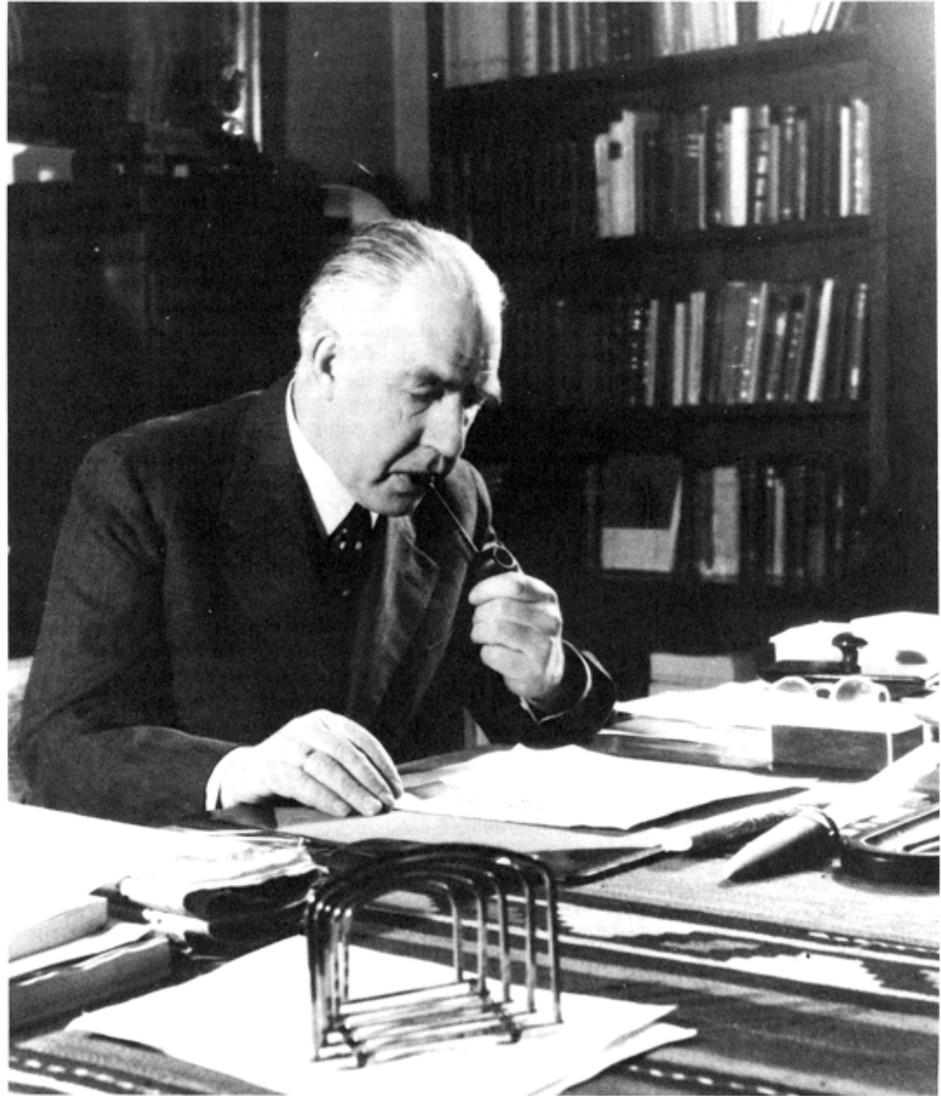
(Just before the discovery of quantum mechanics)

Niels Bohr



Niels Bohr received the
1922 Nobel Prize in Physics.

He was 37 years old.



Niels Bohr in his study at the Carlsberg House of Honor.

Every major advance creates sooner or later new problems. These confusions are not to be deplored. Rather, those who participate experience them as a privilege. As Niels Bohr once said: “Tomorrow is going to be wonderful, because tonight I do not understand anything.”

Abraham Pais
Inward Bound

No progress without a paradox.

Niels Bohr

What is Fundamental?

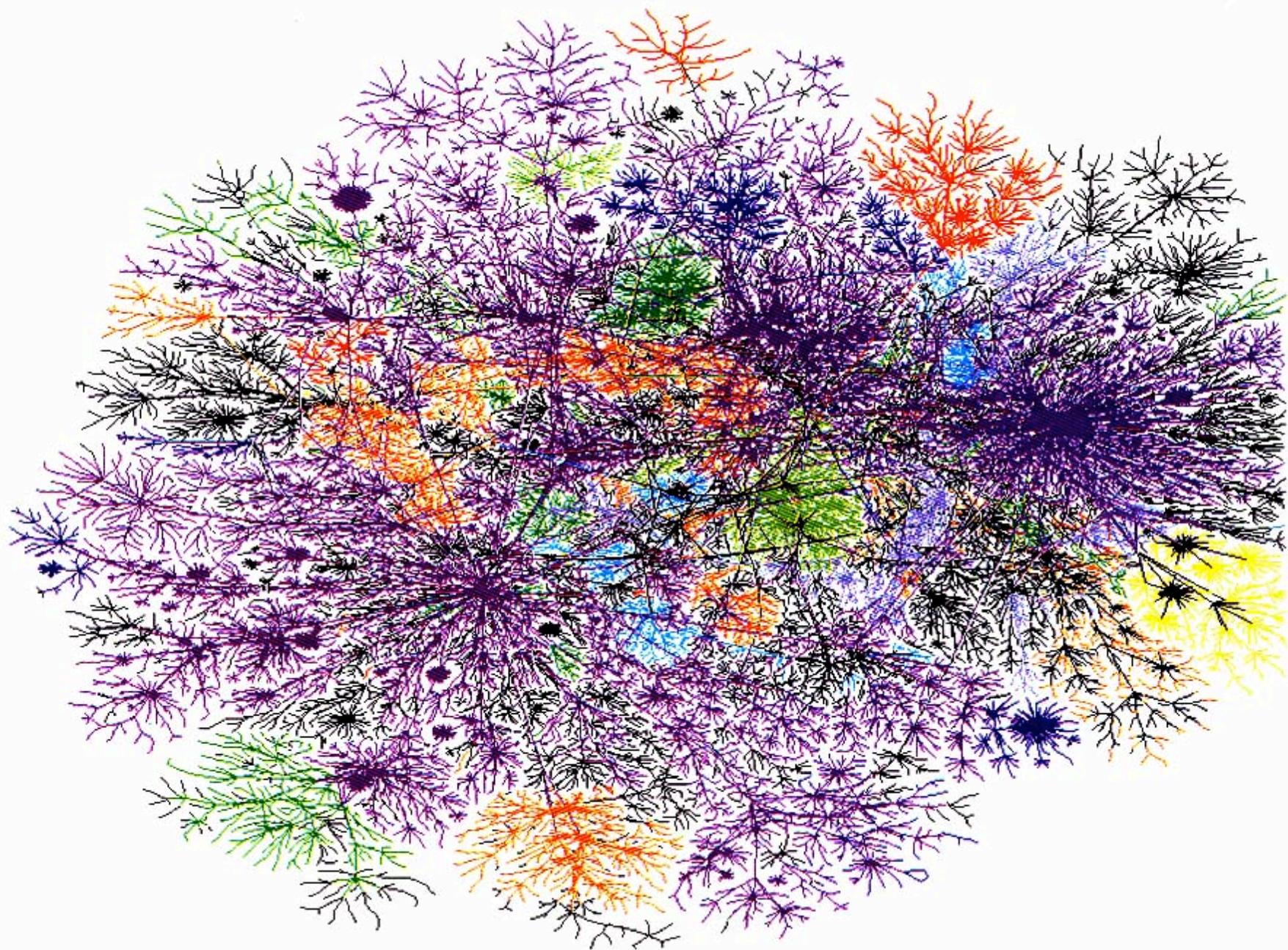
The interest in the best research is in its capacity to astonish.

**The most fundamental research overthrows old paradigms
and substitutes new ones.**

All discoveries are revolutionary.

To the extent that they surprise us,
even small discoveries share the characteristics of scientific revolutions.
To the extent that they don't surprise us, they are not discoveries.





Concern for man and his fate must always form the chief interest of all technical endeavors in order that the creations of our minds be a blessing and not a curse to mankind. Never forget this in the midst of your diagrams and equations.

Albert Einstein
Address to students at the
California Institute of Technology
Quoted in *On Being A Scientist*



The bells that toll for mankind are – most of them, anyway – like the bells on Alpine cattle; they are attached to our own necks, and it must be *our* fault if they do not make a cheerful and harmonious sound.

Sir Peter Medawar
Reith Lectures (1959)

Scientific Progress

Scientific progress gives us a more accurate description of nature.
It allows new practical applications for the benefit of all.

Unexpected beauty emerges:
profound regularities, symmetries, patterns.

Each major discovery takes us to a newer and deeper level of understanding. No-one knows whether there are any limits to the subtlety of nature.

A Metaphor: The Mandelbrot Set

Black $\Rightarrow z_{n+1} = z_n^2 + z_1$ ($z = x + iy; i = \sqrt{-1}$)
remains finite as $n \rightarrow \infty$.

Colors encode how quickly z_n diverges.

It is astounding how much complexity and beauty is hidden in the above simple prescription!



Benoit Mandelbrot

