How do scientists really do science?

Presentation to the
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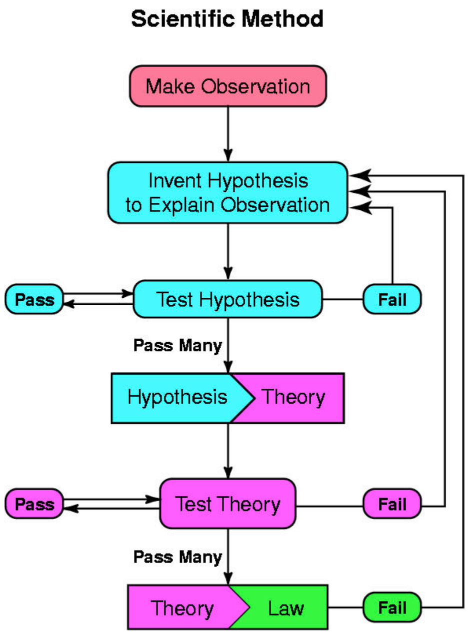
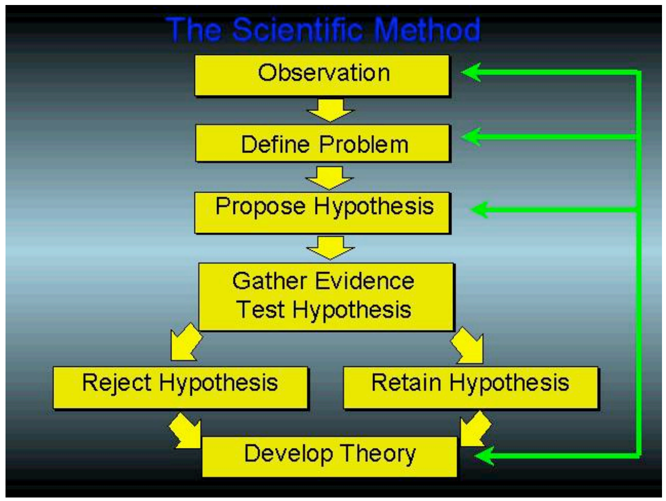
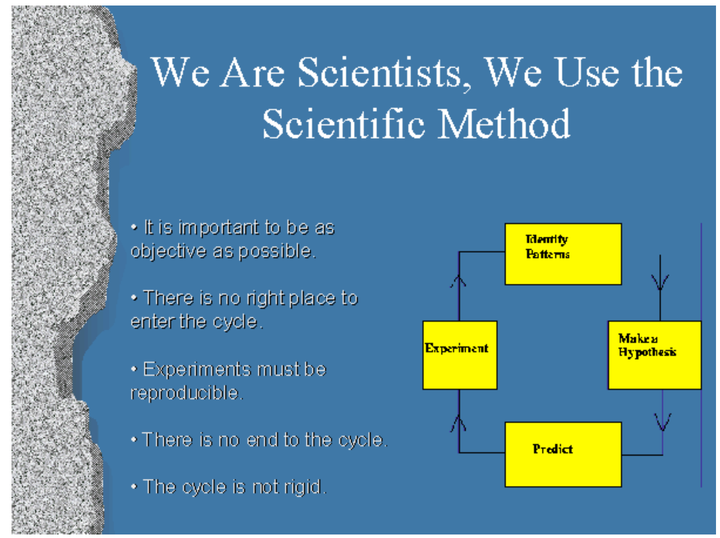
Standard Mantra:
Scientists follow
“The Scientific Method”



The Scientific Method #1



The Scientific Method #2



The Scientific Method #3

The only problem with teaching this is that there is no single simple “scientific method”

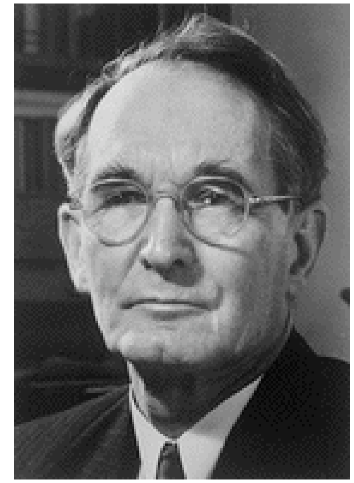
There are a wide variety of ways to do science

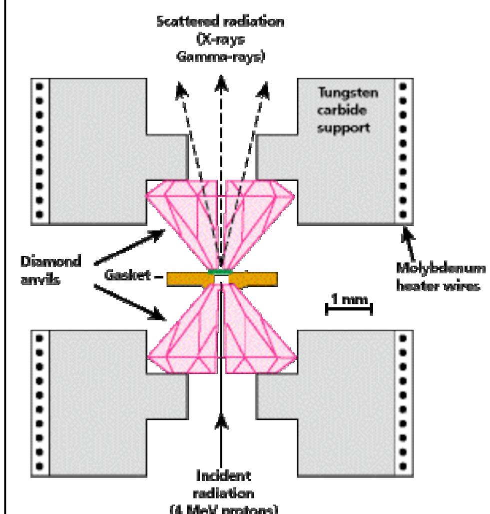
The Scientific Method

"Scientific method is what working scientists do.... No working scientist, when he plans an experiment in the laboratory, asks himself whether he is being properly scientific."

"…[there are] various generalities applicable to most of what the scientists does, but it seems to me that these generalities are not very profound and could have been anticipated by anyone who knew enough about scientists to know what is their primary objective… that they are all trying to get the correct answer to the particular problem at hand."

Percy W. Bridgman – From: *On "Scientific Method"* in Reflections of a Physicist, 1955 (winner of the 1956 Nobel Prize in Physics for high pressure physics)





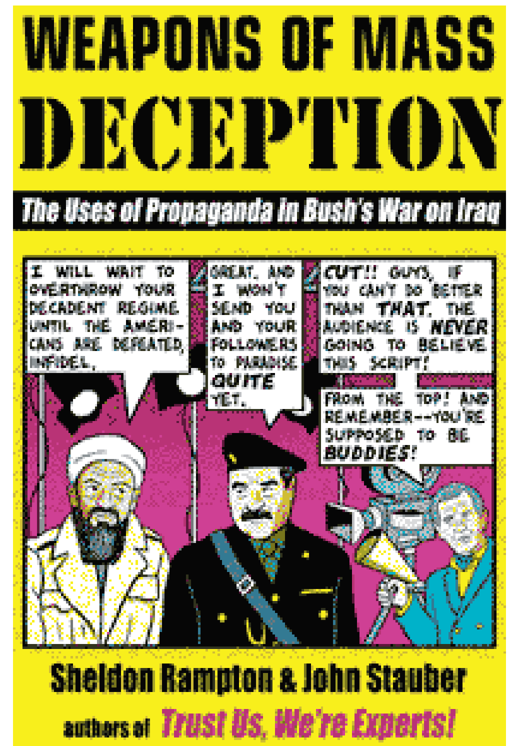
NSTA Position Statement

"Although no single universal step-by-step scientific method captures the complexity of doing science, a number of shared values and perspectives characterize a scientific approach to understanding nature. Among these are a demand for naturalistic explanations supported by empirical evidence that are, at least in principle, testable against the natural world. Other shared elements include observations, rational argument, inference, skepticism, peer review and replicability of work."

<http://www.nsta.org/positionstatement&psid=22>

“Hypotheses” should be banned: they are not part of science

- Scientists don’t make hypotheses (here I mean hypotheses as promoted by science fairs: a guess as to what your experiment will demonstrate)
- They don’t appear in scientific papers
- They are not desirable because they will tend to bias experimental design and analysis (much as the CIA’s bias that Iraq had WMD led to faulty conclusions that Iraq did have WMD)



"Hypotheses" should be banned

"[The scientist] cannot permit himself any preconception as to what sort of results he will get, nor must he allow himself to be influenced by wishful thinking or any personal bias."

Percy W. Bridgman – From: *On "Scientific Method"* in Reflections of a Physicist, 1955

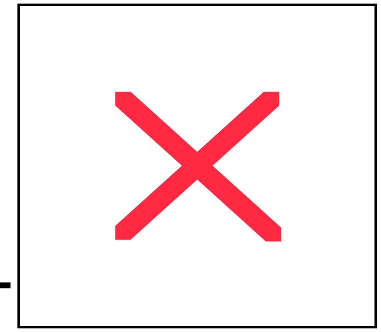
In the American vernacular, "theory" often means "imperfect fact"—part of a hierarchy of confidence running downhill from fact to theory to hypothesis to guess. Thus creationists can (and do) argue: evolution is "only" a theory, and intense debate now rages about many aspects of the theory. If evolution is less than a fact, and scientists can't even make up their minds about the theory, then what confidence can we have in it? Indeed, President Reagan echoed this argument before an evangelical group in Dallas when he said (in what I devoutly hope was campaign rhetoric): "Well, it is a theory. It is a scientific theory only, and it has in recent years been challenged in the world of science—that is, not believed in the scientific community to be as infallible as it once was."

[Stephen Jay Gould, "Evolution as Fact and Theory," May 1981; from *Hen's Teeth and Horse's Toes*, New York: W. W. Norton & Company, 1994, pp. 253-262.] www.stephenjaygould.org

Well, evolution *is* a theory. It is also a fact. And facts and theories are different things, not rungs in a hierarchy of increasing certainty. Facts are the world's data. Theories are structures of ideas that explain and interpret facts. Facts do not go away when scientists debate rival theories to explain them. Einstein's theory of gravitation replaced Newton's, but apples did not suspend themselves in mid-air, pending the outcome. And humans evolved from apelike ancestors whether they did so by Darwin's proposed mechanism or by some other, yet to be discovered.

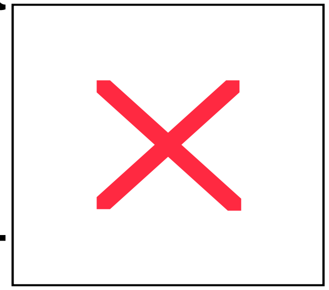
[Stephen Jay Gould, "Evolution as Fact and Theory," May 1981; from *Hen's Teeth and Horse's Toes*, New York: W. W. Norton & Company, 1994, pp. 253-262.] www.stephenjaygould.org

Similarity between scientists and teachers



How do scientists solve problems? Many ways.	How do teachers teach students? Many ways.
Scientists have different styles and strengths	Teachers have different styles and strengths
May spend entire career in one area or may branch into new areas	May spend entire career teaching one subject or may teach new subjects
Constrained by current knowledge, resources	Constrained by standards, district policy, resources, knowledge
Common goal: Improved understanding of nature or technology development	Common goal: Improved student learning

Differences Between School and Work



TOPIC	SCHOOL	WORK
Learning	Curriculum-based learning	Needs-based learning
Memorization	Often	Never
Importance of solving timed problems	Very	Not
Learning resources	Teachers, textbook	Co-workers, books, suppliers, technical papers, web, trade magazines, etc.
Nature of problems	Well-defined Single subject area Work alone	Often ill-defined, e.g. What is the best way to … ? Multidisciplinary Work as part of team

The Scientific Method

" [the working scientist] is … not consciously following any prescribed course of action, but feels complete freedom to utilize any method or device whatever which in the particular situation before him seems likely to yield the correct answer. No one standing on the outside can predict what the individual scientist will do or what method he will follow. In short, science is what scientists do, and there are as many scientific methods as there are individual scientists."

Percy W. Bridgman – From: *On "Scientific Method"* in Reflections of a Physicist, 1955

"Feynman was always the inquisitive type; he had to have the facts. To find out what happened to the shuttle, he went straight to the people who put the shuttle together."

<http://www.fotuva.org/online/frameload.htm?/online/challenger.htm>

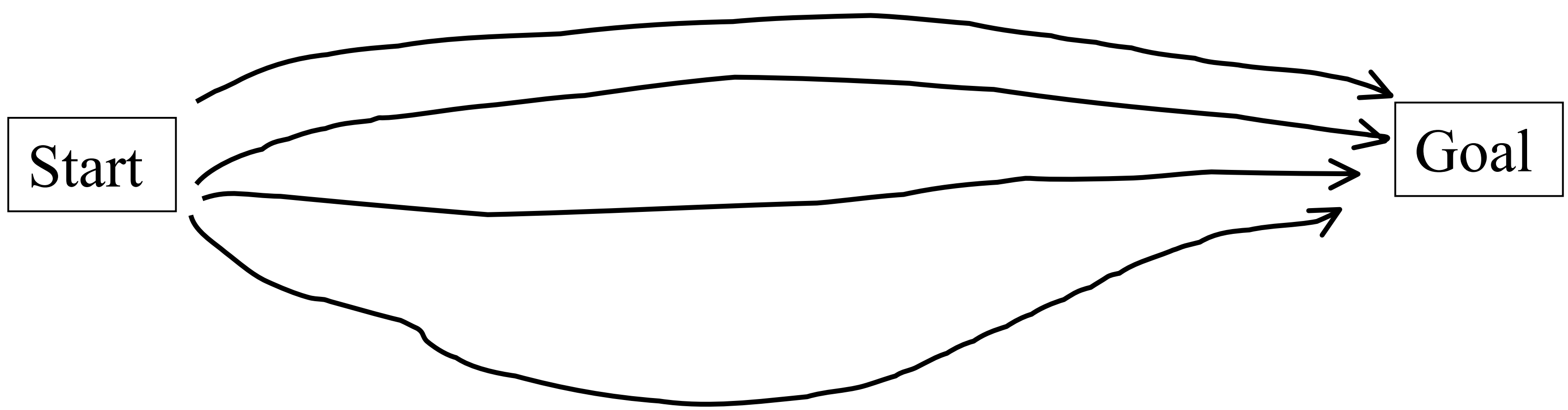
(He did not say: my hypothesis as to why the shuttle blew up is …)

Constraints on solving problems

- Funding
  - Even if you have funding, you are constrained to do your proposed work
- Research team
  - Number, expertise, background
- Equipment
- Competitors
- Research that is "in"
- It's hard to get funding for research that is "out"
- Current modes of thinking – the "box"
- If you have been in the field your entire life, you know the standard ways of solving problems but you may be less likely to use a novel approach
- If you are new, you don't know the standard ways, but may be more likely to use a novel approach

How to approach problems

Develop multiple approaches since you aren't sure which one will work

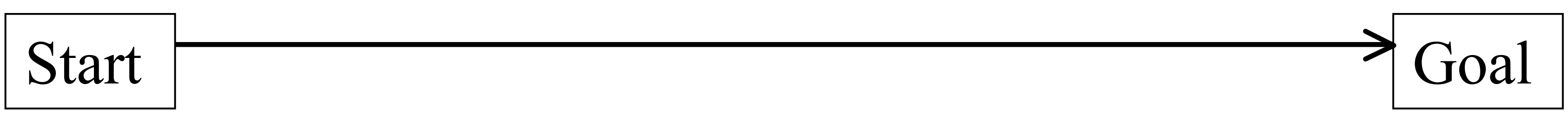


How to approach problems

Develop an initial approach that gets you closer to your goal

Solving problems

If problem and solution are well defined, then just "turn the crank"



Look at some scientific papers to see how published scientific work is organized

- Background material
- Define the problem that is being addressed
- Justification/rationale for the work
- Experimental methods/equipment
- Data and data analysis – tables, graphs
- Discussion
- Summary and concluding remarks
- Acknowledgements and References

The actual work is often not nearly as organized and logically done as the papers indicate!! The so-called "scientific method" reflects how science is ***published****, not necessarily how science is* ***done****.*

Back to Hypotheses:

*The **Discussion** Section in a Scientific Paper is Generally where Hypotheses are Included*

- Discussion Section
  - Words that are typically used include:
    - "We hypothesize that these data can be explained by…"
    - "We tentatively ascribe these results to the following theoretical model …"
    - "We postulate that these results are due to …"
    - "Our results seem to be consistent with the following explanation …"

Solving problems takes time

"To do real good physics you need solid lengths of time, to… [put] ideas together which are vague and hard to remember … it's very much like building a house of cards and each of the cards is shaky, and if you forget one of them the whole thing collapses. You don't know how you got there and you have to build them up again, and if you're interrupted and kind of forget half the idea of how the cards went together – your cards being different parts of the idea – it's easy for [the idea] to slip [away]. [You] needs lots of concentration – that is, solid time to think."

From "The Pleasure of Finding Things Out" by Richard Feynman, p. 19

"When the Special Theory of Relativity began to germinate in me, I was visited by all sorts of nervous conflicts... I used to go away for weeks in a state of confusion."

Albert Einstein

Importance of doubt and the fallibility of authority

"Another of the qualities of science is that it teaches the value of rational thought, as well as the importance of freedom of thought; the positive results that come from doubting that all the lessons are true… Learn from science that you must doubt the experts. As a matter of fact, I can also define science another way: Science is the belief in the ignorance of experts."

From "The Pleasure of Finding Things Out" by Richard Feynman, p. 186-187

Scientific Integrity - an integral part of science

"… That is the idea that we all hope you have learned in studying science in school … It's a kind of scientific integrity, a principle of scientific thought that corresponds to a kind of utter honesty – a kind of leaning over backwards. For example, if you're doing an experiment, you should report everything that you think might make it invalid – not only what you think is right about it … Details that could throw doubt on your interpretation must be given if you know them."

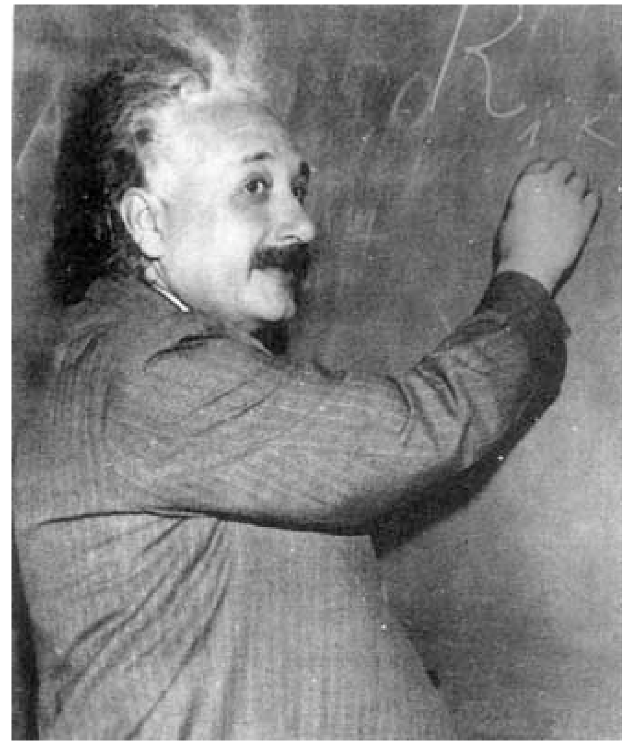
From "The Pleasure of Finding Things Out" by Richard Feynman, p. 209-210

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

Richard Feynman, Challenger Commission Report

Summary

- No single scientific method: ban hypotheses
- Many ways to do science and solve problems
- Scientists formulate multiple alternate approaches to solve problems
- Science performed depends on the state of the field you are working in
- Scientists operate under various constraints
- Science takes extended lengths of time
- Scientists should have doubt and integrity



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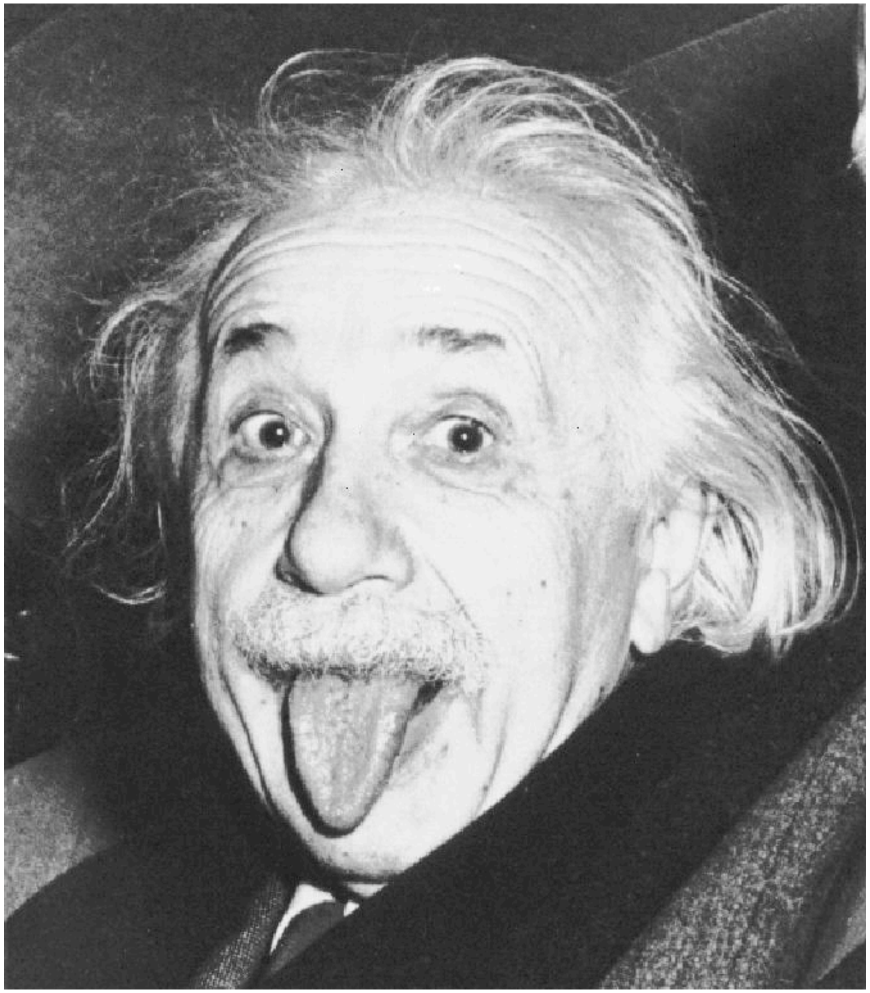

… Scientists have fun!