

How do scientists really do science?

Presentation to the
San Dieguito Unified School District Science Teachers
August 24, 2004

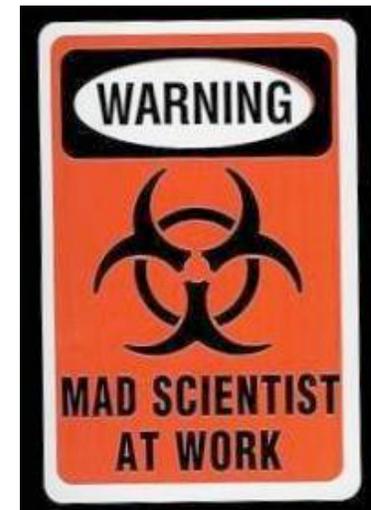
Dr. Larry Woolf

General Atomics

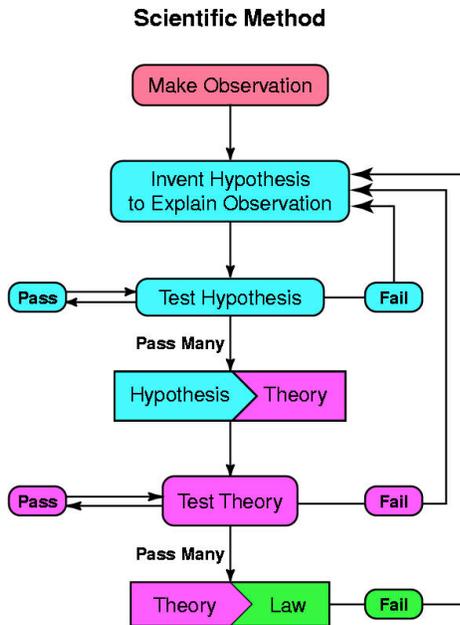
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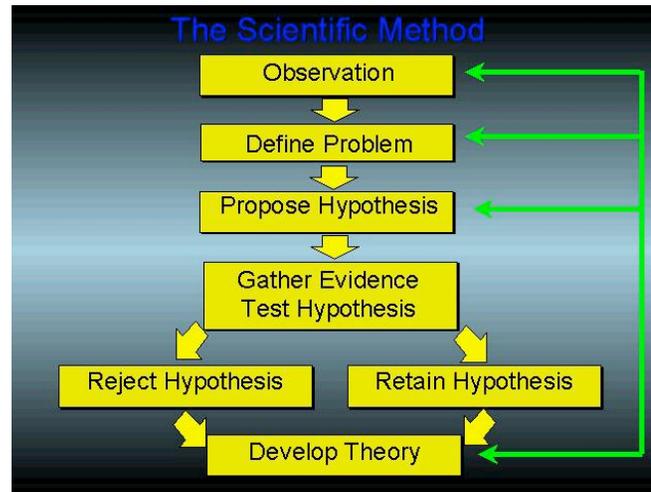
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Standard Mantra: Scientists follow “The Scientific Method”



The Scientific Method #1



The Scientific Method #2

We Are Scientists, We Use the Scientific Method

- It is important to be as objective as possible.
- There is no right place to enter the cycle.
- Experiments must be reproducible.
- There is no end to the cycle.
- The cycle is not rigid.

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    graph TD
      A[Identify Patterns] --> B[Experiment]
      B --> C[Predict]
      C --> D[Make a Hypothesis]
      D --> A
  
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The Scientific Method #3

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

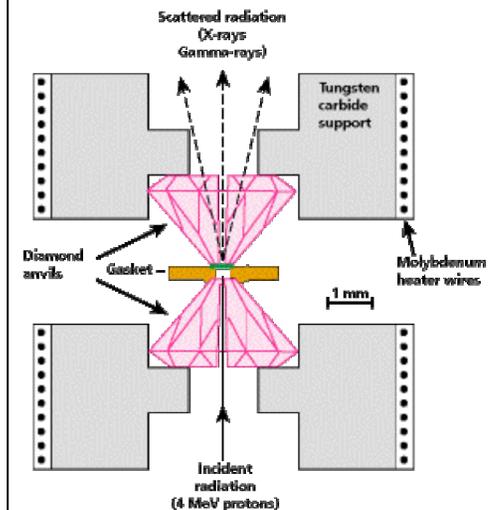
There are a wide variety of ways to do science

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

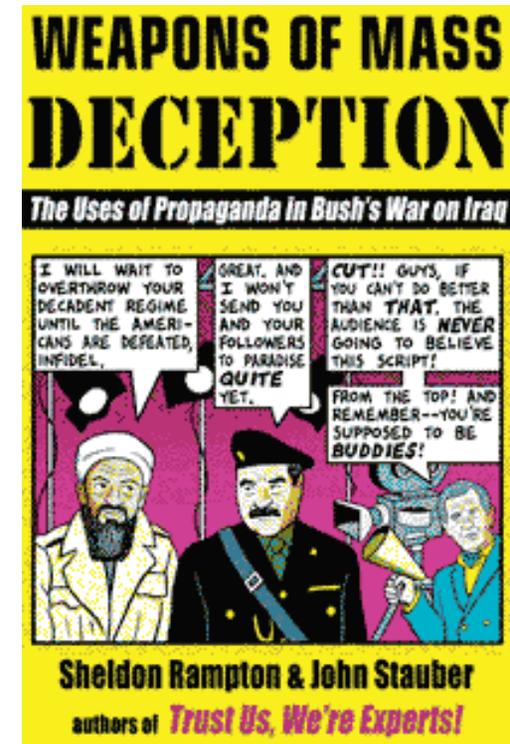


“Although no single universal step-by-step scientific method captures the complexity of doing science, a number of shared values and perspectives characterize a scientific approach to understanding nature. Among these are a demand for naturalistic explanations supported by empirical evidence that are, 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





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

Let's take a slight detour



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

Some Guidelines for Success at Work

1. Become the world expert in your particular area.
2. Continually expand the depth and breadth of your knowledge and skills.
3. Utilize all information resources available
4. Innovate continuously. Always push your envelope as well as the science and technology envelope. Stay uncomfortable with what your skills and knowledge are.
5. Make sure that you learn something useful from any tests or experiments that you perform. These results should form the basis for future tests.
6. Treat everyone you work with (above and below you) with respect.



Push the Envelope

- Students
 - Summer enrichment programs in science and engineering
 - <http://tbp.mit.edu/highschool/>
 - <http://www.sciserv.org/stp/>
 - <http://www.rit.edu/~gtfsbi/Symp/highschool.htm>
- Teachers
 - Project-based learning/inquiry-based science
 - www.glef.org and click on project based learning
 - <http://www.lawrencehallofscience.org/foss/>
 - <http://www.nsrconline.org/>
 - San Diego Science Alliance resource catalog and email alerts: www.sdsa.org
 - Eisenhower National Clearinghouse: www.enc.org
 - Join on-line discussion forums: (with teachers worldwide)
 - <http://www.geocities.com/physhare/> and links noted there



Break out of the box

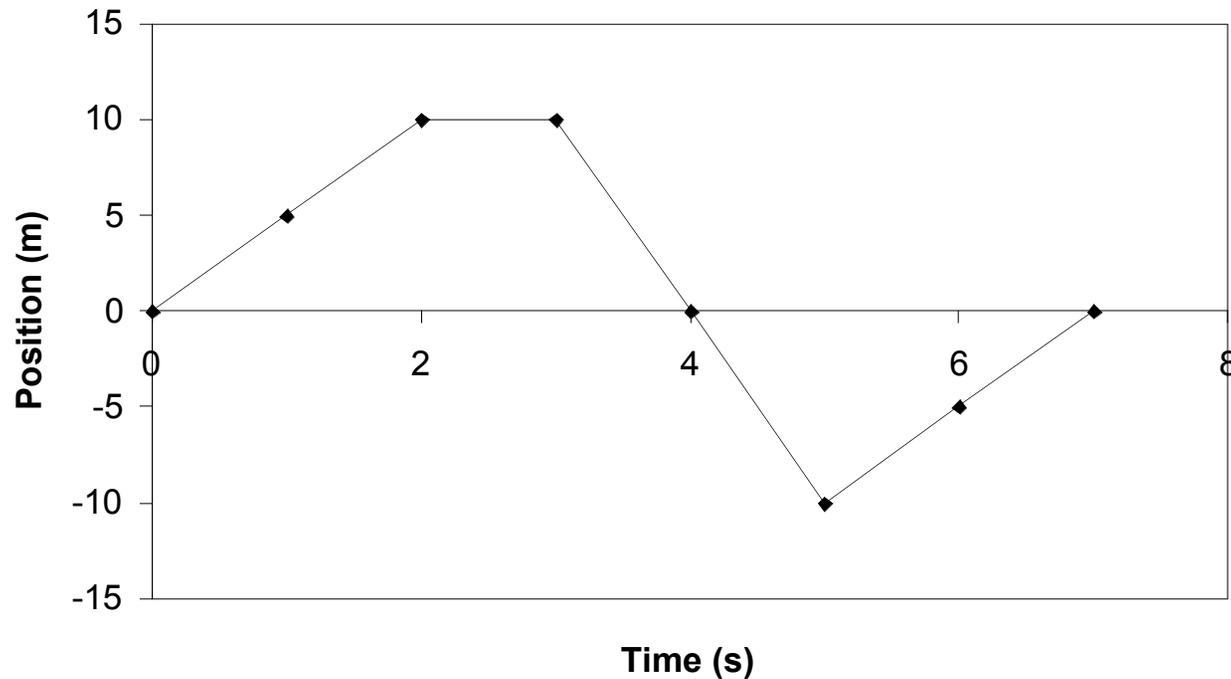
- Try something new, then evaluate student learning and interest vs using your previous approach
- Have students apply learning to a new, ill-defined, real-world problem
 - What is the best way to ...
 - Determine 3 ways that you could ...
- Student learning by interchangeably examining science problems via math, pictorial view of the concept, written analysis, verbal discussions with peers, and graphs (**see next slide**)



What really matters is the students' long term comprehension of science and inquiry and the ability to apply their skills and knowledge to real-life situations – as an informed public or as scientists

For example: motion

Position vs Time



- Describe the motion in words; discuss the motion with another student
- Determine the velocity and displacement for each segment
- Using a toy car or yourself, demonstrate the motion
- Write an equation describing the motion for each segment

More useful than simple $x=vt$ problem



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/frameلود.ad.htm?/online/challenger.htm>>

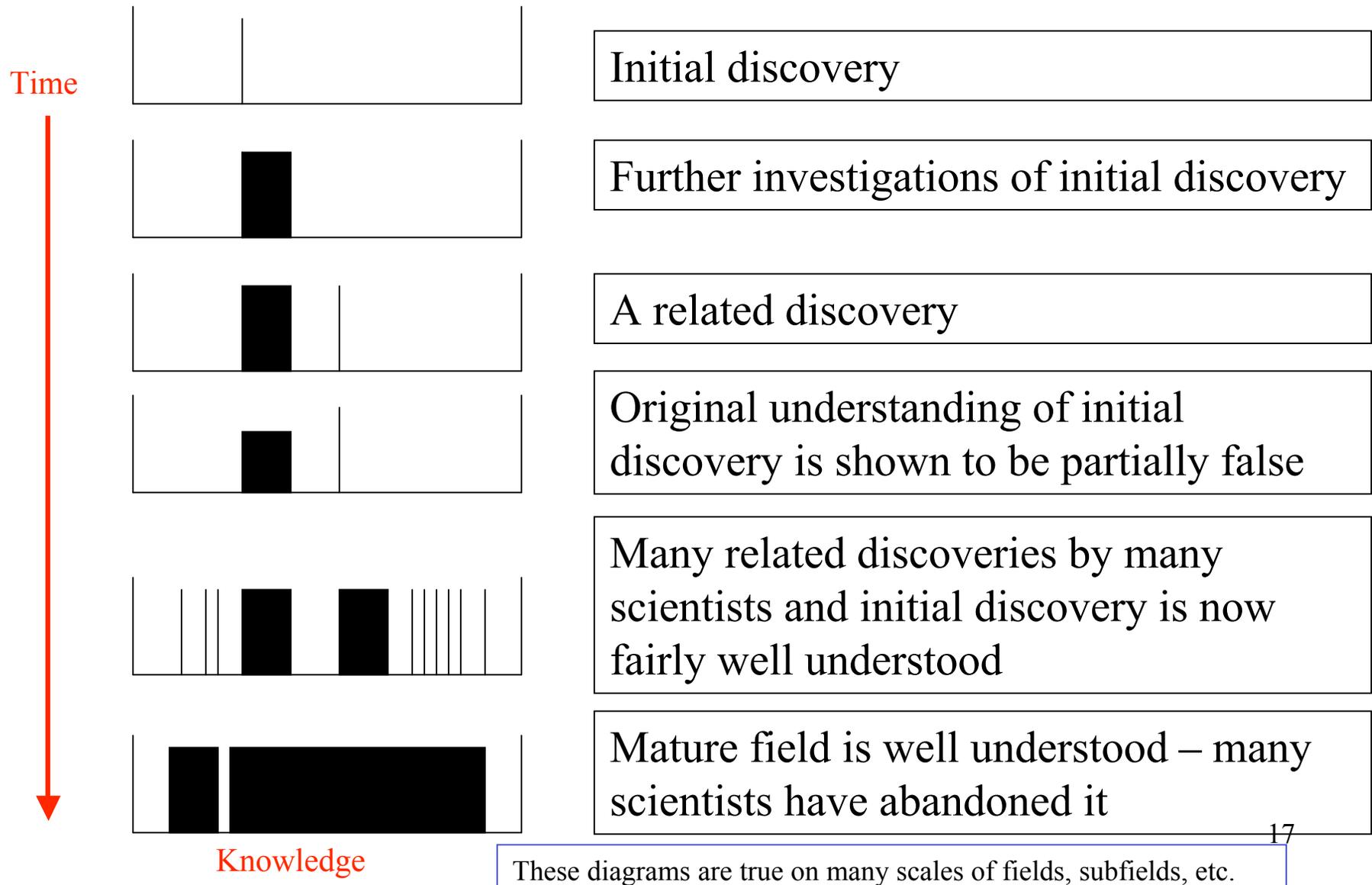
(He did not say: my hypothesis as to why the shuttle blew up is ...)

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

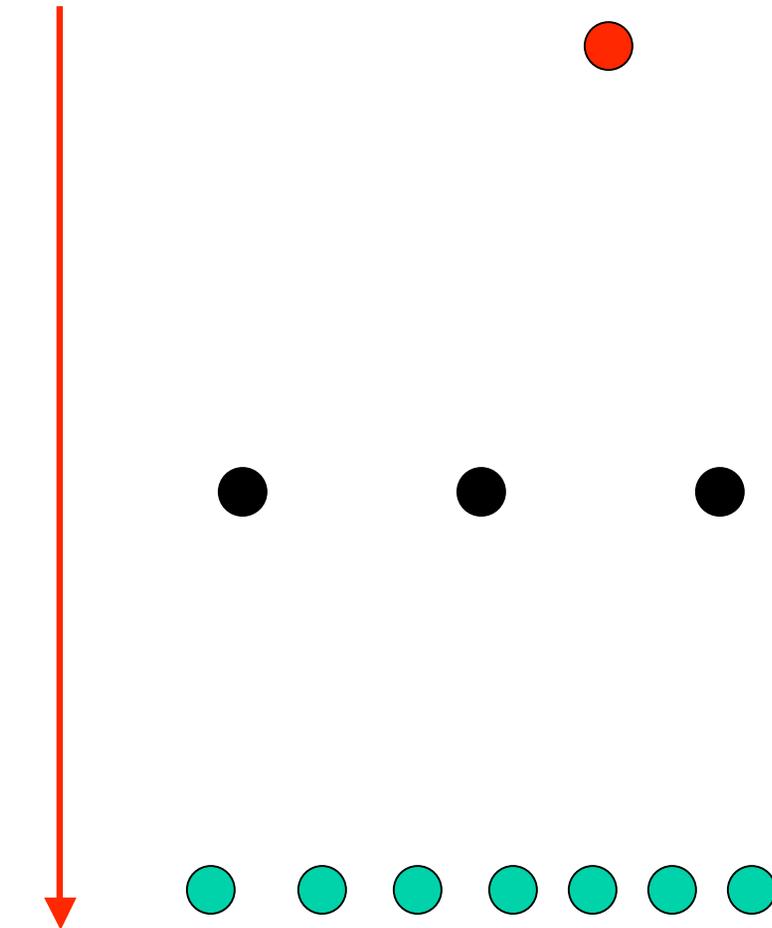


Time line of development of knowledge in a scientific area:
The March of Science



The March of Science: Number/role of participating scientists

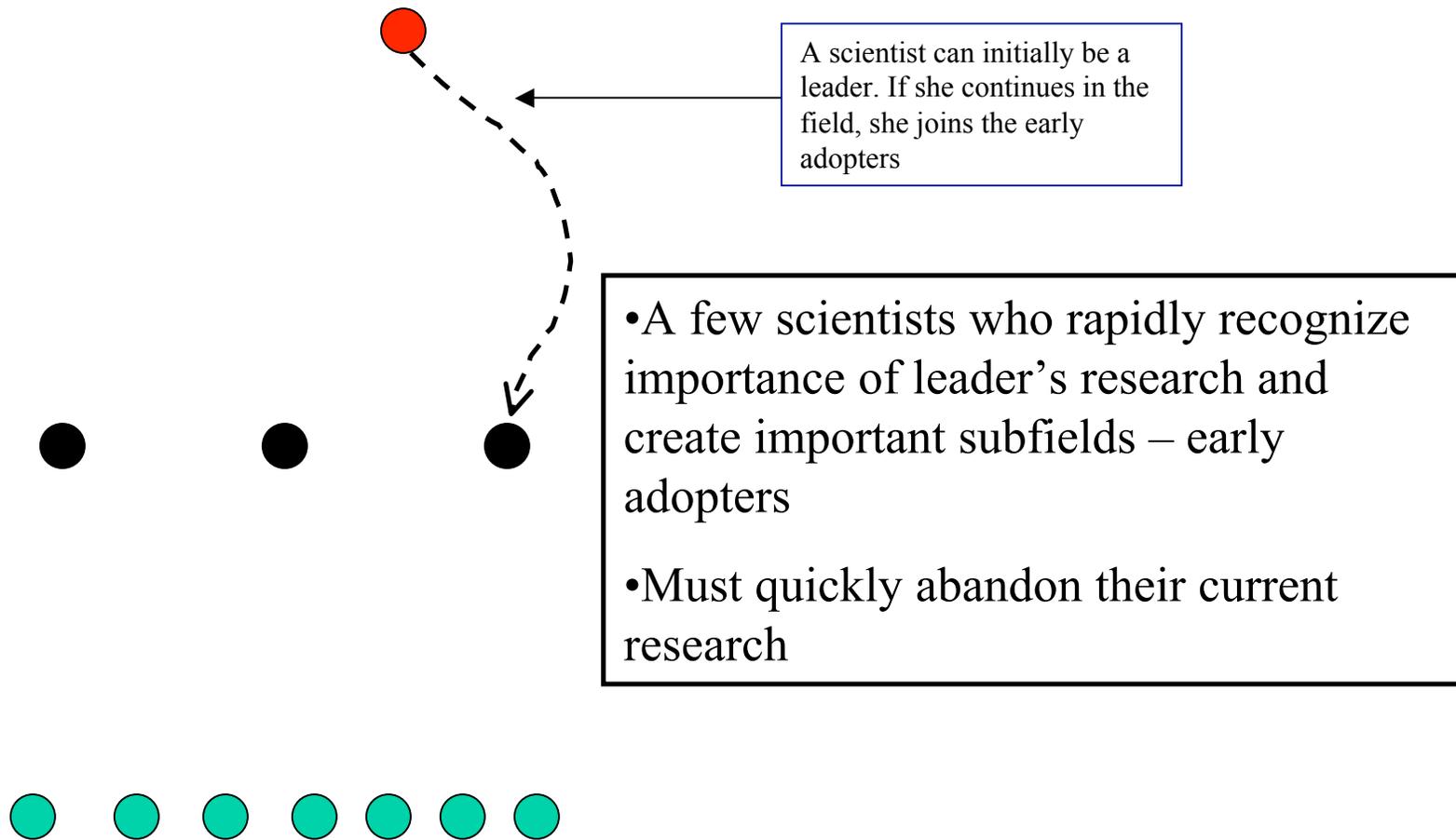
Time



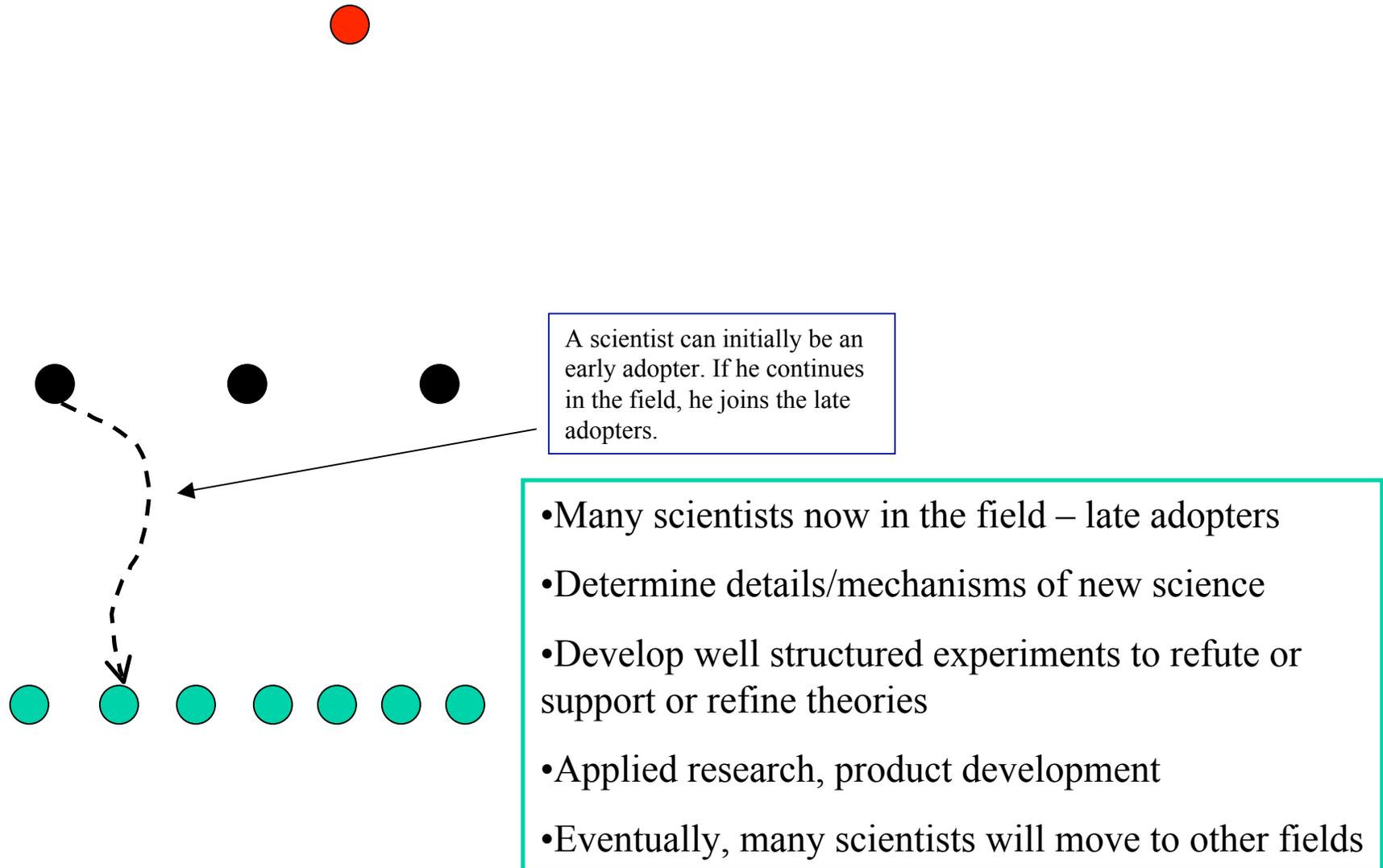
- Leaders/risk takers; one or a small number of people; create new fields
- Good instincts; able to sense new productive fields
- Could lead to Nobel Prize or completely useless/career killing

e.g. chaos, high temperature superconductors, string theory, science education research, nuclear fusion, ultracold atoms

The March of Science: Number/role of participating scientists



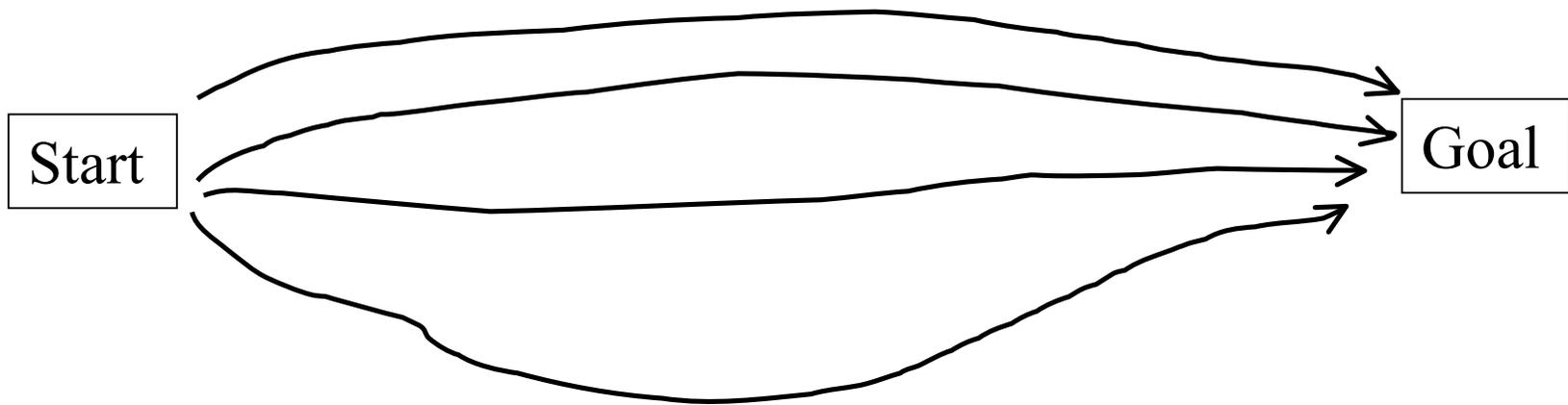
The March of Science: Number/role of participating scientists



Scientists have a vital role to play at each level – all are important to the growth of scientific knowledge

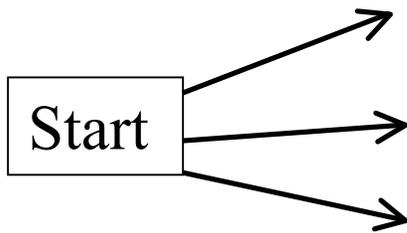
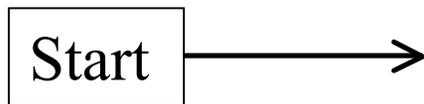
How to approach problems

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



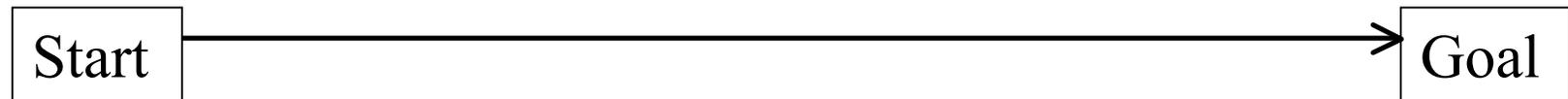
How to approach problems

Develop an initial approach that gets you closer to your goal



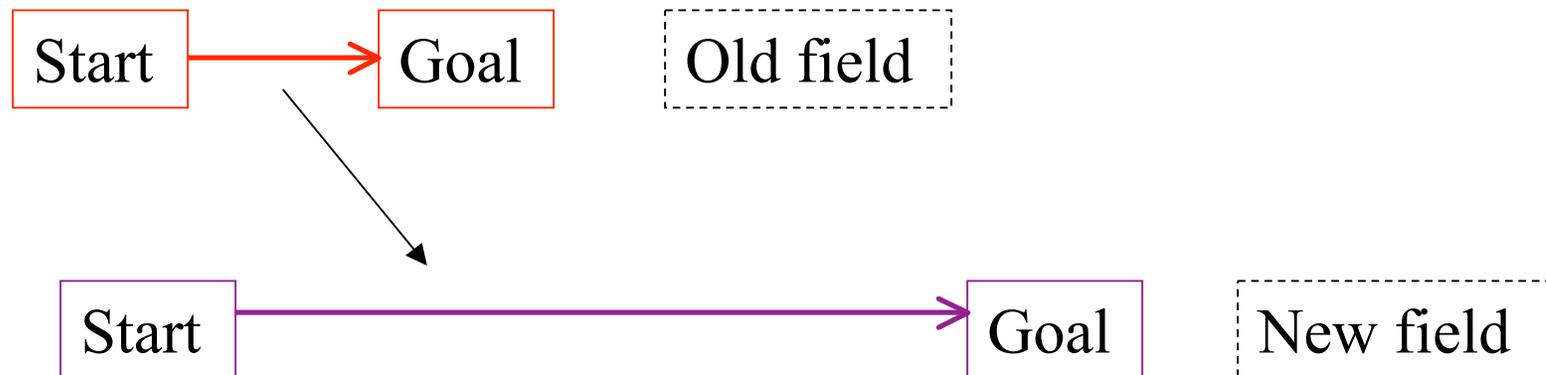
Solving problems

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



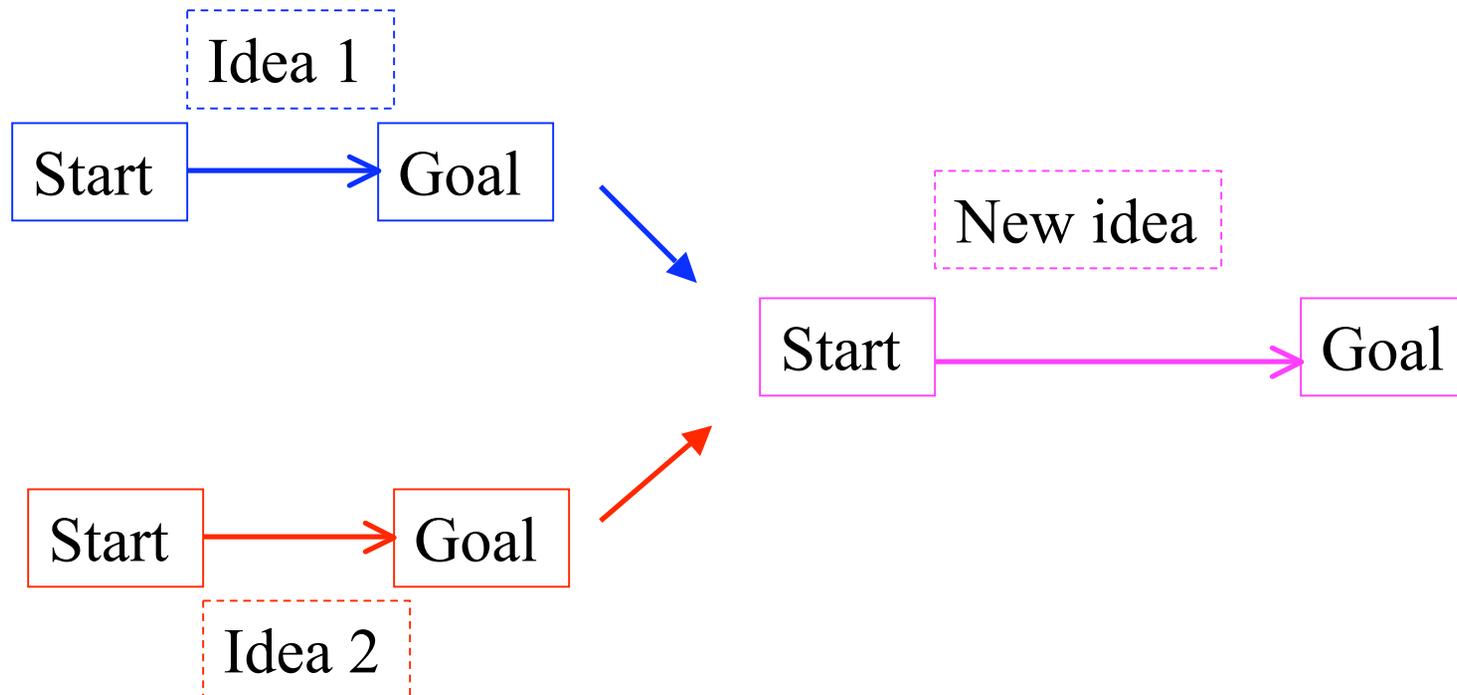
Solving problems

Extend known methodology to a new field



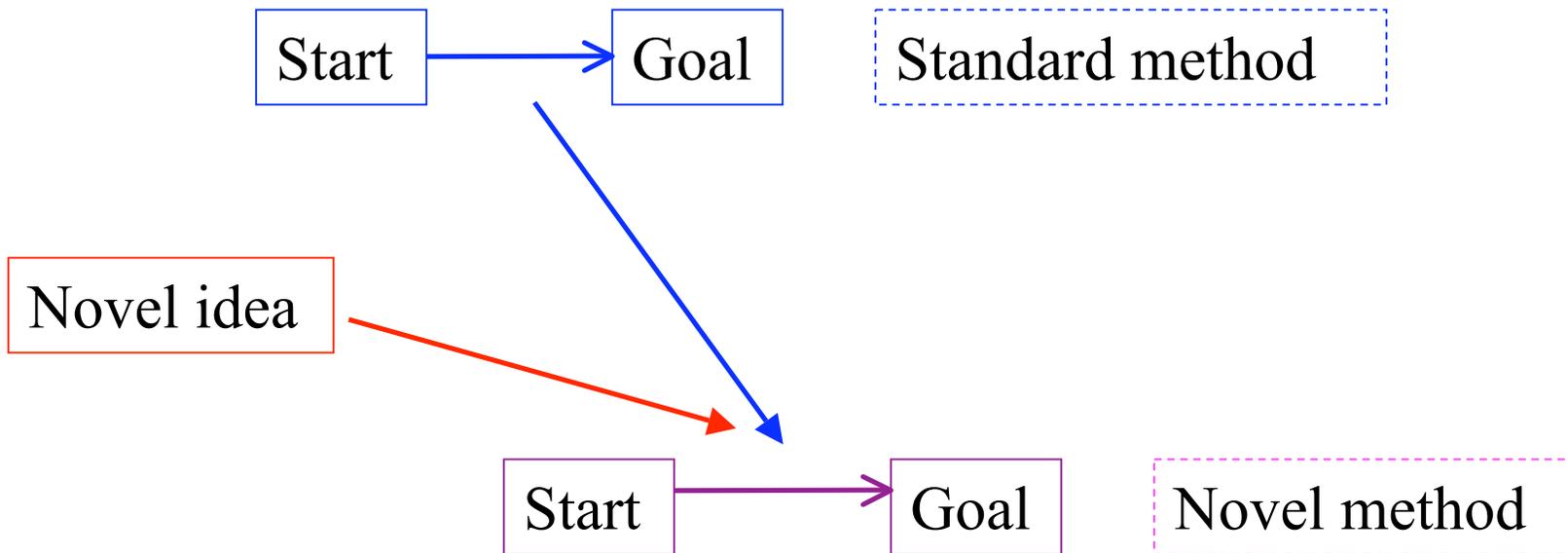
Solving problems

Combine two existing ideas/methods into a new idea/method



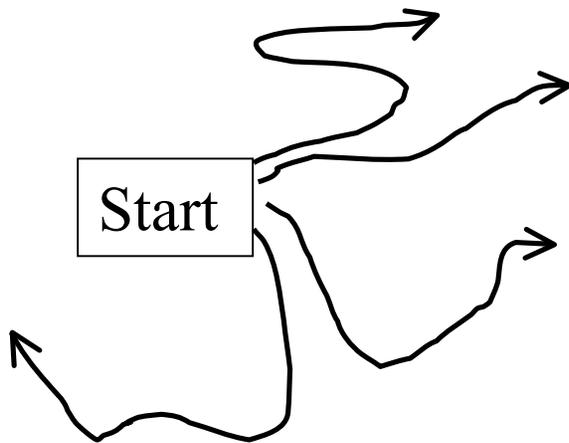
Solving problems

Combine a standard method/idea with a novel method/idea



Solving “problems”

Innovators/discoverers often have no idea of what their goal is ... but they have a loosely formed idea for a research area



"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



See if you can identify the new approach that was used in the following quotes from different scientific papers

- “In this paper, we develop a general theory for the efficiency of multiple bandgap cells that is a generalization of the approach used by Swanson for a single bandgap cell”
- “Therefore, a high efficiency solar energy conversion system ... ,solar PTPV, ... fulfills these objectives. Basically, a PTPV system is a tandem system utilizing first a PV system, then a TPV system.”
- “In this letter, we report the development of a novel technique incorporating a unique electrophoretic deposition process that has produced, for the first time, kilometer lengths of fully superconducting fiber.

- Combine 2 methods
- Combine standard idea and novel method
- Extend known methodology

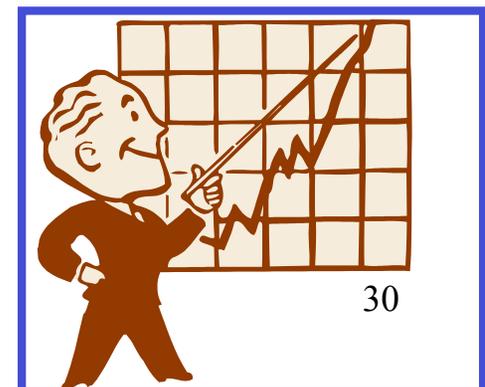
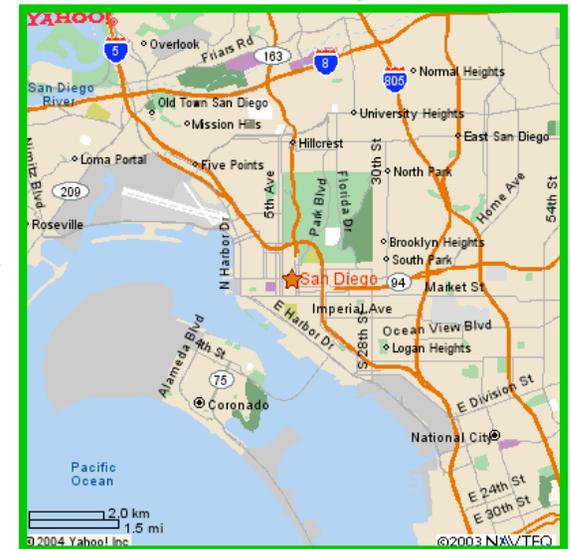
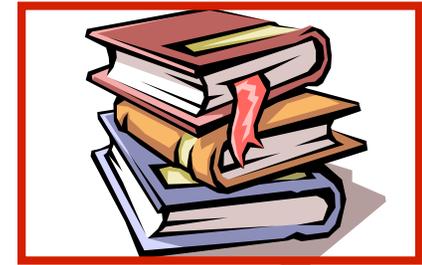
And the answer is ...



- “In this paper, we develop a general theory for the efficiency of multiple bandgap cells that is a generalization of the approach used by Swanson for a single bandgap cell”
[Extend known methodology]
- “Therefore, a high efficiency solar energy conversion system ... We propose that a solar PTPV system fulfills these objectives. Basically, a PTPV system is a tandem system utilizing first a PV system, then a TPV system.” [Combine 2 methods]
- “In this letter, we report the development of a novel technique incorporating a unique electrophoretic deposition process that has produced, for the first time, kilometer lengths of fully superconducting fiber.” [Combine standard idea and novel method]

Solving problems: my general approach

- Define the problem: what am I trying to find do
- Learn relevant background information:
 - papers, patents, review articles, books, web site, vendors that make relevant equipment/materials, competitors that have done related work
- Develop multiple approaches to solve the problem
- Investigate the most likely approach first. If it doesn't work, investigate alternate approaches (analogy: going from point A to point B: use freeway, but if jammed, try alternate route)
- Summarize data into tables and charts that can be understood by someone else a year from now
- Analyze and summarize data and results in report
- Use these results as the basis for further work (and be persistent and don't get discouraged)



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**. Look at real science papers to see for yourself how scientific work is written.*

Back to Hypotheses:

They are present, but are in the discussion section of a paper

- Discussion Section
 - “Hypothesis” type words that are typically used include:
 - “A hypothesis that is consistent with these data is that ...
 - It appears that these results are consistent with 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



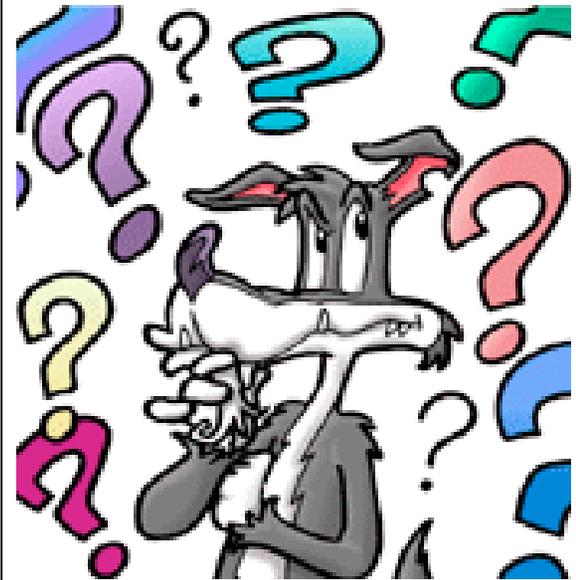
"When the Special Theory of Relativity began to germinate in me, I was visited by all sorts of nervous conflicts... I used to go away for weeks in a state of confusion."

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

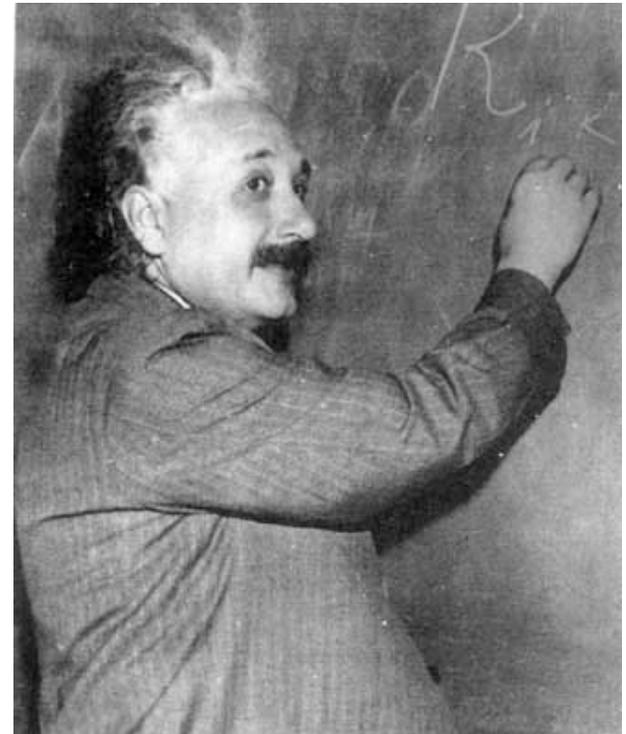


“For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled.”

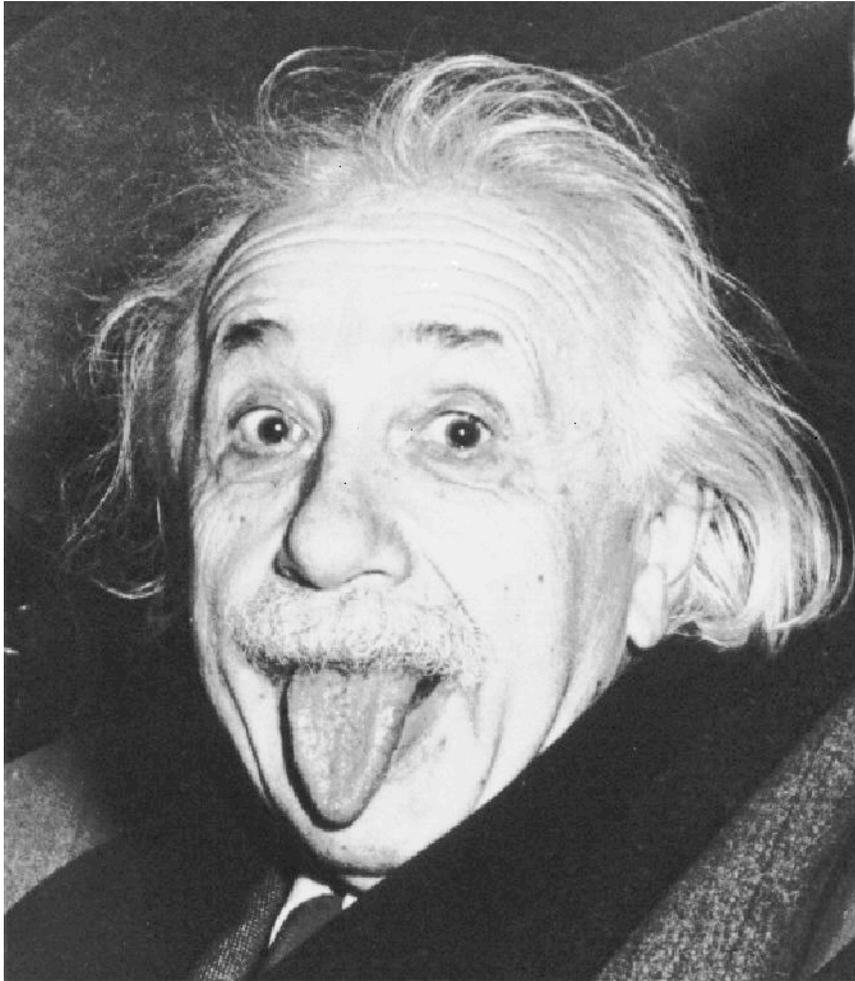
Richard Feynman, Challenger Commission Report

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



And ...



... Scientists have fun!