

# HOW DOES SCIENCE WORK?

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*These are my opinions, not those of colleagues or any government agency.  
This talk has been cleared by AFRRRI for public release.*

# What Are We Doing Here?

- AFRRI Mission
- Scientific Revolution
- Logic
- Prevailing Assumptions
- Empiricism
- Psychology
- Decline Effect

- Karl Popper's Falsification
- Thomas Kuhn's Paradigm
- Naturalism
- Sociological Criticisms
- Scientific Realism
- Explanation and Creativity
- Reductionism
- Optimism

# Challenge

- Nuclear Risks

- Nuclear weapons fundamental part of foreign and defense policies in Middle East and Asia
- Jihadism shows no signs of fading away
- Terrorists can catalyze conflict between countries

- AFRRI's Mission

- Creative solutions to the problem of radiation exposure
- Question basic assumptions, shake things up
- Take a step back, consider what goes into the process of science, how we arrive at useful explanations

# Scientific Revolution

- Scientific Revolution – 16<sup>th</sup> & 17<sup>th</sup> centuries
  - Inspired by previous thinkers throughout the ages advocating observation, hypothesis, experimentation, need for independent verification
  - Copernicus, Galileo: sun, not earth, at center of universe
  - Kepler: movement of the planets
  - Newton: force of gravity; laws of motion
  - Newton & Leibniz: calculus
- Rely on reason (logic and observation), not authority (e.g., Aristotle)

# Induction and Confirmation

- The fundamental problem of science: How can we confirm a theory?
- Deduction: patterns of argument that transmit truth with certainty; if premises are true, conclusion guaranteed
  - All men are mortal, Socrates is a man, therefore Socrates is mortal.
  - Doesn't get you very far

## Induction and Confirmation, cont.

### Induction: generalize from observations

- Observe 1,000 swans; all are white; supports theory all swans white
- Unlike deduction, error possible
- Logical problems
  - Many possible theories explain observations
  - Observations are theory-laden

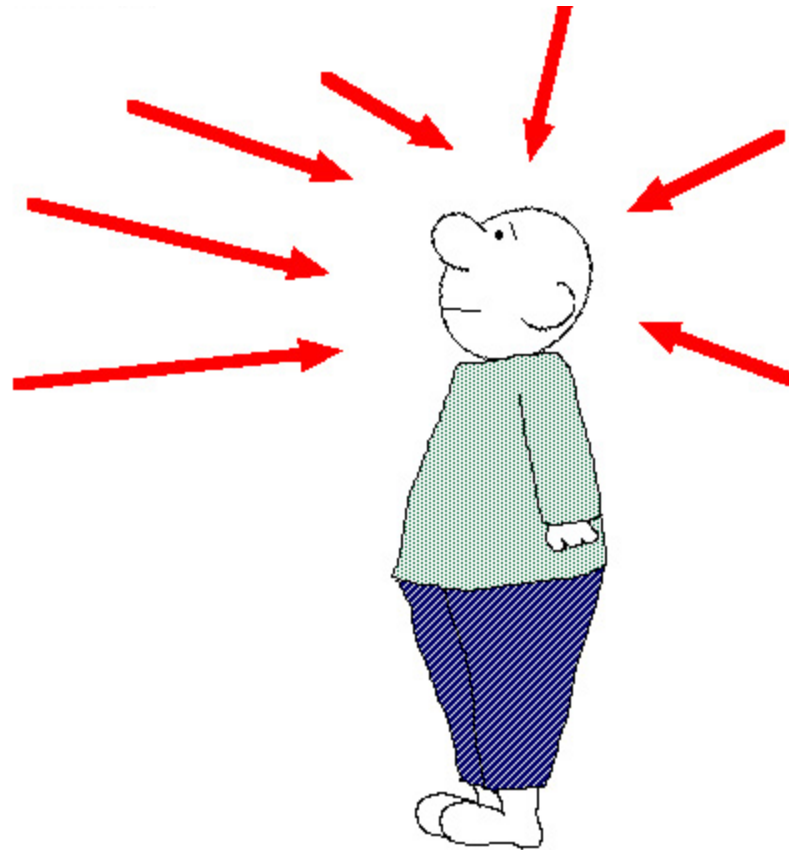


# Prevailing Assumptions of Biology (Memes)

- Reductionism
  - Phenomena understood in terms of small components
  - Understanding higher level phenomena: synthesis of bits
- Empiricism
  - Knowledge derived directly from observable phenomena
  - Explanations spring into mind from observations, pure logic
- These assumptions are debatable.

# Empiricist Tradition

- Source of knowledge about the world: direct experience (observations)





# Empiricist Tradition

- Useful break from reliance on authority and historical assumptions
- Start from pure logic about how to determine truth. Make observations. Conclusions will fall into place.

# Empiricism: Logical Positivism

- Intellectual housecleaning: reaction to pretentious, mystical philosophy of Hegel, Heidegger and others
- Extreme form of empiricism
  - Logic the main tool
  - Experience is the source of all knowledge
  - If a sentence cannot be tested through observation, it has no meaning
  - Observations → Induction → Predictions about future experiences
  - Dismissed relevance of psychology (big mistake)

# Empiricism: Logical Positivism

- Holistic criticism of logical positivism
  - Ideas and hypotheses form single web of belief
  - An unexpected observation can change the whole web; may even require revisions in logical principles

# Logical Empiricism

- Less aggressive version of logical positivism: more holistic. Theories connect many hypotheses
- Logic still the main tool
- Maintained (struggling) notion all truths based on observable phenomena
  - Language referring to unobservable entities (e.g., electrons) really just describing observable world in special abstract way
  - “In science there are no depths, there is surface everywhere.”

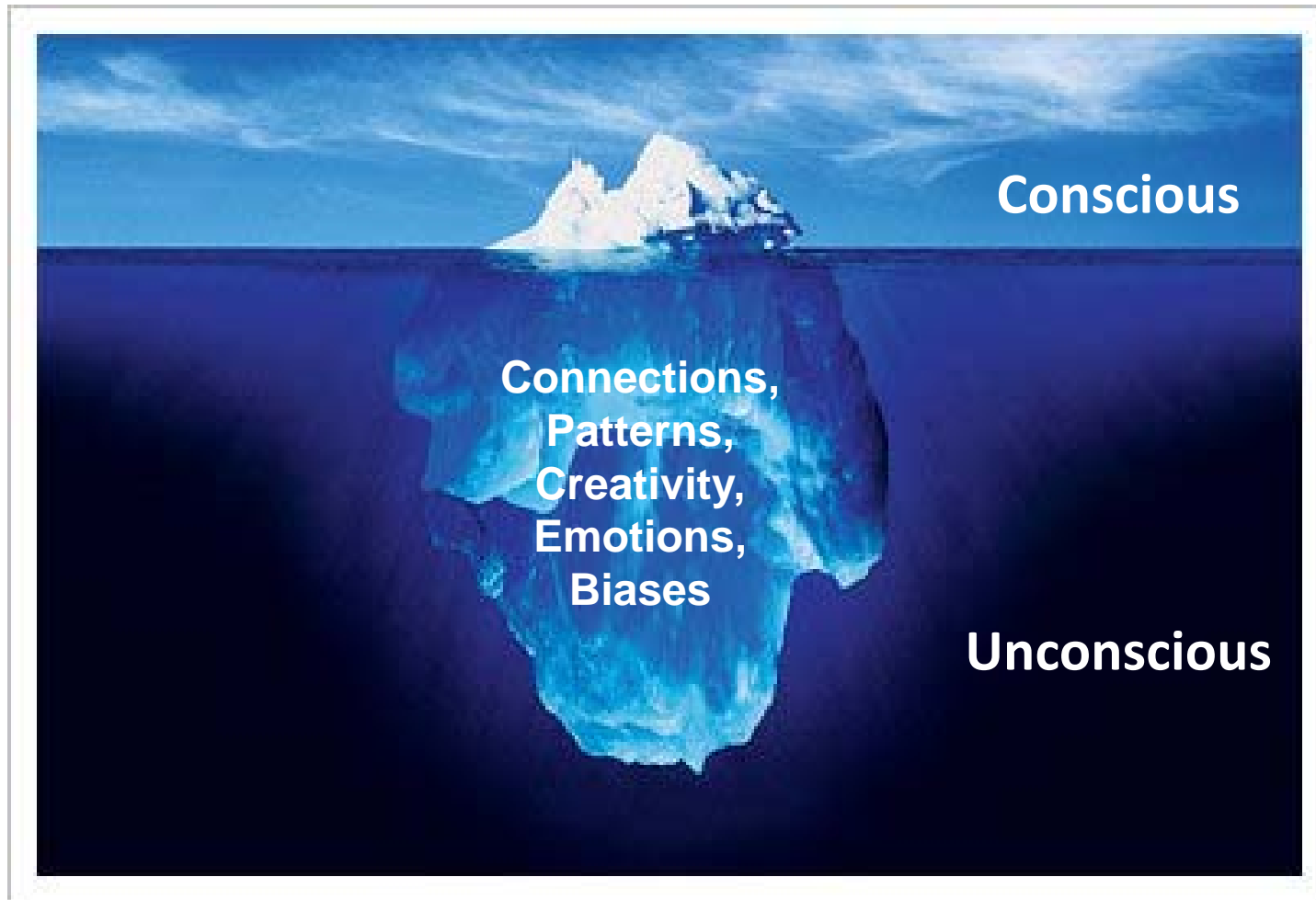
# Problems with Empiricism

- Scientists think of electrons and genes as real objects!
- By mid-70s, logical empiricism near extinction
  - Trouble developing rigorous language and inductive logic
  - Didn't come to grips with holism
  - New role for fields like history and psychology
  - Real unobservable structures can be studied and described (“scientific realism”)
- Empiricism (observation and pure logic) ran into problems – so how do we confirm a theory?

# Psychology

- ✿ Much of what goes on in our minds is unconscious
- ✿ Emotions unconsciously bias decisions
- ✿ Even with best of intentions, observations are biased
- ✿ Emotion and reason inseparably entwined
- ✿ We see what we expect to see
- ✿ Instrumental data processed before publication
- ✿ Researchers look where they think they will find positive results

# Psychology



# The Decline Effect

In every field of science:

- Dramatic new findings published
- Confirmed by multiple independent groups for a few years
- Then found to be false
- Effects statistically solid: not sloppy work ( $p < 0.05$ )
- Problem more severe for fashionable topics

Lehrer, J. New Yorker, December 13, 2010



# The Decline Effect, continued

## Explanations?

- Extraordinary scientific findings can happen by chance
- Groups obtain exciting findings, rush to publish without extensive replication
  - Small sample sizes (underpowered design)
  - Selective reporting
  - Subtle omissions
  - Unconscious misperceptions
  - Scientists find ways to confirm favorite hypothesis (powerful psychological force)
- Subsequent null data (disproving hypothesis) difficult to publish

Lehrer, J. New Yorker, December 13, 2010

# Karl Popper (1902-1994)

## Falsification

- How does one distinguish science (e.g., Einstein) from non-science (e.g., Freud)?
- Hypothesis scientific if and only if it has potential to be refuted by observation
- But support for theories absent; only rejection of theories

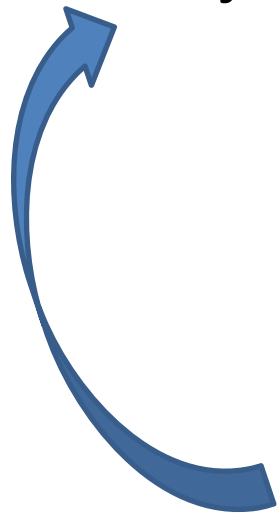
# Karl Popper, continued

## Process of scientific change

Conjecture (the bolder the better, in terms of breadth and precision)



Attempted refutation



Once hypothesis refuted, repeat step 1

Reminiscent of Darwinian variation and natural selection

# Problems with Popper

- Realistically, how does one refute a theory with theory-laden observations?
- Inconsistent with central role of probability in science
- Theories never “supported,” only rejected
  - So what is progress?
  - We can never increase our confidence that a theory is true, no matter how many times it has survived tests.
  - Some of Popper’s admirers do not realize this about his ideas.

Frank and Ernest

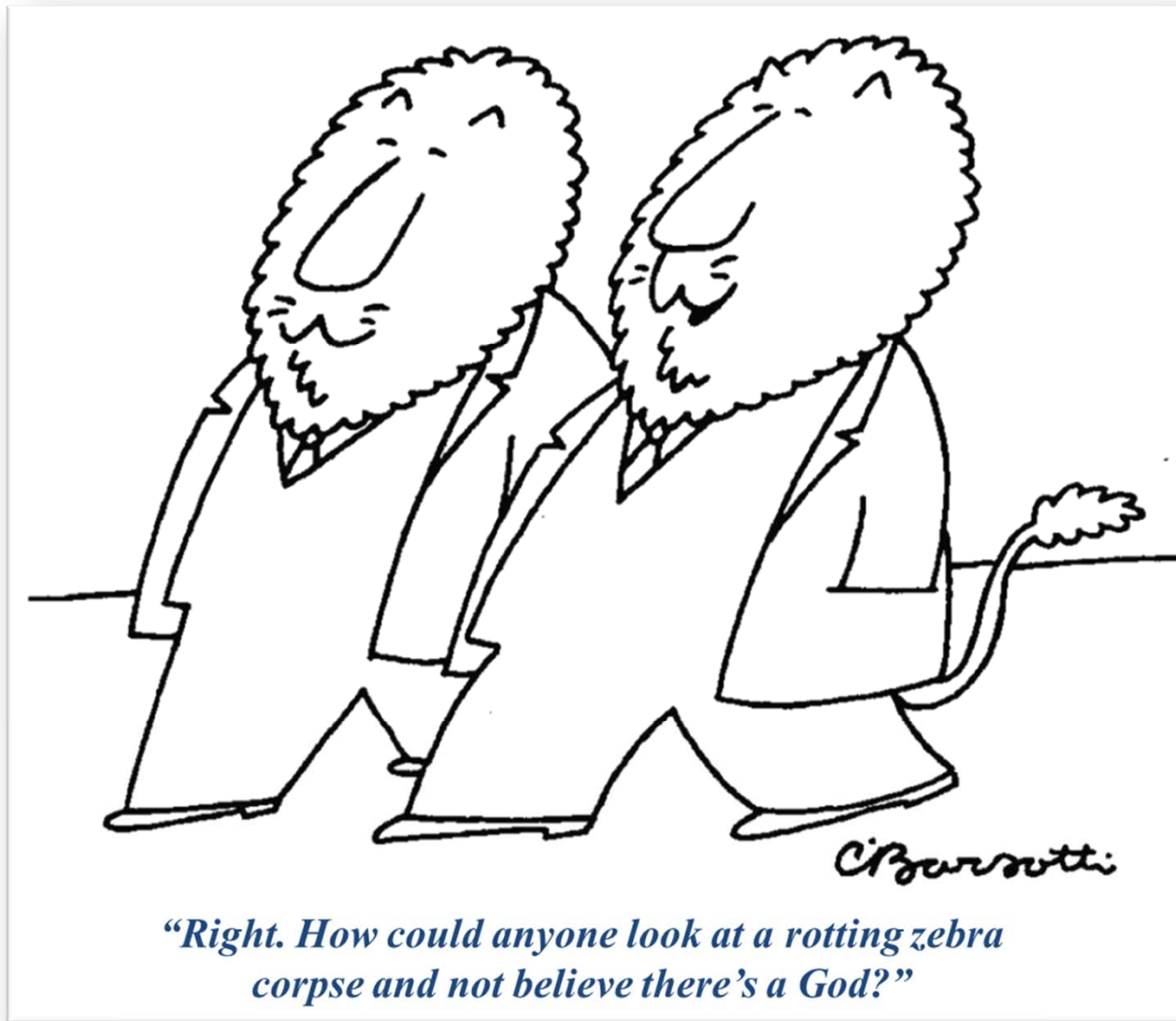


Bob Thaves, 1998

# Thomas Kuhn (1922-1996)

## The Structure of Scientific Revolutions (1996)

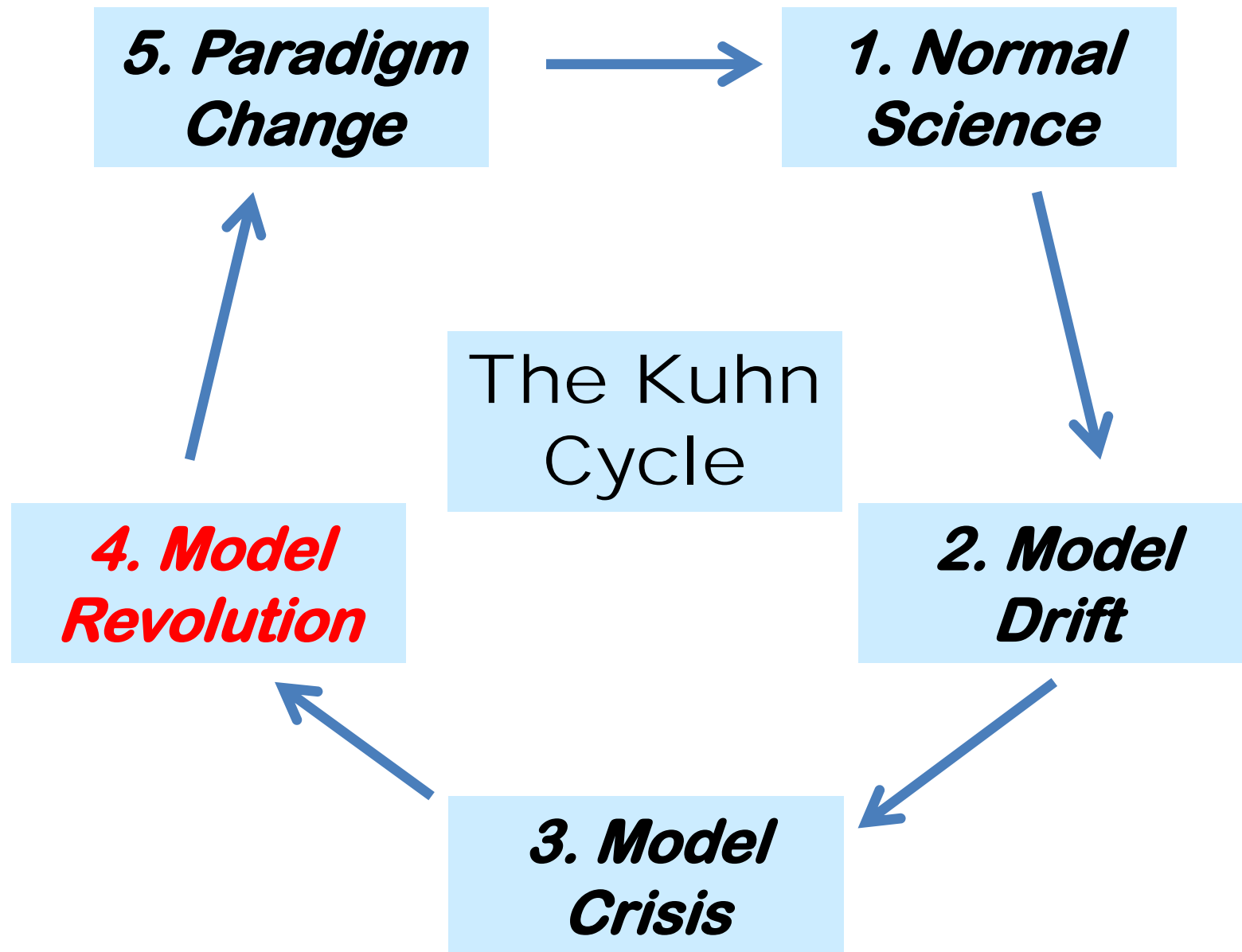
- Most famous book about science in 20<sup>th</sup> century
- “Paradigm”
  - Package of claims about world
  - Methods for gathering and analyzing data
  - Habits of scientific thought and action
- Logical empiricism damaged by Kuhn: objective observations leading to direct conclusions discredited



# Kuhn's Two Types of Science

1. Normal science (within a paradigm)
  - Scientists would be unproductive if they questioned everything all the time!
  - Kuhn: Normal science is good
  - Newtonian physics: gravity is a force
  - Some critics: Normal science is bad! Kuhn encouraging professionalism, narrow-mindedness, exclusion of unorthodox ideas (*peer-review committees, anyone?*)





## Kuhn's Two Types of Science, cont.

2. Anomalies → Crisis → “Paradigm shift”
  - Non-cumulative revolution in thought
  - Different assumptions, different language
  - Einstein: gravity is a distortion of space and time!

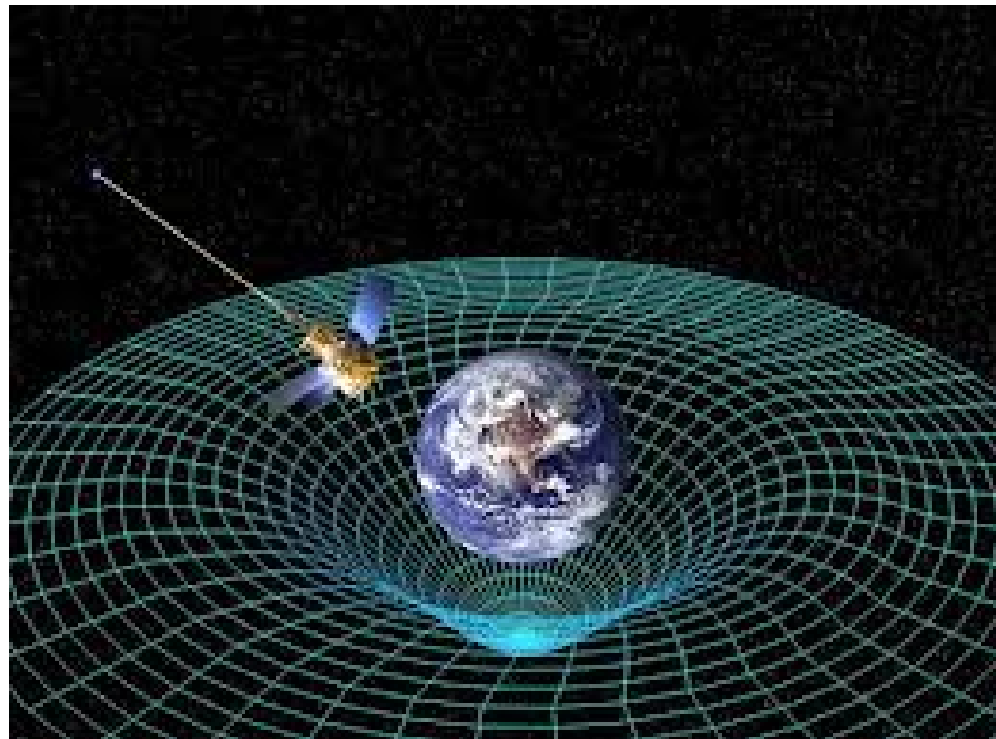


Image credit:  
NASA

# Kuhn's Critics

- Critics of glorifying paradigm shifts
  - Alarming disorder
  - Mob psychology: loudest, most numerous voices prevail
- Are paradigms really this clear-cut?
- Doesn't address problem of confirmation

# Naturalism

- Response to failure of pure logic
- Draw on scientific ideas about our place in universe, not external foundation of pure logic
- Understand assumptions and biases in making observations
- “Theory-ladenness of observations” discredits empiricism?
- Empiricism tempered by naturalism may be defensible

# Sociological Criticisms of Science

- Feminism
- Dominance of ruling class
- Distortions from financial gain
- Politics
- Can lead to nihilism, relativism, post-modernism
  - Nothing can be regarded as true
  - All beliefs are valid
  - *General suspicion of reason*

# Scientific Realism

- One view of science: Electrons, chemical elements and genes existed 1,000 years ago, even though nobody knew it.
- Another view: How do we know that?
  - Existence of electrons dependent on our conceptualization of world?
  - Kuhn: When paradigms change, the world changes.
- **First view is obviously true, right? But...**

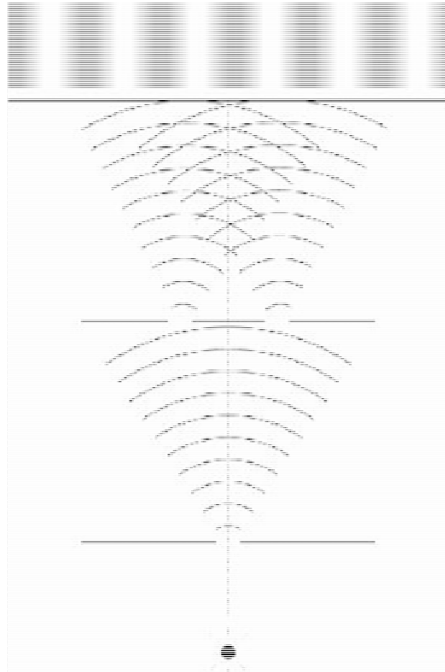
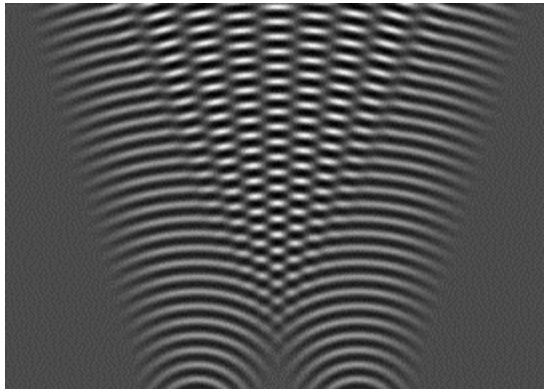
# Do Our Theories Truly Describe the Real World?

We were so sure about Newtonian physics (e.g., gravity is a force)! **Then:**

- **Einstein!**
  - Space and time expand and contract
  - Gravity is a distortion of the space-time continuum
- **Quantum physics!**
  - Wave-particle duality
  - Heisenberg's Uncertainty Principle
  - Probability density functions
  - Interference of single particles
  - Schrödinger's cat
  - Multiverse interpretation

# Quantum Weirdness: Two Point Wave Interference

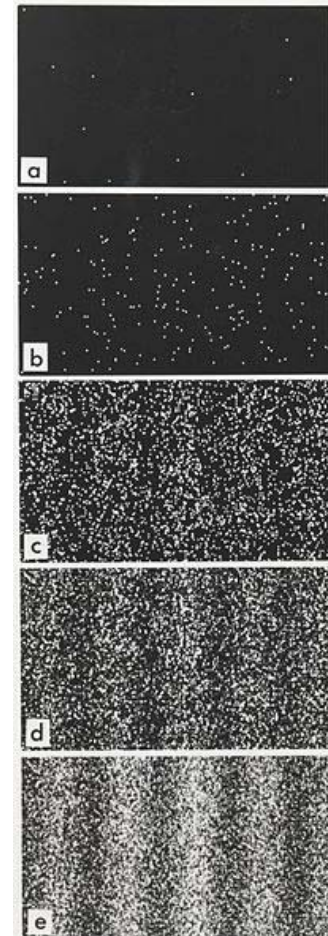
Interference Patterns (water or light)



goldberg.lbl.gov

newton.physics.uiowa.edu

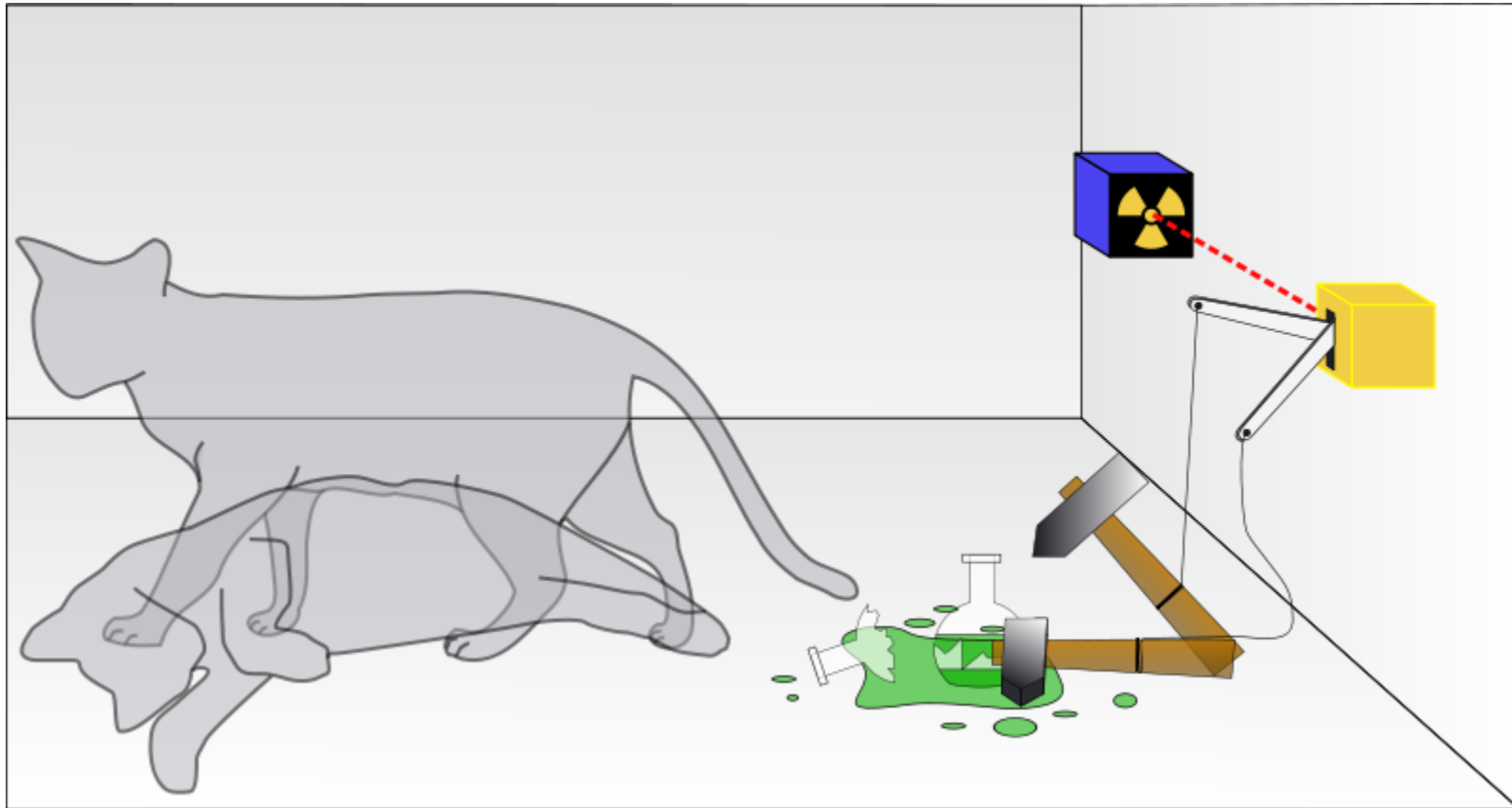
Interference of Single Electrons!



Tonomura A, Endo J, Matsuda T, Kawasaki T, Ezawa H. Am J Phys 57: 117-129, 1989

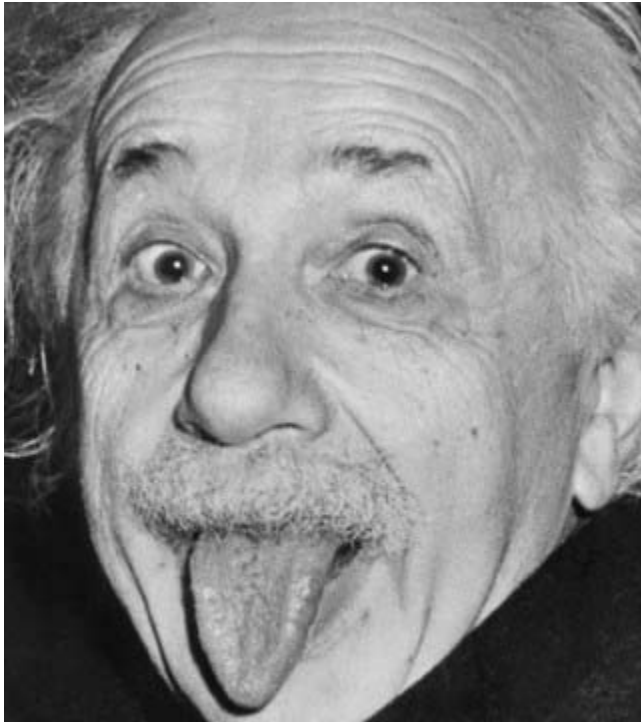


# Schrödinger's Cat: Alive and Dead at the Same Time?



Schrödinger E. Naturwissenschaften 23: 807–812; 823–823, 844–849, 1935

# Scientific Realism?



Arthur Sasse/AFP/Getty Images



physicsworld.com

# Scientific Realism

We aim at describing the real world.

- Including unobservable structures
- Accept science not always successful
- But we believe common reality exists independently of what people think and say about it.

# Explanation and Creativity

- Huge leap in evolution\*: human ability to come up with creative explanations of nature
- Power of explanations depends on
  - Breadth
  - Specificity
  - Falsifiability
- Dynamic vs static societies (reason vs. authority)

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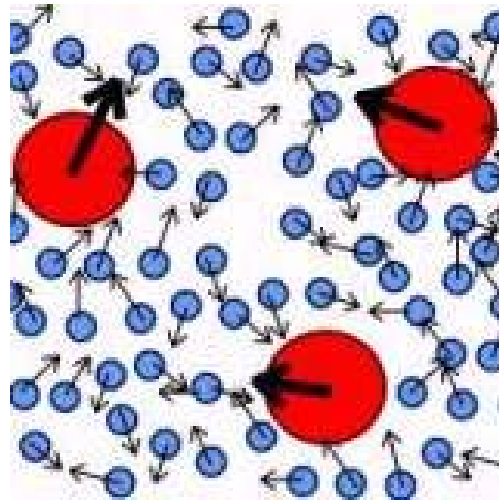
\**Homo erectus* ~2.3 million yrs ago; anatomically modern *H. sapiens* ~200,000 yrs ago

# If humans are so creative, why have static societies been so persistent?





# Reductionism and Emergent Phenomena



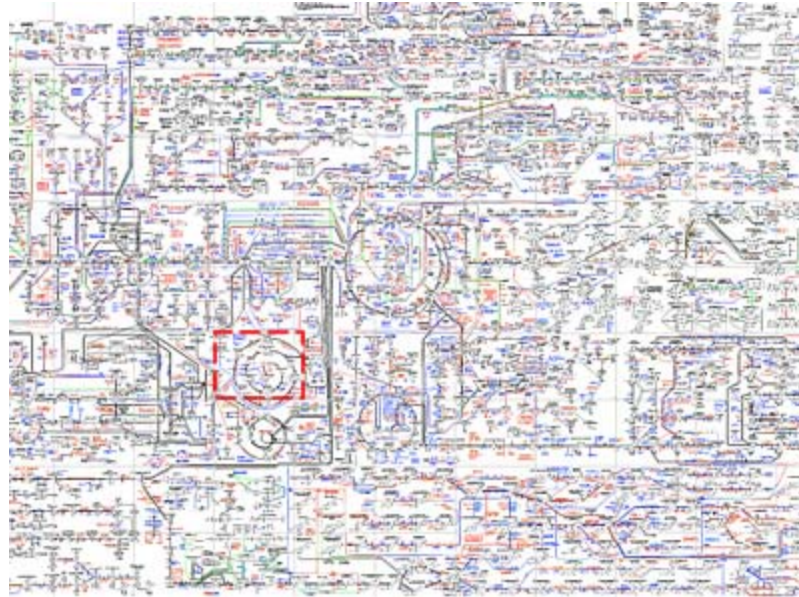
[www.math.uconn.edu](http://www.math.uconn.edu)

From basic properties of particles, explain:

**2<sup>nd</sup> Law of Thermodynamics (disorder increases)**

**Time**

# Reductionism and Emergent Phenomena, cont.



Roche wall chart

From basic knowledge of cellular signaling pathways, explain:

**Multiorgan dysfunction in irradiated animals**

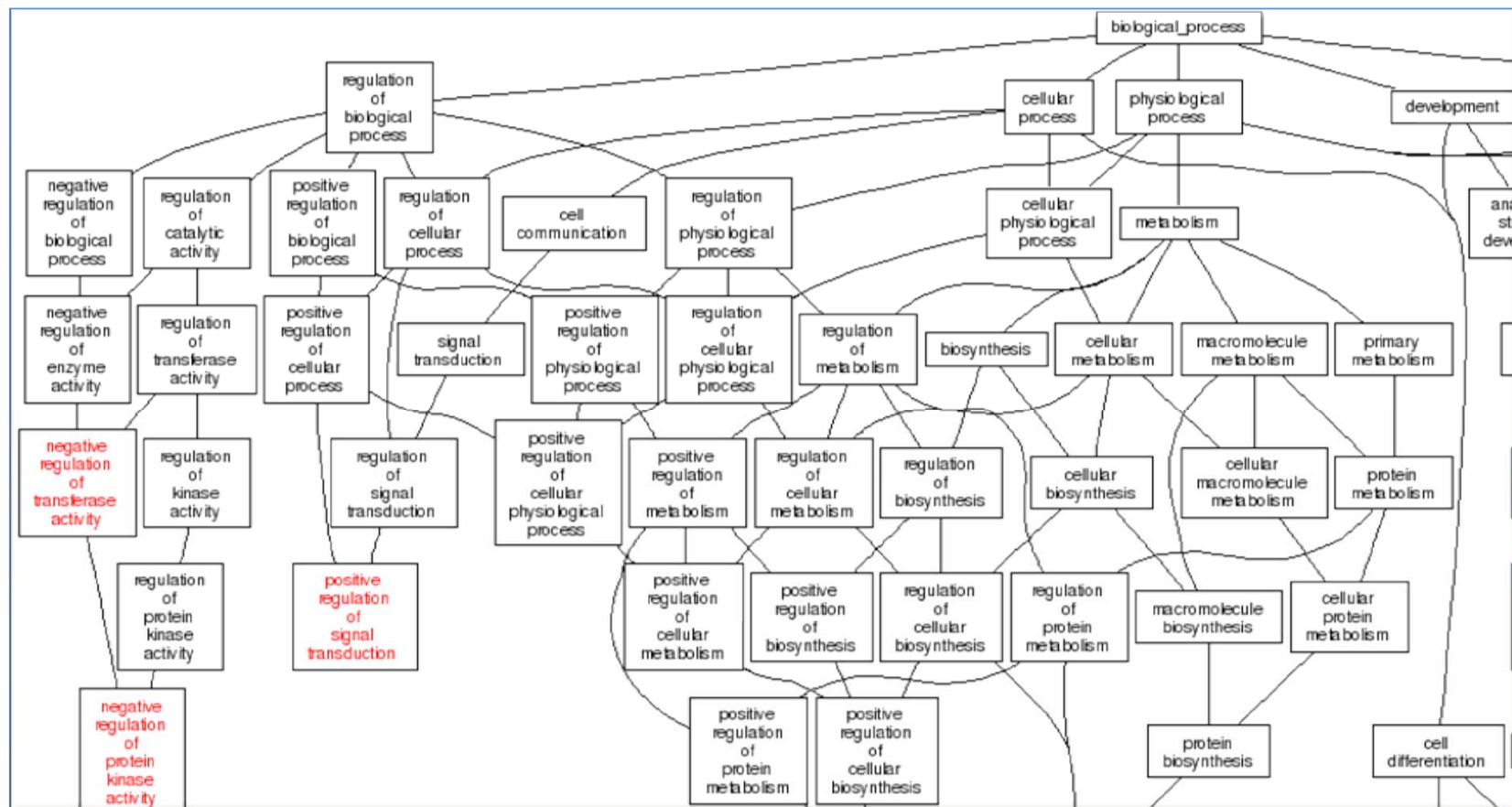
**NHP hematopoietic radiosensitivity 1/2 that of humans**

**Consciousness**

# Reductionism and Emergent Phenomena, cont.

## Response of our research program: Dr Lynn Cary

- Integrating functional cellular studies with genomics
- How does genomics relate to reductionism?



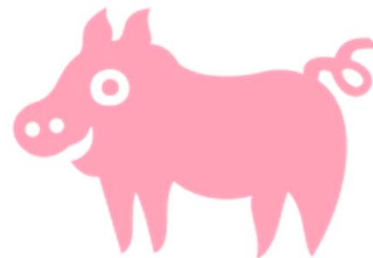


# Reductionism and Emergent Phenomena, cont.

## Response of our research program: **Dr Maria Moroni**

Integrating systems biology with pathology of minipig  
Acute Radiation Syndrome

- Relatively high sensitivity for hematopoietic syndrome
- Role of platelet function in multiorgan dysfunction



# Reductionism and Emergent Phenomena, cont.

**Reality check: The mechanism of action of most approved drugs is unknown!**

Susan McDermott, Office of Counterterrorism and Emergency Coordination (OCTEC), FDA.

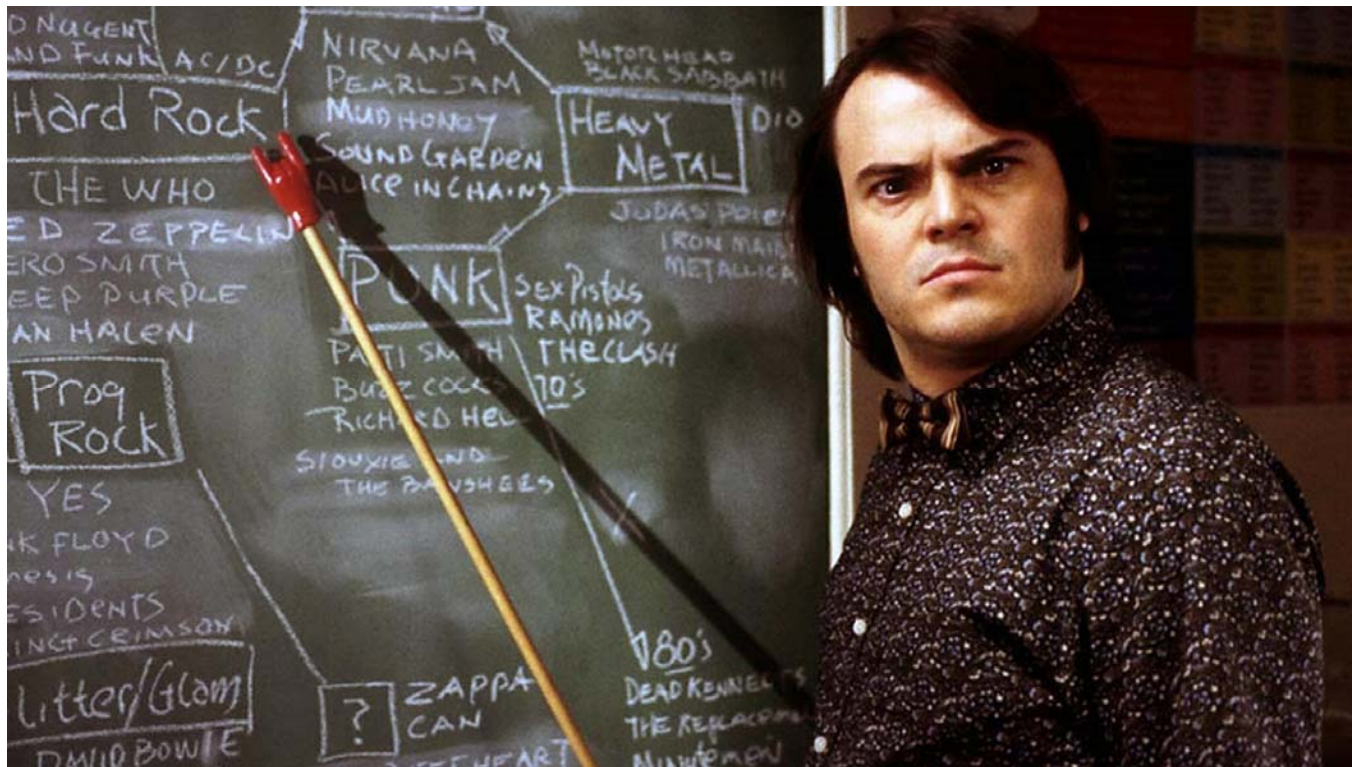
BARDA/NIAID Symposium, Bethesda MD, January 24, 2013

## So What?

- Maybe the data are trying to tell you something!
- What is the overall framework in which you are thinking – how does that affect your hypotheses? Your observations?
- Observing the data is not going to magically create an explanation in your brain.
- Be open to annoying questions from others.

## So What? continued

- Don't trust authority figures.
- Don't pose as an authority figure.



# Optimism

**There will always be problems.**

**All problems are soluble.**

**(Human problem-solving capacity is infinite.)**

# Recommended Reading

## How Does Science Work?

1. Thomas S. Kuhn, The Structure of Scientific Revolutions (1996)  
(“Paradigm shifts” vs. “Normal science”)
2. Peter Godfrey-Smith, Theory and Reality (2003)  
(Empiricism, Popper, Realism, Bayesianism, “Frameworks”)
3. David Deutsch, The Beginning of Infinity (2011)  
(Good vs. Bad Explanations; Role of Creativity; Emergent Phenomena)

## Importance of AFRRRI Mission

1. Paul Bracken, The Second Nuclear Age (2012)  
(Multipolar international rivalries increasingly take place in a nuclear context.)
2. Graham Allison, Nuclear disorder: surveying atomic threats.  
Foreign Affairs 89:74-85 (2010)