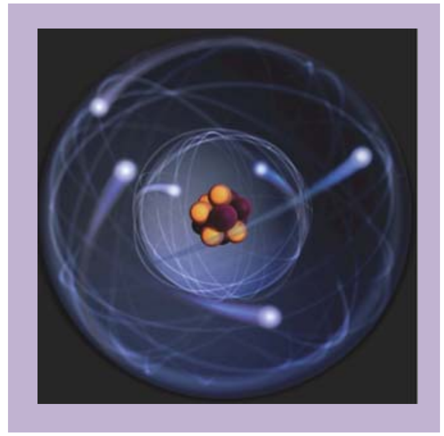
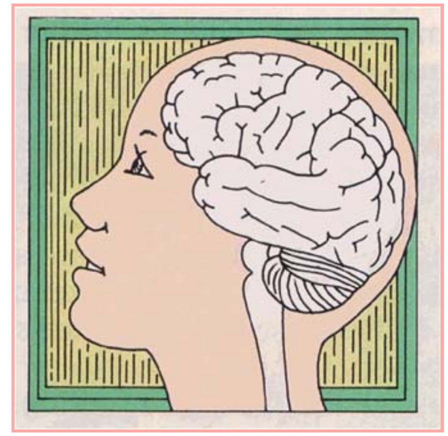
$$-\frac{d}{dt}\int_{\tau} \rho \, d\tau = \oint_{\partial\tau} (\rho\vec{v}) \cdot d\vec{A}$$





How should we think about how our students think?

Edward F. Redish

December 8, 2014

SFSU

+ Alternative Title: **How PER changes how I think about (and do) my teaching**

- Background
  - Theoretical nuclear / many-body physics
  - Interest in teaching from the first
    (I have now taught for 43 years)
- Motivation
  - Get physics majors into research sooner
  - Understand why so many majors seem to run into a wall in the upper division
  - Make sense of my failure to communicate with non-physics majors
- Approach
  - Study teaching and learning scientifically.

+ # My collaborators and research group (30 years worth)

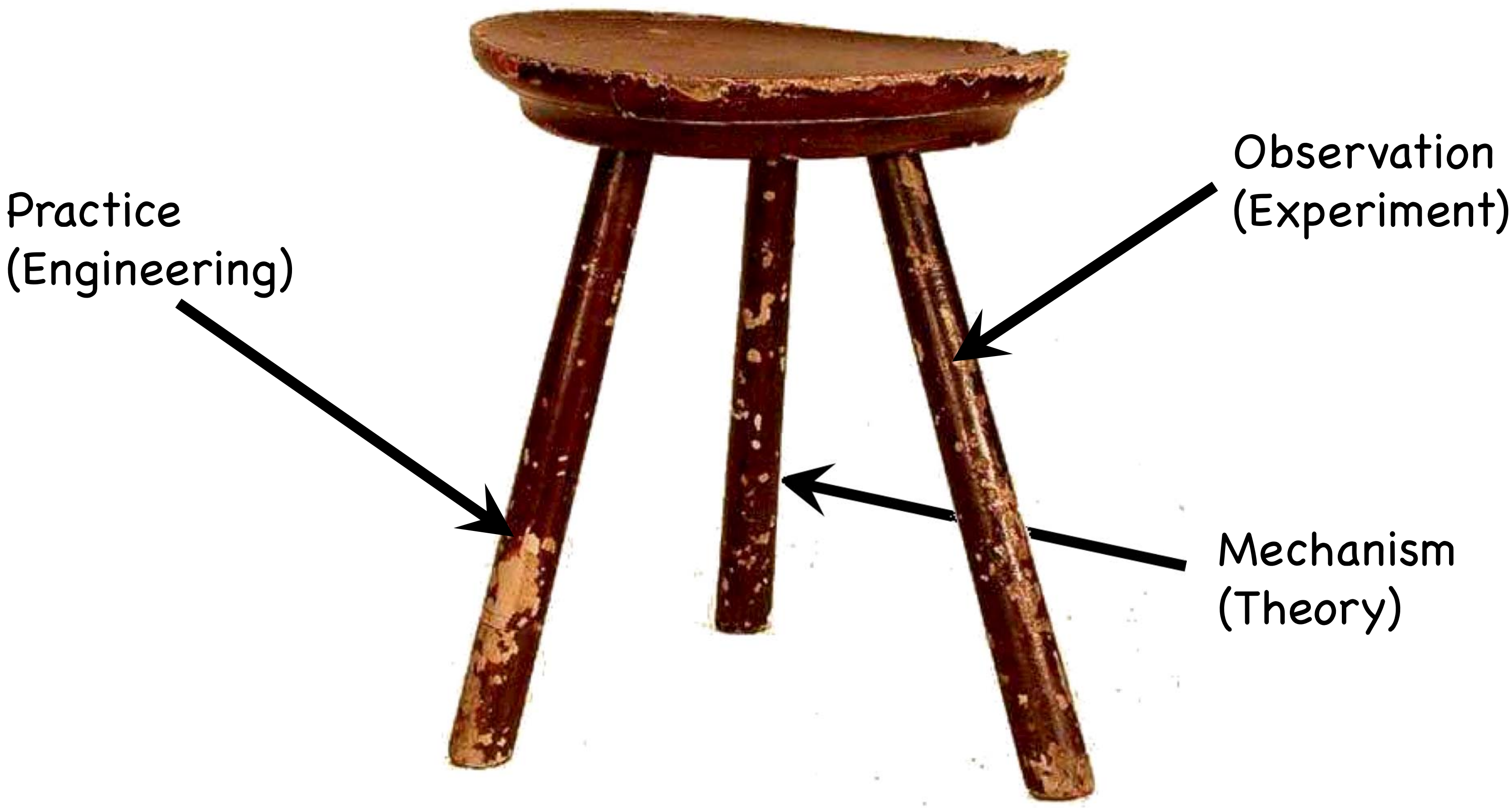
Saalih Allie
Leslie Atkins
Lei Bao
Chris Bauer
Tom Bing
Janet Coffey
Luke Conlin
Todd Cooke
Pat Cooney
Melanie Cooper
Catherine Crouch
Brian Danielak
Ben Dreyfus
Andy Elby

Brian Frank
Ben Geller
Renee-Michelle Goertzen
Paul Gresser
Ayush Gupta
Kristi Hall-Burke
David Hammer
Apriel Hodari
Paul Hutchison
Beth Hufnagel
Ian Johnston
Mike Klymkowsky
Mattie Lau
Priscilla Laws

John Layman
Rebecca Lippmann- Kung
Laura Lising
David May
Tim McCaskey
Lillian McDermott
Dawn Meredith
Charlie Misner
Kimberly Moore
Jen Richards
Rosemary Russ
Mel Sabella
Jeff Saul
Vashti Sawtelle

Rachel Scherr
Karl Smith
Richard Steinberg
Julia Svoboda Gouvea
Jonathan Tuminaro
Chandra Turpen
Emily van Zee
Jessica Watkins
Jack Wilson
Michael Wittmann
Royce Zia

“The most important leg of a three-legged stool is the one that’s missing.”



Remember

- *"It is also a good rule not to put overmuch confidence in the observational results that are put forward until they are confirmed by theory."*

Arthur Eddington

A. D. Wilson & S. Galonka
http://psychsciencenotes.blogspot.com/2013/11/replication-will-not-save-psychology.html

What's a theoretical framework?

Theoretical frameworks

- When we teach physics, we focus on well-developed theories. These come with well-established models that are viewed as integral parts of the theory.
- When we are trying to establish a new framework, it is useful to separate the "bones of the framework" (the basic ontological assumptions) from "fleshing out of the framework" (models and examples)

Redish, Varenna Lectures, arXiv preprint physics/0411149

Redish & Smith, J. of Eng. Educ. 97, 295-307 (July 2008)

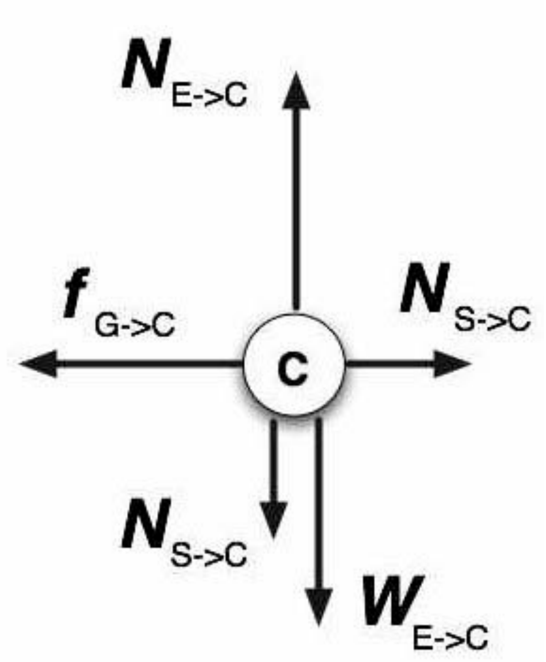
Examples of theoretical frameworks

- Math
  - Euclidean (plane) geometry
  - Cartesian (algebraic) geometry
- Physics
  - Newtonian physics
  - Quantum field theory
- Biology
  - Evolution

The Newtonian Framework

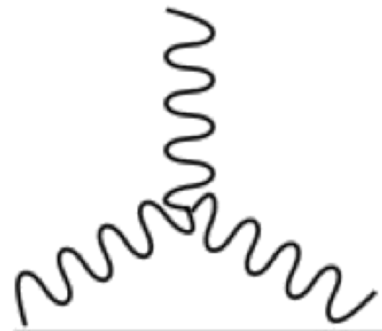
- Identify Objects
- Objects have: mass, position (vector from an origin), and velocity (vector)
- Interactions between objects (force vectors)
  - Satisfy N3
- Objects respond to the vector sum of forces acting on them at the instant they feel them by changing velocity according to

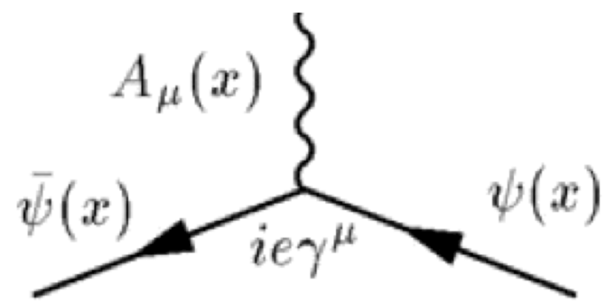
$$\vec{a}_A = \frac{\vec{F}_A^{net}}{m_A}$$



+
The QFT Framework

- Identify quantum fields
  - Choose irreducible representation of the Lorentz group (sc., vec., tens.)
  - Choose internal groups (q. nos.)
- Identify interactions among fields
  - Scalar
  - Point-like
- Generate perturbation series from Lagrangian / Hamiltonian
  - Sum infinite sub-sequences or transform fields according to relevant physics





What good would it do us in DBER if we had a theoretical framework?

- Without a theoretical framework, we tend to interpret student behavior with “natural” or “folk models”.
  - Like the “folk models” of how the physical world works that our students bring to our classes.
- A theoretical framework can warn us when our generalizations of those models lead us astray. Folk models of teaching often miss:
  - Dynamic variability and incoherence of student thinking
  - Importance of students’ expectations
- A theoretical framework helps
  - Decide what it is our observations tell us
  - Frame new research questions
  - Create generalizations

The Resources Framework: The basics

+ What should it look like?

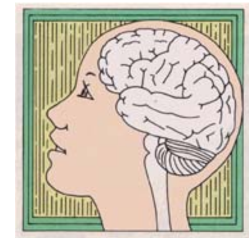
- We don't want a micro → macro fundamental theory (from neurons).
- We want a macro-level system to guide phenomenological modeling. Something like
  - Newton with rigid bodies
  - Kirchhoff level theory of electric currents
  - Biological models of process without micro mechanism
- Draw on
  - Psychology / Neuroscience
  - Sociology / Anthropology
  - Linguistics / Semantics
  - Ethology / ...
- Establish foothold principles.

Experiment 1

- I will show a list of 24 words for one minute.

- Try to memorize as many as you can.

Roediger & McDermott, *J. Exp. Psych.* 21:4 (1995)



Thread	Thimble	Bed	Rest
Pin	Haystack	Awake	Tired
Eye	Knitting	Dream	Snooze
Sewing	Cloth	Blanket	Doze
Sharp	Injection	Slumber	Snore
Point	Syringe	Nap	Yawn

+

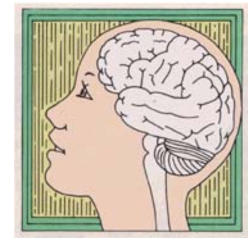
- Now write down as many of the words in the list as you can remember.

How many did you recall?

1. 5 or fewer
2. Between 6 and 10
3. Between 11 and 15
4. Between 16 and 20
5. More than 20

Did you have these words on your list?

1. The word “needle” was on my list – but not the word “sleep”
2. The word “sleep” was on my list – but not the word “needle”
3. Both the words “sleep” and “needle” were on my list.
4. Neither of the words “sleep” and “needle” were on my list.



Thread	Thimble	Bed	Rest
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Sewing	Cloth	Blanket	Doze
Sharp	Injection	Slumber	Snore
Point	Syringe	Nap	Yawn

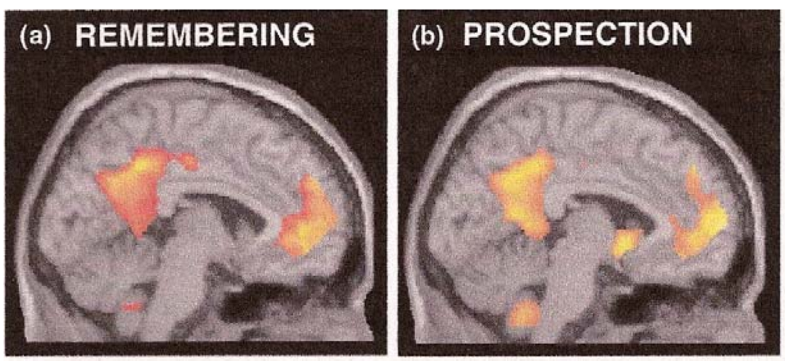
+ Memory is reconstructive not veridical – A model of memory: Predicting the past

(a) Recalling past events

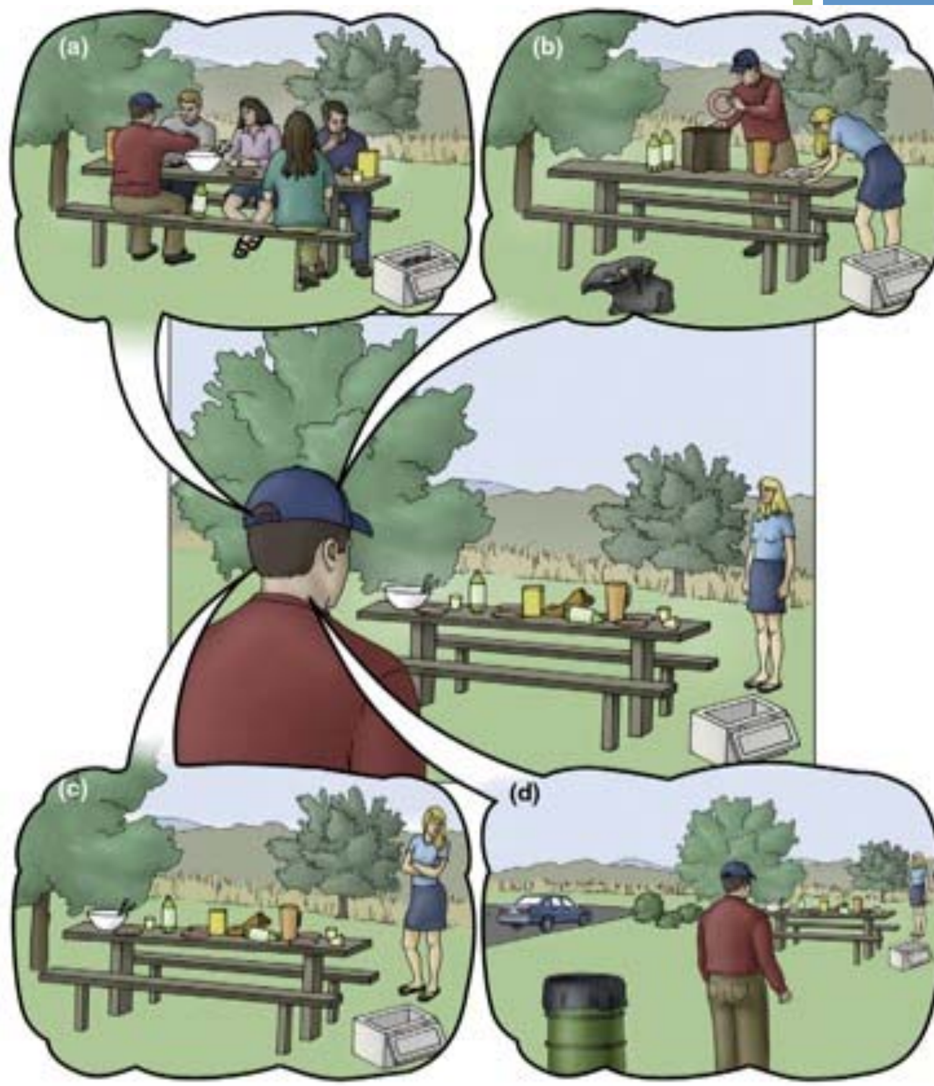
(b) Imagining future events

(c) Seeing things from
someone else's perspective

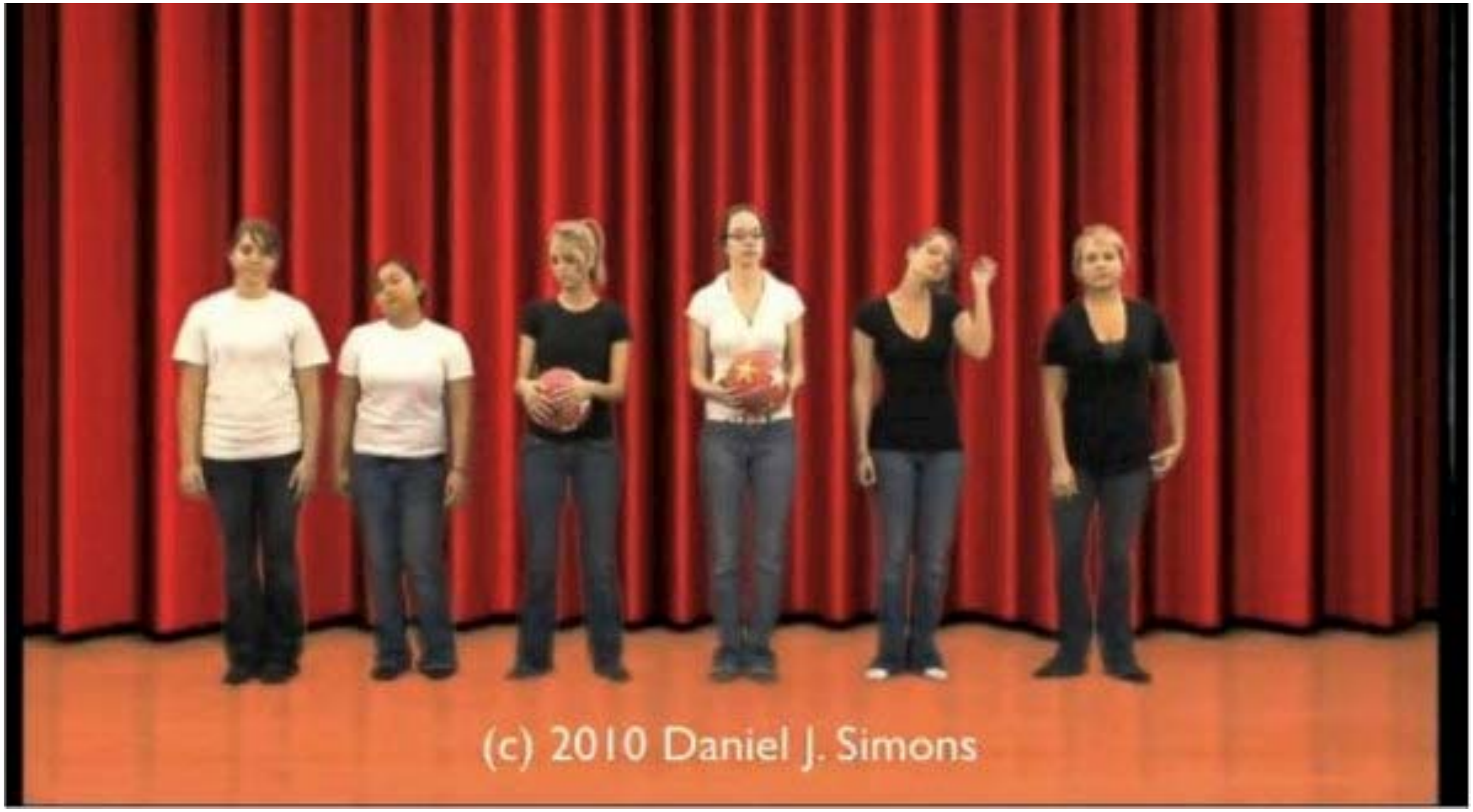
(d) Navigation



**From Buckner & Carroll
Trends in Cog. Sci. 11:2 (2006)**



Experiment 2: Selective attention



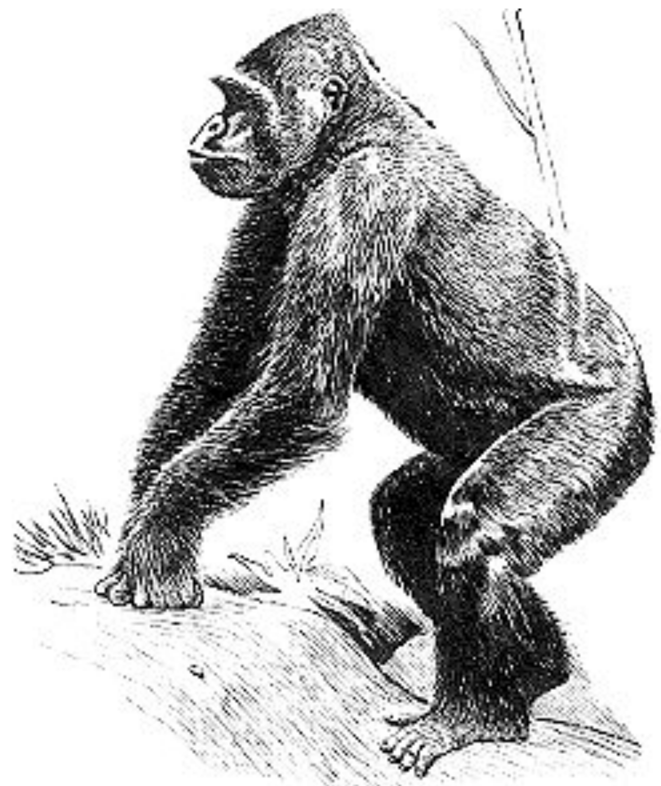
Simons & Chabris *Perception*. 28:9 (1999)

How many passes did you count?

- A. Fewer than 15
- B. 15
- C. 16
- D. 17
- E. More than 17

How many gorillas did you see?

- A. 1
- B. More than 1
- C. You’re kidding, right?



+ # Key cognitive principles

1. Memory is ***reconstructive*** and ***dynamic***.
   - People can bring up different interpretations of what they are seeing and doing quickly.
2. We have huge long-term memories, but working memory is ***severely limited***.
   - At one time you can hold in your mind and manipulate a small number of items (4-10).
3. Strong associations build ***chunks*** that can be manipulated as single units.
   - Clusters of elements can be compiled – to appear to the user as a single unit – then unpacked.
4. Access to long-term memory is controlled by ***executive function***.
   - The structure of how knowledge is organized and accessed is critical.

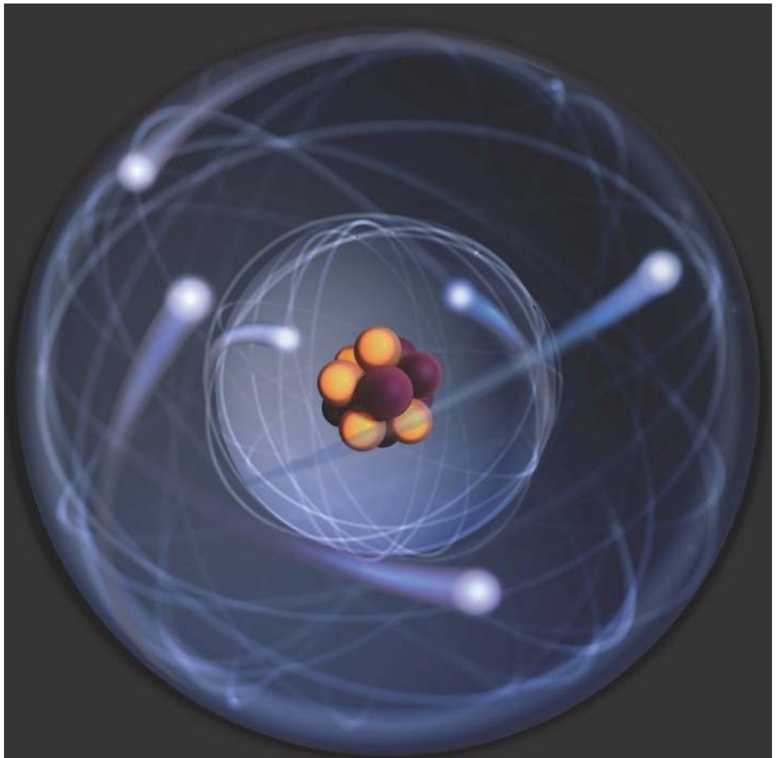
Gak! Can we do all this?

- There are a huge number of factors affecting each individual's behavior at each instant.
- The brain is highly dynamic, continually re-evaluating what knowledge it needs to bring to bear.
- Is it crazy to think that we can describe cognitive and cultural effects on the behavior of an individual student?

Come on! This isn't *that* much harder than strongly interacting many-body quantum physics!

Mean fields

- The behavior
  of an individual electron
  in a complex atom
  fluctuates wildly.
- There are <u>huge</u>
  electron-electron
  correlations.
- Yet a mean field
  approximation – averaging
  over pair correlations –
  enables us to do
  all of chemistry.



The nucleus has been magnified
by a factor of ~1000 so it can be seen

+

The critical constraint is the limitations of working memory.

The way we go beyond this is chunking and chaining – condensing memories and associating from one memory to the next.

Selecting and switching which memories to activate must be essential!

+ The Resources Framework

- A two-level structure
  - Concept knowledge (***basic knowledge***)
    - Compilation and chunking
    - Knowledge organization (associations)
  - Knowledge about when to use knowledge (***switching mechanisms*** or ***control structures***)
    - Cultural knowledge
    - Framing
    - Epistemology

Key concepts for discussing control

- Cultural knowledge
  - Knowledge about what behavior is expected comes from a wide variety of sources at multiple scales.
- Framing
  - The process of "choosing" a set of data in your environment to selectively pay attention to – equivalent to deciding what you expect to be important and that everything else can be safely ignored. (NOT conscious – mostly "under the hood".)
- Epistemology: Knowledge about knowledge
  - What is the nature of the knowledge I am going to learn in this class and what is it that I need to do to learn it?
  - What of the knowledge that I have is appropriate to use in a particular problem or situation?

Framing

- Students' accumulated social knowledge of context and expected behavior acts as a *mean field* that influences their thinking.
- Their behavior is affected by their *perception* and *interpretation* of the social context in which they find themselves.
- That perception and interpretation acts as a control structure that governs which of their wide range of behavioral responses in a given situation.
- Framing is the process in the individual that *interfaces* between their cognitive activity and their long-term accumulated socio-cultural knowledge.

+ Building the Components of the Resource Framework

- Conceptual knowledge
  - Phenomenological primitives (p-prims)
  - Reasoning primitives
  - Symbolic forms
  - Associational structures
    - Mental models / schemata
    - Coordination classes
- Control / Framing / Socio-Cultural
  - Epistemological
  - Social (one-on-one and small group)
  - Cultural scripts
  - Disciplinary expectations
  - Affective responses

http://www.physics.umd.edu/perg/tools/resourcesreferences.pdf

+

Context and Framing

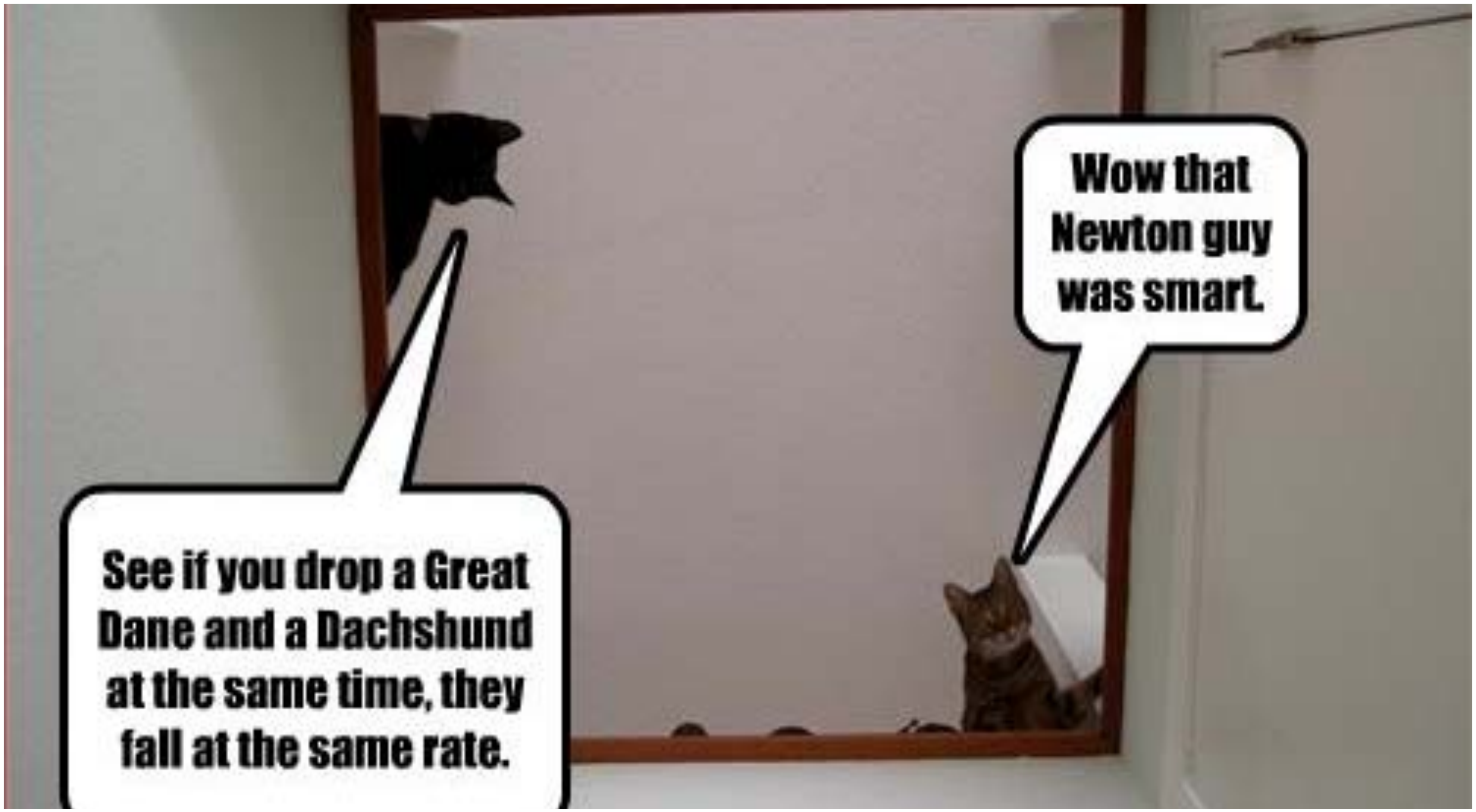
Examples of epistemological framings

1. ***One-step thinking:***
   "The answer is obvious.
   I don't have to worry about coherence."

2. ***P-priming:***
   "The answer is obvious.
   I don't have to worry about mechanism."

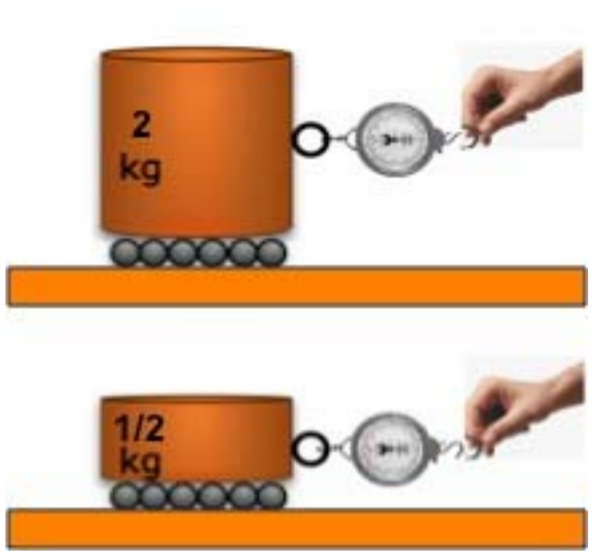
3. ***Just do the math:***
   "Whatever the math gives me has to be right, whether it makes sense or not."

Framing example 1: Coherence



The prof drops two metal spheres, one of ½ kg, the other of 2 kg. They hit the ground at (almost) exactly the same time. Which of the following statements is true?

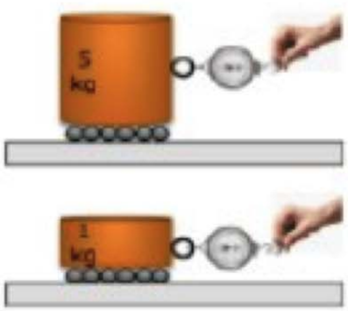
1. The force of gravity on the 2 kg weight is greater than the force on the ½ kg weight
2. The force of gravity on the 2 kg weight is less than the force on the ½ kg weight
3. The force of gravity on the 2 kg weight is the same as the force on the ½ kg weight.
4. There is not enough information to tell.



You are pulling two weights (2 kg & ½ kg) along a table with equal force. **<u>Which one would speed up faster?</u>**

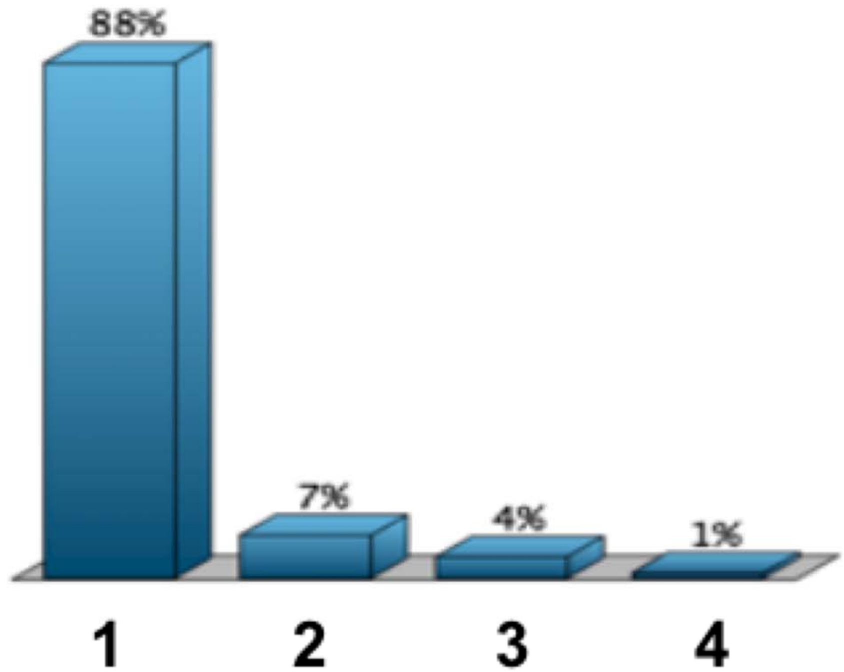
1. The ½ kg weight
2. The 2 kg weight
3. The would speed up the same way.
4. There is not enough information to tell.

Data: Beginning of 1st term of intro physics (F13)



You are pulling two weights along a table with equal force. Which one would speed up faster?

1. The 1 kg weight
2. The 5 kg weight
3. The would speed up the same way.
4. There is not enough information to tell.

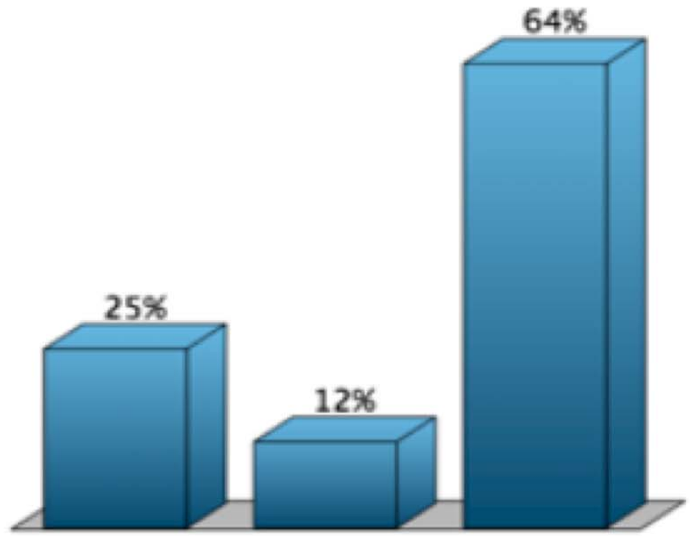


N = 111

Data: Beginning of 1st term of intro physics (F13)

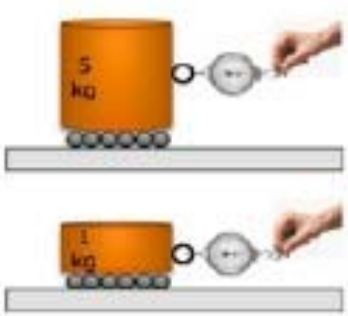
The prof drops two metal spheres, one of ½ kg, the other of 2 kg. They hit the ground at (almost) exactly the same time. The force of gravity on the 2 kg weight is:

1. Greater than the force on the ½ kg weight
2. Less than the force on the ½ kg weight
3. The same as the force on the ½ kg weight.
4. There is not enough information to tell.



N = 111

Data: Beginning of 2nd term of algebra-based physics (S11)



You are pulling two weights along a table with equal force. Which one would speed up faster?

1. The 1 kg weight
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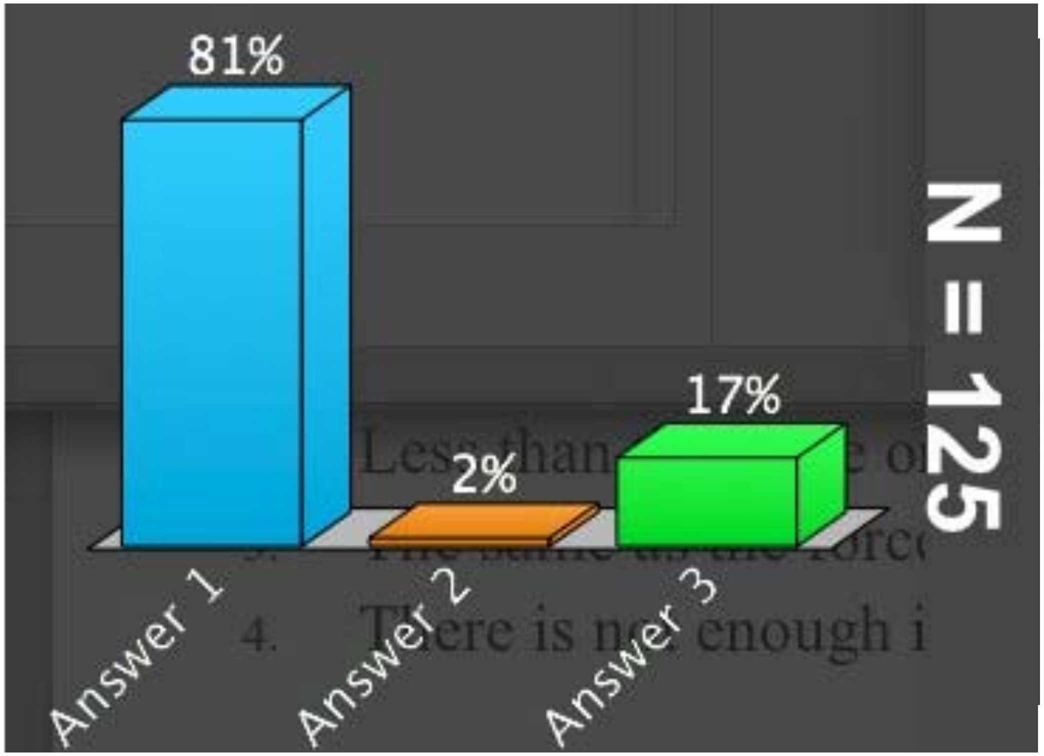
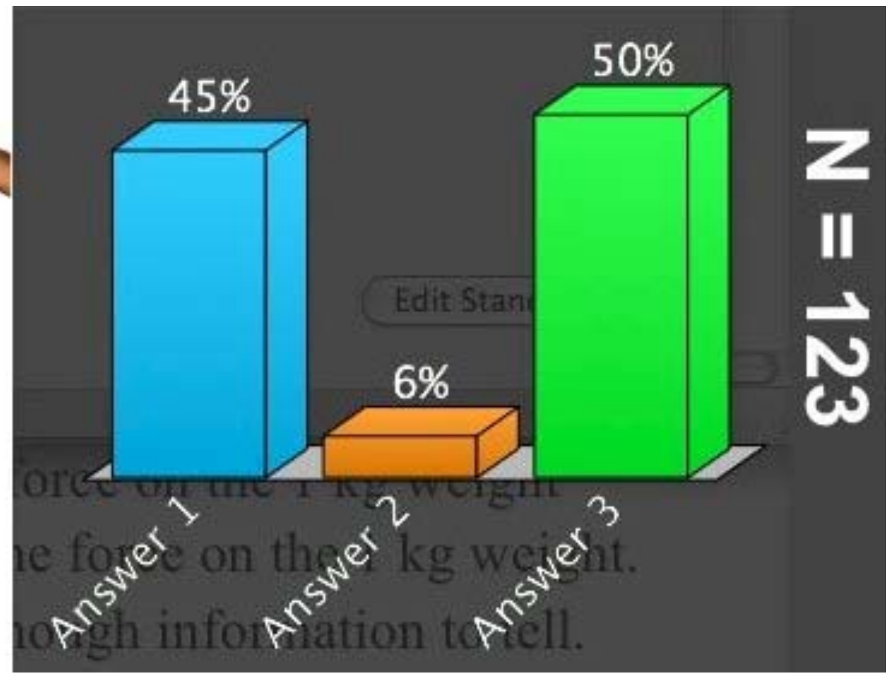
3. The would speed up the same way.
4. There is not enough information to tell.



Data: Beginning of 2nd term of algebra-based physics (S11)

The prof drops two metal spheres, one of ½ kg, the other of 2 kg. They hit the ground at (almost) exactly the same time. The force of gravity on the 2 kg weight is:

1. Greater than the force on the ½ kg weight
2. Less than the force on the ½ kg weight
3. The same as the force on the ½ kg weight.
4. There is not enough information to tell.



+ Implication:

- Many students often exhibit ***one-step thinking*** and fail to call on knowledge that they know perfectly well even when that knowledge would be highly appropriate.
- This is likely associated with a “mean field” brought from school testing experience: *Each question is independent and should be approached anew*.
- Getting them to change their approach may not be easy. (***epistemological misconception***)

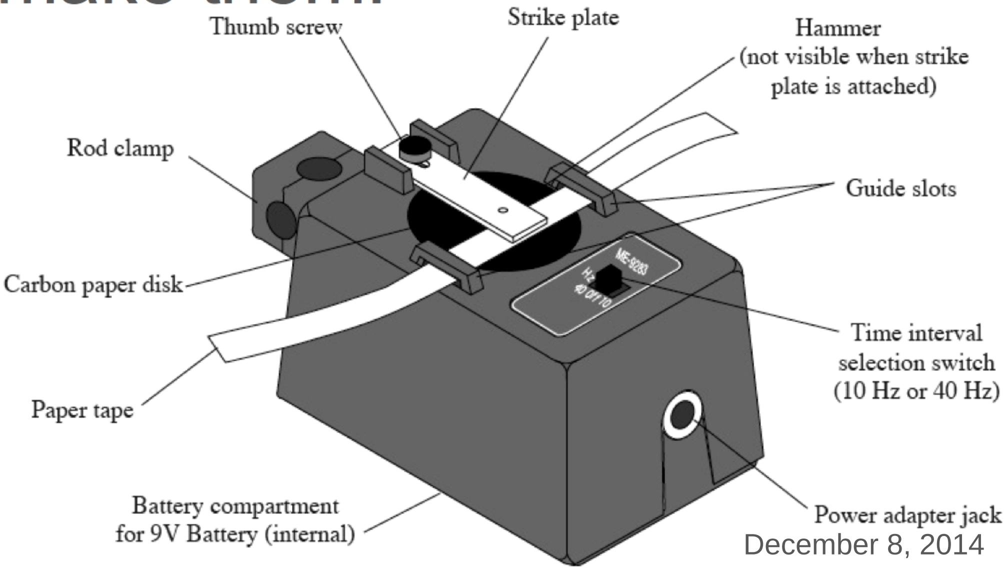
+ Framing example 2: Tutorials

- Tutorials are **research-based** worksheets done in small groups.
- Students are guided through expressing **their own ideas**, comparing them with observations and reasoning qualitatively.
- The critical component of the environment is **independent small group discussion**, *lightly* facilitated by an instructor.

L. C. McDermott, et al., *Tutorials In Introductory Physics* (Prentice Hall, 1998)
M. Wittmann, R. Steinberg, E. Redish, *Activity-Based Tutorials* (Wiley, 2003)
A. Elby et al., *Open Source Tutorials* (UMd, 2008).

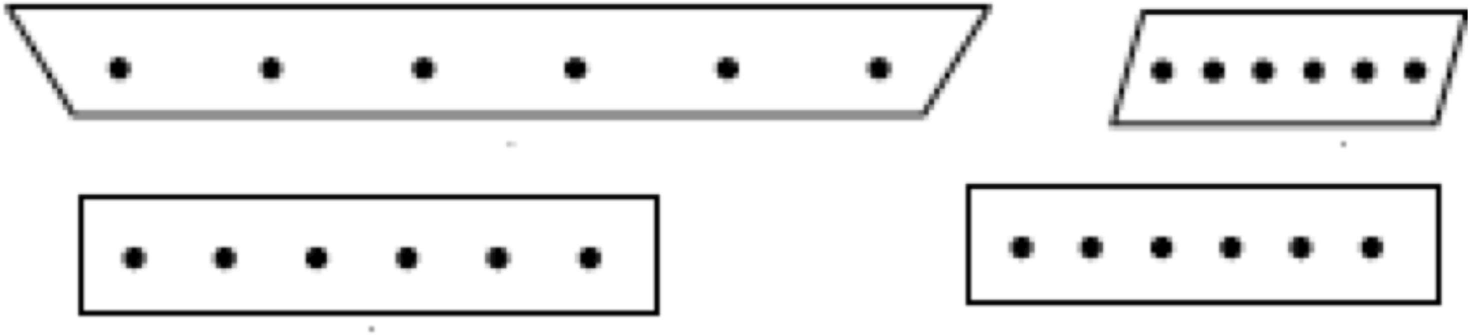
Mechanism

- In our first tutorial of the year, students are asked to analyze speed.
- Paper tapes are made beforehand by a machine tapping at regular intervals (6 times/sec). A cart attached to the tape is slowly accelerated down a long ramp to make them.

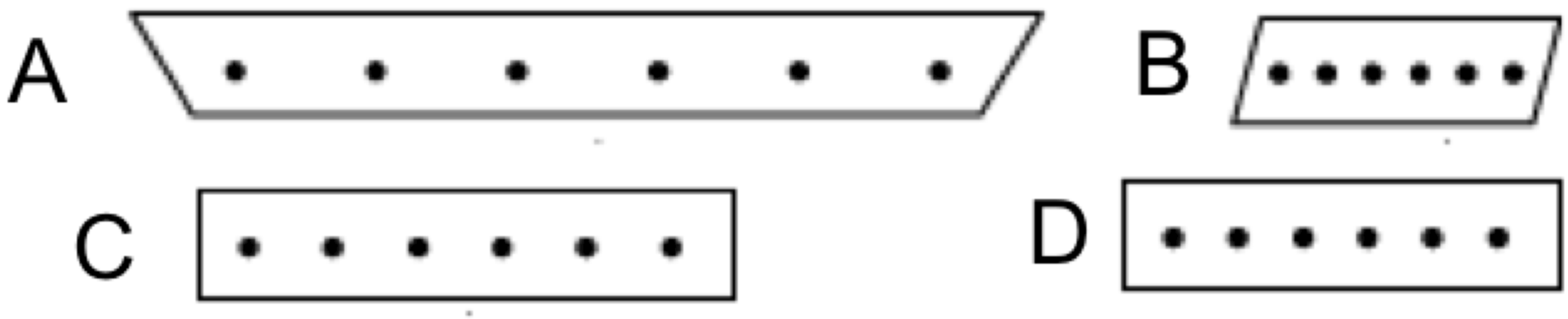


The task

- Each group of students is given 4 tapes containing 6 dots and asked "Which tape took the longest time to make?"



Which took the longest to make?



E. All the same

+ The result

B. Frank, PhD Dissertation, U. of Maryland, 2010

+ A few minutes later

Implication

- In their first look, the students activated a common reasoning primitive – “more is more”. They framed the task as ***answer-making***: that the result could be found directly and did not require considering the mechanism of the process .

- A few minutes later, in a new context, they quickly and easily reframed the task as ***sense-making***; one that required thinking carefully about the mechanism.

- Many students brought a “mean field” expectation:
if a question at the beginning of a lesson sounded easy,
it probably was, and therefore did not require careful thought.

- Appropriate cuing was, however, able to shift many students quickly and easily into a “consider the mechanism” frame –
one that they had in their toolkit and were competent to use.

Framing example 3: Choosing math over physics

- Often, physics students learn to manipulate mathematics effectively, but fail to connect their math with a physical interpretation of what's happening.
- Effective cognitive integration of physical intuition with mathematical tools is a key developmental skill for advanced physics students.
- In our advanced classes, we often fail to stress these skills or give students support in developing them.

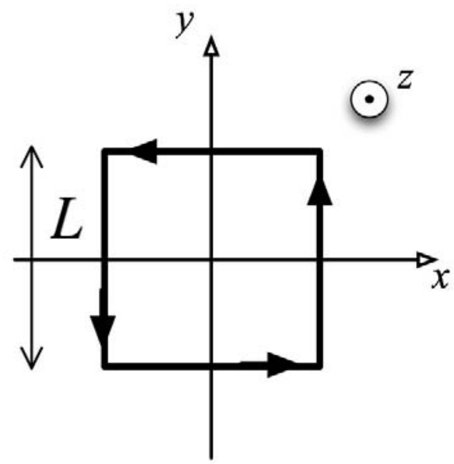
Bing & Redish, *Phys Rev ST-PER* 8, 010105 (2012).

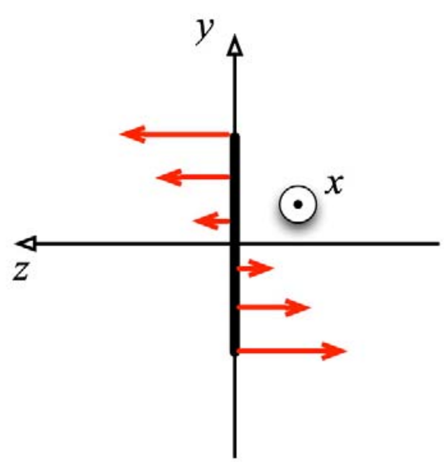
Framing example 3: A vector line integral

- A square loop of wire is centered on the origin and oriented as in the figure. There is a space-dependent magnetic field

$$\vec{B} = B_0 y\hat{k}$$

- If the wire carries a current, *I*, what is the net force on the wire?





+ Two paths to a solution

- Student A
  - Huh! Looks pretty simple – like a physics 1 problem.
  - The sides cancel so I can just do

    $$\vec{F} = I\vec{L} \times \vec{B}$$

    on the top and bottom where *B* is constant.
  - Gonna get

    $$\vec{F} = IL^2 B_0 \hat{j}$$

- Student B
  - I'm pretty sure they want us to do the vector line integral around the loop.

    $$\vec{F} = \oint I\, d\vec{L} \times \vec{B}$$

  - It's pretty straightforward.
  - The sides do cancel, but I get zero.

+ Implications

- Often, physics majors develop a “mean field” – that in physics only learning to manipulate math matters. They perceive that connecting the math with physical meaning is not essential.
- In our introductory classes for majors we often focus on processing, not modeling, and this typically gets worse in our advanced classes.
- So how do you modify your instruction so as to include opportunities for encouraging the blending of physical and mathematical thinking?

+ A homework problem requiring multiple epistemological resources

- In class, we derived the integral constraint that expressed the conservation of matter of a fluid:

$$-\frac{d}{dt}\int_{\tau} \rho \, d\tau = \int_{\partial\tau} (\rho\vec{v}) \cdot d\vec{A}$$

- Suppose *ρ* describes the concentration of a chemical compound in a solution and that compound can be created or destroyed by chemical reactions.

- Suppose that the rate of creation (or destruction) of the mass of the compound per unit volume as a function of position at the point at a time *t* is given by *Q*(*r*, *t*). *Q* is defined to be positive when the compound is being created, negative when it is being destroyed.

- How would the equation above have to be modified?

This problem is written so as to probe how well a student can integrate physical and mathematical knowledge.

+ The solution

$\int_{\tau} \rho \, d\tau$	represents the total mass in the volume
$-\frac{d}{dt}\int_{\tau} \rho \, d\tau$	represents the rate at which the volume is <u>losing</u> mass
$\int_{\partial\tau} (\rho\vec{v}) \cdot dA$	represents the rate at which mass is flowing out of the volume
$Q(\vec{r},t)$	represents the rate mass is created at a point (a density)
$Q(\vec{r},t)\,d\tau$	represents the rate mass is created in a small volume, *dτ*
$\int_{\tau} Q(\vec{r},t)\,d\tau$	represents the rate at which mass is created in the volume, *τ*

Therefore, the equation must look like: $\pm\int_{\tau} Q(\vec{r},t)\,d\tau - \frac{d}{dt}\int_{\tau} \rho \, d\tau = \int_{\partial\tau} (\rho\vec{v}) \cdot dA$

We choose the sign by considering a particular physical situation (e.g., *Q* positive so stuff is created inside, but it all flows out so the total inside stays the same)

$$\int_{\tau} Q(\vec{r},t)\,d\tau - \frac{d}{dt}\int_{\tau} \rho \, d\tau = \int_{\partial\tau} (\rho\vec{v}) \cdot dA$$

Implications for teachers and DBER researchers

What have I learned that's useful in my teaching?

- I have broader goals than I used to state. Knowledge, even process is not enough.
  - I want students to learn good scientific thinking skills – coherence seeking, sense making...
  - I want students to focus on building a picture, telling a story, thinking about mechanism.
  - I want students to learn the math – but to learn to blend the math with physical meaning, to *think with math*.

The bad news and the good news.

- I don’t have a simple message for how to improve your teaching simply or by following a simple algorithm.
- For me, becoming a better teaching has been an evolving process of observing and rethinking.
- But it’s way more fun and intellectually challenging than just teaching for your own benefit – or to just get it over with!

+ Learning a complex subject is complex.

- Understanding student errors is necessary but not sufficient: Understanding context is critical.
  - Student responses don't simply represent activations of their stored knowledge. They are dynamically created in response to their perception of the task and what's appropriate.
  - The (often unconscious) choices they make may be determined by their social and cultural experience (expectations and framing).
- Despite the fact that each student responds complexly and independently, common patterns of expectations can found. These can be used to create lessons that cue appropriate framings.

Some general guidelines I've learned from PER

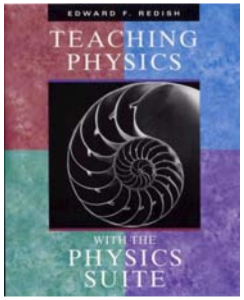
1. Think carefully about what your **real goals** are for the particular population of students you are teaching.
2. Find ways to get sufficient **feedback** from the students that you can figure out, not just whether they have learned what you have taught, but how they have interpreted it and what knowledge and perspectives they bring to your class.
3. **Respect** both the knowledge they are bringing and them as learners. "Impedance match" your instruction to where they are and what they have to work with.
4. **Repeat**. That is, go back and re-think your goals now that you know more about your students.

+ PER

- You don't have to do it alone!
- There is a strong and growing community of physicists taking teaching and learning seriously, treating it as scientific research, and making considerable progress.
- Resources:
  - Physical Review ST-PER
  - American Journal of Physics: PER Section
  - AAPT Meetings / PERC / Topical Group
  - APS Topical Group / GPER

+ For more information

- On our research group (UMd PERG)
  - http://www.physics.umd.edu/perg/
- PER Central and PER Users Guide
  - http://www.compadre.org/per/
- *Teaching Physics with the Physics Suite*
  - http://www.physics.umd.edu/~redish/Book/



- On the Resources Framework
  - http://www.physics.umd.edu/perg/tools/ResourcesReferences.pdf