How People Learn Physics

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Teaching complex subjects

- When teaching complex subjects we have complex goals:
  - Helping students build a broad knowledge base
  - Helping students develop sophisticated skills
  - Helping students build a solid intuition
- When teaching complex subjects we have a variety of tools:
  - Drill-and-practice
  - Lecture and reading
  - Problem-based learning
- But we really have little understanding about how this kind of learning works.
  - Most of what we do is pure phenomenology – alchemy.

Why Focus on Physics Learning?

- We want to help our students develop
  - Life-long learning skills
  - An "adaptive expertise"
- Physics is a good example of learning a complex subject.
- Physics education research (PER) is a well established discipline (nee 1978) and much has been learned.
- We want to learn to transform good teaching from an art to a science (that can be taught) by using the methods of science.

Physics education R&D is well established.

- Physicists have been doing educational research on university level physics for 30 y.
- There are now > 50 physics departments that have a PER person on staff including > 10 R-I universities.
- The AAPT now has a topical group on PER with > 750 members.
- There is now a Physical Review Special Topics section devoted to PER.
- There is a digital library section devoted to PER. [*http://www.compadre.org/per/*]

Physics is a good example of complex learning.

- Although one can sometimes "get by" in an intro physics class with memorizing, developing physics expertise requires sophisticated learning.
  - Sense making
  - Seeking coherence
  - Developing intuitions
  - Translating among multiple representations
  - Making connections to everyday experience

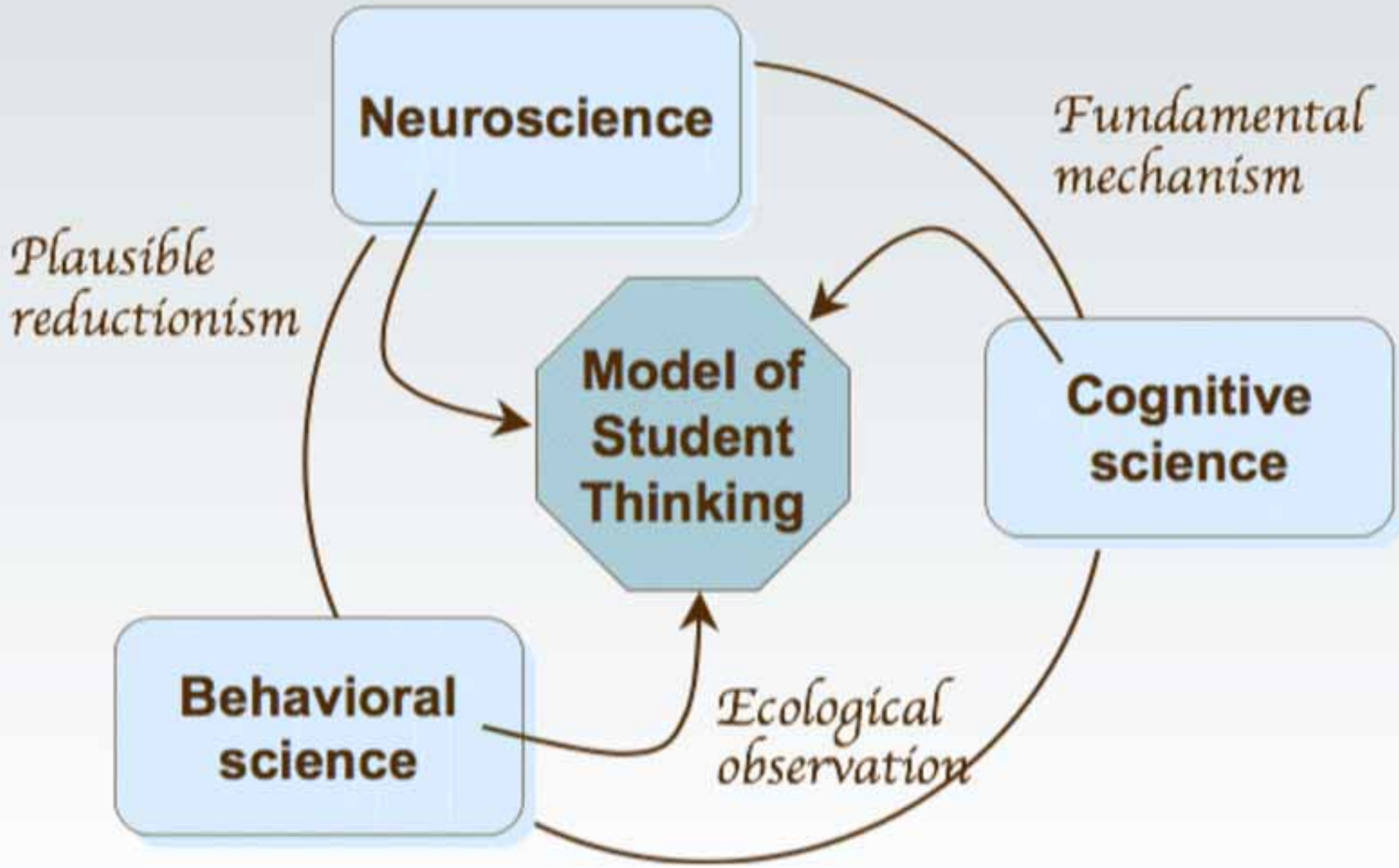
What we have learned about teaching and learning

- Teaching and learning does not take place as a straightforward transfer from teacher (or text) to student.
  - The student has to process whatever knowledge is presented and make sense of it in terms of what s/he already knows.
- Students can make bizarre errors.
  - Why did one of my students report a demonstration as showing the exact opposite of what he saw?
  - Why did one of my students understand the changes in the KE and PE of a falling body and still say energy was not conserved?
  - Why did one of my students report the size of her dorm room as 1 cubic meter?
- Some errors are common and resistant to change.

Making sense of what has been learned

- What has been learned in PER is at the level of phenomenology – observed behavior in realistic circumstances.
- To get beyond alchemy we need insight into the structure and mechanism of learning – the etiology of the difficulties we see.
- Fortunately, explosive developments in cognitive psychology are beginning to provide a path to a deeper understanding.

Triangulating our understanding of cognitive processes



The Resource Framework: Four foothold ideas

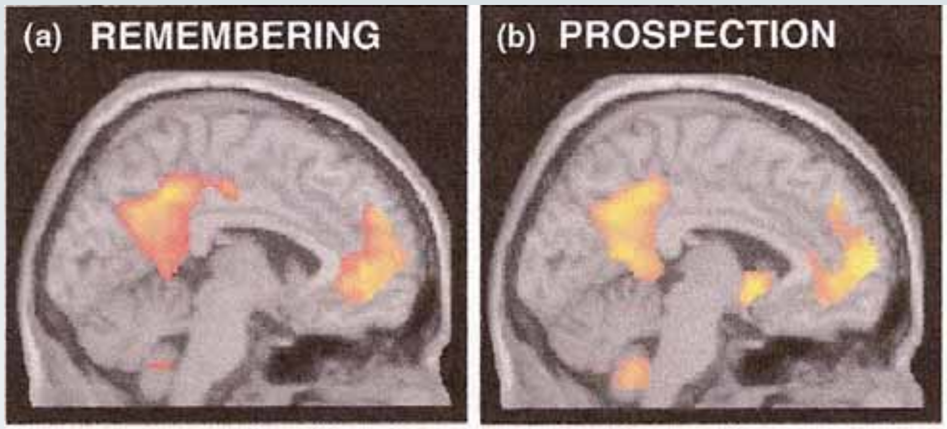
- Activation (Resources)
  - A perception / awareness ("cognit"*) of something corresponds to the activation of a set of linked neurons.
- Association (Linking)
  - The activation of one cognit can lead to the activation of others ("spreading activation")
- Compilation (Binding)
  - Different cognits can become tightly tied so they always activate together – the user becomes unaware of their separate parts.
- Control (Selective attention)
  - Contexts can suppress, prime, or activate clusters of cognits.

Hammer, Am. J. Phys. Suppl. ***68*** *S52-S59 (2000)*
Redish, Fermi Summer School Lectures (2003)
**Fuster, Memory in the Cerebral Cortex (MIT Press, 1999).*

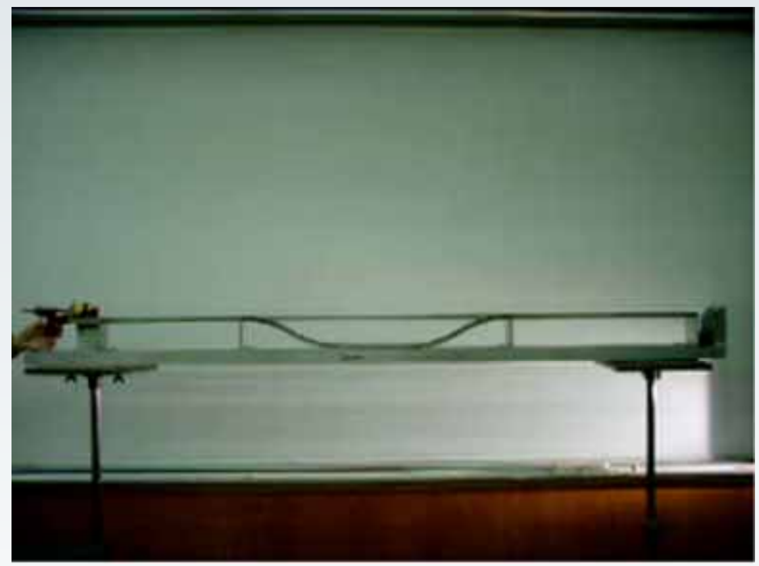
1. Activation: Resources

- Thinking is dynamic.
- Different knowledge elements or processes (resources) “turn on” and activate other related elements.
- Which related elements are turned on depend on context
- Memory is not a “veridical tape” but reconstructs from bits and pieces.

An Example from Physics: Predicting the Past

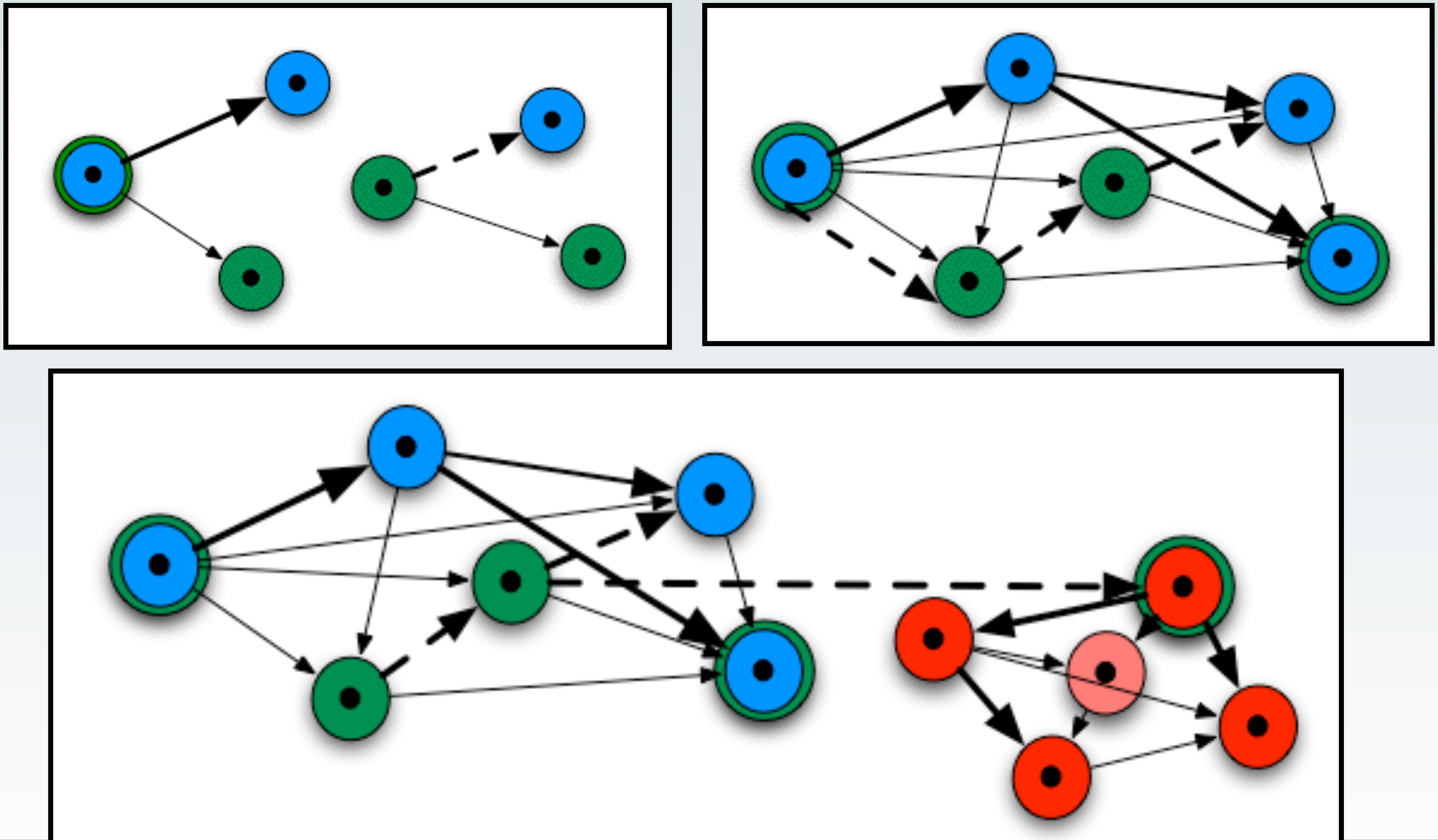


From Buckner & Carroll
Trends in Cog. Sci. 11:2 (2006)



Lecture Demonstration: R. Berg
http://www.physics.umd.edu/deptinfo/facilities/lecdem
c2-11

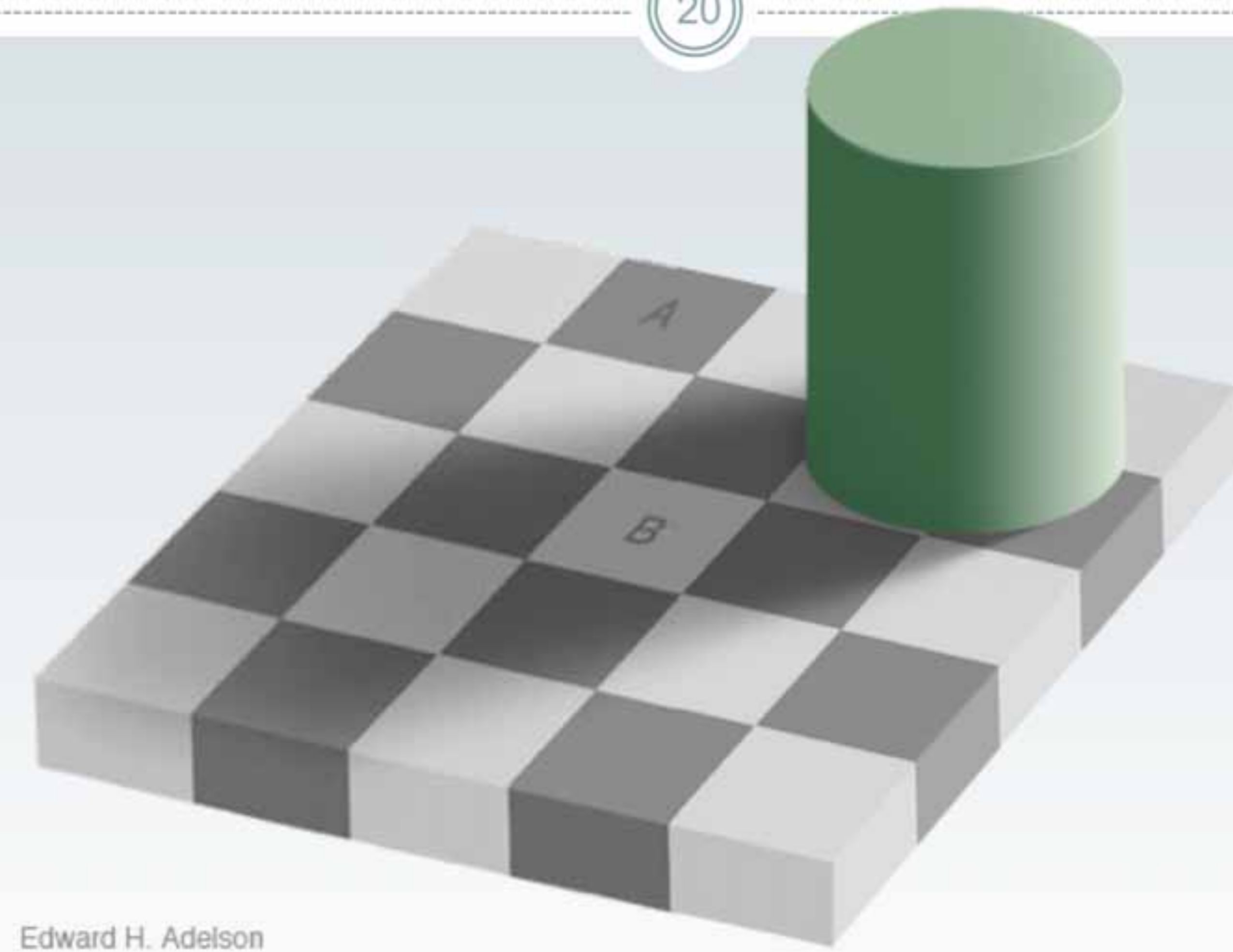
2. Association



3. Compilation (Binding)

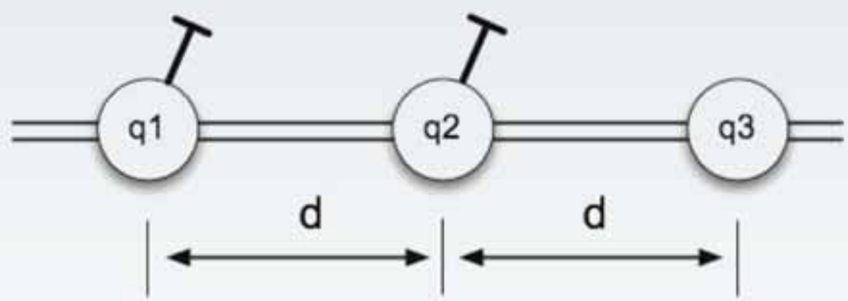
- As we learn, we bring together many different pieces of knowledge, binding them into a single coherent unit.
- Sometimes this process is fast, sometimes it takes seconds, sometimes it takes years.

Which square is darker?



Example: A "simple" problem? (algebra-based physics)

- Three charged particles lie on a straight line and are separated by distances d. q1 and q2 are held fixed. q3 is free to move but is in equilibrium (no net electrostatic force acts on it). If q2 = Q, what value must q1 have?



- Setting:
  - Four students working in the course center.

Redish, Scherr, & Tuminaro, *Phys. Teach.*, **44**, 293 (2006).

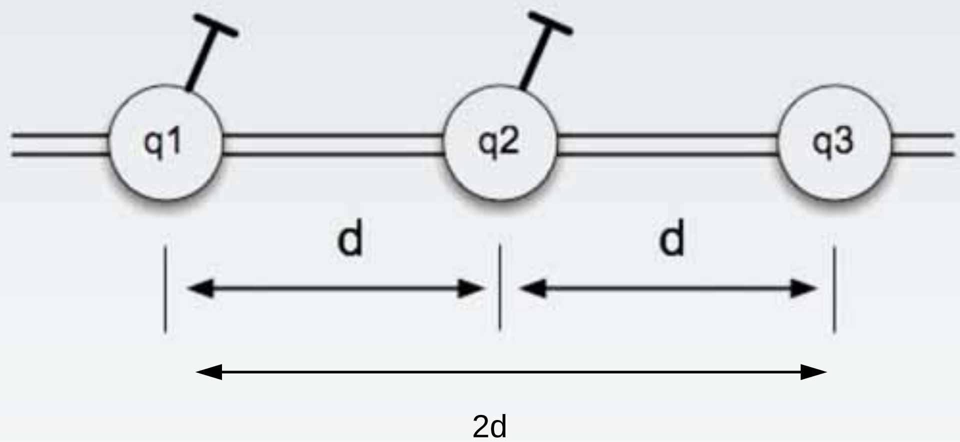
A simple algebra problem – just math?

$$F^{net} = 0 = \frac{k_C q_1 q_3}{(2d)^2} + \frac{k_C q_2 q_3}{(d)^2}$$

$$\frac{k_C q_1 q_3}{(2d)^2} = -\frac{k_C q_2 q_3}{(d)^2}$$

$$\frac{q_1}{4} = -q_2$$

$$q_1 = -4q_2 = -4Q$$



Four students took 45 minutes to solve it.

45 minutes?

- When we first viewed the video we were concerned that they took so long to solve what (on the surface) seemed to be a simple problem.
- After a careful analysis, we became convinced that the work they did was worthwhile and a valuable part of their learning.

Why so long? The professor's "simple" solution involves lots of hidden resources. Our list:

- Like charges repel, unlike attract
- Attractions and repulsions are forces
- Forces can add and cancel (one does not "win"; one is not "blocked")
- "Equilibrium" corresponds to balanced, opposing forces (not a single strong "holding" force)
- Electric force both increases with charge and decreases with distance from charge
- Objects respond to the forces they feel (not those they exert)
- Charges may be of indeterminate sign and still exert balancing forces on the test charge
- "Fixed" objects don't give visible indication of forces acting on them; "free" ones do

- Only forces on the test charge require analysis
- Each other charge exerts one force on test charge
- Each force may be represented by a vector
- "Equilibrium" corresponds to opposing vectors
- Vertical and horizontal dimensions are separable
- One dimension is sufficient for analysis
- Electric force both increases with charge and decreases with distance from charge
- Electric force decreases with the square of the distance

In this case, the students are doing what I want them to.

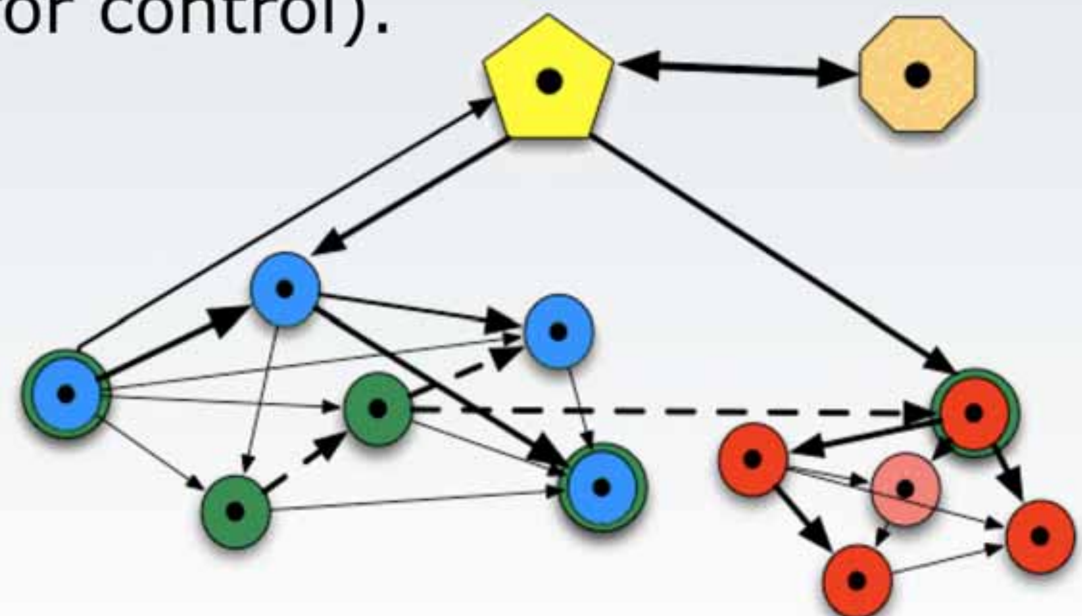
- They first make qualitative sense of the problem.
- Then they:
  - – nail down what they remember from their study of Newton's laws
  - – clarify the nature of the electric force
  - – estimate a qualitative result
  - – refine it by applying the quantitative principle – Coulomb's Law (correctly).

Reverse engineering expert knowledge

- I had failed to appreciate how much was compiled into my "simple" solution.
- Watching these students helped me "reverse engineer" what I had built over many years into a tight, automatic knowledge structure.
- The students are not only solving a problem. They are compiling the knowledge required for the problem and are learning how to solve problems in general.
- The fact that they are willing to work for an hour on a "short" problem is notable.

4. Control

- Synapses can be excitatory or inhibitory.
- The brain is filled with both feedforward links (for association and activation) and feedback links (for control).



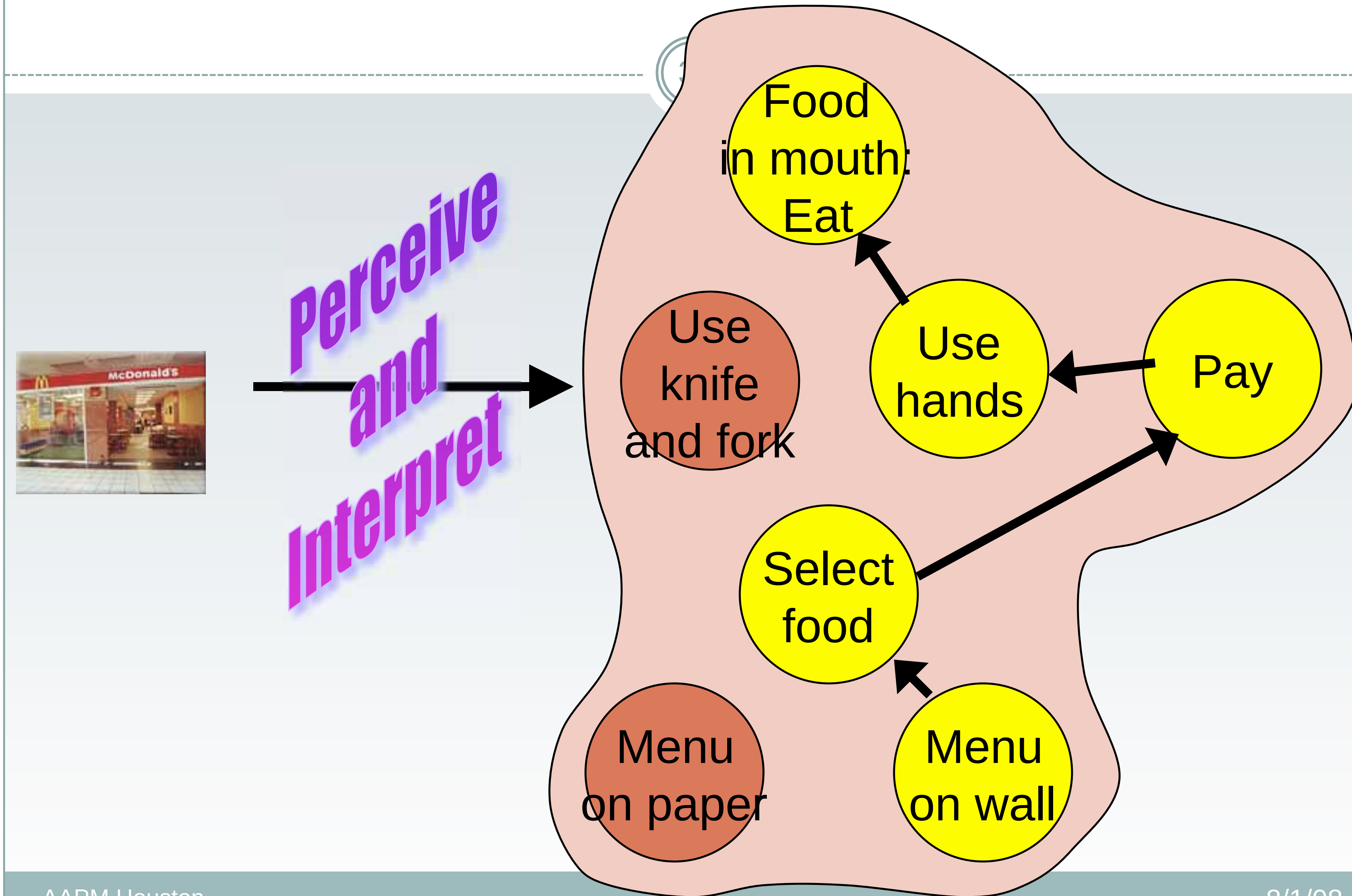
Selective Attention

- Neural systems are wired so as to provide substantial feedback at all layers of structure. Feedback can control activation or inhibition of linked cognits.
- One way control plays out is through selective attention.
- There is too much in the world for our brains to process at once.
- We learn to select and ignore, framing our situation — deciding what matters and what doesn't quickly and (often) unconsciously.

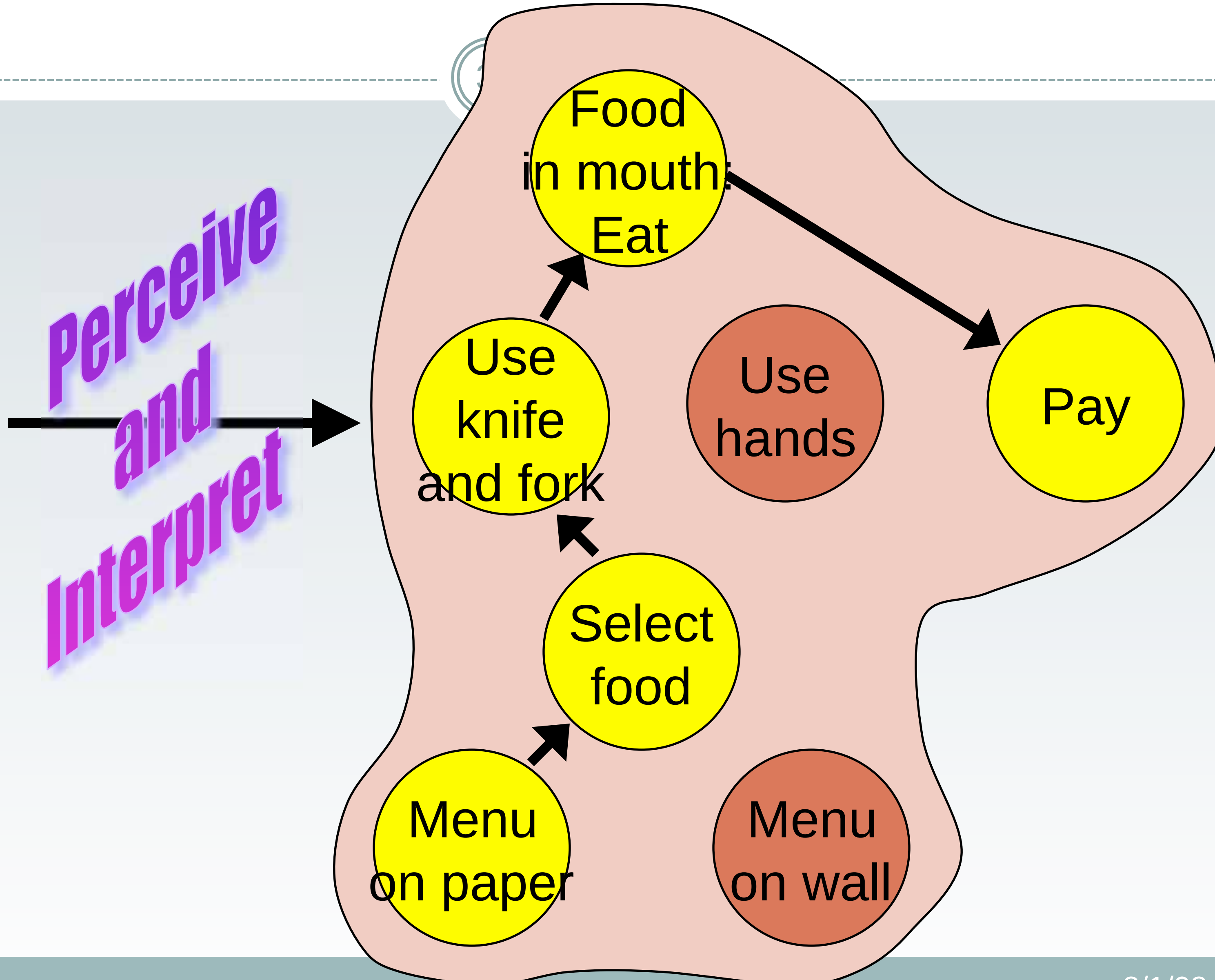
Framing: A restaurant

- We quickly learn to select a relevant subset of what we perceive and to respond in an appropriate fashion.

In a Restaurant: 1



In a Restaurant: 2



Try it in your own brain!
Count the passes

Implications: Expectations

- We have to pay attention not just to what students know when they enter our classes: we have to pay attention to
  what they (perhaps implicitly) assume
  they are going to be doing.
- What is particularly important is their *epistemological expectations*
  - What they think is the nature of the knowledge they are to learn
  - What they think they have to do to learn it.

Example:
Algebra-Based Physics

- The following problem was given in the first semester of an introductory class.
  - *Estimate the difference in air pressure between the floor and the ceiling in your dorm room. (Note: you may take the density of air to be 1 kg/m^3.)*
- A student working on this problem got trapped playing the wrong game.

$$p = p_0 + \rho g d$$

$$p_{ceiling} = p_0$$

$$p_{floor} = p_0 + \rho g h$$

$$p_{floor} - p_{ceiling} = \rho g h \approx \left(1\ \frac{\text{kg}}{\text{m}^3}\right)\left(10\ \frac{\text{N}}{\text{kg}}\right)(3\ \text{m}) = 30\ \frac{\text{N}}{\text{m}^2} = 30\ \text{P}$$

An inappropriate expectation

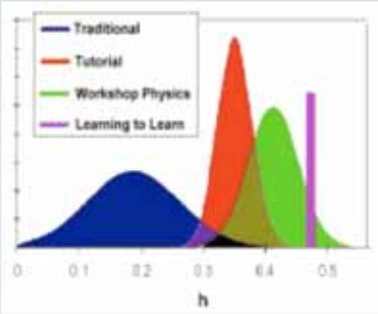
- She decided she needed an equation for pressure: chose $PV = nRT$ (wrong equation)
- She decided she needed the volume for the room.
- Decided it must be 1 m^3. (?!)
- Maintained that, despite TA's hint, "I think you'll agree with me this is an estimation problem."
- Decided if it wasn't 1 m^3, then the prof probably gave the value in a previous HW.
- Critical here was her expectation (false in this case) that you weren't allowed to make up numbers (based on your personal experience).

Implications: Complex subjects need complex teaching goals – beyond content

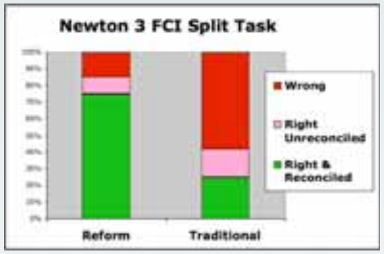
- Concepts
  - It is important that our students learn to seek meaning and sense-making in the physics.
    This means learning concepts –
    and how to reason with them.
- Intuition
  - Students should learn to refine and develop their intuitions, not reject them.
- Coherence
  - Students need to learn the importance of building a web of knowledge – of checking for consistency and seeing things from multiple perspectives.
- Reasoning from Principle / Mechanism
  - ...

Is it possible to teach any of this stuff?

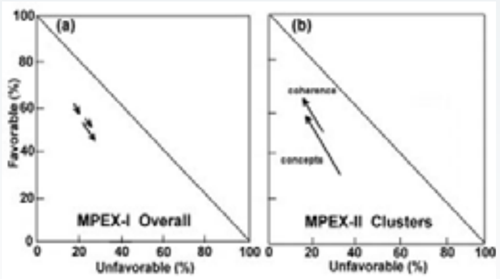
- Concept learning
  - Active learning environments



- Intuition building
  - Intuition building tutorials



- Changing expectations
  - An epistemologized class



Redish and Hammer, http://arxiv.org/abs/0807.4436

Summary: Take away messages

- Students interpret what we teach using what they know.
- But not necessarily all of what they know!
- Expert instructors often fail to realize what students need to know in order to understand something they are supposed to learn.
- Students often fail to realize what they need to use to make sense of something – even if they know it.

Summary: Implications for teaching

- We need to pay significant attention to our students' thinking and reasoning.
  - Even if students don't bring in conceptual misconceptions from previous experience, common and robust misconceptions may be generated on the spot.
  - Extensive feedback is essential.
  - Deeper research studies can help significantly.
- We need to be aware of our students' expectations, especially epistemological ones.
  - If students come to our classes with epistemological misconceptions it can be difficult to get them to pay attention even to explicit messages.
  - We have to be very careful about the "meta-messages" we may inadvertently send.

Summary: Some of what has been learned from studies of how students learn physics.

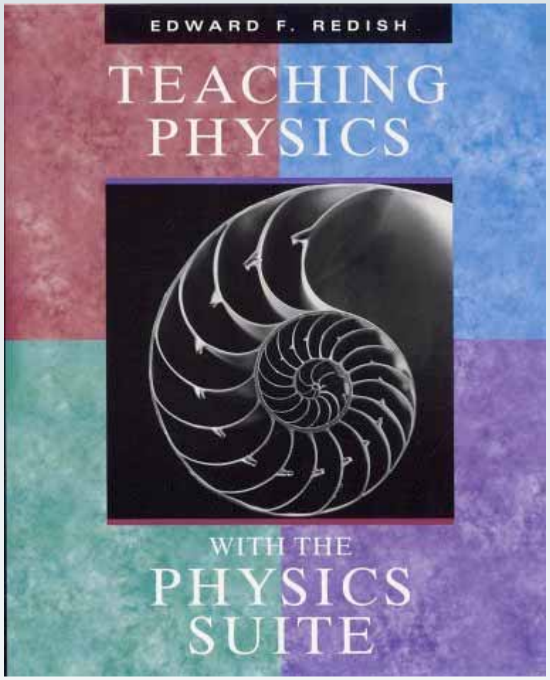
- New curricula are fine – but they need to articulate (impedance match) with where the students are.
- In order for us to understand student difficulties we need to do careful research – formative evaluation of new curricula is critical.
- Research-based active-learning environments can yield dramatic improvements.
- For more information, check out:
  - PER-Central ***http://compadre.org/per/***
  - UMd-PERG ***http://www.physics.umd.edu/perg/***

For more information see

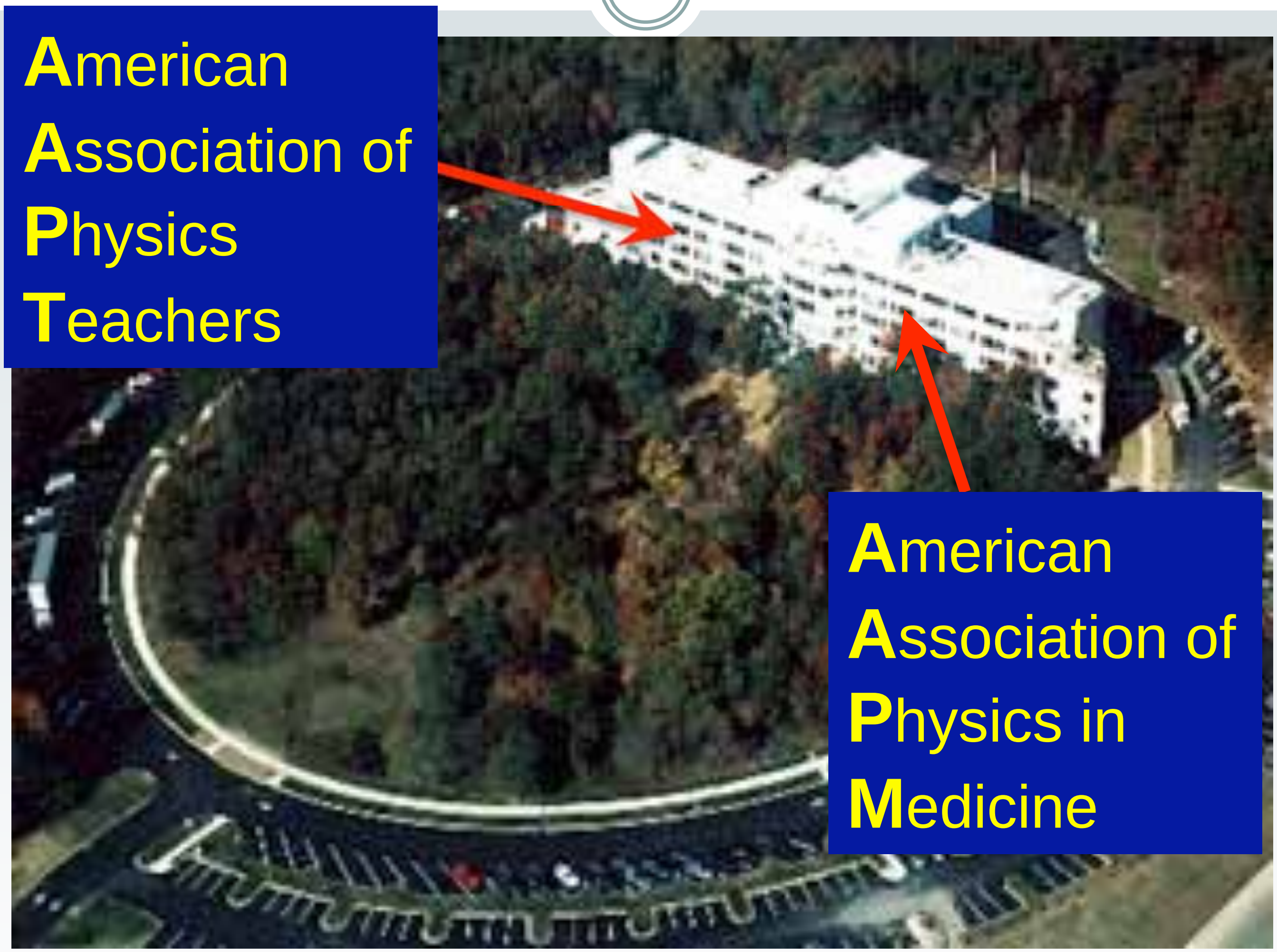
- *Teaching Physics with the Physics Suite*

Available online at

http://www2.physics.umd.edu/~redish/Book/



We're neighbors! Let's not be strangers!



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