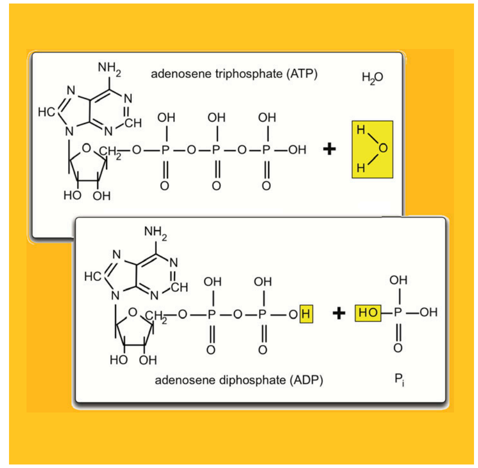
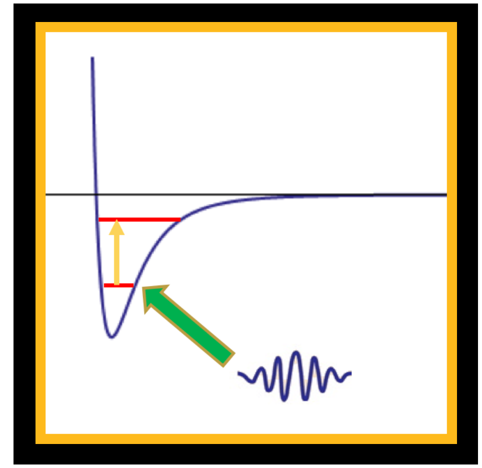
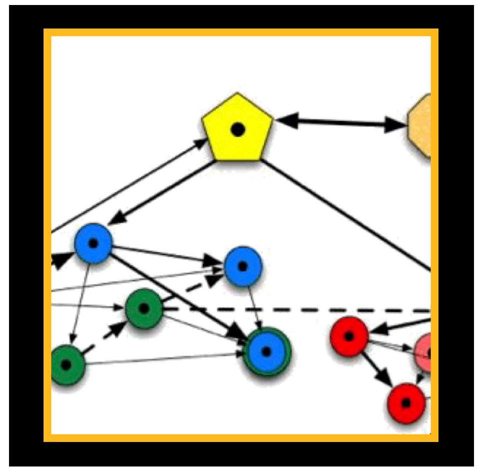






The bond energy misconception as a cross-disciplinary miscommunication: A resources analysis and a modest instructional proposal

E. F. (Joe) Redish
Department of Physics
University of Maryland

Outline

- Interdisciplinarity: The Context
  - NEXUS/Physics
- Chemical Bonding
  - The "energy stored in a bond" misconception
- The Resources Framework
  - A way to think about thinking
- Making sense of energy
  - Where the misconception comes from
- Research to practice
  - And some questions for discussion

Note: the "research" here is qualitative observation combined with theoretical analysis!

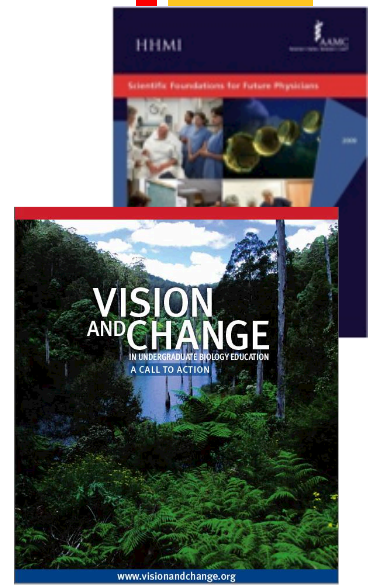
The Context

NEXUS/Physics: A class designed for life science majors

Goal

- Create an intro physics class for life science majors that articulates with their other science classes.
- Focus on building general-purpose scientific skills and a sense of the value of interdisciplinarity.
- What can physics do to help?

NEXUS/Physics



- An introductory physics class designed in response to SFFP/V&C
  - With funding from HHMI & NSF
- Has unusual pre-requisites
  - Calculus
  - Biology
  - Chemistry
- Development involved a large, multi-disciplinary development team.

NEXUS/Physics: An interdisciplinary repurposing of physics for biologists, E. F. Redish, C. Bauer, K. L. Carleton, T. J. Cooke, M. Cooper, C. H. Crouch, B. W. Dreyfus, B. Geller, J. Giannini, J. Svoboda Gouvea, M. W. Klymkowsky, W. Losert, K. Moore, J. Presson, V. Sawtelle, K. V. Thompson, C. Turpen, & R. Zia, *Am. J. Phys*. **82**:5 (2014) 368-377.

Class characteristics

- Students are mostly junior level.
- Explicit discussions of comparison with bio, chem, math
- 3 hours/week lecture (interactive with clickers, discussion, & whiteboards)
- 1 hour/week recitation (worksheets focusing on interaction of physics & biology)
- 2 hour/week lab (non-cookbook, answer a question with an expt., data rich, protocol poor)
- 4-6 hrs out of class HW/week
- Weekly formative quizzes
- 2 hour exams and a 2-hour final

The NEXUS Development Team (UMCP)

- **Physicists**
  - Joe Redish
  - Wolfgang Losert**
  - Chandra Turpen
  - Vashti Sawtelle
  - Ben Dreyfus*
  - Ben Geller*
  - Kimberly Moore*
  - John Gianini* **
  - Arnaldo Vaz (Brazil)
- **Biologists**
  - Todd Cooke
  - Karen Carleton
  - Joelle Presson
  - Kaci Thompson
- **Education (Bio)**
  - Julia Svoboda Gouvea
  - Gili Marbach-Ad
  - Kristi Hall-Berk*

** Graduate student*
*** Biophysicist*

Discussants: UMCP co-conspirators

- **Physicists**
  - Arpita Upadhyaya**
  - Michael Fisher
  - Alex Morozov**
  - Peter Shawhan
- **Biologists**
  - Marco Colombini***
  - Jeff Jensen
  - Richard Payne
  - Patty Shields
  - Sergei Sukharev**
- **Chemists**
  - Jason Kahn***
  - Lee Friedman
  - Bonnie Dixon
- **Education**
  - Andy Elby (Phys)
  - Dan Levin (Bio)
  - Jen Richards (Chem)

** *Biophysicist*
*** *Biochemist*

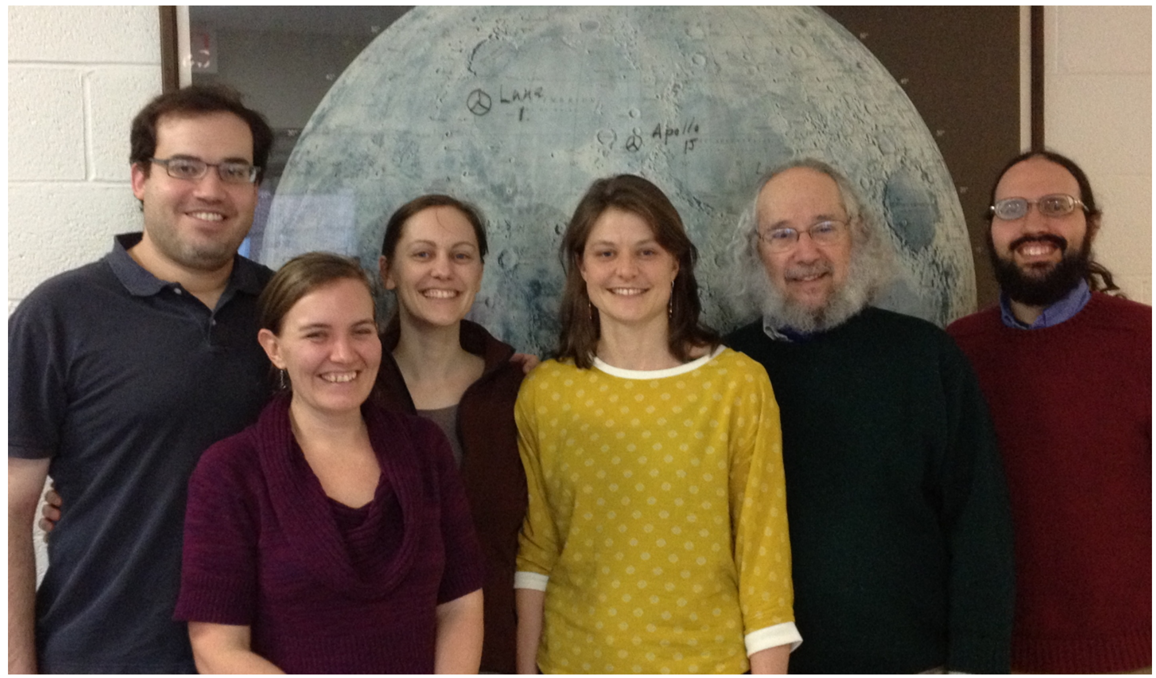
+ Off-campus collaborators

- **Physicists**
  - Catherine Crouch (Swarthmore)
  - Royce Zia (Virginia Tech)
  - Mark Reeves (George Washington)
  - Lilly Cui & Eric Anderson (UMBC)
  - Dawn Meredith (U. New Hampshire)
  - Steve Durbin (Purdue)
- **Biologists**
  - Mike Klymkowsky (U. Colorado)
- **Chemists**
  - Chris Bauer (U. New Hampshire)
  - Melanie Cooper (MSU)
- **Education**
  - Janet Coffey (Moore Foundation)
  - Jessica Watkins (Tufts University)

The NEXUS/Physics "Gang of 5"

Left to right:

Ben Geller
Vashti Sawtelle
Chandra Turpen
Julia Gouvea
Joe Redish
Ben Dreyfus



Chemical Bonding

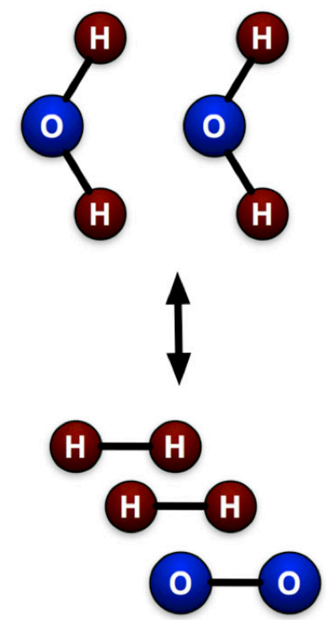
The “energy stored in a bond” misconception and interdisciplinary reconciliation

Data sources

- Set up the class so that a lot of student learning takes place where we can observe it:
  - Class discussions
  - Homework done in group work center
  - Recitations with discussion worksheets
  - Laboratories
  - Interviews
  - Case studies

The energetics of chemical bonding – Interdisciplinary reconciliation

- In introductory chemistry and biology classes, students learn about chemical reactions and the critical role of energy that is made available by molecular rearrangements.



- But students often learn heuristics by rote and that can feel contradictory to them in a way that they often don't know how to reconcile.

  1. ***It takes energy to break a chemical bond.***
  2. ***Breaking the bond in ATP is the "energy currency" providing energy for cellular metabolism.***

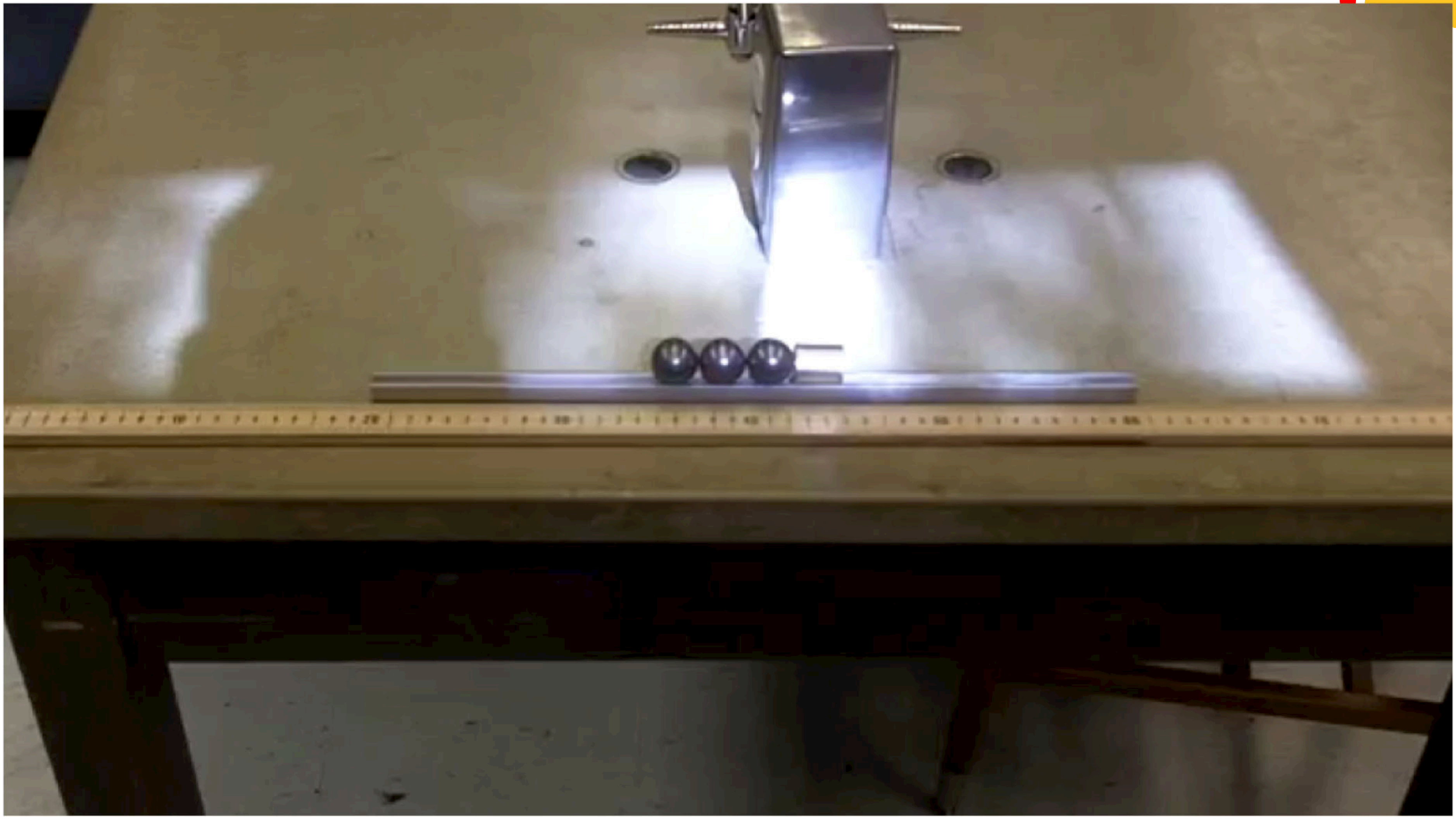
W. C. Galley, J. Chem. Ed., 81:4 (2004) 523-525.
M. Cooper and M. Klymkowsky, CBE Life Sci Educ 12:2 (2013) 306-312

Many students bring a “piñata” model of a chemical bond.

"But like the way that I was thinking of it, I don't know why, but whenever chemistry taught us like exothermic, endothermic, like what she said, I always imagined like the breaking of the bonds has like these little [energy] molecules that float out, but like I know it’s wrong. But that's just how I pictured it from the beginning."

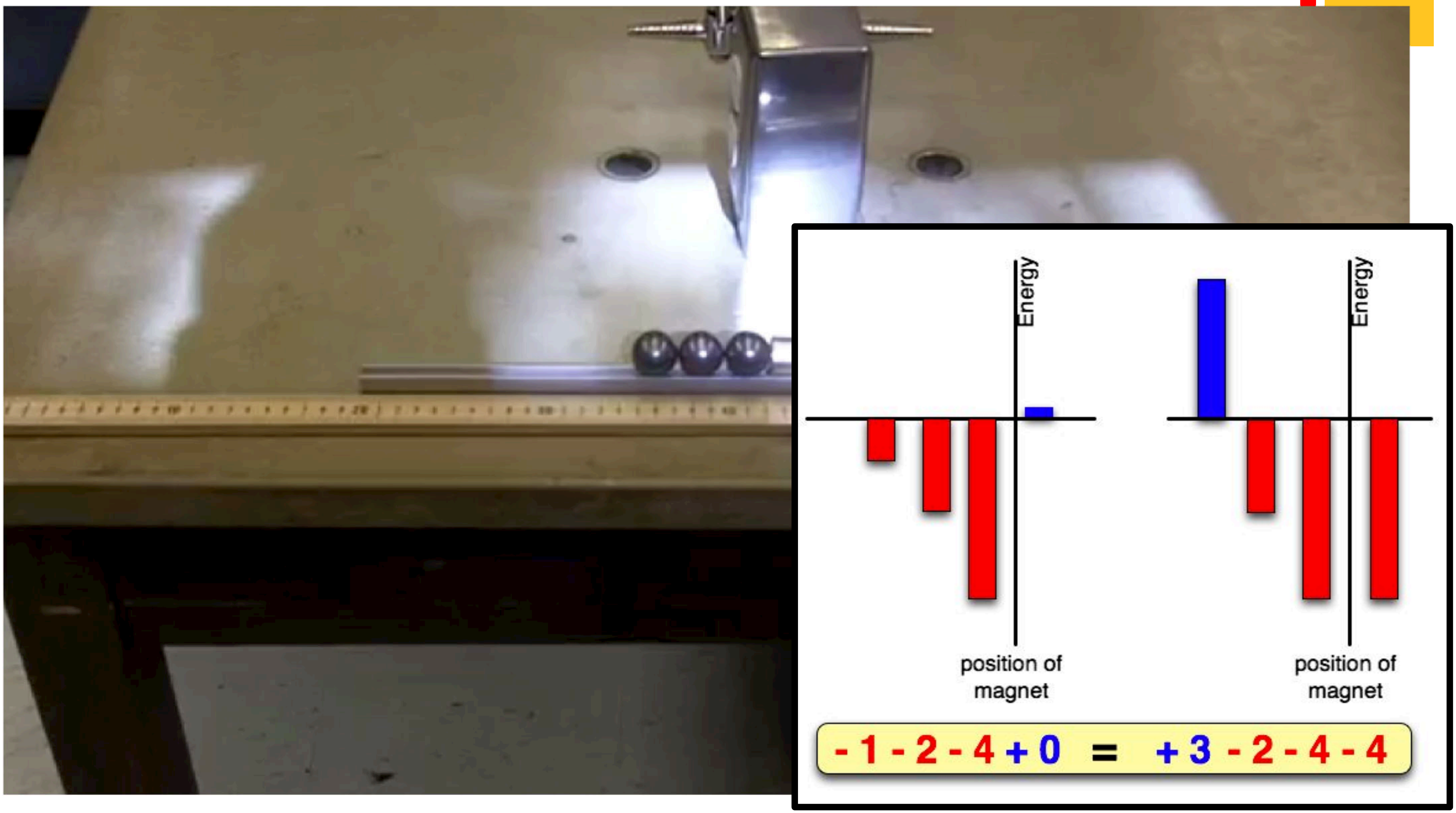
Huh! If it takes energy to break a chemical bond, where DOES the energy come from?
(Like we get from food)
Isn’t it chemical energy?

Here's a classical model. (The Gauss Gun)

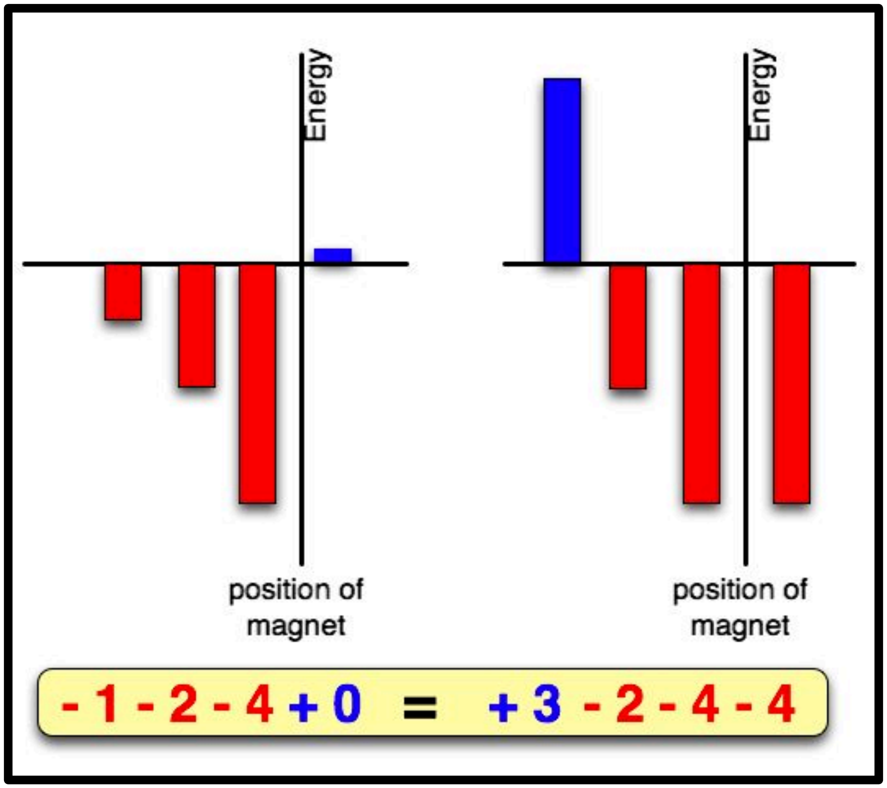


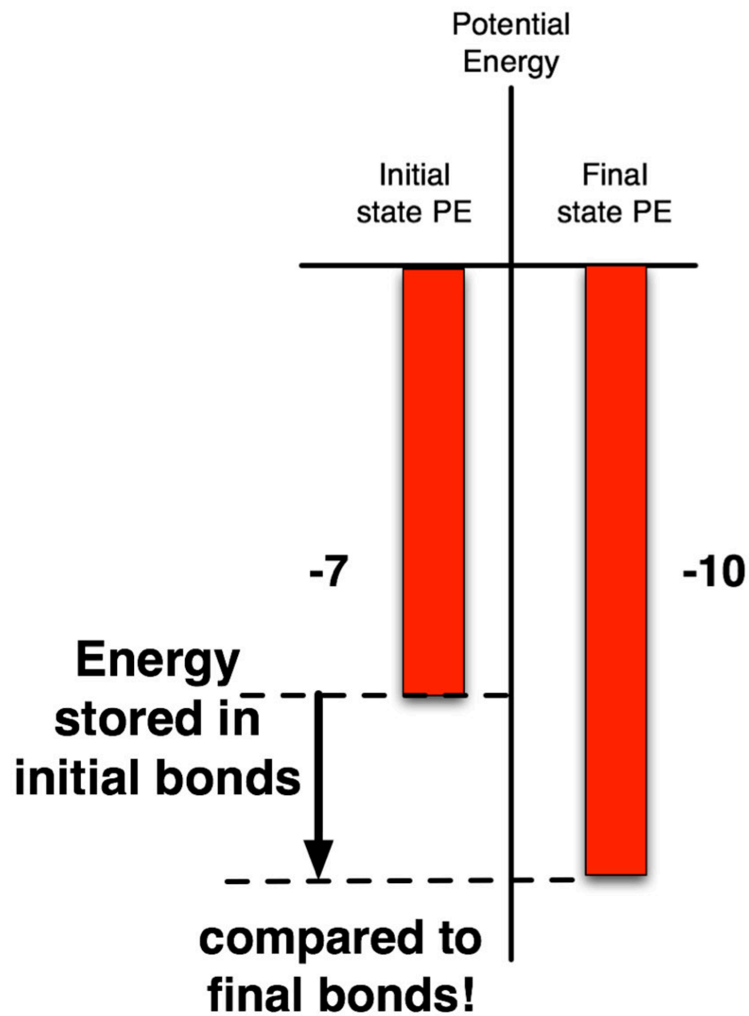
https://www.youtube.com/watch?v=fiSd91sLtS4

Here's how it works:
The energy comes from potential energy!



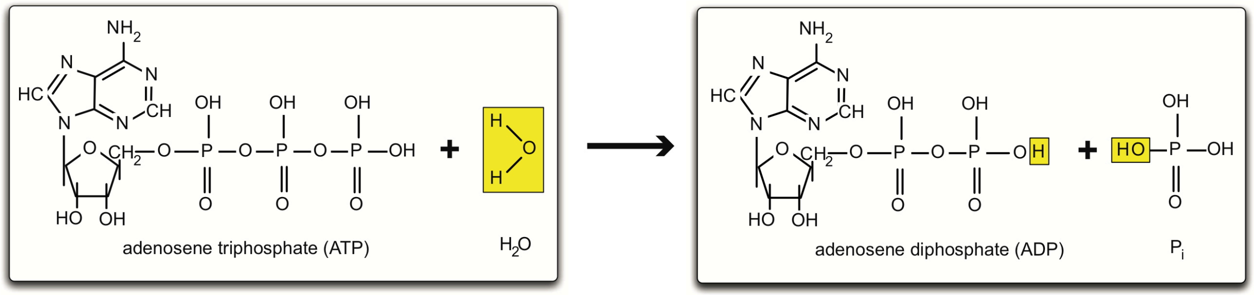
There is energy is stored in the initial bonds. Relative to the final bonds.





Distinct disciplinary perspectives

- Physicists, biologists, and chemists make different tacit assumptions.
- Physicists tend to isolate a system to focus on a particular physical phenomenon and mechanism.
- Chemists tend to assume a context — typically a solution.
- Biologists tend to assume the natural and universal fluid context of life – environmental air and water are taken for granted.



- We learned to not try to condemn one or the other perspective as “wrong” but to be explicit and discuss the different ways different disciplines look at the same phenomenon – and why.

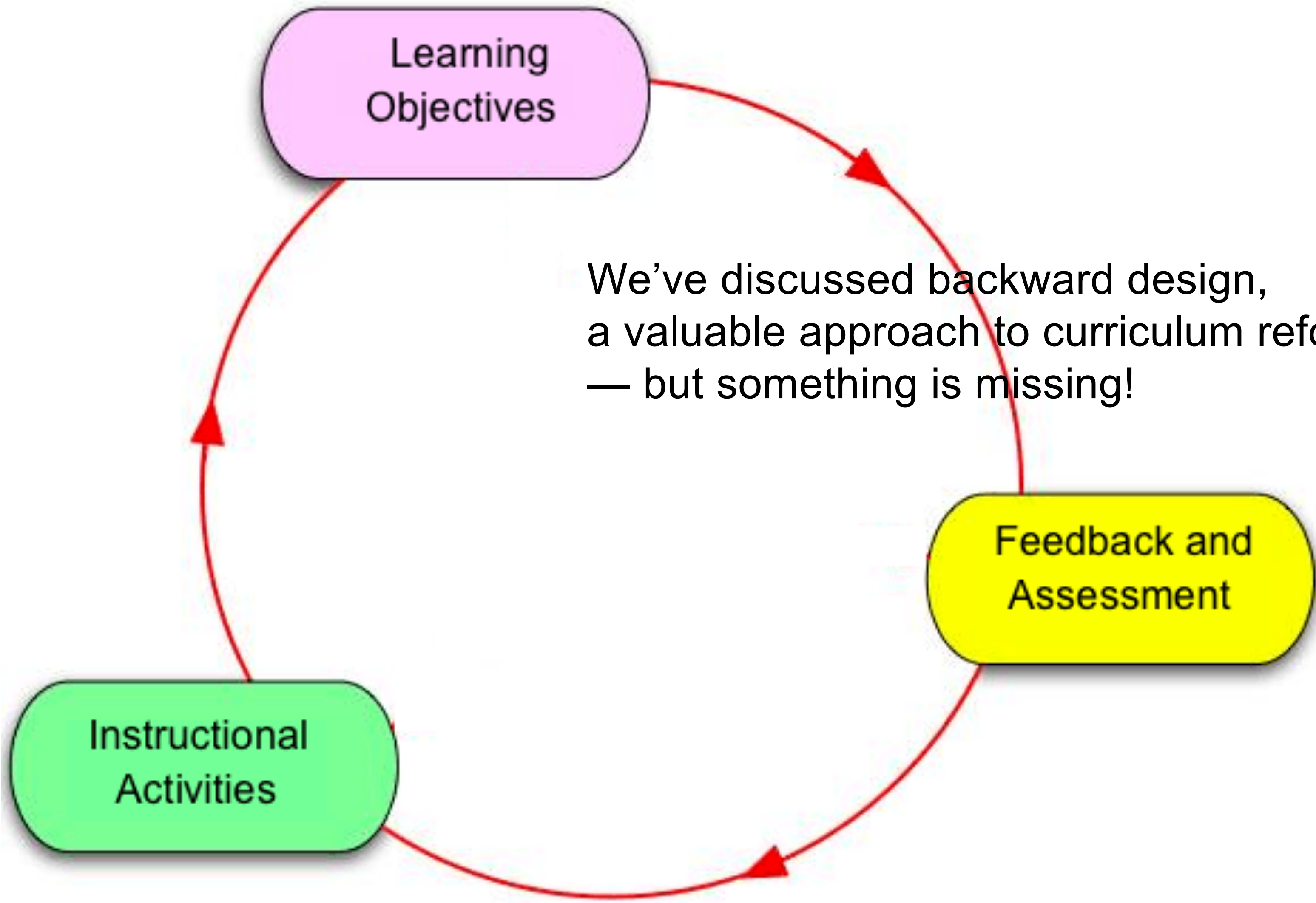
But this error is both common and robust.

- Many students will say ”energy is stored in chemical bonds” and only a few are able to explicitly reference “with respect to the final state.”
- Where does this come from?
- Let’s see if a theoretical perspective can give some insights.

The Resources Framework

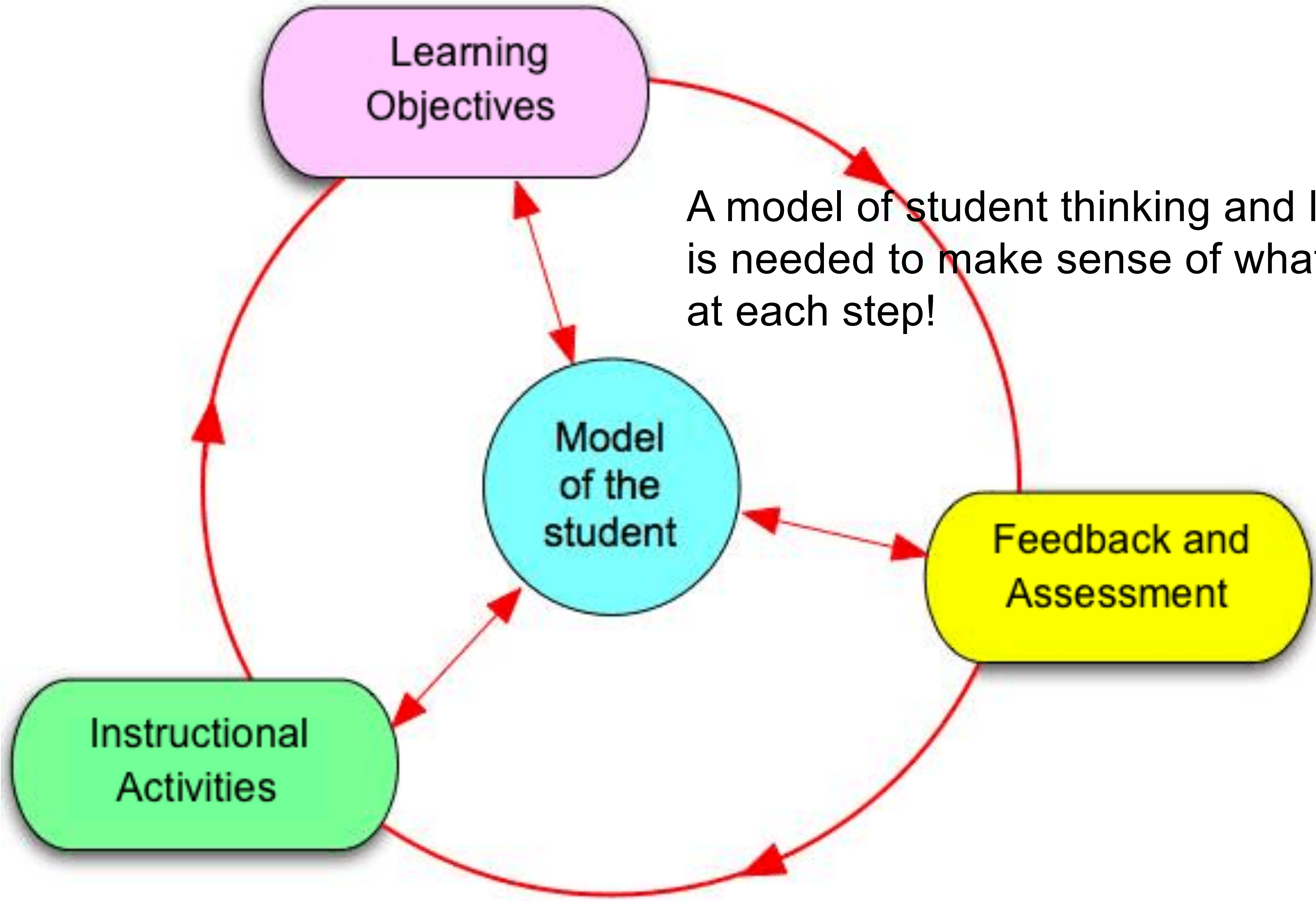
A way to think about thinking

Backward design



We’ve discussed backward design, a valuable approach to curriculum reform — but something is missing!

Backward design



A model of student thinking and learning is needed to make sense of what happens at each step!

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

- Without a theoretical framework, we tend to interpret student behavior with “natural” or “folk models”.
  - Folk models can be misleading and inconsistent, like the “folk models” our students bring to our classes in chemistry and physics.
- A theoretical framework can warn us when our generalizations of those models lead us astray. Folk models of learning 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

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. Building mechanisms to ***compile and swap*** memories in an out of working memory quickly becomes crucial for complex reasoning.
   - 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.

Critical question: Should we model thinking as stabile or labile?

- There are a huge number of factors affecting each individual's behavior at any instant.
- The brain is highly dynamic, continually re-evaluating what knowledge it needs to bring to bear.
- The environmental and social context and affective issues also play critical roles.
- Often student responses are highly resistant to change.
- What's the best starting point? **Knowledge in pieces**? Or **misconceptions** ("theory" theory)?

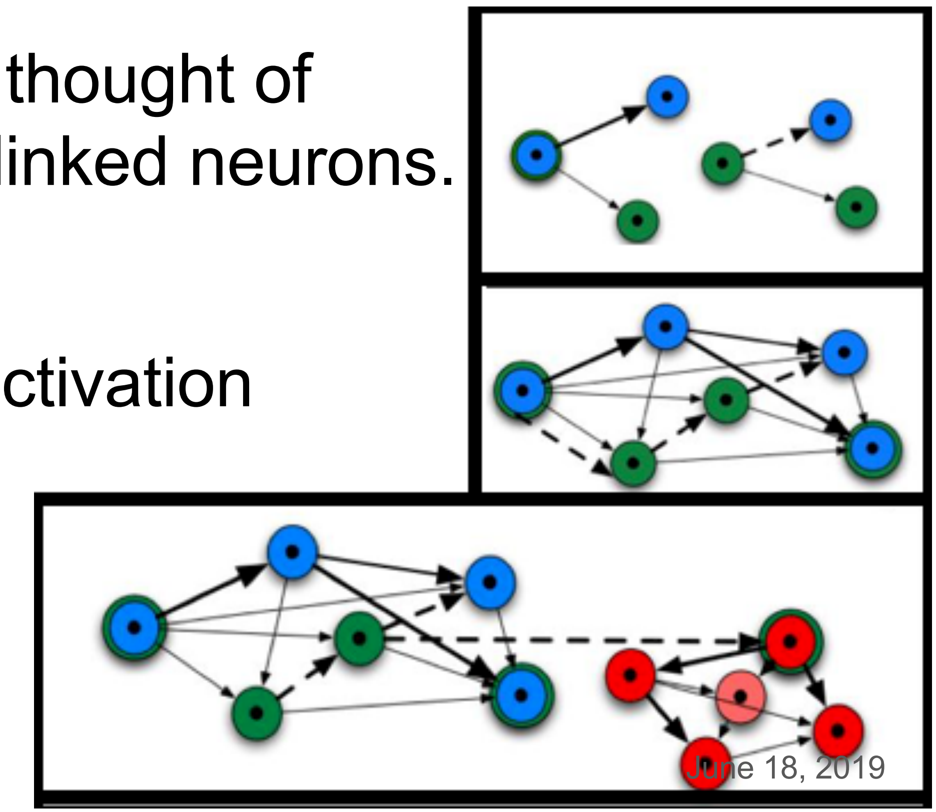
diSessa, Cog. & Instr. 10 (1993) 105
McCloskey, in *Mental Models* (1983) 299

What structures should we look for, given what we know of brain and behavior?

- A two-level K-i-P structure
  - Concept knowledge (***basic knowledge***)
  - Knowledge about when to use knowledge (***mechanisms of selective attention*** or “***expectations***”)
    - Cultural knowledge
    - Framing (viewing a situation and quickly deciding “what matters”)
    - Epistemology (“knowing how to know”)
- With two levels of structure
  - Small dynamic pieces (resources)
    - Associations, chunking, & compilation
  - Somewhat stable expectations
    - Create activation biases -- can also be dynamic

The Structure of the RF: 1 - Resources

- The RF is an associative network model with control structure and dynamic binding.
- The RF is a phenomenological and descriptive framework.
- The activation of knowledge is thought of as the activation of clusters of linked neurons.
- Learning is the establishment of strong connections so that activation of cluster of neurons leads to the activation of other clusters of neurons.

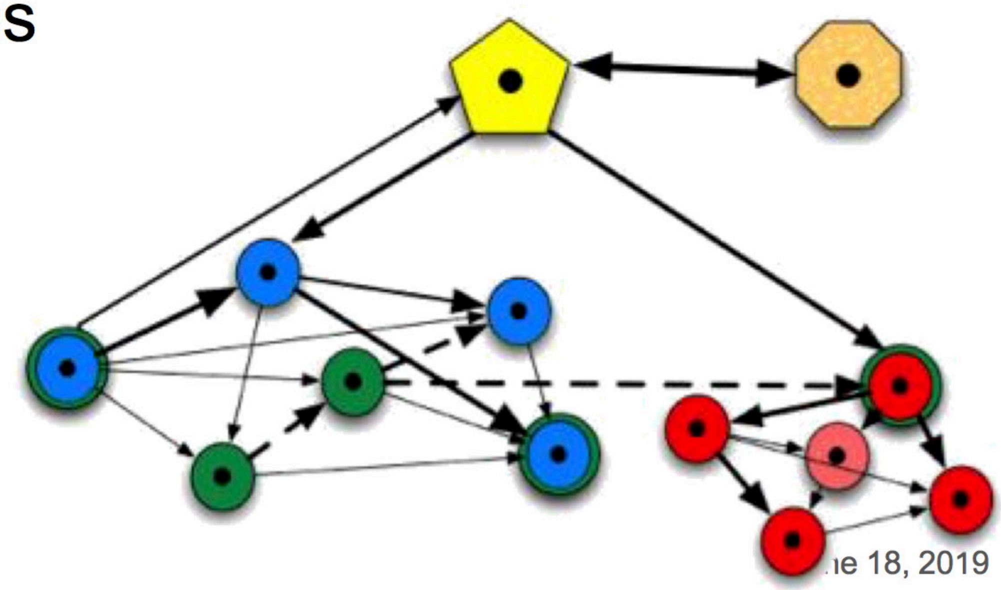


The Structure of the RF: 2 - Control

In this talk we focus on the associational structures of concepts.

We've also gotten some interesting results looking at control structures (epistemological resources).

- Control structures organize what resources are activated in particular contexts.
  - Selective Attention
  - Associational structures
  - Context Dependence
  - Framing
  - Epistemology
  - Metacognition



How do we build knowledge? How do we make meaning?

- In DBER, we often talk of “constructivism” — the idea that new knowledge is built out of old.
- But how?
- Consider tools for building the knowledge of novices — and unpacking the knowledge of experts.

Building complex (and abstract) concepts

How do we build new knowledge from old?

To set up an instructional path to help us understand what's happening, let's analyze how meaning is made in abstract situations using some tools from cognitive linguistics and semantics.

G. Lakoff and M. Johnson, *Metaphors We Live By* (U, if Chicago, 1980/2003)
G. Fauconnier and M. Turner, *The Way We Think* (Basic Books, 2003)

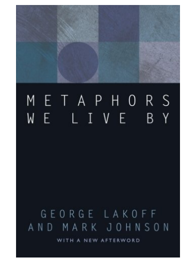
The key cognitive elements

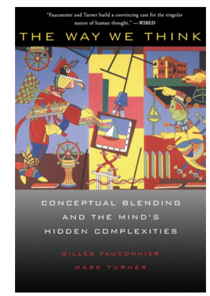
- The critical structure are "mental models" — associations of
  - Objects
  - Processes
  - Relations

that are easily commonly activated and used together.

Building up abstract concepts

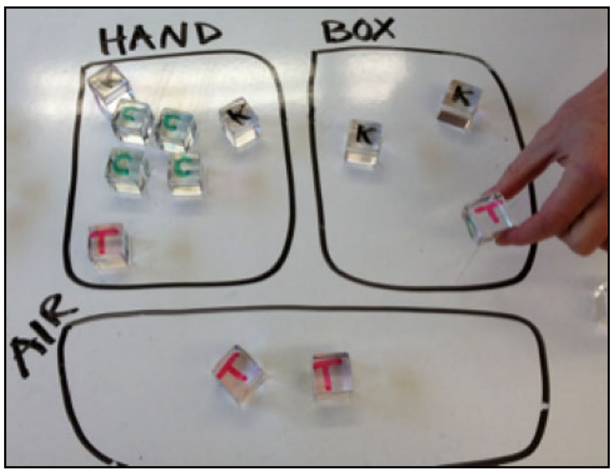
- According to Lakoff & Johnson and Fauconnier & Turner, we build up abstract and complex concepts by beginning with concrete knowledge gained from direct experience, using metaphors that gain meanings of their own to create new mental models.
- We then blend different mental models to create even more complex ideas.
- Often, in physics, we deal with constructed quantities that do not match directly with everyday experience. We often use conceptual blending in creating abstract ideas.



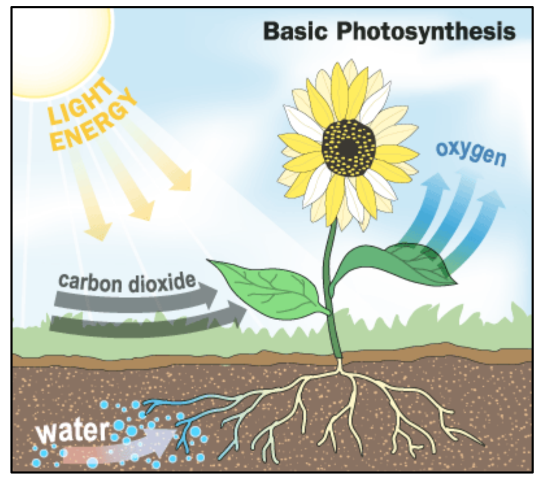


Ontological metaphors for energy: 1

Energy as a substance



Scherr et al. 2012



science.howstuffworks.com

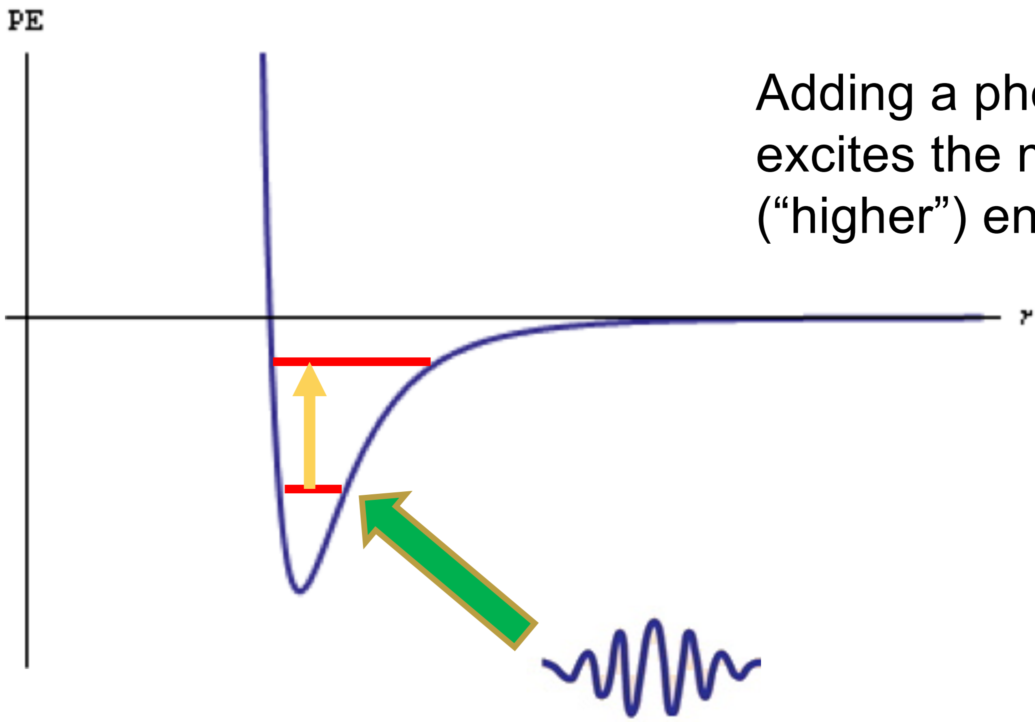
Energy is **in** objects
Objects **have** energy

B. W. Dreyfus, et al., *Phys. Rev, ST-PER* **10** (2014) 020108

Students get confused

- Many of my students — who have had Chem I and Chem II — still think that "breaking a chemical bond releases energy."
- **Bond energies** = the energy it takes to break a bond (a positive number) is often confused by students as
- the energy **stored in a bond** (energy as positive conserved stuff)
- Perhaps if we consider **binding energies** = the potential energy compared to separations (a negative number) students would be able to reconcile what they learnin in chemistry and biology.

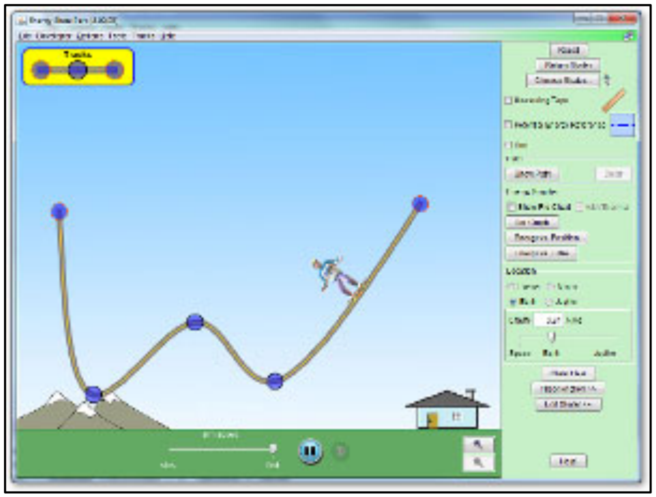
+ By studying the way an expert talks about it we can figure out how to do it.



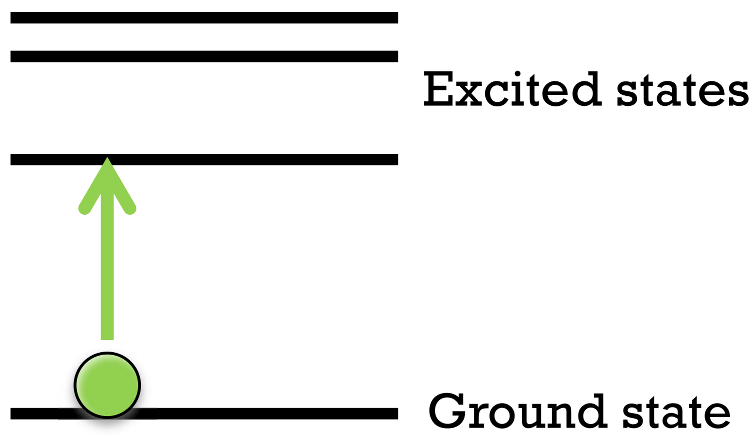
Adding a photon (”stuff”), excites the molecule to an new (“higher”) energy state.

Ontological metaphors for energy: 2

Energy as a vertical location



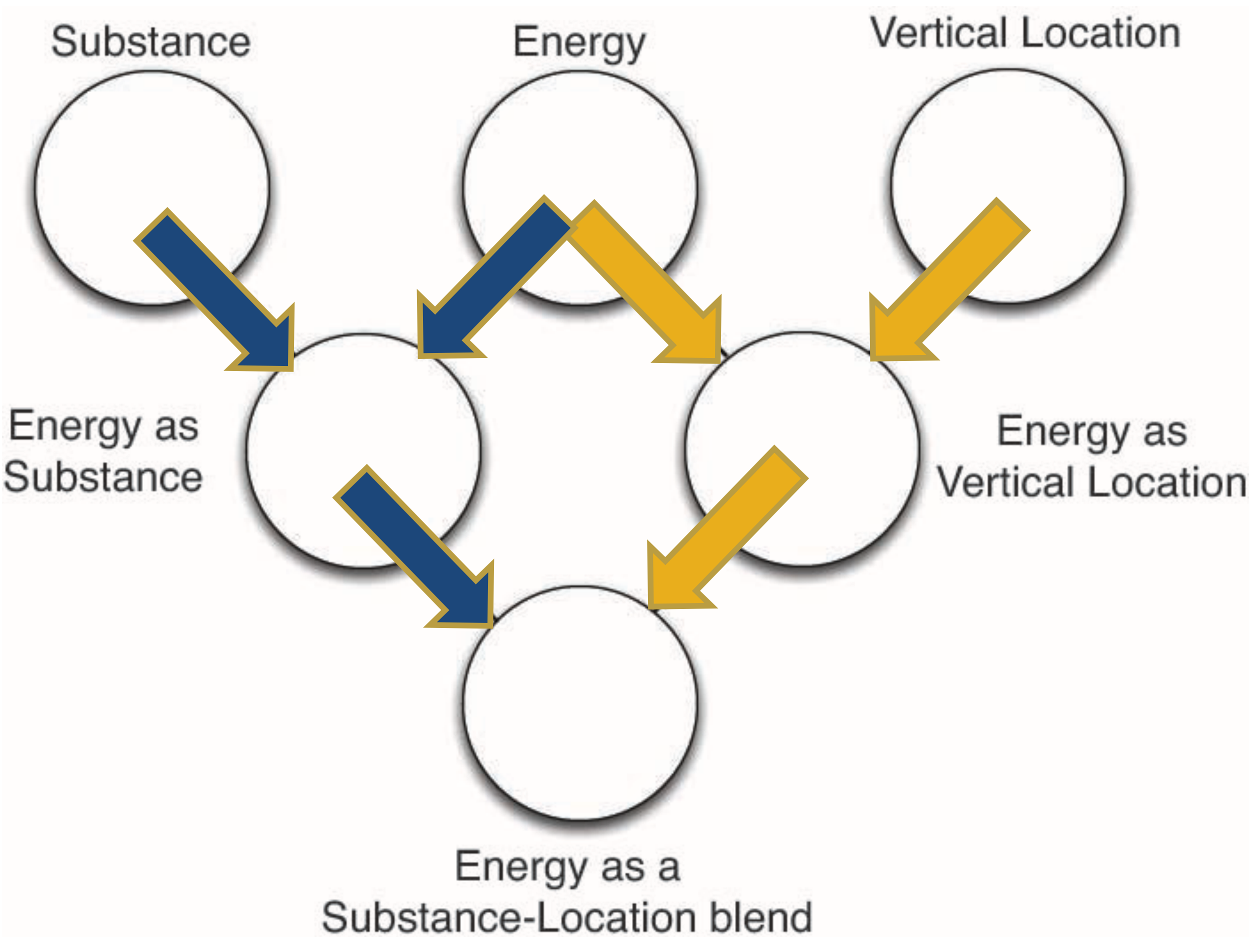
phet.colorado.edu



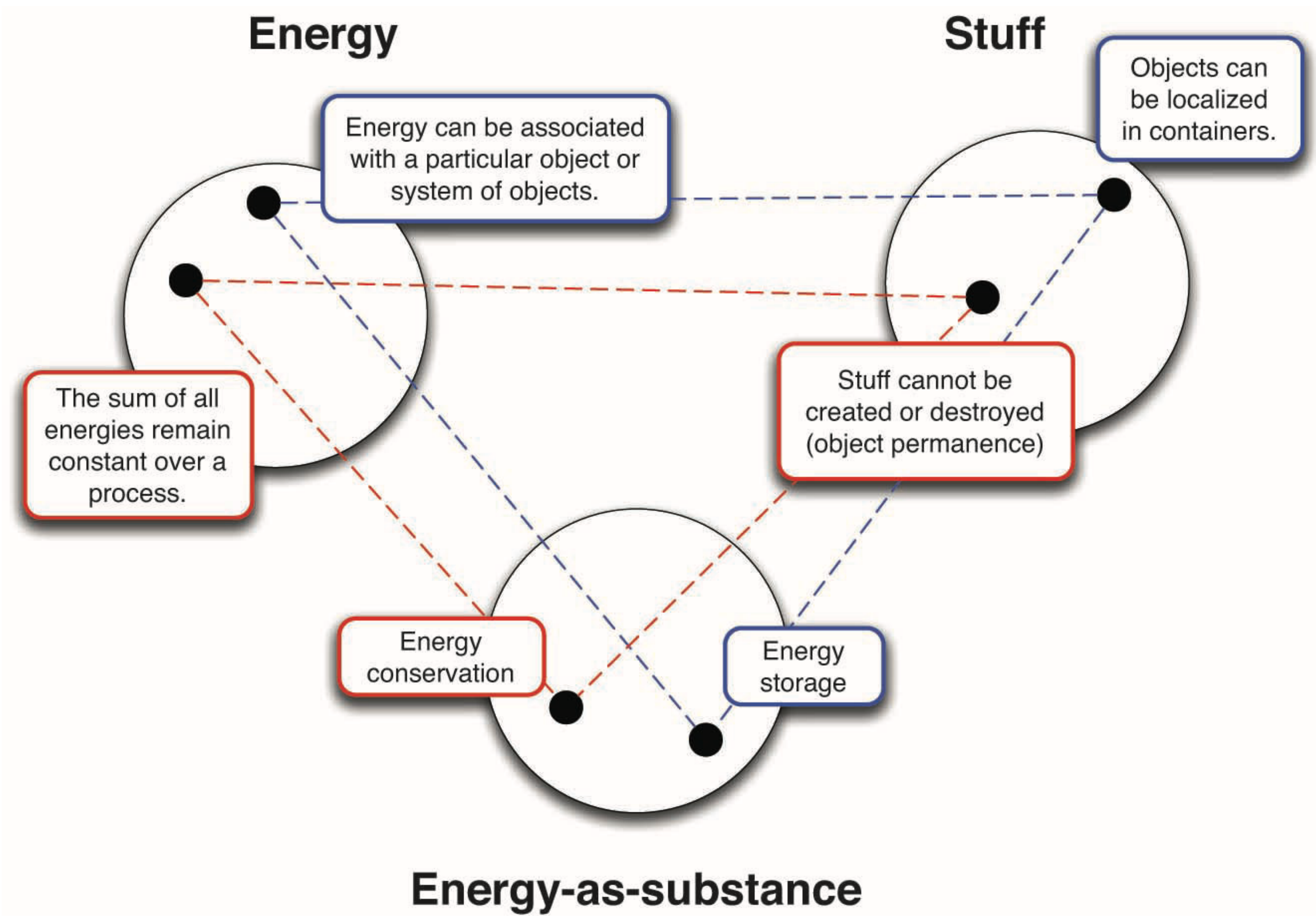
Objects are **at** energies

Objects **go** to **higher/lower** energy

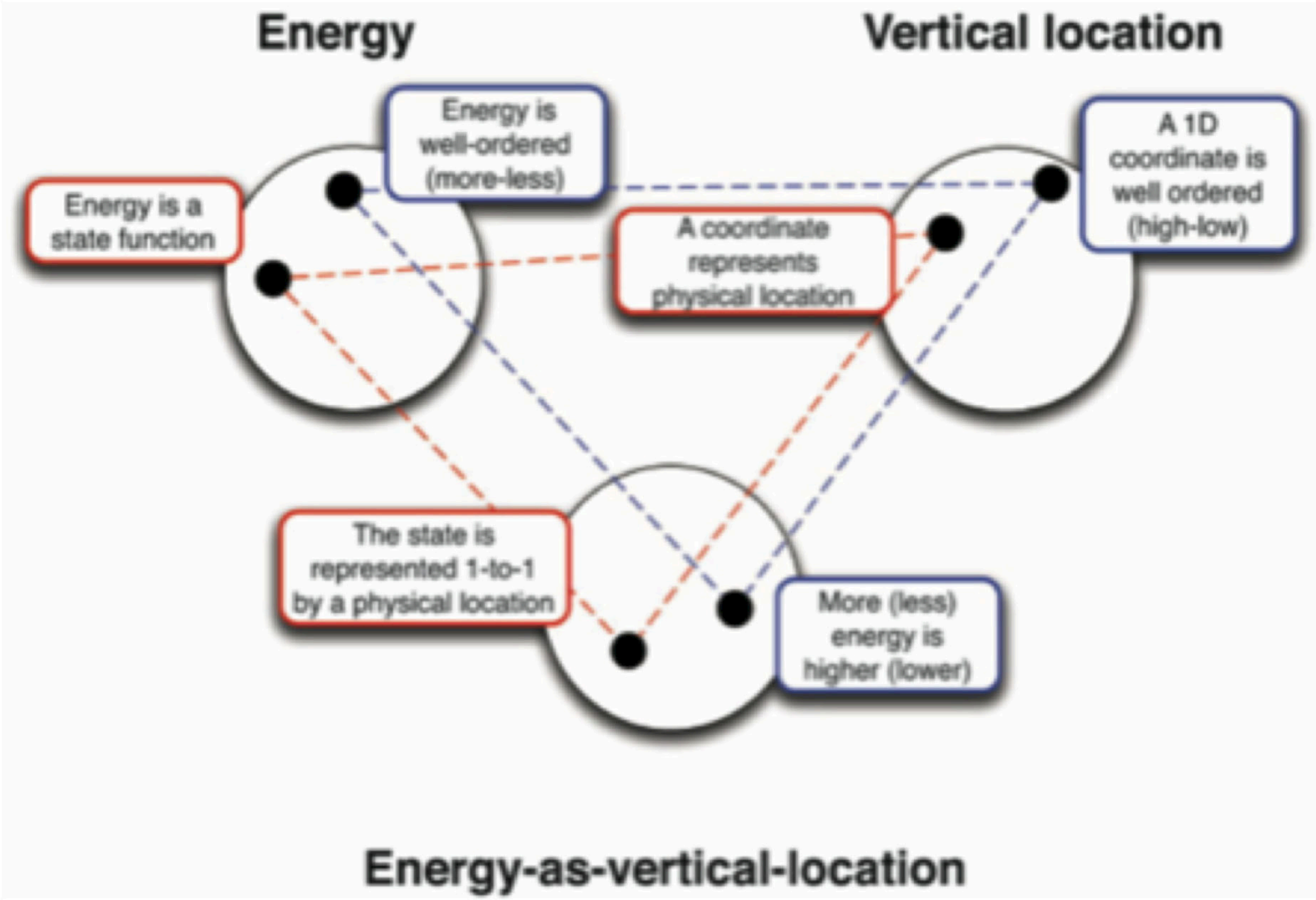
A chain: metaphor and mental model blending.



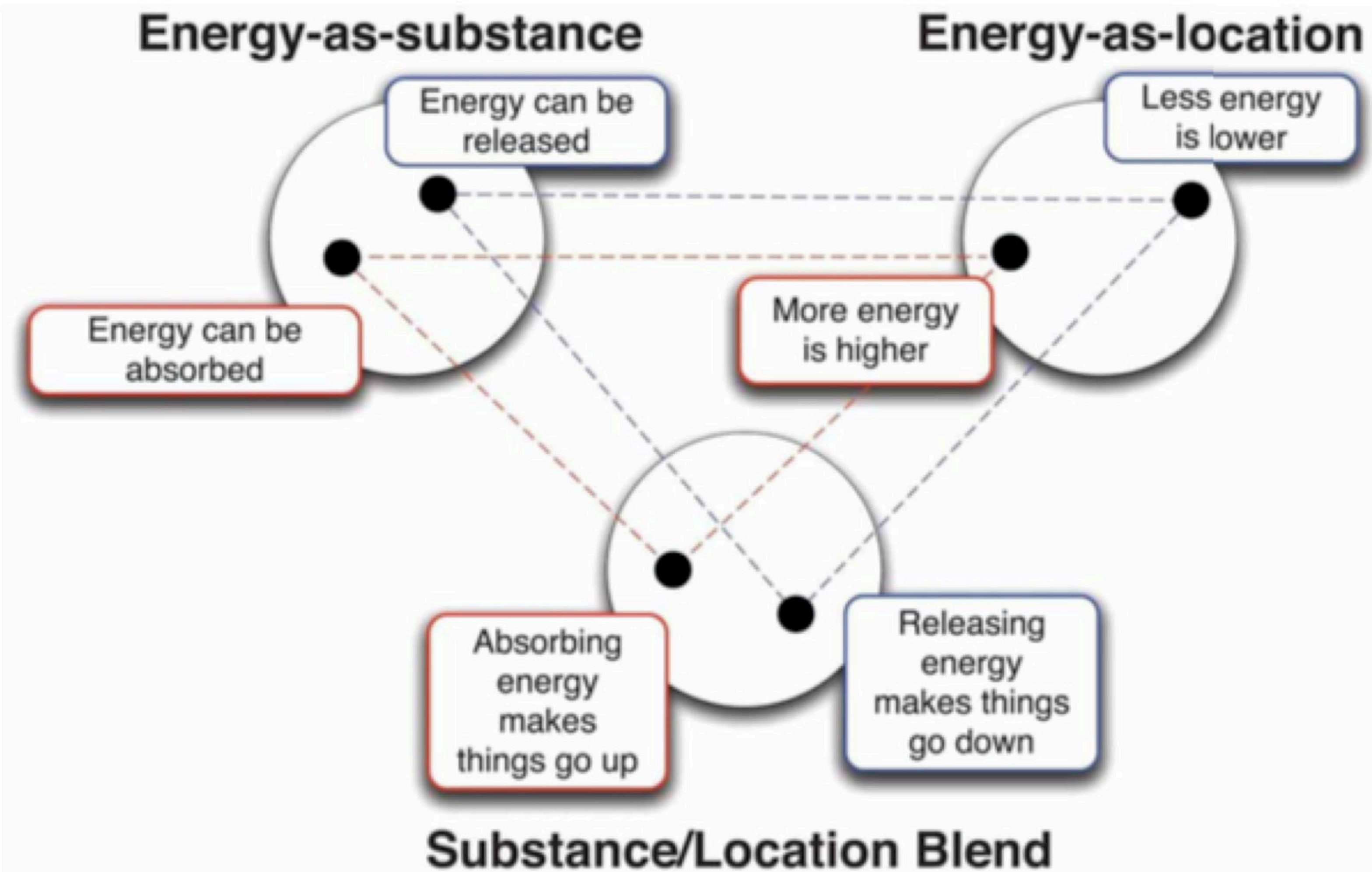
+ Energy as a Substance metaphor as a conceptual blend



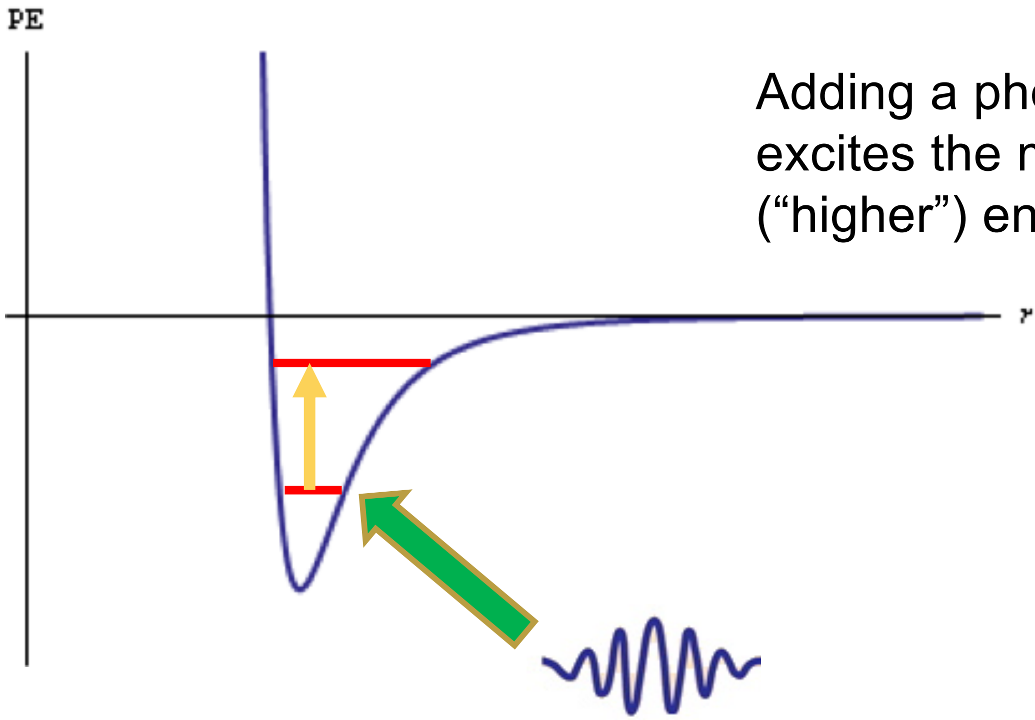
Energy as a Vertical Location metaphor as a conceptual blend



+ Blending the two mental models



Experts blend these metaphors seamlessly, building a new, more complex description.



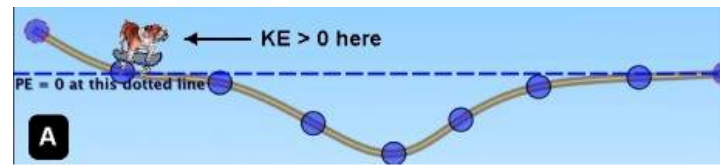
Adding a photon (”stuff”), excites the molecule to an new (“higher”) energy state.

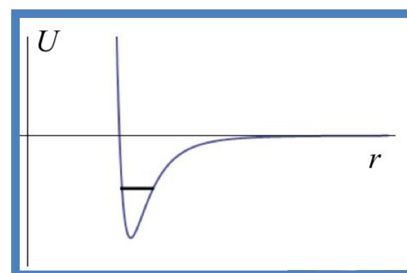
Research to practice

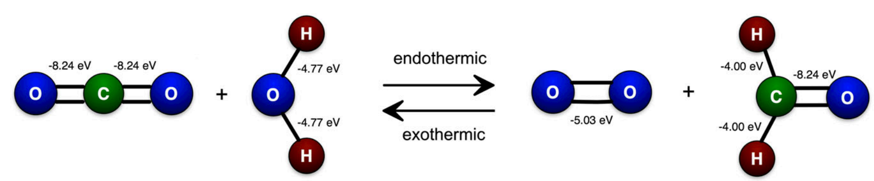
Instructional Implications

Can our understanding of the details of what we usually take for granted help?

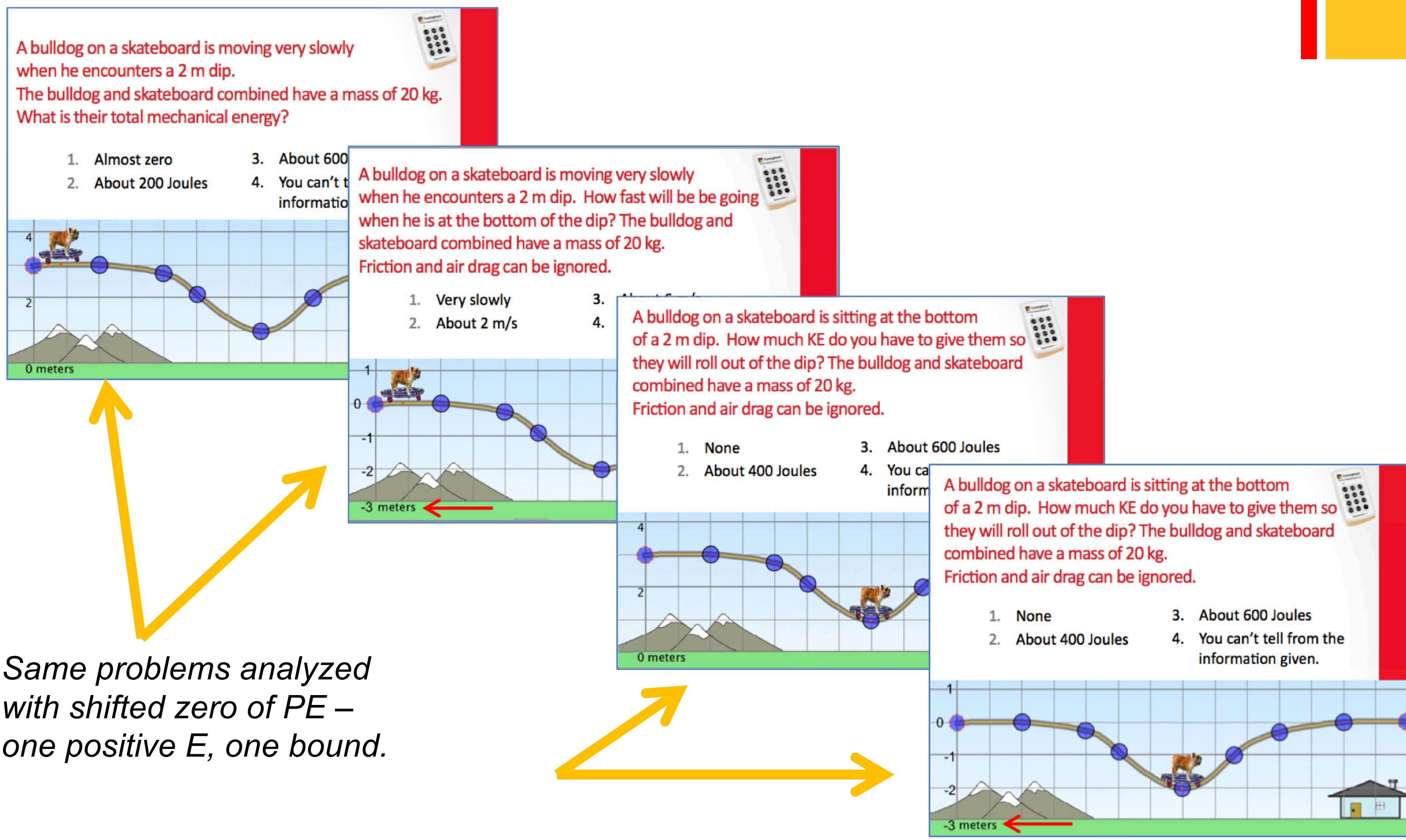
- Build a coherent story using toy models
  - Bulldog on a skateboard
  - Atomic interactions and binding
  - Reactions in which bonds are first broken and then stronger ones formed (the Gauss gun)
  - Biological examples that give authentic insights (photosynthesis).







+ A series of clicker questions (PhET based) helps students get comfortable with negative PE and with the concept of binding energy.

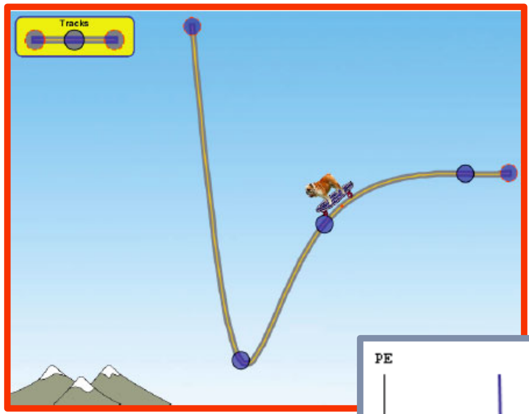


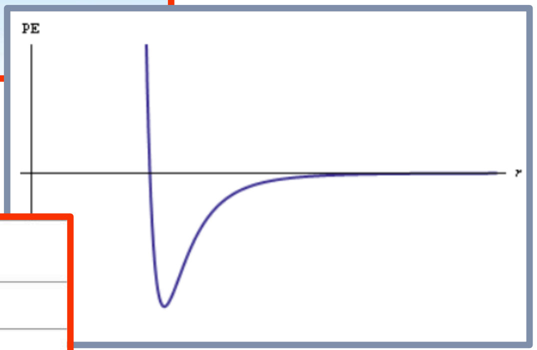
Same problems analyzed with shifted zero of PE – one positive E, one bound.

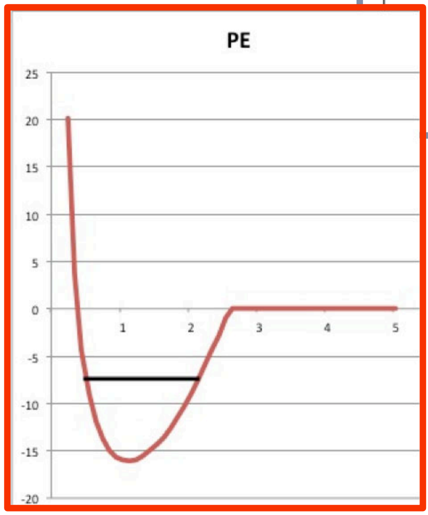
Bound states HW problem

The skateboarder is just an analogy for the cases we are interested in -- interacting atoms.

If the atoms have an energy of -7.5 units as shown by the solid line in the figure, would you have to put in energy to separate the atoms or by separating them would you gain energy? How much? Explain why you think so.

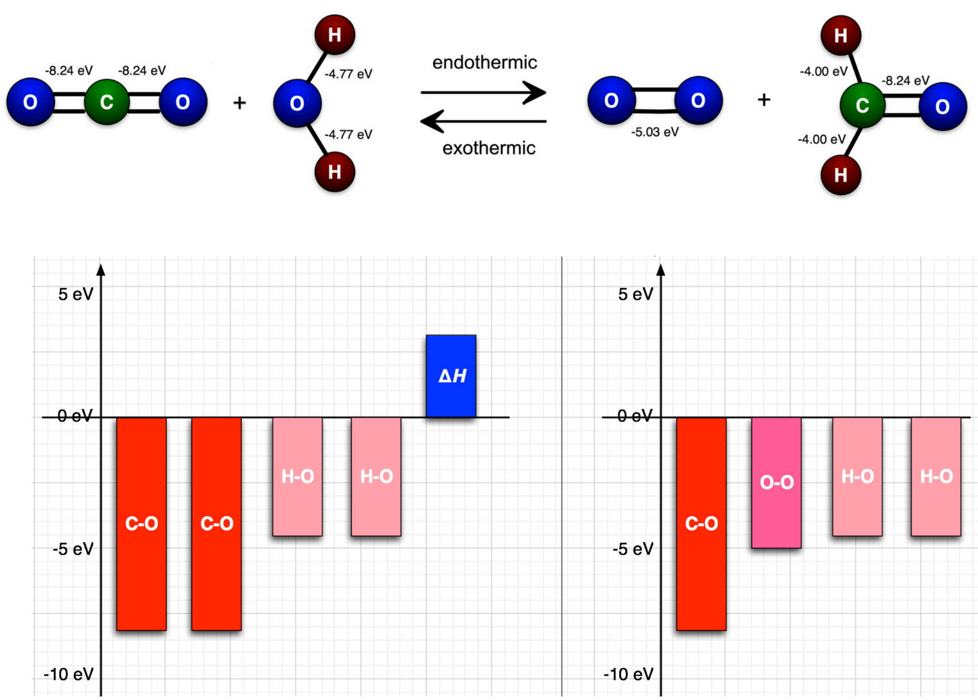




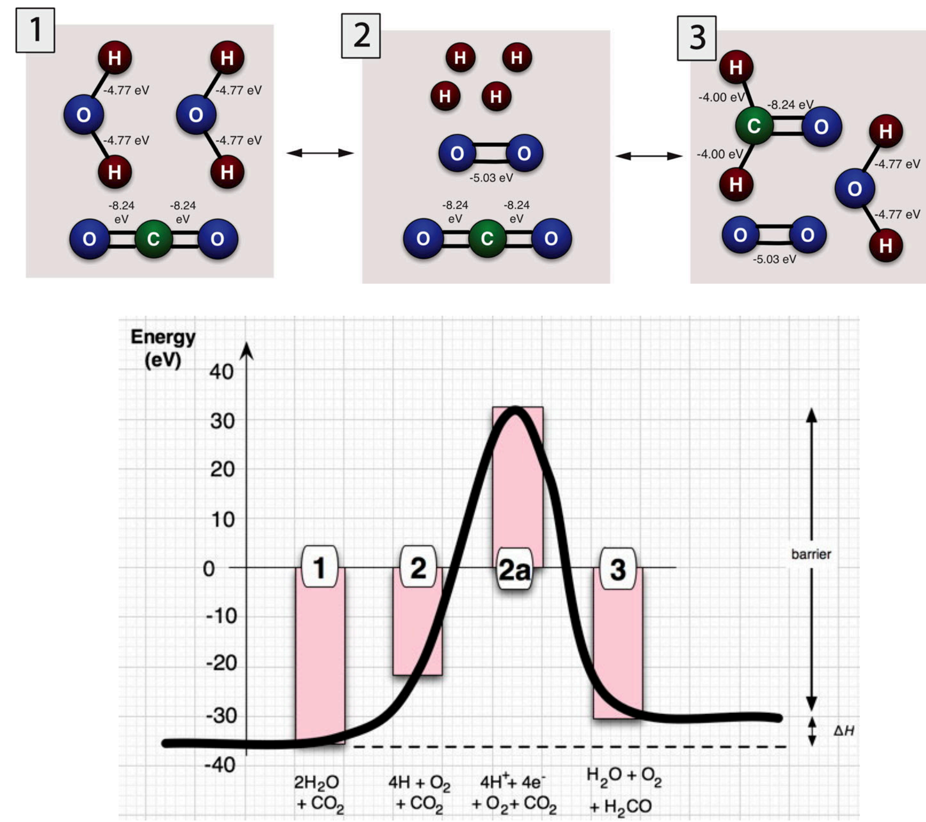


Energy steps: A toy model of photosynthesis

HW #1:
Total energy change

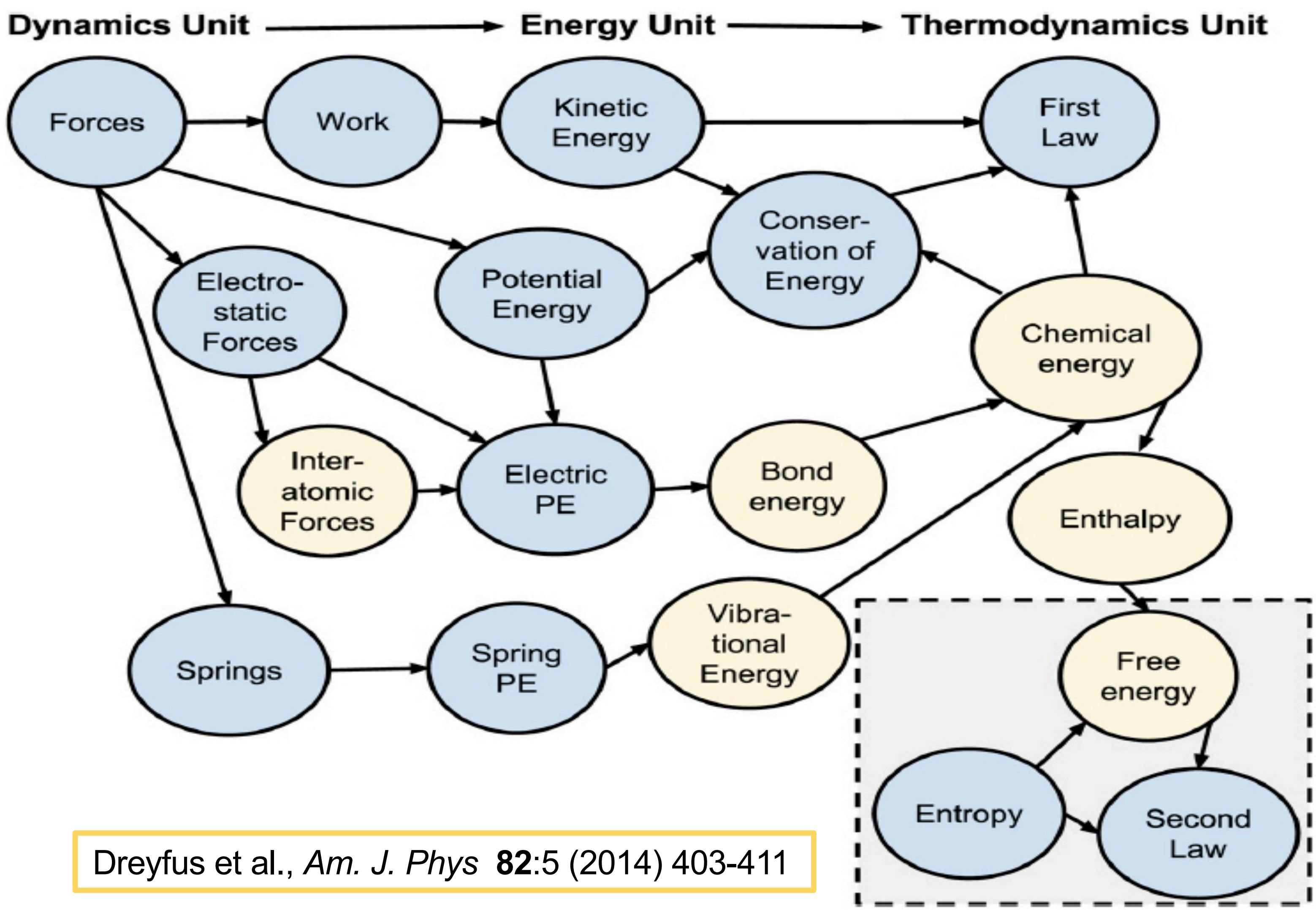


HW #2:
The light and dark reactions



Upon completing HW #2, many students spontaneously made a connection with a reaction-coordinate diagram!

The Chemical Energy Thread affects the entire course



Dreyfus et al., *Am. J. Phys* **82**:5 (2014) 403-411

Some student comments

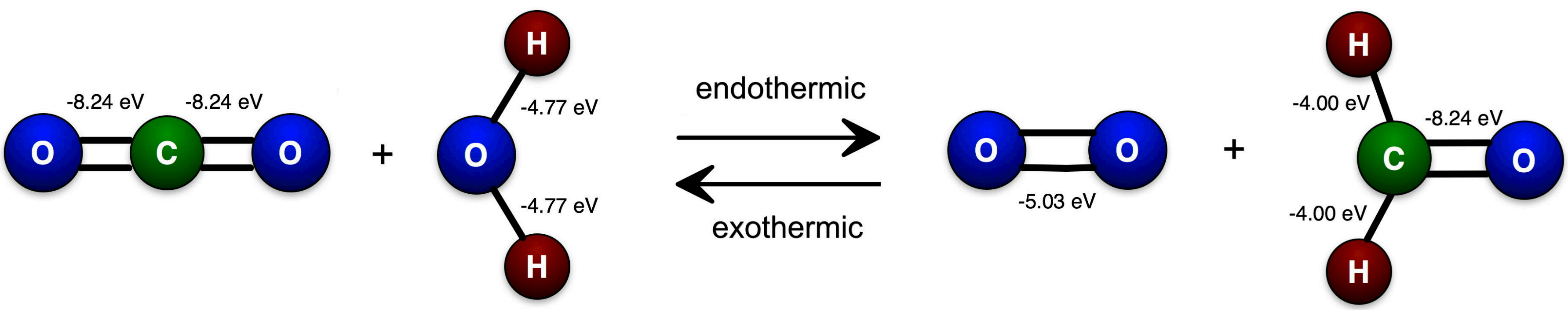
- “At first I was expecting the class to be like the biology calculus class that did not focus on any biology. But, as the semester progressed, I saw that the class was actually directed towards helping students to understand biological ideas using physics. “
- “…[biology professors] have to go over so much stuff that they don't really take the time to go over why things happen. And I'm a very why kind of person. I want to understand why does this happen? ...And you know [diffusion] was never explained to me very well, and then when I take this [physics] class and understand oh well this is why molecules interact the way they do.“
- “I now see that physics really is everywhere, and the principles of physics are used to govern how organisms are built and how they function.”

Take away message

- There are significant cultural differences between how a physics instructor frames an introductory physics class and how a life sciences major frames the same class, especially the role of mathematics and epistemology.
- Physics instructors are strongly tempted to treat these differences with a deficit theory that leads to more confusion and student resistance.
- Only by treating research into these issues as an interaction between two distinct cultures — the student's and the instructor's — can we make sense of what's going on.

+ A modest proposal: Bond energies vs binding energies

- Using binding energies (negative PE = - bond energy) matches easily with the stoichiometric equations.



$$CO_2 \quad + \quad H_2O \quad \Leftrightarrow \quad O_2 \quad + \quad H_2CO$$

$$(-16.48\ eV) \quad + \quad (-9.54\ eV) \quad \Leftrightarrow \quad (-5.03\ eV) \quad + (-16.24\ eV)$$

$$+ (4.75\ eV)$$

Questions for discussion

- In what ways could a detailed analysis of the resources used to sense-make help
  - in understanding what students need to do in order to learn a new concept; and
  - in unpacking what is hidden or tacit in our expert knowledge?
- Why do you use bond energies instead of binding energies? Doesn’t the latter match the stoichiometric equations better conceptually?

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References

- Chemical energy in an introductory physics course for the life sciences, B. W. Dreyfus, B. D. Geller, J. Gouvea, V. Sawtelle, C. Turpen, & E. F. Redish, *Am. J. Phys*., **82**:5 (2014) 403-411.

- Students' reasoning about high energy bonds and ATP: A vision of interdisciplinary education, B. W. Dreyfus, B. D. Geller, J. Gouvea, V. Sawtelle, C. Turpen, & E. F. Redish,*Phys. Rev. ST Physics Education Research* **10** (2014) 010115, 15 pages.

- Ontological metaphors for negative energy in an interdisciplinary context, B. W. Dreyfus, B. D. Geller, J. Gouvea, V. Sawtelle, C. Turpen, & E. F. Redish, *Phys. Rev. ST Physics Education Research* (2014) **10** (2014) 020108, 11 pp.

- Applying Conceptual Blending to Model Coordinated Use of Multiple Ontological Metaphors, B. W. Dreyfus, A. Gupta, and E. F. Redish, *Int. J. Sci. Ed.* **37**:5-6 (2015) 812-838. doi:10.1080/09500693.2015.1025306 (free access to preprint)

- Interdisciplinary reasoning about energy in an introductory physics course for the life sciences, B. Dreyfus, PhD dissertation, U. of Maryland, Dept. of Physics, 2014.