THE GEORGE WASHINGTON UNIVERSITY
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Can we talk?

The challenge of cross-disciplinary STEM instruction and communication

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Cornelius Bennhold (1960- 2009)

STEM Education: Who teaches whom?

- We care about our majors.
  (Of course! They are future us.)
  A lot of our instructional effort focuses on them.
- We not only teach our own majors.
  STEM supports STEM
- "Service courses" represent a large fraction
  of students being taught in many STEM departments.
  - Physicists teach engineers.
  - Chemists teach biologists.
  - Mathematicians teach us all.

In Physics, a growing fraction of our service students are from the life sciences

- Life science is the fastest growing STEM field.
- The total number of life science degrees granted is greater than the number of engineering degrees.*
- We have traditionally taught life science students as “other” – in our catchall class that included non-STEM majors.
- Many life science students tend to be ”turned off” by physics, are afraid of it, and some are explicitly hostile.

* National Science Board, Science and Engineering Indicators (2018).

This presents an interesting opportunity for research!

- Life science students tend to be happy with chemistry. Why do they reject physics?
- These students are going to be our doctors, nurses, and health-care givers. Shouldn't we do whatever we can to help them be better scientists?
- The life sciences have been growing spectacularly in the last few decades, becoming recognizably more scientific (to a physicist) and more technical.

Furthermore, biologists are clamoring for an upgrade

- Leading research biologists and medical professionals have increasingly been calling for a major reform of undergraduate instruction.
- They want more development of scientific skills and more multi-disciplinarity.

A personal trajectory

- My department first asked me to teach algebra-based physics with the pre-meds in 1975.
- In 1992 I turned my research efforts from Nuclear Theory to Physics Education Research.
- Between 2000 and 2009 I did extensive research on student learning in the algebra-based physics class with emphasis on scientific skill development.
- In 2006 I began a close interaction with a biologist and worked with him on adding active engagement to his class in biological diversity.

NEXUS/Physics

- In 2010, building on work that our work in algebra-based physics and biology, we were given a challenge grant from HHMI.
- Our charge was to reform the physics class for life science students as part of a national effort to increase their skill development and multi-disciplinary strengths. (National Experiment in Undergraduate Science Education – NEXUS).

E. F. Redish, et al. (17!) *Am. J. Phys.* **82**:5 (2014) 368-377. doi: 10.1119/1.4870386

Deep research

- We brought together a large team of physicists, biologists, chemists, curriculum developers, and education researchers.
- We spent a year discussing what physics could do as part of a biology program for biologists and pre-health care students.
- We spent two years teaching the class in small classes, videotaping everything in sight and learning as much as we could from listening to (and interviewing) the students.

We learned some things that surprised us

- There were serious issues of disciplinary culture and communication that we had not expected.
- Maybe we should have, since teaching is all about communicating, and I know the key to teaching is to learn to listen to students.
- But did I also have to *learn* to listen to my colleagues in biology, chemistry, and math? We're all scientists, after all.

Sense-making and meaning

- In teaching physics, I want my students to not only learn facts and procedures; I want them to make sense of the physics, — to understand what physics *means*.
- For life science population in particular, I want them to learn to make meaning with math.

The meaning of meaning

Communication and culture

How do we know what we mean?

- We communicate through language, but what matters is not just the words. We make meaning through associations to a rich set of knowledge that we bring from extensive experience.
- Language is both phrased and interpreted through the individual's social and physical knowledge and on their interpretation of their situation: ***culture and context***.

Culture: What we use to interpret context

- Culture is what we learn from experience that lets us make sense of context.
- Culture belongs to individuals and depends on experience with social groups and situations — family, peers, school, media, language.
- These factors strongly affect how we interpret and interact with the world and people around us.
- Individuals can have multiple cultures that they activate under different circumstances.

* Michael Agar, *Language Shock: Understanding the Culture of Conversation* (Perennial, 1994)

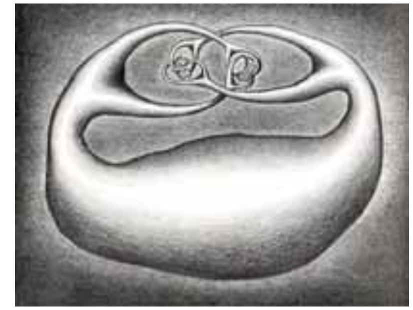
Communication successes and failures

- ***We understand others***
  through our common experience and humanity.
- ***We misunderstand others***
  when we are unaware of our cultural differences.
- When we communicate, we are always translating, inferring the speaker's meaning.
- But our associations and interpretations are cultural and depend on **our own** perception of the context.
- If others bring a different culture or interpretation of the context than we do, we can have serious confusion.

Two ways of looking at differences between you and someone else

1. Notice all the other things that the other person lacks when compared to you, the *deficit theory* approach.
2. Figure out that the differences are the tip of the iceberg, the signal that two different cultural systems are at work.

Rich points



- When we find an unexplained difficulty — a ***rich point*** — we need to understand it as two distinct cultures reaching for each other. We have to put our own culture and assumptions under scrutiny as well as the one we are observing.
- *"The rich points in a languaculture you encounter are relative to the one you brought with you.... If you hit a rich point, think you've solved it, and haven't changed [yourself], then you haven't got it right."* (Agar)

Rich point 1:

The biologists way of looking at math

An interview with a Bio student

- Context: Biology III: Organismal Biology
  - A principles-based class that re-structures the traditional "forced march through the phyla" of a biological diversity class.
- Some of the principles:
  - Common ancestry (deep molecular homology)
  - Individual evolved historical path (divergent structure-function relationships)
  - Biology is constrained by universal chemical and physical laws.
- Uses Group Active Engagement (GAE) lessons (including math!)

"Todd the biologist"

Ashley's response to the use of math in Org Bio

Discussing the use of Fick's Law in controlling diffusion through a membrane of different thicknesses.

$$\langle x^2 \rangle = 2Dt$$

I don't like to think of biology in terms of numbers and variables…. biology is supposed to be tangible, perceivable, and to put it in terms of letters and variables is just very unappealing to me…. Come time for the exam, obviously I'm going to look at those equations and figure them out and memorize them, but I just really don't like them.

I think of it as it would happen in real life. Like if you had a thick membrane and tried to put something through it, the thicker it is, obviously the slower it's going to go through. But if you want me to think of it as "this is *x* and that's *D* and this is *t*", I can't do it.

Another response of a student to math in Org Bio

The small wooden horse supported on dowels stands with no trouble. When all dimensions are doubled, however, the larger dowels break, unable to support the weight.

The same student!

The little one and the big one, I never actually fully understood why that was. I mean, I remember watching a Bill Nye episode about that, like they built a big model of an ant and it couldn't even stand. But, I mean, visually I knew that it doesn't work when you make little things big, but I never had anyone explain to me that there's a mathematical relationship between that, and that was really helpful to just my general understanding of the world. It was, like, mind-boggling.

Watkins & Elby, *CBE-LSE* **12** (2013) 274-286.

Biology students value authenticity

- Biology students valued math much more when it had implications for biological insights they personally viewed as valuable.
- Showing that "physics could be applied to biological organisms" was consistently treated as a "so what" if it did not offer biological insight.
- What about faculty?

J. Watkins, J. Coffey, E. Redish, & T. Cooke, *Phys Rev ST Phys Educ Res* **8** (2012) 010112.

Starting NEXUS/Physics for real

- For our first week of NEXUS/Physics,
  I asked Todd to provide me a problem on scaling (surface and volume effects) for a discussion of measurement and functional dependence.
- He came up with a great problem about worms.
  It looked like this:

A problem posed
by a biologist for a bio class

Dave Coverly: Speed Bump (with permission)

A typical earthworm has the following dimensions:
weight = 3.7 g, length = 12 cm, width = 0.64 cm.
Oxygen consumption of the body = 0.98 µmole O_2/g
Oxygen absorption across the skin = 2.4 nmole O_2/mm^2.

Model the shape of the worm as a solid cylinder. For the worm above, calculate its surface area (ignore the blunt ends), volume, and density.

Worms absorb oxygen through their skin, so proportional to their area, but almost all of the cells in their body use oxygen in respiration, proportional to their volume. Assuming the rates above, show whether or not the typical worm can absorb sufficient oxygen to maintain the respiratory rate of its entire body.

Organisms can grow in two ways: by increasing its length, keeping other dimensions the same, or isometrically -- by increasing all of its dimensions by the same factor. Calculate whether a worm that doubles a length can survive and whether a worm that doubles isometrically can survive.

Added by a physicist for a physics class

Consider a general cylindrical organism of density *d*, length *L*, and radius *R*. If the rate of oxygen absorption through the skin is *A*, and the rate it uses oxygen in the volume is *B*, write a symbolic expression for the total rate of oxygen used by the worm. Find the maximum radius the worm could be before it would have a problem taking in enough oxygen.

Dave Coverly: Speed Bump (with permission)

Rate oxygen is absorbed = $AS = A(2\pi RL)$

Rate oxygen is used = $BdV = B\ d\ \pi R^2 L$

Condition for survival: $AS > BdV$

$$2\pi RLA > \pi R^2 LBd \quad \Rightarrow \quad \frac{2A}{Bd} > R$$

The reaction of the development team to my suggested changes surprised me.

- The physicists around the table to a person, responded, “Oooh! Neat!”
- The biologists around the table reacted differently.
- They said, “Yuck! You’ve removed the biology! That’s not the way worms grow. The radius never grows by itself.”

The compromise: Add this

- Our analysis was a modeling analysis. An earthworm might grow in two ways: by just getting longer or by scaling up in all dimensions. What can you say about the growth of a worm by these two methods?
- In typical analyses of evolution and phylogenetic histories, earthworm-like organisms are the ancestors of much larger organisms than the limit here permits. What sort of variations in the structure of a worm-like ancestor might lead to an organism that solves the problem of growing isometrically larger than the limit provided by the simple model?

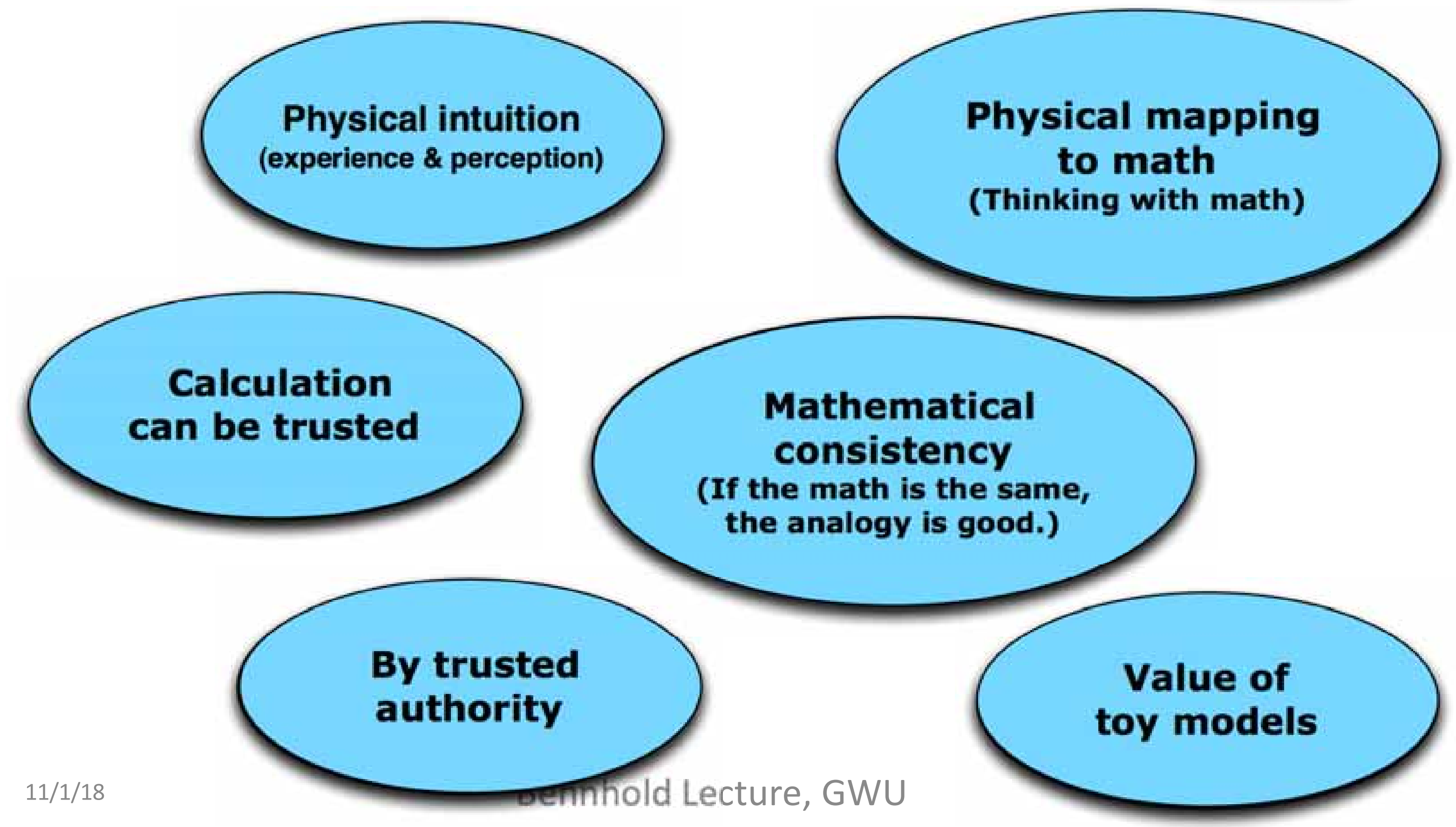
Understanding biologists – and ourselves as physicists as well

- Biologists, both students and faculty, value real world examples. Numbers make the connection between math and reality.
- Physicists, on the other hand, value abstractions, simplifications, and universal mathematical principles.
- We analyzed the differences we saw as ***epistemological resources*** (ways of knowing).

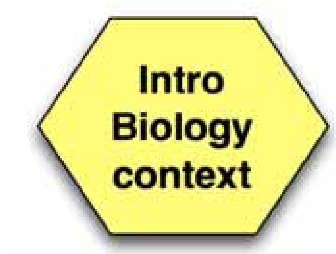
E. F. Redish and T. J. Cooke, *CBE-LSR*, 12 (June 3, 2013) 175-186. *doi:10.1187/cbe.12-09-0147*.

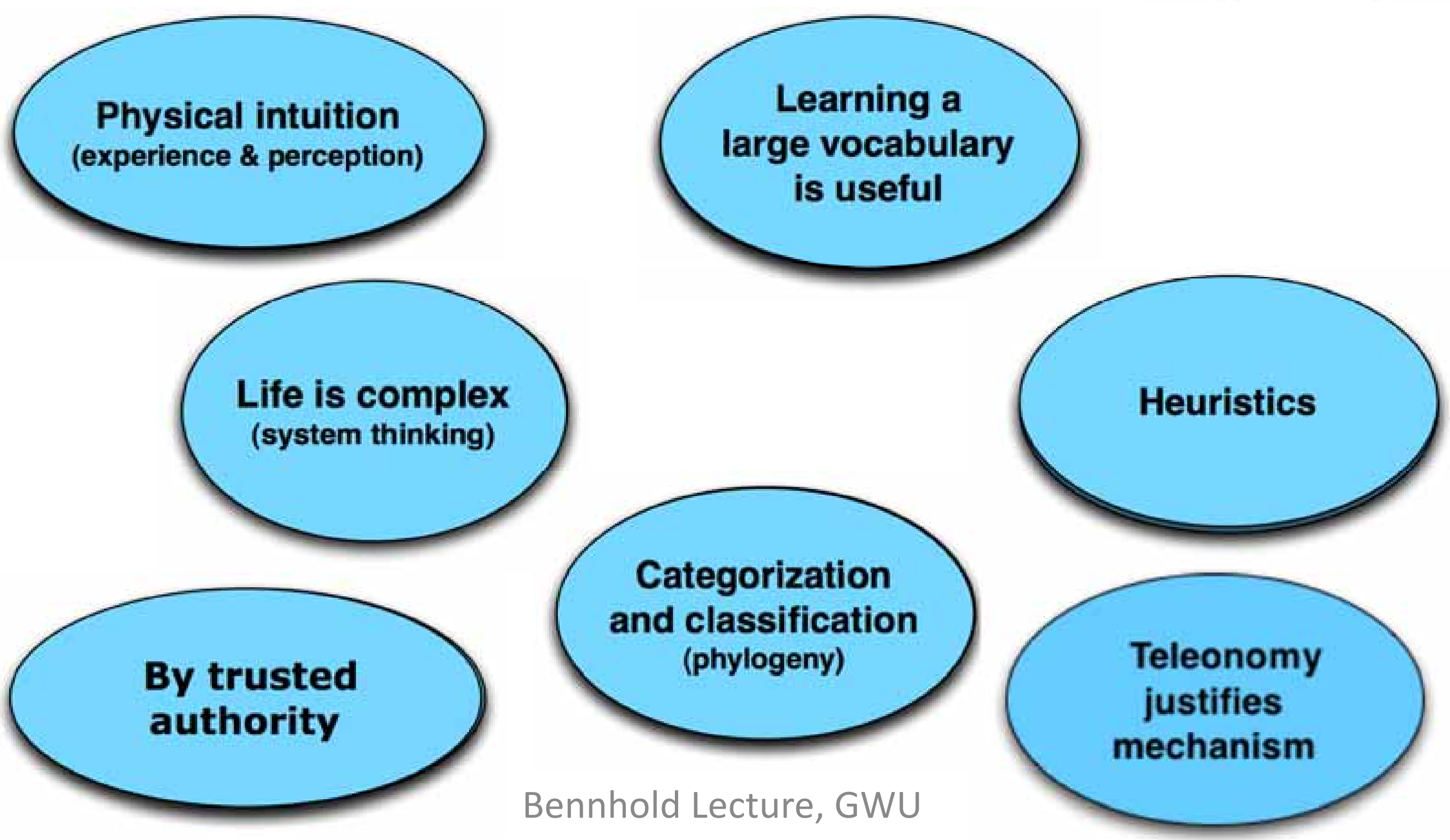
Epistemological resources (Discipline of physics)

Intro Physics context



Epistemological resources (Discipline of biology)





How biologists see physicists

Randall Munroe: xkcd

How physicists see biologists

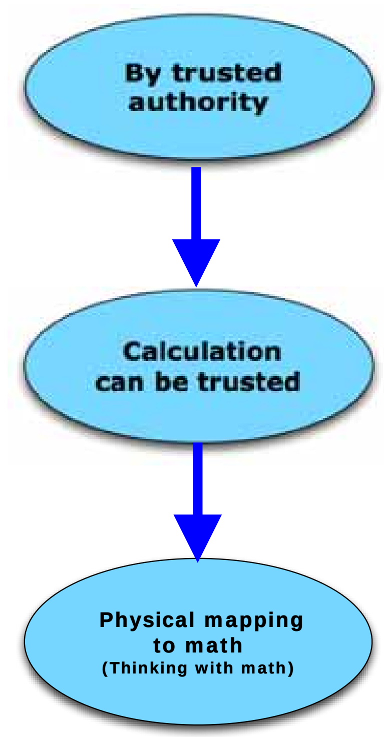
- A biophysicist friend was working with a group of biologists to study single molecular interactions of important reactions that occur in cells.
- The physicist wanted to do the experiment on clean glass in a vacuum.
- He said the biologists wanted to do the experiment "inside a dog."

One cross-disciplinary failure of teaching physics to biologists: The "go-to" e-resource

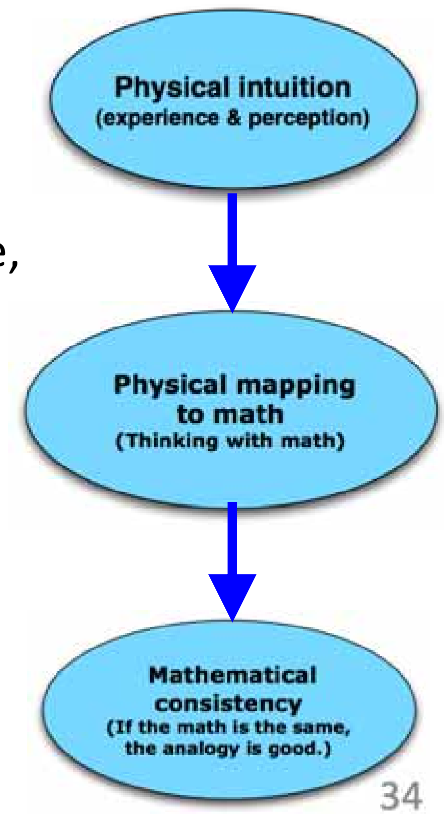
- The ***epistemological stances*** naturally taken by <u>physics instructors</u> and <u>biology students</u> may be dramatically different – even in the context of a physics class.

A conflict between the epistemological stances of instructor and student make things more difficult.

Physics instructors seem more comfortable beginning with familiar equations – which we use not only to calculate with, but to code and remind us of conceptual knowledge.



Most biology students lack the experience of blending math and conceptual knowledge, so they are more comfortable beginning with physical intuitions.



Instructional implication

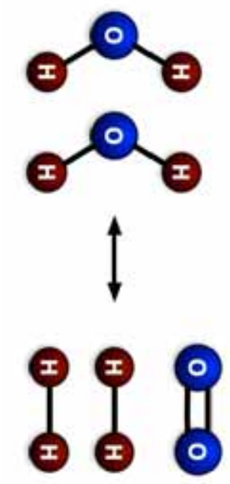
- It may be better for a physics teacher to "teach physics standing on your head", running the epistemological chain backwards from the way that feels most natural to us.
- (And maybe this is even true for our own novice majors.)

Rich point 2:

The source of chemical energy

The energetics of chemical bonding – Interdisciplinary reconciliation

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

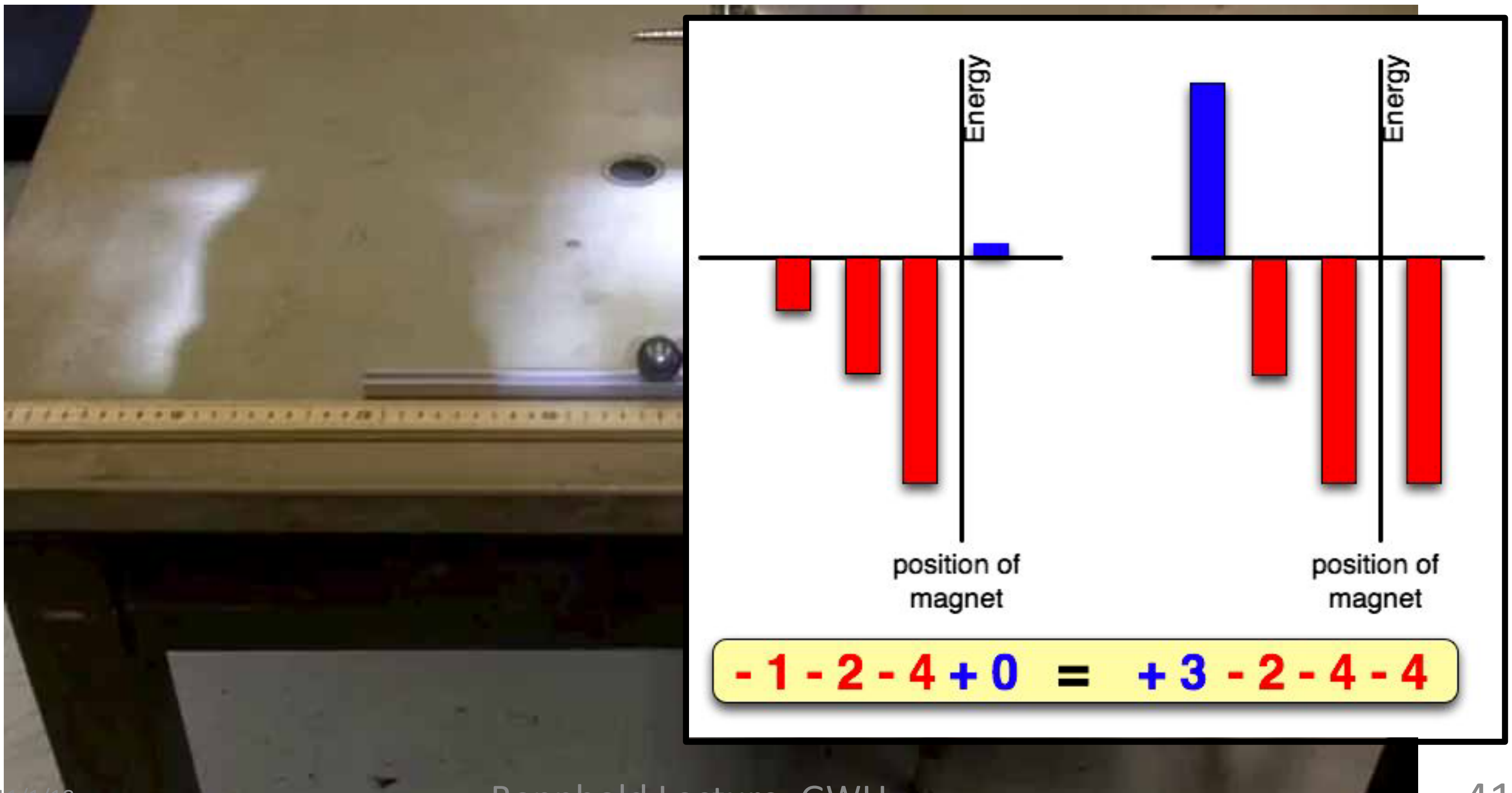
"But like the way that I was thinking of it, I don't know why,
but whenever chemistry taught us like exothermic, endothermic,
like what she said, I always imagined
like the breaking of the bonds
has like these little [energy]
molecules that float out,
but like I know it’s wrong.
But that's just how
I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

Watch it on you tube at (or check out any other version – many are available
https://www.youtube.com/watch?v=fiSd91sLtS4

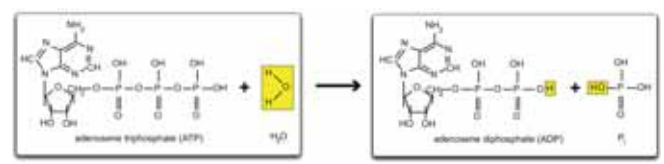
Here’s how it works:
The energy comes from potential energy!



Distinct disciplinary perspectives

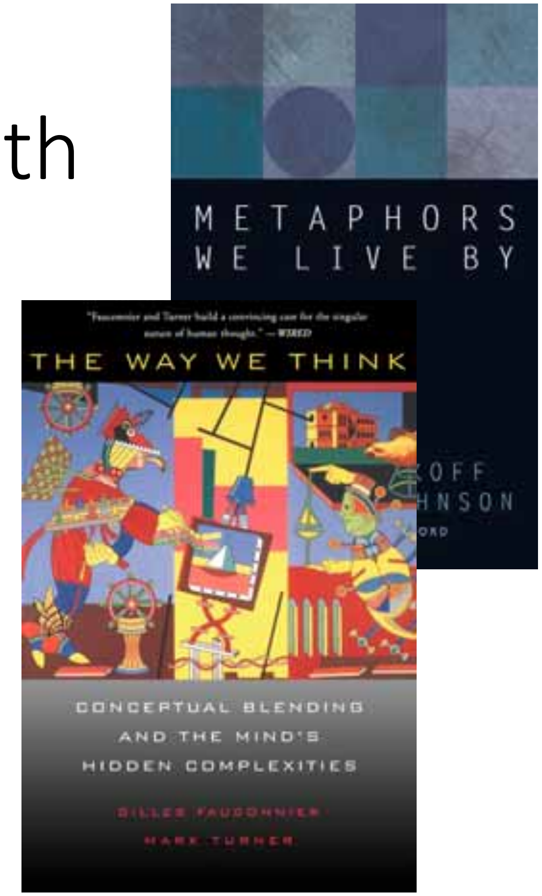
- Physicists and biologists (and chemists) make different tacit assumptions.
- Physicists tend to isolate a system to focus on a particular physical phenomenon and mechanism.
- Biologists (and chemists) tend to assume the natural and universal context of life – a fluid environment (air and water taken for granted).

Sources of energy in biological systems: Glucose and ATP



- 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.

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



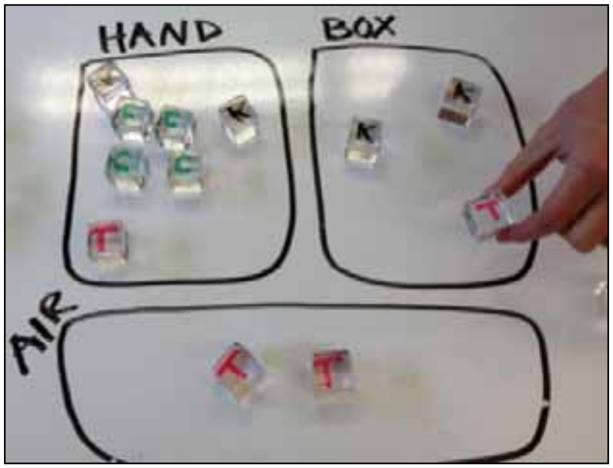
G. Lakoff and M. Johnson, *Metaphors We Live By* (U, if Chicago, 1980/2003)
G. Fauconnier and M. Turner, *The Way We Think* (Basic Books, 2003)

Building up abstract concepts

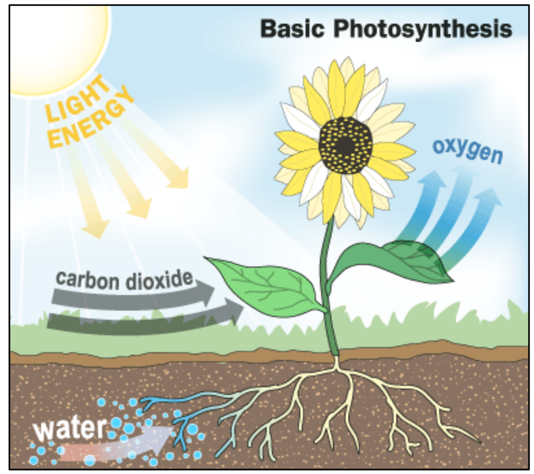
- According to L&J and F&T, we build up abstract and complex concepts by beginning with concrete knowledge gained from direct experience, and using metaphors that gain meanings of their own to create new mental models.
- We then blend different mental models to create even more complex ideas.
- Often,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

Ontological metaphors for energy: 1

Energy as a substance



Scherr et al. 2012



science.howstuffworks.com

Energy is **in** objects

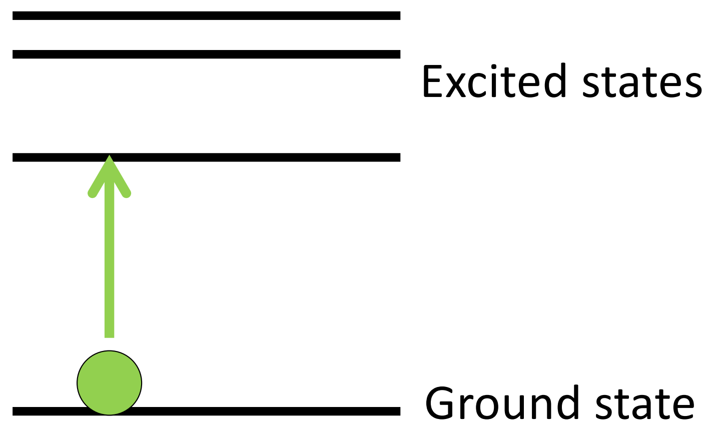
Objects **have** energy

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

Ontological metaphors for energy: 2

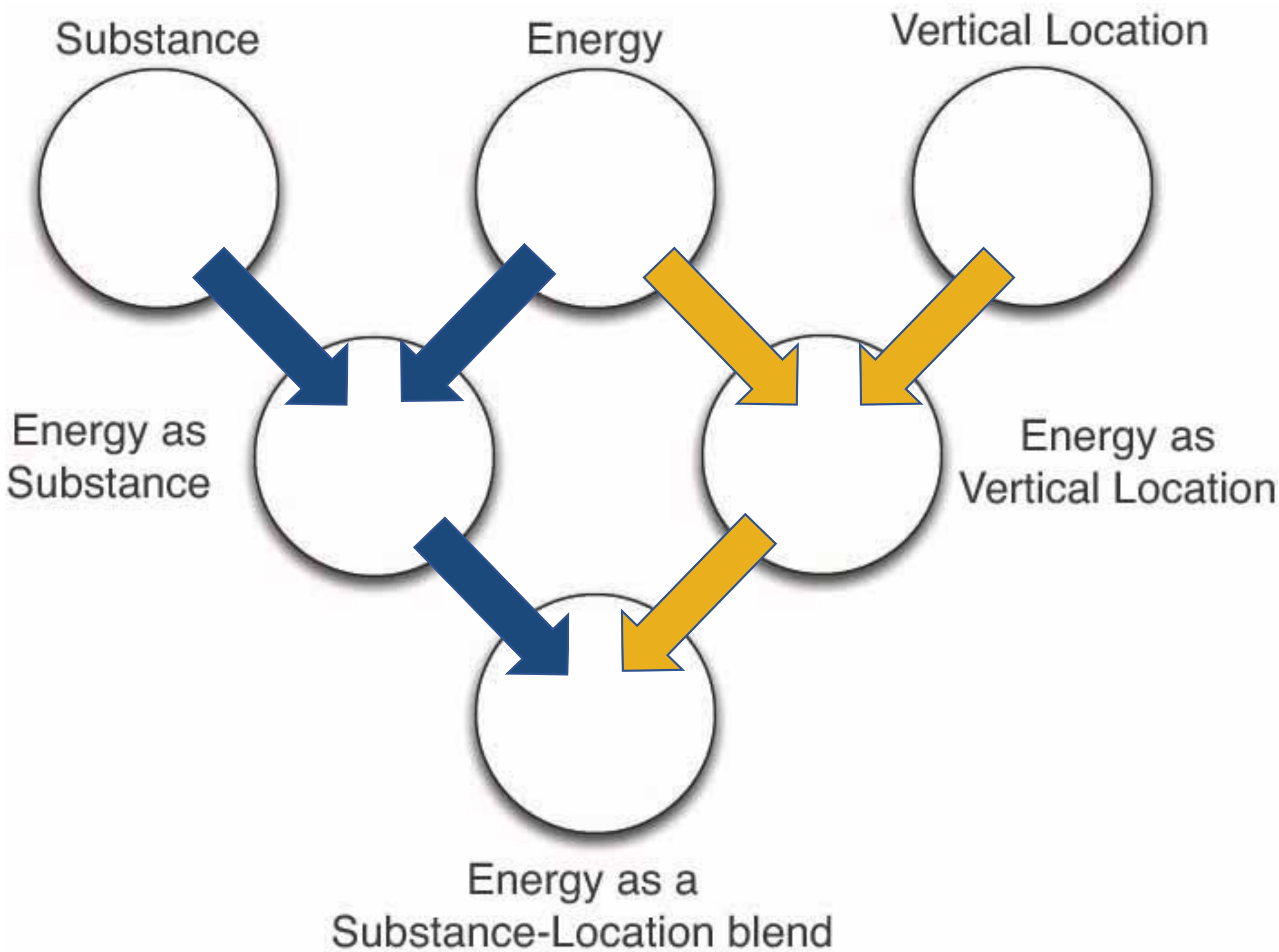
Energy as a vertical location

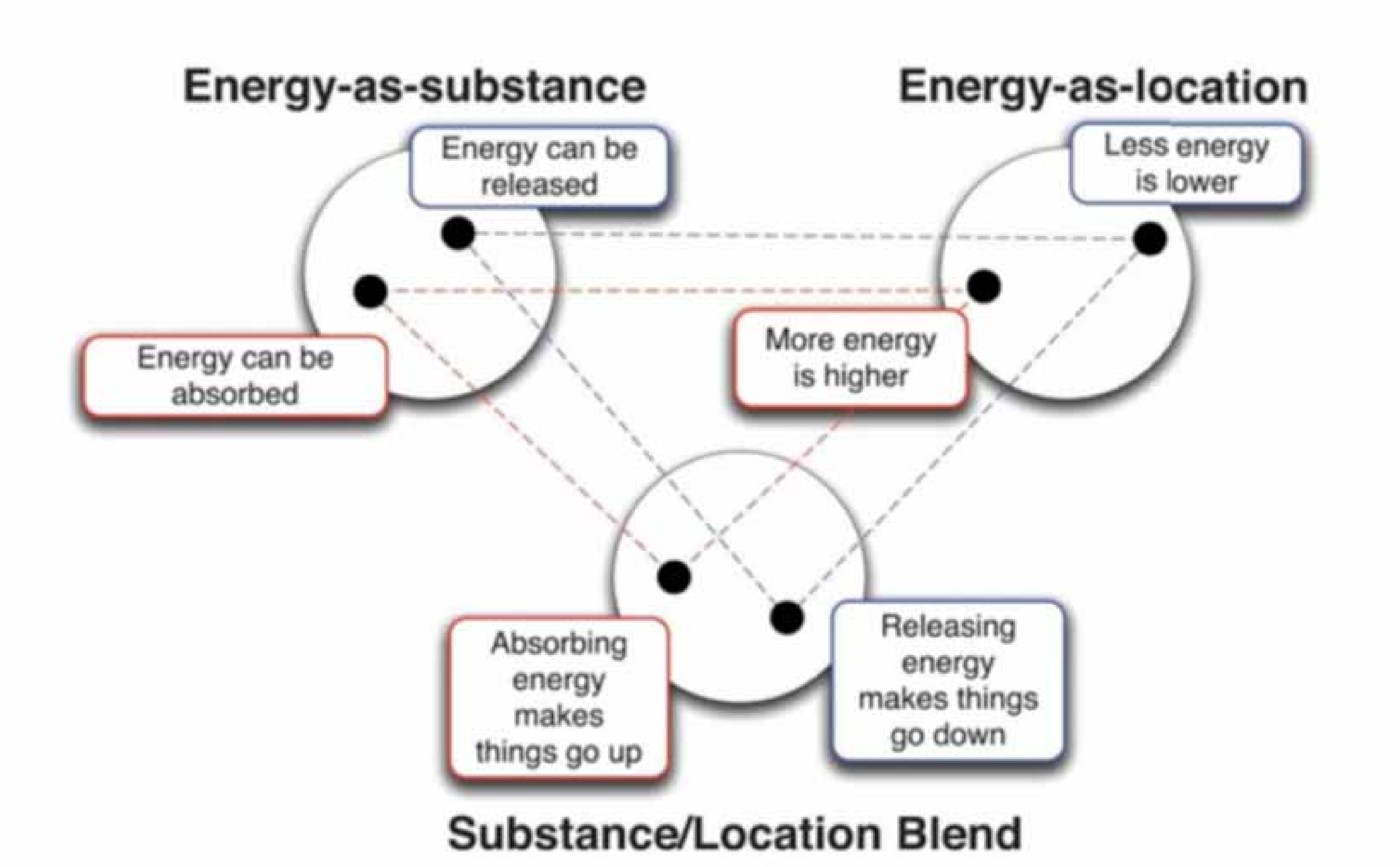
phet.colorado.edu



Objects are **at** energies

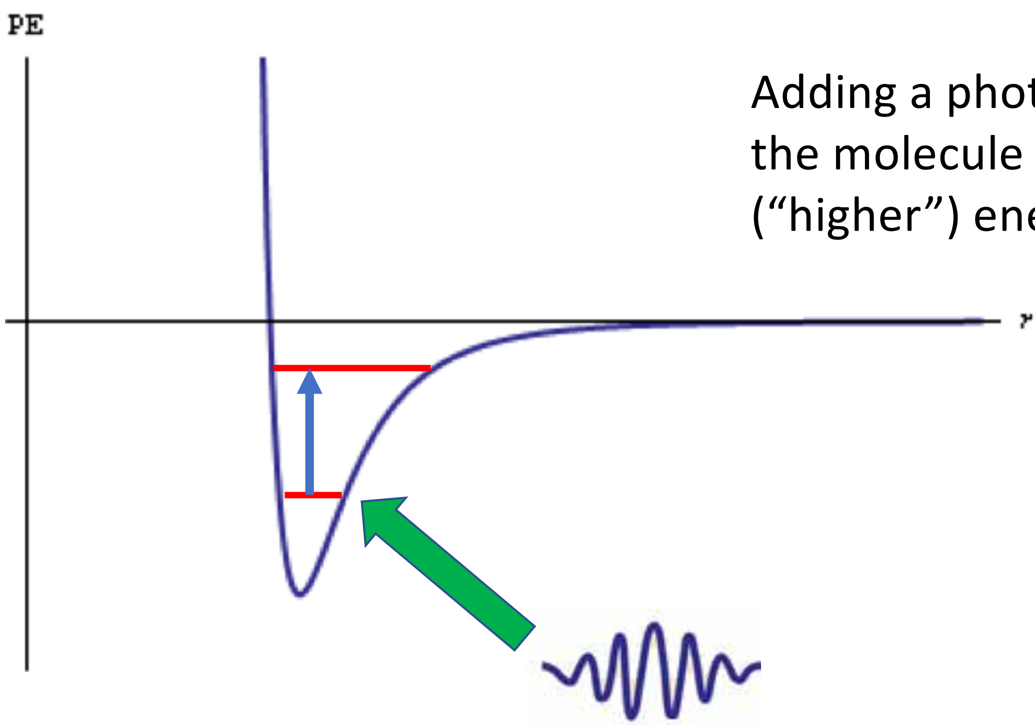
Objects **go** to **higher/lower** energy


Substance
Energy
Vertical Location
Energy as
Substance
Energy as
Vertical Location
Energy as a
Substance-Location blend



Energy-as-substance
Energy-as-location
Energy can be released
Less energy is lower
Energy can be absorbed
More energy is higher
Absorbing energy makes things go up
Releasing energy makes things go down
Substance/Location Blend

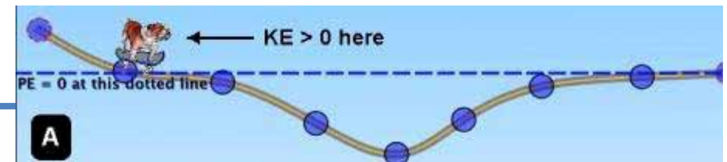
Experts blend these metaphors seamlessly, building a new, more complex description.

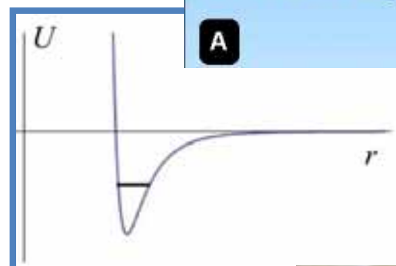


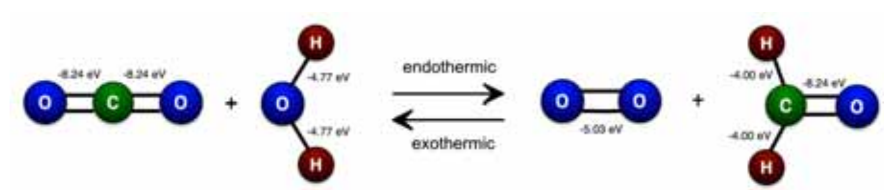
Adding a photon (”stuff”), excites the molecule to an excited (“higher”) energy state.

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

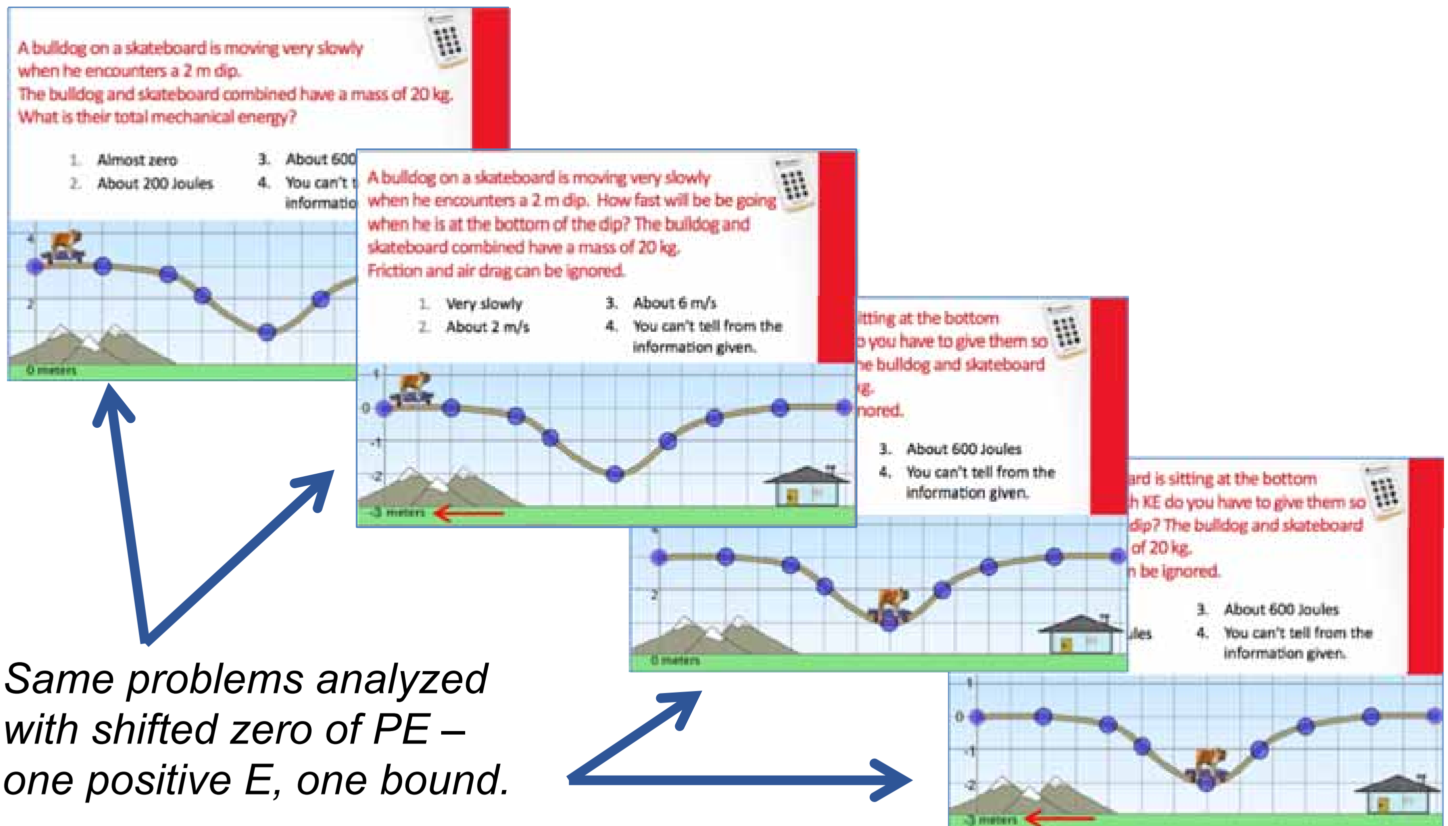
- Build a coherent story using toy models
  - Bulldog on a skateboard
  - Atomic interactions and binding
  - Reactions in which bonds are first broken and then stronger ones formed (the Gauss gun)
  - Biological examples that give authentic insights (photosynthesis).







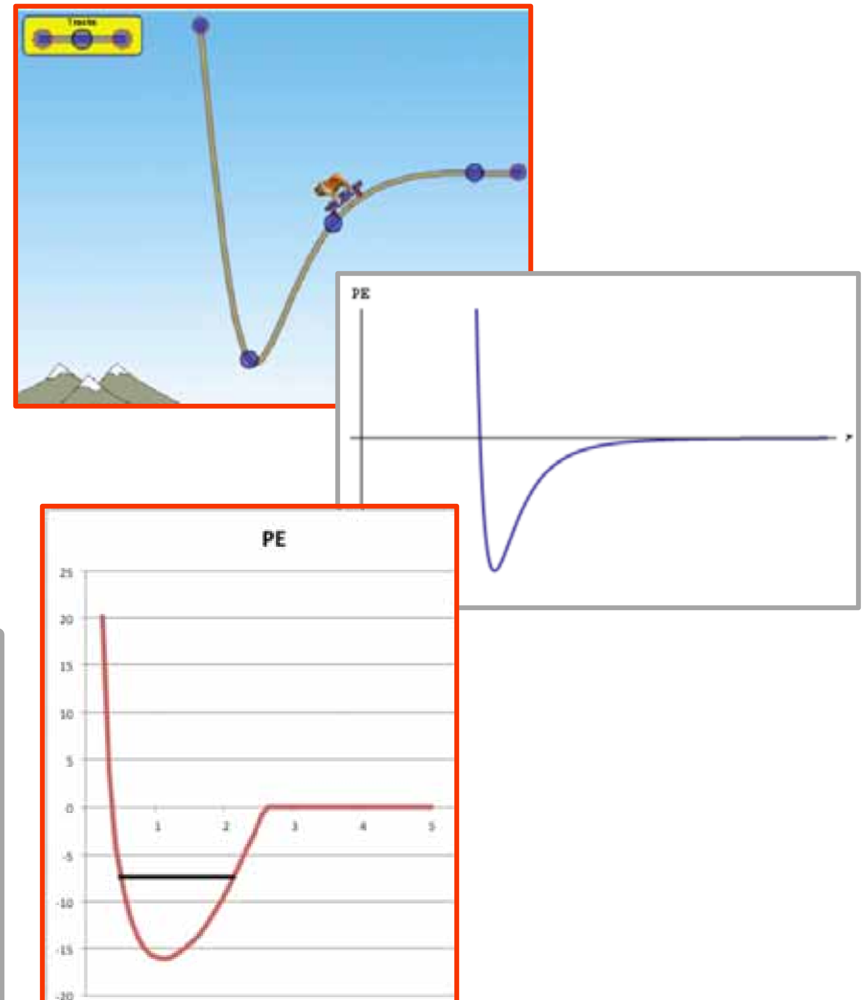
A series of clicker questions (PhET based) helps students get comfortable with negative PE and with the concept of binding energy.



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

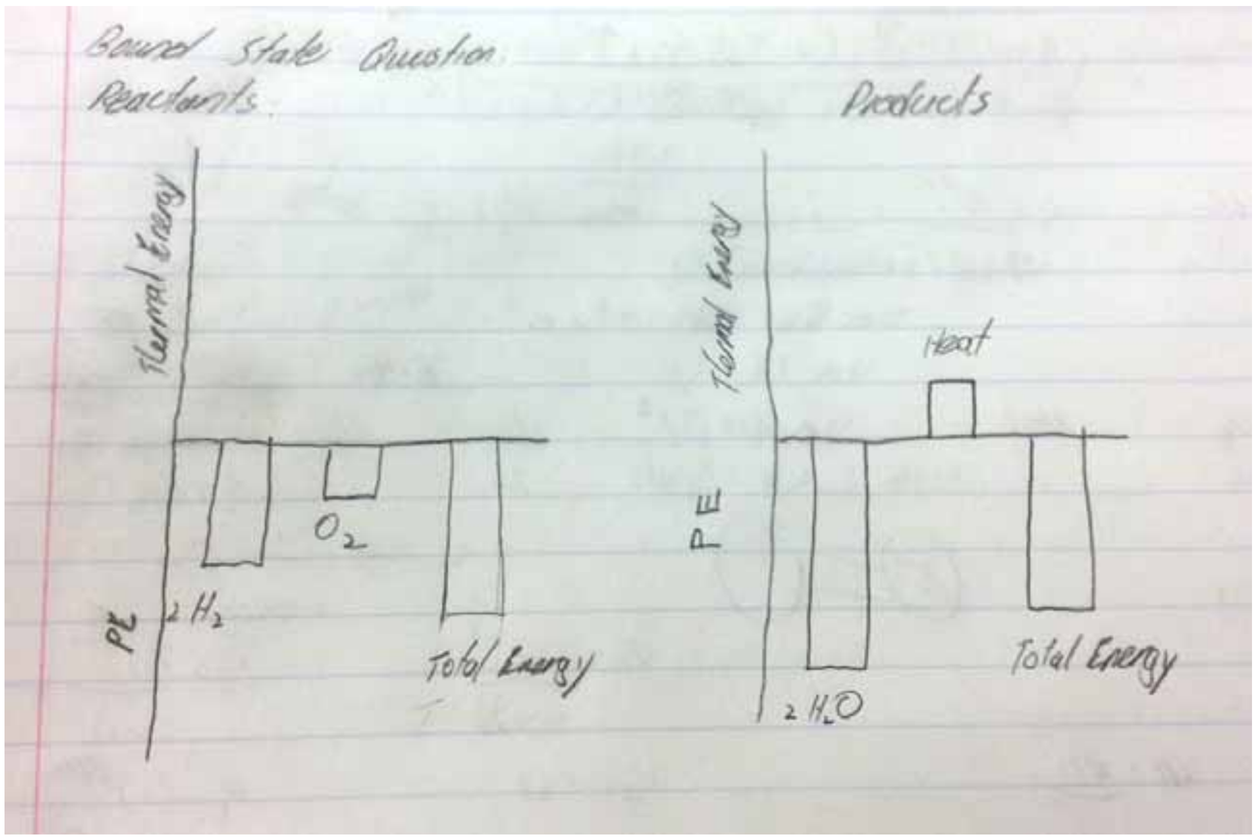
Bound states HW problem

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

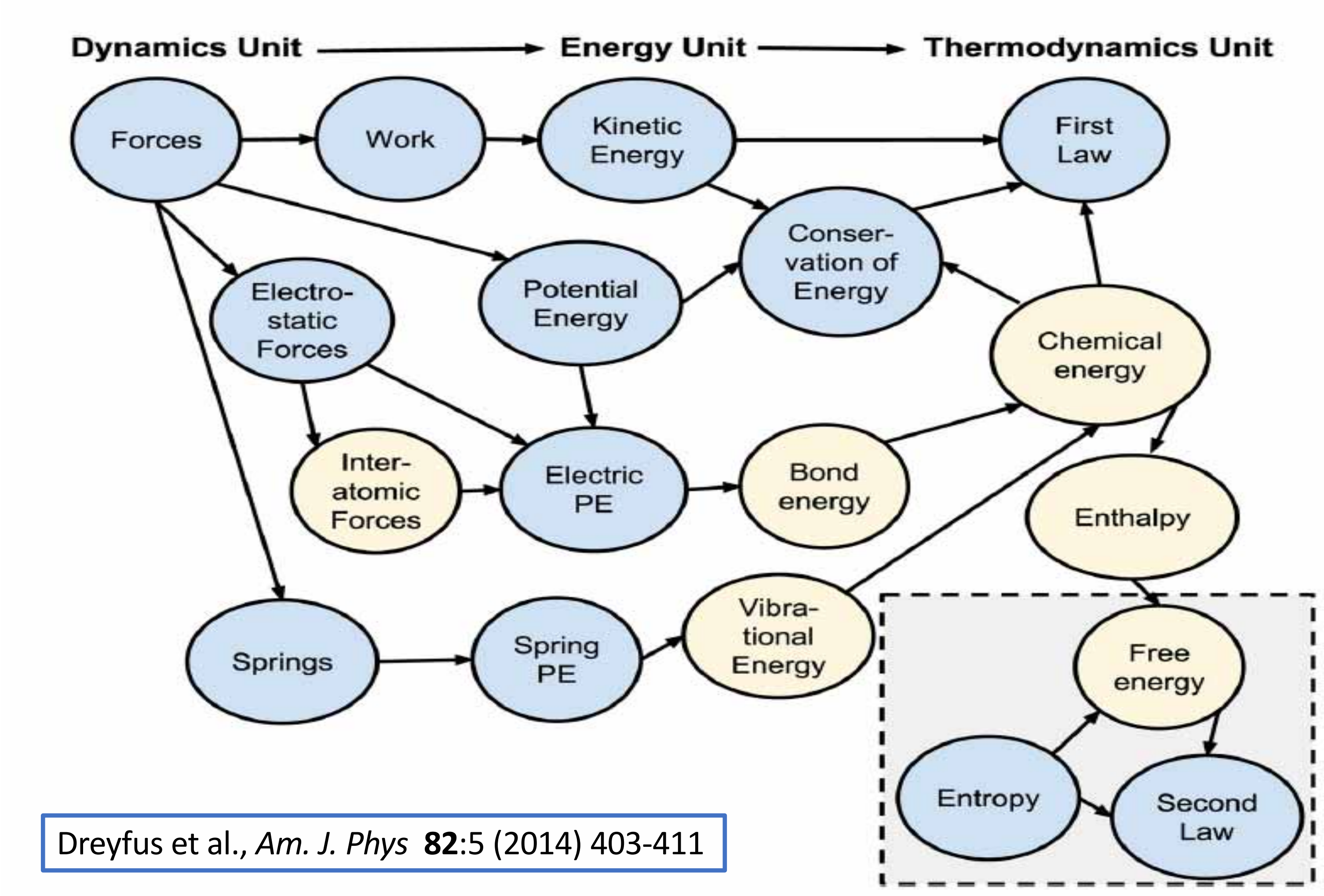


If the atoms have an energy of -7.5 units as shown by the solid line in the figure, would you have to put in energy to separate the atoms or by separating them would you gain energy? How much? Explain why you think so.

Student drawing from a HW on the reaction $H_2 + O_2 \rightarrow 2H_2O$



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.

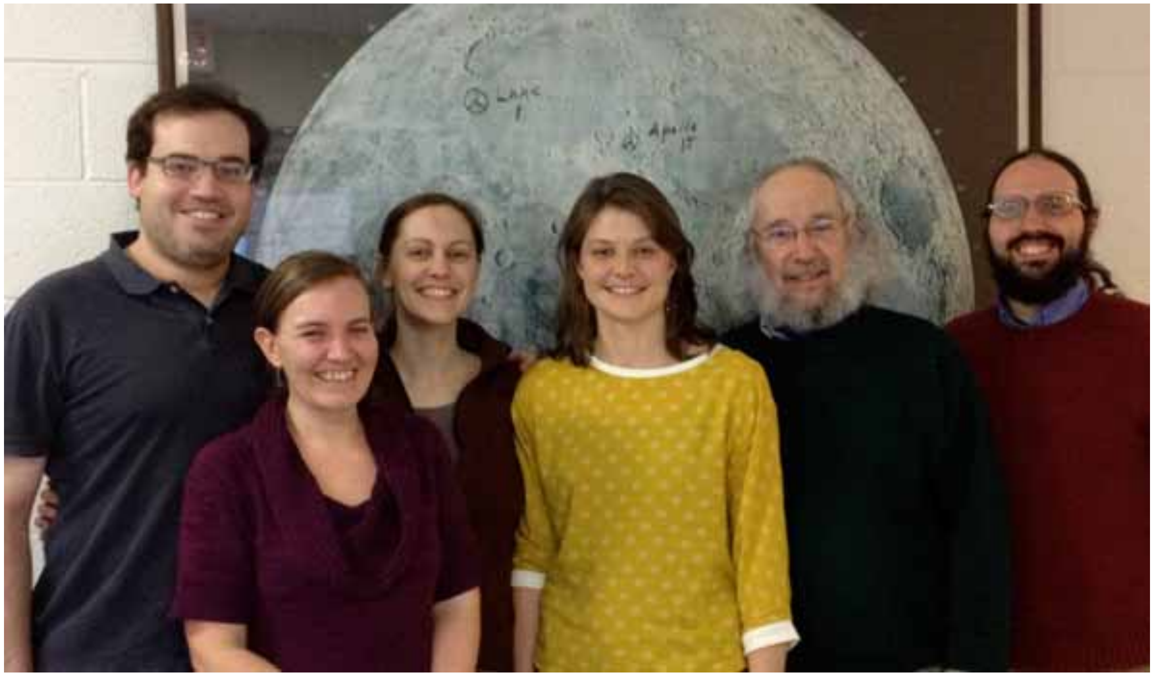
Multi-disciplinary vs inter-disciplinary

- We encountered many rich points in our exploration of the interaction between the cultures of physics and biology.
- We not only learned to respect biology as a scientific discipline with a scientific culture distinct from the culture of physics — we learned a lot about how we as physicists do physics that we had not previously understood!

The NEXUS/Physics "Gang of 5"

Left to right:

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



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- Ben Geller*
- Kimberly Moore*
- John Gianini* **
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- Karen Carleton
- Joelle Presson
- Kaci Thompson

Education (Bio)

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  - Michael Fisher
  - Alex Morozov**
  - Peter Shawhan
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  - Jeff Jensen
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  - Dawn Meredith (U. New Hampshire)
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- **Biologists**
  - Mike Klymkowsky (U. Colorado)
- **Chemists**
  - Chris Bauer (U. New Hampshire)
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- **Education**
  - Janet Coffey (Moore Foundation)
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