

# Course and curricular design and educational engineering

@ ETH May 2019

**Mike Klymkowsky**

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# Acknowledging collaborators

- Kathy Garvin-Doxas and Ed Svirsky: Eds Tools and the BCI
- Valerie Otero, Julie Andrews, Jeff Winters - CU Teach
- Bilge Birsoy - CRIPSR CURE course
- Ernst Hafen, Katje Kohler and Annie Champagne-Queloz - ETH, Zurich

Melanie Cooper & her group  
(Clemson &  
Michigan State University)



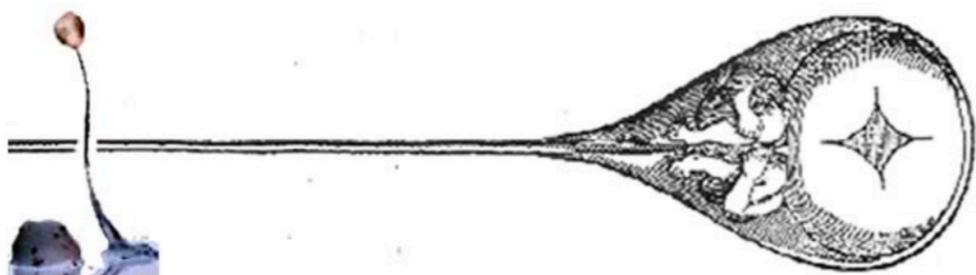
people I need to thank

## I will consider:

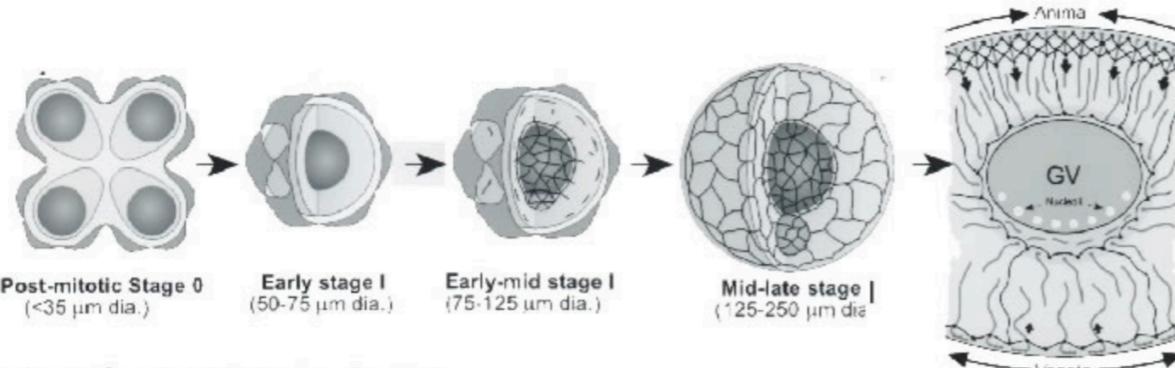
- How do we approach the redesign of course materials to enhance student engagement and educational effectiveness
- consider whether ...
  - is what you teach is what students need?
  - do you explain why what is taught is important?
  - do you emphasize recurrent themes?
  - do your exams reveal what you think students should be able to do?

# An example (in progress): Developmental Biology

On teaching developmental biology in the 21st century (a devo-biofundamentals perspective)

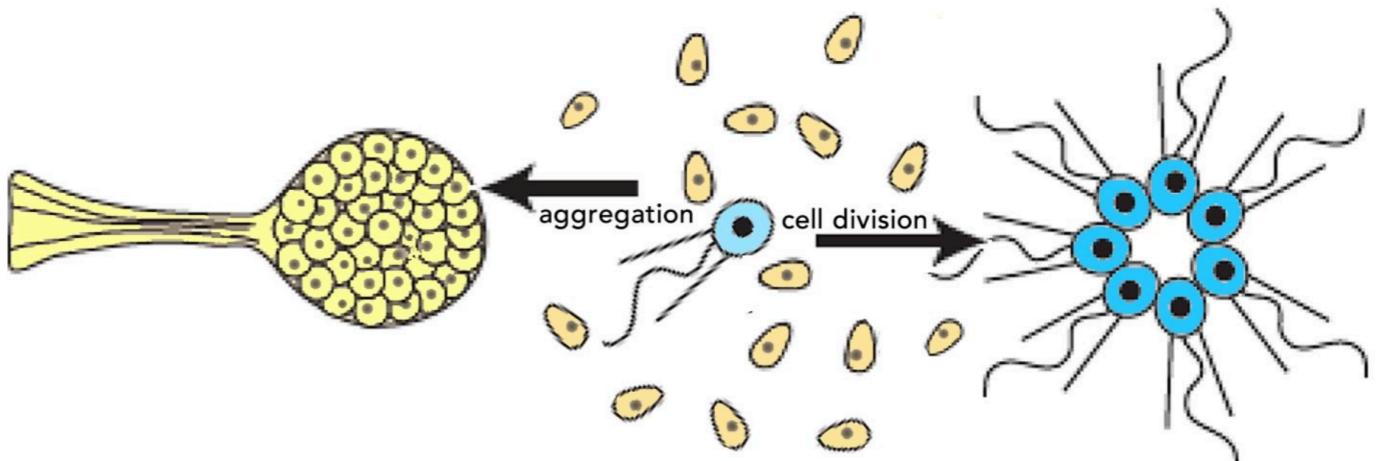


Establishing Cellular Asymmetries (a devo-biofundamentals perspective)

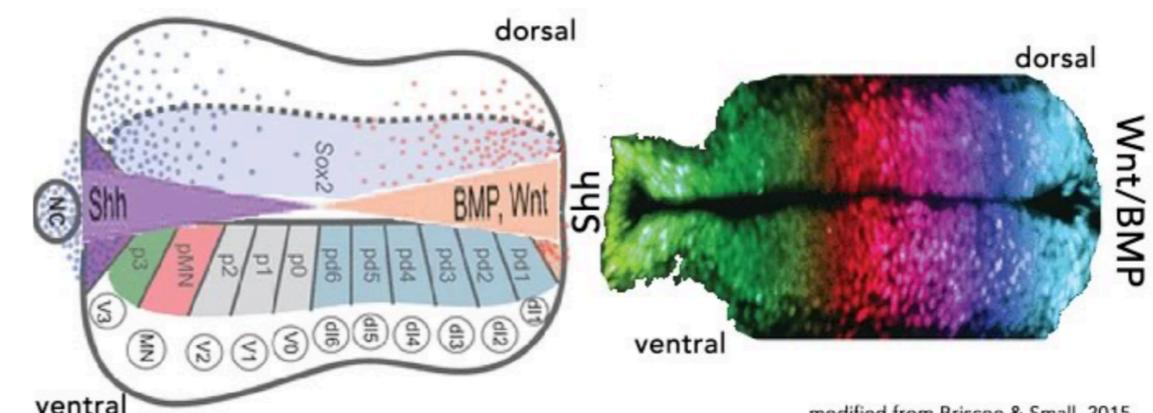


adapted from Gard & Klymkowsky, 1998

Aggregative and clonal metazoans (a biofundamentals perspective)



Gradients and Molecular Switches (a biofundamentalist perspective)



modified from Briscoe & Small, 2015

# Where to start?

- Understand what students know and think
  - concept tests (BCI)

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File Edit

Dialog

▼ 12 ▼ B U I

Genetic drift is basically a change in allele and genotype frequencies. Two of the ways this can be experienced are the Founder Effect and the Bottleneck Effect. The Founder Effect is when a few members of a population become separated and form a new colony. The Bottleneck Effect is when, usually a natural disaster occurs, and only a few members with similar genes survive. The processes can produce both traits that are adaptive and not adaptive. It just depends on the situation.

	What causes changes	del
	changed (e.g., frequency of alleles)	del
	Results of change	del
		del
	Not adaptive	del
	Adaptive	del
	Mutation and evolutionary change	del
	Traits and survival	del
	Genetic drift	del
	Founder effects	del
	Bottlenecks	del
		del
	un-highlight	
	<	>

## Current Question :

Random events such as genetic drift, founder effects, and bottlenecks can influence evolutionary change in a population. [G]  
How does this work, and can these processes produce traits that are not adaptive? [S]

## Caret Status

Viewing concepts for garvindo  
question: 21 answer: 9 word\_length: 82

## What makes DNA a good place to store information?

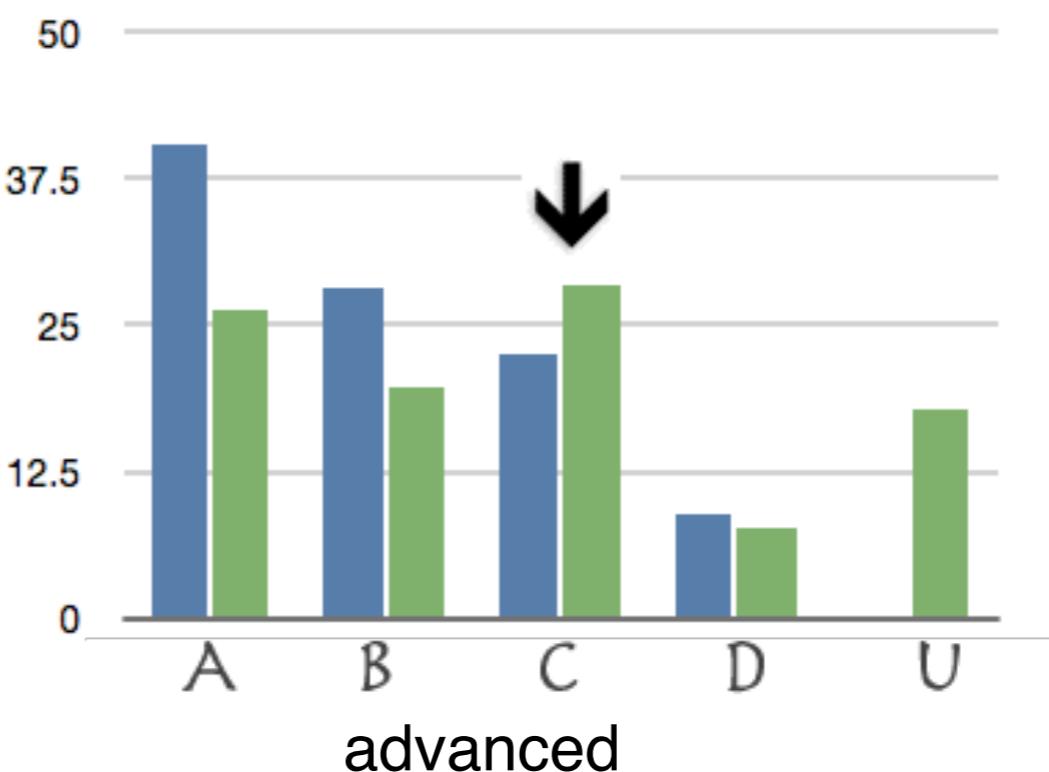
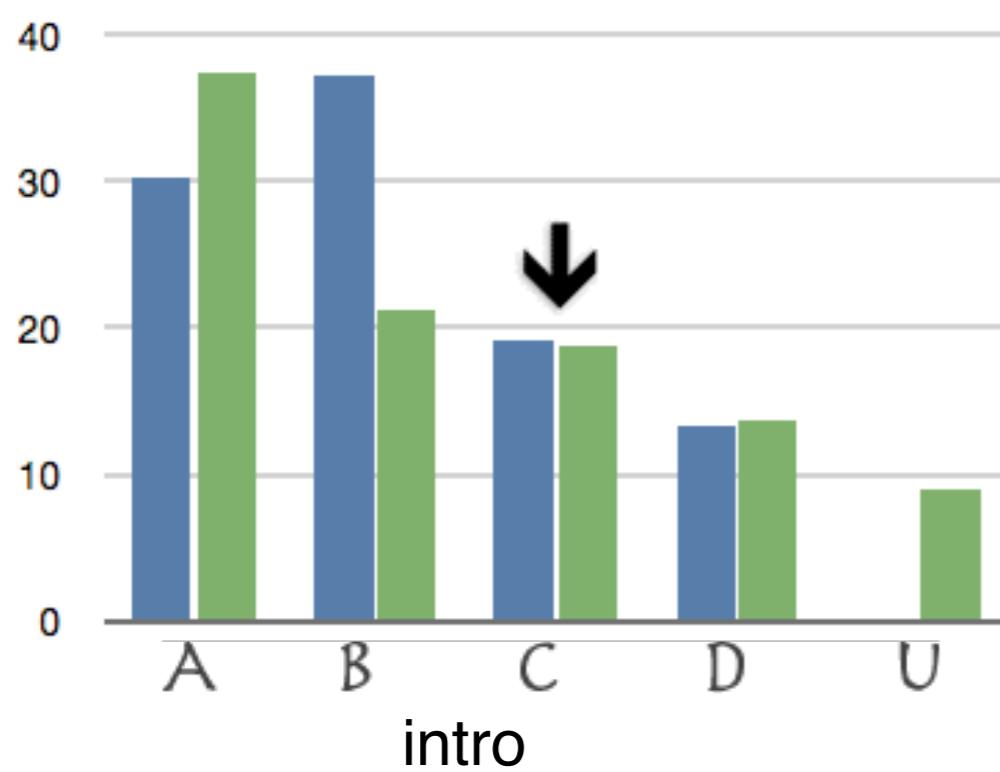
The hydrogen bonds that hold it together are very stable and difficult to break.

The bases always bind to their correct partner.

The sequence of bases does not greatly influence the structure of the molecule.

The overall shape of the molecule reflects the information stored in it.

- teachers 29%



"... Rebello & Zollman (2004) examined students' open-ended responses to FCI questions, their analyses revealed aspects of student thinking not found in the original FCI distractors. **Based on student responses, these authors generated new distractors to replace the original ones**, resulting in a **decrease in the frequency of correct answers**, suggesting that the original FCI distractors did not fully capture aspects of students' thinking.

Lessons to be taken from their observations:

1. it is difficult for instructors to predict what students are thinking
2. different groups of students may hold different ideas
3. concept test are of limited use as measures of learning
4. but can be useful for identifying concepts not taught effectively

- Klymkowsky & Garvin-Doxas (2020), Concept Tests, submitted.



**BeSocratic** : revealing student thinking

**A Short History of the Use of Technology  
To Model and Analyze Student Data  
for Teaching and Research**

Melanie M. Cooper,<sup>\*1</sup> Sonia M. Underwood,<sup>1</sup>  
Sam P. Bryfczynski,<sup>1</sup> and Michael W. Klymkowsky<sup>2</sup>

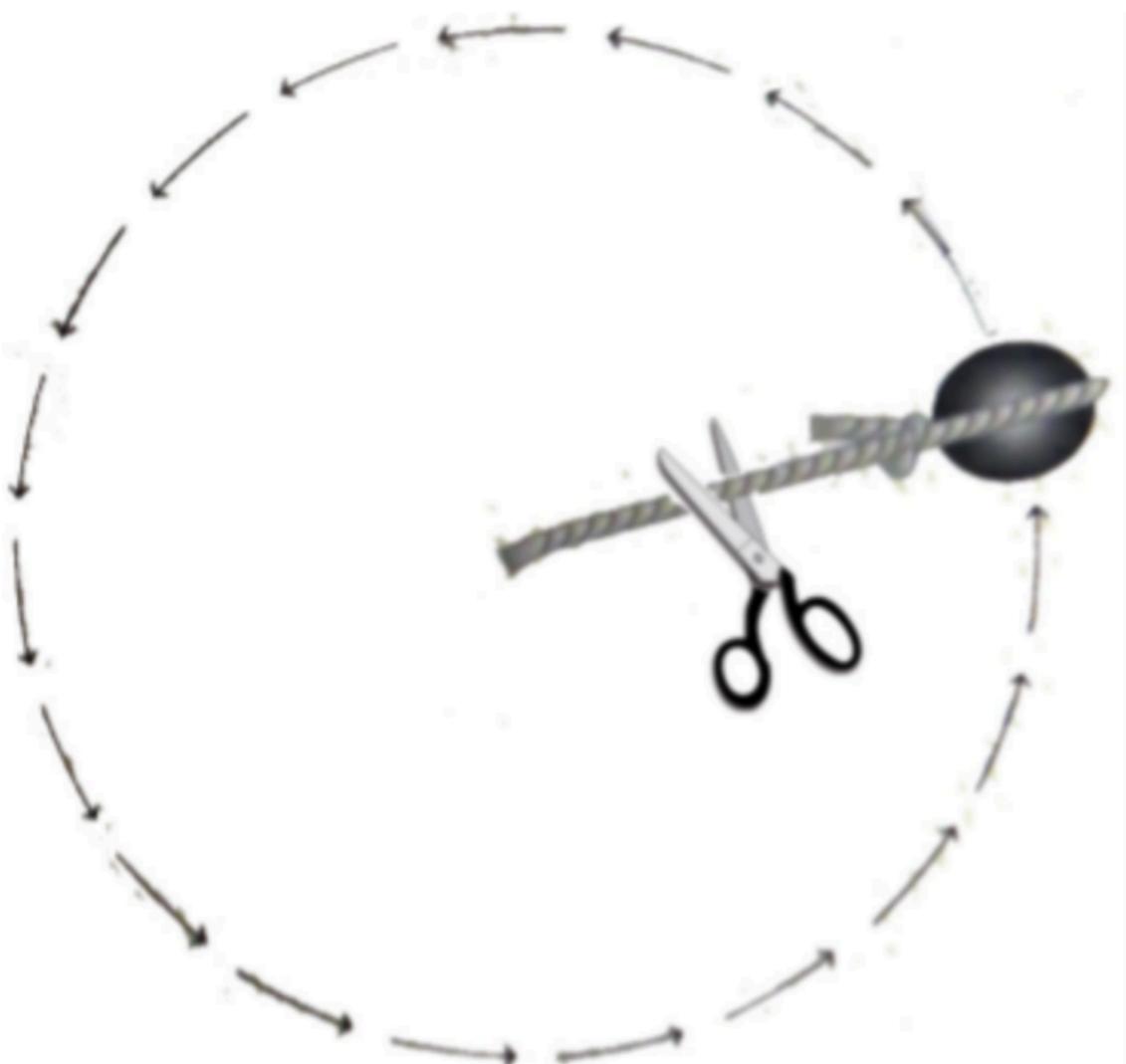
**Sketching the Invisible to Predict the Visible: From  
Drawing to Modeling in Chemistry**

Melanie M. Cooper,<sup>a</sup> Mike Stieff,<sup>b</sup> Dane DeSutter<sup>c</sup>

revealing student thinking

The diagram shows a rock attached by a rope to a person (at the center) who is spinning it around their head. Draw how you think the the rock will move if the person lets go of the rope

What ideas did you use in your answer?



Draw

Erase ▾

Reset

The diagram shows a rock attached by a rope to a person (at the center) who is spinning it around their head. Draw how you think the the rock will move if the person lets go of the rope



Draw

Erase

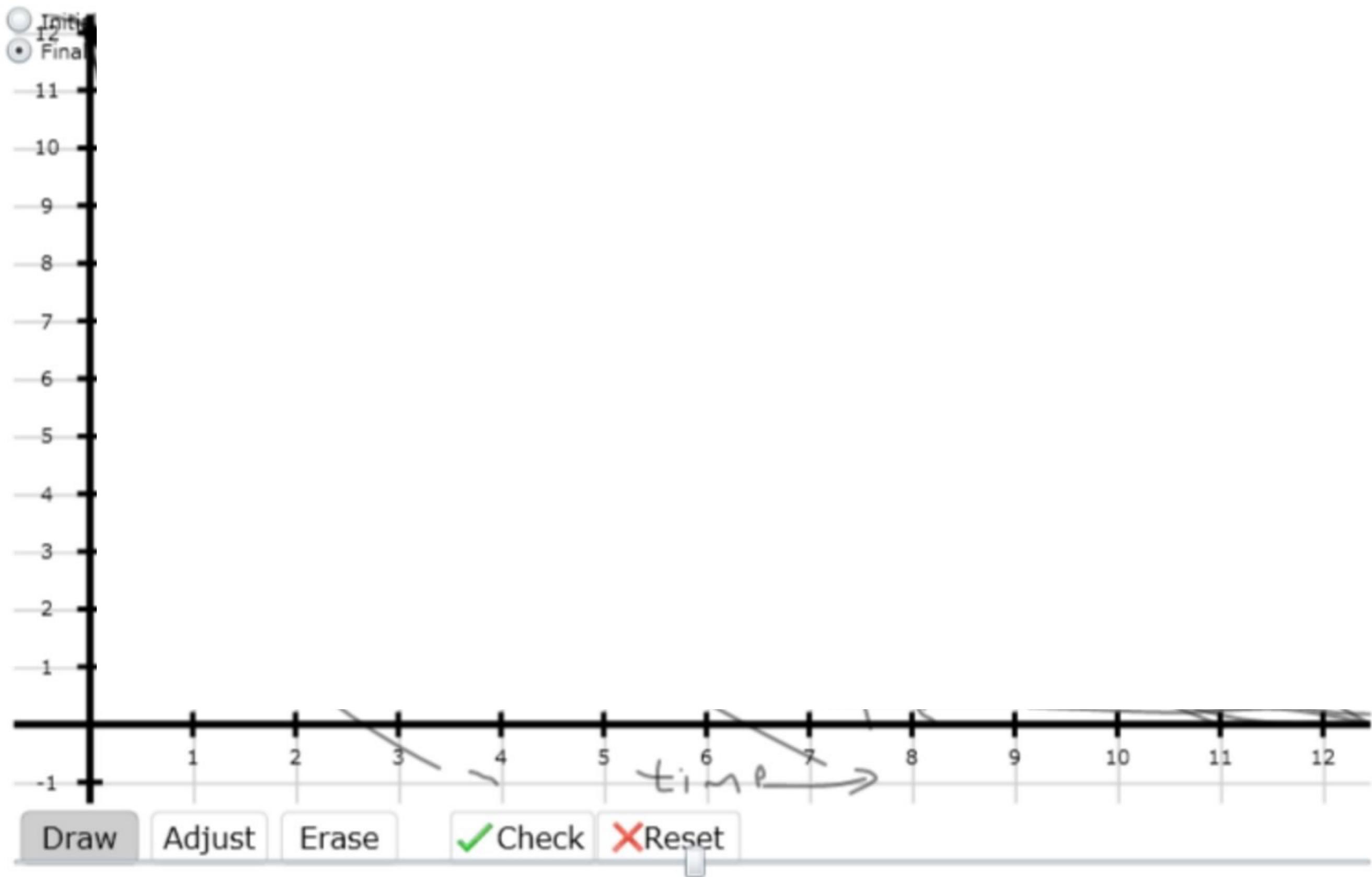
Reset

What ideas did you use in your answer?

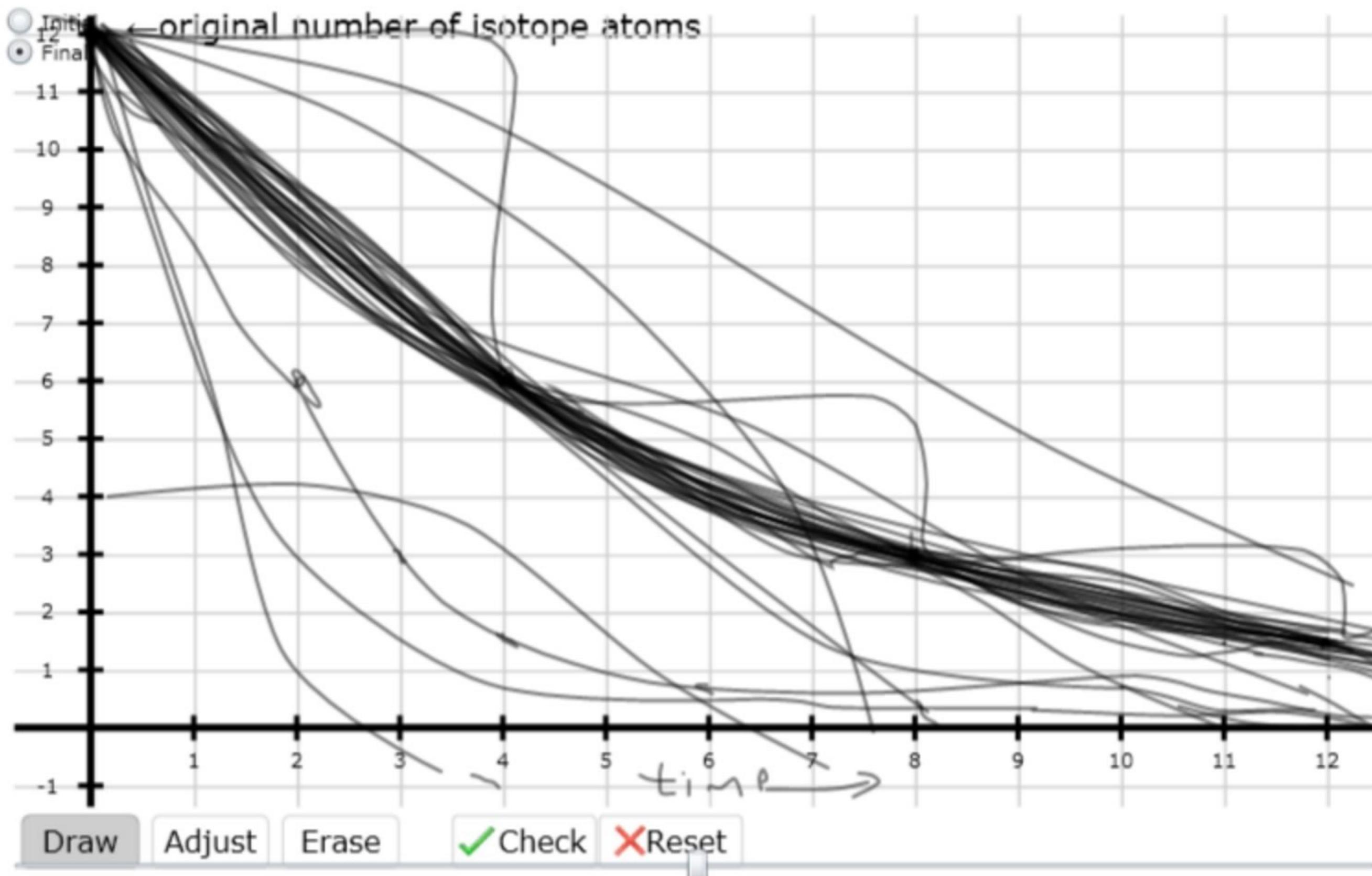
revealing student thinking

<p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>I was thinking that the inertia of the rock would keep it going in the same direction. If one part of the pendulum lets go off the rock, it will fall to the ground.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>The rock will go off tangent to the path it was following while being spun. Once the rock lets go, there is no force acting on the rock because gravity, and so it moves in a parabola in the direction it was moving when it was released, until it hits the ground.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>I used the Law of Inertia, which is that it's hard to move objects. Objects at rest tend to stay at rest, and objects in motion tend to stay in motion with the same velocity. Since velocity has direction and it would keep rotating, the rock would go off in an even longer arc than its circular path.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>
<p><b>30579</b></p> <p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>Cross the swing has been cut, the only thing causing the rock to move is the inertia. The rock's inertia leads it in a straight path in the direction it was heading at the instantaneous moment the string was cut. The rock would not continue in a circular pattern because there is no resultant force applied to move it in that direction.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p><b>30580</b></p> <p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>I visualized this problem in my head. I also used my hands to visualize how I think the rock would fly when it released. I assumed that it would fly straight because the maximum in swinging the rock to the person in a place and when the person lets go there is nothing happening to let the rock continue to follow the arc.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p><b>30582</b></p> <p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>The rock will continue to spin in the same direction it was traveling for a short time before straightening out its path and racing to the ground.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p><b>30583</b></p> <p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>Gravity</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>
<p><b>30586</b></p> <p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>Cross generally all more reason have to the ground because the it's held and the swing will move it released from them, but also in the direction of the swinging.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p><b>30587</b></p> <p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>I just thought about previous experiences and how things move if they're held and then when they're spun. The direction of the person that was when was the person was swinging in the diagram. I also figured it's free from it would fly.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p><b>30588</b></p> <p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>I was in my answer very previous knowledge from Physics class. I can't without knowing it up whether the rock continues moving because once it's released it's going to be in the direction it was going. By thinking about it, it makes very sense that the ball would keep going in a circular motion after it's let go. It's never been released from a platform.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>	<p><b>30589</b></p> <p>The diagram shows a rope attached to a person (at the center) who is swinging in a circular path. Cross these rectangles if the person lets go of the rope.</p> <p><b>What ideas did you use in your answer?</b></p> <p>I use thinking of gravity and how it might have a weight to the rock to hit the ground, but it wouldn't take long for gravity to have an effect on the rock and have it's weight or a string it's on the ground weight. The reason I think about that is that I was thinking what else maybe it could be affected for a second because of the rock the string needed as well.</p>  <p><b>Open</b> <b>Save</b> <b>Print</b></p> <p>Page 4/17</p>
<p><b>30593</b></p>	<p><b>30594</b></p>	<p><b>30595</b></p>	<p><b>30596</b></p>

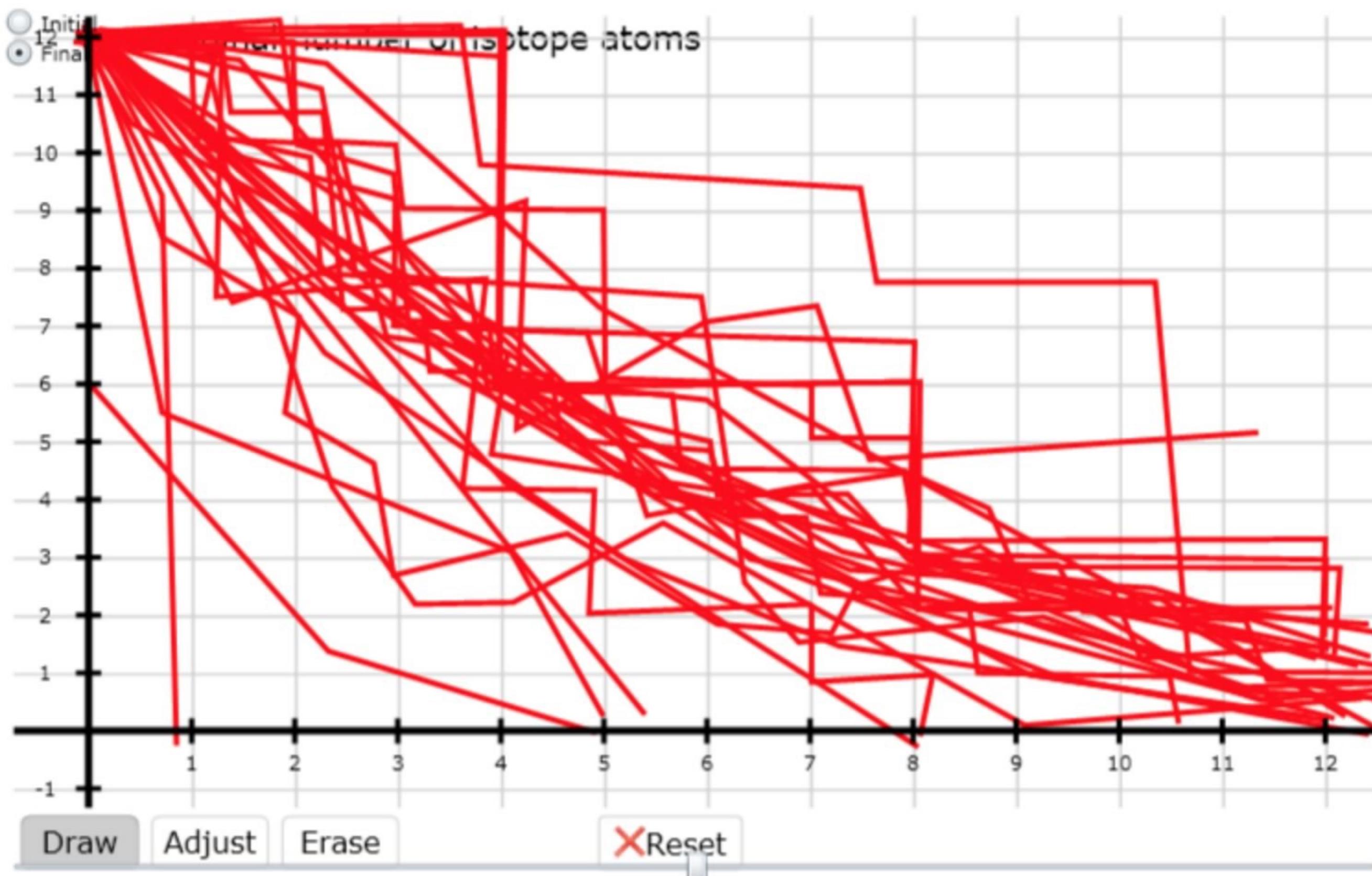
2.2: Now draw the half-life relationship graphically. The half-life of this isotope is 4 time units and you begin with 12,000,000,000 isotope atoms



2.2: Now draw the half-life relationship graphically. The half-life of this isotope is 4 time units and you begin with 12,000,000,000 isotope atoms



2.3: Now consider how your graph will change if you started with only 12 atoms? Draw a plausible graph of the behavior of 12 isotope atoms.



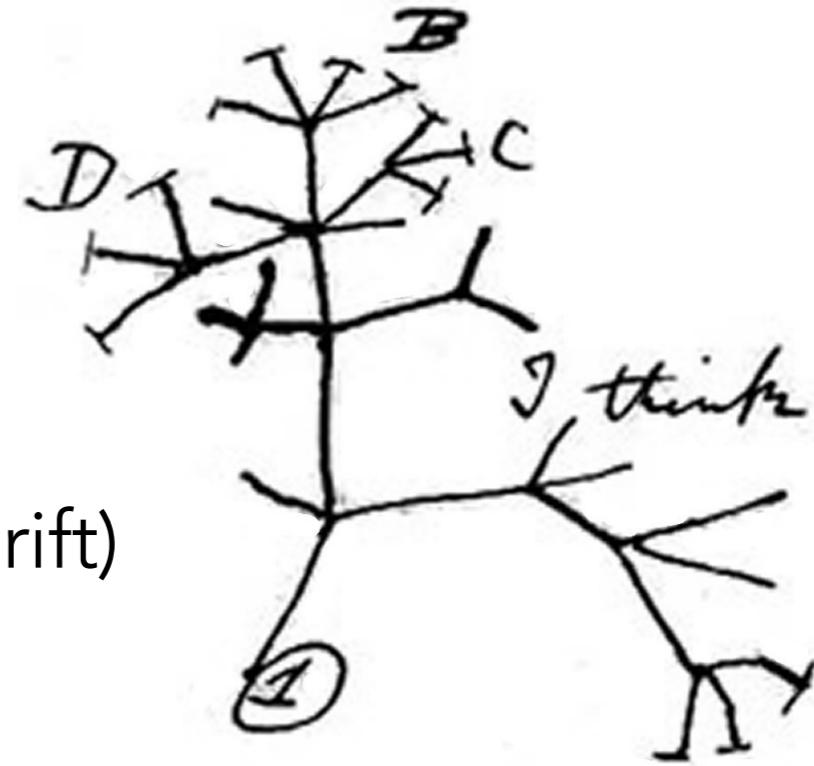
# **biofundamentals: an alternative introductory sequence**

## Existing MCDB course

- no discussion of
  - evolutionary mechanisms (social processes)
  - stochastic processes
- Lack of recurrent themes
  - course built first as interactive web site
  - transformed into an open source book
  - two semester version available free on-line
  - comments welcome!!!

# Focus of biofundamentals

- **Evolutionary processes**
  - continuity (cell theory)
  - stochastic processes (mutation and drift)
  - selection (information generation)
- **Molecular foundations**
  - Thermodynamics: enthalpic and entropic factors
    - self-assembly and systems thinking
    - bond formation and catalysis
    - affinity, specificity, and regulation (allostery)
- **Network behaviors**
  - metabolic (non-equilibrium) coupled reaction networks
  - adaptive, homeostatic, responsive & evolving networks



CBE Life Sci Educ. 2010 Winter;9(4):405-7. doi: 10.1187/cbe.10-04-0061.

**Thinking about the conceptual foundations of the biological sciences.**

Klymkowsky MW<sup>1</sup>.

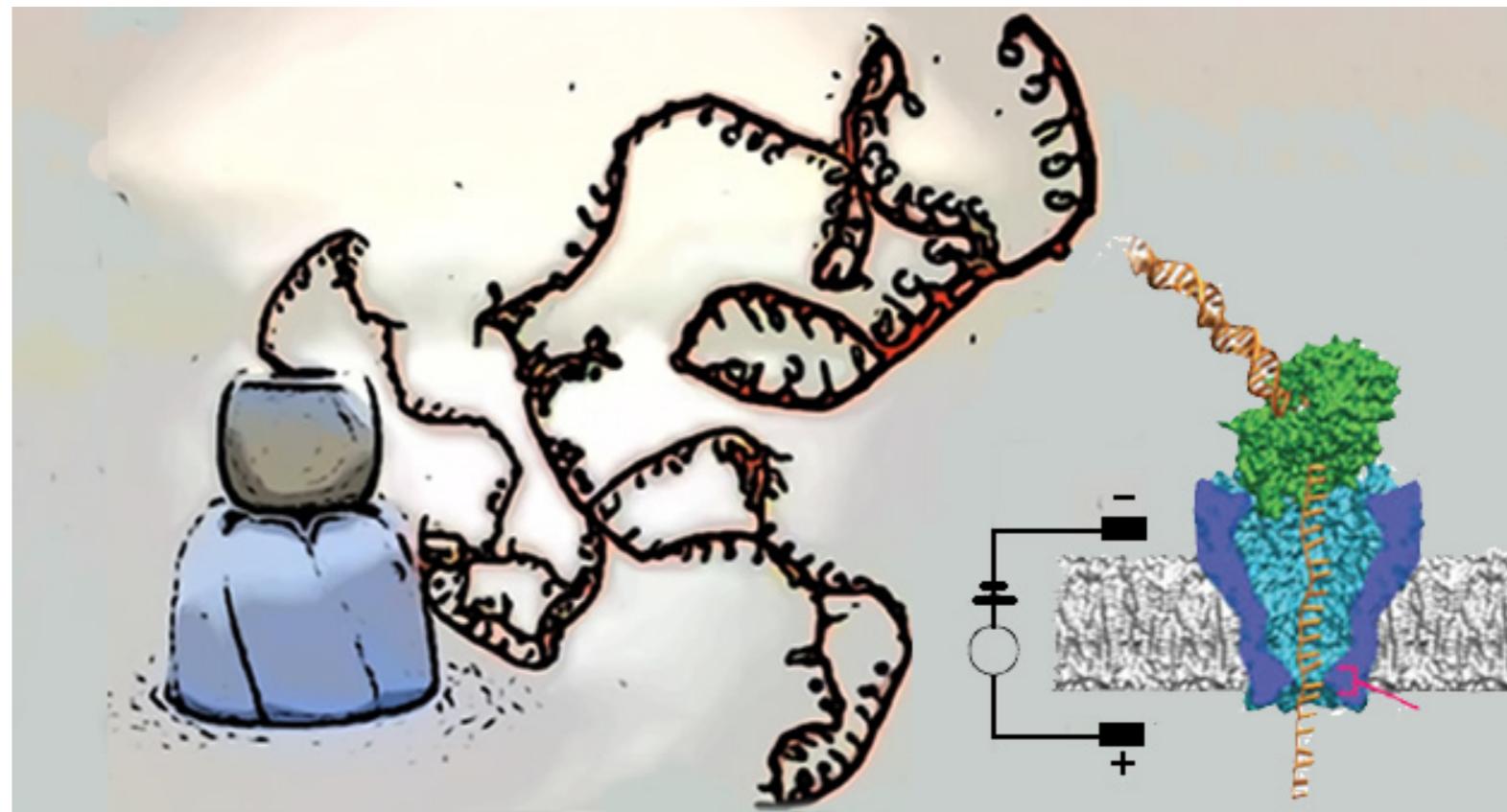
- themes

# The Cell as a Collection of Protein Machines: Preparing the Next Generation of Molecular Biologists

Bruce Alberts  
President, National Academy of Sciences

## common (bio)molecular machines:

- spears and injectors
- molecular importers (nuclear pores)
- walking+dragging (motors)
- propellers and oars (cilia + flagella)
- DNA detanglers (topoisomerases)
- clamps
- chaperones + unfolders
- recyclers (proteosome) ...



engineering more effective courses: biofundamentals

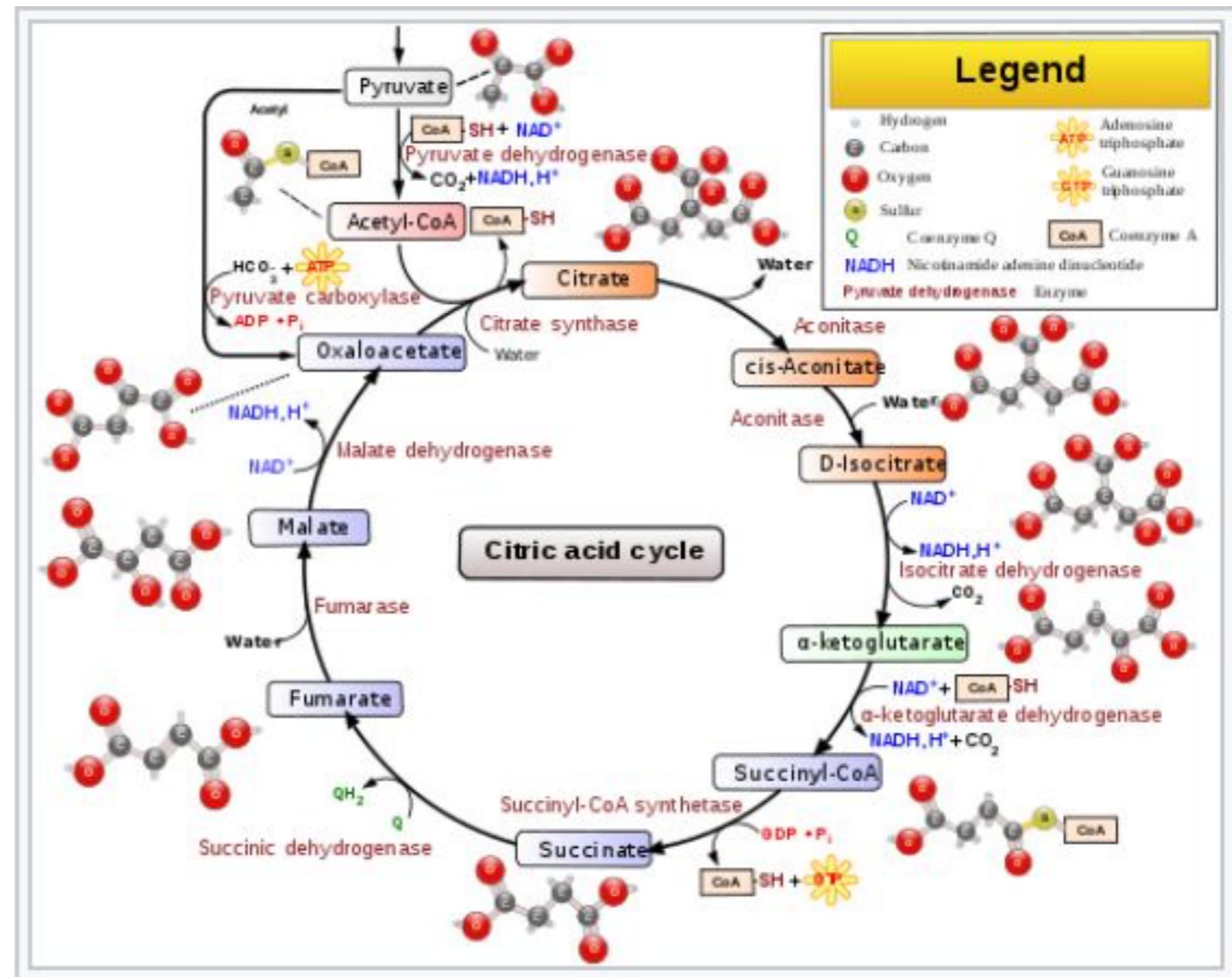
- biological systems are not intelligently designed.



Rube Goldberg

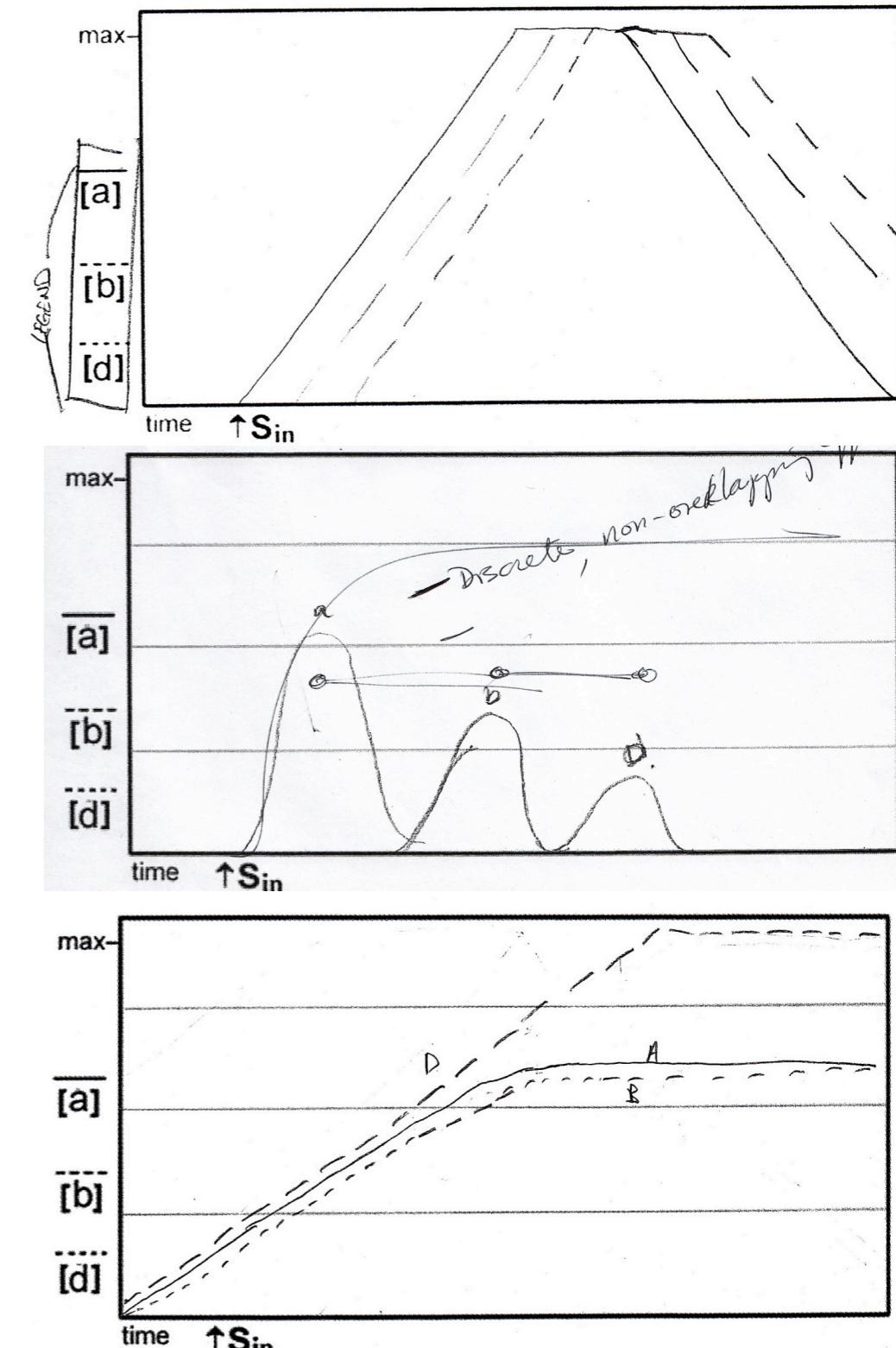
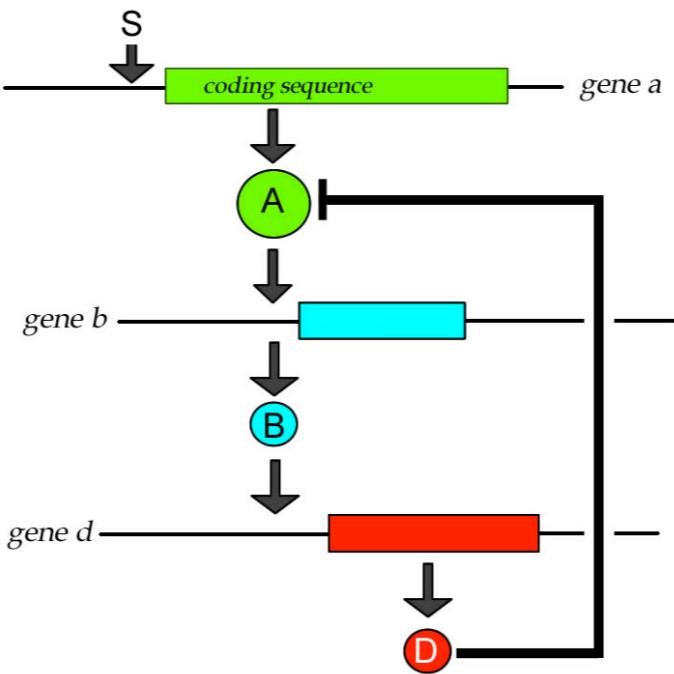
- biological systems are based on systems of coupled chemical reactions.

- what is important, conceptually, is the **ubiquity of coupled reaction**, rather than specific reactions



- students can have issues thinking quantitatively.

**Generate a graph that displays the behavior of the system; state explicitly your assumptions.**

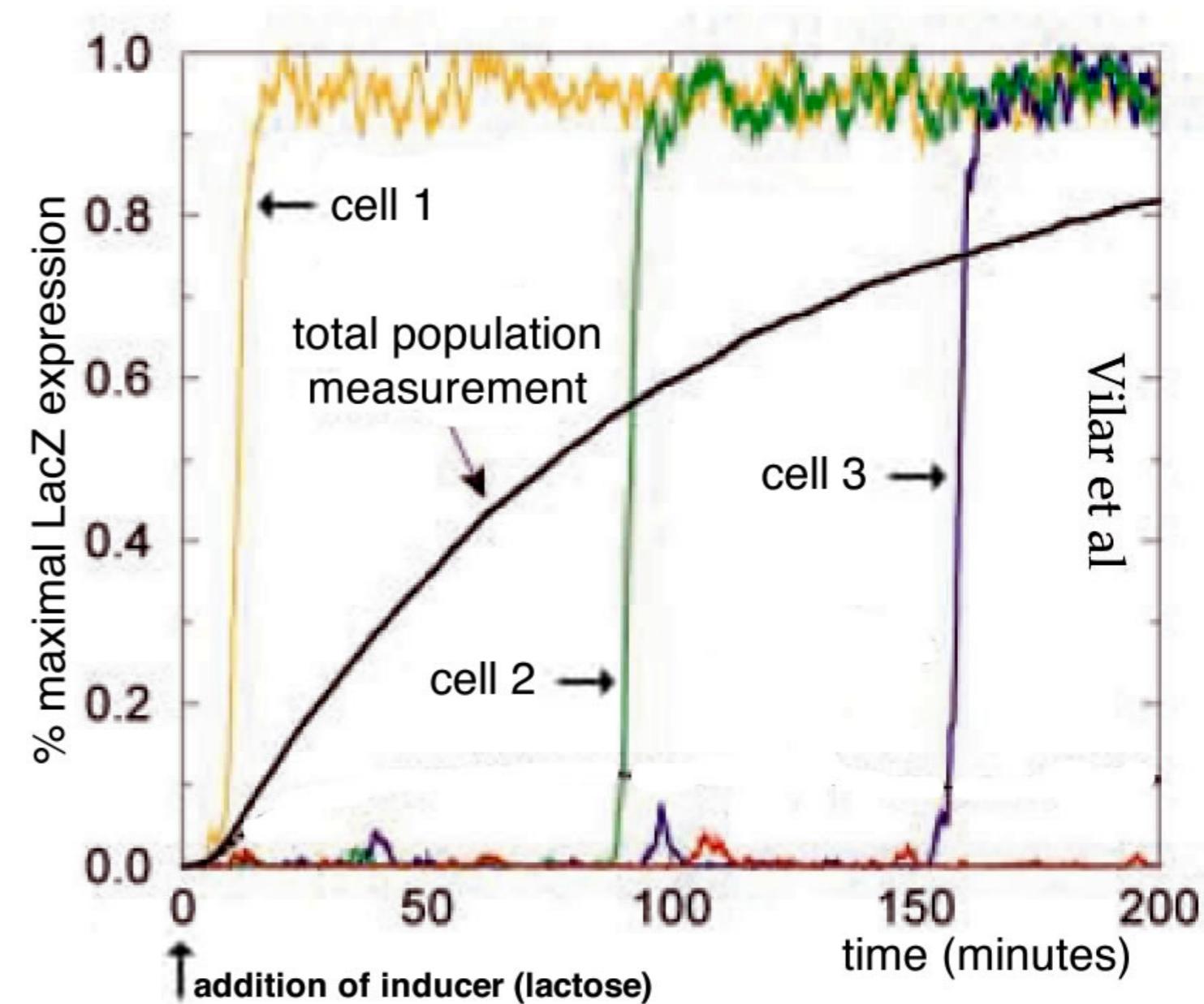
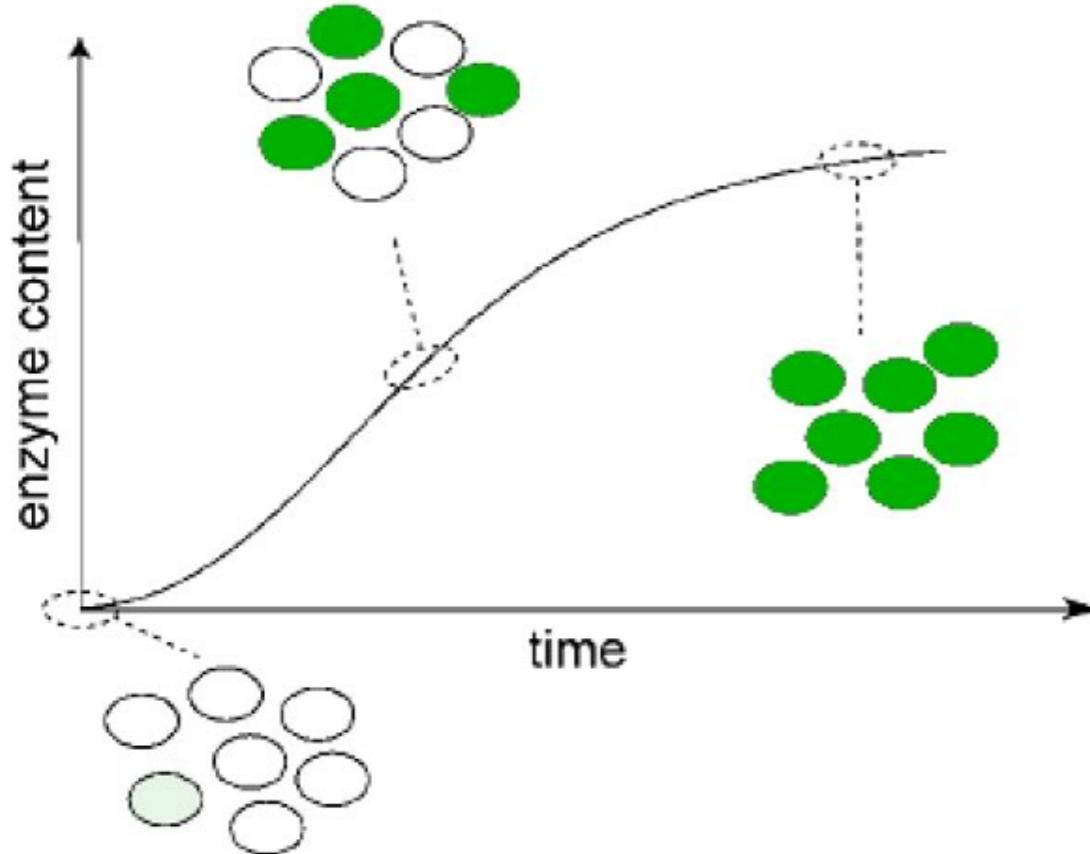
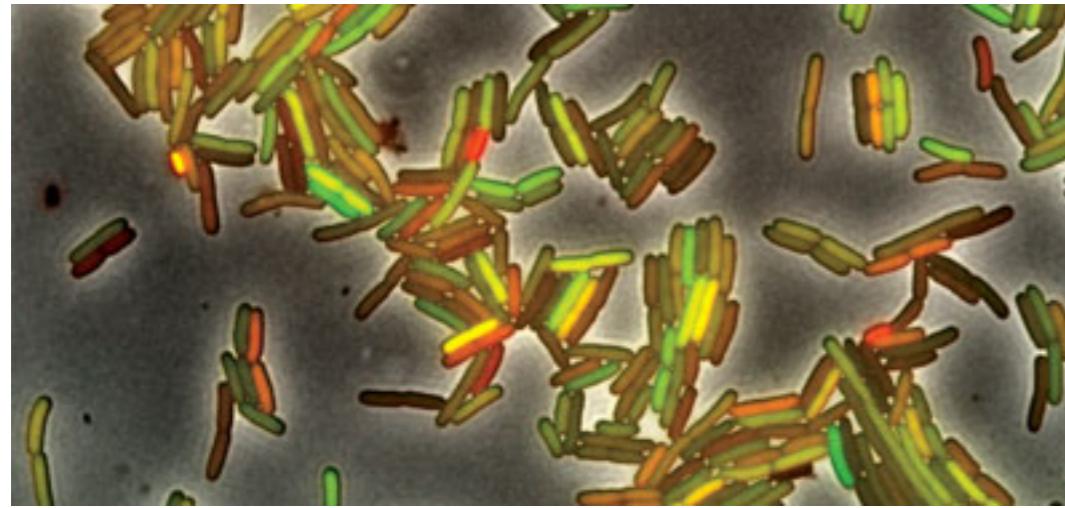


## Using Graph-based Assessments Within Socratic Tutorials to Reveal and Refine Students' Analytical Thinking About Molecular Networks<sup>S\*</sup>

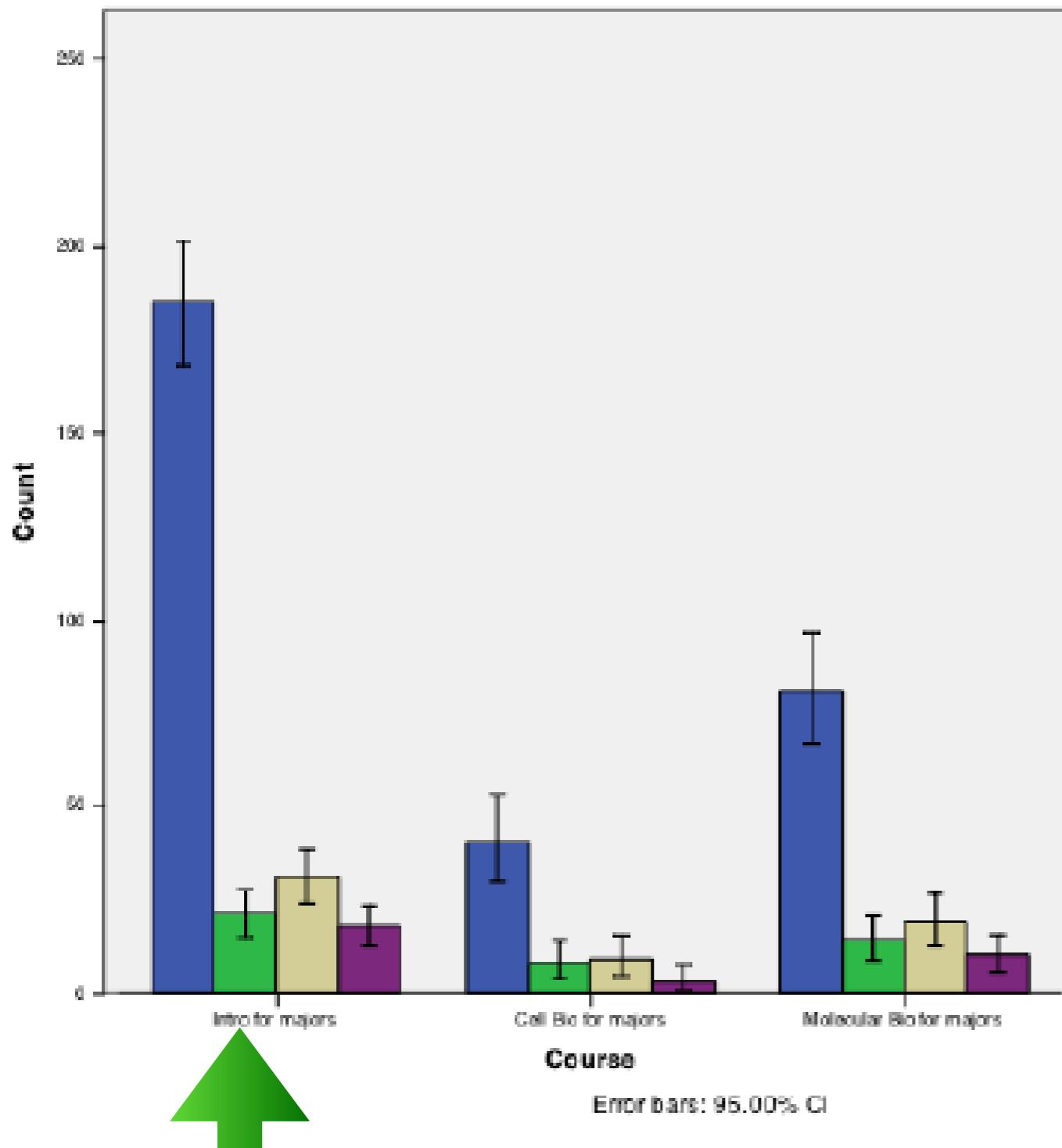
Received for publication, August 6, 2011, and in revised form, November 10, 2011

Caleb Trujillo<sup>‡</sup>, Melanie M. Cooper<sup>§</sup>, and Michael W. Klymkowsky<sup>‡,||</sup>

- biological systems are inherently stochastic.



- students often do not “get” the role of stochastics in system behavior.



Once two molecules bind to one another, how could they come back apart again?

- a) A chemical reaction must change the structure of one of the molecules
- b) Collisions with other molecules could knock them apart
- c) The complex will need to be degraded
- d) They would have to bind to yet another molecule

*Article*

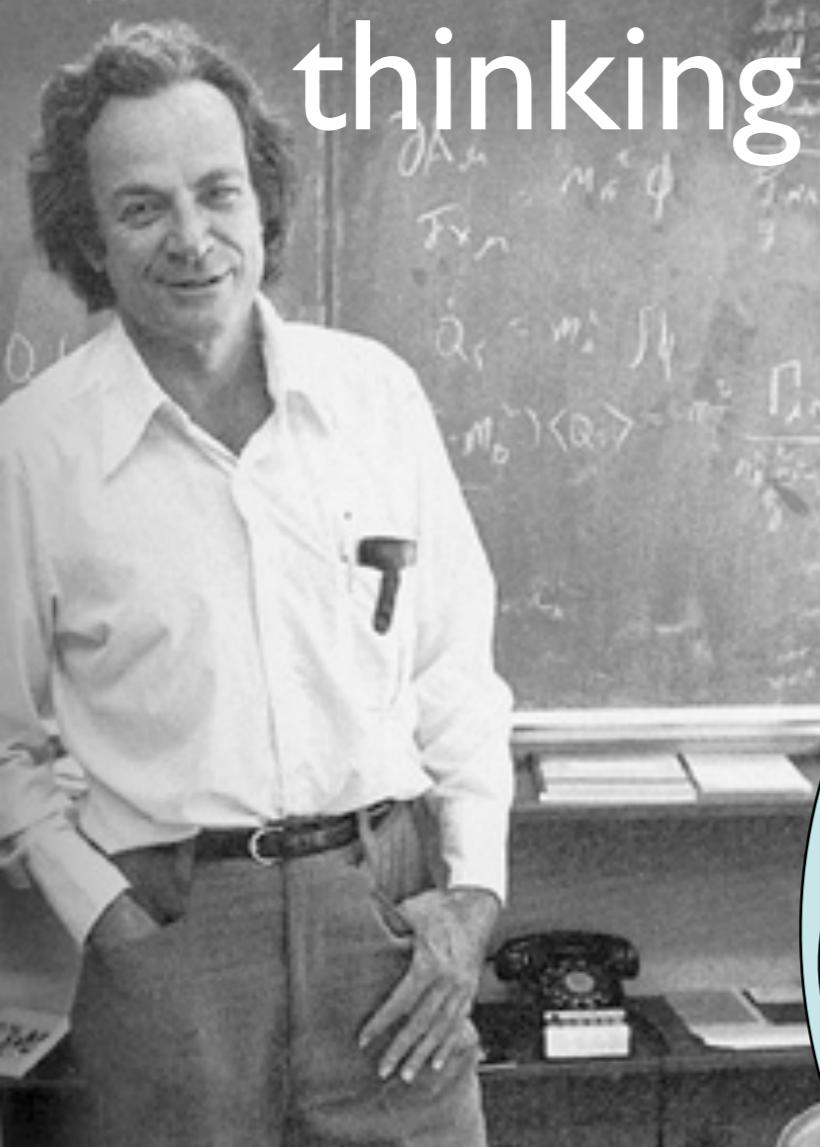
# **Understanding Randomness and its Impact on Student Learning: Lessons Learned from Building the Biology Concept Inventory (BCI)**

**Kathy Garvin-Doxas\*** and **Michael W. Klymkowsky<sup>†</sup>**

\*Center for Integrated Plasma Studies and <sup>†</sup>Molecular, Cellular, and Developmental Biology Department,  
University of Colorado, Boulder, CO 80309

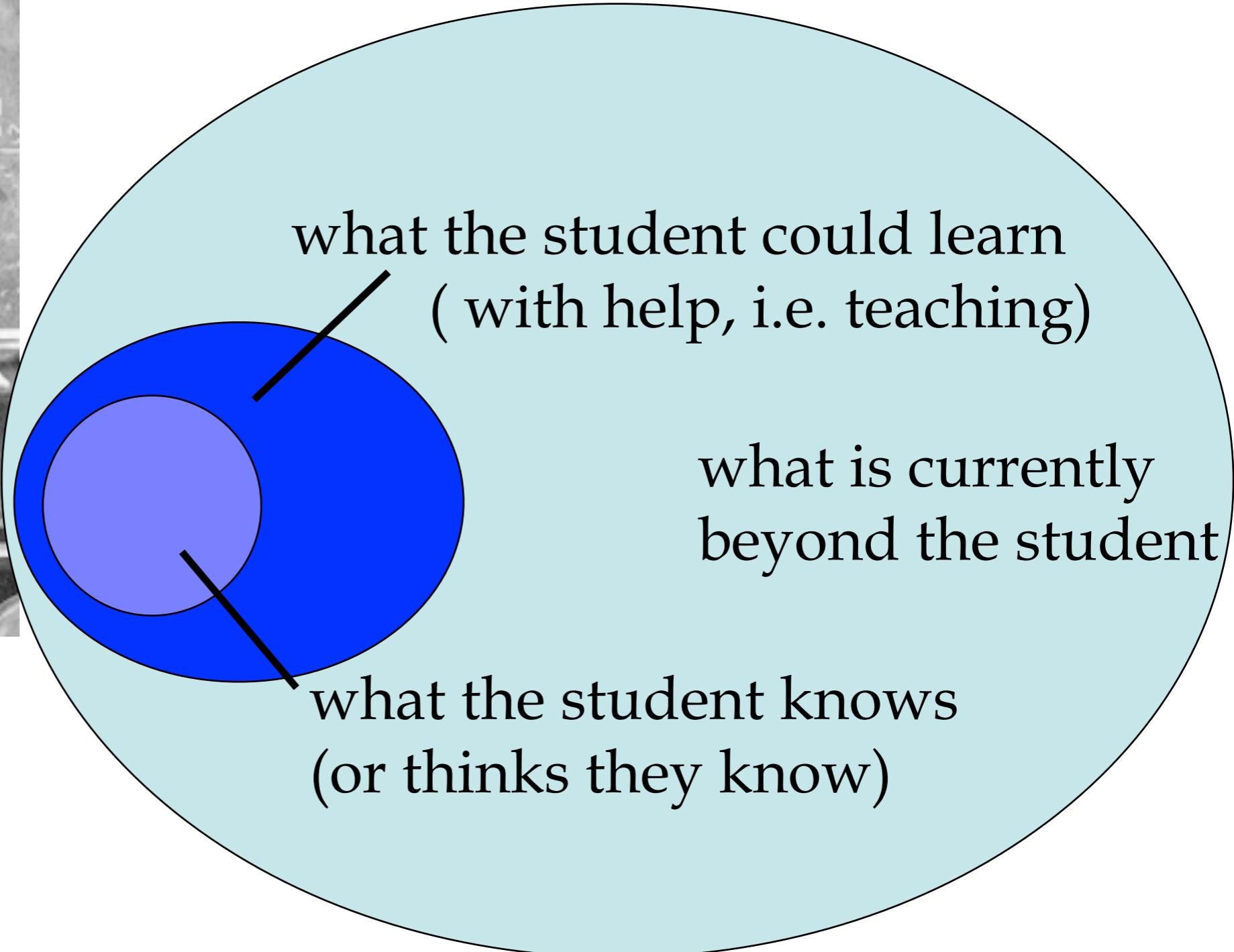
Submitted August 23, 2007; Revised January 14, 2008; Accepted February 7, 2008  
Monitoring Editor: Bruce Alberts

CBE—Life Sciences Education  
Vol. 7, 227–233, Summer 2008



# thinking about magnets

- being explicit about where ideas come from



Vygotsky, L.S. (1978). *Mind and society: The development of higher psychological processes*. Harvard University Pres

# Chapters



- 1: Science & thinking scientifically
- 2: Life and its origins
- 3: Evolutionary mechanisms and the diversity of life
- 4: Social evolution and sexual selection
- 5: Molecular interactions, thermodynamics & reaction coupling
- 6: Membrane boundaries and capturing energy
- 7: The molecular nature of the heredity material
- 8: Peptide bonds, polypeptides, proteins, and molecular machines
- 9: Organizing and expressing genes in regulatory networks
- 10: Cellular topology and intercellular signaling

Available directly from us.

# Different types of questions asked



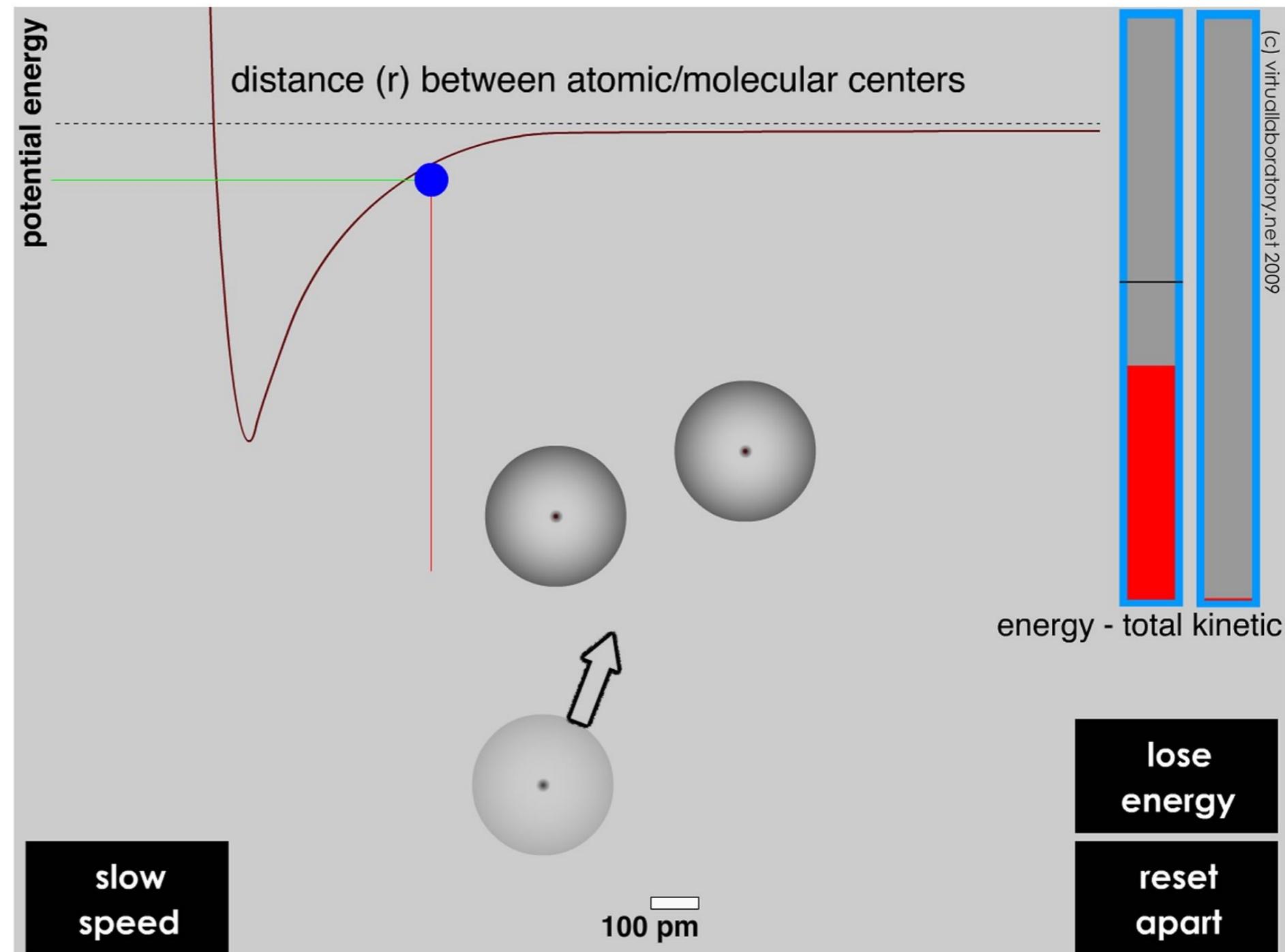
- Why are non-linear responses to a stimuli important in biological systems? How is it achieved?
    - How would the lac operon behave at different concentrations of lac repressor?
    - How it might it impact the social behavior of slime molds if the percentage of spore cells were 1% rather than 80%?
  - **Constructing and testing scenarios** (inspired by Manu Kapur, ETH Zurich)
    - Devise as many mechanisms as you can by which organisms could distinguish self from non-self?
      - How might you test which of your mechanisms is active in a particular organism?



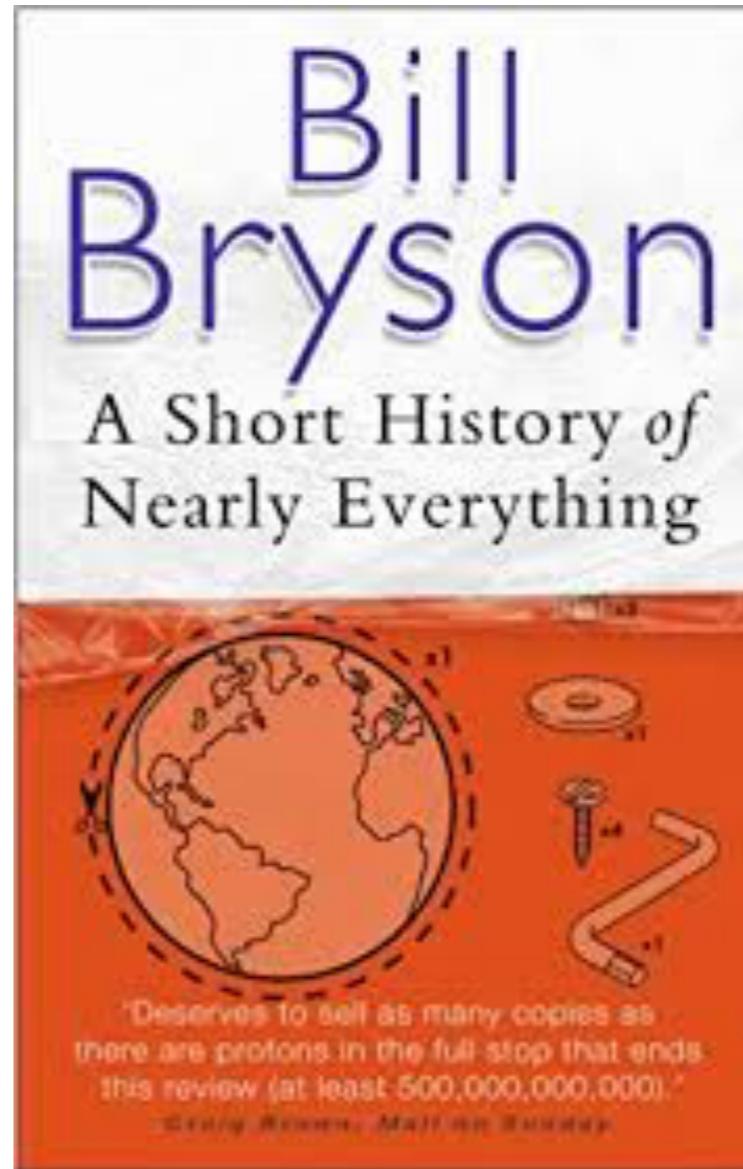
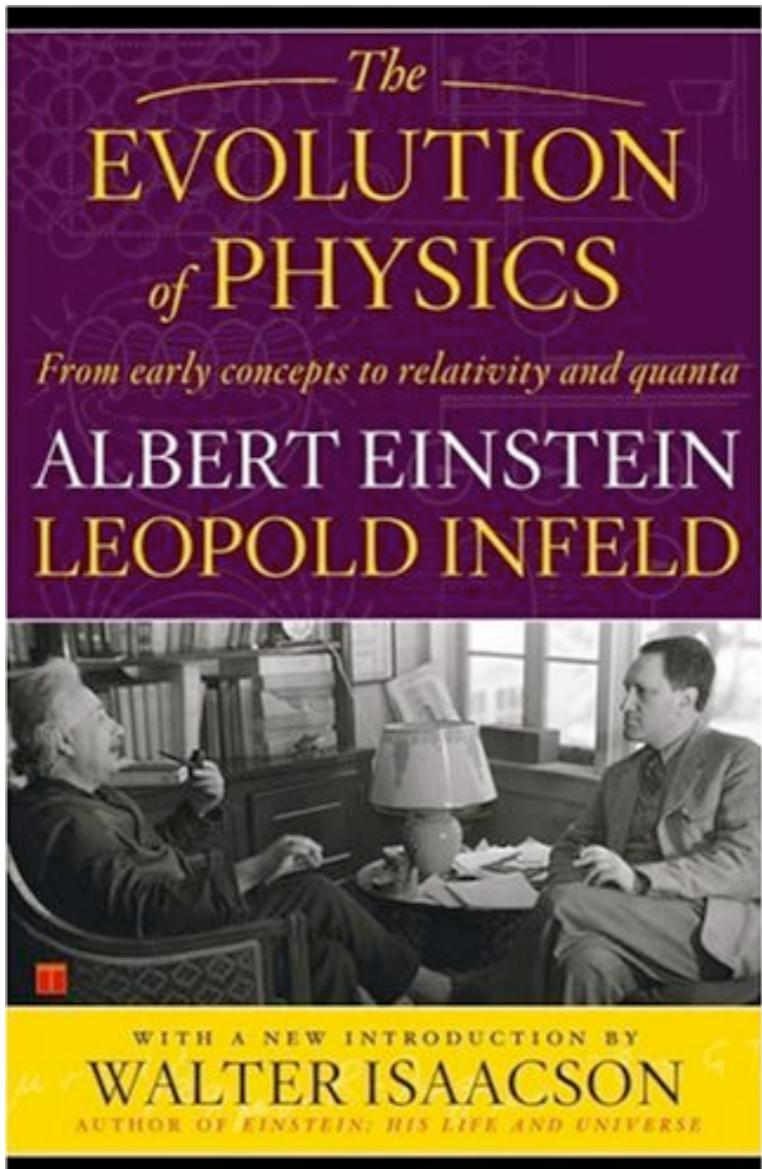
engineering more effective courses: CLUE

# Catalyst for CLUE

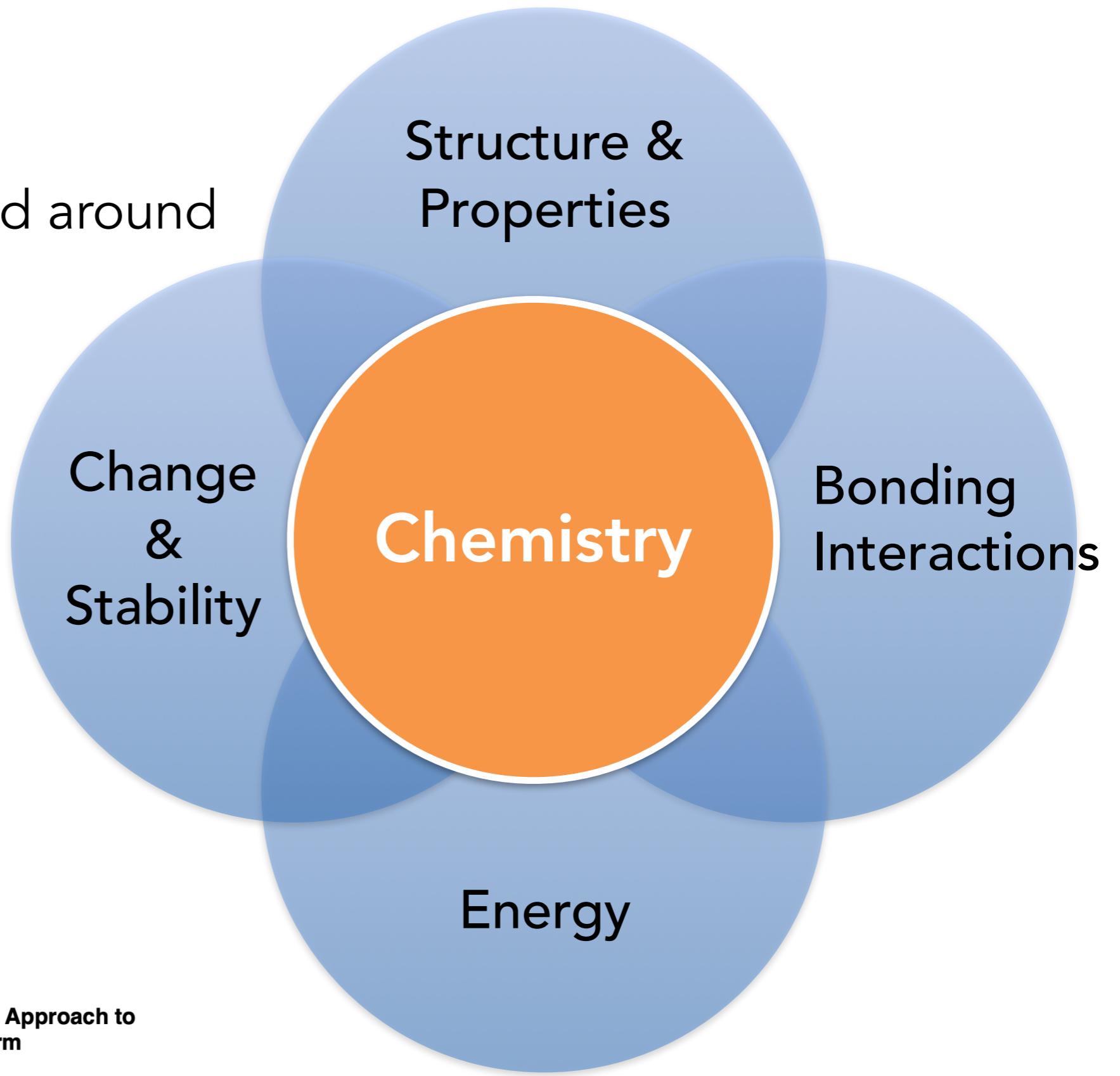
conversations at  
Chemistry  
Education  
Gordon  
Conference  
on energetics of  
bond breaking  
& bond formation



Writing style (minimal figures) – narrative framework for materials presented – practice through beSocratic and in class activities



Focused around



**Chemistry, Life, the Universe, and Everything: A New Approach to  
General Chemistry, and a Model for Curriculum Reform**

Melanie Cooper\*† and Michael Klymkowsky‡

† Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, United States

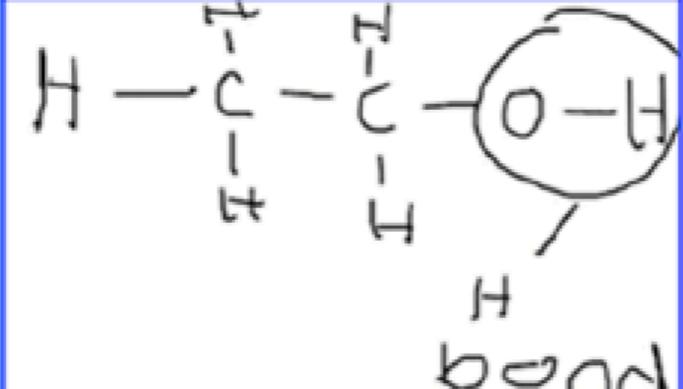
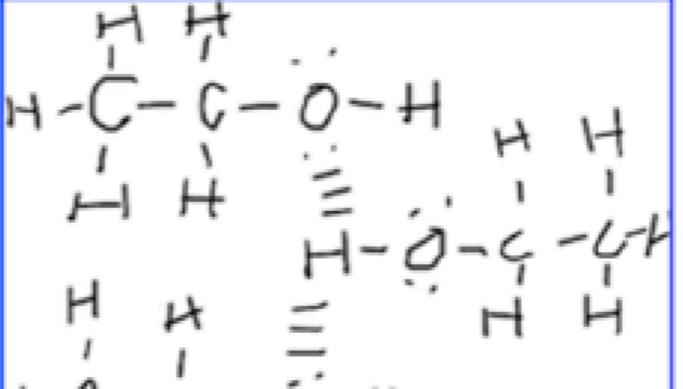
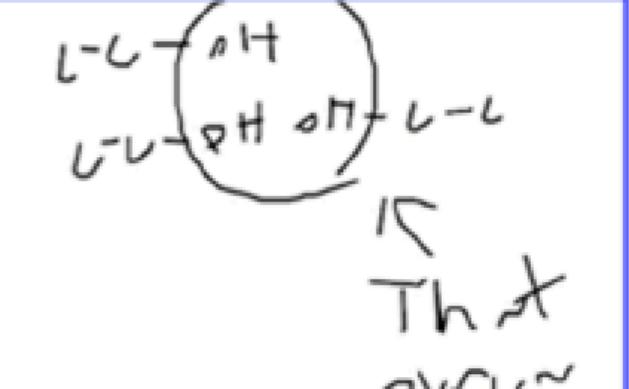
‡ Molecular, Cellular and Developmental Biology and CU Teach, University of Colorado, Boulder, Colorado 80309, United States

# Chemistry, Life, the Universe & Everything

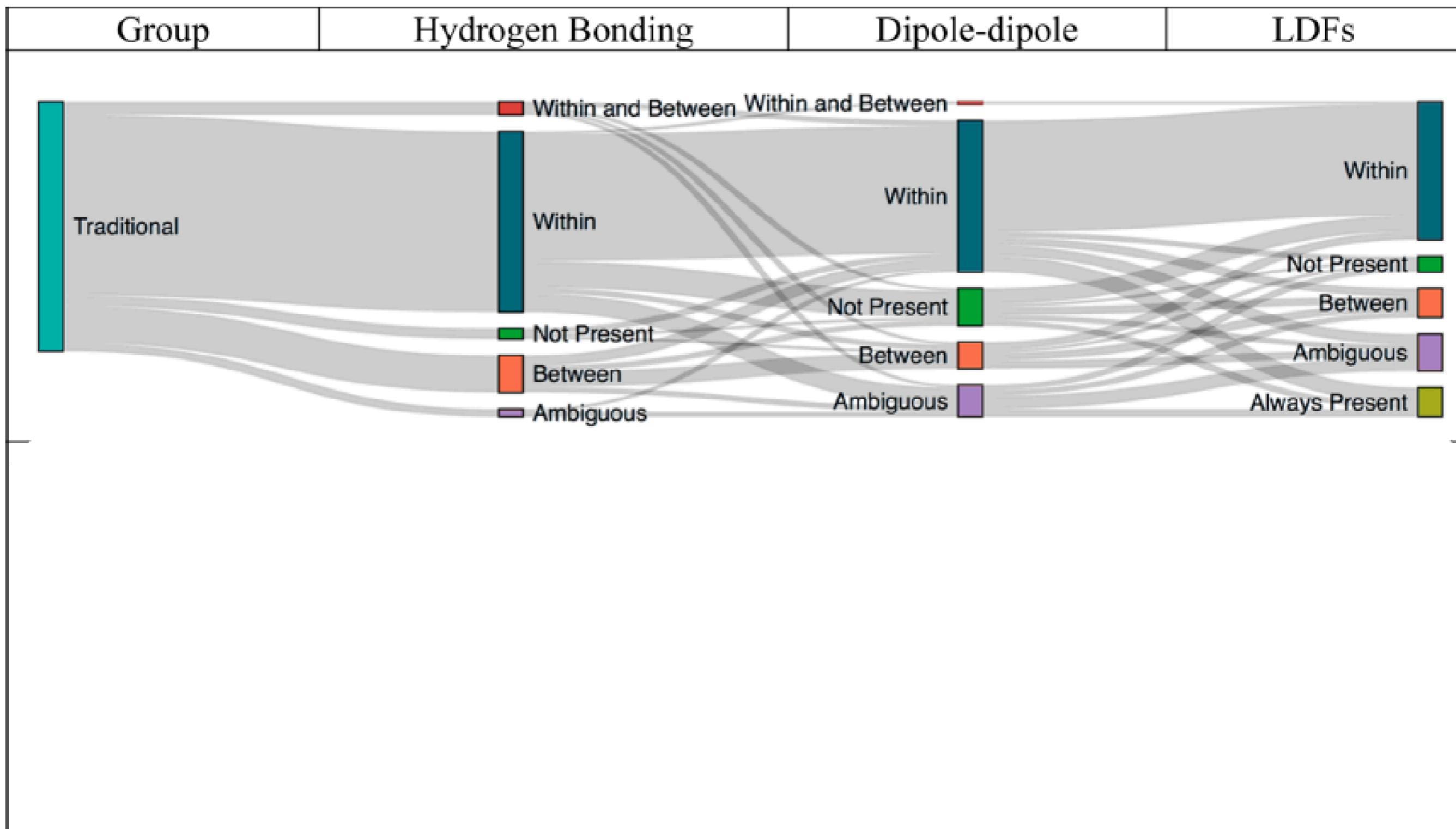
1. Atoms
  2. Electrons & orbitals
  3. Elements, bonding
  4. Heterogenous compounds
  5. Systems thinking
  6. Solutions
  7. Chemical reactions
  8. How far? how fast
  9. Reaction systems



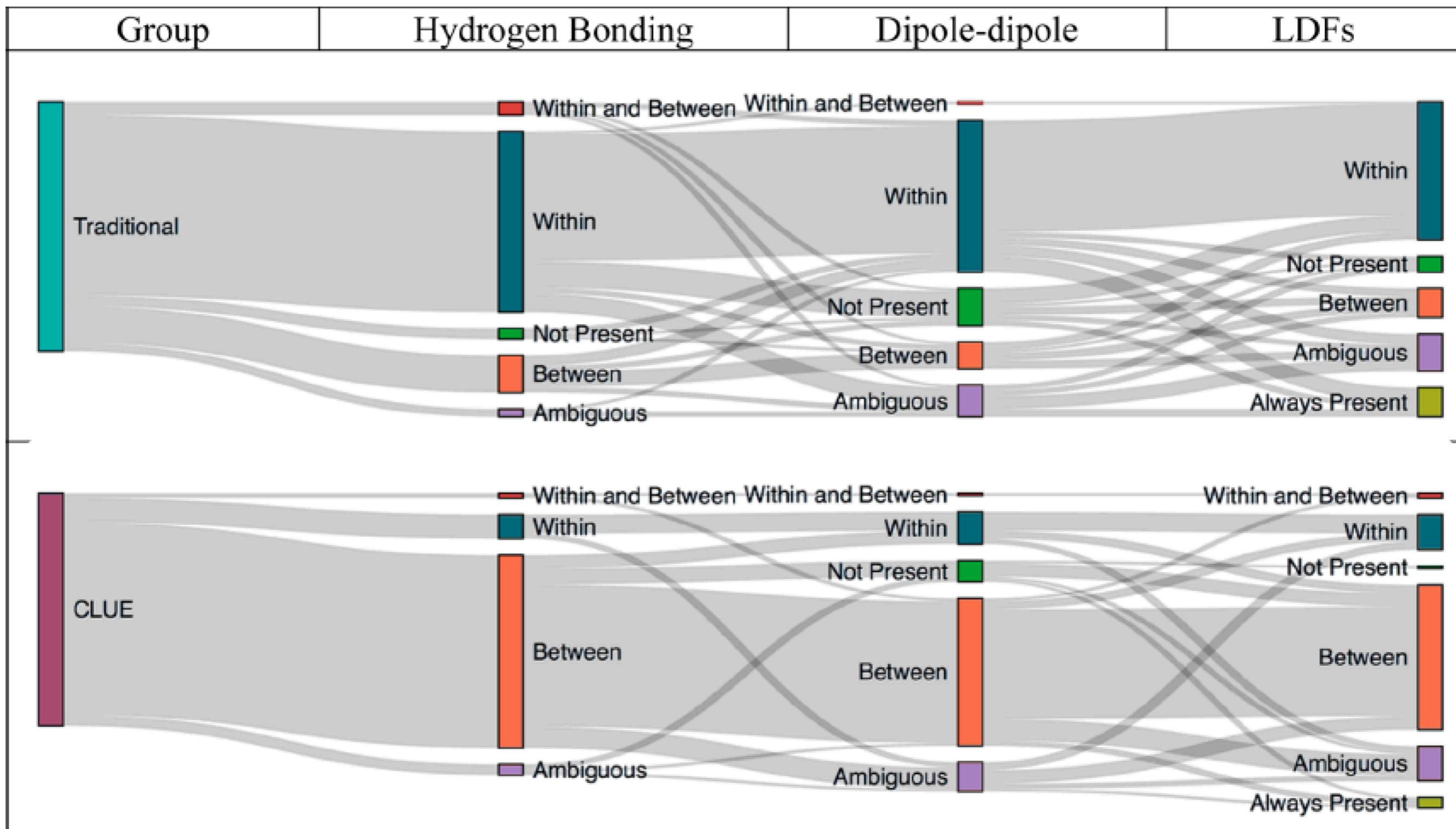
# Types of analyses possible through beSocratic: intermolecular interactions

IMF Type	Code for IMFA Response Drawings Characterizing IMF Locations		
	Within the Molecule	Between Molecules	Ambiguous
Hydrogen Bonding	 <p>Hand-drawn diagram illustrating a hydrogen bond within a molecule. A carbon atom (C) is bonded to two hydrogen atoms (H). It is also bonded to an oxygen atom (O), which is further bonded to a hydrogen atom (H). The bond between the carbon and the oxygen is labeled "H bond".</p> <p>Draw Erase Reset</p>	 <p>Hand-drawn diagram illustrating hydrogen bonding between molecules. Two molecules are shown. The first molecule has a carbon atom bonded to two hydrogen atoms and an oxygen atom. The oxygen atom is bonded to a hydrogen atom. The second molecule has a carbon atom bonded to two hydrogen atoms. The oxygen atom of the first molecule is shown interacting with the carbon atom of the second molecule via a dashed line, indicating a hydrogen bond between them.</p> <p>Draw Erase Reset</p>	 <p>Hand-drawn diagram illustrating ambiguous IMF locations. A molecule is shown with a carbon atom bonded to two hydrogen atoms and an oxygen atom. The oxygen atom is bonded to a hydrogen atom. A dashed line extends from the oxygen atom towards another part of the molecule, suggesting an ambiguous interaction.</p> <p>Draw Erase Reset</p>

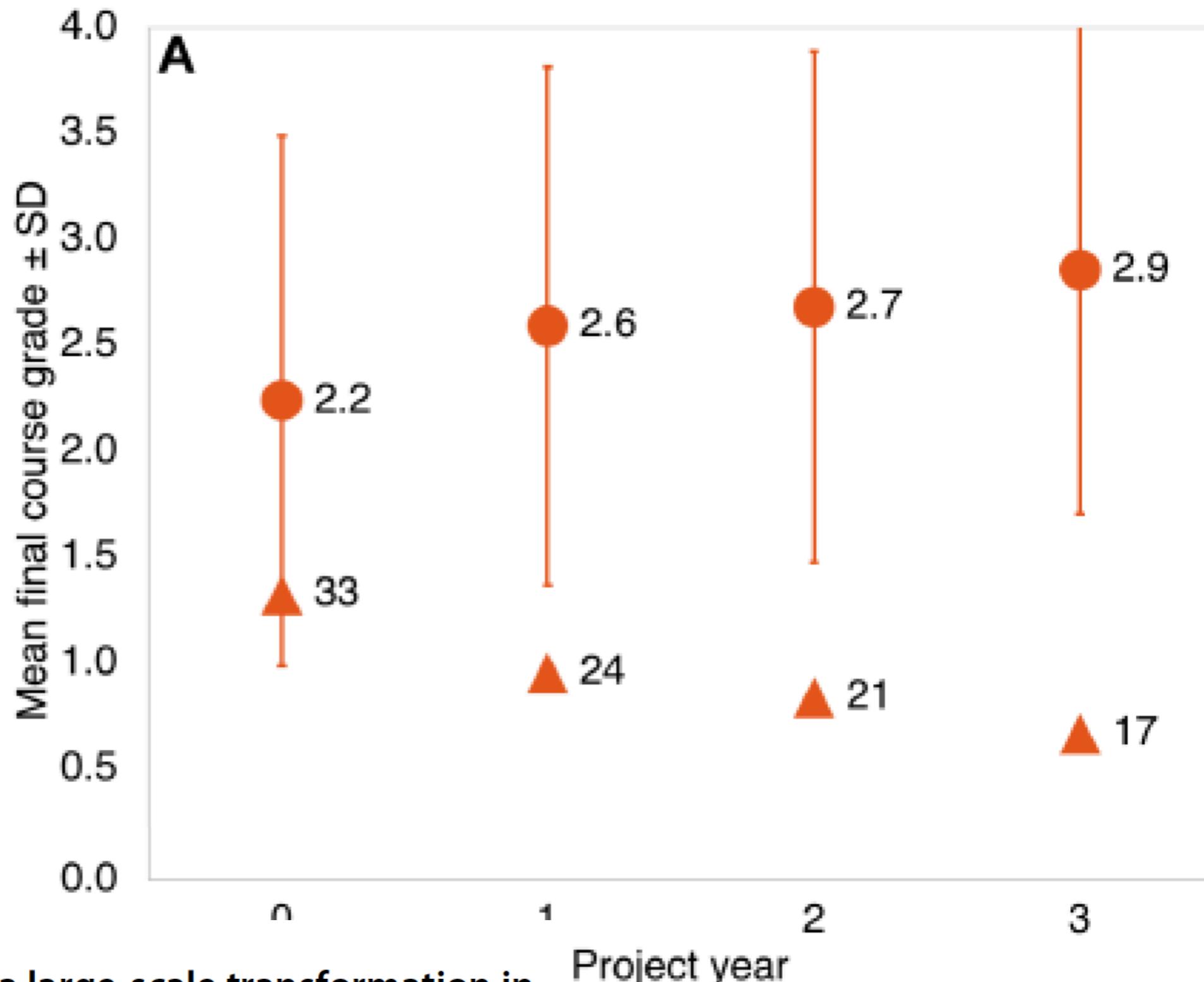
# Type analysis possible through beSocratic: intermolecular interactions



# Type analysis possible through beSocratic: intermolecular interactions



# chemistry (CLUE)



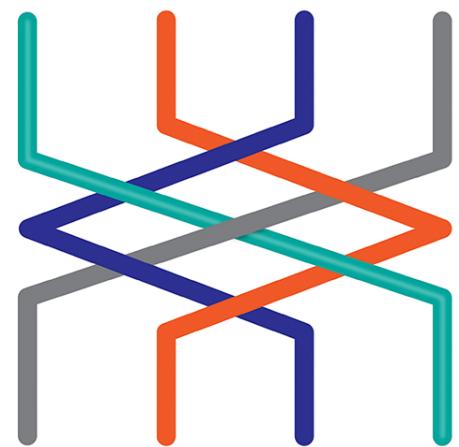
## Evaluating the extent of a large-scale transformation in gateway science courses

Rebecca L. Matz<sup>1\*</sup>, Cori L. Fata-Hartley<sup>2</sup>, Lynmarie A. Posey<sup>3</sup>, James T. Laverty<sup>4</sup>,  
Sonia M. Underwood<sup>5</sup>, Justin H. Carmel<sup>5</sup>, Deborah G. Herrington<sup>6</sup>, Ryan L. Stowe<sup>3</sup>,  
Marcos D. Caballero<sup>7</sup>, Diane Ebert-May<sup>8</sup>, Melanie M. Cooper<sup>3</sup>

# Further evidence for the efficacy of CLUE

- Cooper, Underwood, Hilley & Klymkowsky, 2012. **Development and Assessment of a Molecular Structure and Properties Learning Progression**, J Chem Edu.
- Williams, Underwood, Klymkowsky, & Cooper. 2015 **Are Noncovalent Interactions an Achilles Heel in Chemistry Education? A Comparison of Instructional Approaches**. J. Chem Educ
- Cooper, Reyes-Gastelum, Underwood. 2016. **When do students recognize relationships between molecular structure and properties? A longitudinal comparison of the impact of traditional and transformed curricula**. CERP
- Crandell, Kouyoumdjian, Underwood & Cooper, 2018. **Reasoning about acid-base reactions in organic chemistry - it starts in general chemistry**, J Chem Ed. 2018.

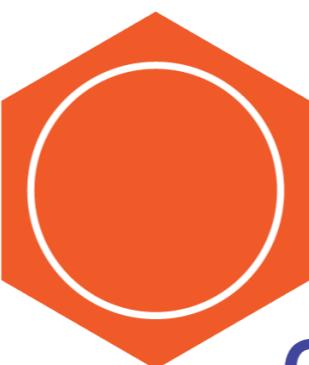
From



CLUE

CHEMISTRY, LIFE, THE UNIVERSE  
& EVERYTHING

to



OCLUE

**ORGANIC CHEMISTRY**  
LIFE, THE UNIVERSE & EVERYTHING

Cooper, Stowe, Crandell & Klymkowsky, M. J. Chem. Educ. submitted

engineering more effective courses: CLUE to OCLUE

# Design



connect topics to core ideas by using scientific practices.

National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, DC, 2012.

Focus on biologically relevant material

engineering more effective courses: OCLUE

# outcomes data from the Cooper group



OCLE  
ORGANIC CHEMISTRY  
LIFE, THE UNIVERSE & EVERYTHING

Traditional Organic Chemistry

## Participants

Mostly Pre-professional majors  
~75% female

Compared on:  
ACT score  
GC1 Grade  
GC2 Grade  
OC1 Grade  
OC2 Grade

GPA Prior to OC1

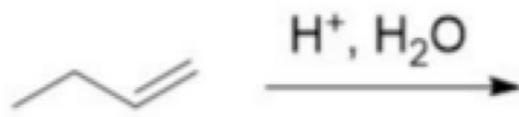
Year 2  
Time  
Point 1

Year 2  
Time  
Point 2

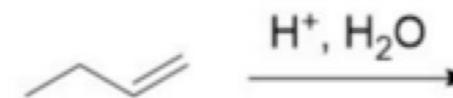
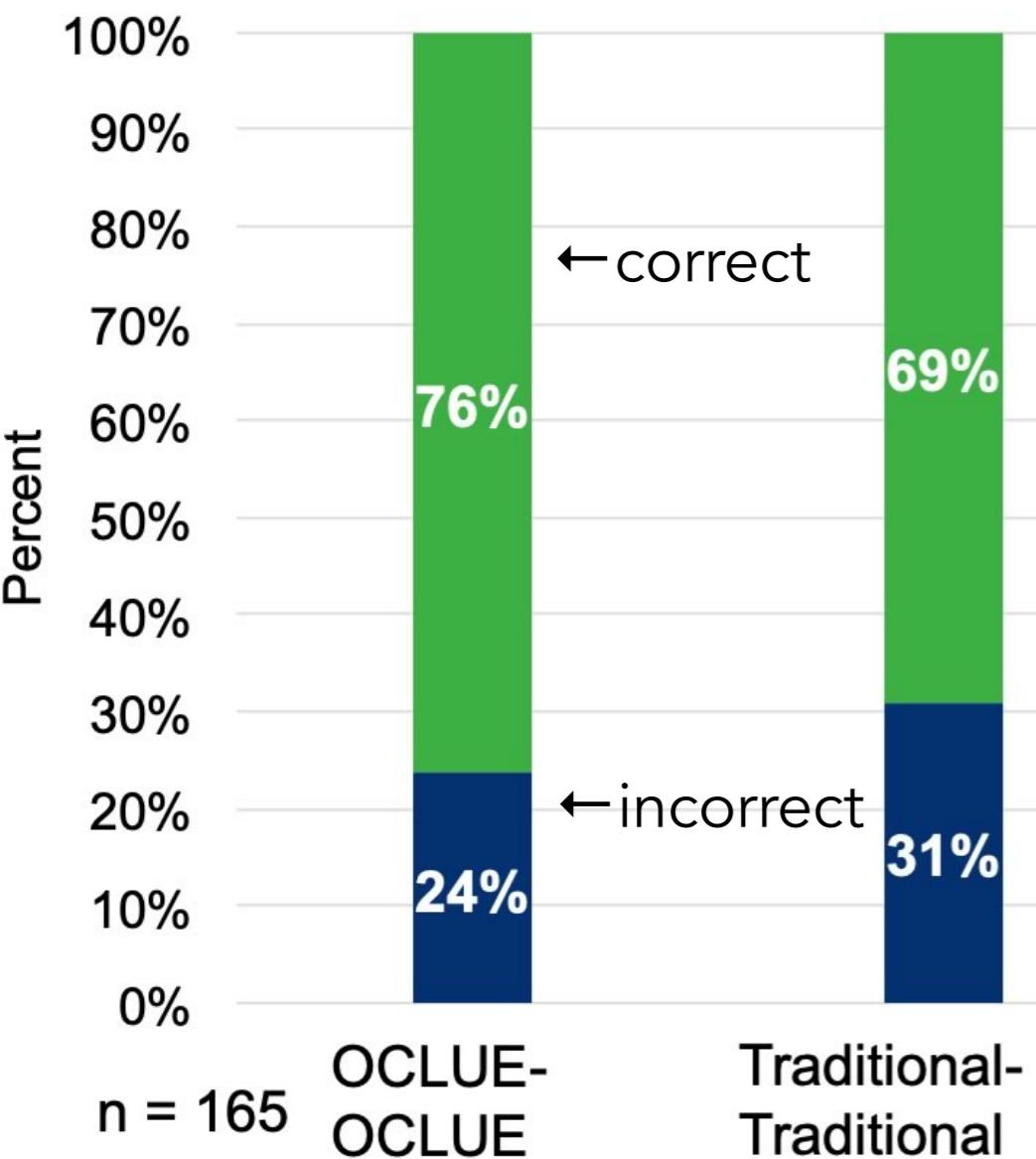


engineering more effective courses: OCLUE

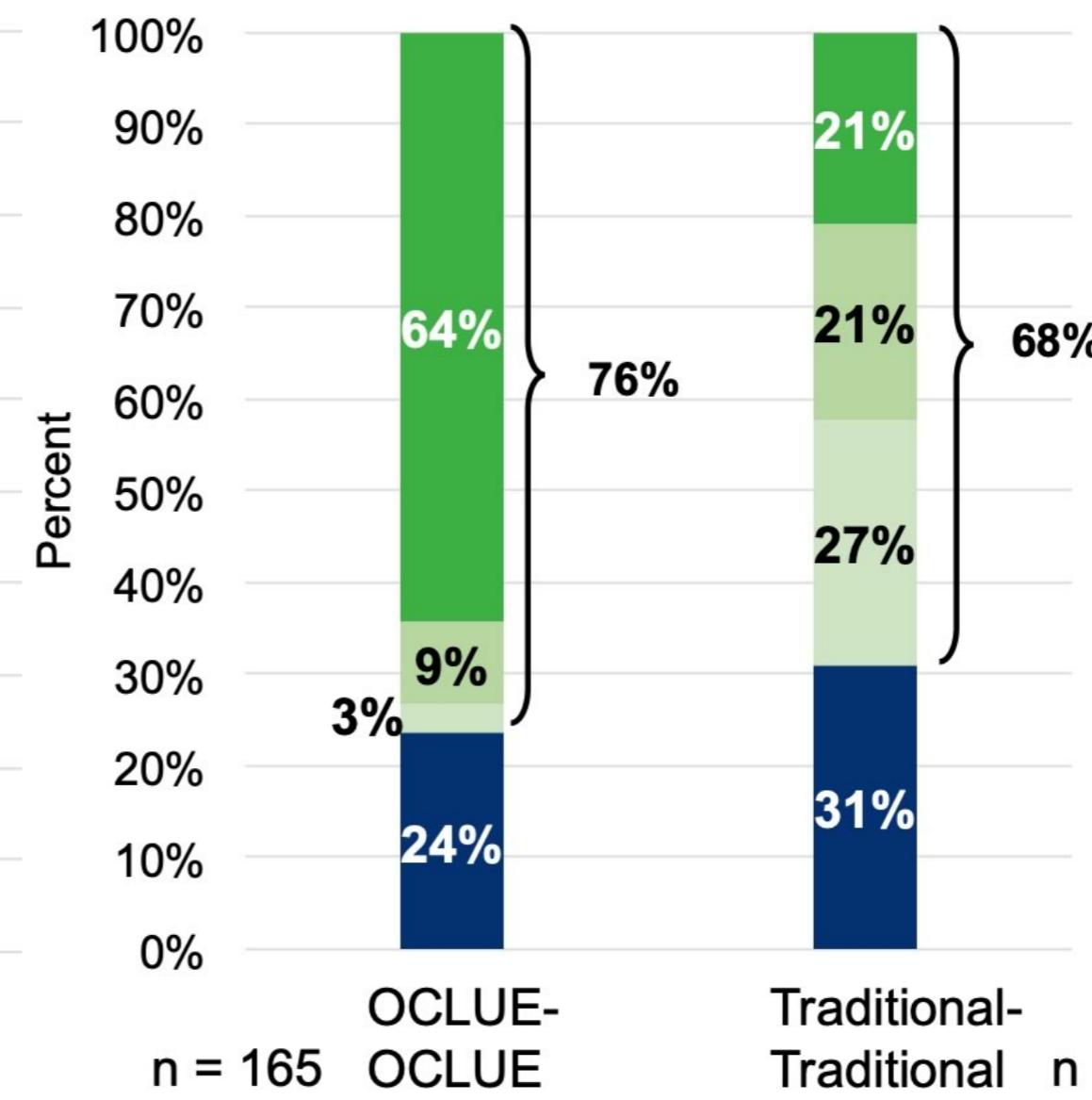
# outcomes data from the Cooper group



Time Point Two



Time Point Two



All Correct Arrows & Correct Product

Some Correct Arrows & Correct Product

No Arrows & Correct Product

Mann-Whit U

p	0.000
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r	0.55
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Significant different and large effect size

– proton transfer (~550)

Holliday et al. 2007

doi:10.1016/j.jmb.2007.07.034

J. Mol. Biol. (2007) 372, 1261–1277



## The Chemistry of Protein Catalysis

Gemma L. Holliday<sup>1,2\*</sup>†, Daniel E. Almonacid<sup>2</sup>†, John B. O. Mitchell<sup>2</sup>  
and Janet M. Thornton<sup>1</sup>

Frequency



– bimolecular nucleophilic addition (~180)

– unimolecular heterolytic elimination (~140)

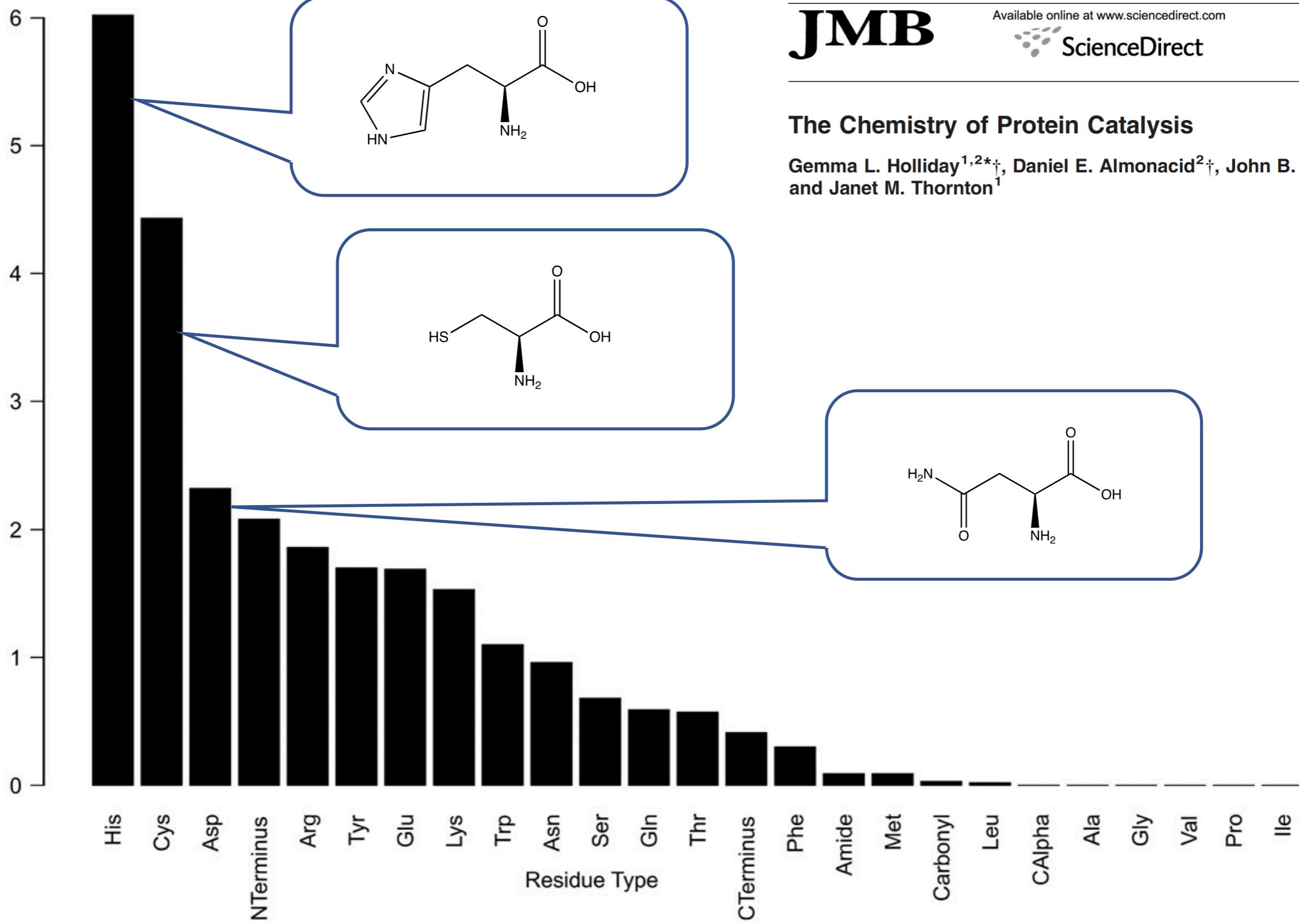
– bimolecular nucleophilic substitution (~120)

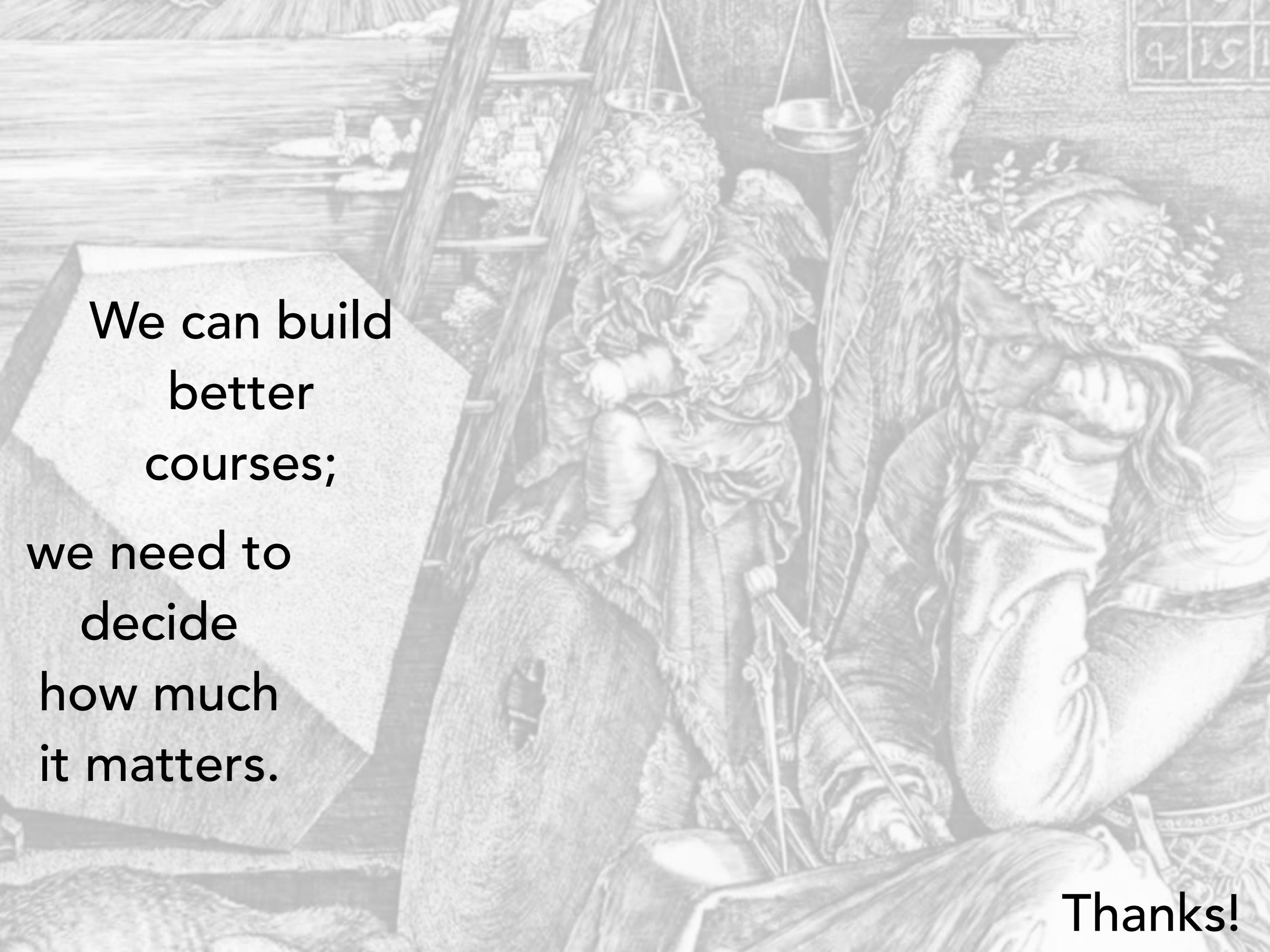
– electron transfer (~80)

– electron + hydride transfer (~50+50)

other mechanisms

Propensity





We can build  
better  
courses;  
we need to  
decide  
how much  
it matters.

Thanks!