3-6-2014

Systems Thinking with Biology Models

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Abstract for DBER Group Discussion on 2014-03-06

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Title:
Systems Thinking with Biology Models

Abstract:
The recent AAAS call to improve undergraduate biology education suggested university instruction should focus on teaching core concepts like matter and energy, evolution, and systems and core competences like quantitative reasoning, modeling and integrating disciplines. My research has focused on how undergraduate biology students organize their knowledge of biological systems and how they reason about the myriad interactions and potential outcomes inherent to these systems. I will report ongoing research into students’ model construction during an introductory biology course and during clinical interviews 2 years after the course. My colleagues and I have found students’ models change dramatically in both quantity and quality of biological relationships during the course. We believe this change in model quality comes from cognitive restructuring as students change from linear thinkers to more systemic thinkers. The enduring effect of model construction is manifest when, after a couple of years, some students are able to use the structure of their mental model to assist in recalling missing details and to apply their mental model to a new scenario. Model construction in Introductory Biology may be a useful tool as we strive to increase students’ understanding of biological interactions and stochasticity.
Research Questions

• How do student’s organize knowledge during introductory biology?
• Can they rely on this organization after leaving the course?
A framework for change in undergraduate biology

Core Concepts
1. Evolution
2. Structure and Function
3. Information Flow, Exchange, Storage
4. Pathways and Transformation of Matter and Energy
5. Systems

Core Competencies
1. Apply process of science
2. Reason quantitatively
3. Model and simulate
4. Connect science disciplines
5. Communicate with other disciplines
6. Relate science and society
Expectations versus Reality

We expect students to operate at higher cognitive levels…
  - Yet we test at the knowledge and comprehension level (Momsen et al. 2010)

We expect students to reason across biological scales…
  - Yet we align our courses and assess in a way that allows naïve conceptions to remain (Knight and Smith 2008)

Can we align our pedagogy in Introductory Biology to the way students learn about biological systems?
Goal: Build long-term memory

Long-term memory is interaction of
• New content
• Background knowledge
• How knowledge is constructed and stored

Nuthall and Alton-Lee 1995
How knowledge is stored

Existing knowledge is stored in schema

In biology, schema are not learned in isolation (Vosniadou 1994)

Relationships among schema make up the cognitive structure (Ifenthaler et al. 2011)

To show how cellular information is organized
Developing a Cognitive Structure

Cognitive Structure

Genetics Schema

Evolution Schema

Structures

Relationships
How are models representations of student’s cognitive structure?
Model construction

• Concept maps and models are tools for eliciting a student’s cognitive model (Shavelson et al. 2005)

• Drawing can improve scientific reasoning compared to textual representations (Löhner et al. 2005)

• Student-generated models focus attention on relationships between concepts (Vattam et al. 2011)
Explain the changes that occurred in the trees and animals. Use your current knowledge of evolution by natural selection.
Gaps in students’ evolutionary thinking

Student Errors
1. The origin of genetic variation
2. Gene inheritance
3. Reasoning at the level of organisms

Explain the changes that occurred in the trees and animals. Use your current understanding of evolution by natural selection

Bray Speth et al. 2009
Our study population

- Introductory Biology course for life science majors
- 2 sections – 366 students
- Mainly freshmen and sophomores
- 4 quizzes, Midterm Exam, and Final Exam
- Used tritiles based on GPA coming into course
  - Lower < 2.84
  - Middle 2.85 – 3.37
  - Upper > 3.38
Introduction to wolves in Isle Royale National Park, Michigan and the genes responsible for vertebrae formation.

Construct a box-and-arrow model that shows:
1. The origin of genetic variation among wolves;
2. The relationship between genetic variation and phenotypic variation in wolves, and
3. The consequence of phenotypic variation on wolf fitness.

Include the following structures in your model, but modify your language to make them specific to the wolf case.

allele, chromosome, DNA, fitness, gene, protein, phenotype
Student versions of models

- **G allele** determines protein
  - Protein expressed by G phenotype
  - G phenotype determines level of fitness

- **gene** codes for **DNA** which compacts to form chromosomes
  - Chromosomes determine **level of fitness**

- **Mutation** impacts nucleotide sequence, which helps in understanding the genetic makeup of organisms.

This diagram illustrates the relationship between genetic traits and their effects on fitness levels.
Quantifying Complexity

Web-like Complexity Index – percentage of structures with multiple relationships (adapted from Plate 2010)

WCI=0

WCI=0.2
Quantifying Correctness

Rubric developed to rate each relationship as:
- 1 – incorrect or no answer
- 2 – plausible (language lacks technical accuracy)
- 3 – technically correct (language conforms to scientific standards)

<table>
<thead>
<tr>
<th>From</th>
<th>allele</th>
</tr>
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<tbody>
<tr>
<td>To</td>
<td>phenotype</td>
</tr>
<tr>
<td></td>
<td>1 - has a, may be, when present in 2 produces, show in, creates</td>
</tr>
<tr>
<td></td>
<td>2 - causes, changes, corresponds/contribute to, codes for, determines, gives different version of, produces variation, expresses</td>
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<tr>
<td></td>
<td>3 - express traits in/through, expressed as</td>
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Changes in Correctness and Complexity

Dauer et al. 2013
Changes in Correctness and Complexity

Average Correctness vs. Web Complexity Index

- Upper
- Middle
- Lower

- Quiz 2 to Midterm
- Midterm to Final
Cognitive Development with Model Construction

Quiz 2 to Midterm:
- Accumulating and restructuring schema

Midterm to Final:
- “Tuning” their cognitive structure
Can we align our pedagogy in Introductory Biology to the way students learn about biological systems?

- Accumulating and restructuring takes time and effort. Students need opportunities to practice.
- The biology language is not simple. Instruction and assessment should emphasize the quality of relationships.
- Modeling can help lower-performing students.
Research Questions

• How do student’s organize knowledge during introductory biology?
• Can they rely on this organization after leaving the course?

Hypothesis: Students that developed a more complete cognitive structure will be able to retrieve that cognitive structure.
Retrieval Interview

• 30 students, 2.5 years after Introductory Biology (just before they graduated)

• Model Construction: similar to final exam model

• Cognitive Structure: questions about their knowledge
  – *Procedural knowledge*: “Why did you start with ___?”, “Were their terms you were unfamiliar with?”
  – *Relational knowledge*: “Describe the relationship you show between X and Y?”, “How does DNA fit?”
Introduction to stoneflies in the Kalamazoo River, Michigan and the genes responsible for exoskeleton permeability.

Construct a box-and-arrow model that shows:

1. The origin of genetic variation among stoneflies;
2. The relationship between genetic variation and phenotypic variation in stoneflies, and
3. The consequence of phenotypic variation on stonefly fitness.

Include the following structures in your model, but modify your language to make them specific to the stonefly case.

allele, chromosome, nucleotide, fitness, gene, protein, phenotype
Final Exam Models

Black = On average incorrect relationships
Red = On average plausible or technically correct
Change in Student Models

Interview Models (2.5 years later)

Final Exam Models

- Nucleotides
- DNA
- Protein
- Gene
- Allele
- Fitness
- Phenotype

Micro-scale
Macro-scale
Categorizing Students’ Cognitive Structures

Absent Cognitive Structure – no coherent explanation of the processes or concepts

Incomplete Cognitive Structure – some gaps, but good explanations

Complete Cognitive Structure – explained their model and the scenario as well as could be expected
# Categorizing Students’ Cognitive Structures

The table below shows the categorization based on transcripts:

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<tbody>
<tr>
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</tr>
<tr>
<td>Middle</td>
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<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Upper</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>
Model Quality

Mean model correctness (p < 0.045)

- Absent – 1.5
- Incomplete – 1.8
- Complete – 2.0

Complete students performed better on the model construction task
Searching for the Cognitive Structure

Most of the words/concepts provided were remembered
- 8 of 13 Incomplete students reported unfamiliar terms
- 2 of 9 Complete students reported unfamiliar terms

Complete students use their cognitive structures to compensate for unfamiliar terms.
Search within the cognitive structure

Prompt: Why did you organize your model in this way?

“in my mind I see how this goes together” (stu. 514)
“trying to piece it together in my head” (stu. 119)
“trying to remember my order of hierarchy” (stu. 208)

Students access a visual representation that may take the shape of a drawing or cognitive map (Nesbit and Adesope 2006).
Capturing the whole cognitive structure

Only 7 students started with an eye towards the overall function

“I started with nucleotide sequence because to me that’s what causes the difference. The main issue here is the difference in phenotype, and differences in genotype cause differences in phenotype” (stu. 342)

Experts more likely than novices to discuss or show the function of the model (Hmelo-Silver et al. 2006). Students still aren’t experts.
A missing cognitive structure?

Prompt: How do you think DNA fits into your model?

“I will go, after, by chromosomes, cause chromosomes, do you have two chromosomes? You have DNA, your chromosomes are DNA? DNA is chromosomes? Chromosomes. DNA.” (stu. 36)

Some schema are not connected in a cognitive structure and cannot be retrieved.
Conclusions

• Some students had long-term benefits of constructing models in Introductory Biology

• Some evidence to support the hypothesis that better developed cognitive structures help students compensate for gaps

• Modeling and drawing creates a visual and verbal representation for multiple access points (Paivio 1990, Verdi and Kulhavy 2002)
Can we align our pedagogy in Introductory Biology to the way students learn about biological systems?

- Emphasis on definitions has no long-term staying power
- Knowledge of cellular organization and functional relationships was vital
- Modeling can prepare student for future learning (Singha et al. 2013)
Research for Improved Student Learning

“One of the most important contributions that classroom research can make to the reform of schooling is to make transparent the underlying cognitive processes that determine how classroom activities shape the knowledge and minds of students.”

Nuthall 2000, pg. 129
Thank You

UG Collaborators

• Megan Gustafson
• Sasha Makohon-Moore
• Andy George
• Jon Walters
• Steve Grabinski
• Trisha Zdziarska
• Neelima Wagley
• Etiowo Usoro

Faculty Collaborators

• Tammy Long
• Jenni Momsen
• Diane Ebert-May
• Elena Bray-Speth
• Kristen Kostelnik
• Stephen Thomas
## Benefit analysis of conceptual modeling

### Benefits

1. Improves scientific reasoning  
   (Löhner et al. 2005)

2. Experts use them effectively  
   (Hmelo-Silver et al. 2007)

3. Focus students on relationships  

### Drawbacks

1. Grading
   - Time and reliability

2. Reflective of students’ thinking?

3. Cognitive load can be high  
   (Schwamborn et al. 2011)
Entering the Retrieval Cycle

Find the Cognitive Structure → Search within the Cognitive Structure → Verify the Quality of the Relationships