Seeing the forest through the trees: fostering abstract thinking to promote scientific reasoning

Rebecca Jordan
Rutgers University
Director, Program in Science Learning
School of Environmental and Biological Sciences
Scientific Reasoning

- Involves systematic thinking about multiple variables across scales, often using generalizations, in an effort to explain particular phenomena.

- This type of thinking requires abstractions or the reduction of specific parameters to enable thinking about the essential or important parts of the idea.
Models: Simplified Abstractions

Google image search: “scientific models”
Scientific Reasoning Permeates Practices

BOX 3-1

PRACTICES FOR K-12 SCIENCE CLASSROOMS

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information
Scientific Reasoning Permeates Practices

BOX 3-1

PRACTICES FOR K-12 SCIENCE CLASSROOMS

1. Asking questions (for science) and defining problems (for engineering)  
   - Evaluate Scientific Claims and Investigations

2. Developing possible answers (for science) or solutions (for engineering)

3. Planning and carrying out investigations
   - Support Scientific Claims with Evidence

4. Analyzing and interpreting data

5. Using mathematics and computational thinking

6. Constructing explanations (for science) and designing solutions (for engineering)

7. Engaging in argument from evidence

8. Obtaining, evaluating, and communicating information
Scientific Reasoning Permeates Practices

BOX 3-1

PRACTICES FOR K-12 SCIENCE CLASSROOMS

1. Asking questions (for science) and defining problems (for engineering)
2. Planning and carrying out investigations
3. Analyzing data
4. Using models
5. Constructing explanations (for science) and designing solutions (for engineering)
6. Engaging in argument from evidence
7. Obtaining, evaluating, and communicating information

- Evaluate Scientific Claims and Investigations
- Support Scientific Claims with Evidence
- Claims = Explanations = Models
- Argumentation
The Undergraduate Laboratory
Recipes and Cookbooks: steps for conducting investigations
Recipes and Cookbooks: steps for conducting investigations

Materials facilitating investigations
Recipes and Cookbooks: steps for conducting investigations

Materials facilitating investigations

Context dependent ideas and solutions
Laboratory Task
Laboratory Task

- Open-ended design task
  - Requiring global thinking
  - Additional materials

- Video Recorded and transcribed
  - Expert Students (animal behavior grad students)
  - Novice Students 1 (physics graduate students)
  - Novice Students 2 (undergraduate students)

- Emergent coding scheme
  - Themes
    - Context, Planning, & Creativity

*Jordan et al. (2011), JRST*
Context-novices

N1: How many different environments do we have?
N2: What can we use this stuff for?
N1: We have paintbrushes... so that’s probably to put the solution on the surface

From here, both novice groups created manipulations that focused entirely on using all of the available materials. This is also evident by one of the other pair’s conversation.
Context-experts

E1: Okay, so I mean what, you don’t know anything about these animals, and even before you came into this experiment, you would assume that they liked the glucose right, based on your biological...

E2: It's a basic energy source that many organisms use...

E1: Okay, so that’s a reasonable hypothesis to come up with...
Planning-novices

N1: so this is the type of environment, we have foil. Plastic, foil, we have this screen
N2: yeah are you trying to say that we should see which one they move on.

NSF ROLE-ISE, Transfer of Scientific Abilities (with Etkina and Hmelo-Silver )

Jordan et al. (2011), JRST
Planning-experts

“I think what we should do is have multiple trials of placing the isopods in the middle of this conveniently, I think our experimental design will be influenced by the materials we have... placing one or multiple isopods in the center, and having them, and measure how many.”

Jordan et al. (2011), JRST
Creativity-novices

N1: [We] should set up two different solutions in here and then see where the bugs go to

N2: Why don’t we put the two different textures in there and we can put them side by side and see which ones they go to.
Creativity-experts

E1: we can’t be for certain that the acidic nature it is interacting with, it is enjoying... it could be for example, what kind of vinegar is it?
E2: No, there are different kinds of vinegar, it's not balsamic vinegar
E1: it can be any kind of vinegar, any compound of vinegar that it's going to
E2: in order to generalize for the fact that it's enjoying the acid, you’d have to...
Controlled Study

Will the removal of laboratory materials during initial discussions result in more planning, creativity, and ideas that are not tied to the lab bench?

Design two experiments to determine transpiration rate using stem cuttings from a single species of plant.

With Materials: water, beaker holding plant cuttings, Parafilm®, tubing, ring stand, graduated pipette, timers, humidity sensor, cup, cup with hole, scissors, and two droppers.

---

NSF ROLE-ISE, Transfer of Scientific Abilities (with Etkina and Hmelo-Silver)

Jordan et al. (2011), JRST
Controlled Study

Will the removal of laboratory materials during initial discussions result in more planning, creativity, and ideas that are not tied to the lab bench?

Design two experiments to determine transpiration rate using stem cuttings from a single species of plant. Without Materials

NSF ROLE-ISE, Transfer of Scientific Abilities (with Etkina and Hmelo-Silver )

Jordan et al. (2011), JRST
Hypothesis

Encouraging discussion prior to dissemination of the laboratory materials would result more sophisticated (i.e., compared to expert) discussions with respect to planning, creativity, and context and that by directing the students to more sophisticated activities time to task completion will decrease.

NSF ROLE-ISE, Transfer of Scientific Abilities (with Etkina and Hmelo-Silver)  

Jordan et al. (2011), JRST
| Context       | Refers to the extent to which the discussion focuses on elements of the laboratory environment versus the elements beyond. In the case of the ethology task elements beyond likely refer to the habitat of the animals |

NSF ROLE-ISE, Transfer of Scientific Abilities (with Etkina and Hmelo-Silver)  

*Jordan et al. (2011), JRST*
Coding

| Context | Refers to the extent to which the discussion focuses on elements of the laboratory environment versus the elements beyond. In the case of the etymology task elements beyond likely refer to the habitat of the animals |
| Planning | Refers to the extent to which the discussion focuses on experimental design, hypotheses, and outcomes with respect to the task goals versus a sole focus on the task with reference to laboratory materials alone |

NSF ROLE-ISE, Transfer of Scientific Abilities (with Etkina and Hmelo-Silver)  

*Jordan et al. (2011), JRST*
Coding

NSF ROLE-ISE, Transfer of Scientific Abilities (with Etkina and Hmelo-Silver)

Jordan et al. (2011), JRST
### Table 4

Controlled experiment averages. Average scores and standard deviations (in parentheses) across 12 groups in each treatment (i.e., with or without materials). TTC represents time to completion and is given in minutes. The coded variables (i.e., planning, context, and creativity) were coded in four categories ranging from 0-3. See Table 3 for a description.

<table>
<thead>
<tr>
<th></th>
<th>With Materials</th>
<th>Without Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC</td>
<td>27.17 (4.82)</td>
<td>14.33 (5.84)</td>
</tr>
<tr>
<td>Planning</td>
<td>1.50 (0.52)</td>
<td>2.25 (0.62)</td>
</tr>
<tr>
<td>Context</td>
<td>2.00 (0.74)</td>
<td>2.75 (0.62)</td>
</tr>
<tr>
<td>Creativity</td>
<td>1.83 (0.83)</td>
<td>2.58 (0.67)</td>
</tr>
</tbody>
</table>

TTC in Minutes
Scaled 0-3. The greater the number, the more sophisticated the average response.

*TTC (F(1,23) = 34.49, p< 0.001)
*planning, context, and creativity (F(1,71) = 22.23, p< 0.001.).
Laboratory materials?

<table>
<thead>
<tr>
<th></th>
<th>With Materials</th>
<th>Without Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTC</td>
<td>27.17 (4.82)</td>
<td>14.33 (5.84)</td>
</tr>
<tr>
<td>Planning</td>
<td>1.50 (0.52)</td>
<td>2.25 (0.62)</td>
</tr>
<tr>
<td>Context</td>
<td>2.00 (0.74)</td>
<td>2.75 (0.62)</td>
</tr>
<tr>
<td>Creativity</td>
<td>1.83 (0.83)</td>
<td>2.58 (0.67)</td>
</tr>
</tbody>
</table>

TTC in Minutes
Scaled 0-3. The greater the number, the more sophisticated the average response

*TTC (F(1,23) = 34.49, p< 0.001)
*planning, context, and creativity (F(1,71) = 22.23, p< 0.001.)
Controlled Study

Will the removal of laboratory materials during initial discussions result in more planning, creativity, and ideas that are not tied to the lab bench?

- Design two experiments to determine transpiration rate using stem cuttings from a single species of plant.
- **With Materials:** water, beaker holding plant cuttings, Parafilm®, tubing, ring stand, graduated pipette, timers, humidity sensor, cup, cup with hole, scissors, and two droppers.

-- Jordan et al. (2011), JRST
Novice students, when posed with a typical laboratory based experimental task are likely to quickly focus on the available materials, procedures, and narrower contexts when compared to the directed and global discussion of the expert group.
Image of Science?

Jordan and Duncan (2009), JBE
Image of Science?
Lack of Integration between classroom context and the lived world?

1. Expert learners planned and discussed global contexts and discussed more solutions than novice students.

2. Novice students do more planning, discussion of global contexts, and pose more solutions without being given materials first AND in doing so they are moving *between the context and a semi-generic layer of abstraction*. 
(Internal processes) $\rightarrow$ Conceptual Representations (CR)

= internal or cognitive framework for organizing ideas

Cindy Hmelo-Silver: Discussed the development and use of SBF and then CMP as a CR for reasoning about systems.

Helped learners to move beyond what is visible and beyond linear narratives to more complex and dynamic accounts in their work with models.

***But...transfer is limited, HO: moving between contexts with the mechanisms (and evidences) that they are learning about.
(Internal processes) \(\rightarrow\) Conceptual Representations (CR)

= internal or cognitive framework for organizing ideas

Cindy Hmelo-Silver: Discussed the development and use of SBF and then CMP as a CR for reasoning about systems.

Helped learners to move beyond what is visible and beyond linear narratives to more complex and dynamic accounts in their work with models.

***But...transfer is limited, HO: moving between contexts with the mechanisms (and evidences) that they are learning about.
CMP 2.0 = PMC-2E (Explanations and Evidence)

<table>
<thead>
<tr>
<th>System element</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>P = Phenomena</td>
<td>Overall pattern or outcome that is explicitly being explained in the model</td>
</tr>
<tr>
<td>M = Mechanism</td>
<td>Processes that are generic (i.e., happen in other systems) and specific to the phenomena being represented. (Note if students did not explicitly represent a phenomena their model received a P = 0, but for mechanism the phenomena was inferred based on the curriculum)</td>
</tr>
<tr>
<td>C = Components</td>
<td>Physical parts that exist in the system</td>
</tr>
</tbody>
</table>

Question: Why have the fish died?
Phenomena: Dead fish.
What could have happened?

Dead Fish

NSF, Learning About Complex Systems in Middle School by Constructing Structure Behavior Function Models (with Hmelo-Silver and Goel)
What could have happened?

Possible mechanisms?
Starvation
Not enough oxygen
Too much carbon dioxide
Preyed upon
Disease
Pollution
Etc.

Dead Fish
What could have happened?

Possible mechanisms?
Starvation
Not enough oxygen
Too much carbon dioxide
Preyed upon
Disease
Pollution
Etc.

Dead Fish

What is plausible?
Structures/components?
Fish
Food? Predators?
Illnesses, Crowding (of what kind?), Pollutants, Rocks, etc.
Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Evidence → Related to the Dead Fish

Notes:
- Explanations
- Fish → Oxygen
- Lots of fish will use up the oxygen
- Fish need oxygen to live

Possible mechanisms?
- Starvation
- Not enough oxygen
- Too much carbon dioxide
- Preyed upon
- Disease
- Pollution
- Etc.

Notes:
- Evidence
- Fish → Oxygen
- Mechanisms: Respiration
- Data: fish tank death correlated with decreased oxygen levels

What is plausible?
- Structures/components?
- Fish
- Food? Predators?
- Illnesses, Crowding (of what kind?), Pollutants, Rocks, etc.

Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Formalization: ecomodeler (ecomodeler.org)

Department of Education: Institute of Educational Studies. Using Structure-Behavior-Function (SBF) Ontology to engage students in ecosystem studies, in collaboration with Georgia Tech. (with Hmelo-Silver and Goel)
Hypothesis

Using pre-post drawing task assessments, we test the hypothesis that—after completing a PMC-2E rich curriculum—students will create more mechanistic explanations (when compared to the pre-assessment).

Methods: Course layout

<table>
<thead>
<tr>
<th>Week</th>
<th>Assignment</th>
<th>Activity</th>
<th>Model collection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
<td>Introduction</td>
<td>Pre individual, Pre Collaborative Models</td>
</tr>
<tr>
<td>2</td>
<td>Reading paper</td>
<td>Identify key environmental issues</td>
<td>None</td>
</tr>
<tr>
<td>3</td>
<td>Reading paper</td>
<td>Outdoors and science</td>
<td>None, created paper models</td>
</tr>
<tr>
<td>4</td>
<td>Field trip</td>
<td>Field Trip: outdoors</td>
<td>None</td>
</tr>
<tr>
<td>5</td>
<td>Quiz 1</td>
<td>Issue investigation</td>
<td>None, but 1 question on modeling was included.</td>
</tr>
<tr>
<td>6</td>
<td>Reading paper</td>
<td>Eutrophication</td>
<td>Ecomodel Eutrophication</td>
</tr>
<tr>
<td>7</td>
<td>Reading paper</td>
<td>Eutrophication</td>
<td>Drawings turned in</td>
</tr>
<tr>
<td>8</td>
<td>Teaching</td>
<td>Teaching presentation</td>
<td>None</td>
</tr>
<tr>
<td>9</td>
<td>Reading paper</td>
<td>Carbon Mitigation</td>
<td>Ecomodel Carbon Mitigation</td>
</tr>
<tr>
<td>10</td>
<td>Reading paper</td>
<td>Carbon Mitigation</td>
<td>Drawings turned in</td>
</tr>
<tr>
<td>11</td>
<td>Teaching</td>
<td>Unit presentation</td>
<td>None</td>
</tr>
<tr>
<td>12</td>
<td>Quiz 2</td>
<td>Environmental communication</td>
<td>None, but 1 question on modeling was included.</td>
</tr>
<tr>
<td>13</td>
<td>Reading paper</td>
<td>Bringing themes together</td>
<td>Post individual models, Post Collaborative Models</td>
</tr>
<tr>
<td>14</td>
<td>Final xxam</td>
<td>Final exam</td>
<td>None</td>
</tr>
</tbody>
</table>

Methods: Data Sources

<table>
<thead>
<tr>
<th>Data source</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing task-pre-post</td>
<td>Classroom</td>
</tr>
<tr>
<td>Ecomodeler-collaborative model</td>
<td>Classroom</td>
</tr>
<tr>
<td>Ecomodeler-eutrophication</td>
<td>Homework</td>
</tr>
<tr>
<td>Ecomodeler-carbon mitigation</td>
<td>Homework</td>
</tr>
<tr>
<td>Drawing task-terrestrial model</td>
<td>Classroom</td>
</tr>
<tr>
<td>Drawing task-microbial model</td>
<td>Classroom</td>
</tr>
<tr>
<td>Drawing task-pre-post</td>
<td>Classroom</td>
</tr>
<tr>
<td>Ecomodeler-collaborative model</td>
<td>Classroom</td>
</tr>
</tbody>
</table>

Methods: Coding models

Methods: Coding models

Change in # of modeled phenomena from pre to post
Out of 13 students

<table>
<thead>
<tr>
<th># Students</th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Results: Mechanism

Change in mechanisms from pre to post
Out of 13 students

<table>
<thead>
<tr>
<th># Students</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Added mechanisms</td>
</tr>
<tr>
<td>2</td>
<td>No Change</td>
</tr>
<tr>
<td>3</td>
<td>No mechanisms</td>
</tr>
</tbody>
</table>

Results: Collaboration

Average number of conceptual representation (CR) elements compared between individual and group models.

<table>
<thead>
<tr>
<th>CR</th>
<th>Individual</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenomena</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Mechanism</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Components</td>
<td>7.2</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Results

Final model sophistication* was highly correlated with students’ overall course grade** (r = 0.854, p < 0.000, n = 13).

*Included mechanistic explanations supported by data
**Models only 5% of course grade.

This small classroom test was used to inform a broader curriculum committee about model-based learning for our introductory life science courses.

From the Micro to the Meso...
Modeling as a way of life in the classroom
CRs as a critical scaffold
Models as...tools for thinking and assessment in the classroom: ecomodeler
Models as tools for community learning and decision-making: MentalModeler

NSF. IIS – Cyberlearning: Sustaining ecological communities through citizen science and online collaboration
Problem Based Learning: Asian Tiger Mosquito Control

Collaborative Model Building

Establishes the need to know

- Evidence to support/refute model

Need to:
- Link between data and model
- Refine model

Employing readily available tools...

Testing multiple plausible alternatives

Making the most out of the given time...

...and making the most out of the context

- The varying context is essential for abstraction
What does “in the field” mean in science?
Or Here?
Where is the science laboratory?
Here?
Ever changing science identity of our learners

Cyber-enabled authentic science

NSF. IIS – Cyberlearning: Sustaining ecological communities through citizen science and online collaboration 

(Jordan et al. 2016, Conservation Biology)
Who are our learners?
What questions are relevant to ask?
Foster integration and abstraction socio-ecologically = systems thinking

• Bio-Physical (aka the science!) + Social Systems
• Dynamically Interacting → Resilience
  • Capacity to respond to change
Q1: What is the role of riparian buffers along this stream?
NSF. IIS – Cyberlearning:-Sustaining ecological communities through citizen science and online collaboration
Water Sampling
Supporting the model with Evidence

Data Collection (Monthly):
- Bacterial Coliform and *E. Coli*
- Presence/Absence Cows
- Sedimentation
- Prior Stream Buffering
Supporting the model with Evidence

Data Collection (Monthly):
- Bacterial Coliform and *E. Coli*
- Presence/Absence Cows
- Sedimentation
- Prior Stream Buffering
Supporting the model with Evidence

Data Collection (Monthly):
Bacterial Coliform and E. Coli Presence/Absence Cows
Sedimentation
Prior Stream Buffering
Q2. Does unmanaged container habitat in underserved neighborhoods support greater mosquito production?
Community Citizen Science

- Highly Urbanized West-Baltimore Neighborhoods
- Non-engaged community in terms of local decision-making, underserved with respect to municipal resources

(Jordan, et al. 2016, CB)

Habitat Assessment

Meso to Macro

• Systemic change through institutional leaders
  • Time consuming
  • Iterative
  • Collaborative
Michigan State University
The burden of positive change falls on the champions and leaders to remind us all of the shared vision but making a safe place for us to model and test models collaboratively...
The burden of positive change falls on the champions and leaders to remind us all of the shared vision but making a safe place for us to model and test models collaboratively...
Collaborative Decision-Making (evidence)!

Socio-Environmental Synthesis Center, Annapolis, MD Pursuit (With R. Shwom)
“If we knew what we were doing it would not be called research”
A. Einstein

Thank you!
Special thanks to S. Gray and A. Sorensen