Improving Introductory STEM Course Sequences to Provide Cohesive, Cross-Disciplinary Experiences

Alo Basu, Ph.D.
Emily Borda, Ph.D.
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Integrative STEM Pedagogy: Courses, Curricula and Culture Change for Inclusive Excellence

Alo Basu
Associate Professor
Director, Neuroscience Program
College of the Holy Cross
Worcester, MA
Overall goal: Inclusive excellence in STEM

**Working definition:** Inclusive Excellence (IE) in STEM is the principle that the successful future of STEM is dependent on how well the full diversity of students is valued, engaged and included in STEM learning.

A **student-centered view** considers diverse:
- **Perspectives and goals** as individuals
- **Approaches** to the curriculum and programs
- **Patterns of exposures** to the curriculum and context
- **Emotional responses** and identity development

An **achievement-oriented framework** means:
- **Aiming questions** at factors that promote achievement
- **Creating new opportunities** for students to achieve
- **Taking responsibility** for all students
- **Actively eschewing** a deficit-oriented framework

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Currently, the introductory STEM learning environment can be a hard place to make connections across disciplines or develop a flexible identity as a STEM student.

Integrative STEM courses and curricula can provide new opportunities for students to learn STEM concepts and practice integrative thinking skills.

Pursuit of inclusive excellence in STEM requires that educators think more broadly than departmental/disciplinary perspectives to adopt a student-centered perspective.

Integrative thinking is the flexible use of knowledge and tools from multiple disciplines.

A project to learn about foundational STEM learning goals

- Immersive, *embodied* curriculum mapping project

- Audited 4 courses that I last took in AY 1993-94
  - MATH 135: Calculus 1
  - PHYS 116: Introductory Physics 2
  - BIOL 161: Introduction to Cell and Molecular Biology
  - CHEM 181: Atoms & Molecules

- Attended almost all lectures; completed problem sets, quizzes and exams

- Instructors were tenured faculty, outstanding teachers, close colleagues

*A way to learn about the learning environment that is not extractive towards students*
Who am I?

- A person of color, South Asian American
- A cis woman
- A neurobiologist
- An educator
- A graduate of elite universities
- A 3rd generation Ph.D.

Recognizing my own sources of privilege is an important step toward understanding how social factors may affect learning.
We often attempt to interpret people’s grades - here are mine

<table>
<thead>
<tr>
<th>Course</th>
<th>Exam 1</th>
<th>Exam 2</th>
<th>Exam 3</th>
<th>Exam 4</th>
<th>Exam 5</th>
<th>Final Exam</th>
<th>Course Grade</th>
<th>Hours per week</th>
<th>Hours Total</th>
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</thead>
<tbody>
<tr>
<td>BIOL 161</td>
<td>98%</td>
<td>94%</td>
<td>83%</td>
<td></td>
<td>??</td>
<td>A-? (no lab)</td>
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<td>4</td>
<td>71</td>
</tr>
<tr>
<td>CHEM 181</td>
<td>81%</td>
<td>91%</td>
<td>97%*</td>
<td>83%</td>
<td>88%</td>
<td>?</td>
<td>A-? (no lab)</td>
<td>6</td>
<td>98</td>
</tr>
<tr>
<td>PHYS 116</td>
<td>64%</td>
<td>93%</td>
<td>79%</td>
<td></td>
<td>95%</td>
<td>B-?</td>
<td></td>
<td>14</td>
<td>237</td>
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<tr>
<td>MATH 135</td>
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<td>A</td>
<td></td>
<td>12</td>
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<td>601</td>
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</tbody>
</table>

My Holy Cross GPA from introductory STEM courses is ~3.5-3.6 -- lower than my final GPA as an MIT undergrad (Class of ‘97, double majoring in Brain & Cognitive Sciences and Biology).
What did I find out that is relevant to cross-disciplinary learning?

• Curriculum mapping is a useful *tool* for identifying concepts and skills used in multiple introductory STEM courses.

• Foundational concepts are presented differently in different disciplines, with *distinct learning goals* and emphases.

• Common *assessment and communication practices* pose challenges to developing a flexible identity as a STEM student.
Underlying concepts and skills required before the first exam in Introductory Biology, Chemistry, Calculus

Certain concepts and skills are assumed heavily in multiple introductory courses. **CAVEAT:** There are pitfalls of using this information to design deficit-remedial interventions.
Sometimes students may not make connections across courses

**Reaction rate and equilibrium**

Ex. glucose-1-phosphate $\rightarrow$ glucose-6-phosphate

$K = \frac{[P7]}{[R]}$ 19

Chemistry:

$K_a = \frac{[CH_3COOH][Cl^-]}{[CH_3COOH]}$

Acids: H ions and H+ ions may charge in spread over many electronegative atoms.

**Molecular dipoles and dipole moments**

A dipole is a separation of opposite electrical charges within a molecule and a dipole moment is a vector quantity representing the net polarity of the molecule.

**Can learning increase through awareness of overlapping learning goals between courses?**
Dipoles: The points that got away

Can learning increase through awareness of overlapping learning goals between courses?
Common verbal references to disciplinary boundaries and identity

**Boundary-reinforcing**

- “hello, <biologists/chemists/physicists/etc.>”
- “…think like a <biologist/chemist/physicist/etc.>”
- “this is the <biology/chemistry/physics/etc.> way, so it is the right way!”

**More open to diverse student experiences**

- “hello, <students/students of science>”
- “adopt a <disciplinary> perspective on this <concept/question/problem>”
- “you may encounter this concept in <other discipline(s)>; in this context, we <use/represent> it in this way because <explanation>.”

Will taking time to neutralize communication result in net learning gains and transfer?
Claims

- Currently, the introductory STEM learning environment can be a **hard place** to make connections across disciplines or develop a flexible identity as a STEM student.

- Integrative STEM courses and curricula can **provide new opportunities** for students to learn STEM concepts and practice integrative thinking skills.

- Pursuit of inclusive excellence in STEM **requires** that educators think more broadly than departmental/disciplinary perspectives to adopt a student-centered perspective.

*Integrative thinking is the flexible use of knowledge and tools from multiple disciplines.*

Design of an integrative STEM course for first-semester students

- Collaborative identification of neuroscience learning goals
- Collaborative identification of STEM learning goals
- Co-design of modules with faculty from biology, chemistry, physics, math, CS
- Enrollment based on interest in studying neuroscience and other STEM subjects
- Application of inclusive pedagogy principles
  - instructor growth mindset and responsibility for all students
  - multiple modes of engagement and assessment
  - affirmation of diverse identities and social constructivist learning approaches
  - learning materials for underlying concepts and skills built into assignments


Opportunities for integrative STEM learning at introductory level

<table>
<thead>
<tr>
<th>STEM Concept</th>
<th>Learning Goal for Introduction to Neuroscience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Theory</td>
<td>Cellular specializations of neurons</td>
</tr>
<tr>
<td>Central Dogma of Molecular Biology</td>
<td>Molecular specializations of neurons</td>
</tr>
<tr>
<td>Ions and Electrochemical Gradients</td>
<td>Ion transport underlying neuronal excitability</td>
</tr>
<tr>
<td>Lewis Structures, Amino Acids</td>
<td>Neurotransmitter structure and biosynthesis</td>
</tr>
<tr>
<td>Oscillations</td>
<td>Action potential waveform, firing rate</td>
</tr>
<tr>
<td>Ohm’s Law</td>
<td>Relationships between current, ionic conductance, and voltage (as they relate to membrane potential)</td>
</tr>
<tr>
<td>Natural Log Function</td>
<td>Goldman-Hodgkin-Katz equation for membrane potential</td>
</tr>
</tbody>
</table>
Integrative STEM exposure increases interdisciplinary awareness

What is neuroscience? Week 1 versus Week 14


An integrative STEM core curriculum for neuroscience

“...a ‘spiral curriculum.’...One starts somewhere—where the learner is. And one starts whenever the student arrives to begin his career as a learner.” - J.S. Bruner


Claims

- Currently, the introductory STEM learning environment is a hard place to learn how to make connections across disciplines or develop a flexible identity as a STEM student.

- Integrative STEM courses and curricula can provide new opportunities for students to learn STEM concepts and practice integrative thinking skills.

- Pursuit of inclusive excellence in STEM requires that educators think more broadly than departmental/disciplinary perspectives to adopt a student-centered perspective.

\textbf{Integrative thinking is the flexible use of knowledge and tools from multiple disciplines.}

Reasons to move beyond departmental/disciplinary perspectives

- **Identifying** common or related learning goals for STEM students broadly construed
- **Exchanging and sharing** disciplinary pedagogical expertise
- **Saving time** in the STEM curriculum for activities that increase overall learning and transfer
- **Advocating collectively** for strategic allocation of teaching and learning resources
- **Assessing** outcomes according to a broad achievement-oriented framework

*Creating an inclusive and affirming “all-STEM” culture*
Summary of recommendations

- Take a *student’s view of the curriculum* and communicate across disciplines about common learning goals.

- **Reduce** the use of language that prematurely imposes discipline-specific identity on students.

- **Promote** communication, cooperation, and collaboration among faculty across disciplines in the pursuit of curricular transformation.

- Embed integrative STEM teaching and learning opportunities within an *achievement-oriented framework*.

*Envision and destigmatize an inclusive future for STEM.*

THANK YOU to many colleagues

**Neuroscience Curriculum Development**
- Alexis Hill (Biology/Neuroscience)
- Ryan Mruczek (Psychology/Neuroscience)
- André Isaacs (Chemistry)
- Michelle Mondoux (Biology)
- Tomohiko Narita (Physics)
- Stanzi Royden (Computer Science/Neuroscience)

**Broader Perspectives**
- Kelly Saintelus (Academic Services & Learning Resources)
- Ann Marie Leshkowich (Dean, Anthropology)
- Lauren Capotosto (Education)
- **Students**

**Curriculum Mapping & Applications**
- Tomohiko Narita (Physics)
- Amber Hupp (Chemistry)
- Ann Sheehy (Biology)
- Alisa DeStefano (Mathematics)
- André Isaacs (Chemistry)
- Andrew Hwang (Mathematics)
- Richard Lent (Educational Technology)

**Administration**
- Margaret Freije (Provost, Mathematics)
- Madeline Vargas (Dean, Biology)

**Encouragement**
- Barbara Lom (Biology, Davidson College)
THANK YOU for your interest, and welcome to the discussion!

Building an inclusive and collaborative “all-STEM” culture

Alo Basu
Associate Professor
Director of Neuroscience Program
College of the Holy Cross, MA

What curriculum and faculty development strategies can help foster an inclusive and collaborative culture across STEM disciplines?

abasu@holycross.edu

Design of integrative STEM assignments for diverse learners

Alexis Hill
Assistant Professor
Biology, Neuroscience
College of the Holy Cross, MA

What are some strategies for designing integrative STEM assignments and assessments to be suitable for students with a wide range of prior academic exposures?

Reducing social reinforcement of disciplinary boundaries in STEM

Michelle Tong
Assistant Professor
Neuroscience, Biology
University of St. Thomas, MN

What are some ways that instructors might reduce disciplinary boundaries in the learning environment to affirm diverse academic and social backgrounds?
Concrete indicators of an achievement-oriented framework

- **Enrollment**
  - Participation in STEM courses
  - Continuation within STEM (same and/or other disciplines)
  - Majoring and/or minoring in STEM programs

- **Enrichment**
  - Participation in co-curricular opportunities and enrichment programs
  - Meaningful mentoring relationships with faculty and staff
  - Participation in research

- **Achievement**
  - Academic merit-based honors and awards
  - Continuation to STEM-related graduate education
  - Continuation to STEM-related postgraduate occupations

- **Qualitative metrics - e.g., sense of belonging, self-efficacy, identity, motivation**
Curriculum mapping applications

• Analyzing content for curriculum review/transition
• Analyzing content for curriculum sequencing
• Coordinating content for purposes of coverage
• Coordinating content for purposes of integration of multiple courses
• Creating content to address gaps in curriculum
• Creating content for integrative courses
• Creating bridge courses
## Opportunities for Integrative STEM learning at intermediate level

<table>
<thead>
<tr>
<th>Physics Concepts</th>
<th>Learning Goals for Neuroethology</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC Circuits and Ohm’s Law</td>
<td>Excitability of the neuronal membrane</td>
</tr>
<tr>
<td>The Electromagnetic Spectrum</td>
<td>UV and infrared sensing; navigation of bees by polarized light detection</td>
</tr>
<tr>
<td>Optics</td>
<td>Comparative evolution of the eye</td>
</tr>
<tr>
<td>Oscillations</td>
<td>Echolocation by bats</td>
</tr>
<tr>
<td>Mechanics and Energy</td>
<td>Diverse forms of locomotion</td>
</tr>
<tr>
<td>Electric and Magnetic Fields</td>
<td>Electoreception and magnetoreception</td>
</tr>
</tbody>
</table>

**Current question:** *Can we increase the value of this course for physics students?*

*Co-instructor Tomohiko Narita, Physics*
Multiple modes of faculty collaboration across disciplines

Assessing learning across science disciplines

Emily Borda
chemistry/science education

Andrew Boudreaux
physics/science education

Todd Haskell
psychology
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- Lauren Stredicke
- Jessica Trottier
- Autumn Welker
- Luke Westbrook

- Co-PI: Sara Julin
- Student Participants
- Advisory Board:
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  - Ben Geller
  - Amy Robertson
- Funding: NSF-IUSE DUE-1612251
Goals of this workshop

- Define cross-disciplinary learning
- Think about how to recognize, and thus reward, cross-disciplinary learning in STEM programs
Amara is beginning her second term at university. She hopes to become an engineer and has thrown herself enthusiastically into her coursework. Despite this, she struggled in first-semester physics and chemistry. In her second chemistry course, she is learning about exothermic and endothermic reactions. When the class discusses the combustion of methane as an exothermic reaction, Amara is puzzled that energy seems to come from nowhere. She remembers the Law of Conservation of Energy from physics and thinks, “The energy must come from somewhere, but from where?” Her professor says something about energy being stored in the methane, which makes Amara think of potential energy, another idea she studied in physics. She recalls an example of a skateboarder riding down a hill, in which potential energy was transformed into kinetic energy. She wonders if potential energy is transforming as methane burns, but isn’t sure what potential energy is for methane or what other type of energy it is transformed into.

Miguel is in the same second-term chemistry course. An aspiring biochemist, he studied hard during his first term and earned top grades in both physics and chemistry. Now, during the class discussion of methane combustion, he writes down notes and definitions, highlights words like enthalpy, and memorizes heuristics such as exothermic = exit and endothermic = enter. He launches into learning these new facts. “Energy again,” he thinks. “Enthalpy must be a new type of energy for chemistry. Glad we’re not talking about that potential energy stuff anymore.”

Compare Amara’s and Miguel’s approaches to learning. What appeals to you? What concerns you?
Context for our work: Science course series for preservice teachers

- Unifying theme: Flow of matter and energy
- Physics course is a prerequisite for the other 3 courses
- Next Generation Physics & Everyday Thinking (NGPET) used in physics
- Curricula for other courses collaboratively developed locally using NGPET as a model

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Cross-disciplinary learning is a process of sequential learning in which students activate, transform, and integrate knowledge from different disciplines, combining previous learning with new learning to construct new knowledge within a specific discipline.

Connecting cross-disciplinary learning to existing frameworks

- Conceptual Resources

Connecting cross-disciplinary learning to existing frameworks

- **Conceptual Resources**


- **Interdisciplinary reasoning and communication**

Connecting cross-disciplinary learning to existing frameworks

- Conceptual Resources
  

- Interdisciplinary reasoning and communication
  

- Preparation for Future Learning (PFL) Transfer
  

She wonders if potential energy is transforming as methane burns, but isn’t sure what potential energy is for methane or what other type of energy it is transformed into.

- Recognition/Activation:
  
  Energy transforms from potential to kinetic as a skateboarder rides down a hill

- Knowledge from physics class
  
  Potential energy in methane is being transformed into another type of energy when methane combusts

- Integration
  
  Potential energy can be transformed into other types of energy

- Heat is released when methane combusts

- Knowledge from chemistry class
  
  Energy cannot be created or destroyed
Cross-disciplinary learning

How could a focus on cross-disciplinary learning affect students’ sense of belonging in STEM?

She wonders if potential energy is transforming as methane burns, but isn’t sure what potential energy is for methane or what other type of energy it is transformed into.

Potential energy in methane is being transformed into another type of energy when methane combuts

Integration

Transformation

Potential energy can be transformed into other types of energy

Recognition/Activation:

Knowledge from physics class:
- Energy transforms from potential to kinetic as a skateboarder rides down a hill

Knowledge from chemistry class:
- Heat is released when methane combuts
- Energy cannot be created or destroyed

Energy from physics class:
- Energy tranforms from potential to kinetic as a skateboarder rides down a hill
How could a focus on cross-disciplinary learning affect students’ sense of belonging in STEM?
Energy as a cross-cutting concept

Energy:
- is associated with objects
- is represented as a quantity
- can increase or decrease
- can transfer from one object to another
- has different forms
- each of which has an observable indicator
- can transform
- is conserved


Measuring cross-disciplinary learning of energy

Quantitative: Paired instrument set

- To what extent do students apply the conservation principle across disciplines?
Measuring cross-disciplinary learning of energy

Quantitative: Paired instrument set
- To what extent do students apply the conservation principle across disciplines?

Qualitative: Cross-disciplinary think-aloud interviews
- What resources do students use, and how do they use them, when reasoning with energy across disciplines?
Example items from paired instrument set:

1. Chemistry
2. Physics

As shown at right, an electron in a hydrogen atom jumps from a lower to a higher shell. The speed of the electron is the same before and after the jump. From the earlier to the later time:

a. There was an energy transfer to the hydrogen atom from the environment.
b. There was an energy transfer from the hydrogen atom to the environment.
c. There was zero energy transfer.

For this question, assume that the effects of air resistance are negligible. A child, standing on the ground, throws a ball up to an adult, who is standing on a deck above the level of the ground. After the ball has left the child’s hand, and while it is moving upward:

a. the total energy (gravitational potential energy + kinetic energy) of the ball-Earth system increases
b. the total energy decreases
c. the total energy remains constant

Teaching narratives place focus of assessment on reasoning

- Defines parts of the atom and how they interact
- Describes how electrostatic potential energy increases and decreases when an electron gets farther away from and closer to a proton
- Explains how electrostatic potential energy combines with kinetic energy to sum to total energy.
- Asks two comprehension questions about these concepts.
Administration and scoring of paired instrument set

- Chemistry administered first to avoid cueing
- Physics score is used to predict chemistry score
- “Concept Integration index” is based on the deviation between predicted and actual score
Administration and scoring of paired instrument set

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Administration and scoring of paired instrument set

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Todd’s Breakout Room
Qualitative approach: Think-aloud interviews

Overall goal: Probe how students transform and integrate conceptual resources for energy across disciplines

- Biology Scenario 1
- Biology Scenario 2
- Physics Scenario A
- Geology Scenario 1
- Geology Scenario 2
- Physics Scenario B
- Chemistry Scenario 1
- Chemistry Scenario 2
- Physics Scenario C
Example: Chemistry

A flask is filled with powder and placed on a room temperature table. A liquid is added to the powder and a stopper is added to the top of the flask. As soon as the substances are mixed, you observe fizzing and bubbling in the mixture. After a few minutes, the stopper pops off the flask. Create a scientific explanation to answer the question, “Why did the stopper pop off of the flask?” As the reaction progressed, you noticed that the flask became warm. Create a scientific explanation to answer the question, “why did the glass get warm?”

You hold two magnets, one in each hand, that are attracted to each other, on top of a low-friction table. You give each a tap so that they move farther away from each other. As they do so, they slow down. The magnets eventually stop, then start moving toward each other. Create scientific explanations to answer the question, “Why do the magnets slow down as they move farther apart from each other?” “Why do the magnets stop and begin to move toward each other?”
Analyzing interview transcripts

- Developed and used energy resource codes
- Quantified how often which types of codes were used in which contexts
- Used codes to identify episodes of rich sensemaking
- Analyzed episodes to develop themes
Analyzing interview transcripts

- Developed and used energy resource codes
- Quantified how often which types of codes were used in which contexts
- Used codes to identify episodes of rich sensemaking
- Analyzed episodes to develop themes
Summary of some preliminary results

Paired instrument set:

- Accessible to students with varied formal course experiences in physics and chemistry (from those who have had no college chemistry or physics to those who have had upper division chemistry, physics, or both)
- Normalized scores improve with more science course experience

Interviews:

- Students were capable of reasoning within the energy framework
- About as many energy resources were activated, on average, in the unfamiliar discipline as in the familiar discipline
- Allowed us to see instances where students brought up a learned idea but didn’t quite know how to apply it yet (e.g. applying elastic potential energy to earthquakes).
Summary of some preliminary results

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How could program-level assessment of cross-disciplinary learning influence your department or college’s vision, mission, or agenda?
Prioritizing cross-disciplinary learning

Developing assessments and pedagogy focused on cross-disciplinary learning requires collaboration between disciplinary units to determine learning outcomes, frame them with common vocabulary, and develop curricular coherence.

Prioritizing cross-disciplinary learning challenges us to think of ourselves as science educators first and disciplinary experts second.
Emily’s Breakout Room

Focus: Cross-disciplinary learning and STEM culture

How can a focus on cross-disciplinary learning transform how students experience and succeed in STEM?

Contact Emily at: bordae@wwu.edu

Todd’s Breakout Room

Focus: Quantitative measurement of cross-disciplinary learning

How could you use paired questions to recognize cross-disciplinary learning in your class?

Andrew’s Breakout Room

Focus: Qualitative measurement of cross-disciplinary learning

How could you use open-ended questions to identify conceptual resources students are applying across disciplines?
### Facilitated Breakout Rooms:

<table>
<thead>
<tr>
<th>Room Name</th>
<th>Discussion Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building “All-STEM” Culture</td>
<td>What curriculum and faculty development strategies can help foster an inclusive and collaborative culture across STEM disciplines?</td>
</tr>
<tr>
<td>Integrative STEM Assignments</td>
<td>What are some strategies for designing integrative STEM assignments and assessments to be suitable for students with a wide range of prior academic exposures?</td>
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<tr>
<td>Disciplinary Boundaries</td>
<td>What are some ways that instructors might reduce disciplinary boundaries in the learning environment to affirm diverse academic and social backgrounds?</td>
</tr>
<tr>
<td>CDL and STEM Culture</td>
<td>How can a focus on cross-disciplinary learning transform how students experience and succeed in STEM?</td>
</tr>
<tr>
<td>Quantitatively Assessing CDL</td>
<td>How could you use paired questions to recognize cross-disciplinary learning in your class?</td>
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</tbody>
</table>
Discussion Breakout Room Recap
Thank you for attending!

Slides and recording will be available in the coming weeks.

We value your feedback, please take a few minutes to complete the survey.

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