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F.W. Wright Senior Lecturer in Astronomy
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA
Abstract

The U.S. is unique in the variety of teaching methods and curricula used in science and math classrooms. We have mined 20,000 college students’ histories taking critical college “gate-keeper” courses in biology, chemistry, physics, and calculus, putting to the test K-12 educators' beliefs about the kinds of preparatory experiences and key resources that impact both college grades and students’ career choice. I will share findings on the impact of lab experience, graphing calculators, computerized labs and simulations, demonstrations, content coverage, Advanced Placement courses, project work, teacher professional development, and mathematics preparation.
Harvard-Smithsonian Center for Astrophysics

- Largest astronomical research institution in the world
- A partnership between:
  - Harvard’s Department of Astronomy
  - Harvard College Observatory
  - Smithsonian Astrophysical Observatory
- More than 250 scientists in a staff of over 900
- Telescopes on earth and in space
- Precollege Science Education K-12 since 1985
CfA’s Science Education Department

- Formed in early 1990’s
  - Grown to 30 staff
  - $4M/year grants & contracts
    - NSF
    - NASA
    - Annenberg
    - NIH
  - 1/3 Astronomy
  - 1/3 Physical Sciences
  - 1/3 Life Sciences and Mathematics

Goal

National impact on science education in formal and informal settings
Cutting-edge Technologies
MicroObservatory Telescopes

- 5 online telescopes taken more than 1 million images
- In-school, after-school, clubs, camps, and museums
Research on Educational Assessment and Effectiveness

- Identify beliefs of STEM stakeholders
- Generate hard evidence that supports or refutes hypotheses
- Disseminate findings to the educational community and the public
With limited time and money, where do you put your resources?

- Advanced Placement
- Block scheduling
- Labs and demonstrations
- Assessment
- Instructional practices
- Technology
- Facts vs Concepts
- Coverage
- Physics First
- Mathematics
- Inquiry
- Teacher Knowledge
Epidemiological Methods

• Retrospective Cohort Studies
  – Quicker than longitudinal methods
  – Relies on accurate recall
  – Tests many hypotheses at the same time
  – When done well, halfway between
    • Correlational and Experimental studies
    • Includes alternative hypotheses & controls
    • Lack of correlation implies lack of causality
Stratified Random Sample
Context

How and when does STEM career interest develop? What influences progress toward a STEM career?
When do college graduates say they first became interested in “science”?
When do college graduates say they first became interested in “science”?

- K-5th grade: 40%
- 6-8th grade: 20%
- 9-10th grade: 10%
- 11-12th grade: 10%
- First 2 yr college: 5%
- After 2 yr off: 0%
When do college graduates say they first became interested in their career discipline?
When do college graduates say they first became interested in their career discipline?
How Does Interest in a STEM Career Change in High School?

- Does it change?
- Is it different by field?
- Are there differences by gender?
- What is the role of HS physics?
How Does Interest in a STEM Career Change in High School

End of High School
Beginning of High School

Males

Engineering 24.8% 28.3%
Sciences, Math, Science Teaching 15.0% 11.0%
Medicine 12.7% 7.9%
Health 3.0% 6.9%
Other 44.5% 46.9%
### Beginning of High School
- **Engineering**: 24.8%
- **Sciences, Math, Science Teaching**: 15.0%
- **Medicine**: 12.7%
- **Health**: 3.0%
- **Other**: 44.5%

### End of High School
- **Engineering**: 28.3% 3.7%
- **Sciences, Math, Science Teaching**: 11.0% 13.3%
- **Medicine**: 7.9% 19.6%
- **Health**: 6.9% 14.3%
- **Other**: 46.9% 49.1%

### Beginning of High School (Females)
- **Engineering**: 5.0%
- **Sciences, Math, Science Teaching**: 8.7%
- **Medicine**: 15.0%
- **Health**: 18.4%
- **Other**: 53.0%
Do HS courses impact STEM persistence?
What the public hears

“It is better to take a tougher course and get a low grade than to take an easy course and get a high grade.”

Clifford Adelman, Senior Research Analyst, U.S. Dept. of Ed.
STEM Courses in High School
# of years vs rigor

- Biology: 98%
- Chemistry: 84%
- Physics: 52%
- Calculus: 25%

- AP AB: 25%
- AP BC: 15%

Courses in AP:
- Biology: 98%
- Chemistry: 32%
- Physics: 52%
- Calculus: 25%
HS Coursework and $\Delta$ Probability of Wanting to Pursue a STEM Career at the End of High School, controlling for Initial Interest, SAT, SES, Gender

<table>
<thead>
<tr>
<th>Years</th>
<th>non-AP</th>
<th>no exam</th>
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Diagram showing the change in probability over years for different coursework types.
HS Coursework and ∆ Probability of Wanting to Pursue a STEM Career at the End of High School, controlling for Initial Interest, SAT, SES, Gender

### Biology

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<th>Years</th>
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### Calculus

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Persistence

- STEM interest shifts in HS
- Engineering > science & math
- HS volatility higher for females
- HS coursework impacts interest
  - Bio: - for years; no impact for AP
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  - Phys: + for years; no impact for AP
  - Math: + for calc; no impact for AP
Gender Issues


Plotkin, G, Hazari, Z., & Sadler, P.M., (in press) Unraveling Bias from Student Evaluations of their Science Teachers, *Science Education*
Career Variables for College Freshmen by Field and Gender
N=5570 students at 40 randomly chosen U.S. colleges
Units in standard deviation from the mean, bubble areas reflect N
Interest in a STEM Career at the end of high school by career interest at the start of high school

Carrer Interest at the Start of High School
Is there a connection between students' participation in OST activities and their STEM career intention?

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<th>B</th>
<th>Sig.</th>
<th>SE</th>
<th>Odds ratio</th>
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<td>0.163</td>
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<td>Science</td>
<td>0.592</td>
<td>***</td>
<td>0.090</td>
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<td>0.093</td>
<td>1.904</td>
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<tr>
<td>Science</td>
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<td>0.875</td>
<td>0.083</td>
<td>1.013</td>
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<tr>
<td>Math</td>
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<td>***</td>
<td>0.079</td>
<td>1.490</td>
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<td>0.086</td>
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<td>OST reading/Watching</td>
<td>0.287</td>
<td>**</td>
<td>0.084</td>
<td>1.332</td>
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</table>

*p < 0.05, **p < 0.01, ***p < 0.001.
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- People orientation
  - Low for STEM, high for Med/Health
  - Higher for females

- Extrinsic Reward orientation
  - Higher for males
  - Engineering > science and math

- Science reading/watching and OST clubs and competitions
- Discuss challenges and benefits of a STEM career
Performance in Introductory College Courses

- Studying Science Gatekeeper Courses
  - STEM & Medicine
  - Grades based on professor’s assessments
  - Authentic measure
• What prepares students for success in college science courses?
Does the Order in Which Science Courses Are Taken Make a Difference?

Testing the *Physics First* Hypotheses

1. Taking more physics will have a positive impact on later learning in chemistry

2. Taking more chemistry will have a positive impact on later learning in biology
HS Chemistry Effect

Difference in College Grade

College Biology  College Chemistry  College Physics

-2 -1 0 1 2 3

HS Biology  HS Chemistry  HS Physics  HS Mathematics
HS Physics Effect

Difference in College Grade

College Biology | College Chemistry | College Physics

- HS Biology
- HS Chemistry
- HS Physics
- HS Mathematics
Mathematics Effect

Difference in College Grade

- College Biology
- College Chemistry
- College Physics

HS Biology
HS Chemistry
HS Physics
HS Mathematics
Is Advanced Placement the Answer?


Surprise! AP students often take introductory college courses in science. How do they do when “repeating” a course?
College Science and Math Performance: raw grades

Biology, Chemistry, Physics

- AP not taken
- AP Exam Taken

College Grade in Calculus

- AP
- Non AP, no exam

AP Exam Score

- none
- 1
- 2
- 3
- 4
- 5
College Science and Math Performance: + controls

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<th>AP Exam Score</th>
<th>College Science Grade</th>
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AP not taken, AP Exam Taken, 1, 2, 3, 4, 5
Difference in Performance in “102” for Students Who Took AP in High School
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Performance in College

- Prepare for
  - science with same science & math
  - calculus with HS calculus

- AP:
  - Small impact on STEM courses
  - AP Exam: 5 impressive; 1 or 2, not
  - College retakers benefit
Pedagogy and Curriculum


The Impact of Coverage: Depth vs. Breadth

- In teaching my high school science course so that students are well-prepared for college science, I make sure that we cover:
  - All the major topics so that students are familiar with most terms and concepts
  - A few key topics in great depth so that students have mastered essential foundational concepts
The Impact of Coverage: Depth vs. Breadth

- All topics covered Same time for each
- Fewer topics Same time for each
- All topics covered Extra time for 1 or 2
- Fewer topics Extra time for 1 or 2
The Impact of Coverage: Depth vs. Breadth

<table>
<thead>
<tr>
<th>% in Each High School Group</th>
<th>Difference in College Grade</th>
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</thead>
</table>

- **Biology**
  - All topics covered: Same time for each
  - Fewer topics: Same time for each
  - All topics covered: Extra time for 1 or 2

- **Chemistry**
  - All topics covered: Same time for each
  - Fewer topics: Same time for each
  - All topics covered: Extra time for 1 or 2

- **Physics**
  - All topics covered: Same time for each
  - Fewer topics: Same time for each
  - All topics covered: Extra time for 1 or 2
Laboratory Activities


What Appears to:

Help:

- Often Draw/Interpret Graphs by Hand
- Often Analyzed Pictures or Illustrations
- Labs Addressed Student’s Beliefs
- More prediction, less demo discussion
- Focus on key foundational concepts
What Appears to:

Help:
• Often Draw/Interpret Graphs by Hand
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• Labs Addressed Student’s Beliefs
• More prediction, less demo discussion
• Focus on key foundational concepts

Hinder:
• Emphasis on lab procedure
  – Read & Discuss Labs a Day Before
  – Doing labs only once
• Testing on labs vs. reports
• Demonstrations with no predictions
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- AP:
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  - AP Exam: 5 impressive; 1 or 2, not
  - College retakers benefit
- Coverage
  - Less content, more mastery
- Pedagogy
  - Pictures, illustrations, graphs
  - Simplify lab and demo prediction
HS Calculus Teacher Choices

Positive Practices
• Heavy emphasis on functions
• Review homework daily
• Emphasize conceptual understanding
• Emphasize vocabulary

Negative Practices
• Plotting graphs on calculator
• “cheat sheets” for tests
• preparing for tests
• reviewing past lessons
• Teacher manipulates physical objects as teaching aids
How effective are we at teaching foundational concepts?
Clinical Interviews

On-on-one with students

Minds of Our Own consists of 3-one hour programs broadcast on PBS in 1997-98. It explores the ideas of students as they come to understand scientific concepts.

A Private Universe documents students’ ideas through their own drawings and explanations.

www.ficss.org

www.learner.org
Professional Development

Institutes
>1000 teachers

Conference Workshops
>30,000 teachers

On-line courses
Reaching 85,000 schools
Minds Of Our Own (Photosynthesis)
Both students and teachers have (or had) preconceptions

- Exist prior to formal instruction
- At odds with accepted scientific thought, “misconceptions”
- Commonly held, not idiosyncratic
- Embedded in larger knowledge structures, not just a simple “error” (that is easy to correct)
- Resistant to change, over-estimation of Δ
- Best teachers can predict their occurrence
Methods for assessing conceptions

• Interviews
  – Lengthy and costly
  – Well-trained interviewer

• Open-ended items:
  – Students might not explain their thinking
  – Misconceptions might not be uncovered
  – Difficult and time consuming to score

• Multiple-Choice items
  – Must know misconceptions beforehand
  – Must include misconceptions as distractors
  – Other items are too easy
Our Process of Instrument Development

- Targeting content
- Constructing items
- Validating tests
- Samples

Joel Mintzes
Professor of biology and chair of the Department of Science Education, Cal State Chico

Kimberly Tanner
Assistant Professor; Director of SEPAL, U Cal, San Francisco
Steps in instrument development based on student ideas

- Employ NRC standards
  - the root of state standards
- Construct assessment instruments based on misconceptions
  - Using research literature
- Validation with both students and teachers
  - Pilot and field tests
  - Final instruments
- Measure both SMK and PCK
Middle School Life Science
Sample Items
33. Cells inside the human body get energy from:
   a. circulating oxygen in the blood.
   b. breaking down sugars that come from food.
   c. breaking down sugars that they make themselves.
   d. giving off carbon dioxide.
   e. giving off oxygen.
Cells inside the human body get energy from:

a. circulating oxygen in the blood. 27%

b. breaking down sugars that come from food. 52%

c. breaking down sugars that they make themselves. 9%

d. giving off carbon dioxide. 9%

e. giving off oxygen. 3%

P(difficulty) = .52  D(discrimination) = .42
MS(misconception strength) = .57
273.2. In a forest, which of the following are consumers, organisms that get food by eating other organisms?

a. Only the trees.
b. Only the squirrels.
c. Only the foxes.
d. Both the trees and the squirrels.
e. Both the squirrels and the foxes.
273.2. In a forest, which of the following are consumers, organisms that get food by eating other organisms?

a. Only the trees. 3%
b. Only the squirrels. 6%
c. Only the foxes. 55%
d. Both the trees and the squirrels. 5%
e. Both the squirrels and the foxes. 36%

P=.36  D=.41  MS=.78
337.1. Which of the following can become extinct?
   a. Plants, animals and microorganisms.
   b. Plants and animals, but not microorganisms.
   c. Only plants.
   d. Only animals.
   e. Only microorganisms.
337.1. Which of the following can become extinct?

a. Plants, animals and microorganisms. 52%

b. Plants and animals, but not microorganisms. 33%

c. Only plants. 1%

d. Only animals. 12%

e. Only microorganisms. 2%

P=.52     D=.40     MS=.69
Comparisons

• To what degree have students who completed science courses mastered the NRC standards?
  – At grade level
  – At prior grade levels

• Are there patterns of strength and weakness?
Patterns in Test Data
Teacher Knowledge, MS-LS

Pedagogical Content Knowledge (PCK)
Subject Matter Knowledge (SMK)
Yearly Classroom Gain in Middle School Physical Science Courses, N= 15029 students of 160 teachers

Concepts without Strong Misconceptions  

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<th>SMK</th>
<th>No SMK</th>
<th>SMK Only</th>
<th>SMK &amp; PCK</th>
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<tbody>
<tr>
<td>No Misconception</td>
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Effect Size (in Units of Standard Deviation)

SMK=Subject Matter Knowledge (knows correct answer)
PCK=Pedagogical Content Knowledge (can identify student misconceptions)
Results of Teacher Professional Development
Gain in SMK and PCK

Δ Subject Matter Knowledge

Δ Pedagogical Content Knowledge
Next Steps:
How do gains vary with PD attributes
Lectures or Workshops led by Science Educators
  Experiencing Active Learning with other teachers
    Learning previously designed curricula
      Developing original curricula
    Learning uses of technology in classroom
  Developing assessment tools for the life sciences
  Collaborating with colleagues
  Understanding of students misconceptions
Experiencing Inquiry-Based Learning Techniques
Teacher Educators:
  Master teachers:
  Curriculum developers:
Conducting/Assisting with Scientific Research
  Going on field trips
  Designing student field trips
Graduate Students:
  Observing and critiquing classroom instruction
  Assessing student work
Lectures or Workshops led by Research Scientists
  Life science research scientists:
    Learning the newest scientific thinking on a topic
    Foundational concepts in the life sciences

PD Attributes, difference in emphasis

- Never
- Rarely
- Often
- Constantly
4-Factor Solution
Controlling for teacher experience, pre-test score, Grade level

1. Curriculum, not significant
   - Lectures or Workshops led by Science Educators
   - Learning previously designed curricula, activities (experiments, kits, field trips, etc.)
   - Collaborating with colleagues in your domain, grade or geographic area
   - Experiencing Active Learning with others
   - Experiencing Inquiry-Based Learning Techniques
   - Involvement of Teacher Educators
   - Involvement of Master teachers
   - Involvement of Curriculum developers

2. Creating New Materials, interaction
   - Developing original curricula or activities (experiments, kits, field trips, etc.)
   - Assessing student work
   - Observing and critiquing classroom instruction
   - Developing assessment tools for the life sciences

3. Lab Research and Field Trips, not significant
   - Conducting/Assisting with Scientific Research
   - Going on field trips
   - Designing student field trips
   - Involvement of Life science research scientists
   - Involvement of Graduate Students

4. Life Science Content, +0.38* SD
   - Lectures or Workshops led by Research Scientists
   - Learning the newest scientific thinking on a topic
   - Learning foundational concepts in the life sciences, ecology, etc.
   - Learning uses of technology for classroom simulations, data collection or analysis

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Graph: Low Pretest vs. High Pretest
- Do not develop new materials
- Develop New Materials

**Factors:**
- Factor 1: Curriculum
- Factor 2: Creating New Materials
- Factor 3: Lab Research and Field Trips
- Factor 4: Life Science Content
Which factors make a difference? Curriculum, Creating New Materials, Research, Content

• In SMK
  – Content emphasis for all
  – Avoid developing new materials with low SMK teachers

• In PCK
  – none
“The unlearning of preconceptions might very well prove to be the most determinative single factor in the acquisition and retention of subject-matter knowledge.”

David Ausubel 1978
Persistence

- STEM interest shifts in HS
- Engineering > science & math
- HS volatility higher for females
- HS coursework impacts interest
  - Bio: - for years; no impact for AP
  - Chem: + for 2 years; none for AP
  - Phys: + for years; no impact for AP
  - Math: + for calc; no impact for AP
- People orientation
  - Low for STEM, high for Med/Health
  - Higher for females
- Extrinsic Reward orientation
  - Higher for males
  - Engineering > science and math
- Science reading/watching and OST clubs and competitions
- Discuss challenges and benefits of a STEM career

Performance in College

- Prepare for
  - science with same science & math
  - calculus with HS calculus
- AP:
  - Small impact on STEM courses
  - AP Exam: 5 impressive; 1 or 2, not
  - College retakers benefit
- Coverage
  - Less content, more mastery
- Pedagogy
  - Pictures, illustrations, graphs
  - Simplify lab and demo prediction
- Students maintain misconceptions
  - often unchanged after taking science
- Teacher knowledge
  - Subject matter necessary
  - Knowledge of misconceptions essential
- Teacher Professional Development
  - Content for all, New Materials (high SMK)
  - No impact on PCK
LORD KELVIN (1824-1907)

• “IF YOU CAN MEASURE THAT OF WHICH YOU SPEAK, AND CAN EXPRESS IT BY A NUMBER, YOU KNOW SOMETHING OF YOUR SUBJECT;
LORD KELVIN (1824-1907)

• "IF YOU CAN MEASURE THAT OF WHICH YOU SPEAK, AND CAN EXPRESS IT BY A NUMBER, YOU KNOW SOMETHING OF YOUR SUBJECT;
• BUT IF YOU CANNOT MEASURE IT, YOUR KNOWLEDGE IS MEAGER AND UNSATISFACTORY."
MOSART Website – free assessments
www.cfa.harvard.edu/smgphp/mosart

Welcome to MOSART

"I'm teaching, but they're not learning!"

This is one of the most common laments from educators. Your students may perform well on your assessment instruments, yet say things in class which leave you wondering if they really understand the underlying concepts. Or perhaps you're at the beginning of a unit and are unsure about what your students already know. Which concepts do they already grasp, and which will you have to address? If any of these doubts and questions sound familiar, then the MOSART project was designed to help you.

The acronym MOSART stands for:

- **Misconceptions-Oriented**: The project recognizes that students do not come to your class as “blank slates” but rather have their own theories.
- **Standards-based**: The NRC NSSEs comprise a unifying thread among all MOSART items and tests.
- **Assessment Resources for Teachers**: The project provides educators with multiple-choice tests that can be used to assess their students’ understanding of this content.
Assessment in Math and Science: What’s the Point?

A video workshop for K-12 teachers; 8 ninety-minute video programs, workshop guide, and Web site; graduate credit available.

"Will this be on the test?" "Is this going to count?" How often do students ask these questions? This workshop examines current assessment issues and strategies in K-12 math and science classrooms. Through video segments of real classrooms interspersed with lively discussions of practicing teachers and content experts, see how teachers deal with common issues and discover ways to use assessment to improve teaching and learning.

Produced by the Harvard-Smithsonian Center for Astrophysics and Massachusetts Corporation for Educational Telecommunications (MCET). 1997.

Factors Influencing College Science Success
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