Separating Facts From Fads: How Our Choices Impact Students' Performance and Persistence in Science, Technology, Engineering, and Mathematics

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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”?

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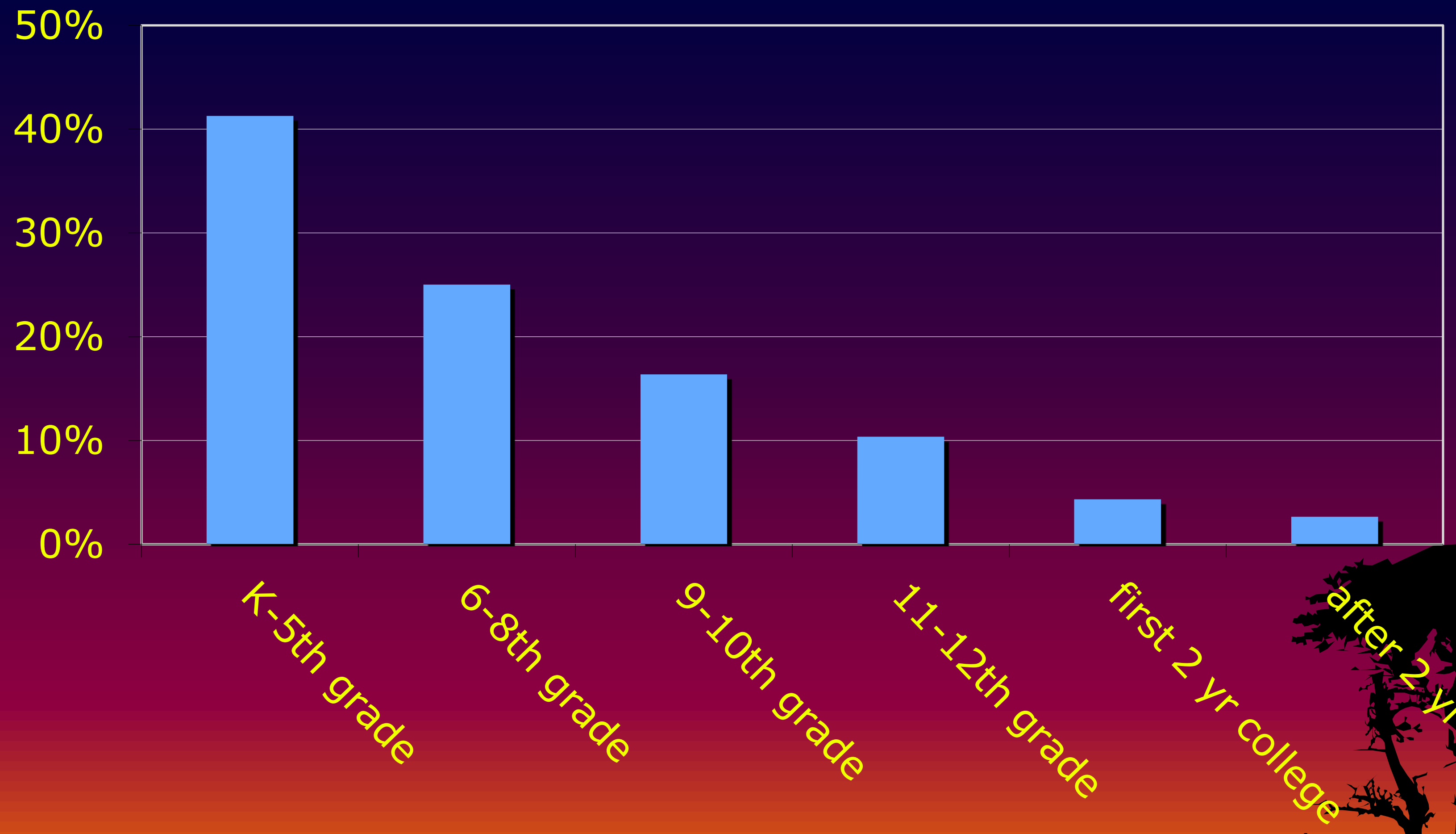

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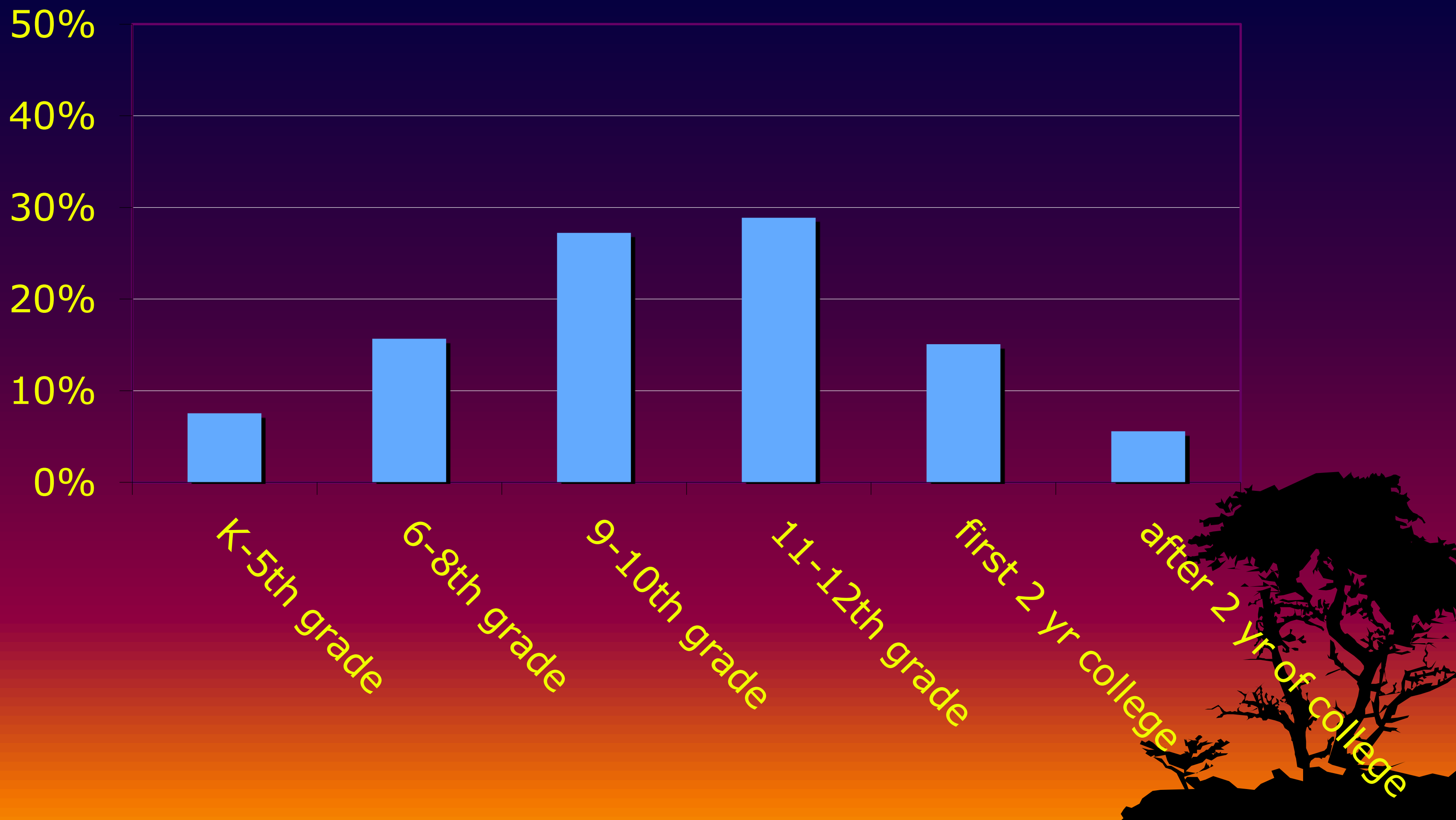
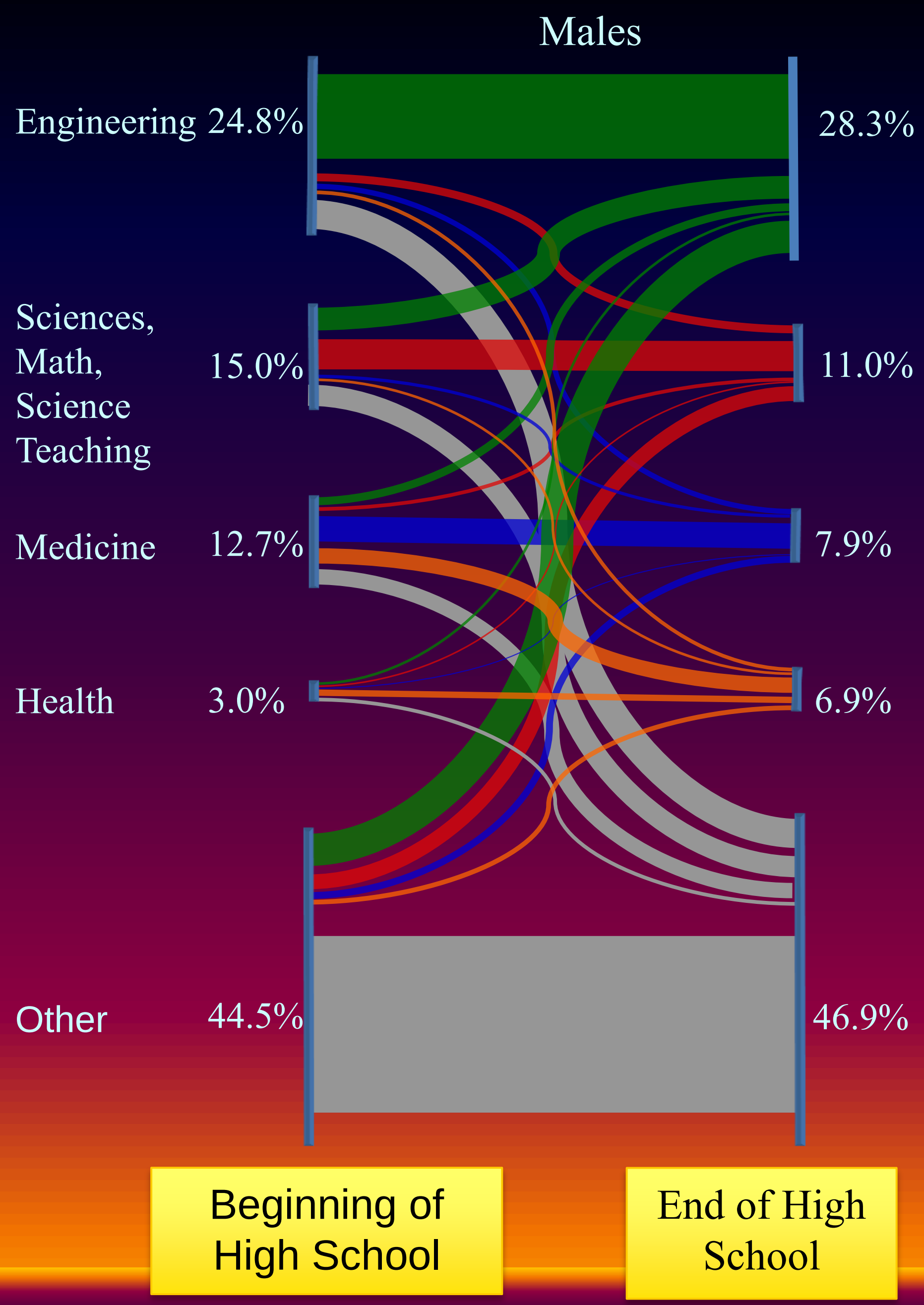


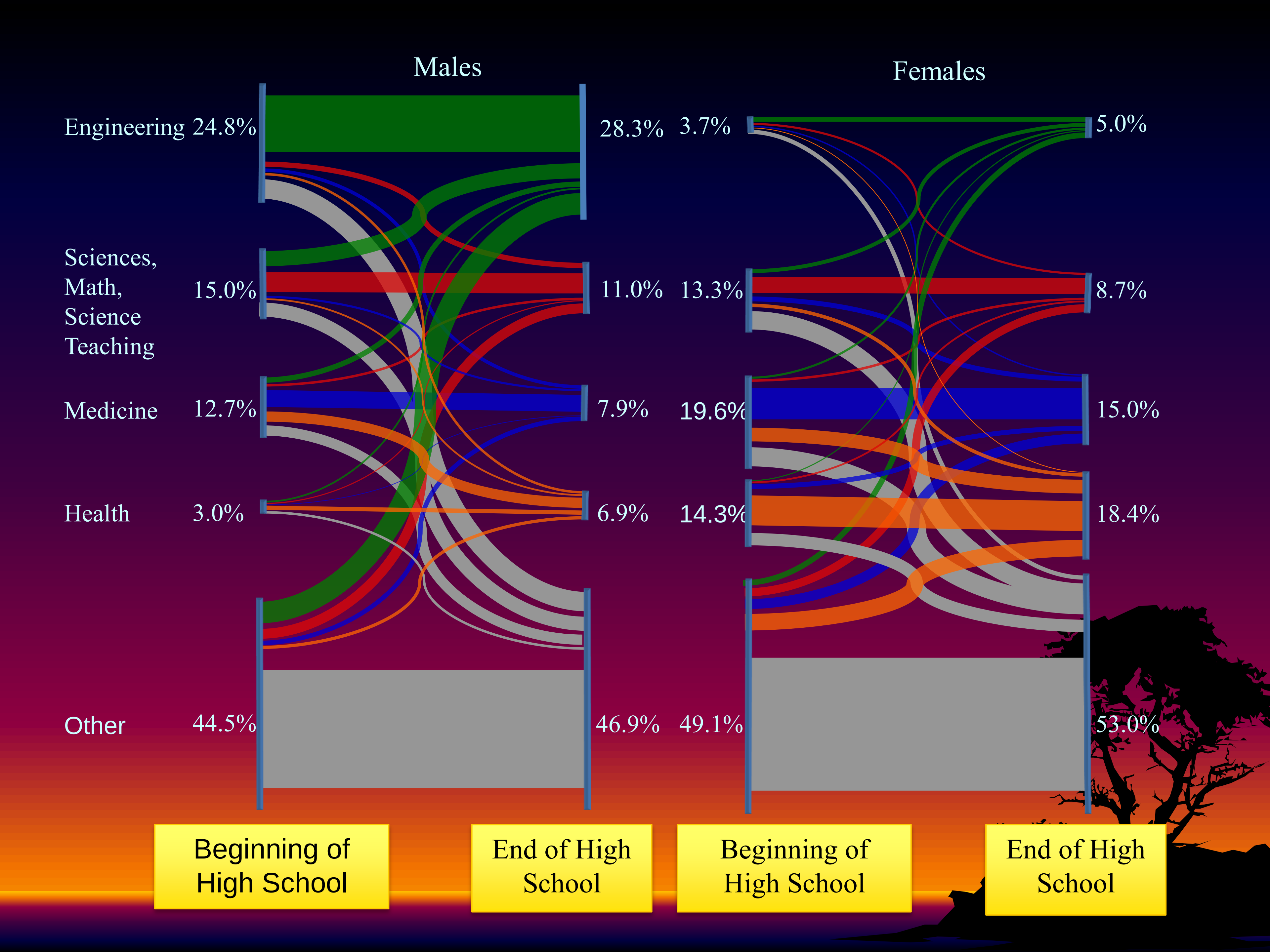
How Does Interest in a STEM Career Change in High School?

- Does it change?
- Is it 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

- Hazari, Z., Plotkin, G, Sadler, P.M., and Sonnert, G. (2010) Connecting High School Physics Experiences, Outcome Expectations, Physics Identity, and Physics Career Choice: A Gender Study, *Journal of Research in Science Teaching*, 47(8), 978-1003.
- Sonnert, G., Sadler, P.M. & Michaels, M. (in press) Gender aspects of participation, support, and success in a state science fair, *School Science and Mathematics.*
- Dabney, K. P, Almarode, J.T., Miller-Friedmann, J.L., Tai, R.H., Sonnert, G. & Sadler, P.M. (in press) Out-of-School Time Science Activities and Their Association with Career Interest in STEM, *International Journal of Science Education*
- Sadler, P.M., Sonnert, G., Hazari, Z., & Tai, R.H. (2012) Stability and Volatility of STEM Career Interest in High School: A Gender Study, *Science Education.*


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
End of High School



Males
Females
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19.6%
15.0%
Health
3.0%
6.9%
14.3%
18.4%
Other
44.5%
46.9%
49.1%
53.0%
Beginning of High School
End of High School
Beginning of High School
End of High School

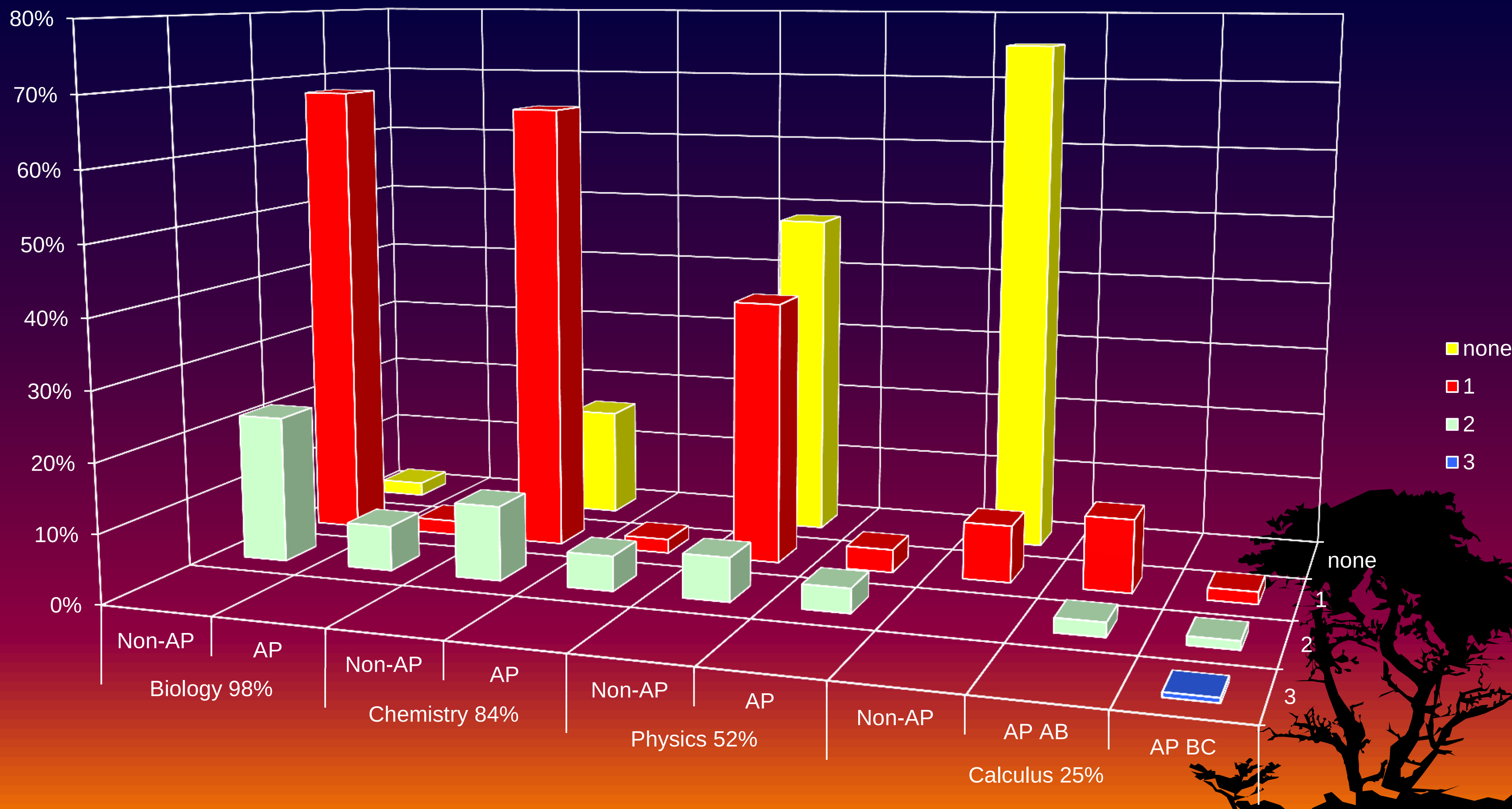
Do HS courses impact STEM persistence?

What the public hears

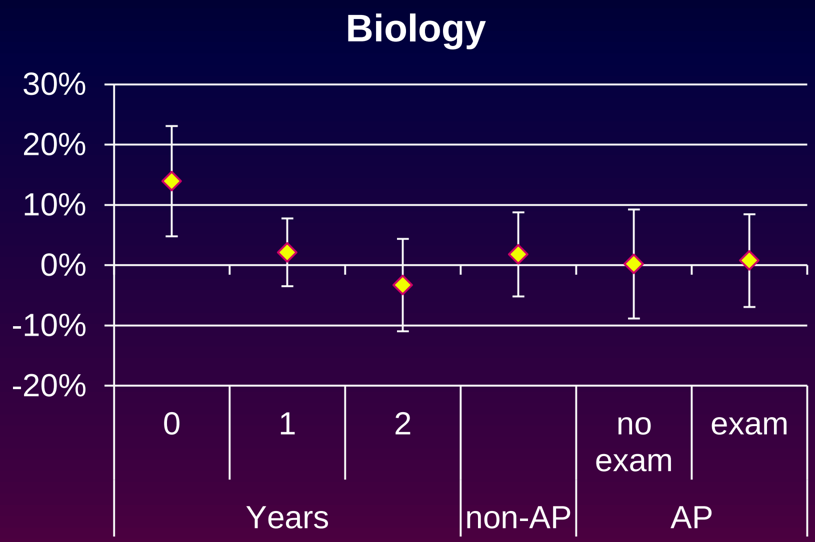
"It is better to take a tougher course and get a low grade than to take an easy course and get a high grade."

Clifford Adelman, Senior Research Analyst, U.S. Dept. of Ed.

STEM Courses in High School
of years vs rigor



HS Coursework and Δ Probability of Wanting to Pursue a STEM Career at the End of High School, controlling for Initial Interest, SAT, SES, Gender



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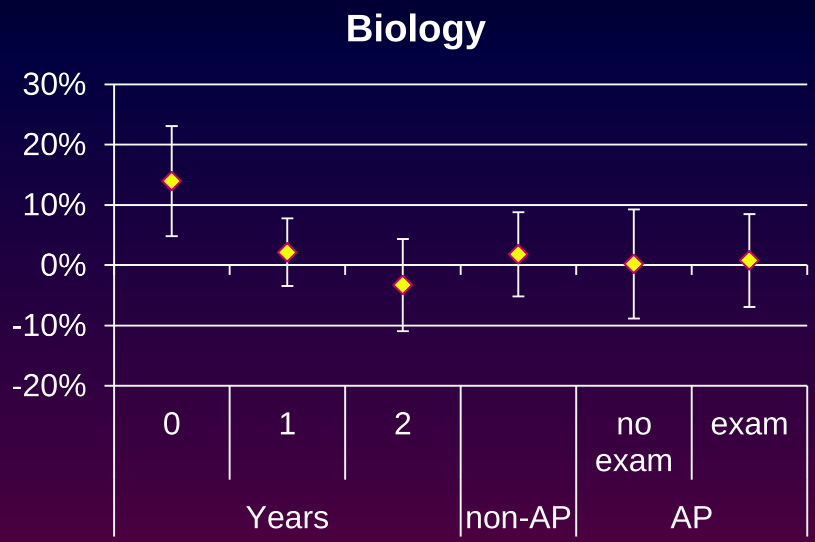

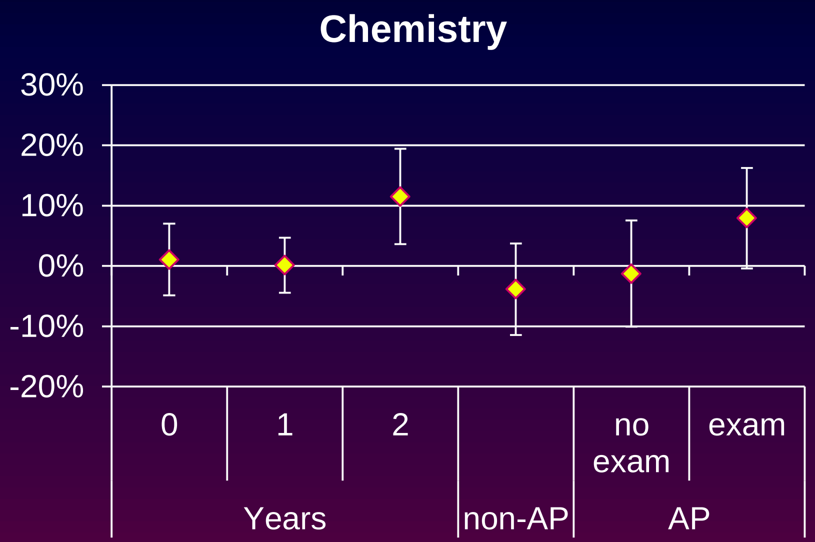

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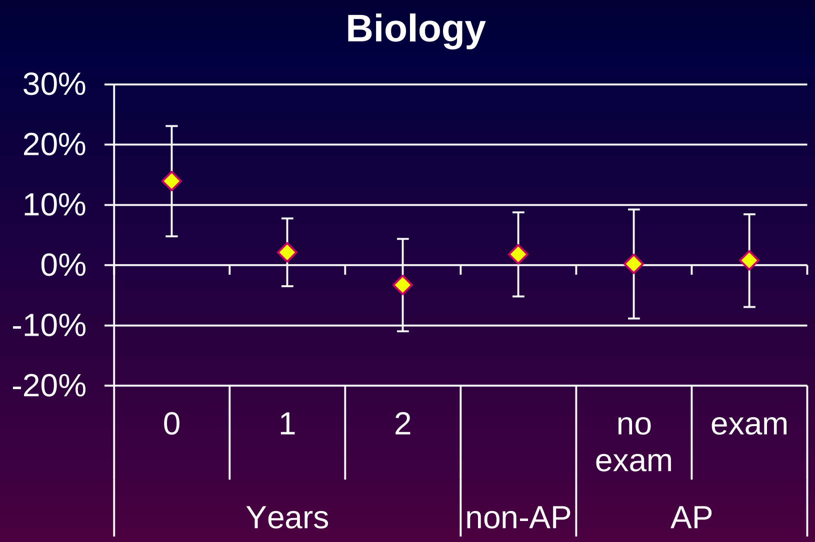

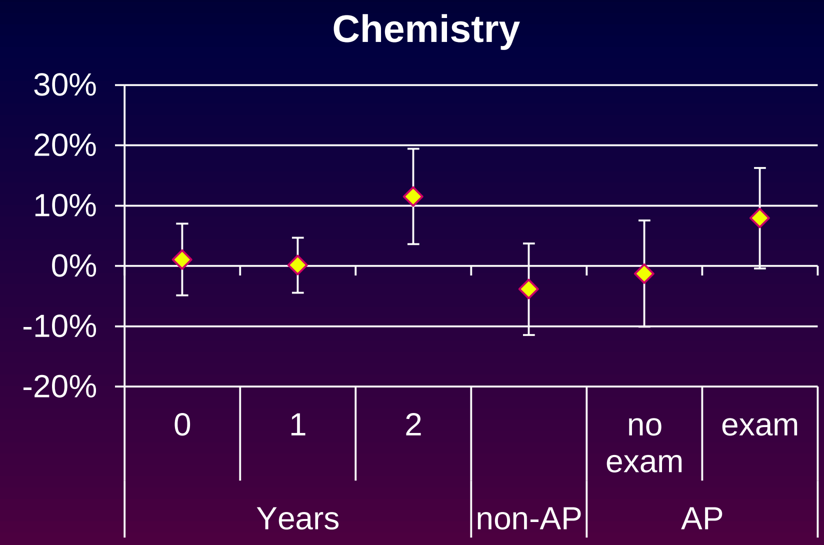

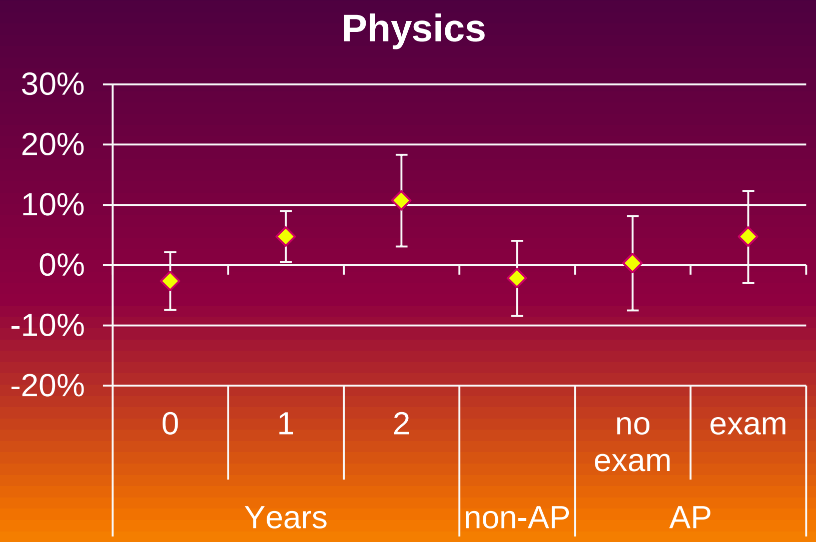

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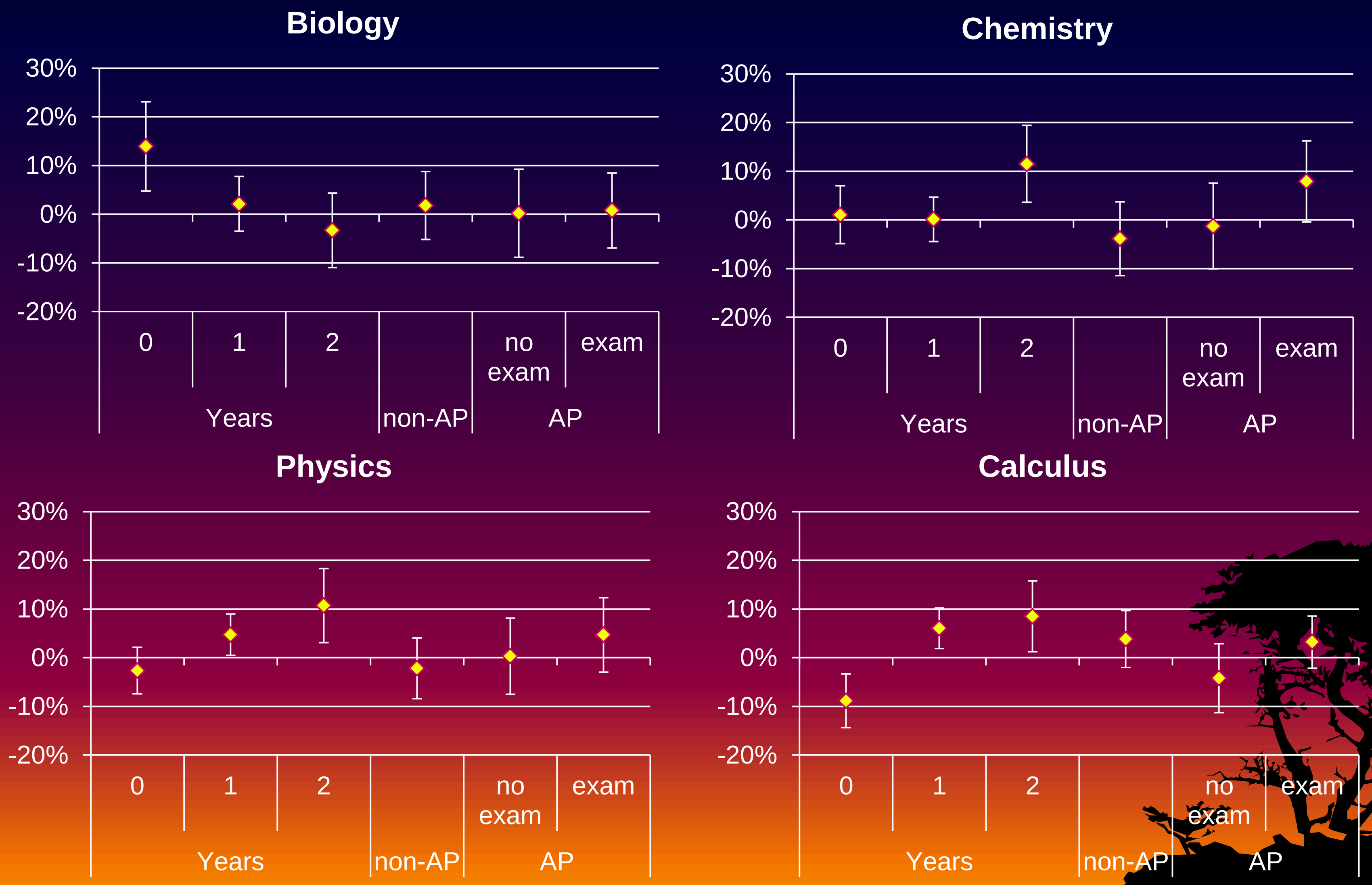

Persistence

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  - Phys: + for years; no impact for AP
  - Math: + for calc; no impact for AP

Gender Issues

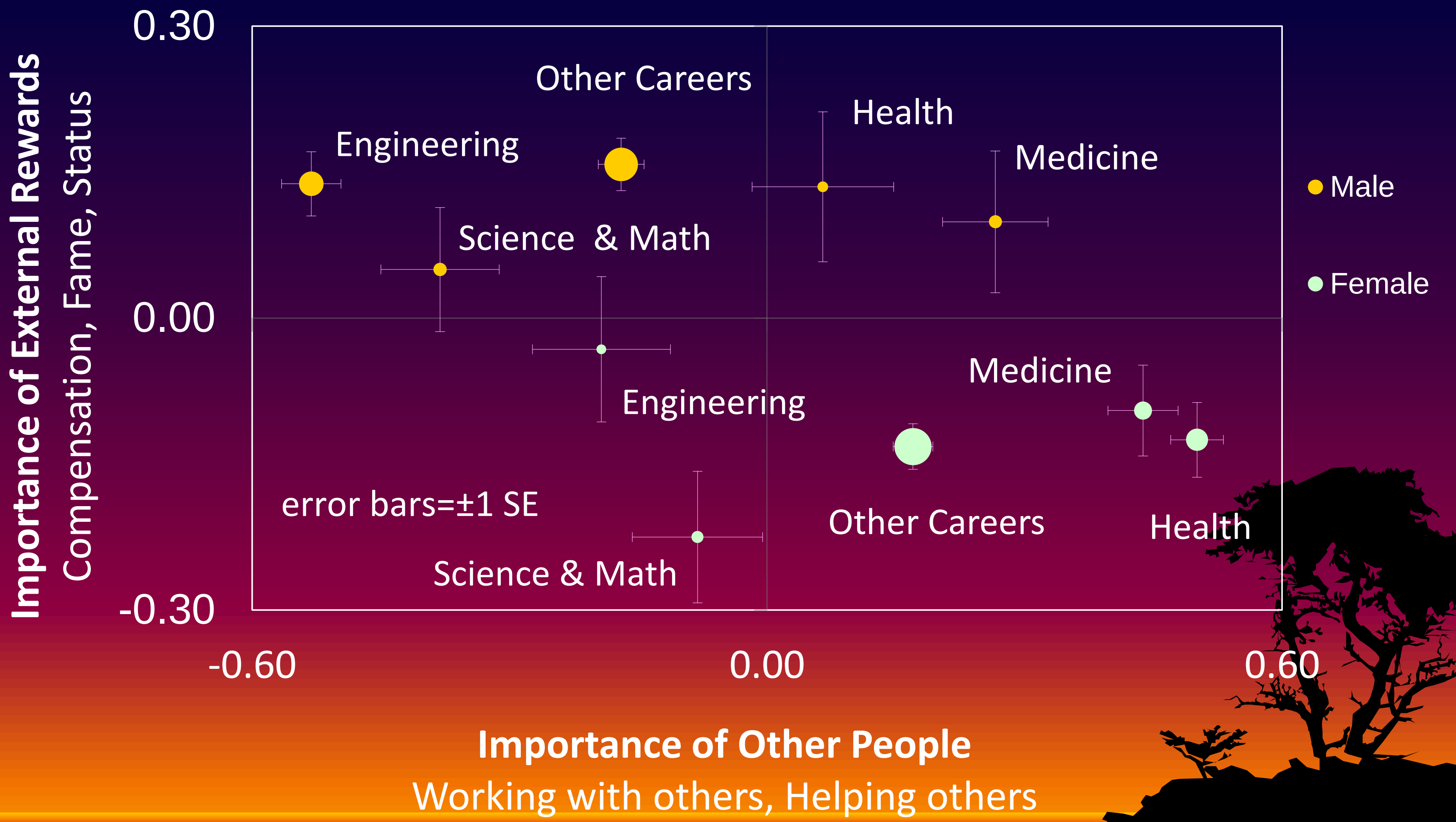
Tai, R. H. & Sadler, P. M. (2001) Gender Differences in Introductory Undergraduate Physics Performance: University Physics and College Physics in the United States. *International Journal of Science Education*, 1017-1037.

Hazari, Z. S., Tai, R. H., & Sadler, P.M. (2007). Gender differences in introductory university physics performance: The influence of high school physics preparation and affect. *Science Education. 1-30.*

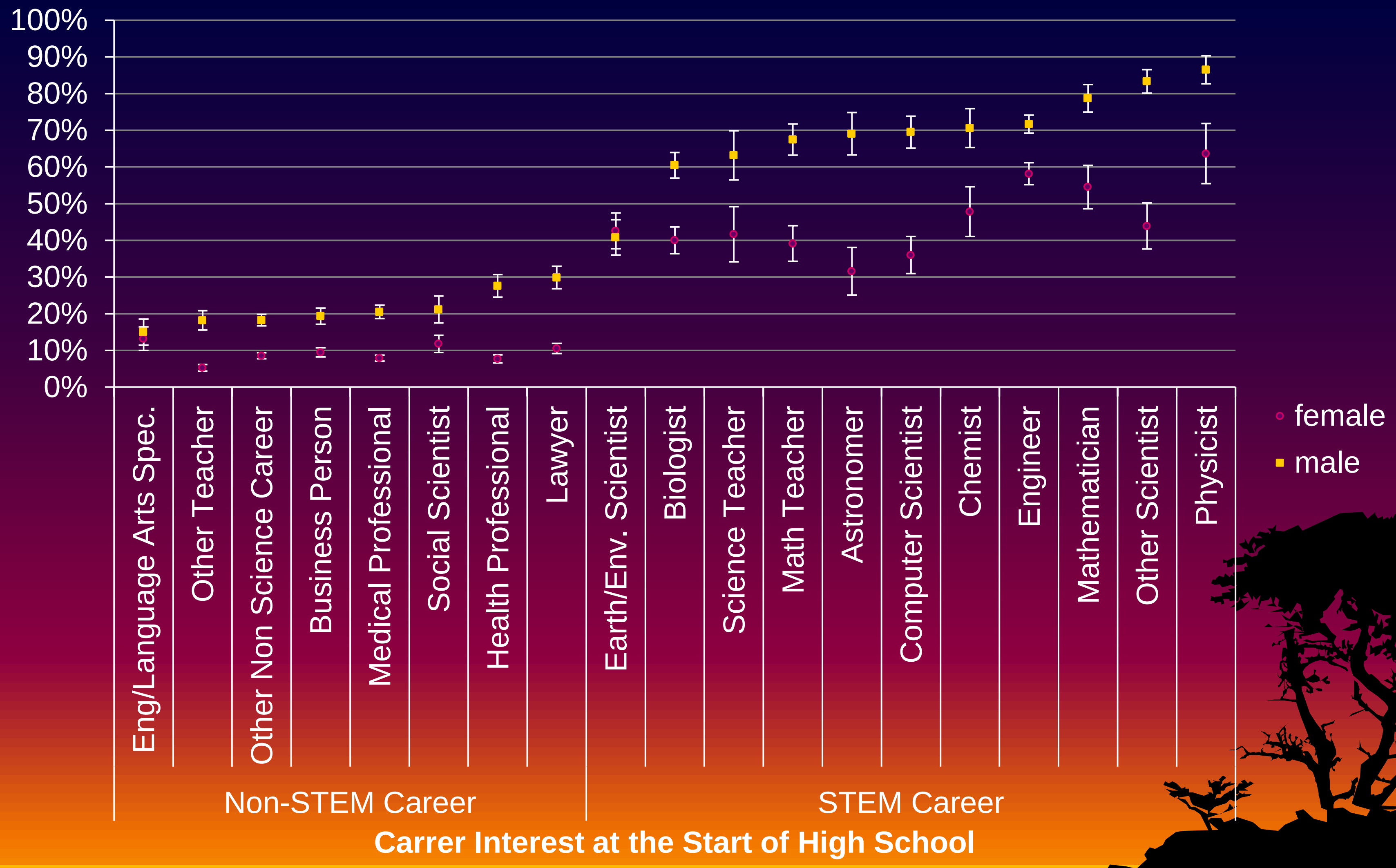
Hazari, Z., Sadler, P.M., & Tai, R.H. (2008) Gender Differences in the High School and Affective Experiences of Introductory College Physics Students, *The Physics Teacher*, 46, 423-427.

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



Is there a connection between students' participation in OST activities and their STEM career intention?

Table 2. Logistic regression model summary with odds ratio

	B	Sig.	SE	Odds ratio
Intercept	−4.943	***	0.281	0.007
Gender	1.514	***	0.080	4.544
Parental education	0.004	0.819	0.019	1.004
Socioeconomic status	0.000	**	0.000	1.000
Race/Ethnicity				
East Asian	−0.203	0.247	0.175	0.817
Caucasian	−0.007	0.949	0.110	0.993
African-American	−0.006	0.969	0.163	0.994
MS interest				
Science	0.592	***	0.090	1.808
Math	0.664	***	0.093	1.904
MS grade				
Science	0.013	0.875	0.083	1.013
Math	0.399	***	0.079	1.490
OST clubs/Competitions	0.409	***	0.086	1.506
OST reading/Watching	0.287	**	0.084	1.332

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

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  - 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

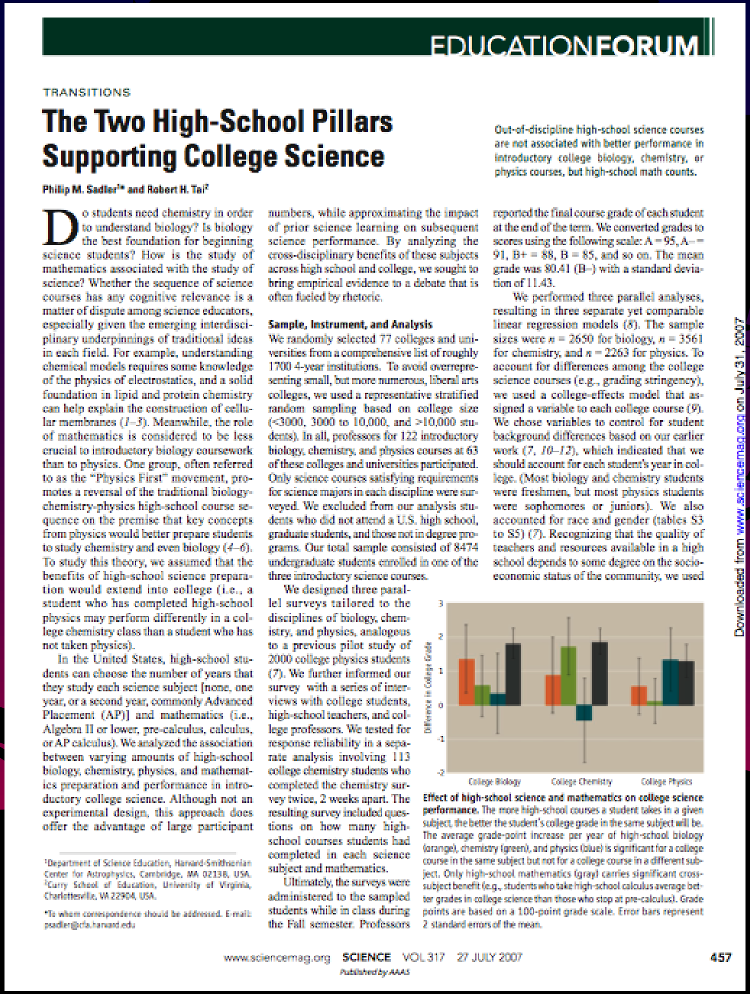
- What prepares students for success in college science courses?

Does the Order in Which Science Courses Are Taken Make a Difference?

Sadler, P.M. & Tai, R. H. (2007) The Two High-School Pillars Supporting College Science. *Science*

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



EDUCATIONFORUM

TRANSITIONS

The Two High-School Pillars Supporting College Science

Philip M. Sadler[1*] and Robert H. Tai[2]

Out-of-discipline high-school science courses are not associated with better performance in introductory college biology, chemistry, or physics courses, but high-school math counts.

Do students need chemistry in order to understand biology? Is biology the best foundation for beginning science students? How is the study of mathematics associated with the study of science? Whether the sequence of science courses has any cognitive relevance is a matter of dispute among science educators, especially given the emerging interdisciplinary underpinnings of traditional ideas in each field. For example, understanding chemical models requires some knowledge of the physics of electrostatics, and a solid foundation in lipid and protein chemistry can help explain the construction of cellular membranes (*1–3*). Meanwhile, the role of mathematics is considered to be less crucial to introductory biology coursework than to physics. One group, often referred to as the "Physics First" movement, promotes a reversal of the traditional biology-chemistry-physics high-school course sequence on the premise that key concepts from physics would better prepare students to study chemistry and even biology (*4–6*). To study this theory, we assumed that the benefits of high-school science preparation would extend into college (i.e., a student who has completed high-school physics may perform differently in a college chemistry class than a student who has not taken physics).

In the United States, high-school students can choose the number of years that they study each science subject [none, one year, or a second year, commonly Advanced Placement (AP)] and mathematics (i.e., Algebra II or lower, pre-calculus, calculus, or AP calculus). We analyzed the association between varying amounts of high-school biology, chemistry, physics, and mathematics preparation and performance in introductory college science. Although not an experimental design, this approach does offer the advantage of large participant numbers, while approximating the impact of prior science learning on subsequent science performance. By analyzing the cross-disciplinary benefits of these subjects across high school and college, we sought to bring empirical evidence to a debate that is often fueled by rhetoric.

Sample, Instrument, and Analysis

We randomly selected 77 colleges and universities from a comprehensive list of roughly 1700 4-year institutions. To avoid overrepresenting small, but more numerous, liberal arts colleges, we used a representative stratified random sampling based on college size (<3000, 3000 to 10,000, and >10,000 students). In all, professors for 122 introductory biology, chemistry, and physics courses at 63 of these colleges and universities participated. Only science courses satisfying requirements for science majors in each discipline were surveyed. We excluded from our analysis students who did not attend a U.S. high school, graduate students, and those not in degree programs. Our total sample consisted of 8474 undergraduate students enrolled in one of the three introductory science courses.

We designed three parallel surveys tailored to the disciplines of biology, chemistry, and physics, analogous to a previous pilot study of 2000 college physics students (*7*). We further informed our survey with a series of interviews with college students, high-school teachers, and college professors. We tested for response reliability in a separate analysis involving 113 college chemistry students who completed the chemistry survey twice, 2 weeks apart. The resulting survey included questions on how many high-school courses students had completed in each science subject and mathematics.

Ultimately, the surveys were administered to the sampled students while in class during the Fall semester. Professors reported the final course grade of each student at the end of the term. We converted grades to scores using the following scale: A = 95, A− = 91, B+ = 88, B = 85, and so on. The mean grade was 80.41 (B−) with a standard deviation of 11.43.

We performed three parallel analyses, resulting in three separate yet comparable linear regression models (*8*). The sample sizes were n = 2650 for biology, n = 3561 for chemistry, and n = 2263 for physics. To account for differences among the college science courses (e.g., grading stringency), we used a college-effects model that assigned a variable to each college course (*9*). We chose variables to control for student background differences based on our earlier work (*7, 10–12*), which indicated that we should account for each student's year in college. (Most biology and chemistry students were freshmen, but most physics students were sophomores or juniors). We also accounted for race and gender (tables S3 to S5) (*7*). Recognizing that the quality of teachers and resources available in a high school depends to some degree on the socio-economic status of the community, we used

Effect of high-school science and mathematics on college science performance. The more high-school courses a student takes in a given subject, the better the student's college grade in the same subject will be. The average grade-point increase per year of high-school biology (orange), chemistry (green), and physics (blue) is significant for a college course in the same subject but not for a college course in a different subject. Only high-school mathematics (gray) carries significant cross-subject benefit (e.g., students who take high-school calculus average better grades in college science than those who stop at pre-calculus). Grade points are based on a 100-point grade scale. Error bars represent 2 standard errors of the mean.

[1]Department of Science Education, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA. [2]Curry School of Education, University of Virginia, Charlottesville, VA 22904, USA.

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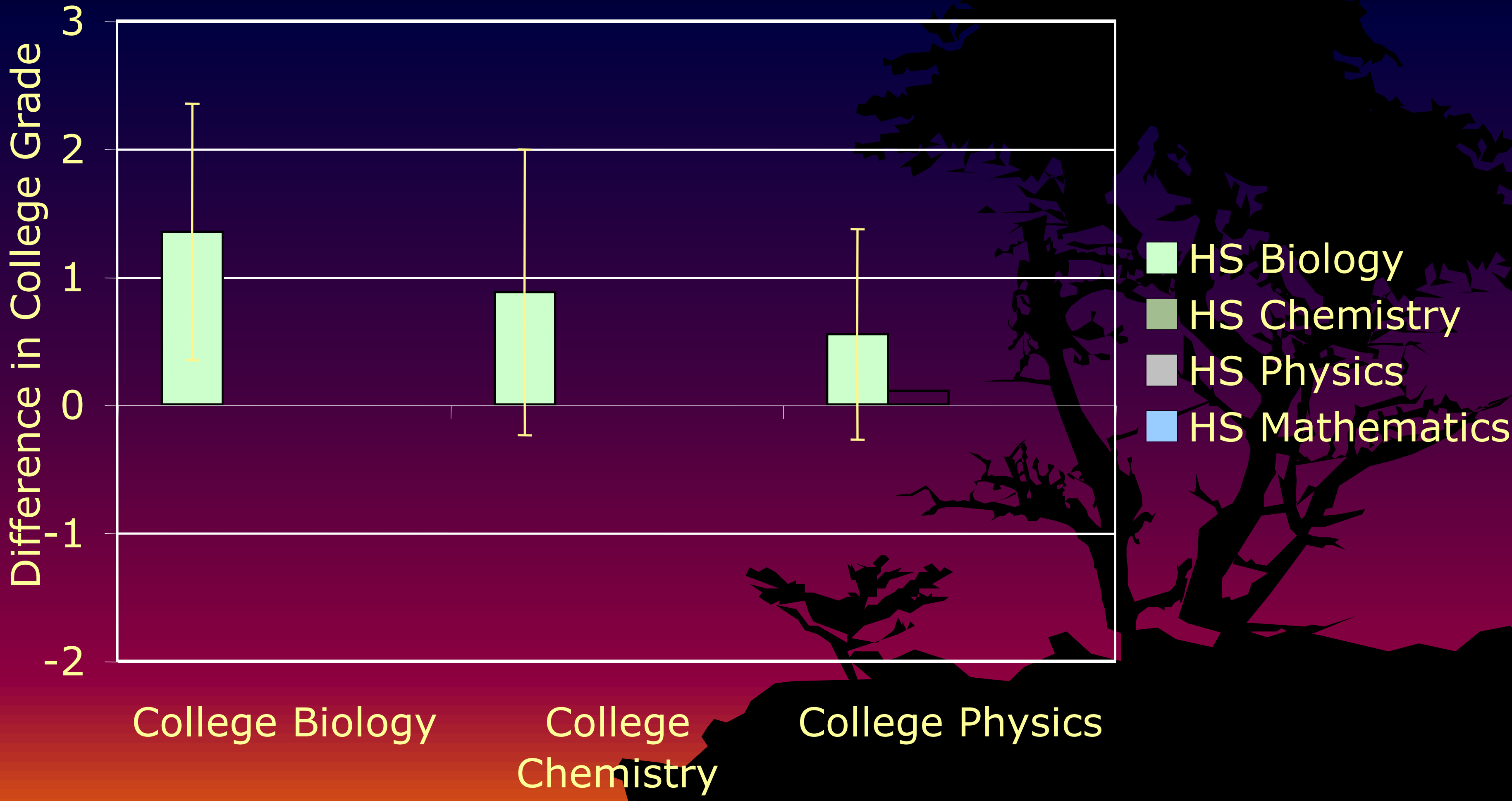
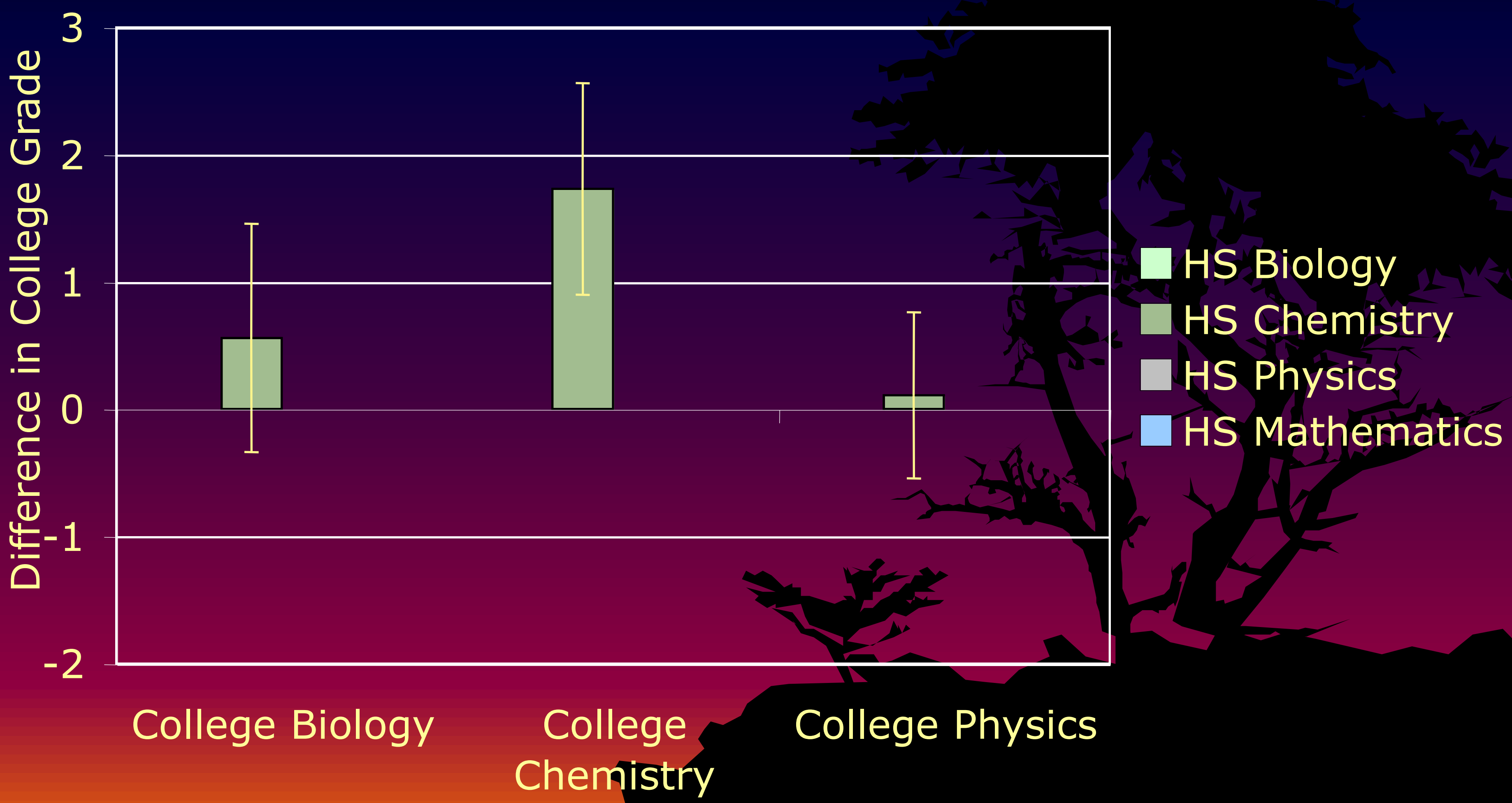
HS Biology

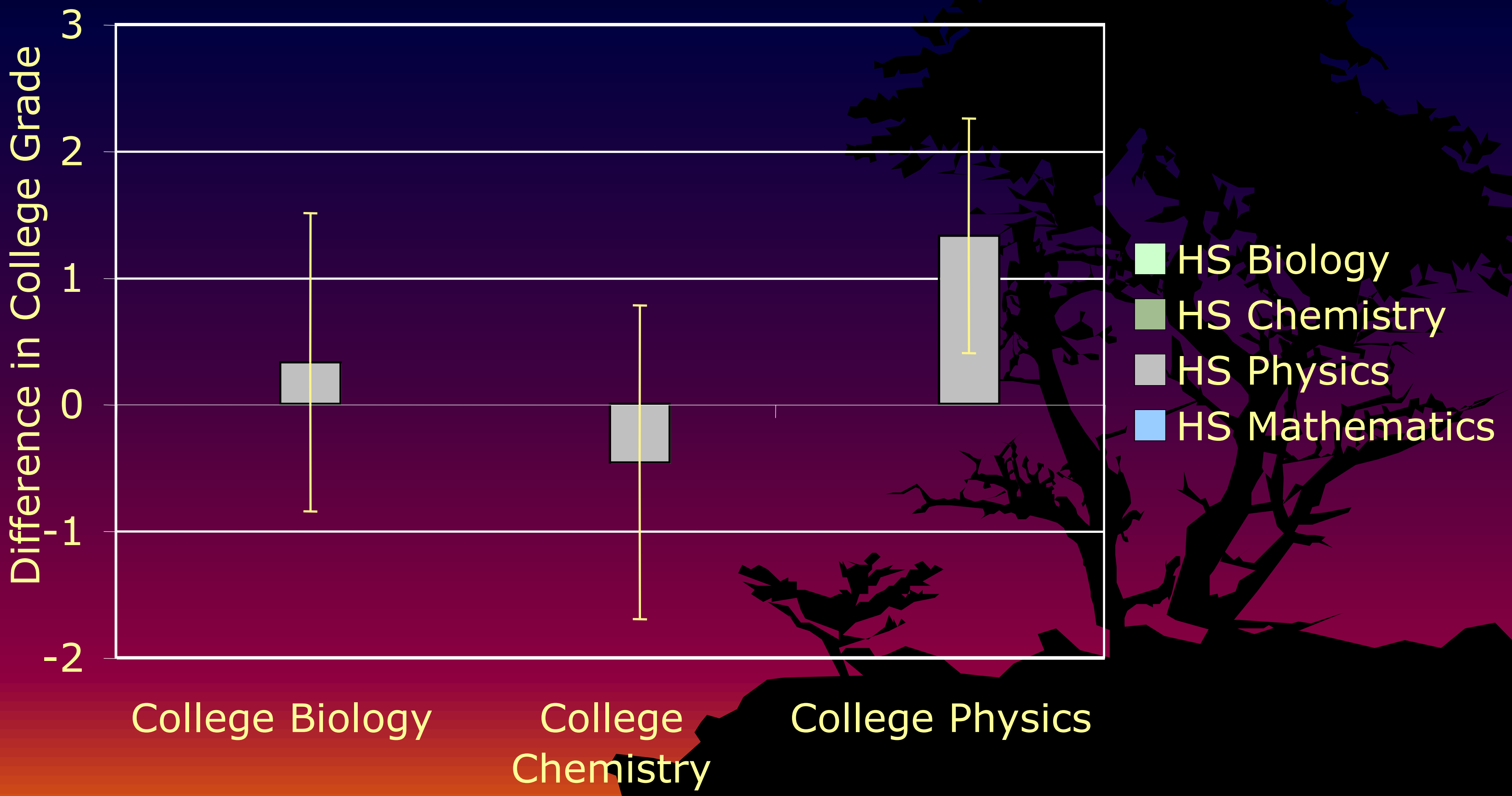


Difference in College Grade
3
2
1
0
-1
-2
HS Biology
HS Chemistry
HS Physics
HS Mathematics
College Biology
College Chemistry
College Physics

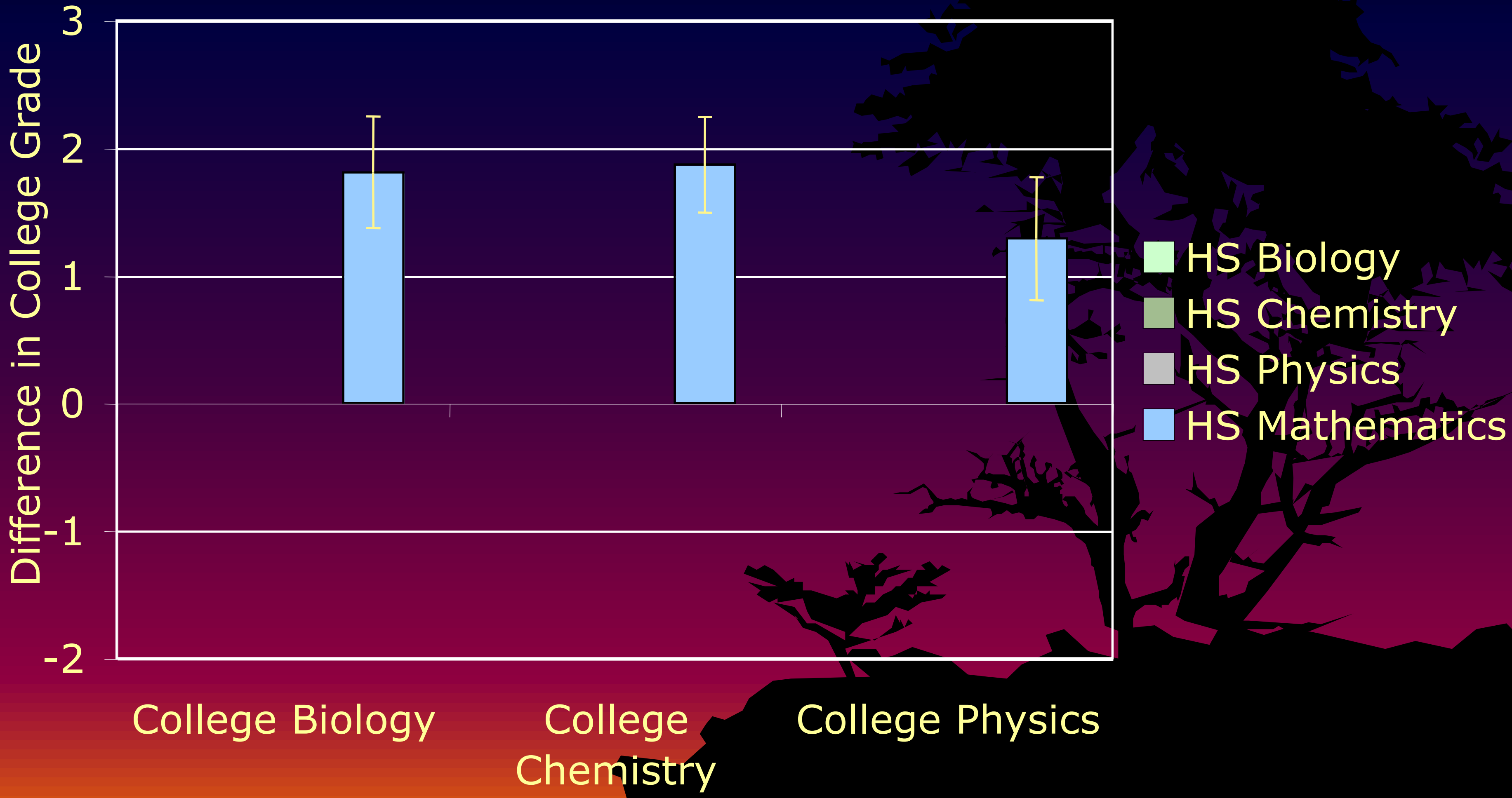
HS Chemistry Effect



HS Physics Effect



Mathematics Effect

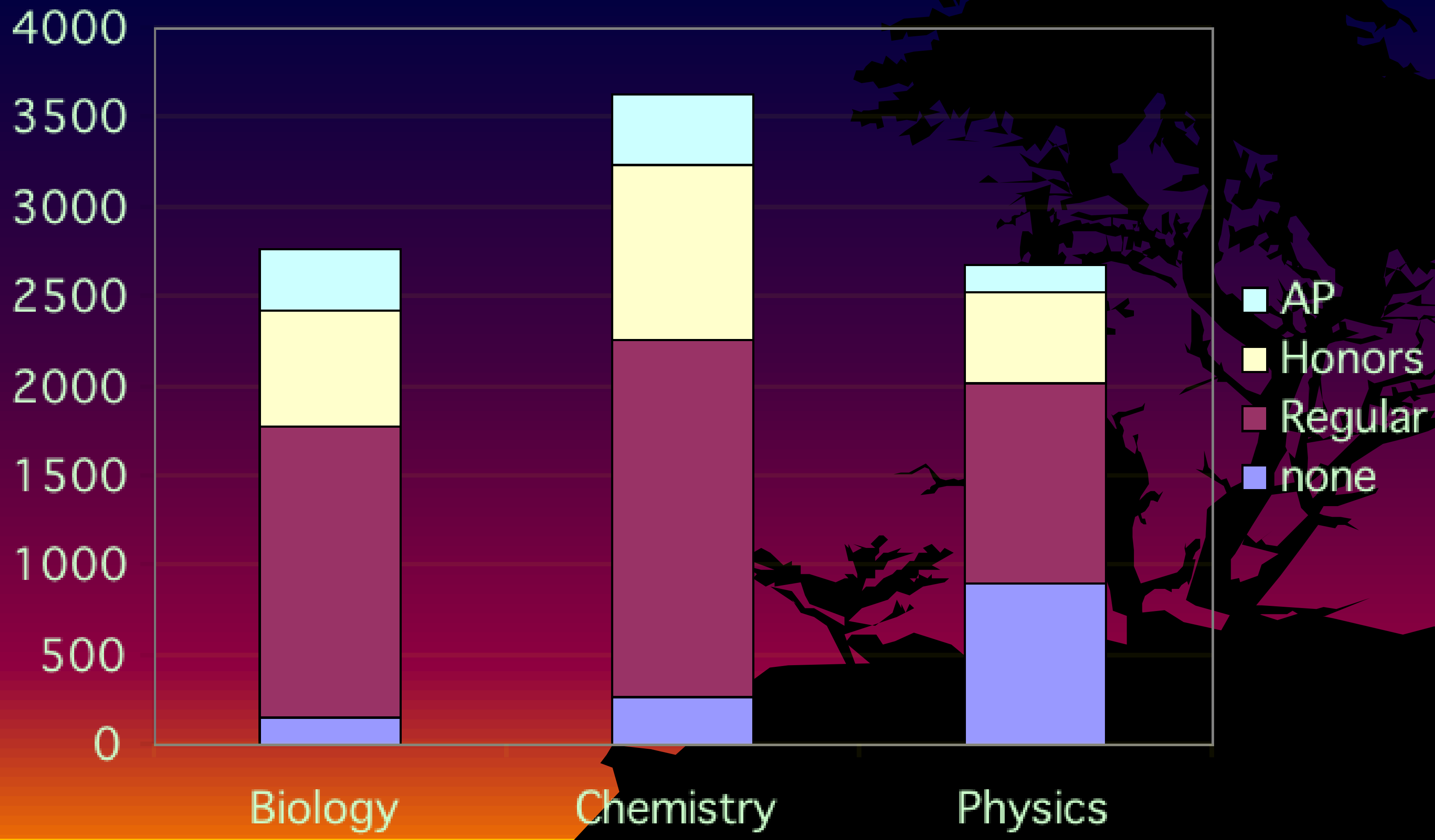


Is Advanced Placement the Answer?

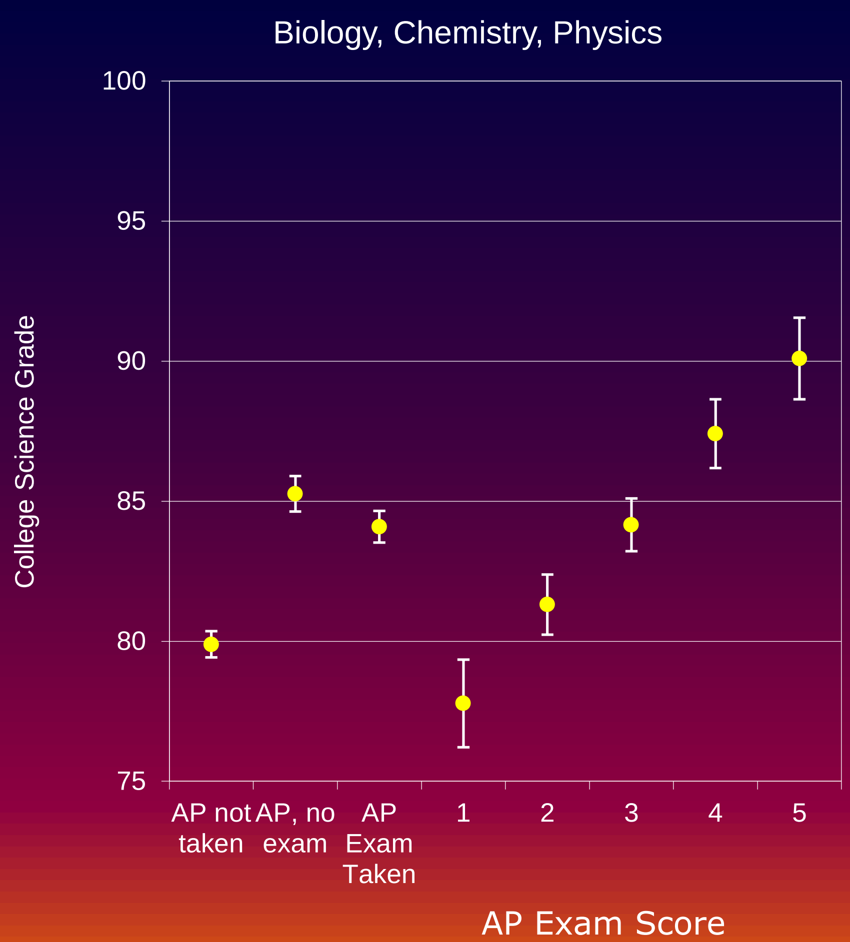
Sadler, P.M. & Tai, R. H. (2007). Advanced Placement exam scores as a predictor of performance in introductory college biology, chemistry, and physics courses. *Science Educator*, 16(1).

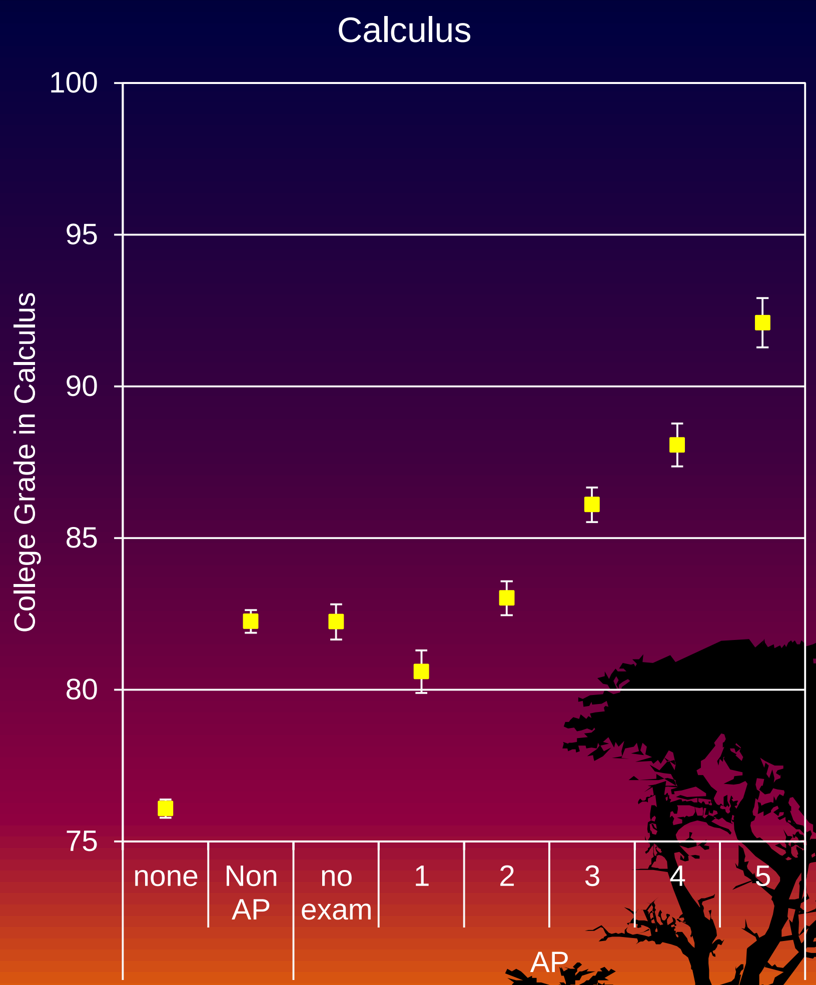
Sadler, P.M., Sonnert, G. Tai, R.H. & Klopfenstein, K. (2010) *AP: A Critical Examination of the Advanced Placement Program*, Cambridge, MA: Harvard Education Press.

Surprise! AP students often take introductory college courses in science
How do they do when "repeating" a course?

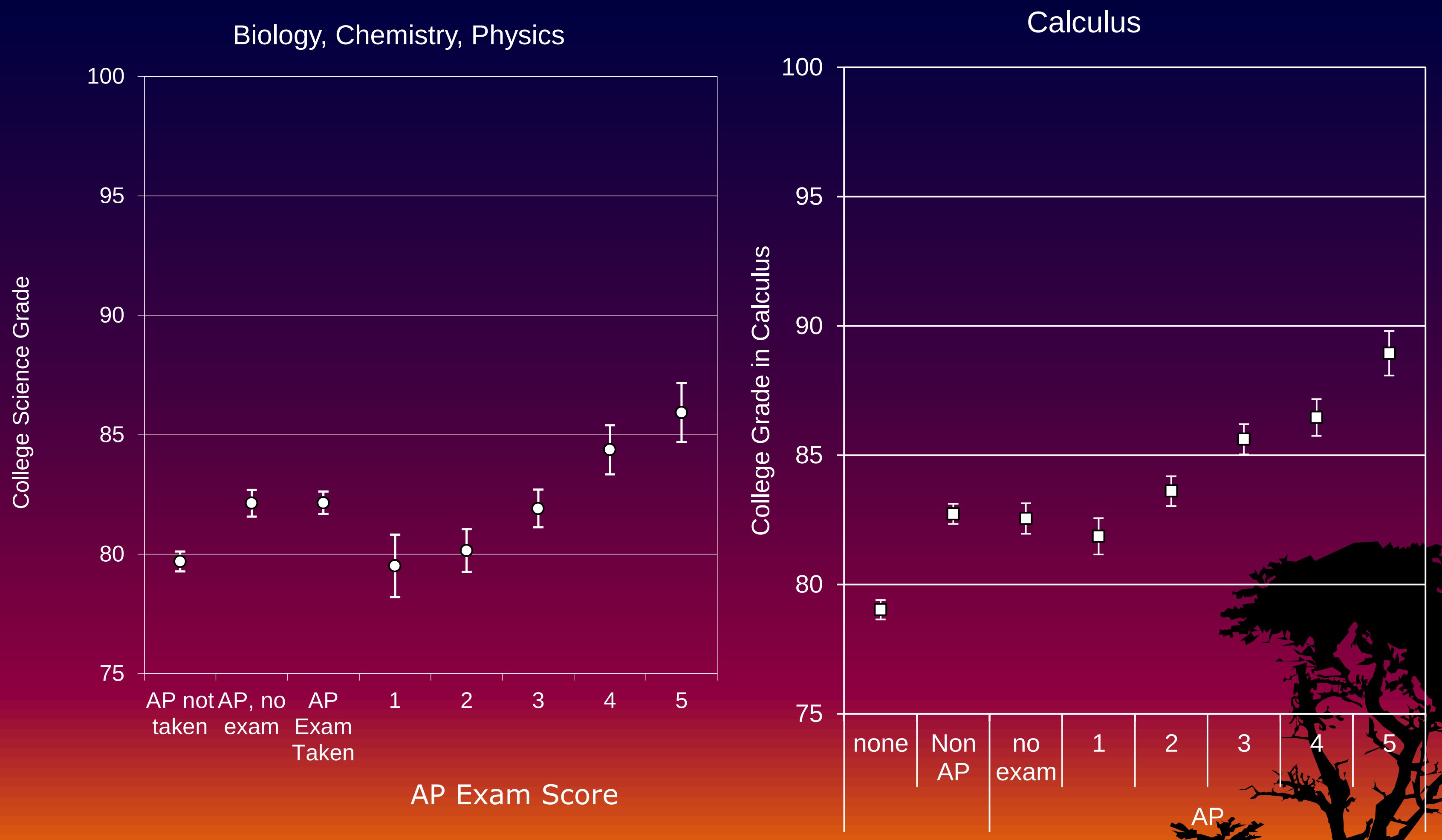


College Science and Math Performance: raw grades

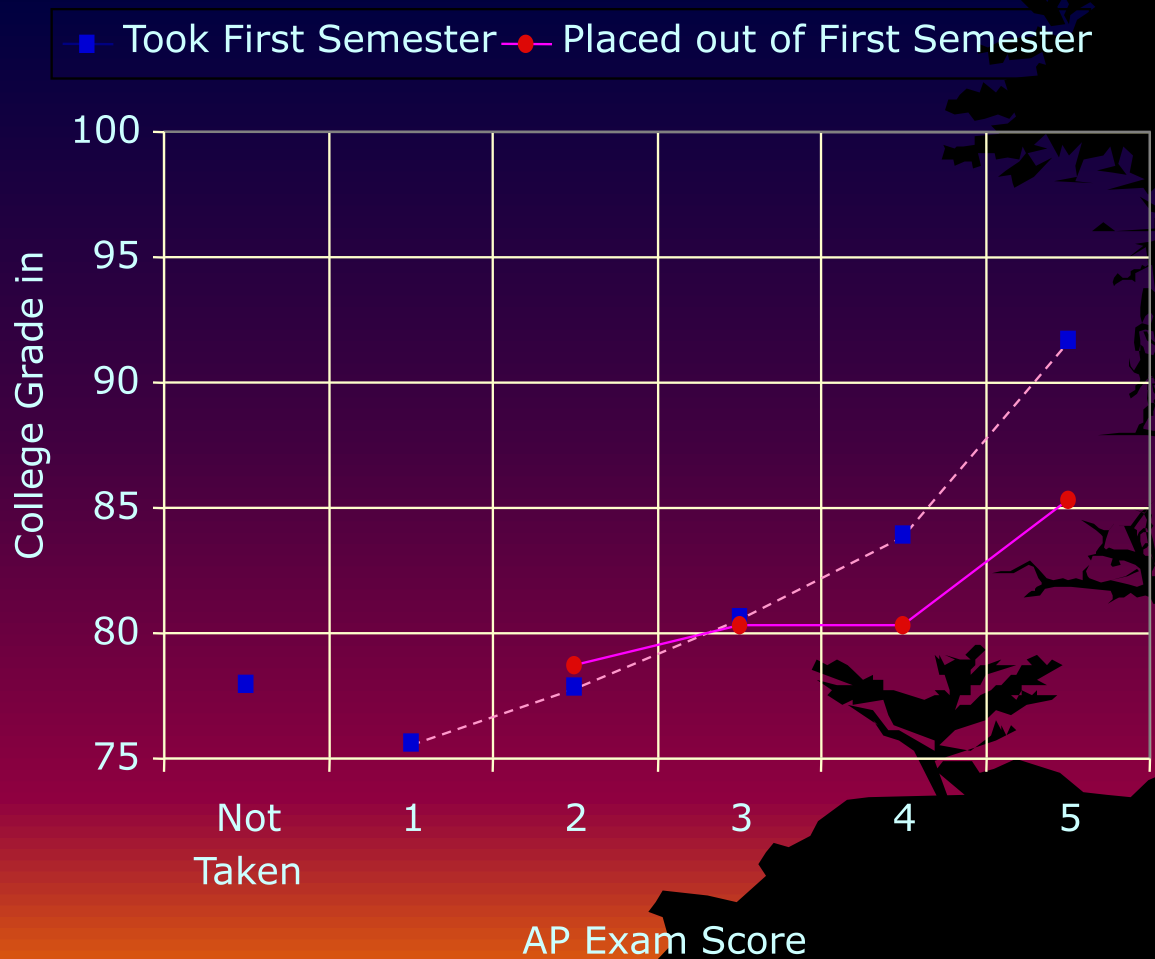




College Science and Math Performance: + controls



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

Wyss, V. L., Tai, R. H., & Sadler, P.M. (2007). High school class-size and college performance in science. *High School Journal*. 90(3), 45-53.

Sadler, P.M. & Tai, R. H. (2007) The Two High-School Pillars Supporting College Science. *Science.* 317(5837) 457-458.

Sadler, P.M. & Tai, R. H. (2007). Advanced Placement exam scores as a predictor of performance in introductory college biology, chemistry, and physics courses. *Science Educator*, 16(1). 1-19.

Tai, R. H., Sadler, P.M. & Maltese, A. V. (in press). A study of the association of autonomy and achievement on performance. *Science Educator,* 16(1), 22-28.

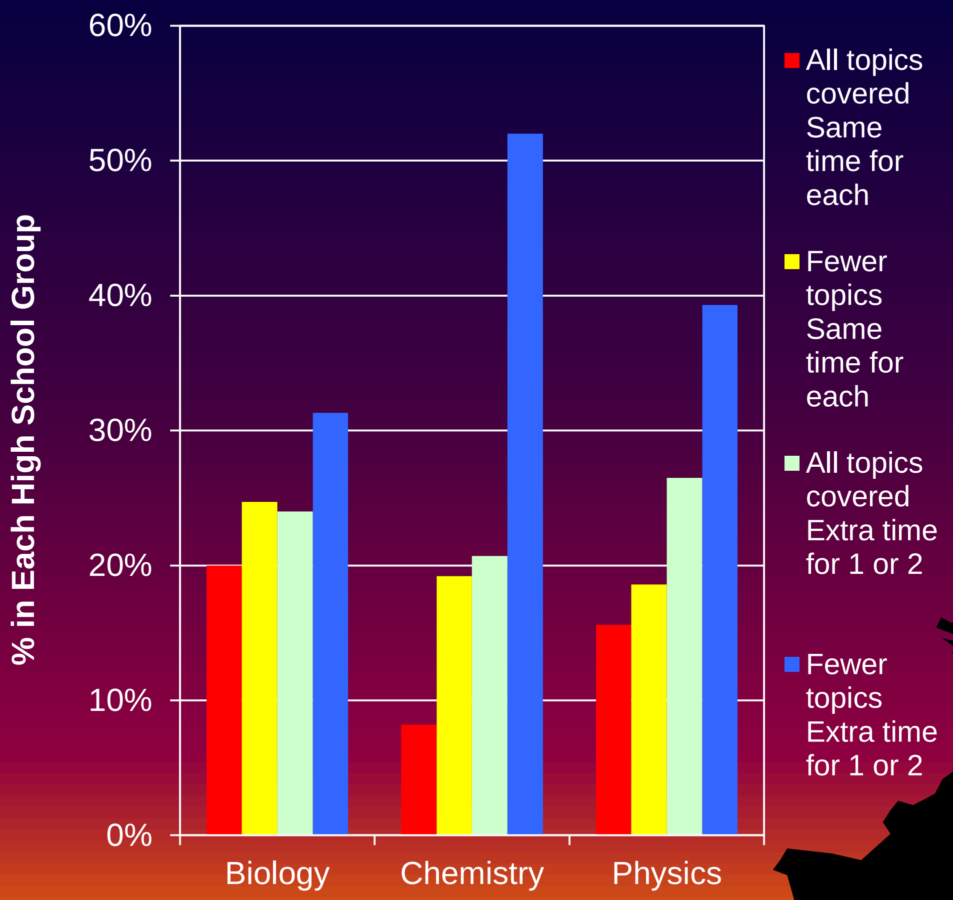
Tai, R. H. & Sadler, P.M. (2009). Same science for all? Interactive association of structure in learning activities and academic attainment background on college science performance in the USA. *International Journal of Science Education. 31(5), 675-696.*

Maltese, A. V., Tai, R. H., & Sadler, P.M. (2010). The Effect of High School Physics Laboratories on Performance in Introductory College Physics, *The Physics Teacher,* 48(5), 333-337.

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 a essential foundational concepts

The Impact of Coverage: Depth vs. Breadth



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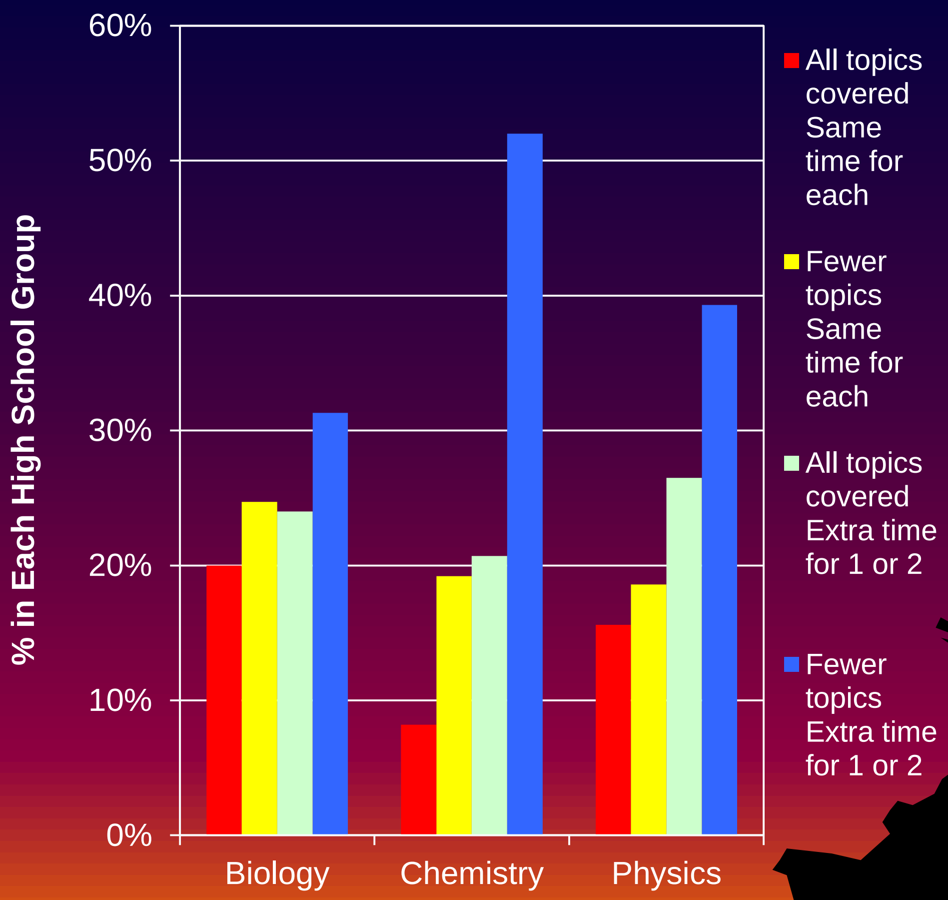

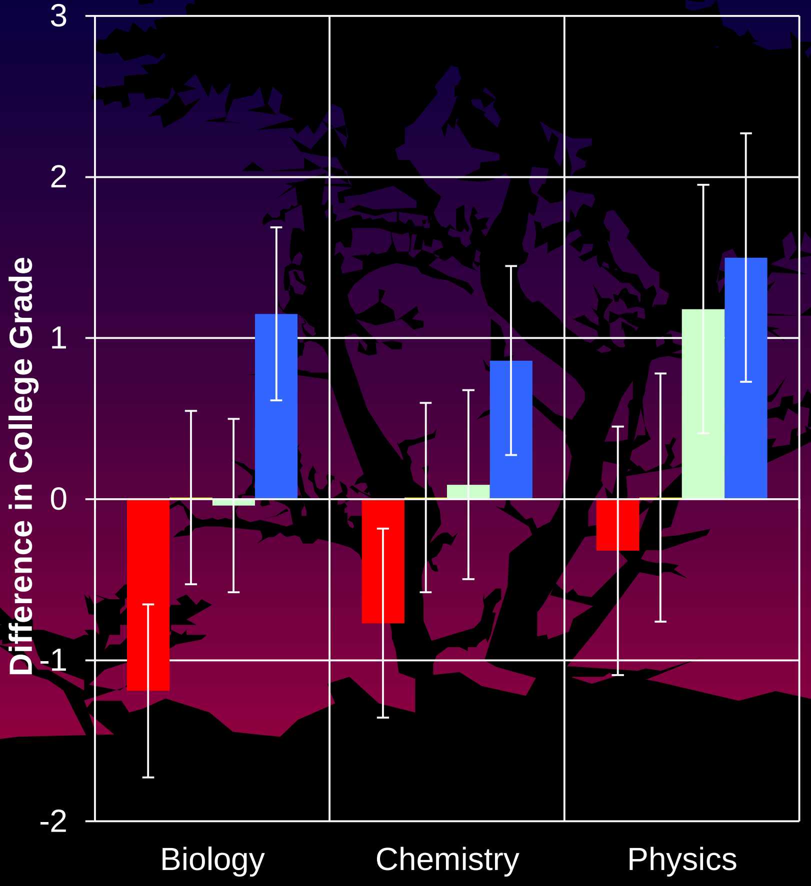

Laboratory Activities

Sadler, P.M., Coyle, H.A. & Schwartz, M., (2000) Successful Engineering Competitions in the Middle School Classroom: Revealing Scientific Principles through Design Challenges, *Journal of the Learning Sciences*. 9(3), 299-327.

Schwartz, M. S. & Sadler, P.M. (2007) Empowerment in Science Curriculum Development: A microdevelopmental approach. *International Journal of Science Education*. 29(18), 987-1017.

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

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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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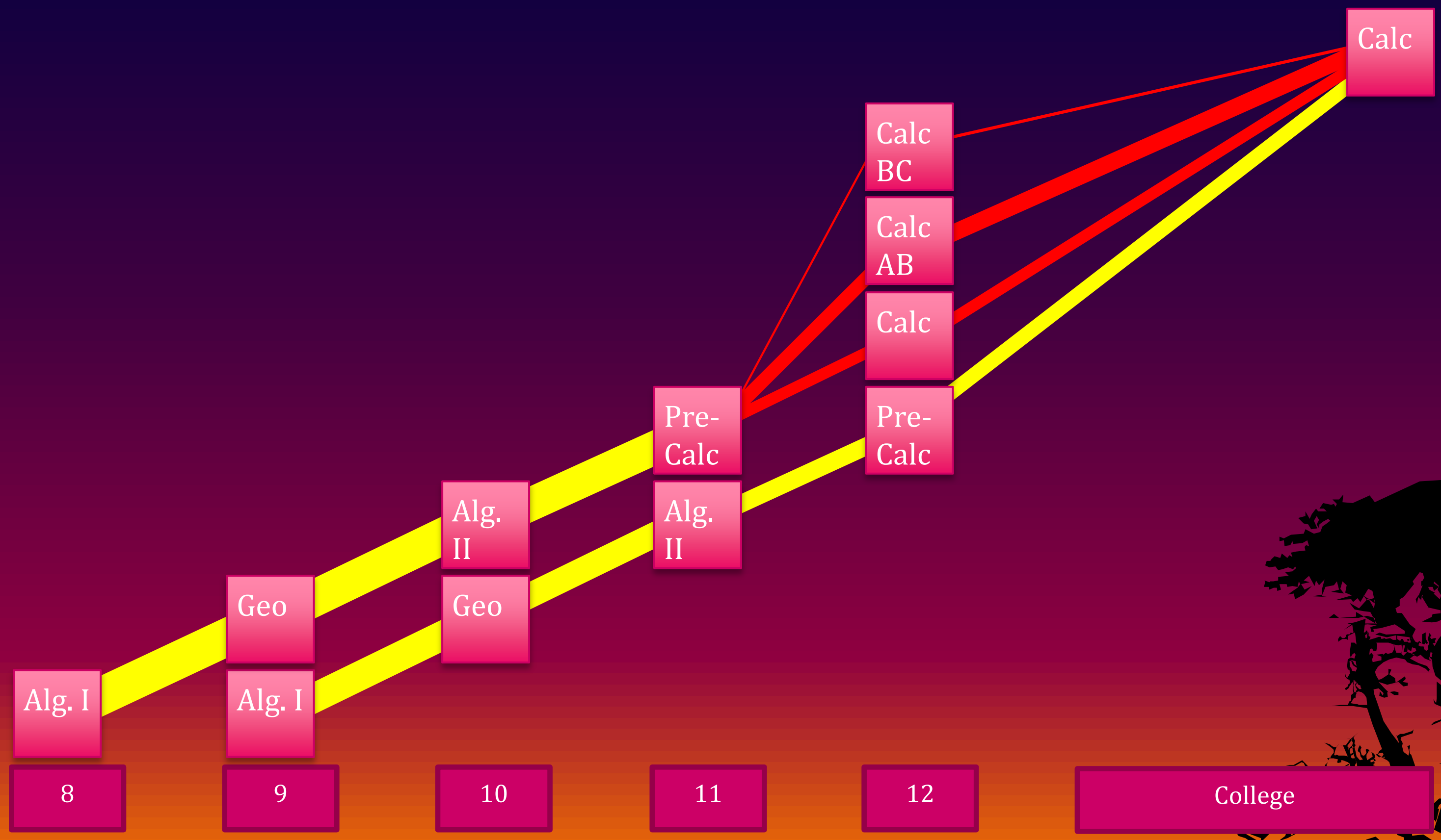
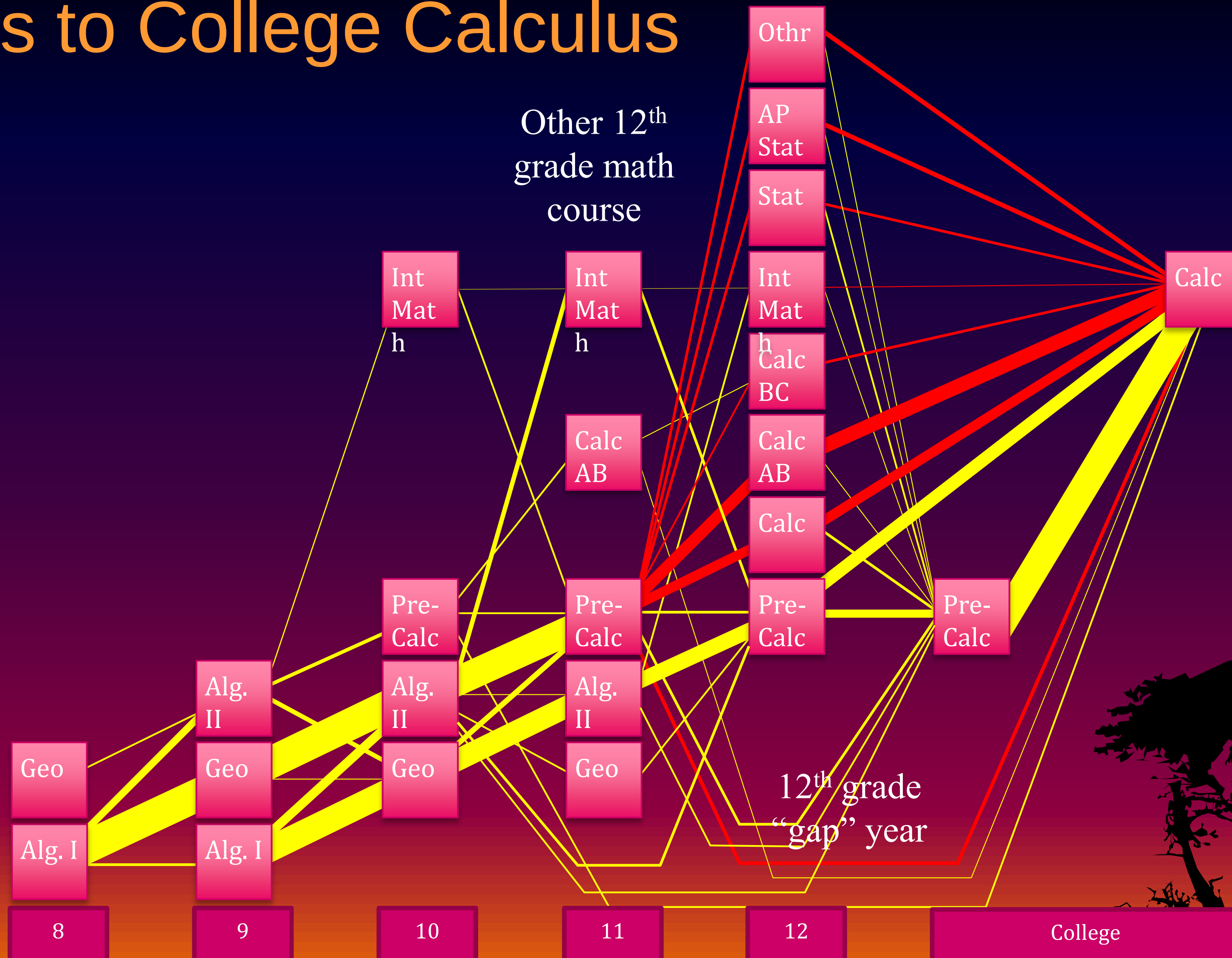
- Coverage
  - Less content, more mastery
- Pedagogy
  - Pictures, illustrations, graphs
  - Simplify lab and demo prediction

Paths to College Calculus



Paths to College Calculus



HS Calculus Teacher Choices

Positive Practices

- Heavy emphasis on functions
- Review homework daily
- Emphasize conceptual understanding
- Emphasize vocabulary

Negative Practices

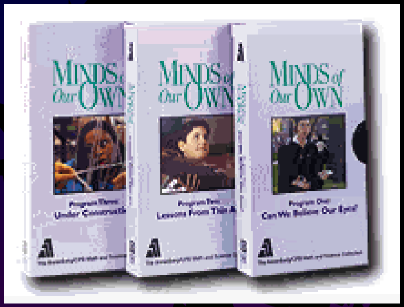
- Plotting graphs on calculator
- “cheat sheets” for tests
- preparing for tests
- reviewing past lessons
- Teacher manipulates physical objects as teaching aids

How effective are we at teaching foundational concepts?

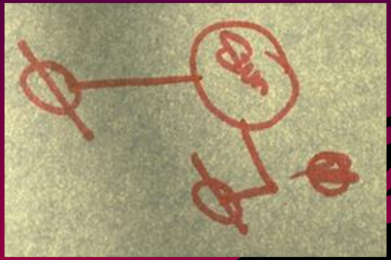
Clinical Interviews

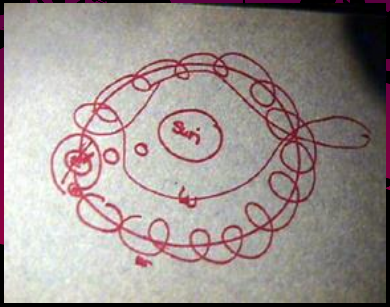
www.ficss.org

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



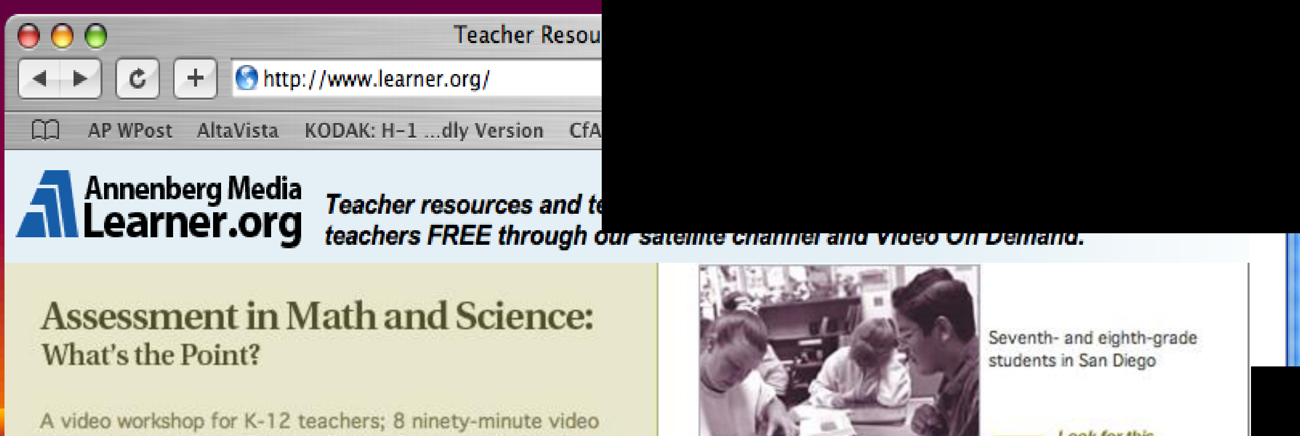


A Private Universe documents students' ideas through their own drawings and explanations

www.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

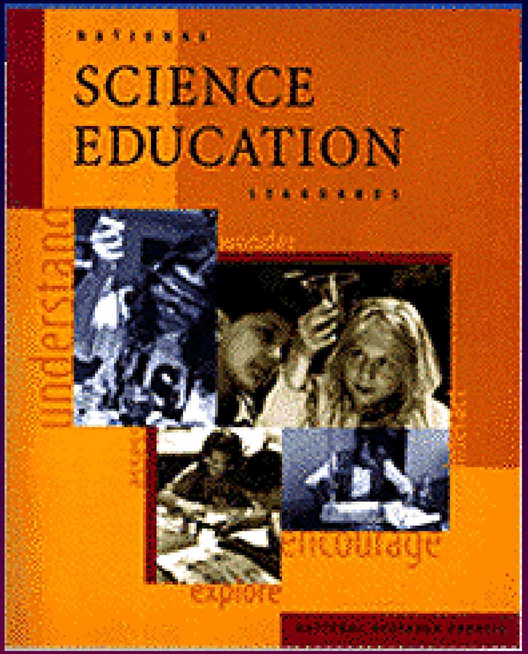
- Targeting content
- Constructing items
- Validating tests
- Samples

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

MS: Cells

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.

MS: Cells

33. Cells inside the human body get energy from:

a. circulating oxygen in the blood. 27%

<u>b. breaking down sugars that come from food. 52%</u>

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

MS: Ecosystems

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.

MS: Ecosystems

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

MS: Extinction

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.

MS: Extinction

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%

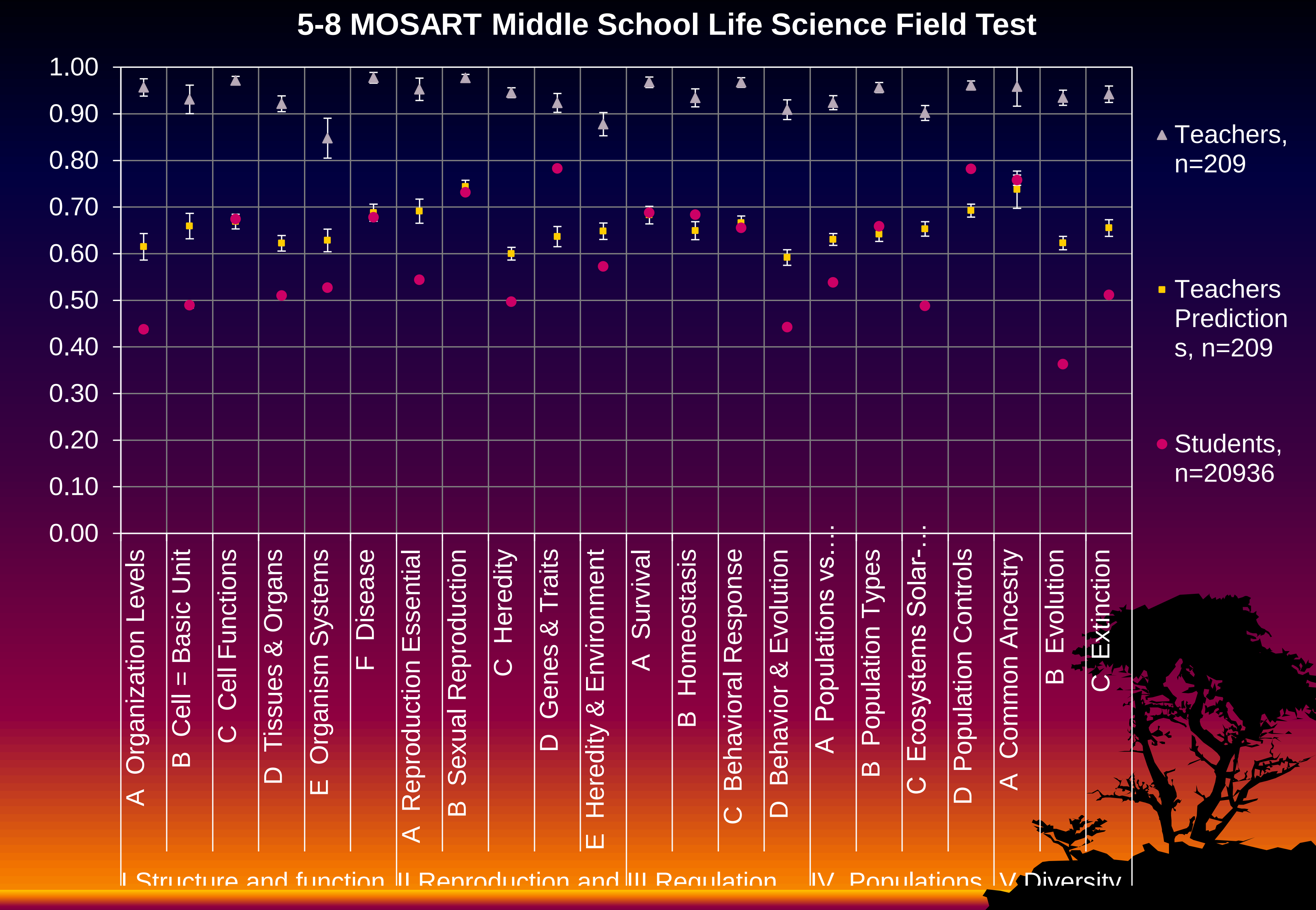
e. Only microorganisms. 2%

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

Comparisons

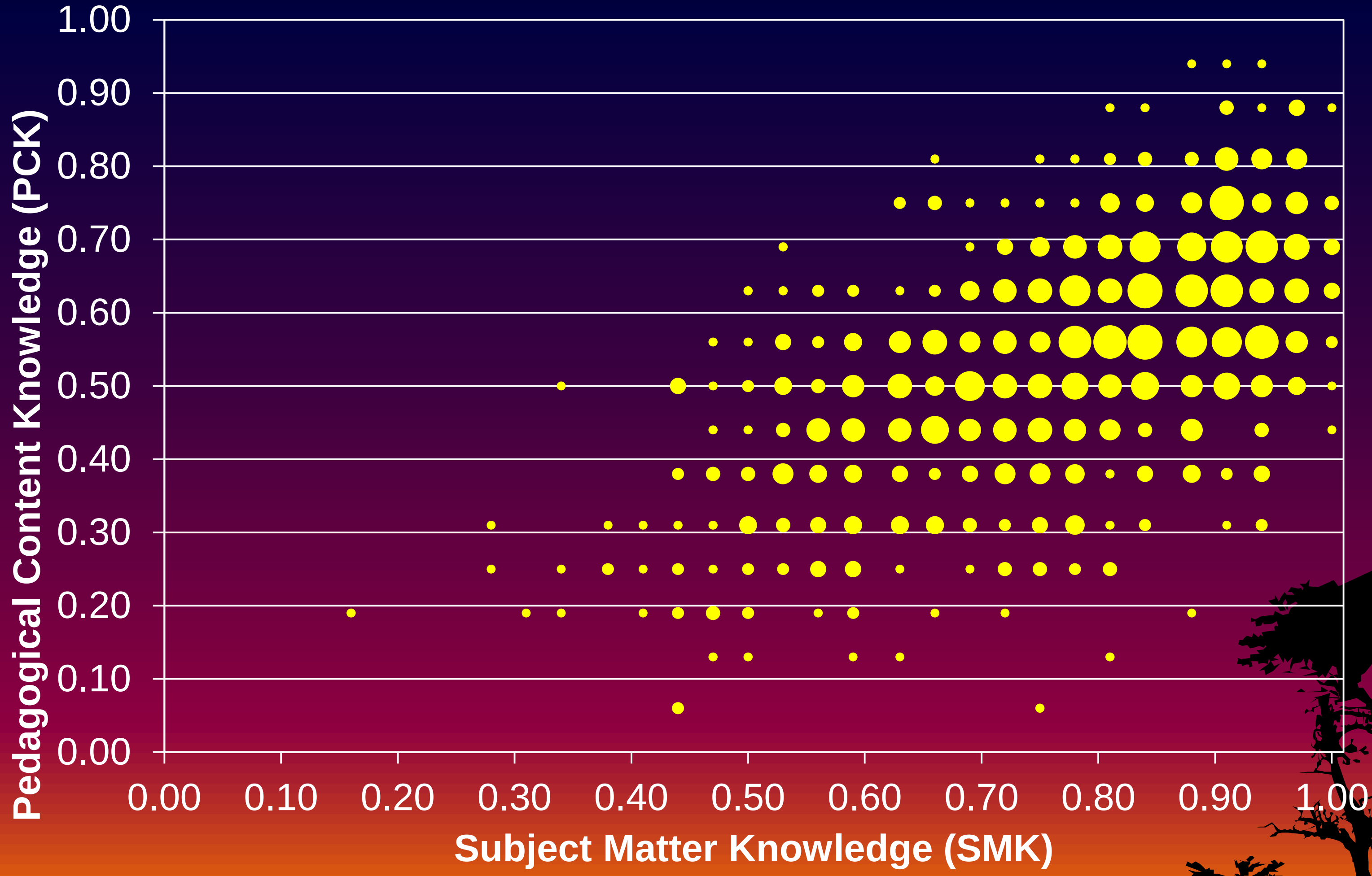
- To what degree have students who completed science courses mastered the NRC standards?
  - At grade level
  - At prior grade levels
- Are there patterns of strength and weakness?

Patterns in Test Data

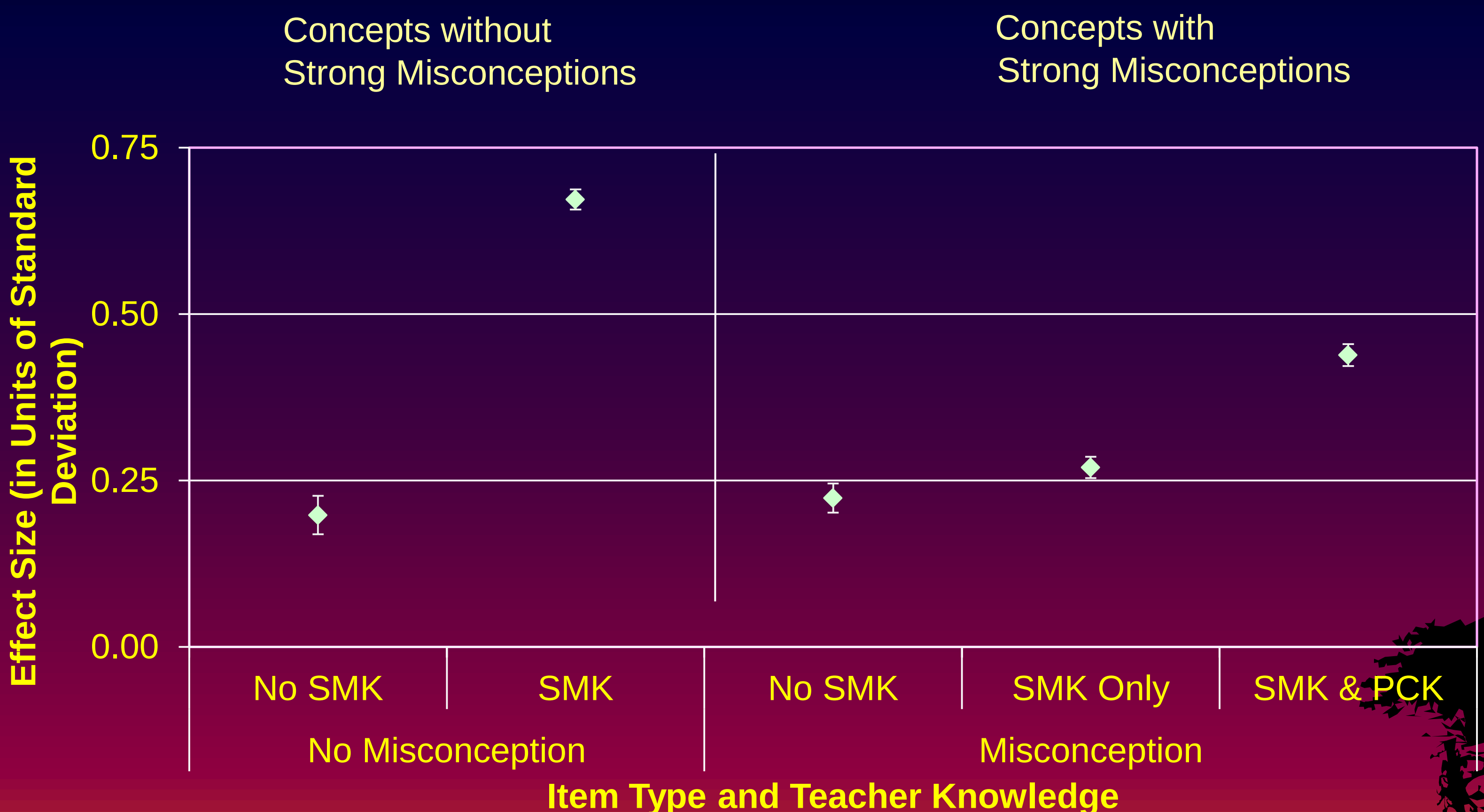


5-8 MOSART Middle School Life Science Field Test
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Teachers, n=209
Teachers Predictions, n=209
Students, n=20936
A Organization Levels
B Cell = Basic Unit
C Cell Functions
D Tissues & Organs
E Organism Systems
F Disease
A Reproduction Essential
B Sexual Reproduction
C Heredity
D Genes & Traits
E Heredity & Environment
A Survival
B Homeostasis
C Behavioral Response
D Behavior & Evolution
A Populations vs.…
B Population Types
C Ecosystems Solar-…
D Population Controls
A Common Ancestry
B Evolution
C Extinction
I Structure and function
II Reproduction and
III Regulation
IV Populations
V Diversity

Teacher Knowledge, MS-LS



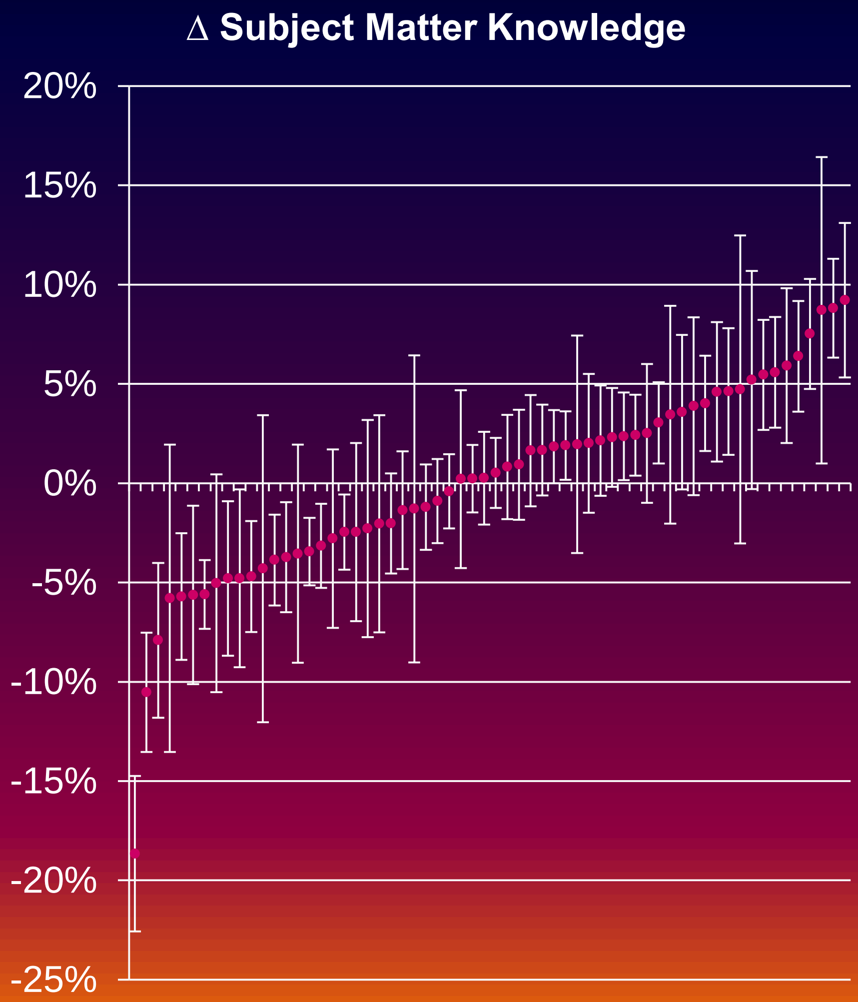
Yearly Classroom Gain in Middle School Physical Science Courses, N= 15029 students of 160 teachers

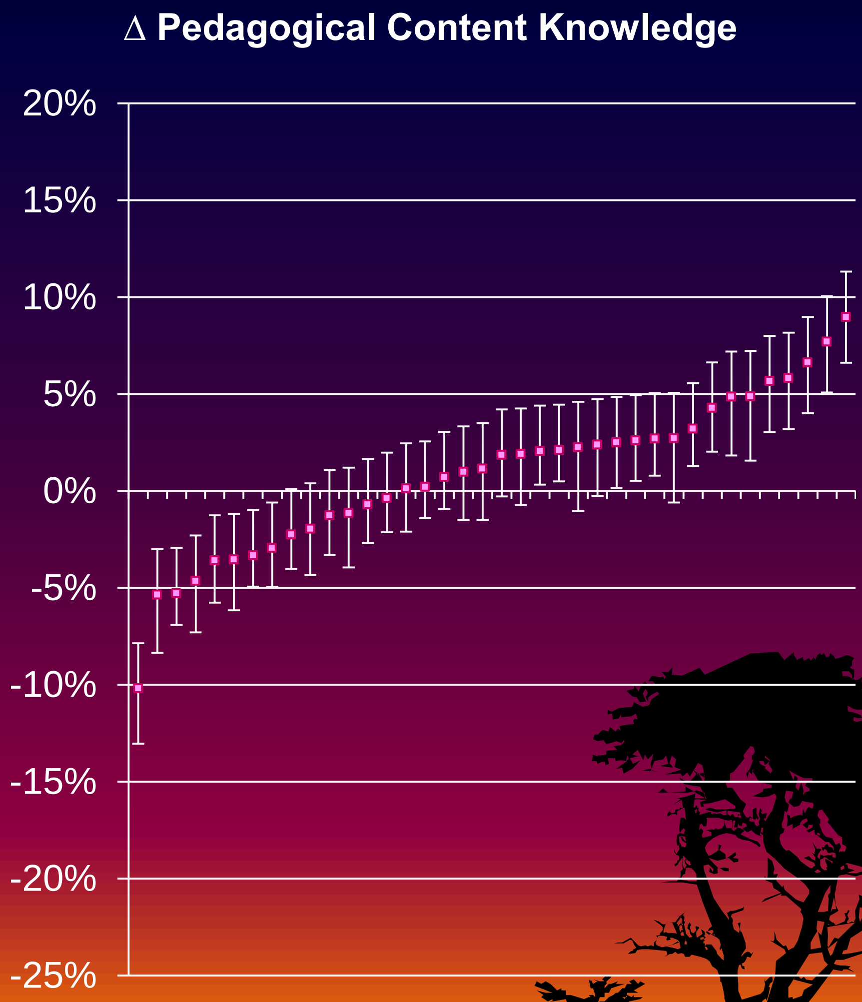


SMK=Subject Matter Knowledge (knows correct answer)
PCK=Pedagogical Content Knowledge (can identify student misconceptions)

Results of Teacher Professional Development

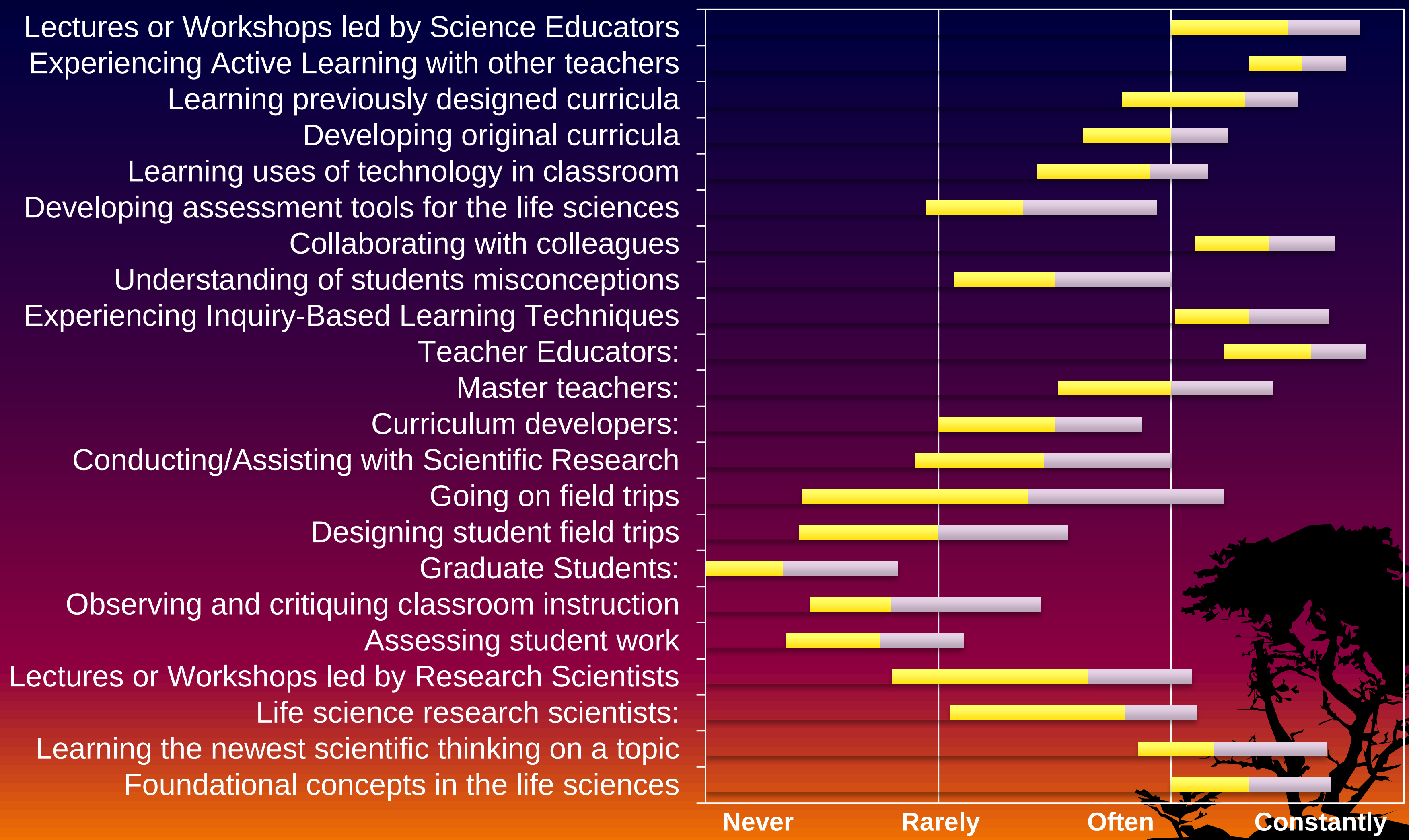
Gain in SMK and PCK





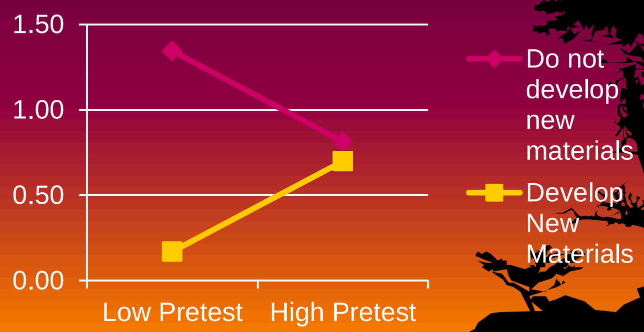
Next Steps:
How do gains vary with PD attributes

PD Attributes, difference in emphasis



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



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

Psychological Foundations

"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

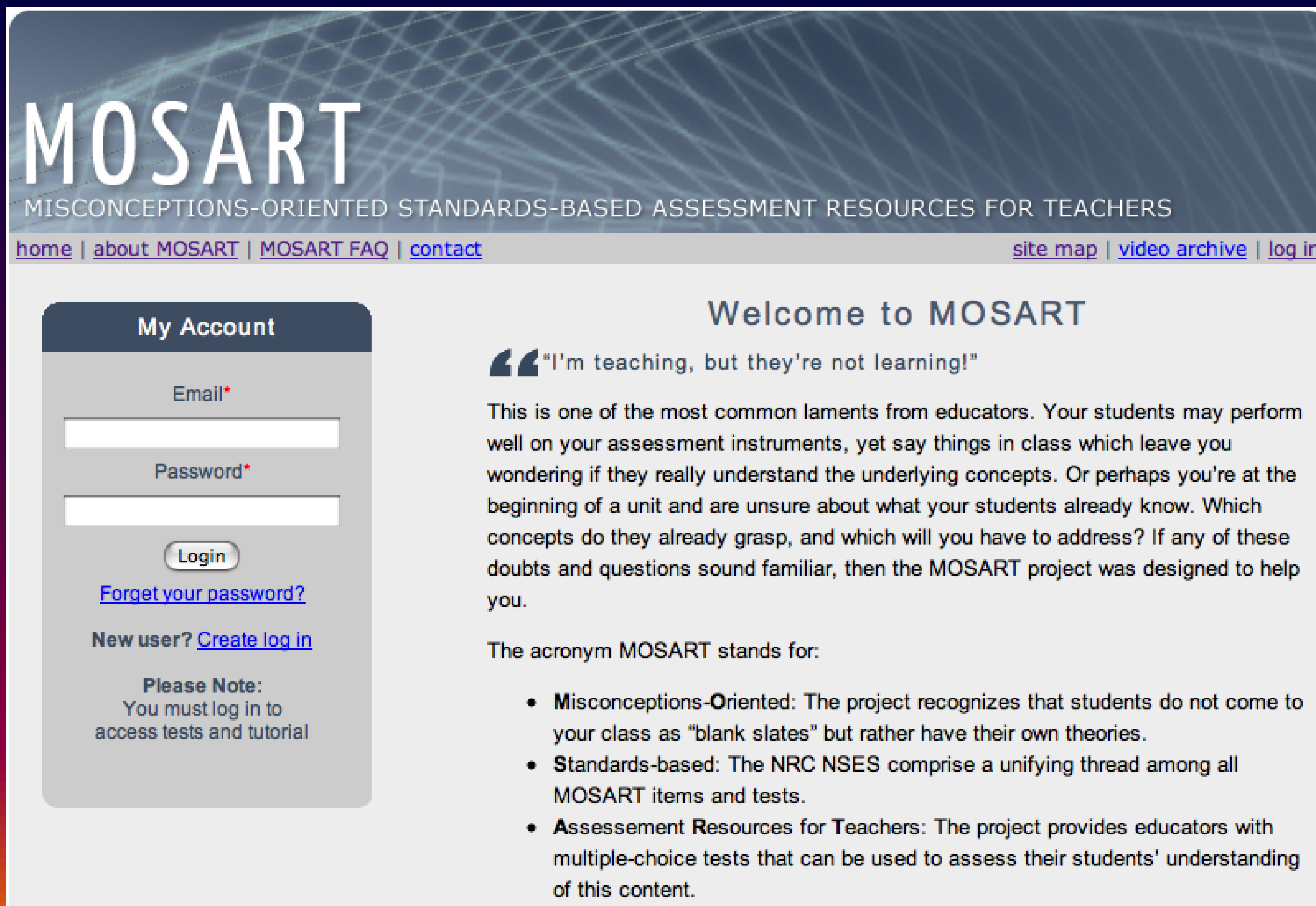
Lord Kelvin (1824-1907)

- ”If you can measure that of which you speak, and can express it by a number, you know something of your subject;

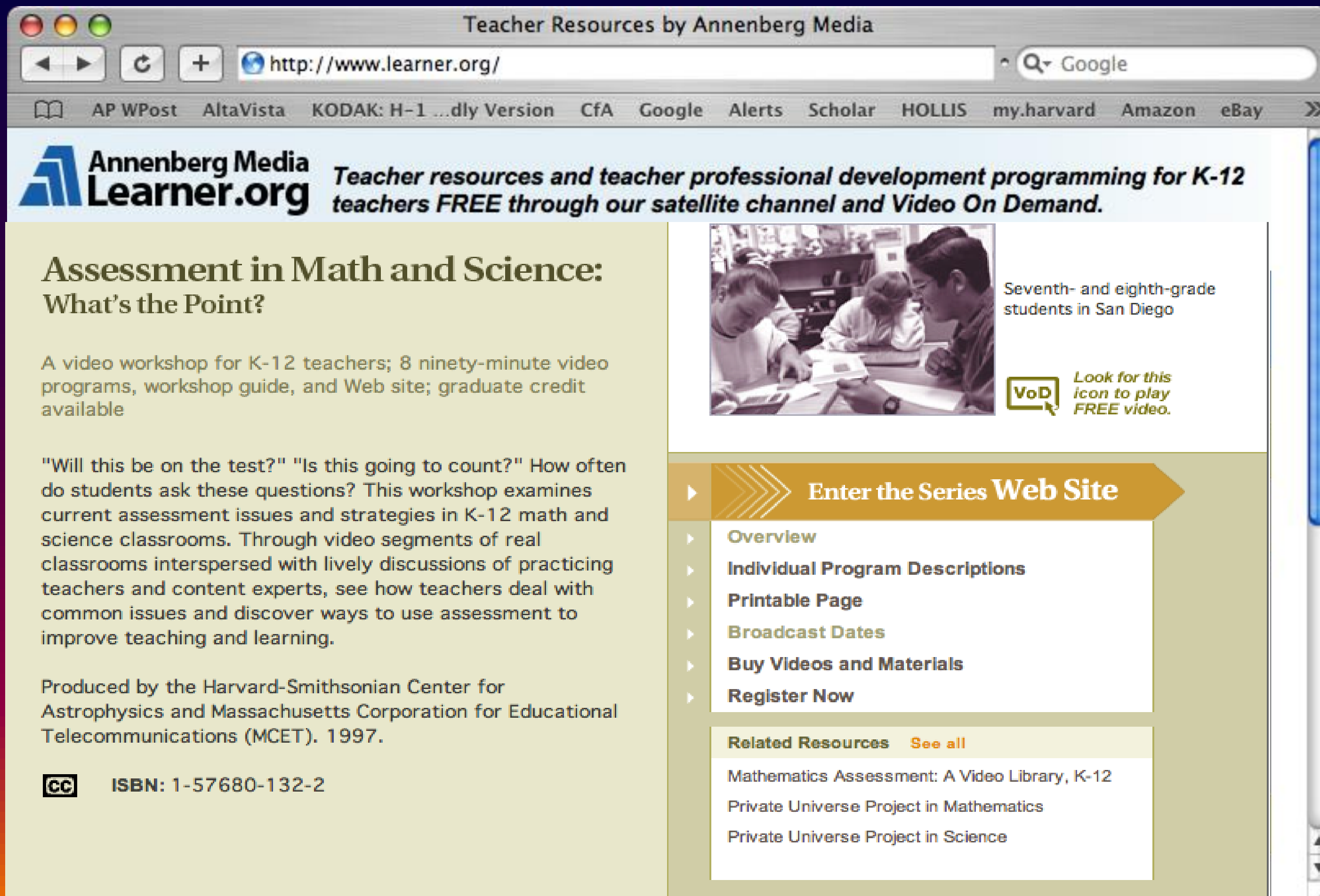
Lord Kelvin (1824-1907)

- "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



Annenberg Channel free videos and PD



FICSS Website – research results

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