

**Changing the way undergraduates are taught**  
in a research-oriented biology department

Bill Wood  
Department of MCD Biology  
University of Colorado, Boulder

## Assumptions:

- In general, we are not doing a good job of teaching science to undergraduates at large research universities.
- Educational research has identified "promising practices" for doing a better job, but science departments have been very slow to adopt them.

How can we change the teaching culture of an entire institution so that science is taught more effectively?

One approach: Carl Wieman's Science Education Initiative (SEI)

at U. of Colorado, Boulder and U. B. C., Vancouver, Canada

Funding from the University:

~ \$4 M over 5 years, 2006-2011

Competitive applications from departments to participate in the program

## Five science departments:

Chemistry and Biochemistry

Earth sciences

Integrative Physiology

**MCD Biology**

Physics

All strongly research-oriented

All teaching many undergraduates

# The Science Education Initiative At University of Colorado, Boulder

Formulate  
Learning  
Goals

What should  
students  
learn?

What are  
students  
learning?

Develop  
pre-/post-  
assessments  
to measure  
learning gains

**SEI**

Which instructional  
approaches  
improve  
student  
learning?

Develop and test activities for formative  
assessment and achievement of learning gains

## MCD Biology Team

**Jia Shi, Ph.D.**                      **Science Teaching Fellow**

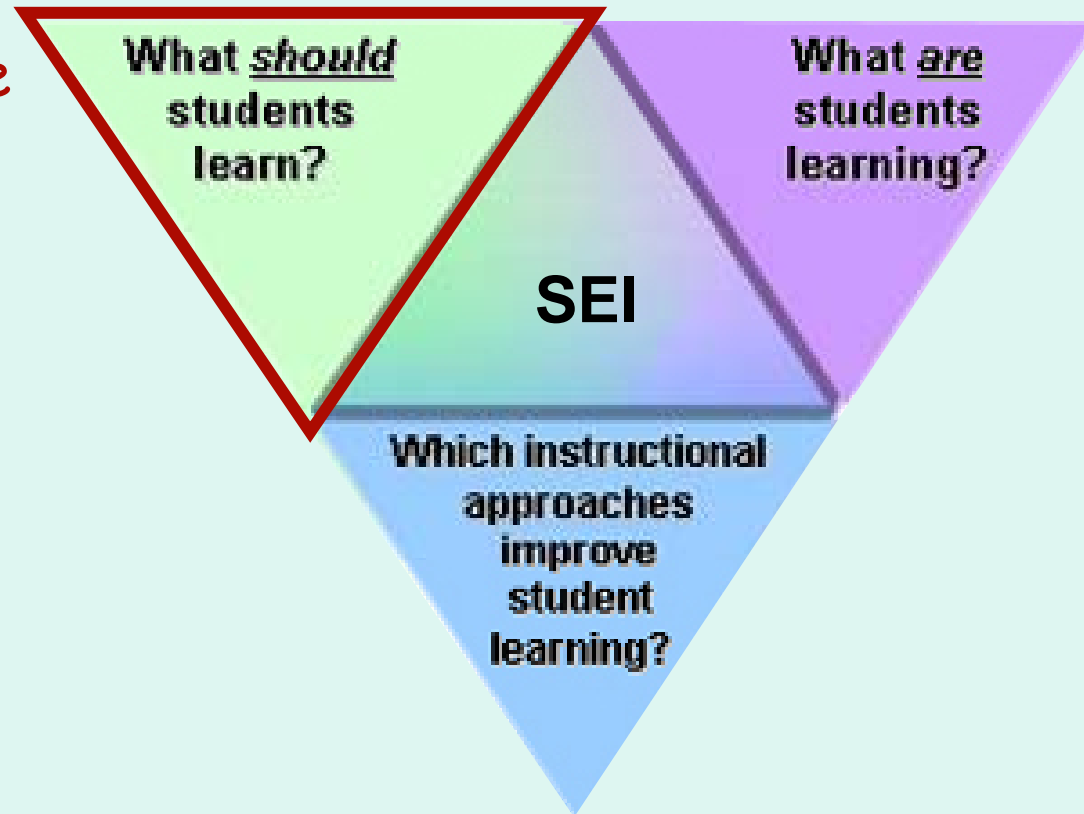
**Michelle Smith, Ph.D.**              **Science Teaching Fellow**

Jennifer Knight, Ph.D.              Senior Instructor and  
SEI Coordinator

Bill Wood, Ph.D.                      MCDB Faculty Director

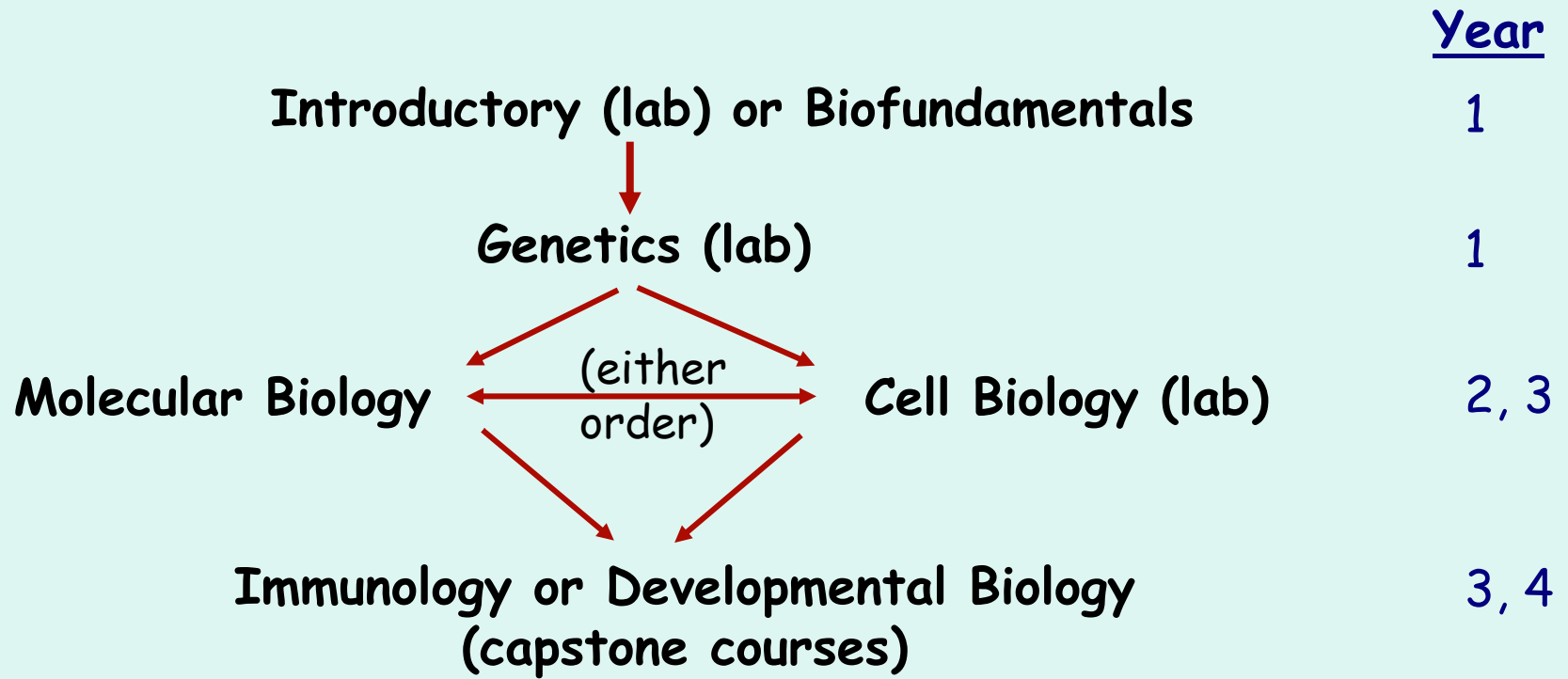
with help from several course instructors

Formulate  
Learning  
Goals



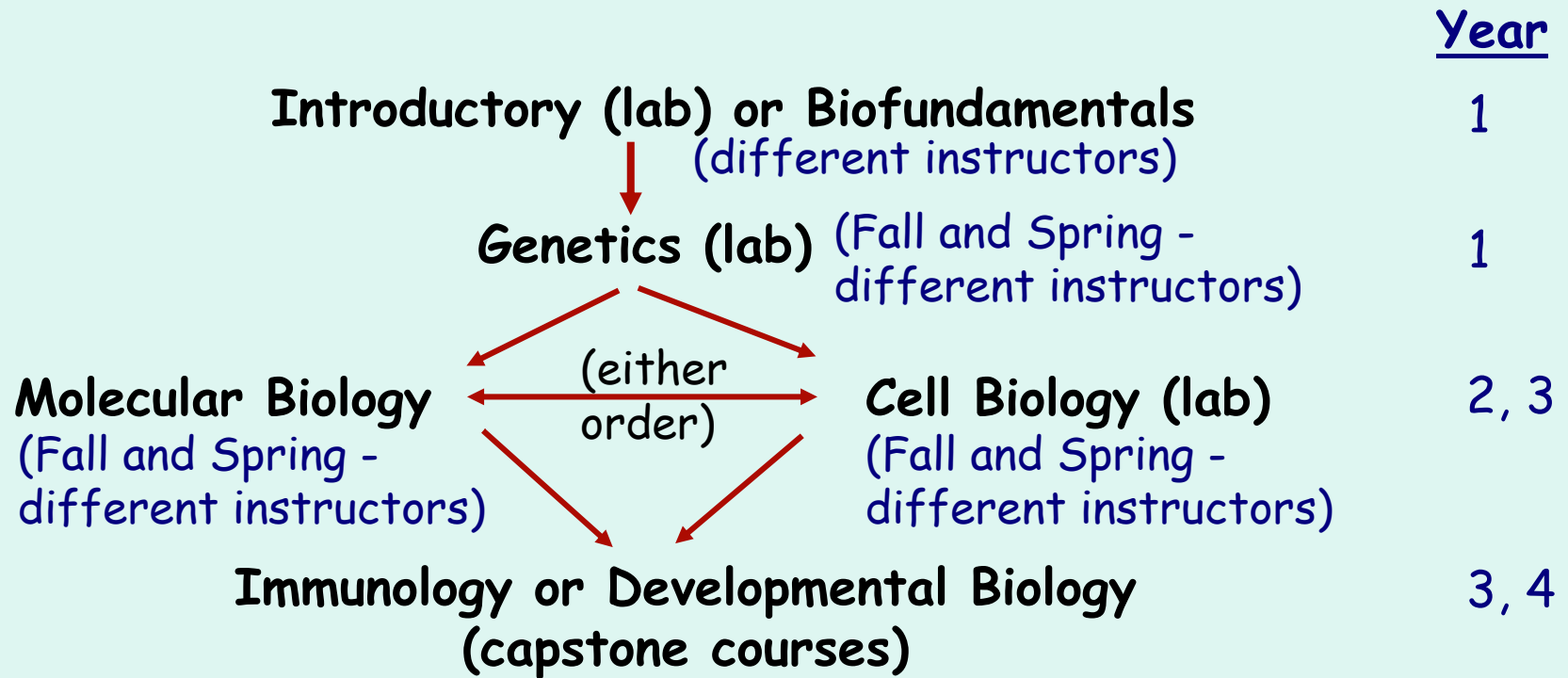
for the core majors courses in the department;  
I.e. define the curriculum in terms of learning goals.

# The MCD Biology Curriculum for Majors

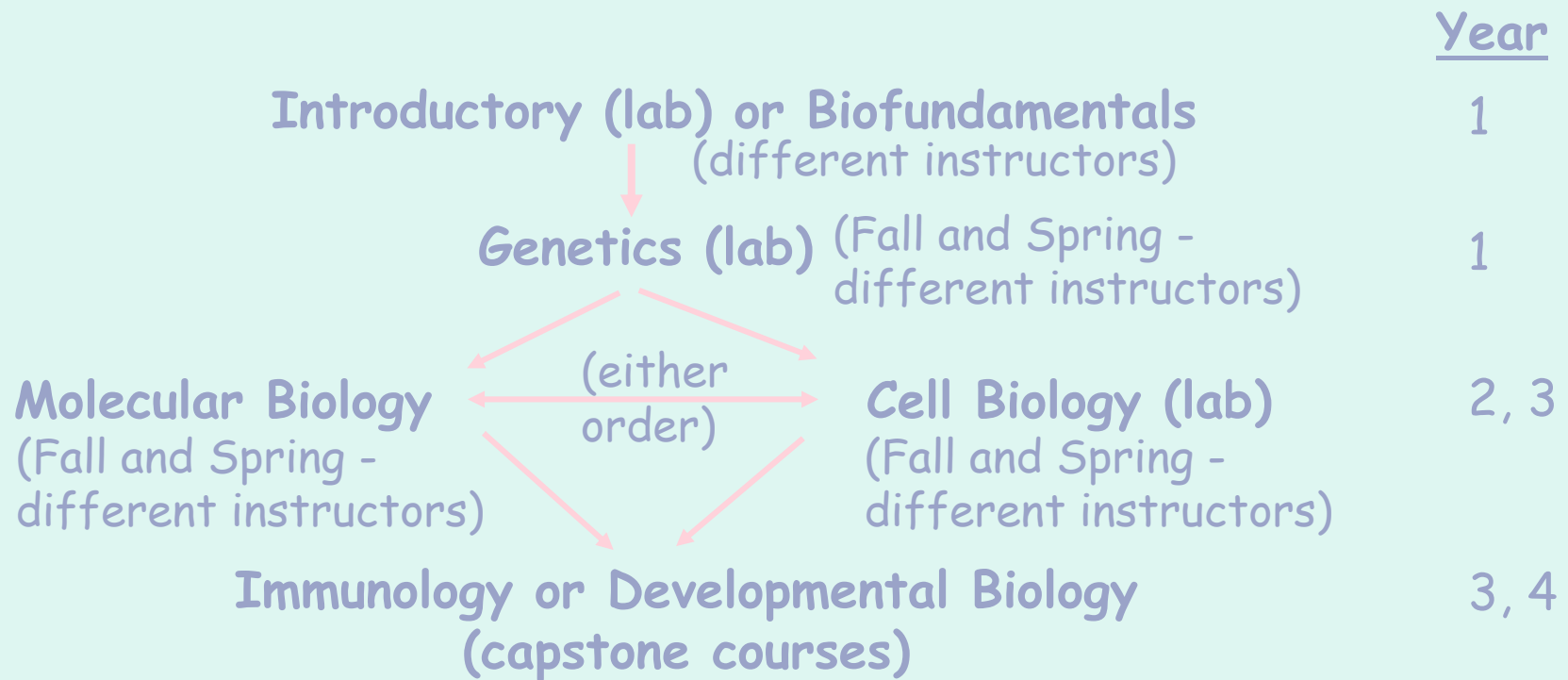




# The MCD Biology Curriculum for Majors



# The MCD Biology Curriculum for Majors



**Task: Formulate a set of learning goals** at course and topic levels, agreed on by all current instructors of each course, subject to approval by the undergraduate committee and eventually the faculty as a whole.

[Jia, Michelle, Bill, Course Instructors]

## Example:

### Syllabus for a workshop on active learning

Introduction

→ Use of clickers in class

Why bother with learning goals?

Setting learning goals

Syllabi and what information they give students

Learning goals and how they differ from syllabi

Using Bloom's taxonomy in setting learning goals

Making instructor's learning goals explicit

Assessing how well learning goals are met

Whose learning goals are they?

How instructors can affect student learning goals

Assessing student learning in class

Assessing student learning gains in a course:

pre- and post-tests

Comparing different teaching methods for effectiveness

## Syllabus

## Specific Learning Objectives

Use of clickers  
in class

**After this workshop, you should be able to:**

- operate these clickers well enough to use them in discussions like this.
- use clickers effectively in your own classes.
- choose the best clicker system for your classes, based on knowledge about the various commercial clicker systems.
- describe the history of how clickers and their use evolved.
- predict the effects that introduction of clickers will have on a large lecture course.
- defend the introduction of clickers to skeptical colleagues based on established principles of learning and published evidence.

## Syllabus

### Transcription

## Specific Learning Objectives - be able to:

Define transcription.

Name the enzyme that catalyzes it.

Distinguish between transcription and translation.

Compare transcription in prokaryotes and eukaryotes.

Diagram a DNA duplex in the process of transcription showing base-pairing and strand polarity for all polynucleotides.

Predict a situation where transcription rates must be regulated, and describe how transcription factors accomplish such regulation.

## Example: Learning goals for Genetics, MCDB 2150

Students enrolling in this course should be able to demonstrate achievement of the learning goals for Introductory Biology MCDB 1150 and 1151 or Biofundamentals MCDB 1111.

Teaching toward the learning goals below is expected to occupy 60%-70% of class time. The remaining course content is at the discretion of the instructors. The relative emphasis placed on the goals below and the order in which they are dealt with may also vary according to the tastes and interests of individual instructors. However, all students who receive a passing grade in the course should be able to demonstrate achievement of the following minimal goals.

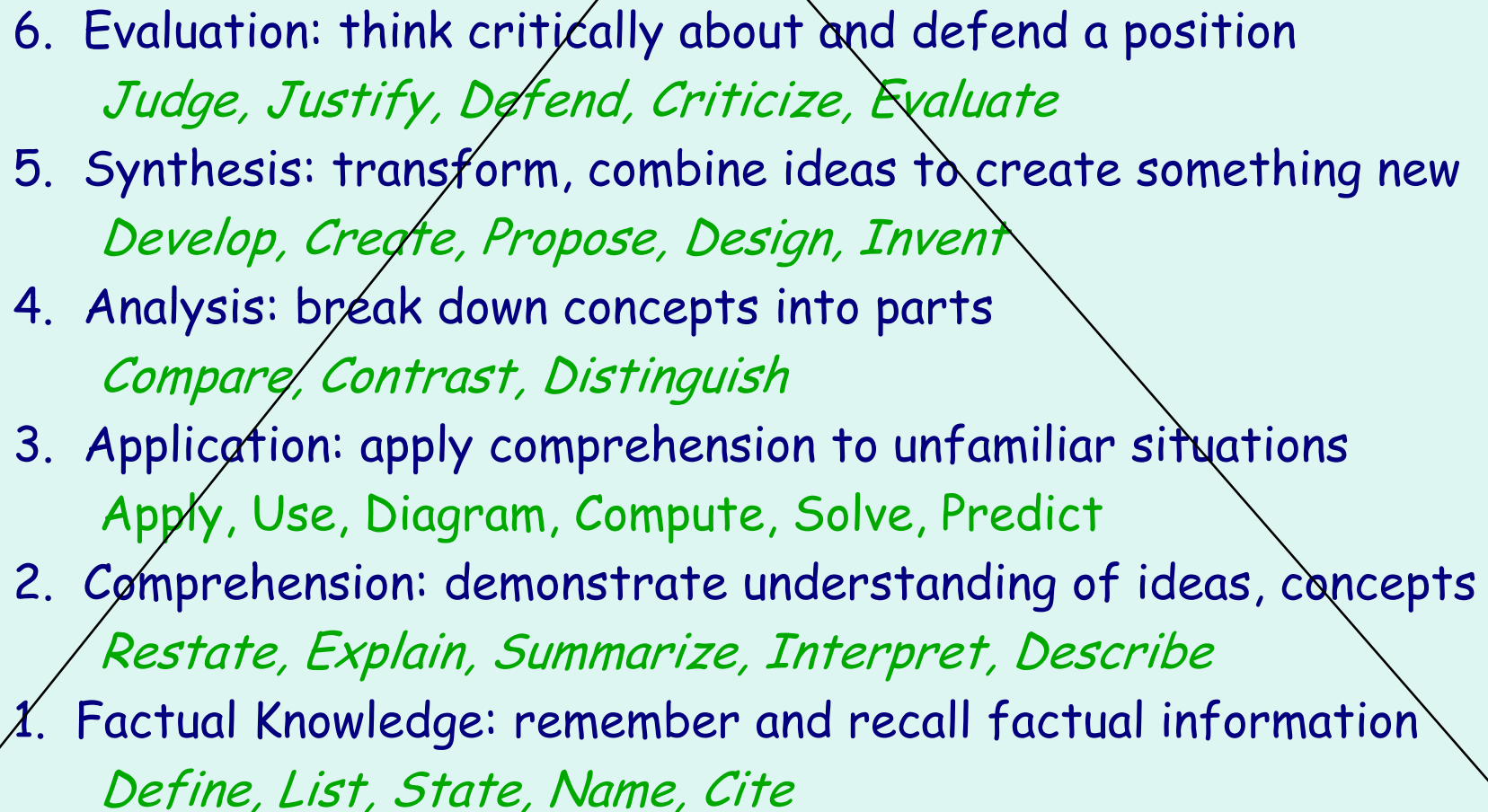
\* Achievement of starred goals will be aided by work in the lab course, MCDB 2151.

After completing this course, students should be able to:

1. Analyze phenotypic data and deduce patterns of inheritance from family histories.
  - a) Draw a pedigree based on information in a story problem.
  - b) Distinguish between dominant, recessive, autosomal, X-linked, and cytoplasmic modes of inheritance.
  - c) Calculate the probability that an individual in a pedigree has a particular genotype.
  - d) Define the terms *incomplete penetrance*, *variable expressivity*, and *sex-limited phenotype*, and explain how these phenomena can complicate pedigree analysis.
2. Describe the molecular anatomy of genes and genomes.
  - a) Explain the meaning of *ploidy* (haploid, diploid, etc.) and how it relates to the number of homologs of each chromosome.
  - b) Describe how the positions of individual genes on a given chromosome are related to their positions on the homolog of that chromosome.
  - c) Differentiate between a gene and an allele.

ETC. **9 Course-level and 49 topic-level goals in total**

# Bloom's Levels of Understanding

- 
6. Evaluation: think critically about and defend a position  
*Judge, Justify, Defend, Criticize, Evaluate*
  5. Synthesis: transform, combine ideas to create something new  
*Develop, Create, Propose, Design, Invent*
  4. Analysis: break down concepts into parts  
*Compare, Contrast, Distinguish*
  3. Application: apply comprehension to unfamiliar situations  
*Apply, Use, Diagram, Compute, Solve, Predict*
  2. Comprehension: demonstrate understanding of ideas, concepts  
*Restate, Explain, Summarize, Interpret, Describe*
  1. Factual Knowledge: remember and recall factual information  
*Define, List, State, Name, Cite*

Adapted from Allen, D. and Tanner, K., Cell Biol. Educ. 1: 63-67 (2002)

# Bloom's Levels of Understanding

6. **Evaluation:** think critically about and defend a position

**What students really need to learn how to do!**

5. **Synthesis:** transform, combine ideas to create something new

4. **Analysis:** break down concepts into parts

Some, but not many questions on MCAT, GRE exams

3. **Application:** apply comprehension to unfamiliar situations

2. **Comprehension:** demonstrate understanding of ideas, concepts

Most questions on introductory biology exams!

1. **Factual Knowledge:** remember and recall factual information



# Bloom's Levels of Understanding

Students should be able to:

6. Evaluation: think critically about and defend a position  
*Judge, Justify, Defend, Criticize, Evaluate*
5. Synthesis: transform, combine ideas to create something new  
*Develop, Create, Propose, Design, Invent*
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1. Factual Knowledge: remember and recall factual information  
*Define, List, State, Name, Cite*

Students should:

Understand . . .

Appreciate . . .

Be aware of . . .

Not useful learning goals

## Current progress

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### Learning goals

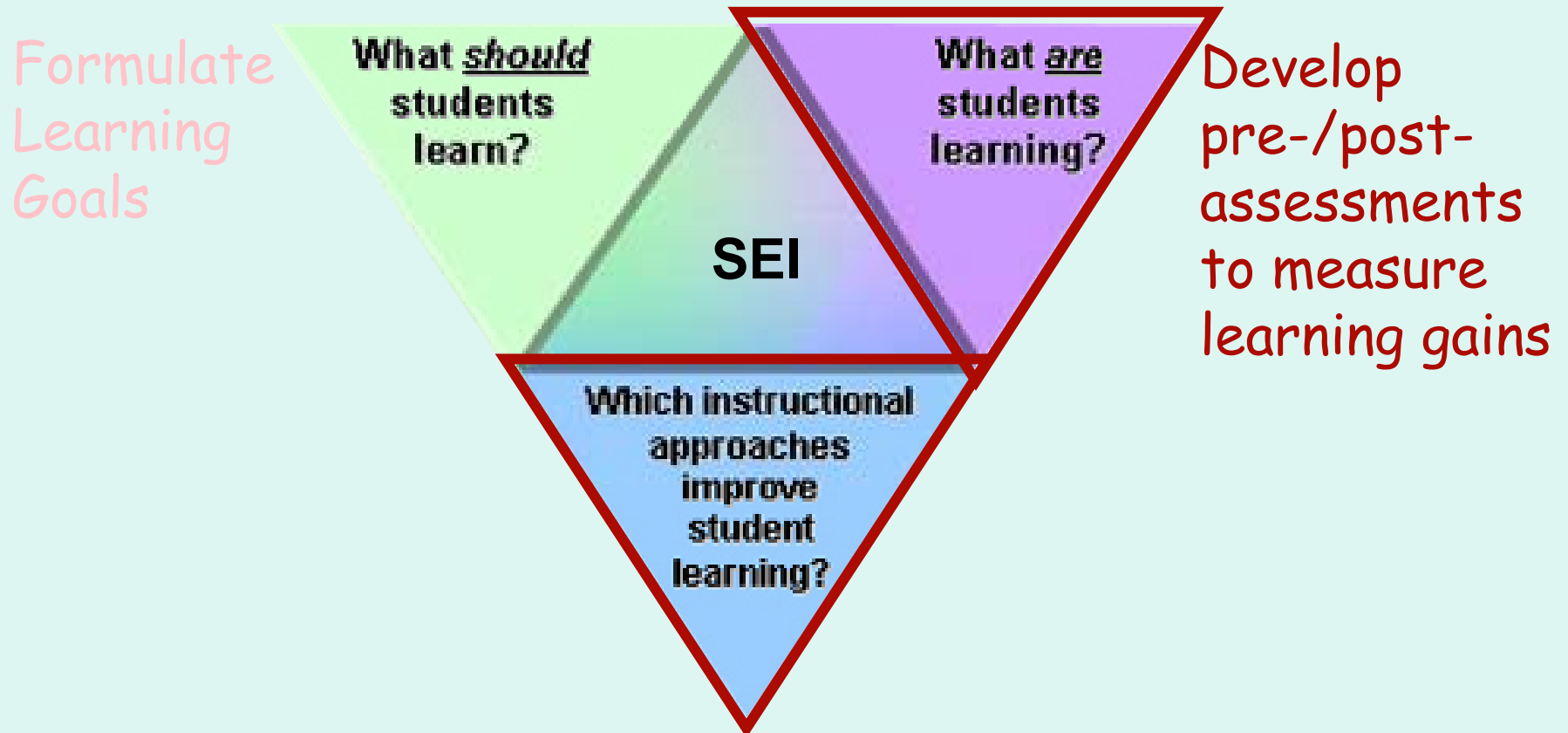
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Introductory	Done
Genetics	Done
Cell	Done
Molecular	Done
Development	Done*
Immunology	Done*

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\* Course level only

# The Science Education Initiative At University of Colorado, Boulder



Develop and test activities for formative assessment and achievement of learning gains

## **Design and validate a pre-post multiple-choice assessment**

for use in measuring student learning gains relating to the learning goals.

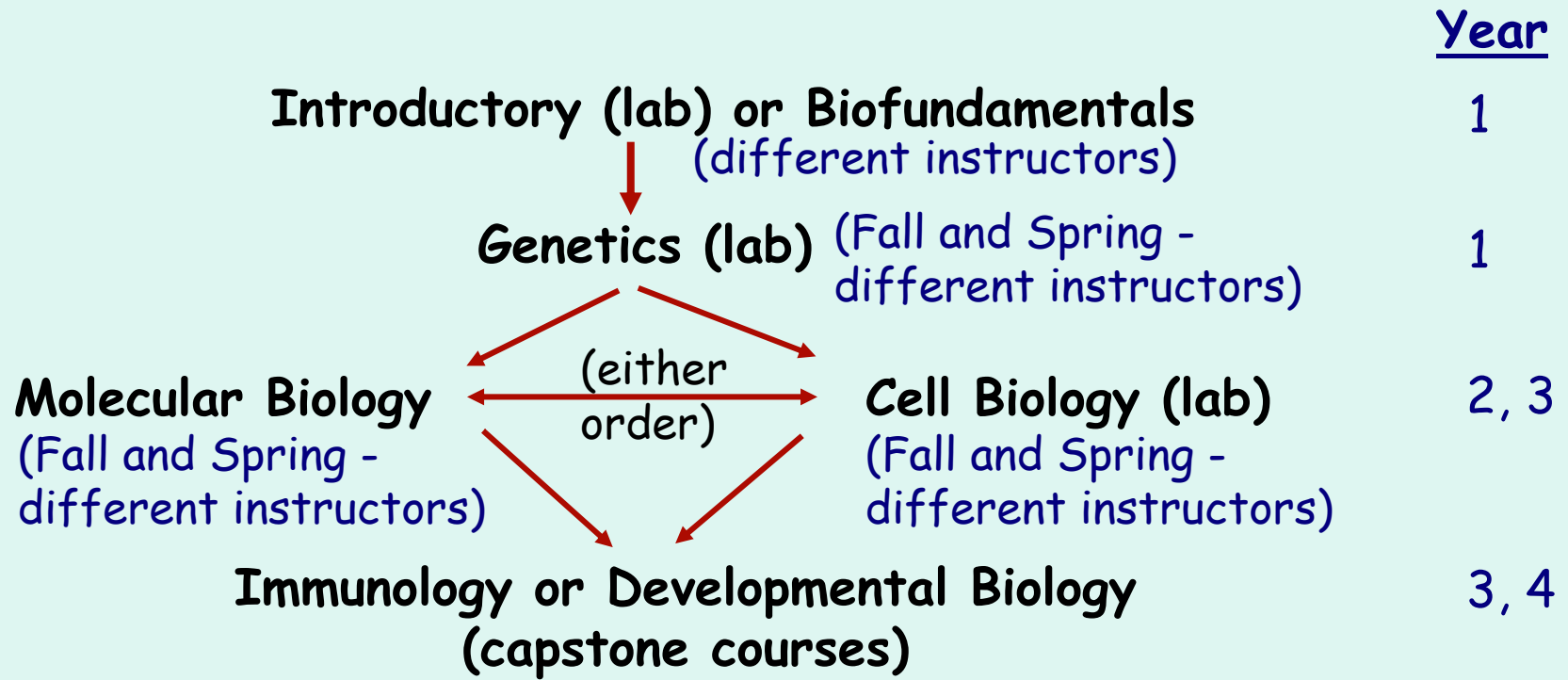
[Jia, Michelle, Jenny, Bill]

## **Design and test active-learning materials**

for use in and out of class (e.g. clicker questions, other in-class learning activities, homework problems).

[Jia, Michelle, Jenny, Course Instructors]

# The MCD Biology Curriculum for Majors



## Current progress

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	Learning goals	Pre-post assessment	Active-learning materials
Introductory	Done	Done	On hand
Genetics	Done	→ Done	On hand
Cell	Done	In progr.	In progr.
Molecular	Done	In progr.	In progr.
Development	Done	Done	On hand
Immunology	Done	To be done	In progr.

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## The Genetics Concept Assessment:

a new concept inventory for gauging student understanding of genetics

Michelle Smith, Bill Wood, Jenny Knight

A multiple-choice assessment designed as a pre-/post-test for several possible uses

*CBE-Life Sciences Education 7, Winter Issue, 2008, in press.*



## Developing the GCA: Overview of the Process

1. Review literature on common genetics misconceptions.
2. Interview genetics faculty, and develop learning goals that most instructors consider vital to genetics understanding.
3. Develop and administer a pilot assessment based on known and perceived misconceptions relating to the learning goals.
4. Eliminate jargon, replace distracters with student-supplied incorrect answers, revise questions answered correctly by more than 70% of students pre-instruction.
5. Validate and revise through student interviews (33) and input from faculty experts (10) at several institutions.
6. Administer the resulting GCA to students (607) in both majors and non-majors courses (5) at three different institutions.
7. Evaluate the GCA by several statistical criteria: reliability, item difficulty, and item discrimination.

## The 25 questions on the GCA were designed to assess achievement of each of 9 broad learning goals

An example:

LG 3: Describe the mechanisms by which an organism's genome is passed on to the next generation.

Q 8: A young man develops skin cancer that does not spread to any other tissues; the mutation responsible for the cancer arose in a single skin cell. If he and his wife (who does not have skin cancer) subsequently have children, which of the following statements is most correct:

- a) All the man's children will inherit the mutation.
- b) All the man's children will inherit the mutation if the mutation is dominant.
- c) Some of the man's children may inherit the mutation, depending on which of his chromosomes they inherit.
- d) None of the man's children will inherit the mutation.

Another example:

LG 5: Extract information about genes, alleles, and gene functions by analyzing the progeny from genetic crosses.

Q 14: Cystic fibrosis in humans is caused by mutations in a single gene and is inherited as an autosomal (non-sex-chromosome) recessive trait. A normal couple has two children. The first child has cystic fibrosis, and the second child is unaffected. What is the probability that the second child is a carrier (heterozygous) for the mutation that causes the disease?

- a)  $1/4$
- b)  $1/2$
- c)  $2/3$
- d)  $3/4$
- e) 1

## Student interviews

33 student volunteers

from Colorado majors and non-majors courses, and others.

Range of achievement levels: A to D grades.

Think-aloud answers to test questions,

with rationales for correct or incorrect choices.

## Summary of expert responses to three queries about the 25 GCA questions

Query	Agreement of experts		
	>90%	>80%	>70%
The question tests achievement of the specified learning goal	21	3	1
Information given in the question is scientifically accurate	25	0	0
The question is written clearly and concisely	22	3	0

## Five 1-semester courses in which GCA was administered as a pre- and post-test, 2007-2008 AY

U. Colorado MCDB Genetics, majors (Fall)

U. Colorado MCDB Genetics, majors (Spring)

U. Colorado Human Genetics, non-majors

Large Private Research U., Genetics, majors

Small Liberal Arts College, Genetics, majors

8 instructors, total

JK taught the Colorado non-majors course

Other instructors played no role in developing GCA

Post-test embedded as first 25 questions in longer final exam

## Statistical criteria for evaluating assessments

Criterion	Accepted range*	GCA pre-test	GCA post-test
Reliability **	0.80-0.90	0.93	NA
Item difficulty index (P)	0.3-0.8	0.09-0.69	0.48-0.92
Item discrimination index (D)	$\geq 0.3$	0.11-0.60	0.15-0.58

\* By psychometricians, for standardized tests such as the SAT

\*\* Coefficient of stability, test-retest method

## Mean pre-test, post-test, and learning-gain scores for students, TAs/LAs, and experts

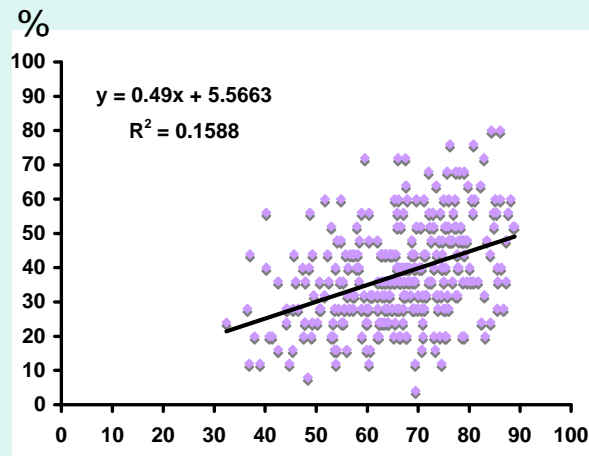
Group	n	Mean pre-test	Mean post-test	Mean normalized learning gain
Students	607	40.5% (+/- 0.6%)	74.0% (+/- 0.7%)	56.7% (+/- 1.0%)
TAs/LAs	18	76.9% (+/- 3.7%)	87.8% (+/- 3.8%)	40.0% (+/- 12.1%)
Experts	10	NA	93.0% (+/- 5.2%)	NA

Standard errors are shown in parentheses

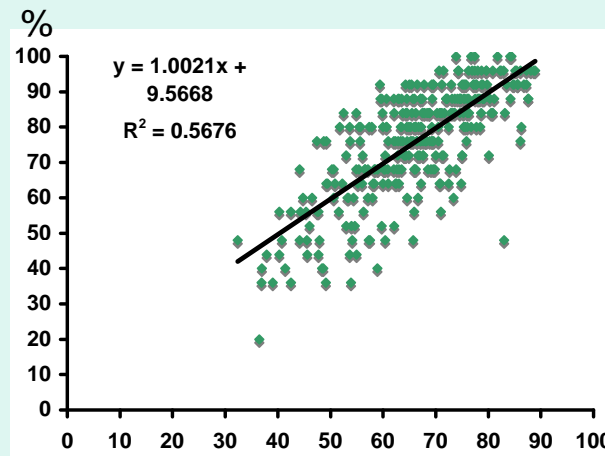


# Correlations of pre-test, post-test, and learning gain percentages with average exam scores in one of the Colorado majors courses

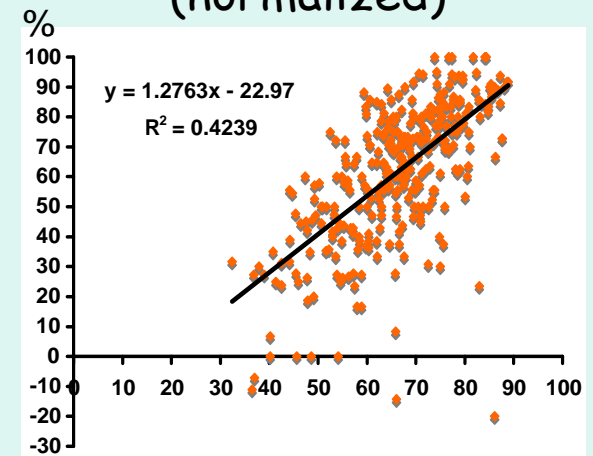
Pre-test scores



Post-test scores

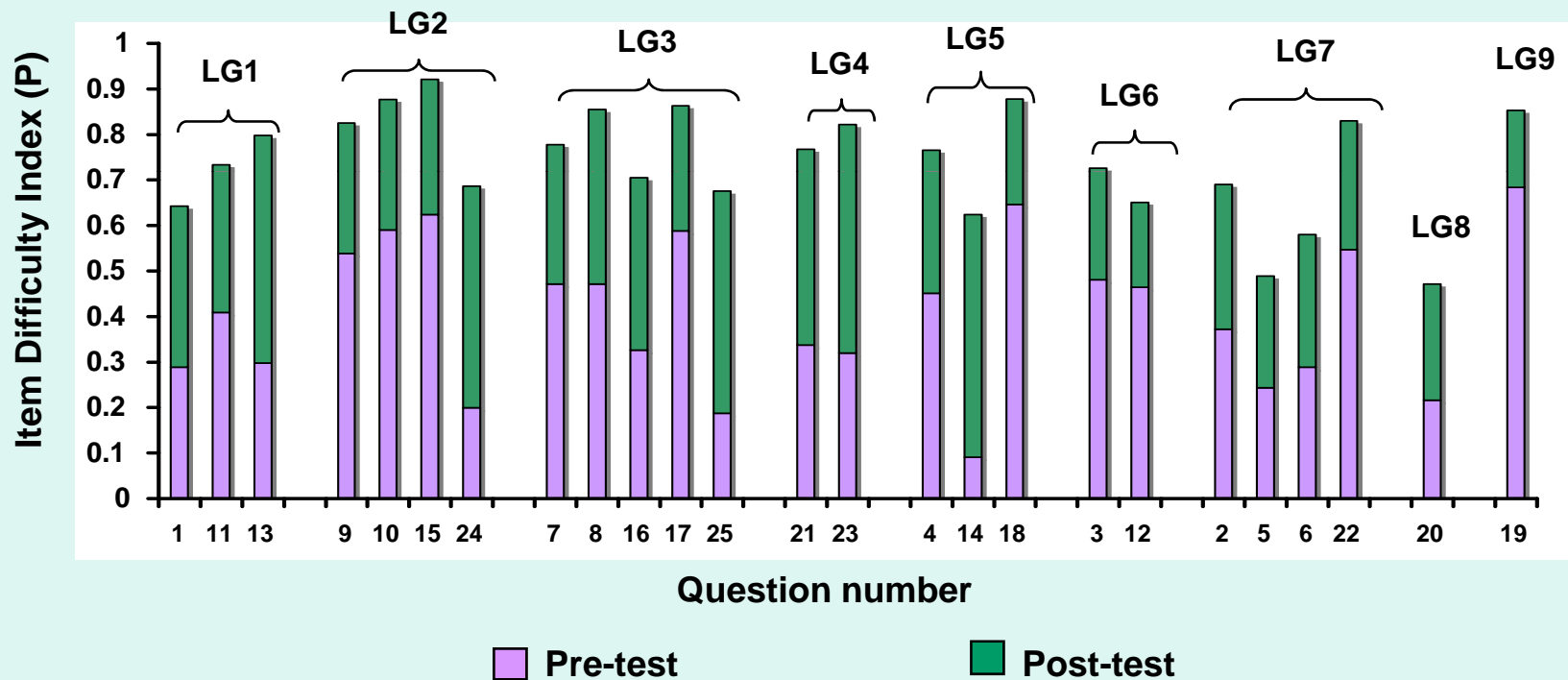


Learning gains  
(normalized)



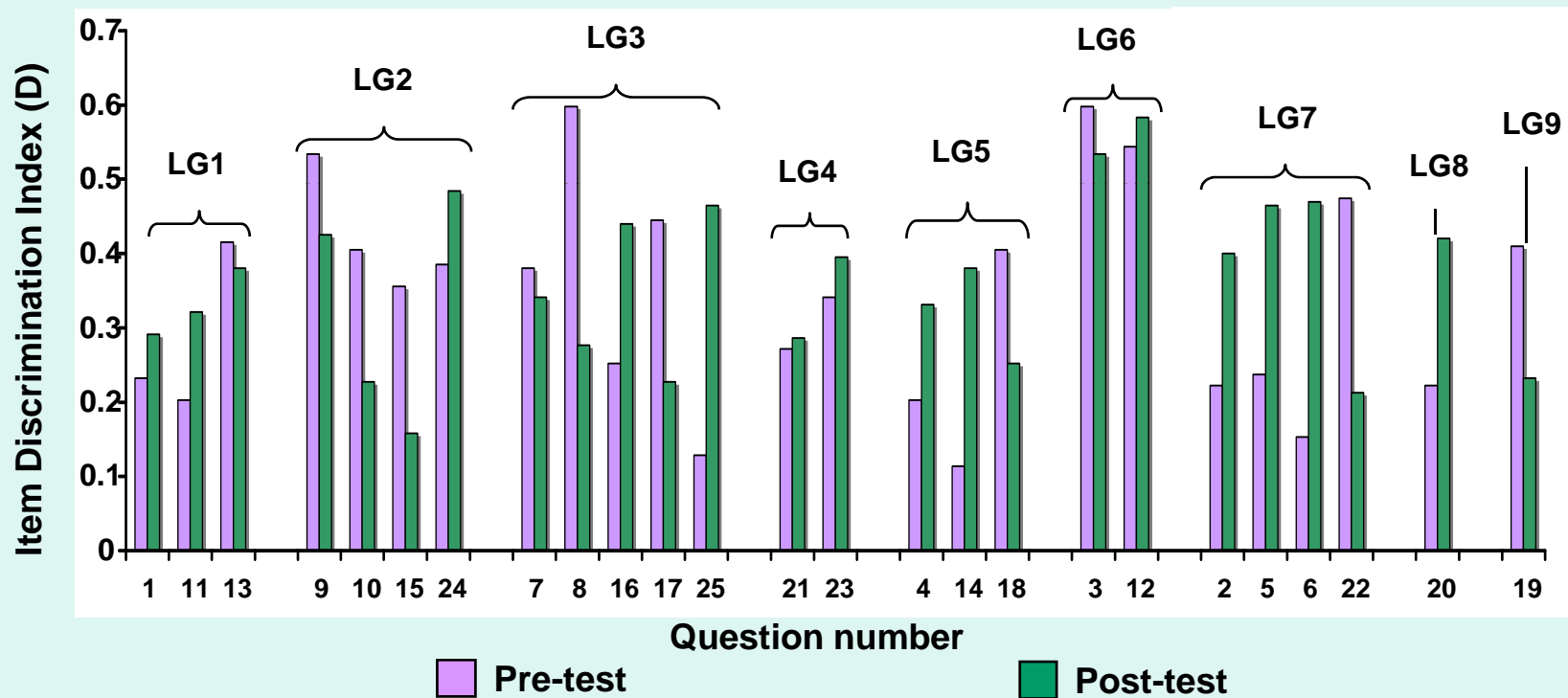
Average exam score

# P values (mean fraction correct answers) on each of the 25 GCA questions, pre- and post-tests, grouped by learning goal



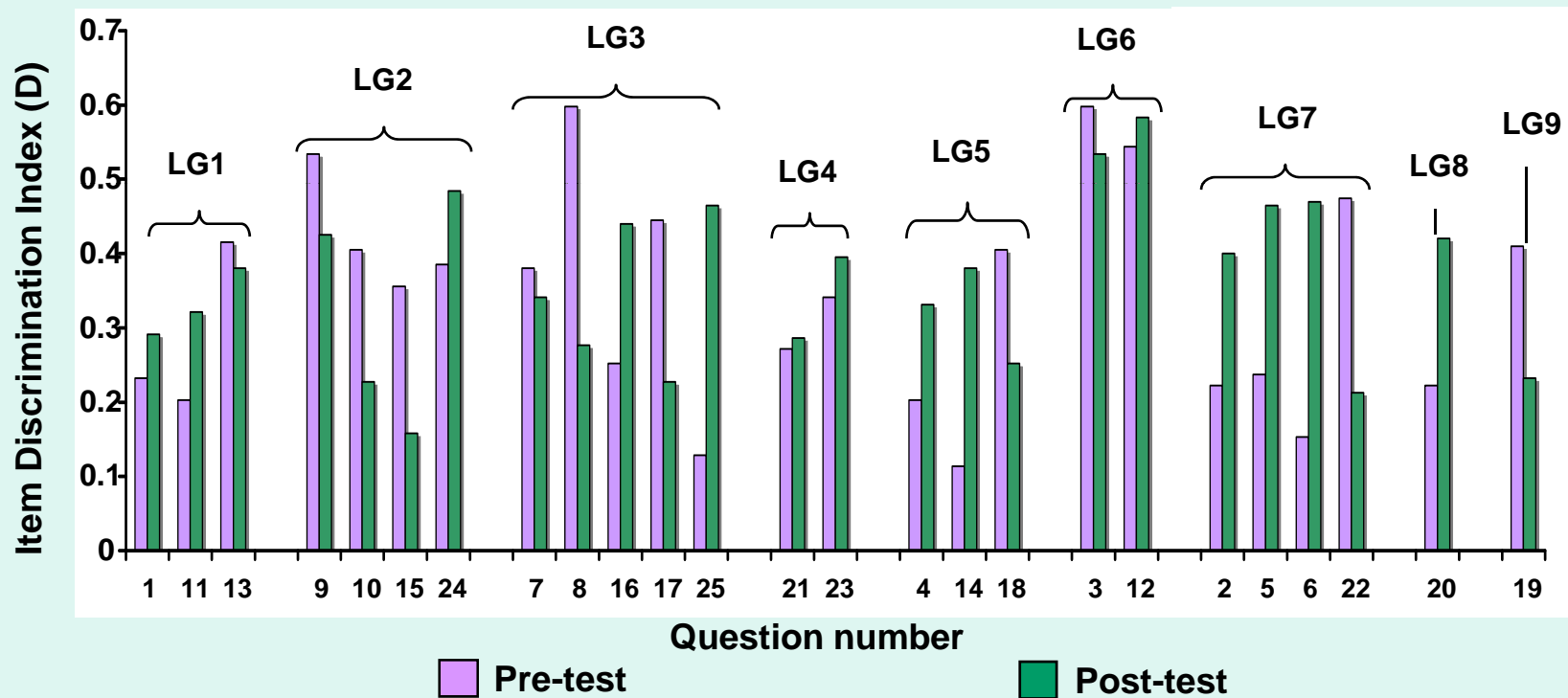
n = 607 students

D values (discriminates between strong and weak students) on each of the 25 GCA questions, pre- and post-tests, grouped by learning goal



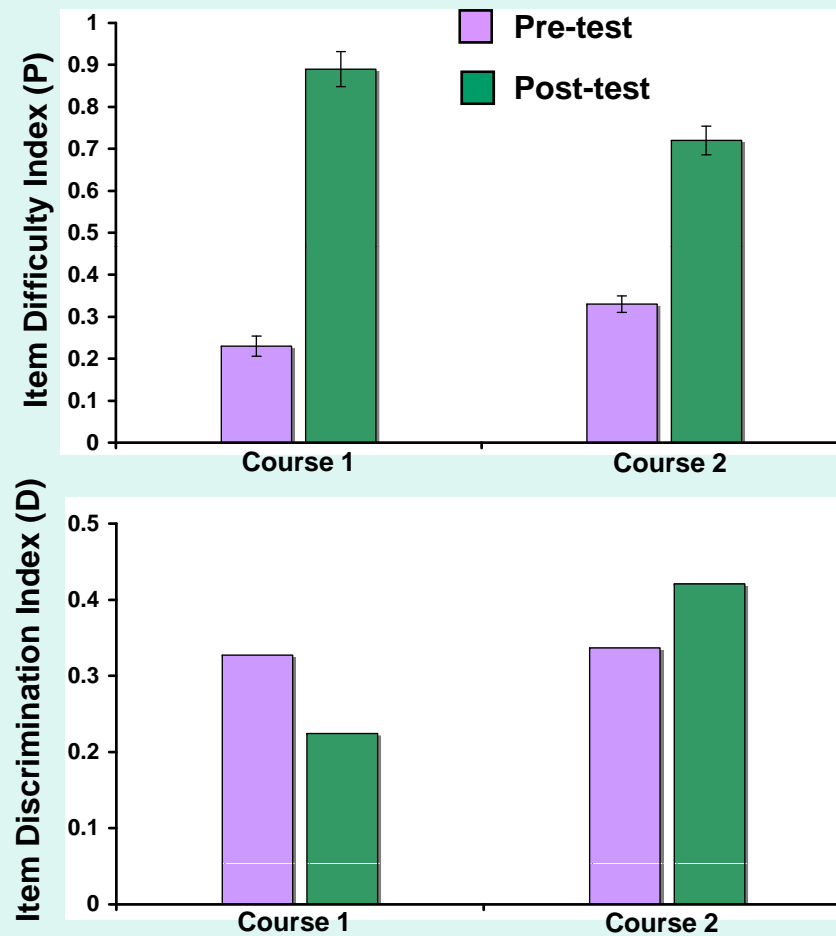
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D values (discriminates between strong and weak students) on each of the 25 GCA questions, pre- and post-tests, grouped by learning goal



**LG 6: Describe the processes that can affect the frequency of phenotypes in a population over time.**

# Student understanding of mitochondrial inheritance in two majors genetics courses, judged by P and D values for the relevant GCA question



## Statistical criteria for evaluating assessments

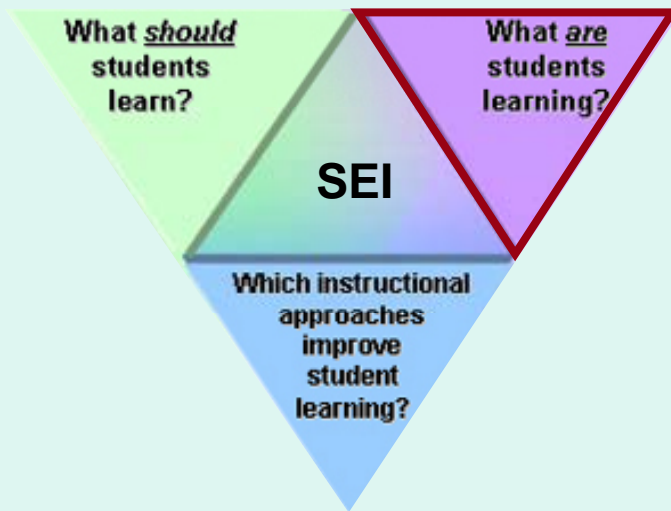
Criterion	Accepted range*	GCA pre-test	GCA post-test
Reliability**	0.80-0.90	0.93	ND
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Item discrimination index (D)	$\geq 0.3$	0.11-0.60	0.15-0.58

\* By psychometricians, for standardized tests such as the SAT

\*\* Coefficient of stability, test-retest method

### Conclusions:

- SAT criteria don't necessarily apply to concept inventories.
- Pre-post changes in P and D values provide useful information.



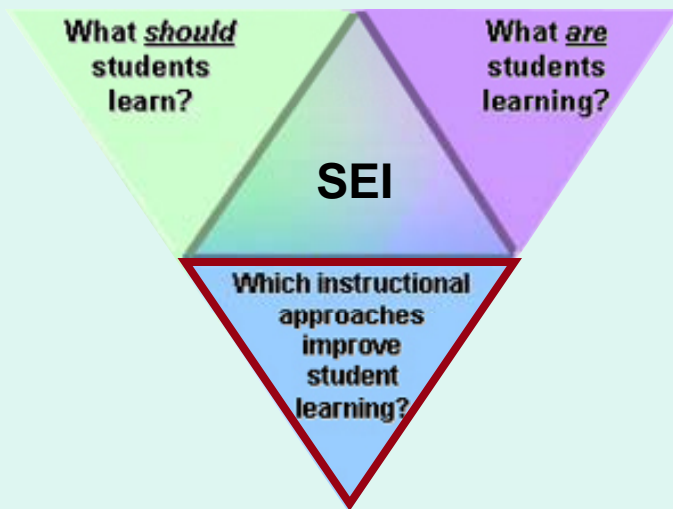
**Design and validate a pre-post multiple-choice assessment** for use in measuring student learning gains during the course that relate to the learning goals.

[Jia, Michelle, Jenny, Bill]

**Design and test active-learning materials**

for use in and out of class (e.g. clicker questions, other in-class learning activities, homework problems).

[Jia, Michelle, Jenny, Course Instructors]



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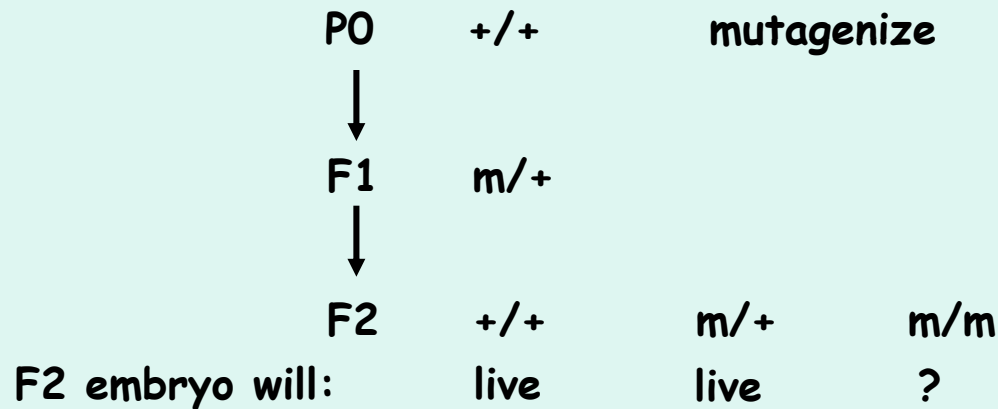
[Jia, Michelle, Jenny, Course Instructors]



# Development and use of active-learning materials

Michelle Smith, Prof. Tin Tin Su, and clickers in the genetics course

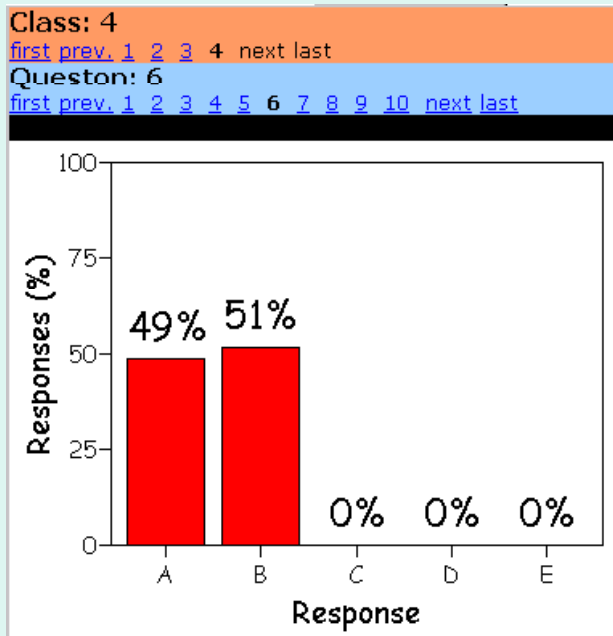
# Maternal-effect lethal mutants



**Question:** If *m* is a strict maternal-effect recessive mutation:

- A) *m/m* embryo will live.
- B) *m/m* embryo will die.

initial individual answers

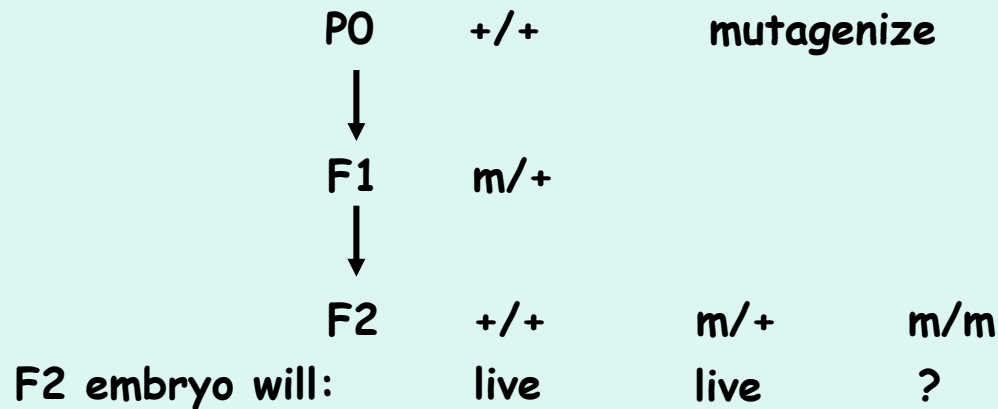


n=70

# Video of classroom during discussion

QuickTime™ and a  
Video decompressor  
are needed to see this picture.

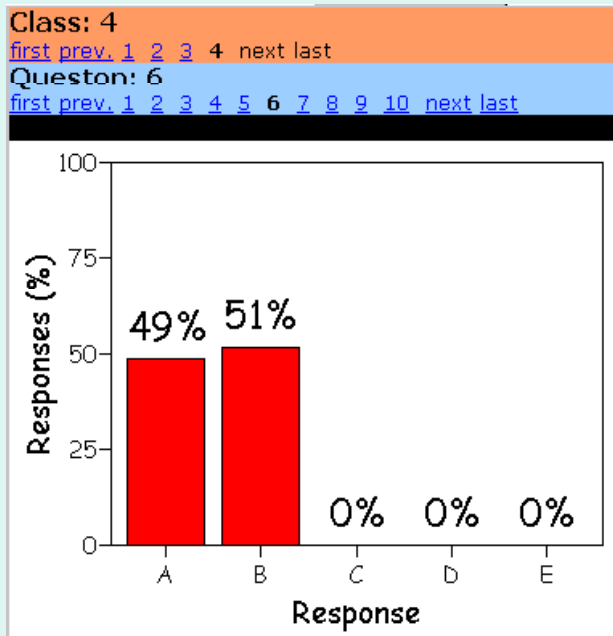
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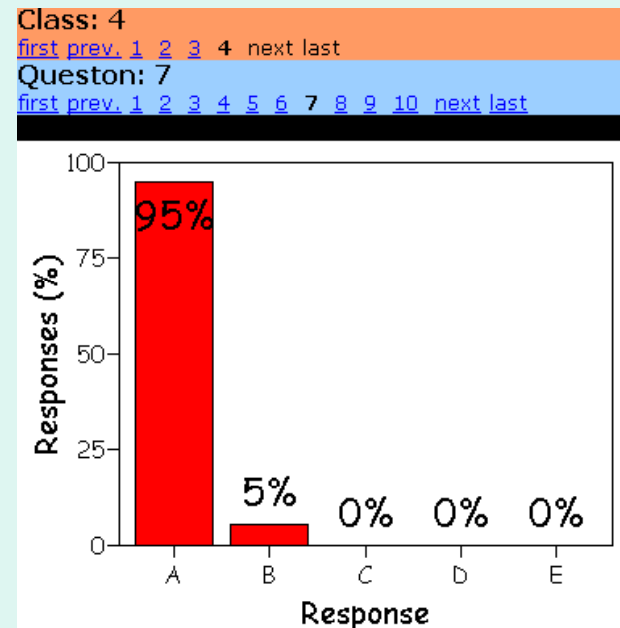
- A) *m/m* embryo will live.
- B) *m/m* embryo will die.

initial individual answers



n=70

after group discussion



# Why peer discussion improves student performance on in-class conceptual questions

Michelle Smith, Bill Wood, Wendy Adams, Carl Wieman,  
Jenny Knight, Nancy Guild, Tin Tin Su

*Science*, in revision, October 2008

Question: Do students learn during the discussion, or are they simply influenced by their knowledgeable peers to choose the right answer?

Experiment using isomorphic questions, Q1 and Q2:

Q1

Students vote individually, correct answer and distribution not revealed.



Q1<sub>ad</sub>

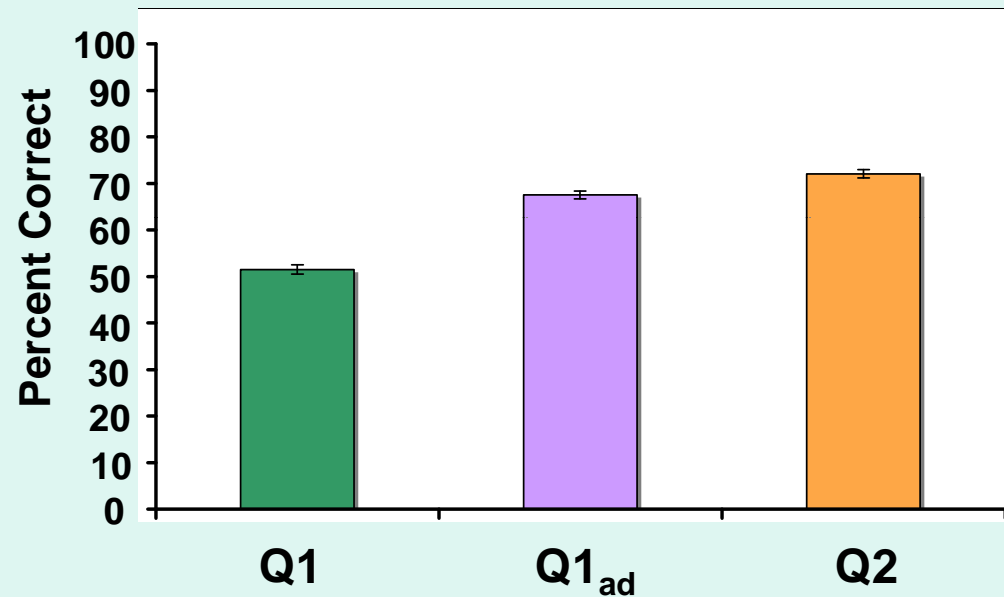
Students re-vote, correct answer and distribution still not revealed.



Q2

Isomorphic question: students vote individually, correct answers and distributions revealed.

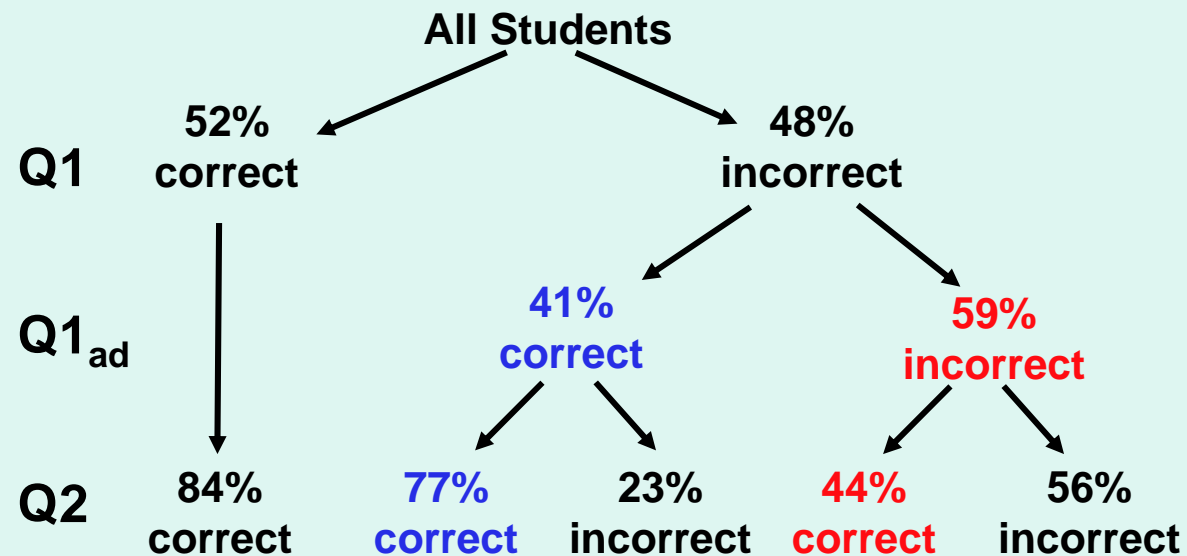
## Mean individual improvement from Q1 to Q2 for 16 isomorphic question pairs



Mean Q2 score is significantly higher than mean Q1 score ( $16\% \pm 1\%SE$ )

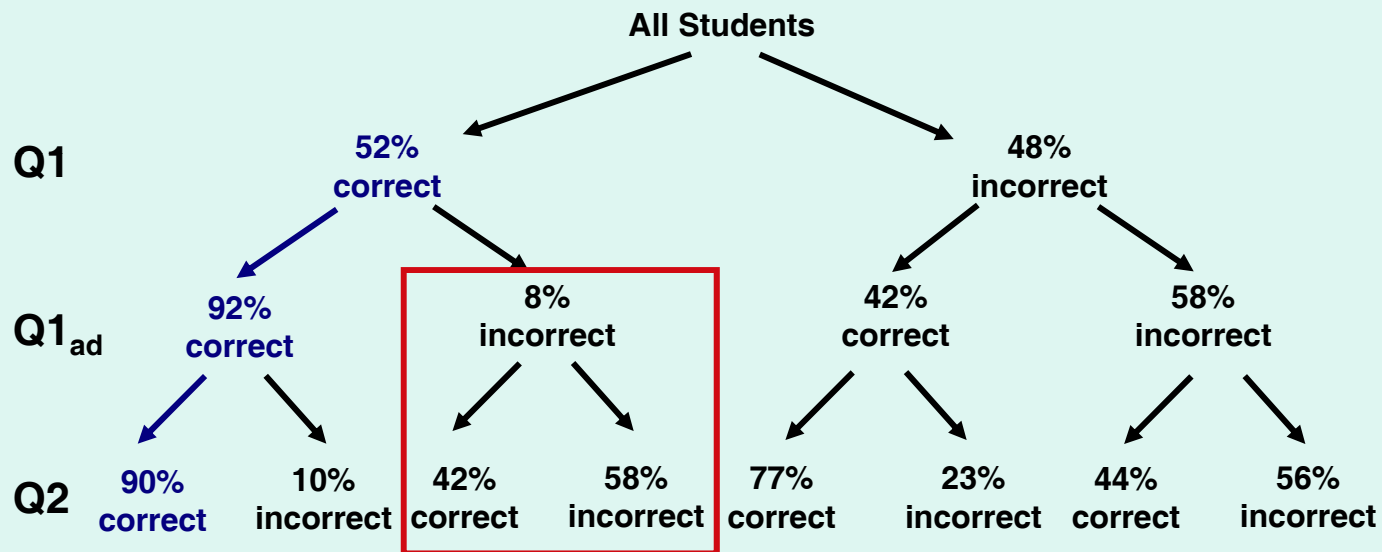
Data from one of the Colorado majors genetics courses, 350 students

On average, students who corrected their initial response on Q1 did much better on Q2 than students who did not correct their initial response

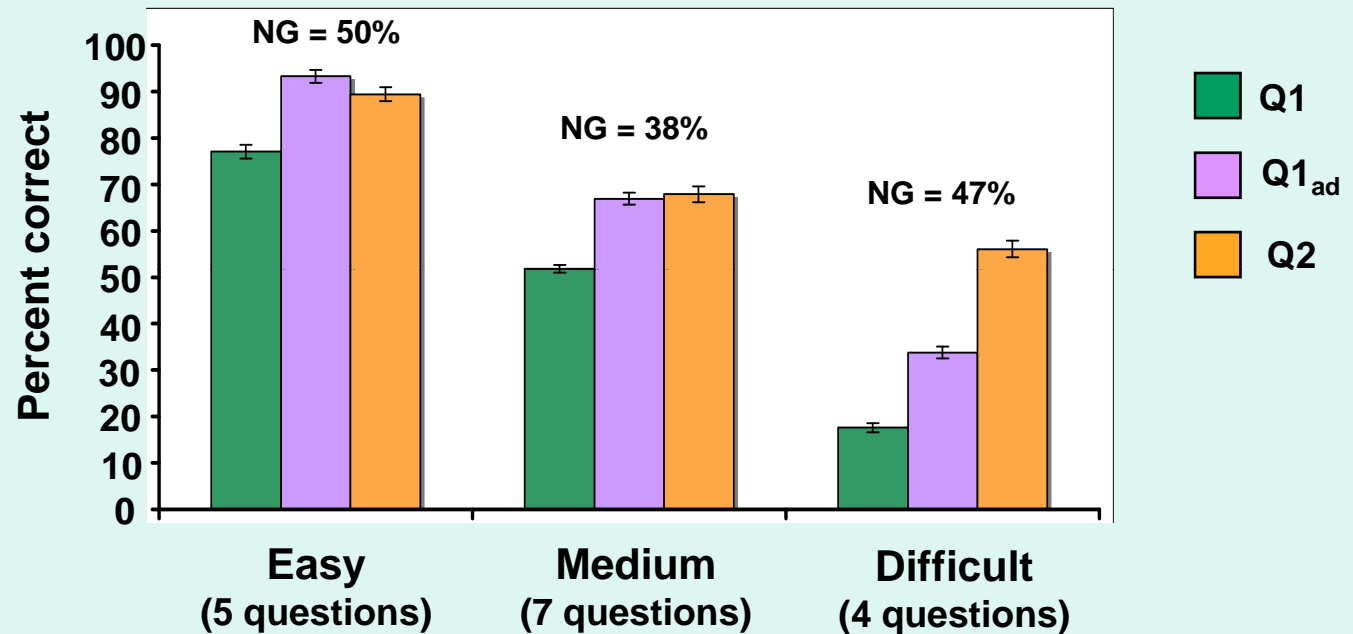




Almost all students who answered Q1 correctly also answered Q1ad and Q2 correctly



## Mean individual improvement from Q1 to Q2 for question pairs of different difficulty



NG: normalized gain from Q1 to Q2.

Note significant increase from Q1<sub>ad</sub> to Q2 on difficult questions (22%±2%SE).

## Conclusion:

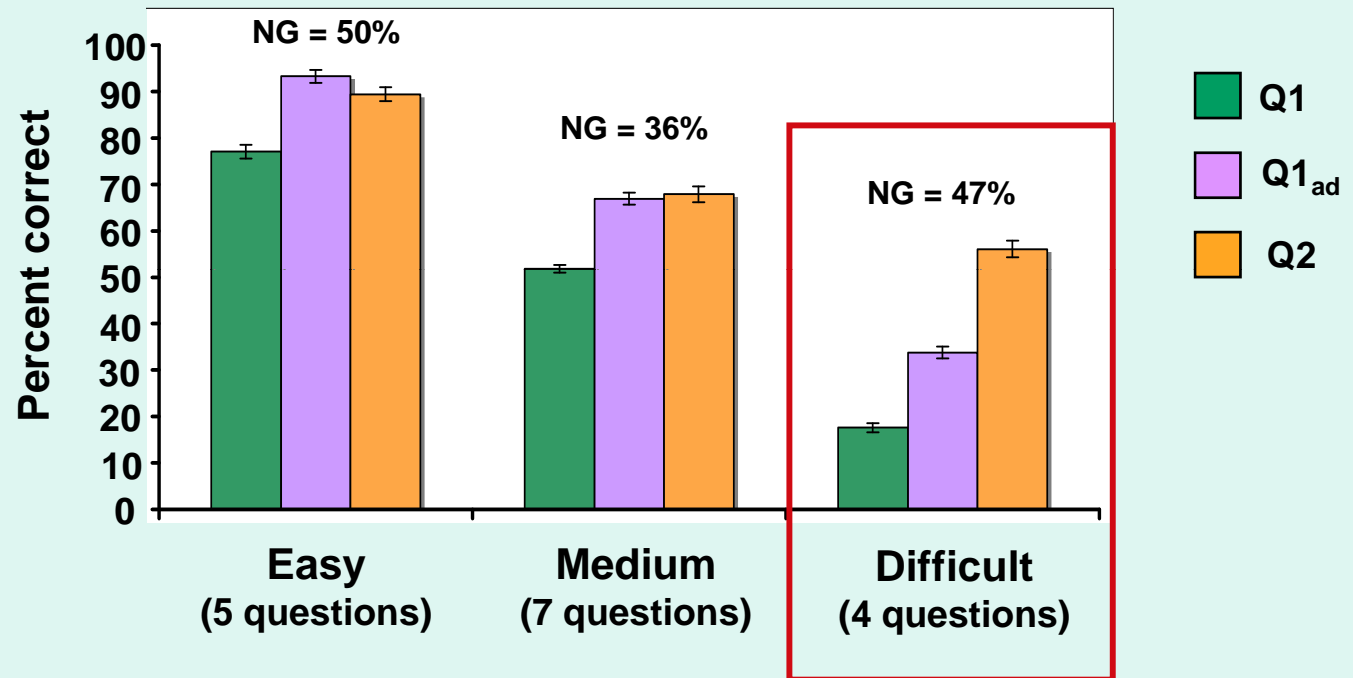
Most students are learning from peer discussion

But how??

Transmissionist view: the stronger students explain the correct reasoning to the weaker students, who therefore now understand it (Mazur).

Constructivist view: in the process of actively discussing and defending different points of view, students arrive at a correct understanding by themselves.

## Mean individual improvement from Q1 to Q2 for question pairs of different difficulty



NG: normalized gain from Q1 to Q2.

For the group of four difficult question pairs, about 30/150 students who answered Q2 correctly were in a group where no one initially knew the answer to Q1 (naïve group)

Average group size:	3 students
Number of groups among 254 (mean) participants:	~88 groups
Students who answered Q1 correctly (mean)	44 students
Non-naïve groups *	~40 groups
Students in non-naïve groups	~120 students
Total students who answered Q2 correctly	150 students
Students from naïve groups who answered Q2 correctly	<hr/> ~30

\* Assuming these students are randomly distributed.

## Chi-square analysis on responses to each of the four difficult question pairs

**Model:** Q1-correct students are randomly distributed among the participating groups.

All students in these non-naïve groups, and only these students, answer Q2 correctly.

Observed correct on Q1	Predicted* correct on Q2	Observed* correct on Q2	Total students participating	$\chi^2$	p
24 (12%)	64	102	203	33.3	<0.01
44 (16%)	114	147	277	15.9	<0.01
50 (18%)	122	141	275	5.1	=0.02
52 (20%)	125	185	258	56.3	<0.01

\*Significantly different,  $p < 0.05$  for 3rd question,  $<< 0.001$  for others,  $df = 1$

## Student surveys support the constructivist explanation

Survey question (n=328 responding): When I discuss clicker questions with my neighbors, having someone in the group who knows the correct answer is necessary in order to make the discussion productive (agree/disagree).

47% of students disagreed.

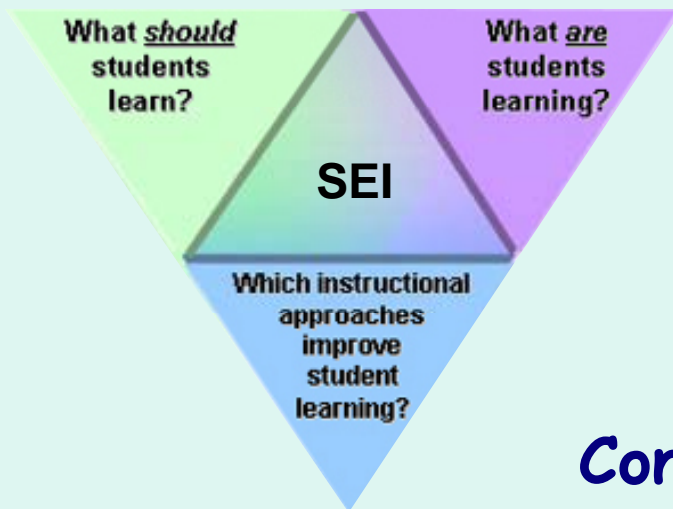
## Student surveys support the constructivist explanation

Comments from these students included:

"Often when talking through the questions the group can figure out the questions without originally knowing the answer, and the answer almost sticks better that way because we talked through it instead of just hearing the answer."

"Discussion is productive when people do not know the answers because you explore all the options and eliminate the ones you know can't be correct."





## Conclusions

- The SEI is making progress.
- More pre-/post-assessments are needed.
- Assessments confirm best-practices are effective.
- Preparations for evaluating the impact of the SEI are underway.

## Two isomorphic questions for clicker experiments

Question Q1/Q1ad: *C. elegans* Mel-2 gene products are deposited into the egg by the mother and are required for embryonic development. Mutations in the *mel-2* gene are recessive and cause maternal effect embryonic lethality.

In a cross between *mel-2* heterozygotes, what percent of embryos will die?

- A) 100%
- B) 50%
- C) 25%
- D) 0%

Question Q2: Zebrafish *Ack15* gene products are deposited into the egg by the mother and are required for embryonic development. Mutations in the *ack15* gene are recessive and cause maternal effect embryonic lethality.

In a cross between an *ack15* homozygous mutant female and a heterozygous male, what percent of embryos will die?

- A) 100%
- B) 50%
- C) 25%
- D) 0%

## Standard course planning

Choose textbook



Create syllabus



Write/revise lectures, notes



Prepare PowerPoint presentations



Write exams

**Instructor-centered**

## vs Backward design

Formulate broad learning goals



Set specific learning objectives



Prepare learning activities



Design assessments  
(formative and summative)

**Student-centered**

