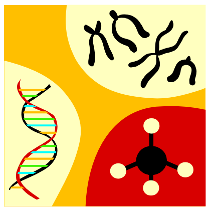
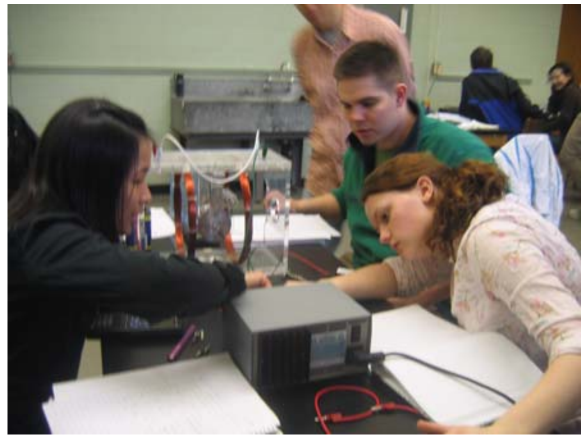
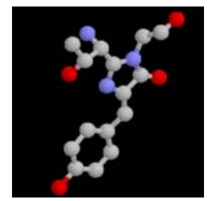
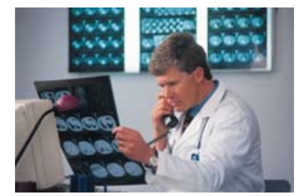
Designing an Introductory Physics Course For Biology Majors

Ken Heller
School of Physics and Astronomy
University of Minnesota

6 year continuing project to improve this course contributions by:
Many faculty and graduate students of U of M Physics Department especially A. Grosberg
In collaboration with U of M Physics Education Group - P. Heller, grad students, post docs

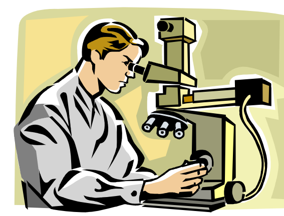
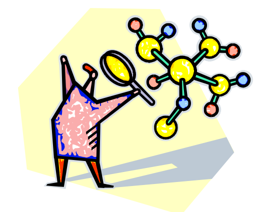
Details at http://groups.physics.umn.edu/physed/

Supported in part by Department of Education (FIPSE), NSF,
and the University of Minnesota

Students in Physics for Biology Majors
600 students/term (class size 150 – 300)

Majors

Biological Science	36%
Pre-Med	31%
Allied Health	18%
Social Science	3%
Kinesiology	2%
Architecture	1%
Agriculture/Ecology	1%
Other	8%

Freshman	7%
Sophomore	38%
Junior	19%
Senior	17%

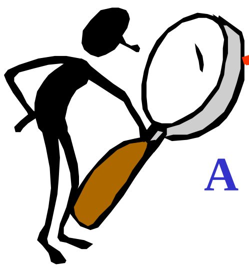
Male	41%
Female	59%

Pre FCI – 33%

Had U. Calculus	71%
(Had HS Calculus)	50%
Had HS Physics	71%

Expect A	48%
Work	74%
Work more than 10 hrs/wk	50%

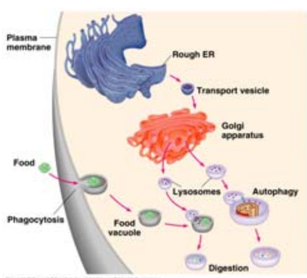
Setting Goals

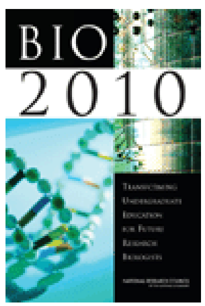


A questionnaire

- Whose Goals?
  - Biology Faculty
  - Physics Faculty
  - Students
  - Employers
  - Society
- Do they make sense?
  - Student Skill & Knowledge Base
  - Internal Logic of Physics
  - Research Background on Learning
  - Instructional Framework
  - Constraints of Reality
- At what level can you accomplish them?
  - How Much Is Enough
  - Data and Quality Assurance

Physics for Biology Majors





Questionnaire for Faculty

- **Goals for Their Students**
  - **Rate Possible Goals**
  - **Free Response**
- **Content**
  - **Choose Textbook Chapters**
- **Discussion Section Format**
  - **Choose Format**
- **Laboratory Format**
  - **Choose Format**

http://groups.physics.umn.edu/physed

Responding Faculty

N = 20 (60% response)

- **Biochemistry, Molecular Biology and Biophysics (5)**
- **General Biology (1)**
- **Genetics, Cell Biology and Development (3)**
- **Ecology, Evolution and Behavior (2)**
- **Microbiology (3)**
- **Neuroscience (3)**
- **Plant Biology (3)**

Biology Faculty Questionnaire

In what year should your students take physics?

	Freshman	Sophomore	Junior	Senior
%	20	75	5	0

How many semesters of physics do you think should be required for your students?

	0	1	2	3	4	5	6
%	0	15	75	0	0	0	0

Goals: **Biology Majors Course 2003**

Highest Rated (5 pt scale)

4.9 **Basic principles behind all physics (*1)**

4.4 **General qualitative problem solving skills**

4.3 ***Use biological examples of physical principles (*2)***

4.2 ***Overcome misconceptions about physical world*** **(*4)**

4.1 **General quantitative problem solving skills (*3)**

4.0 ***Real world application of mathematical concepts and techniques***

4.0 ***Know the range of applicability of the principles of physics***

Modified survey in response to CBS Curriculum Committee

Goals: **Calculus-based Course (88% engineering majors) 1993**

4.5 **Basic principles behind all physics**

4.5 **General qualitative problem solving skills**

4.4 **General quantitative problem solving skills**

4.2 **Apply physics topics covered to new situations**

4.2 ***Use with confidence***

Goals: **Algebra-based Course (24 different majors) 1987**

4.7 **Basic principles behind all physics**

4.2 **General qualitative problem solving skills**

4.2 ***Overcome misconceptions about physical world***

4.0 **General quantitative problem solving skills**

4.0 **Apply physics topics covered to new situations**

Lowest Rated Goals (5 pt scale)

Prepare students for the MCAT	**20**	**25**	**40**	**5**	**5**	**0**	**2.4**
Understand and appreciate the historical development and intellectual organization of physics	**10**	**25**	**50**	**15**	**0**	**0**	**2.7**
Understand and appreciate 'modern physics' (e.g. nuclear decay, quantum optics, cosmology, quantum mechanics, elementary particles,...)	**0**	**30**	**45**	**25**	**0**	**0**	**3.0**
Use computers to solve problems within the context of physics	**10**	**10**	**35**	**30**	**10**	**0**	**3.1**
Formulate and carry out experiments	**10**	**10**	**40**	**25**	**15**	**0**	**3.3**
Express, verbally and in writing, logical, qualitative thought in the context of physics	**5**	**0**	**35**	**45**	**10**	**0**	**3.4**

Free Faculty Responses - Goals

1. In your opinion, what is the primary reason your department requires students to take this physics course?

Underlying Principles **Application** **Problem solving/math**

- **To understand the basic laws of physics; to be able to apply physical principles to other problems; to overcome fear of math, quantitative approach to science.**

- **General understanding of how 1st & 2nd order linear differential equations explain behavior of various physical systems (mechanics, thermodynamics, electricity).**

- **Living things rely on a number of physical principles. Concepts we cover in lecture & techniques/equipment used in the laboratory require an understanding of physics. Physics is fundamental to many biological processes, & develop skills in problem-solving & modeling.**

- **Provide basic concepts in physics as applied to biological functions; learn how to think quantitatively about these applied physics concepts.**

Content

In two semesters it is impossible to cover every topic in physics. The purpose of this question is to determine your priorities of the topics in the course. Below are the chapter headings from a typical textbook at this level. Please place the integer number of weeks for each chapter that, in your judgment, allows students to understand the material at the level you desire. Each week consists of 3 lectures, 1 discussion section, and a 2-hour laboratory. The total number of weeks should equal 26 to account for a course introduction at the beginning of the semester and a review at the end. Please do not use fractions of a week.

Please place a star (*) next to the FOUR chapters listed above that you consider to be the MOST IMPORTANT for your students.

%T		%*	
90	✓	15	Potential energy and conservation of energy
85	✓	15	Kinetic energy and work
85	✓	20	Entropy and the second law of thermodynamics
85	✓	15	Electric charge and force
85	✓	13	Electric potential
80	✓	0	Linear motion
80	✓	0	Forces and Newton's Laws
75	✓	15	Units, dimensions and vectors
75	✓	5	Temperature and ideal gas
75	✓	0	Electric field
75		5	Molecules and gases (e.g. probability distributions of velocity, equipartition)
75	✓	9	Mirrors and lenses
70		0	Momentum and collisions
70	✓	9	Nuclear physics and radioactive decay
65	✓	0	Two dimensional motion
65	✓	0	Gravitation
65		4	Currents in materials (e.g. resistance, insulator, semiconductors)
65	✓	15	Heat flow and the first law of thermodynamics
65	✓	0	Magnetic forces and fields
60	✓	4	Geometrical optics (e.g. reflection and refraction)
60	✓	0	Diffraction
55	✓	0	Oscillatory motion
55	✓	4	Currents and DC circuits

✓ Included in course

20/23 Chapters

✓ Included in course

10/21 Chapters

%T		%*	
50	✓	0	Rotations and torque
45	✓	5	Applications of Newton's laws
45		0	Angular momentum
45		0	Gauss' law
45	✓	4	Currents and magnetic fields (e.g. Ampere's law, Biot-Savart law)
45	✓	0	Interference
40	✓	5	Fluid mechanics
40		5	Properties of solids (e.g. stress, strain, thermal expansion)
40	✓	0	Capacitors and dielectrics
40		4	Maxwell's equations and electromagnetic waves
40		0	Relativity
35	✓	4	Faraday's law
35	✓	0	Superposition and interference of waves
30		0	Mechanical waves
30	✓	0	Statics
30		0	Magnetism and matter (e.g. ferromagnetism, diamagnetism)
30		9	AC circuits
30		0	Atomic physics
20		0	Quantum physics
15	✓	0	Magnetic Inductance
15		0	Particle physics
0		0	Other. Please specify.

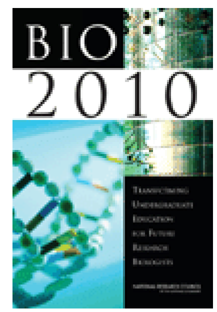
Choices Based on Responses

- **Emphasize Basic Principles**
  - – Causality
  - – Interaction
  - – System
  - – Dynamics
  - – Conservation
  - – Field

- **Vectors and Scalars**
- **Newton's 2nd and 3rd Law**
- **Conservation of Energy**
- **Description of Motion**
- **Entropy and Free Energy**

- **Conservation of Charge**
- **Electric Field and Force**
- **Magnetic Field and Force**
- **Ampere's Law**
- **Faraday's Law**
- **Electromagnetic Waves, Light, and Imaging**

- **Emphasize Biological Systems Context**
  - – Complex
  - – Open
  - – Cyclic
  - – Rates of change



- **Emphasize Mathematical Problem Solving**
  - – Logic and organization
  - – Justified decisions and approximations important
  - – Use Calculus
  - – Rates (differential equations where possible instead of integrals)
- **Assume an Introductory Biology, Chemistry & Calculus Vocabulary**

Yr 1 Content (first semester) – Physics for Biology Majors

Week	Topic	Chapter
1-2	Conservation, Systems, & Cyclic Processes - Electric Circuits	21, 20
2-3	Energy & Energy Transfer	6
4-5	Energy & Thermal Processes	16, 17
6-7	Cyclic Processes & Heat Engines	18
8-9	Conservation of Energy & Momentum	7, 8

Week	Topic	Chapter
10-11	Interaction Mechanisms -Forces	4
11-12	Applications - Forces	5, 11, 19
13-14	Predicting Motion Velocity dependent force Oscillations	3, 12
14-15	Predicting Motion in 2-D Constant acceleration	2, 3

Unacceptable to most physics professors to start with circuits.

Too much material for students to understand

Textbook: Serway & Jewitt
Principles of Physics – 3rd Edition

Yr 2 Content (first semester) – Physics for Biology Majors

Week	Topic	Chapter
1-3	Forces & Equilibrium	1, 4, 5, 15
4	Torque & Equilibrium	10
5-6	Force, Energy Transfer, Conservation of Energy	6
7-8	Energy & Thermal Processes	16, 17
8-9	Potential Energy	7, 17

OK with most physics professors but prefer to put thermodynamics at the end.

Week	Topic	Chapter
10-11	Cyclic Processes, Entropy, Free Energy	18
12-13	Predicting repetitive Motion – Kinematics, Dynamics, Oscillations	2, 4, 12
14-15	Predicting Non-repetitive Motion – Kinematics, Dynamics	3, 5, 15

Enough time for average student to grasp material

Students don't like jumping around the textbook

Textbook: Serway & Jewitt Principles of Physics – 3rd Edition

Yr 3-6 Content (first semester) – Physics for Biology Majors

Week	Topic	Chapter
1-3	Forces, Torques & Equilibrium (includes fluids)	1, 4, 5, 15
4-5	Force, Energy Transfer, Conservation of Energy	6
6	Potential Energy (includes fluid flow)	7, 15
7-8	Predicting Motion – Dynamics & Oscillations	2, 4, 10, 12
9-10	Predicting Non-repetitive Motion (includes motion in fluids)	3, 5, 11, 15

Week	Topic	Chapter
11-12	Energy & Thermal Processes	16, 17
12-14	Cyclic Processes, Energy, Free Energy	18

14 Chapters in 15 weeks

Includes fluid statics and dynamics, thermodynamics

No momentum, rotational kinematics, or rotational kinematics.

Reduced constant acceleration kinematics.

Textbook: Serway & Jewitt Principles of Physics – 3rd Edition

Yr 1-3 Content (second semester) – Physics for Biology Majors

Week	Topic	Chapter
1-3	Geometrical Optics- Energy Transfer by Light	25, 26
4-6	D.C. Circuits- Energy Transfer by Electricity	21, 20
7-8	Electric Force and Electric Field	7, 19
8-9	Energy and Electric Potential	20
10-11	Magnetic Fields and Forces	3, 5, 11, 15

Textbook: Serway & Jewitt Principles of Physics – 3rd Edition

Week	Topic	Chapter
12-13	Changing Magnetic Fields, Electric Fields, and Potential	23
13-15	Electromagnetic Wave Optics – Interfere and Diffraction	24, 27
15	Nuclear Spins and MRI	30

14 Chapters in 15 weeks

OK for most physicists but some want to teach circuits after electric potential

Includes optics and NMR

No Gauss' Law, Biot-Savart Law, AC Circuits, Maxwell's Equations

Some want to add quantum physics, nuclear physics

Discussion Section Structure from Questionnaire

The discussion sections associated with this course are typically taught by graduate teaching assistants and could be structured in several ways. Please place an 'X' by that structure most appropriate for your students.

9 % **Students ask the instructor to solve specific homework problems on the board.**

35 % **Instructor asks students to solve specific homework problems on the board.**

17 % **Instructor asks students to solve unfamiliar textbook problems, then gives the solution on the board.**

17 % **Instructor asks students to solve "real world" problems individually and write their solution on the board.**

65 % **Students work in small groups to solve "real world" problems with coaching from the instructor.**

9 % **Students work in small groups to solve conceptual questions with coaching from the instructor.**

17 % **Other. Please describe.**

Other:

x: Progression from 2 to 3 to 4 to 5.

x: It might be best to start with 1 - perhaps half of the hour - then give the students some "real world" examples to solve.

x: Again, I don't think any single approach is ideal on its own.

Laboratory Structure from Questionnaire

The laboratory associated with this course is typically taught by graduate teaching assistants and could be structured in several ways. Please place an 'X' by that structure most appropriate for your students.

39% **A lab with well defined directions explaining how to use a simple apparatus to verify a physical principle.**

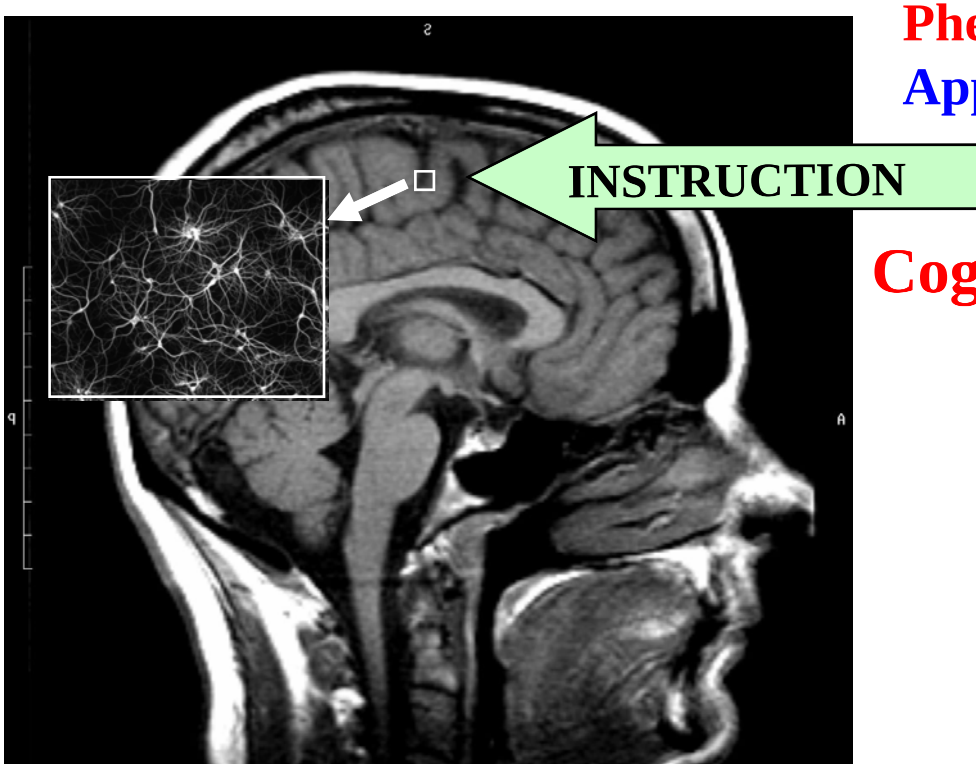
39% **A lab with a well defined question or problem illustrating a physical principle and minimal guidance about how to use the simple apparatus.**

30% **A lab where the students are given a general concept from which they must formulate an experimental question, then design and conduct an experiment from a choice of apparatus.**

26% **Other. Please describe.**

Other:
The first option followed by a lab section in which students design the experiment.
Progression from 1 to 2 to 3.
I suspect most students would benefit from 1 most. But the better students (honors?) would find 2 more interesting.
A mixture of these approaches.

Pedagogy - Learning is a Biological Process



Neurons that fire together, wire together

Simplification of Hebbian theory:
Hebb, D (1949). *The organization of behavior*. New York: Wiley.

Phenomenological Learning Theory

Apprenticeship Works

Cognitive Apprenticeship

Learning in the environment of expert practice

- **Why it is important**
- **How it is used**
- **How is it related to a student's existing knowledge**

model

coach

fade

Collins, Brown, & Newman (1990)

Brain MRI from Yale Medical School
Neuron image from Ecole Polytechnique Lausanne

Pedagogy – Cooperative Group Problem Solving

LECTURES

Four hours/week, sometimes with informal cooperative groups. Model constructing knowledge in response to problems, model organized problem solving framework.

RECITATION SECTION

One hour each Thursday – cooperative groups practice using a problem-solving framework to solve context-rich problems. Peer coaching, TA coaching.

LABORATORY

Two hours/week -- *same* cooperative groups practice using a framework to solve context-rich experimental problems. *Same* TA. Peer coaching, TA coaching.

TESTS

4 quizzes/semester on Friday -- problem-solving & conceptual questions (2 problems, 10 multiple choice) (1 group problem in previous discussion section).

Scaffolding

Additional structure used to support the construction of a complex structure.

Removed as the structure is built

Examples of Scaffolding in teaching Introductory Physics

- An explicit problem solving framework
- A worksheet that structures the framework – removed early in the course
- Cooperative group structure that encourages productive group interactions
- Limit use of formulas by giving an equation sheet (only allowed equations)
- Explicit grading rubric for problem solutions to encourage expert-like behavior
- Problems that discourage novice problem solving
- Explicit grading rubric for lab problems to encourage expert-like behavior
- TA education and support in pedagogy

Individual Context- Rich Problem on an Exam

Your task is to design an artificial joint to replace arthritic elbow joints in patients. After healing, the patient should be able to hold at least a gallon of milk while the lower arm is horizontal. The biceps muscle is attached to the bone at the distance 1/6 of the bone length from the elbow joint, and makes an angle of 80^{o} with the horizontal bone. How strong should you design the artificial joint if you assume the weight of the bone is negligible.

Gives a motivation – allows some students to access their mental connections.
Gives a realistic situation – allows some students to visualize the situation.
Does not give a picture – students must practice visualization.
Uses the character "you" – allows some students to visualize the situation.

Group Context-Rich Problem in Discussion Section – Peer Coaching

Your research team uses interference to determine the thickness of thin films such as guanine (index of refraction 1.80) that give fish scales their sheen. The apparatus used has two slits 1.0 mm apart, a 600 nm laser light source, and a lens system to assure that parallel rays hit the slits. A screen is 1 meter from the slits. Initially you measure the interference pattern on the screen. You then find the thickness of the guanine by putting it just behind one of the slits and observing that the position of the central maximum on the screen shifts to the position formally occupied by the 30th bright fringe from the central maximum

The problems students practice while being coached have the same structure as those on their tests.

What Using Cooperative Groups Does for Teaching Problem Solving

1. Following a logical problem solving framework seems too long and complex for most students.

   Cooperative-group problem solving allows practice until the framework becomes more natural.

2. Complex problems that need a strategy are initially difficult.

   Groups can successfully solve them so students see the advantage of a logical problem-solving framework early in the course.

What Using Cooperative Groups Does for Teaching Problem Solving

3. The group interactions externalize the planning, connection, and monitoring skills needed to solve problems allowing students to observe them in others.

4. Students practice using the language of the field, "talking physics“, and explicitly connecting it to their existing knowledge base.

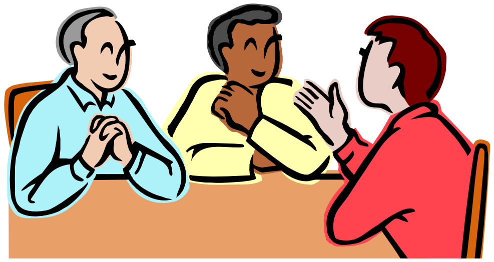
5. Students must deal with and resolve their misconceptions.

6. Coaching by instructors is more effective

External clues of group difficulties
Group processing of instructor input

Students Working Together in Structured Groups for Peer Coaching

Cooperative Groups



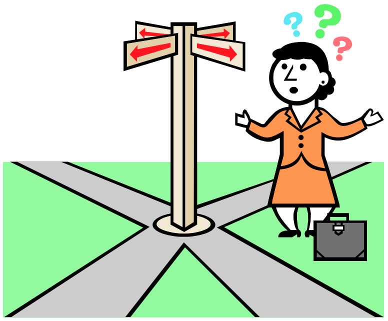
- **Positive Interdependence**
- **Face-to-Face Interaction**
- **Individual Accountability**
- **Explicit Collaborative Skills**
- **Group Functioning Assessment**

Just having students work together in groups is not beneficial

Teaching Students to Solve Physics Problems

Solving Problems Requires Conceptual Knowledge:

From Situations to Decisions using internal knowledge



- **Visualize situation**
- **Determine goal**
- **Choose applicable principles**
- **Choose relevant information**
- **Construct a plan**
- **Arrive at an answer**
- **Evaluate the solution**

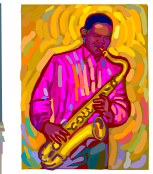
Students must be taught a problem solving framework that does this *explicitly*

General Problem Solving Skills

(i.e. Polya 1945)

How to solve a problem when you don't know how





STEP #1

Recognize the Problem

What's going on?

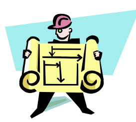
STEP #2

Describe the problem in terms of physics

What does this have to do with physics ?

STEP #3

Plan a solution



Can I use what I know to get an answer?

STEP #4

Execute the plan

Get an answer

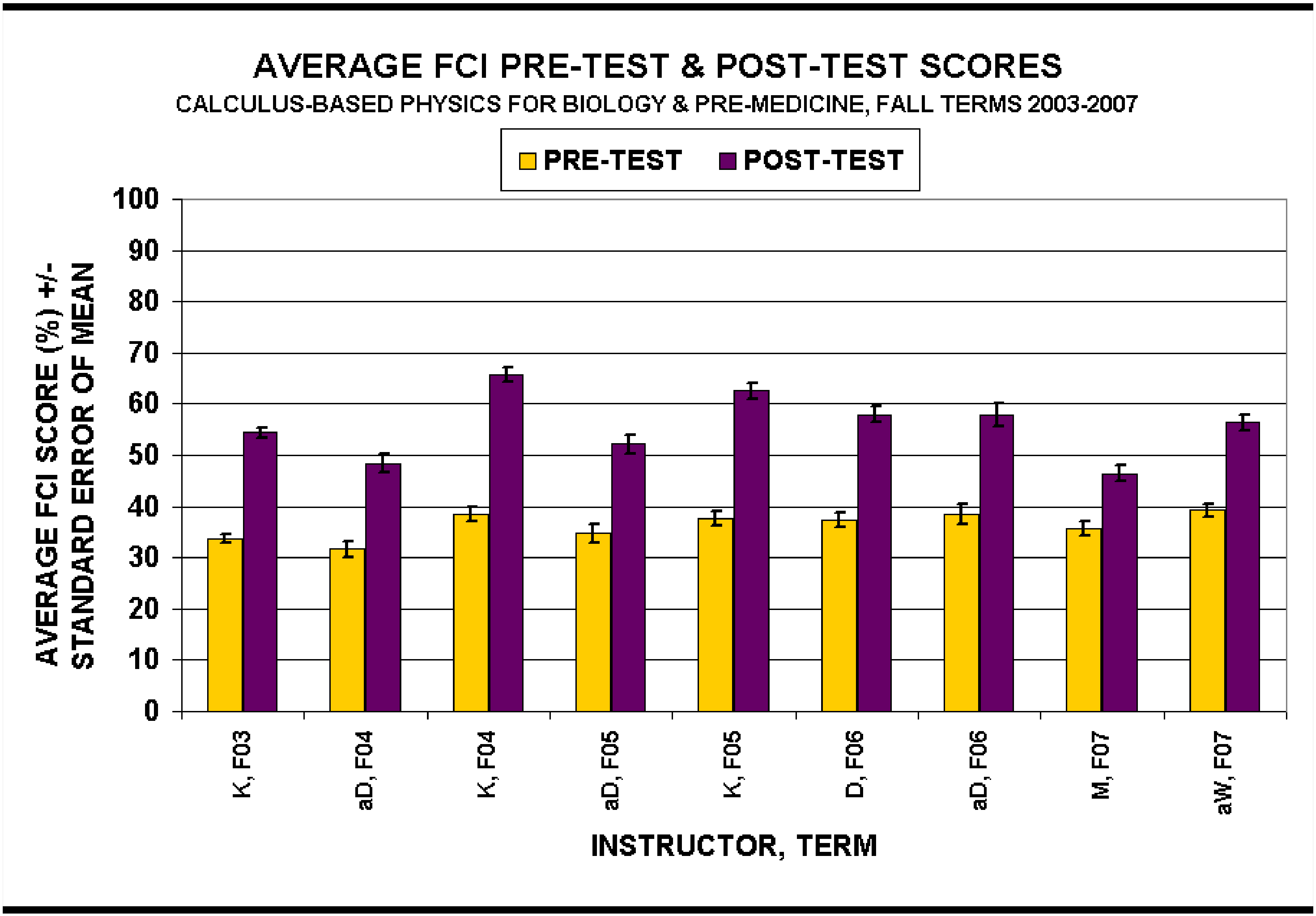
STEP #5

Evaluate the solution

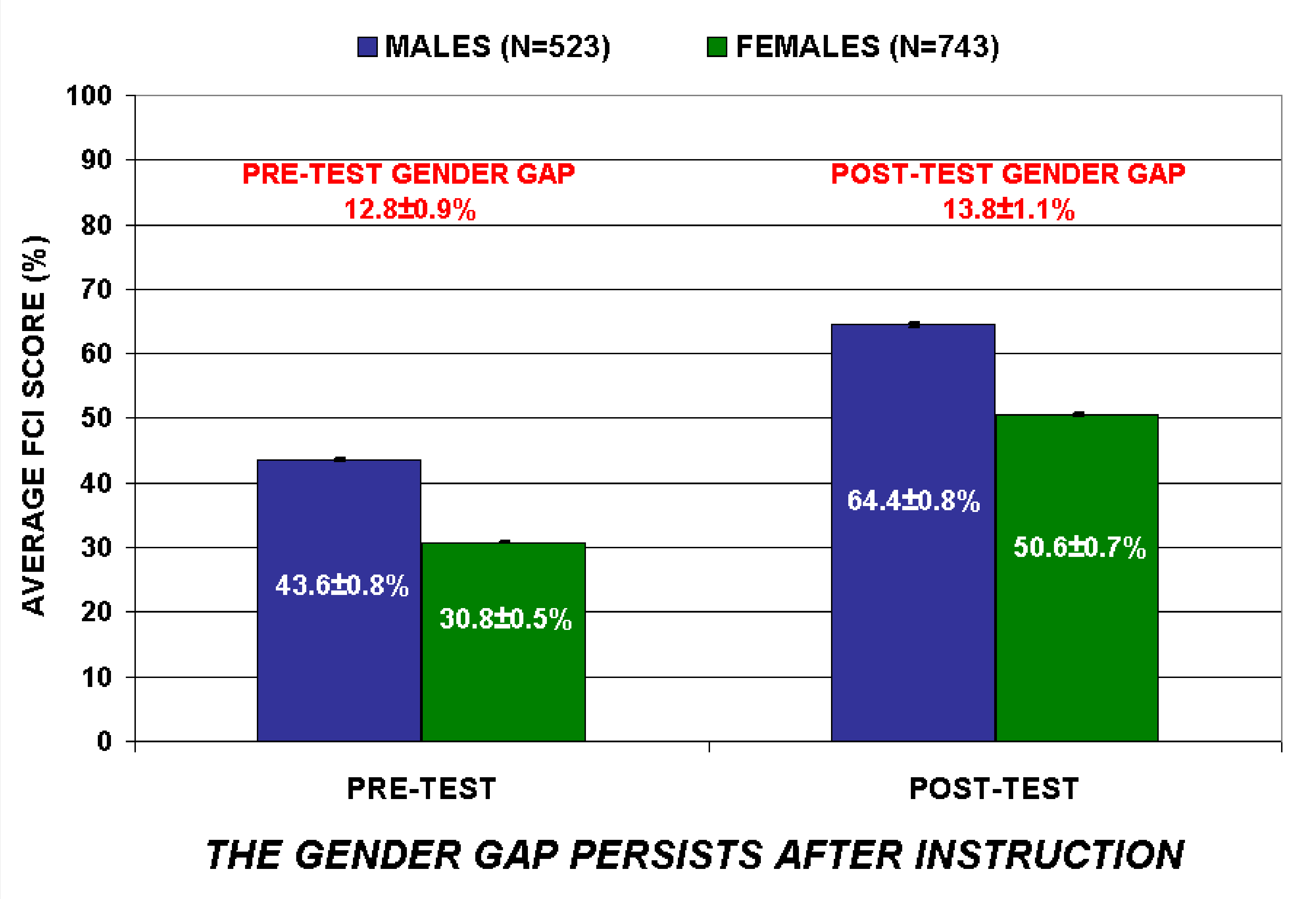
Can this be true?

Problem-solving Framework Used by experts in all fields

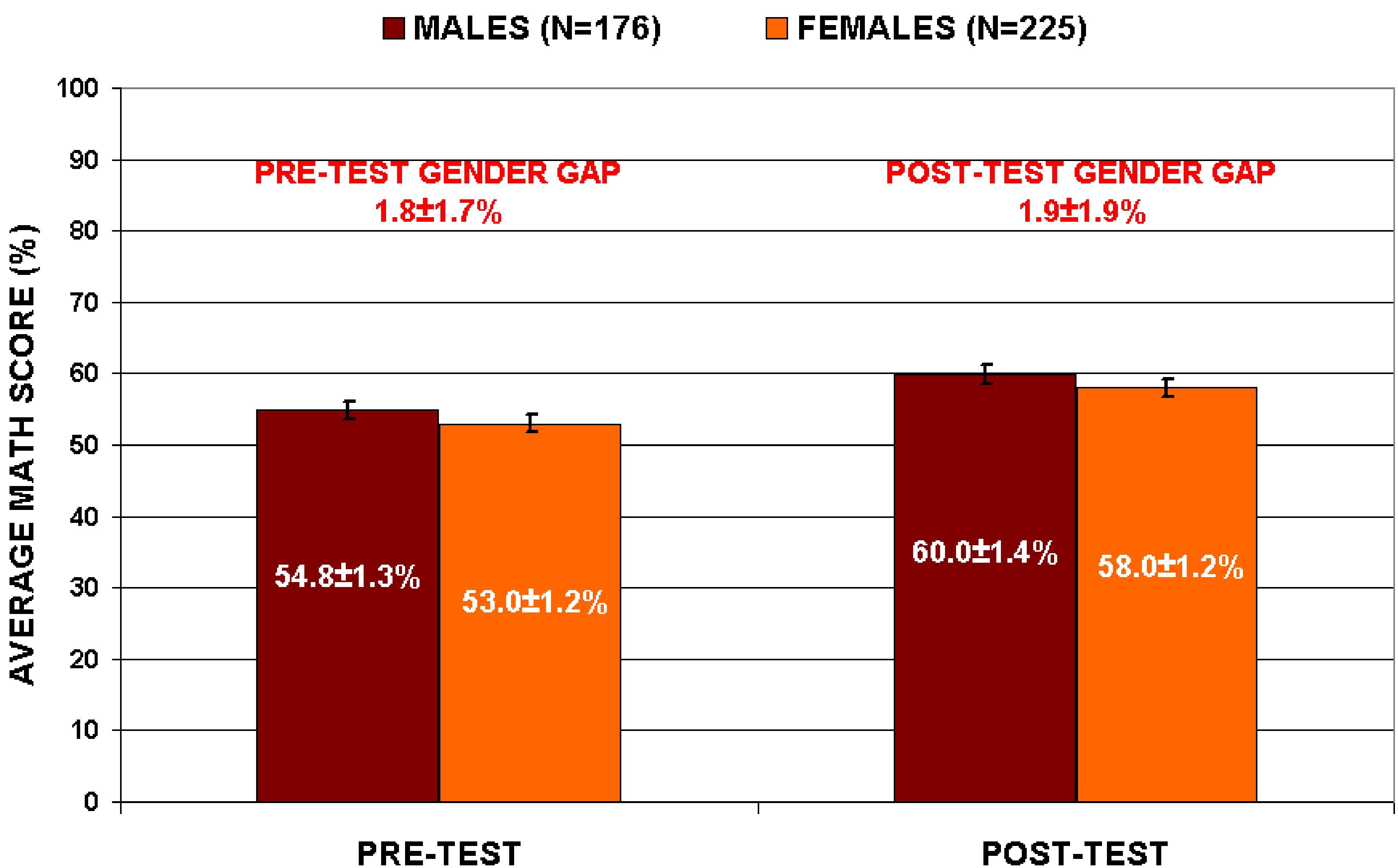
Chi, M., Glaser, R., & Rees, E. (1982)


AVERAGE FCI PRE-TEST & POST-TEST SCORES
CALCULUS-BASED PHYSICS FOR BIOLOGY & PRE-MEDICINE, FALL TERMS 2003-2007
PRE-TEST
POST-TEST
AVERAGE FCI SCORE (%) +/- STANDARD ERROR OF MEAN
100
90
80
70
60
50
40
30
20
10
0
K, F03
aD, F04
K, F04
aD, F05
K, F05
D, F06
aD, F06
M, F07
aW, F07
INSTRUCTOR, TERM

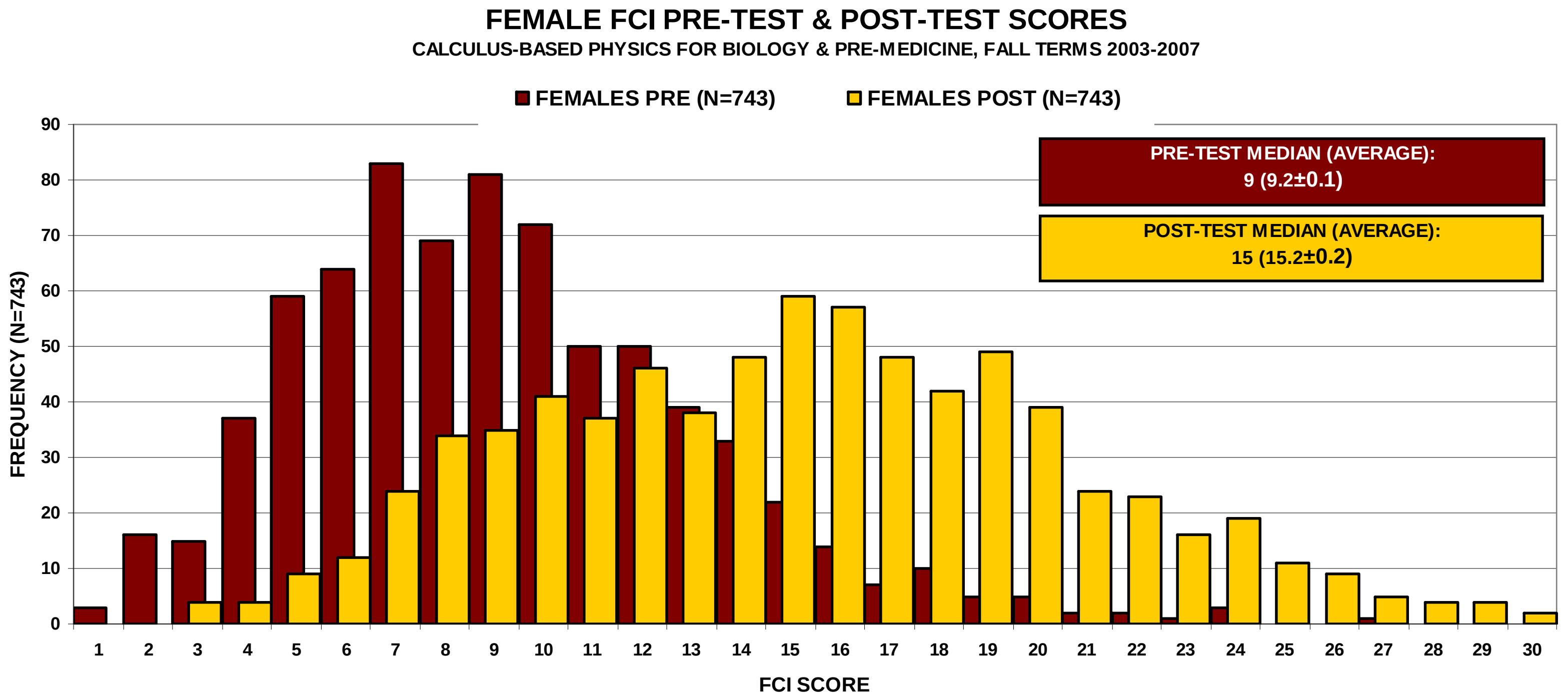
FCI for Calculus Based Physics for Biology Students

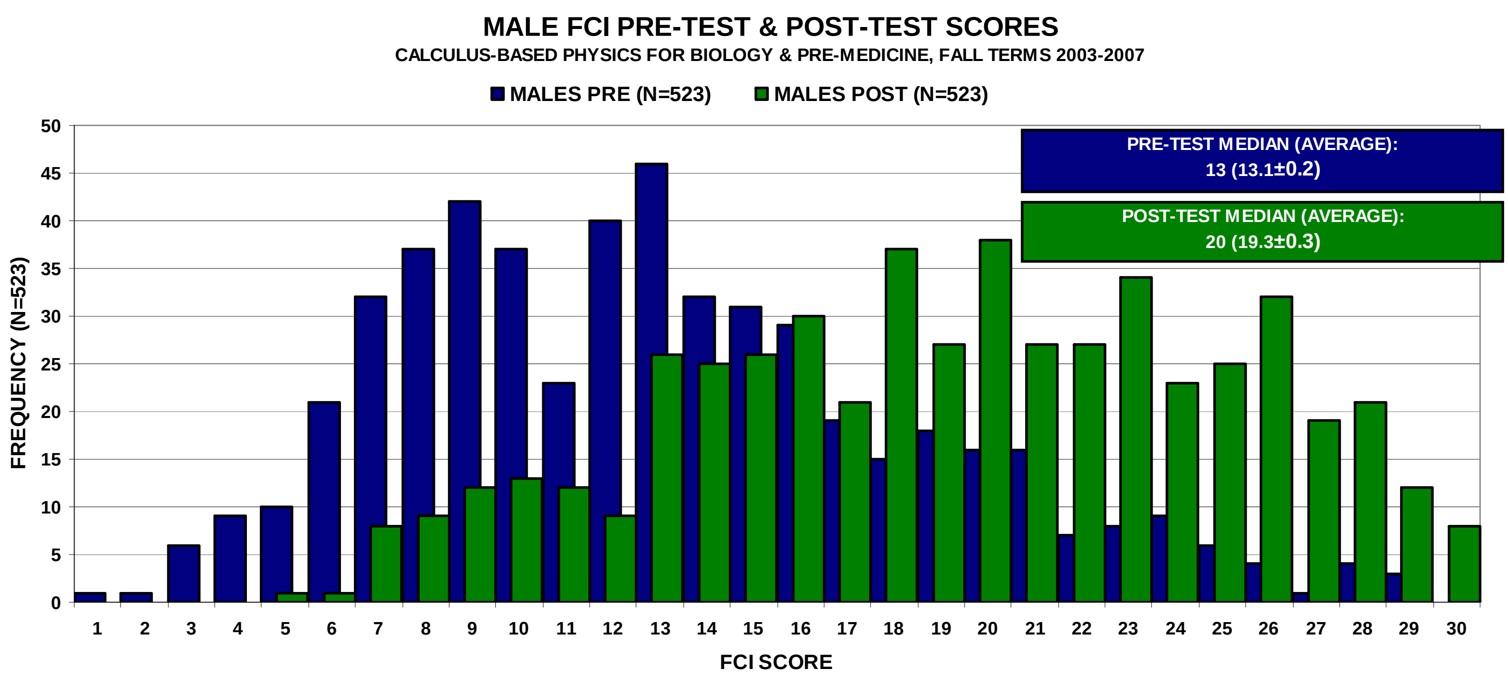


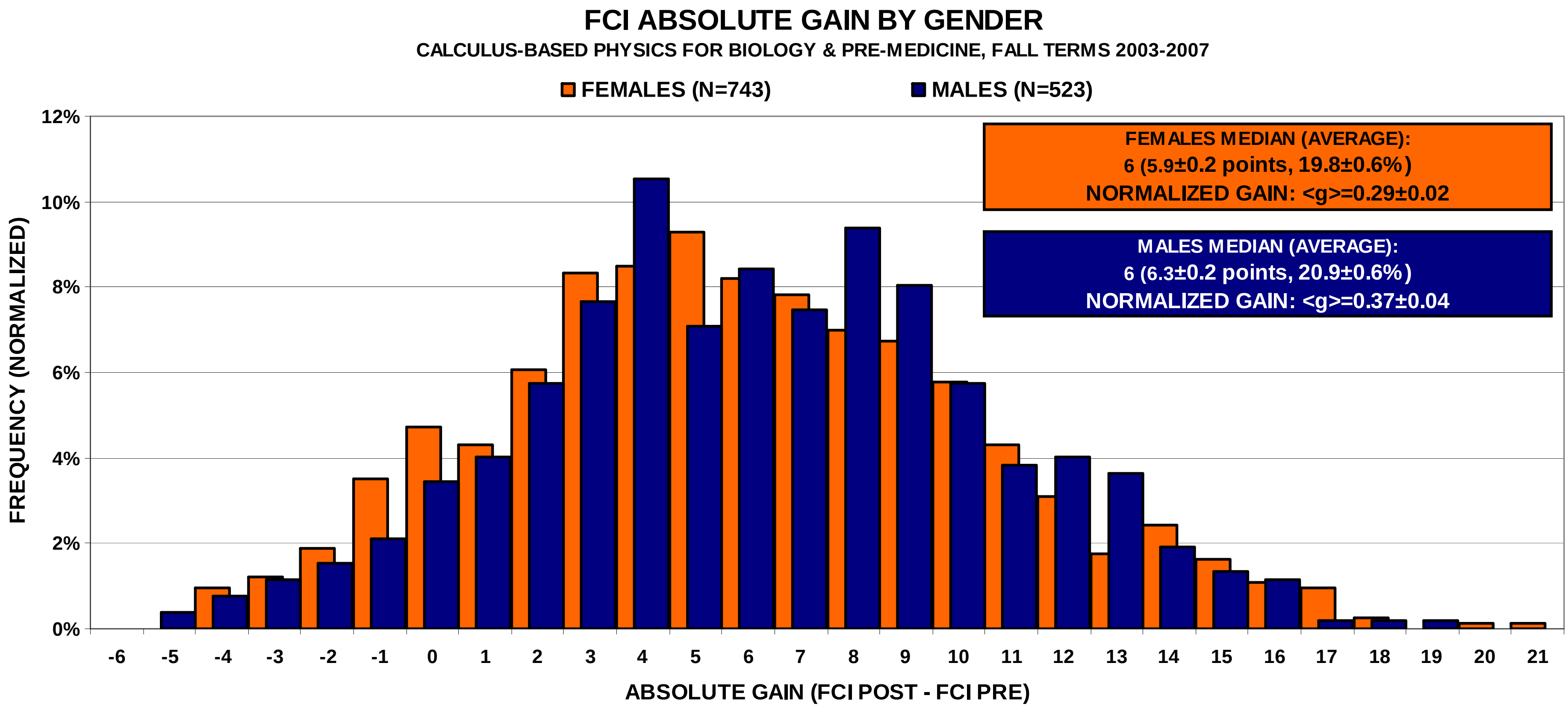
Math Diagnostic for Calculus Based Physics for Biology Students



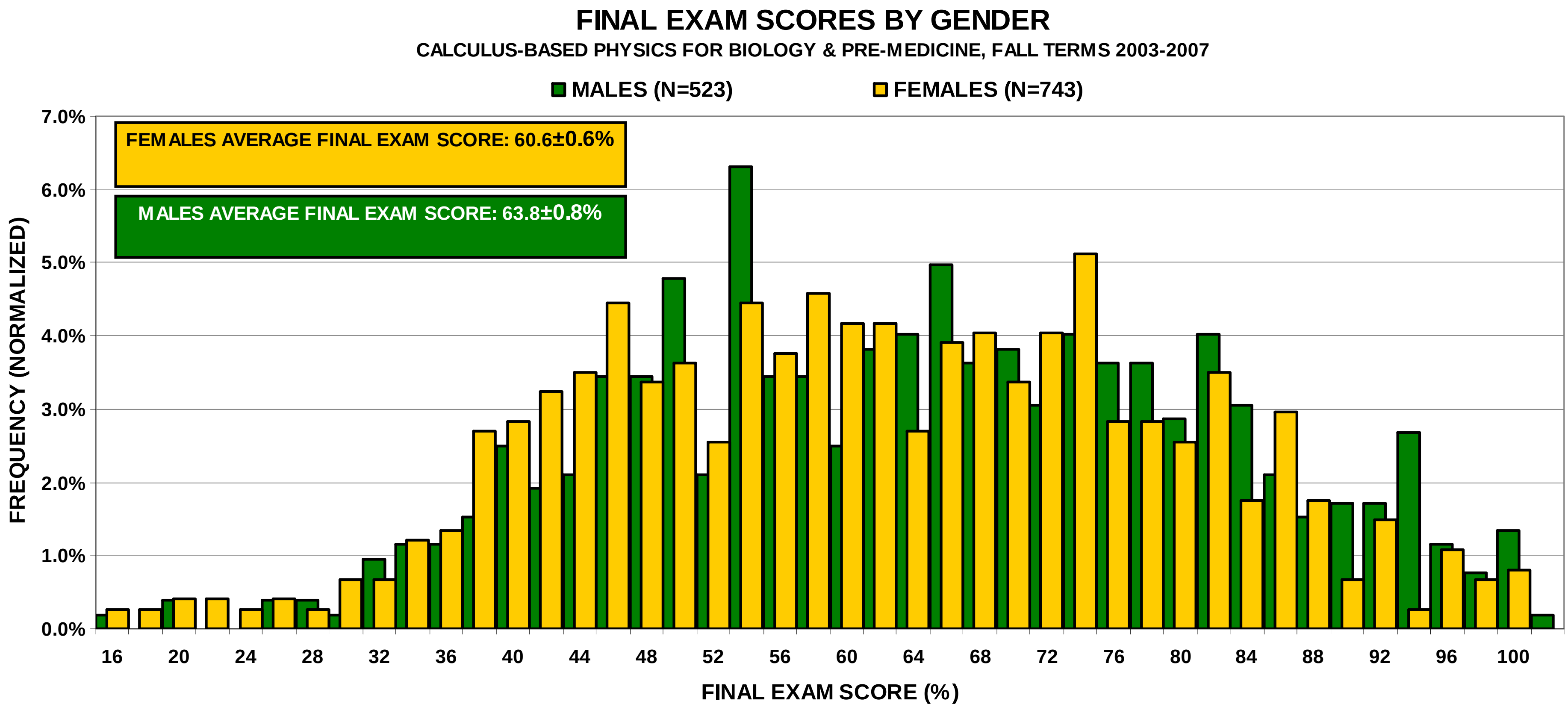
ESSENTIALLY NO GENDER GAP ON THE MATH DIAGNOSTIC


FEMALE FCI PRE-TEST & POST-TEST SCORES
CALCULUS-BASED PHYSICS FOR BIOLOGY & PRE-MEDICINE, FALL TERMS 2003-2007
FEMALES PRE (N=743)
FEMALES POST (N=743)
PRE-TEST MEDIAN (AVERAGE):
9 (9.2±0.1)
POST-TEST MEDIAN (AVERAGE):
15 (15.2±0.2)
FREQUENCY (N=743)
FCI SCORE

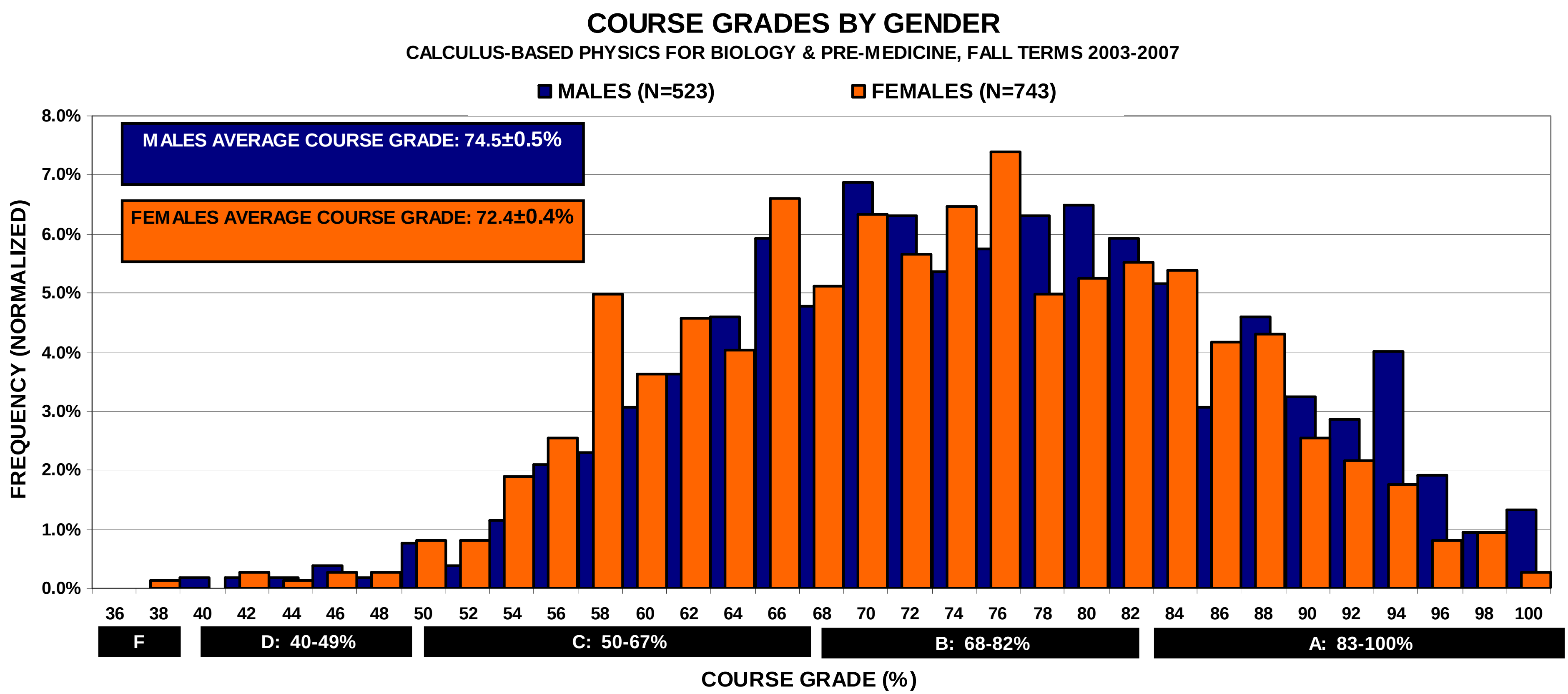

MALE FCI PRE-TEST & POST-TEST SCORES
CALCULUS-BASED PHYSICS FOR BIOLOGY & PRE-MEDICINE, FALL TERMS 2003-2007
MALES PRE (N=523)
MALES POST (N=523)
PRE-TEST MEDIAN (AVERAGE):
13 (13.1±0.2)
POST-TEST MEDIAN (AVERAGE):
20 (19.3±0.3)
FREQUENCY (N=523)
FCI SCORE



FCI ABSOLUTE GAIN BY GENDER
CALCULUS-BASED PHYSICS FOR BIOLOGY & PRE-MEDICINE, FALL TERMS 2003-2007
FEMALES (N=743)
MALES (N=523)
FEMALES MEDIAN (AVERAGE):
6 (5.9±0.2 points, 19.8±0.6%)
NORMALIZED GAIN: <g>=0.29±0.02
MALES MEDIAN (AVERAGE):
6 (6.3±0.2 points, 20.9±0.6%)
NORMALIZED GAIN: <g>=0.37±0.04
FREQUENCY (NORMALIZED)
12%
10%
8%
6%
4%
2%
0%
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
ABSOLUTE GAIN (FCI POST - FCI PRE)

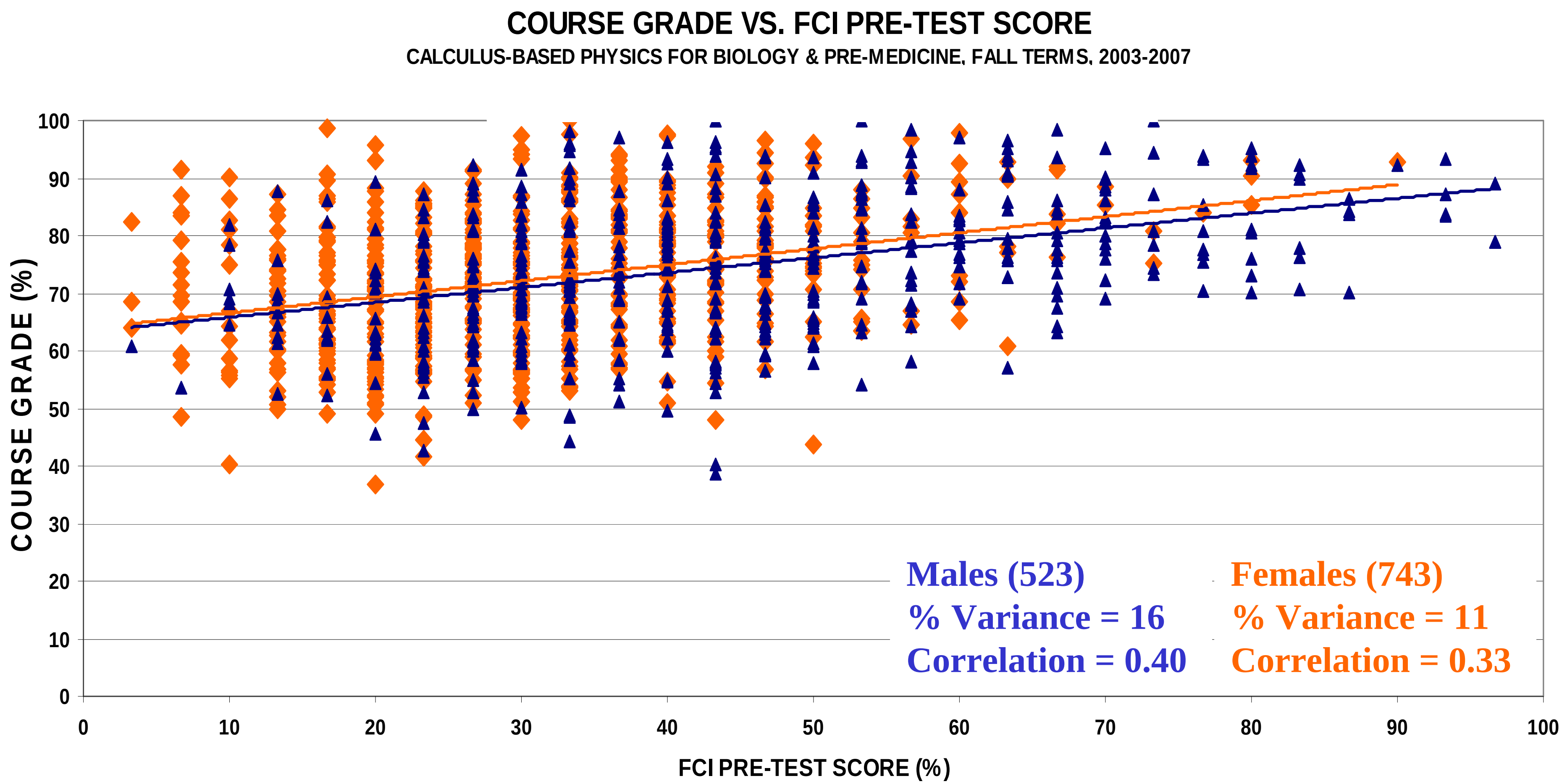


FINAL EXAM SCORES BY GENDER
CALCULUS-BASED PHYSICS FOR BIOLOGY & PRE-MEDICINE, FALL TERMS 2003-2007
MALES (N=523)
FEMALES (N=743)
FEMALES AVERAGE FINAL EXAM SCORE: 60.6±0.6%
MALES AVERAGE FINAL EXAM SCORE: 63.8±0.8%
FREQUENCY (NORMALIZED)
7.0%
6.0%
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
92
96
100
FINAL EXAM SCORE (%)



COURSE GRADES BY GENDER
CALCULUS-BASED PHYSICS FOR BIOLOGY & PRE-MEDICINE, FALL TERMS 2003-2007
MALES (N=523)
FEMALES (N=743)
MALES AVERAGE COURSE GRADE: 74.5±0.5%
FEMALES AVERAGE COURSE GRADE: 72.4±0.4%
FREQUENCY (NORMALIZED)
8.0%
7.0%
6.0%
5.0%
4.0%
3.0%
2.0%
1.0%
0.0%
36 38 40 42 44 46 48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100
F
D: 40-49%
C: 50-67%
B: 68-82%
A: 83-100%
COURSE GRADE (%)

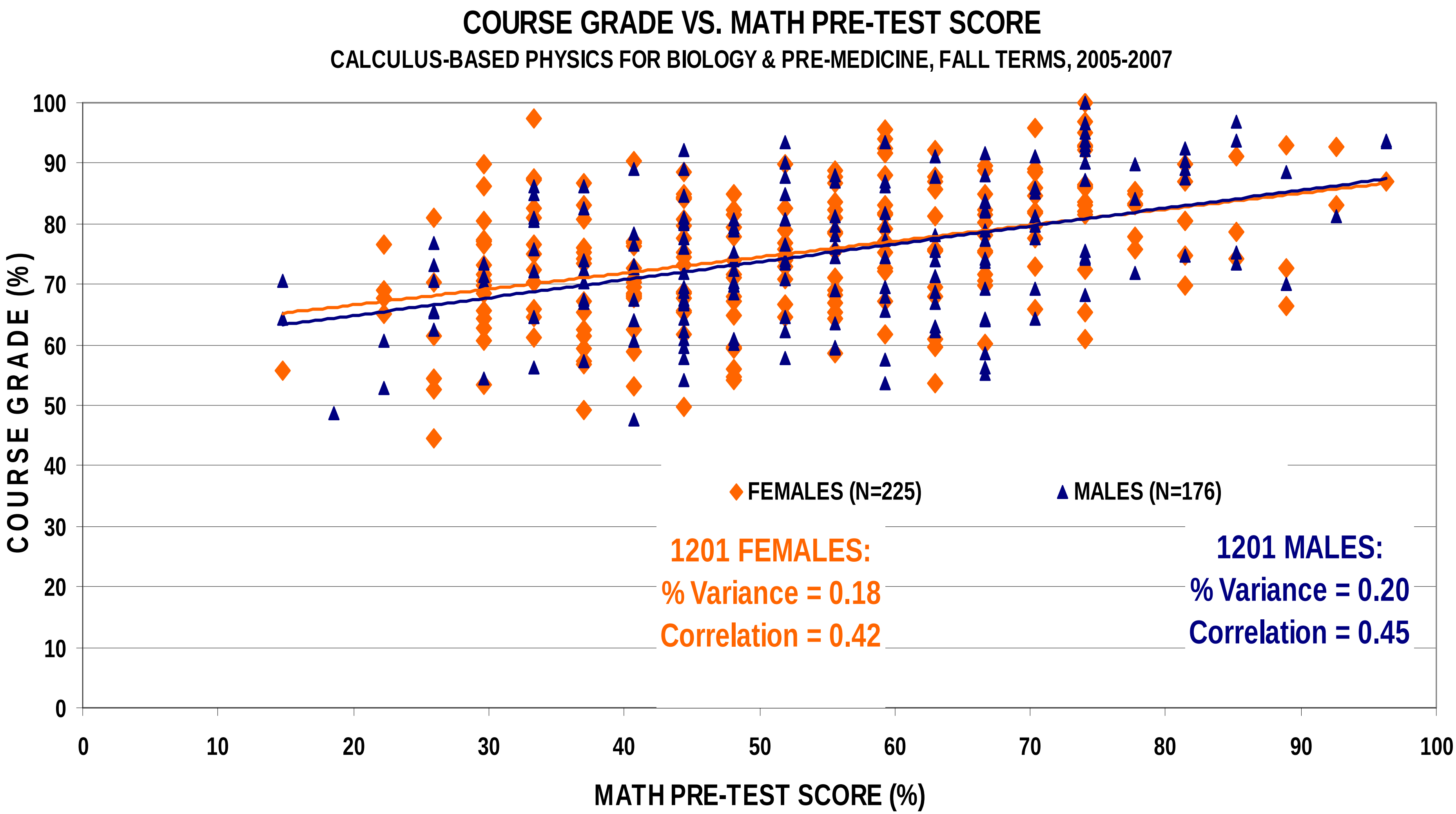
Can the FCI be used as a Placement Test for physics?



The FCI is not a good placement test and would discriminate against females.

Accounts for only about 15% of final grade

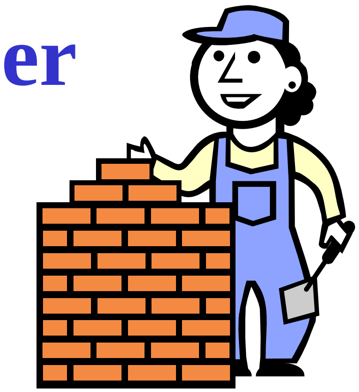
Can a Math Skills Test be used as a Placement Test for physics?



A Math Skills Test is not a good placement test

Accounts for only about 20% of final grade

Course Components Work Together

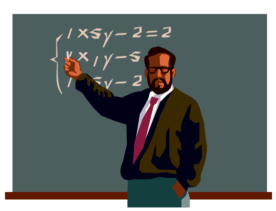


- Teach Students an Organizational Framework
  - Emphasize decision making using physics
  - Use writing as working memory
  - Emphasize rule-based mathematics
- Use Problems that Require
  - An organized framework
  - Physics conceptual knowledge
  - Connection to existing knowledge
- Use Existing Course Structure
  - Lectures and handouts - 200 students (Professors) MODELING
  - Discussion Sections – 18 students (TAs) COACHING
  - Labs – 18 students (TAs) COACHING
- All in contexts that connect with biology
  - Modeling connections to biological systems
  - Context-rich problems
  - Context-rich problem solving labs

Average dropout rate 5%
average D/F rate 3%

Absolute grading scale

Average course grade
73.5±0.3% B-



Modeling

Peer

Instructor

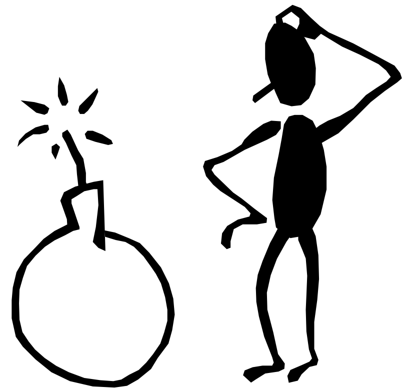
Coaching

Fading

Identify Critical Failure Points

Pedagogy Must Fail Gracefully

Non-optimal implementation gives some success



1. Inappropriate Tasks

Must engage all group members (not just one who knows how to do it)

2. Inappropriate Grading

Must not penalize those who help others (no grading on the curve)

Must reward for individual learning

3. Poor structure and management of Groups

The End

Please visit our website for more information:

http://groups.physics.umn.edu/physed/

The best is the enemy of the good.

"le mieux est l'ennemi du bien"

Voltaire