Strengthening the Link Between Research and Instruction in Physics Education

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Outline

- Brief Overview of Physics Education Research
- A Measurement Dilemma
- A Model Problem
  Student Concepts of Gravitation
- Curriculum Development for Large Classes
  Active-Learning Materials for Algebra-based Physics
- Tightening the Link to Research
  Dynamics of Student Learning of Thermodynamics in Physics and Chemistry

Physics Education As a Research Problem

Within the past 25 years, physicists have begun to treat the teaching and learning of physics as a research problem

- Systematic observation and data collection; reproducible experiments
- Identification and control of variables
- In-depth probing and analysis of students' thinking

U.S. Physics Departments with Active Research Groups in Physics Education

- American University
- Arizona State University †
- Black Hills State University
- Boise State University
- California Polytechnic State University, San Luis Obispo
- California State University, Chico
- California State University, Fullerton
- California State University, San Marcos
- Carnegie Mellon University
- City University of New York
- Clarion University
- Grand Valley State University
- Harvard University
- Indiana University-Purdue University Fort Wayne
- Iowa State University*
- Kansas State University†
- Montana State University*
- New Mexico State University
- North Carolina A&T University
- North Carolina State University*
- Ohio State University*
- Rensselaer Polytechnic Institute*
- San Diego State University†
- Southwest Missouri State University
- Syracuse University
- Texas Tech University
- Tufts University
- University of Central Florida
- University of Maine*
- University of Maryland*
- University of Massachusetts – Amherst
- University of Minnesota†
- University of Nebraska*
- University of Northern Arizona
- University of Northern Iowa
- University of Oregon
- University of Washington*
- University of Wisconsin – Stout

*offer Ph.D. in Physics Education in Physics Department

†offer Ph.D. in Physics Education in collaborating department

Role of Physics Education Research

- Investigate students' learning difficulties
- Develop (and ***assess***) curricular materials that address learning difficulties
- Implement new instructional methods that make use of improved curricula

Tools of Physics Education Research

- Conceptual surveys (“diagnostics”)
  - sets of written questions emphasizing qualitative understanding *(often given “pre” and “post” instruction)*
  - Examples: *Force Concept Inventory, Conceptual Survey of Electricity and Magnetism*
- Students’ written explanations of their reasoning
- Interviews with students

Some Specific Issues

Many (if not most) students:

- develop weak ***qualitative*** understanding of concepts
  - don't use qualitative analysis in problem solving
  - lacking quantitative problem solution, can't reason "physically"
- lack a **"*functional*"** understanding of concepts (which would allow problem solving in unfamiliar contexts)

Conceptual Learning Gains in Mechanics

Nationwide survey of scores on Force Concept Inventory in "traditional" courses [R. R. Hake, *Am. Jour. Phys.* **60**, 64 1998]

	N	**Pretest Score**	**Posttest Score**	**g [gain / max. possible gain]**
Algebra-based Courses	*73*	40%	53%	0.22
Calculus-based Courses	*1248*	51%	62%	0.19

Conceptual Learning Gains in Electricity and Magnetism

Nationwide survey of scores on Conceptual Survey of Electricity and Magnetism [Maloney, O'Kuma, Hieggelke, & Van Heuvelen, 2000]

	N	**Pretest Score**	**Posttest Score**	**g [gain / max. possible gain]**
Algebra-based Courses	*273*	25%	44%	0.25
Calculus-based Courses	*1213*	31%	47%	0.23

Origins of Learning Difficulties

- Students hold many firm ideas about the physical world that may conflict strongly with physicists' views.

    Examples:

    - **An object in motion *must* be experiencing a force**
    - **A given battery always produces the *same* current in *any* circuit**
    - **Electric current gets "used up" as it flows around a circuit**

- Most introductory students need much guidance in scientific reasoning employing abstract concepts.

- Most introductory students lack "active learning" skills that would permit more efficient mastery of physics concepts.

But … ***some*** students learn efficiently . . .

- Highly successful physics students are ***"active learners."***
  - they continuously probe their own understanding

    [*pose their own questions; scrutinize implicit assumptions; examine varied contexts; etc.]*
  - they are sensitive to areas of confusion, and have the confidence to confront them directly

- Majority of introductory students are unable to do efficient active learning on their own: they don't know "which questions they need to ask"
  - they require considerable prodding by instructors, aided by appropriate curricular materials

Keystones of Innovative Pedagogy

- problem-solving activities during class time
- deliberately elicit and address common learning difficulties
- guide students to “figure things out for themselves” as much as possible

Assessment of Instruction

- Need measure of instructional effectiveness
- Post-test by itself measures what students ***know***, not what they've ***learned***
- Key measure: student learning <u>***gain***</u> (change in score) on some diagnostic instrument

How can ***improved*** instruction be detected?

- First approximation: Local measurements
  - Student population in same course at same institution is consistent year-to-year: pretest measures show little variation
  - Same exam in same course can reflect year-to-year changes in instruction
- Cross-institutional comparisons
  - Needed to encourage use of "best practices"
  - Must take into account differences in student population
  - Better-prepared students show superior performance ***independent*** of instructional variations

A Figure of Merit: “Normalized” Gain [*g*]

- Practical problem: maximum score = 100%, so if students have different pretest scores their maximum ***possible*** gain is different.

- One solution: Use ***normalized gain “g”*** (introduced by R. Hake)

$$g = \frac{\text{gain}}{\text{maximum possible gain}}$$

$$= \frac{[\textit{posttest score} - \textit{pretest score}]}{[100\% - \textit{pretest score}]}$$

→ ***Normalized gain yields a gain score that corrects for pretest score.***

What affects ***g***?

Study of 6000 students by Richard Hake (1998):

- <*g*> is ***not*** correlated with mean FCI pretest score.

- Mean normalized gain <*g*> on the FCI is ***independent of instructor*** for traditional instruction.

- <*g*> ***<u>does</u>*** depend on instructional method: *higher* for courses with "interactive engagement."

  ® *Equal instructional effectiveness is often assumed to lead to equal <g> for all groups of students* ***regardless*** *of pretest score or other factors.*

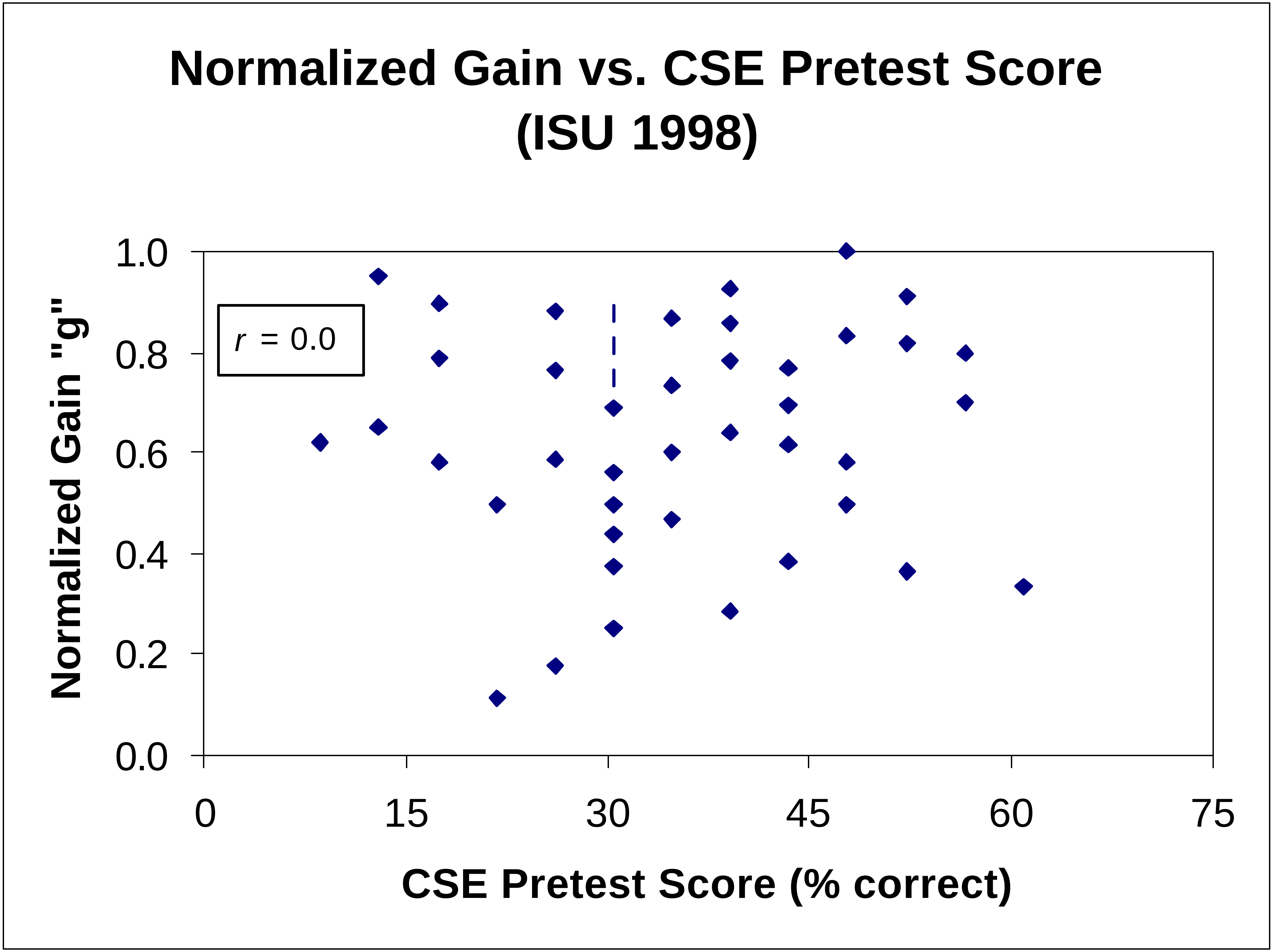
  (<g> > 0.35 a "marker" of interactive engagement)

Is Normalized Gain of ***Individual*** Students Correlated with their Pretest Score?

- We investigate learning gains on "Conceptual Survey of Electricity" (CSE) [O'Kuma, Hieggelke, Maloney, & Van Heuvelen]
  - *Conceptual, qualitative questions*

- Four student samples, two different universities

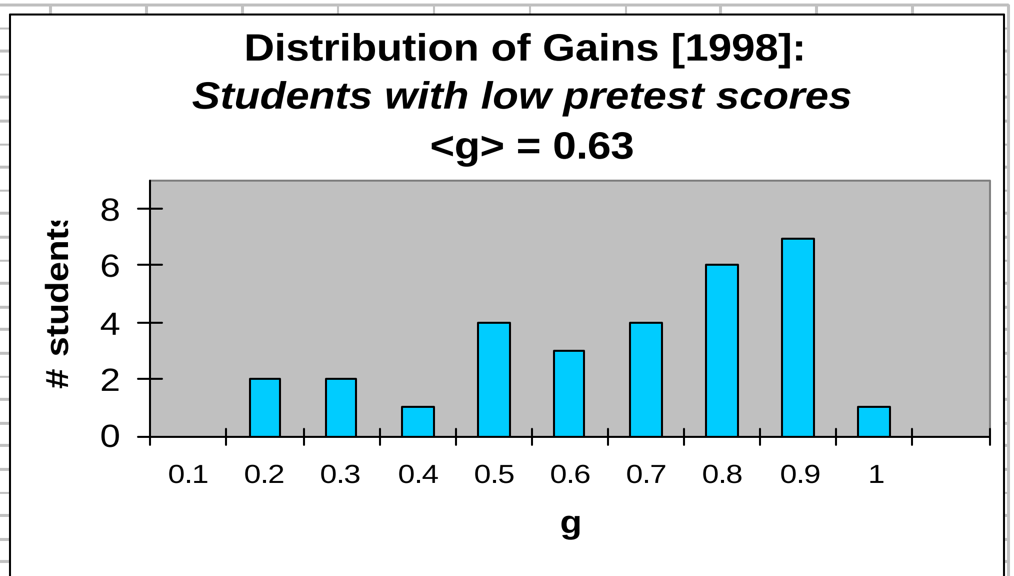
- Algebra-based general physics: instruction used interactive lectures, "peer instruction," "tutorials," etc.


Normalized Gain vs. CSE Pretest Score
(ISU 1998)
r = 0.0
Normalized Gain "g"
1.0
0.8
0.6
0.4
0.2
0.0
0
15
30
45
60
75
CSE Pretest Score (% correct)

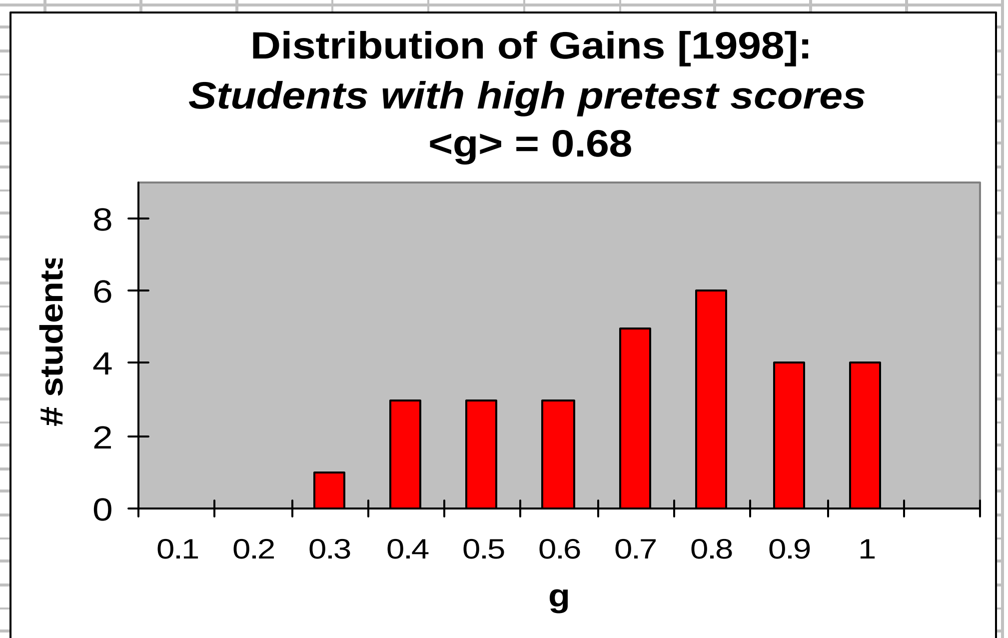
Is a student's learning gain ***g*** correlated with their ***pretest*** score?

	N	Correlation coefficient between student learning gain ***"g"*** and CSE pretest score	Statistical significance
SLU 1997	46	0.07	p = 0.65 ***(not significant)***
SLU 1998	37	0.10	p = 0.55 ***(not significant)***
ISU 1998	59	0.00	p = 0.98 ***(not significant)***
ISU 1999	78	0.10	p = 0.39 ***(not significant)***

® ***No statistically significant relationship Between g and pretest score.***



Distribution of Gains [1998]:
Students with low pretest scores
<g> = 0.63



Distribution of Gains [1998]:
Students with high pretest scores
<g> = 0.68

Gain comparison, students with high and low CSE pretest scores [1998]

	N	**CSE Pretest Score**	**<g>**
Top half	29	44%	0.68
Bottom half	30	25%	0.63
			D<g> = 0.05 ***(not significant)***
Top quartile	15	50%	0.65
Bottom quartile	16	20%	0.66
			D<g> = 0.01 ***(not significant)***

Consistent Result: ***No*** Correlation of ***g*** With Pretest Score on CSE

- Even though lower half of class scored ≈20% on pretest (random guessing), while upper half scored 40-50%, ***both groups achieved <u>same</u> normalized gain***.
- Implication: Can ***not*** use pretest score to predict student's performance (as measured by ***g***).

So . . . Can ***Any*** Pre-instruction Measure Predict Student Performance?

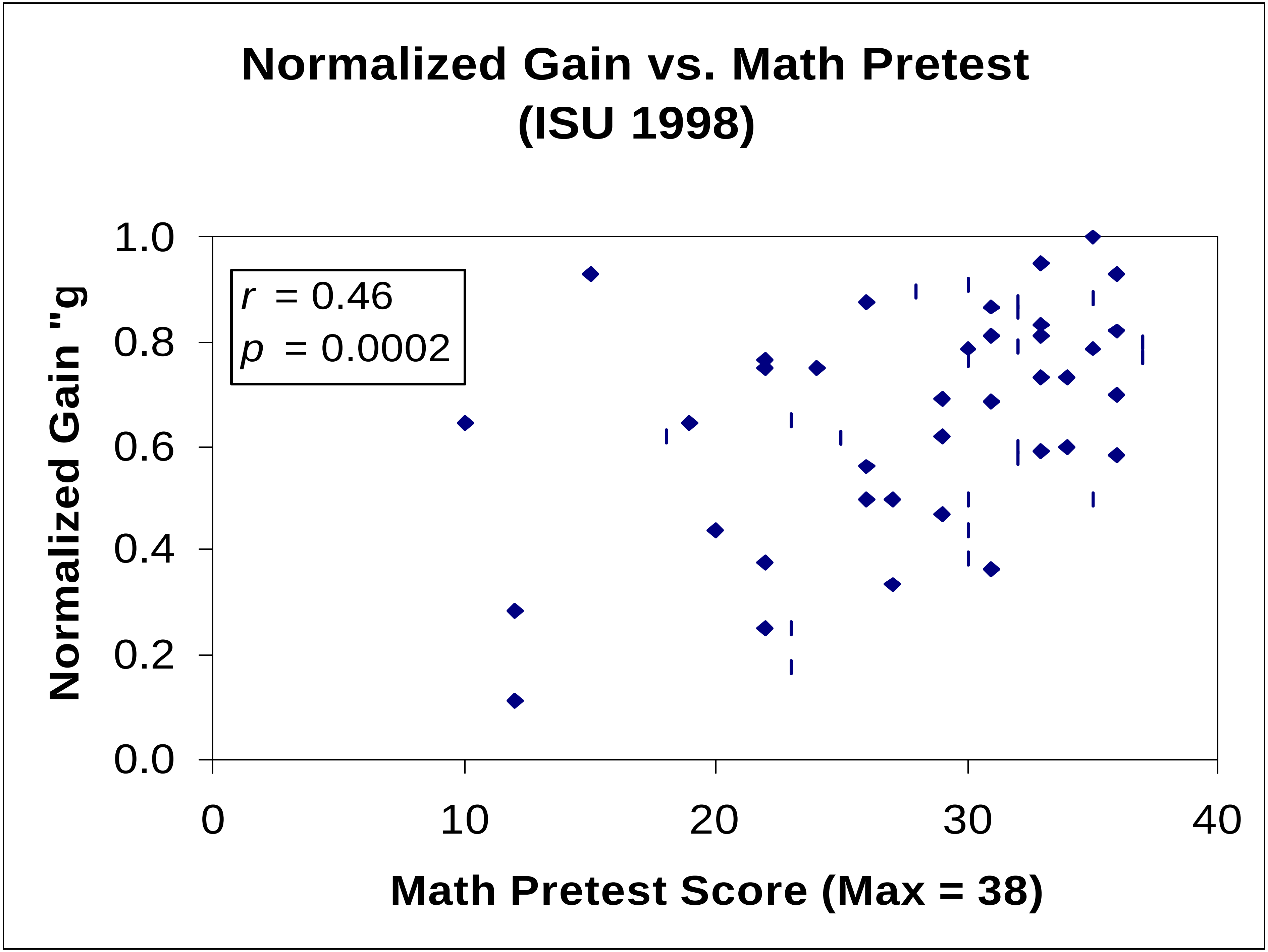
® Many studies have demonstrated a correlation between ***math skills*** and physics performance, HOWEVER:

– performance was measured by traditional quantitative problems

– student’s pre-instruction knowledge was not taken into account (i.e., only posttest scores were used)

Is Physics Performance Correlated With Students' Math Skills?

- Measure performance on conceptual, qualitative questions (CSE);
- Define performance as ***normalized gain g***, i.e, how much did the student ***learn.***
- Use pre-instruction test of math skills:
  - ***SLU 1997, 1998: ACT Math Score***
  - ***ISU 1998, 1999: Algebraic skills pretest***


Normalized Gain vs. Math Pretest
(ISU 1998)
r = 0.46
p = 0.0002
Normalized Gain "g
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
Math Pretest Score (Max = 38)

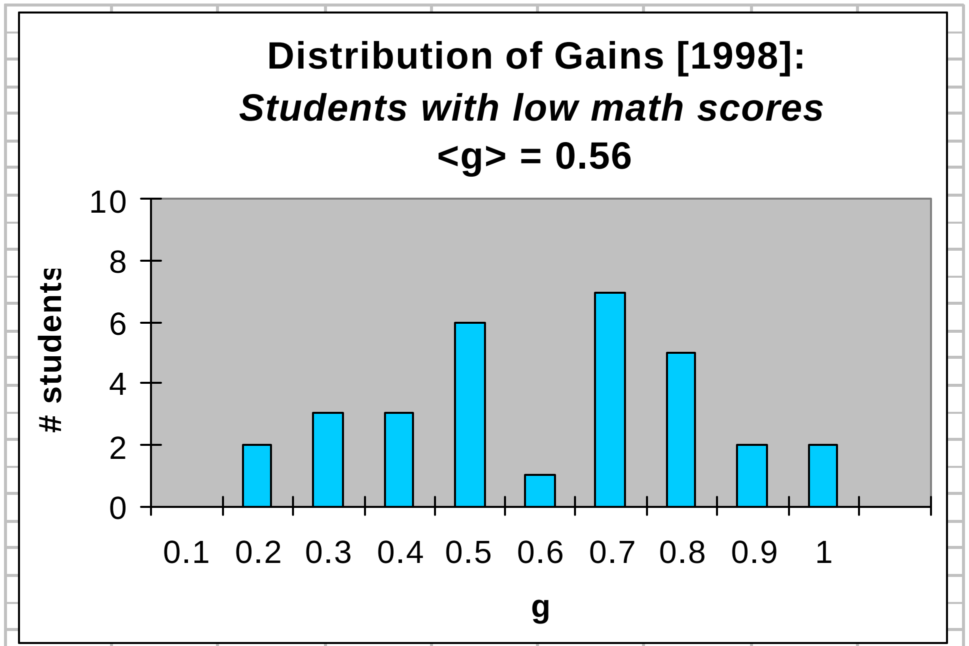
Is a student's learning gain *g* correlated with their *math* score?

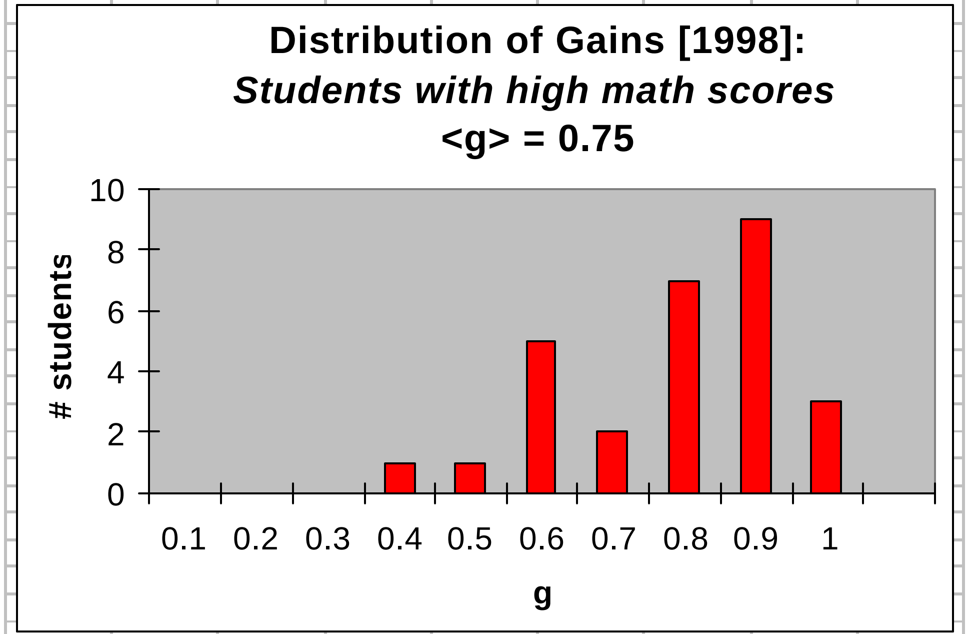
	N	Correlation coefficient between student learning gain ***"g"*** and math pretest score	Statistical significance
SLU 1997	45	0.38	$p < 0.01$
SLU 1998	37	0.10	$p = 0.55$ ***(not significant)***
ISU 1998	59	0.46	$p = 0.0002$
ISU 1999	78	0.30	$p < 0.01$

® ***Three out of four samples show strong evidence of correlation between g and math pretest score.***

Gain comparison, students with high and low math scores [1998]

	N	**Math Score**	**<g>**
Top half	28	89%	0.75
Bottom half	31	63%	0.56
			D<g> = 0.19 *p = 0.0001*
Top quartile	13	93%	0.77
Bottom quartile	14	49%	0.49
			D<g> = 0.28 *p = 0.001*


Distribution of Gains [1998]:
Students with low math scores
<g> = 0.56
students
10
8
6
4
2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
g


Distribution of Gains [1998]:
Students with high math scores
<g> = 0.75
students
10
8
6
4
2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
g

Implications: Extra caution needed for comparisons between different student populations

- Strong evidence of *correlation* (***not causation!***) between computational math skills and conceptual learning gains.

  (Are there additional "hidden" variables?)

- Results suggest that diverse populations may achieve significantly different normalized learning gains (measured by "***g***") ***even with identical instruction.***

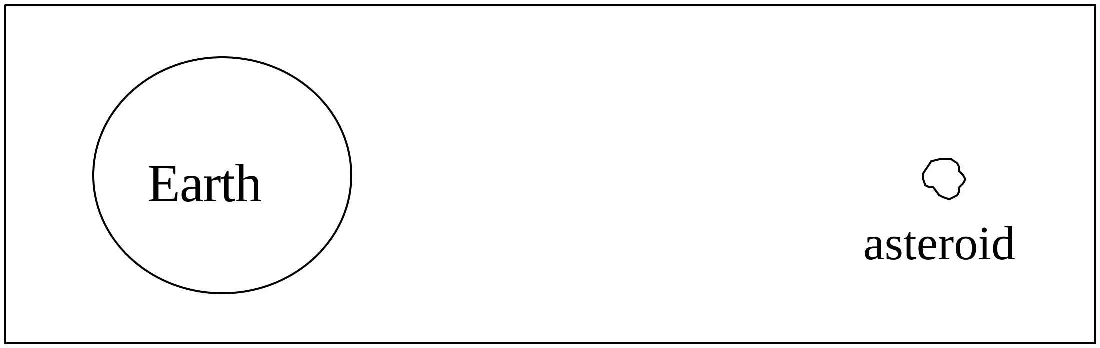
Addressing Learning Difficulties: A Model Problem

Student Concepts of Gravitation

[Jack Dostal and D.E.M.]

- 11-item multiple-choice diagnostic administered to over 500 ISU students during 1998-2000.
- 10-item free-response diagnostic administered to over 2000 ISU students during 1999-2000.
  - *Concepts investigated:* Newton's third law in context of gravity; direction and superposition of gravitational forces; inverse-square law; universality of gravitation.
- 28 interviews with students carried out
  - (40-60 minutes; recorded on videotape)
- Worksheets developed to address learning difficulties; tested in Physics 111 and 221, Fall 1999

Example: Newton's Third Law in the Context of Gravity



Is the magnitude of the force exerted **by the asteroid on the Earth** *larger than, smaller than, or the same as the magnitude of the force exerted* **by the Earth on the asteroid?** *Explain the reasoning for your choice.*

[Presented during first week of class to all students taking calculus-based introductory physics (PHYS 221-222) at ISU during Fall 1999.]

First-semester Introductory Physics *(N = 546)*: ***15% correct responses***

Second-semester Introductory Physics *(N = 414)*: ***38% correct responses***

Majority of students <u>persist</u> in claiming that Earth exerts greater force because it is larger or more massive

Another Example: Students' Beliefs About Gravitation

Imagine that an astronaut is standing on the surface of the moon holding a pen in one hand. If that astronaut lets go of the pen, what happens to the pen? Why?

This question was presented in the first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.

First-semester Introductory Physics *(N = 534)*:

32% state that it will "float" or "float away"

Second-semester Introductory Physics *(N = 408)*:

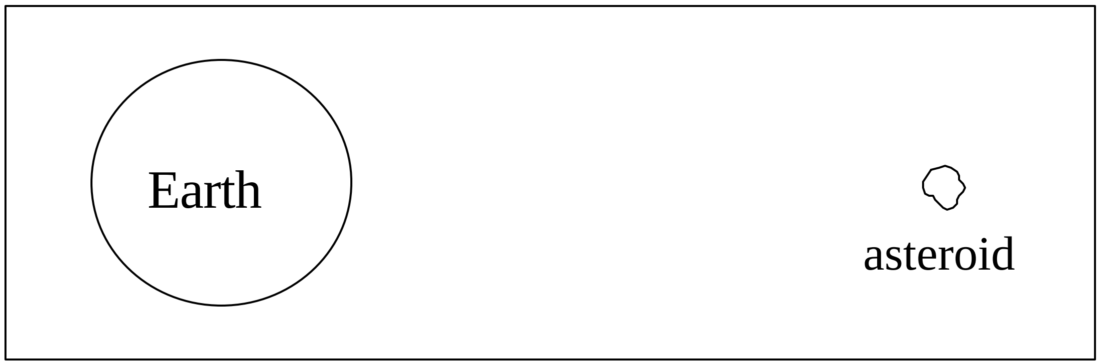
23% state that it will "float" or "float away"

Significant fraction of students persist in claiming that there is "no gravity" or "insignificant gravity" on the moon

Protocol for Testing Worksheets
(Fall 1999)

- 30% of recitation sections yielded half of one period for students to do worksheets
- Students work in small groups, instructors circulate
- Remainder of period devoted to normal activities
- No net additional instructional time on gravitation
- Conceptual questions added to final exam with instructor's approval

Pretest Question
(Newton's third law)



Is the magnitude of the force exerted **by the asteroid on the Earth** *larger than, smaller than, or the same as the magnitude of the force exerted* **by the Earth on the asteroid***?* *Explain the reasoning for your choice.*

Post-test Question (Newton's third law)

The rings of the planet Saturn are composed of millions of chunks of icy debris. Consider a chunk of ice in one of Saturn's rings. Which of the following statements is true?

- The gravitational force exerted by the chunk of ice on Saturn is **greater than** the gravitational force exerted by Saturn on the chunk of ice.
- ➡ The gravitational force exerted by the chunk of ice on Saturn is **the same magnitude as** the gravitational force exerted by Saturn on the chunk of ice.
- The gravitational force exerted by the chunk of ice on Saturn is **nonzero, and less than** the gravitational force exerted by Saturn on the chunk of ice.
- The gravitational force exerted by the chunk of ice on Saturn is zero.
- Not enough information is given to answer this question.

Results on Newton's Third Law Question

(Students who gave *incorrect* answer on pretest question)

	N	**Post-test Correct**
Non-Worksheet	*289*	58%
Worksheet	*82*	84%

(Physics 221 Fall 1999: calculus-based course, first semester)

Post-test Question
("Lead spheres")

Two lead spheres of mass *M* are separated by a distance *r*. They are isolated in space with no other masses nearby. The magnitude of the gravitational force experienced by each mass is *F*. Now one of the masses is doubled, and they are pushed farther apart to a separation of 2*r*. Then, the magnitudes of the gravitational forces experienced by the masses are:

A. equal, and are equal to *F.*

B. equal, and are larger than *F.*

➡ C. equal, and are smaller than *F.*

D. not equal, but one of them is larger than *F.*

E. not equal, but neither of them is larger than *F.*

Results on “Lead Spheres” Question
(All students)

	N	**Post-test Correct**
Non-Worksheet	*384*	45%
Worksheet	*116*	70%

(Physics 221 Fall 1999: calculus-based course, first semester)

Further Results on “Lead Spheres” Question

Including ***only*** students who answered A, B, or C (“forces are equal”)

	N	**Post-test Correct**
Non-Worksheet	*276*	63%
Worksheet	*106*	77%
		(p = 0.01)

(Physics 221 Fall 1999: calculus-based course, first semester)

The Biggest Challenge: Large Lecture Classes

- Very difficult to sustain active learning in large classroom environments
- Two-way communication between students and instructor becomes paramount obstacle
- Curriculum development must be matched to innovative instructional methods

Example:

Curriculum and Instruction in Algebra-based Physics

Active Learning in Large Classes

- **De-emphasis of lecturing**; Instead, ask students to respond to many questions.
- Use of communication systems (e.g., "Flash Cards") to obtain **instantaneous feedback** from entire class.
- Cooperative **group work** using carefully structured free-response worksheets (e.g., ***"****Workbook for Introductory Physics")*

Goal: *Transform large-class learning environment into "office" learning environment (i.e., instructor + one or two students)*

Curricular Material for Large Classes

"Workbook for Introductory Physics"

- Lecture Notes
  - Expository text (with examples) for reference
- Multiple-choice "In-Class" Questions
  - Conceptual questions for whole-class interaction
- Worksheets
  - Sequenced sets of qualitative and quantitative questions requiring written explanations

Sequence of Activities

- Very brief introductory lectures (≈10 minutes)
- Students work through sequence of multiple-choice questions, signal responses using flash cards
- Some “lecture” time used for group work on worksheets
- Recitations run as “tutorials” (University-of-Washington style); students use worksheets with instructor guidance
- Homework assigned out of Workbook

Curriculum Development on the Fast Track

- Need curricular materials for complete course $\Rightarrow$ must create, test, and revise "on the fly"
- Daily feedback through "flash-card" interaction aids assessment
- Worksheets tested, revised, and re-tested through repeated use in recitation "tutorials"
- Pre- and post-testing with standardized diagnostics helps monitor progress

Conceptual Learning Gains in Electricity and Magnetism

ISU Physics 112 compared to nationwide sample:
14 ***electricity*** *questions from the*
Conceptual Survey of Electricity and Magnetism

	N	**Pretest Score**	**Posttest Score**	**g [gain / max. possible gain]**
Algebra-based Courses	*402*	27%	43%	0.22
Calculus-based Courses	*1496*	37%	51%	0.22
ISU Physics 112, F1998, F1999, F2000	*240*	28%	78%	0.69

Conceptual Learning Gains in Electricity and Magnetism

ISU Physics 112 compared to nationwide sample:
*four **magnetism** questions from the*
Conceptual Survey of Electricity and Magnetism

	N	**Pretest Score**	**Posttest Score**	**g [gain / max. possible gain]**
Algebra-based Courses	*431*	16%	39%	0.27
Calculus-based Courses	*1420*	20%	42%	0.28
ISU Physics 112, F1999, F2000	*164*	--	61%	--

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

	N	**Mean Score**
Physics 221: F97 & F98 **Six final exam questions**	*320*	56%
Physics 112: F98 **Six final exam questions**	*76*	77%
Physics 221: F97 & F98 **Subset of three questions**	*372*	59%
Physics 112: F98, F99, F00 **Subset of three questions**	*241*	78%

Trade-Offs

- Fewer topics covered (e.g., reduced coverage of modern physics)
- Two teaching assistants needed in recitation/tutorials (may use qualified undergraduates)

Tightening the Link to Research

- Carry out detailed investigation of student learning in particular subject area
- Develop curricular material closely based on research results
- Test and revise curricular materials in both class settings and controlled environments (research interviews)

Example: Student Learning of Thermodynamics

Dynamics of Student Learning of Thermodynamics Concepts

[D.E.M. and Tom Greenbowe; Supported by ISU Miller Faculty Fellowship and NSF]

Our Goal: Investigate learning difficulties in thermodynamics in both chemistry and physics courses

- First focus on students' ***initial*** exposure to thermodynamics (i.e., in chemistry courses), then follow up with their ***next*** exposure (in physics courses).

- Investigate learning of same or similar topics in two different contexts.

Initial Hurdle: Different approaches to thermodynamics in physics and chemistry

- ***For physicists:***
  - Primary (?) unifying concept is transformation of ***internal energy U*** of a system through heat absorbed and work done;

- ***For chemists:***
  - Primary (?) unifying concept is ***enthalpy H***

    $$[H = U + PV]$$

    (ΔH = heat absorbed in ***constant-pressure*** process)

How might this affect physics instruction?

- For many physics students, initial ideas about thermodynamics are formed during ***chemistry*** courses.

- In chemistry courses, a particular state function (enthalpy) comes to be identified -- in students' minds -- with ***heat in general***, which is ***not*** a state function.

Initial Objectives:

Students' understanding of "*state functions*" and First Law of Thermodynamics

Diagnostic Strategy: Examine two ***different*** *processes leading from state "A" to state "B":*

Physics Diagnostic

- Given in second semester of calculus-based introductory course (Physics 222)
- Traditional course; thermal physics comprised 18% of course coverage.
- Diagnostic administered in last week of course:
  – Fall 1999: practice quiz during last recitation; *N = 186*
  – Fall 2000: practice quiz during final lecture; *N = 188*

Samples of Students' Answers

(All considered correct)

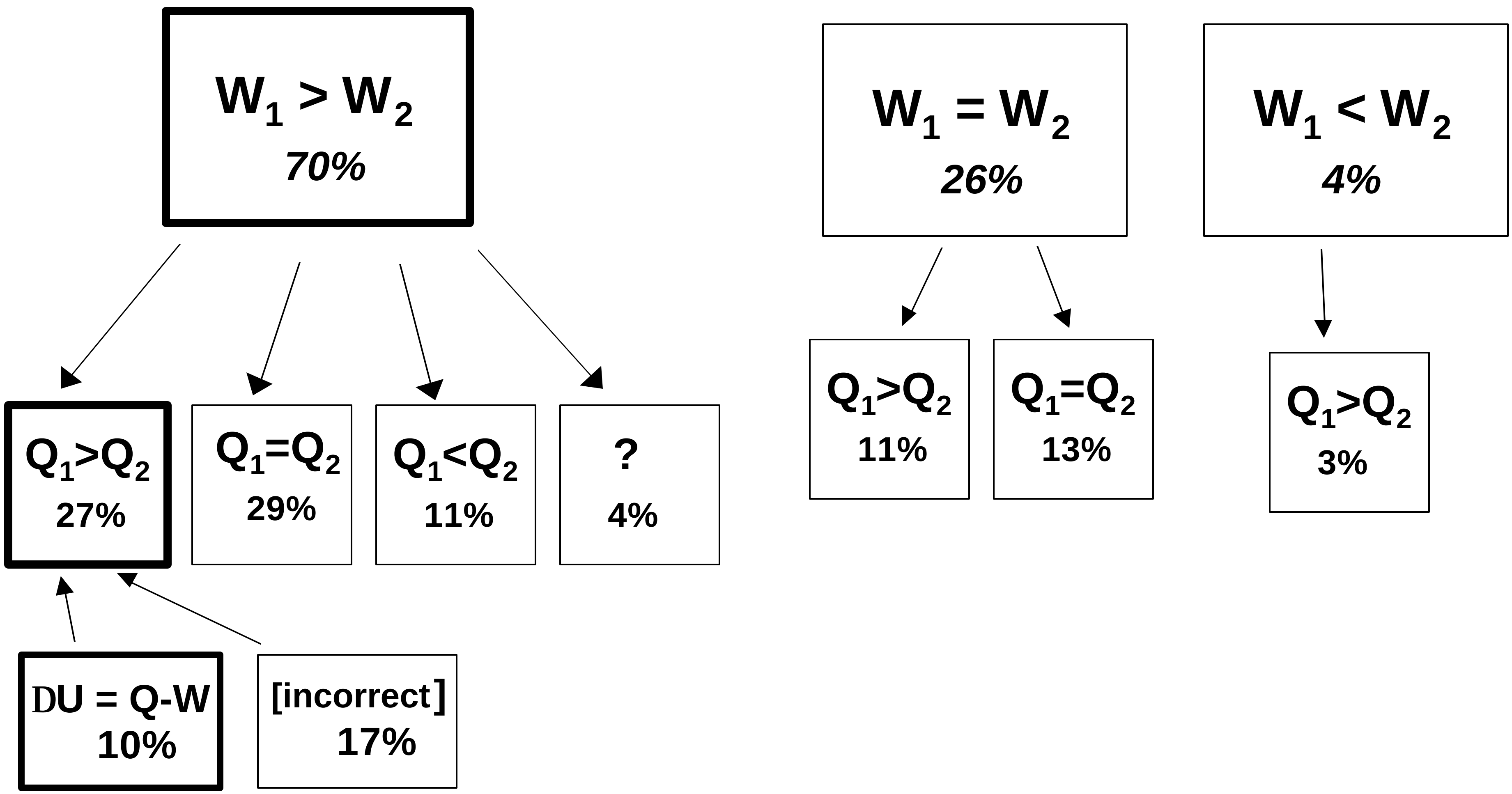
"DU = Q – W. For the same DU, the system with more work done must have more Q input so process #1 is greater."

"Q is greater for process 1 since Q = U + W and W is greater for process 1."

"Q is greater for process one because it does more work, the energy to do this work comes from the Q_{in}*."*

Results, Fall 2000

[N = 188]



Students' Reasoning on Work Question

[Fall 2000: N = 188]

- Correct or partially correct 56%
- Incorrect or missing explanation 14%
- Work is independent of path 26%
  (majority explicitly assert path independence)
- Other responses 4%

Of the students who correctly answer that $W_1 > W_2$:

[Fall 2000: 70% of total student sample]

- 38% correctly state that $Q_1 > Q_2$
- 41% state that $Q_1 = Q_2$
- 16% state that $Q_1 < Q_2$

Of the students who assert that $W_1 = W_2$:

[Fall 2000: 26% of total student sample]

- 43% correctly state that $Q_1 > Q_2$
- 51% state that $Q_1 = Q_2$
- 4% state that $Q_1 < Q_2$

Relation Between Answers on Work and Heat Questions

- Probability of answering $Q_1 > Q_2$ is almost independent of answer to Work question.

  [However, correct explanations are only given by those who answer Work question correctly.]

- Probability of claiming $Q_1 = Q_2$ is ***slightly*** greater for those who answer $W_1 = W_2$.

- Probability of justifying $Q_1 = Q_2$ by asserting that "*Q is path-independent*" is ***higher*** for those who answer Work question correctly.

  ➔ Correct on Work question and state $Q_1 = Q_2$: 61% claim "Q is path-independent"

  ➔ Incorrect on Work question and state $Q_1 = Q_2$: 37% claim "Q is path-independent"

Students' Reasoning on Heat Question

[Fall 2000: N = 188]

- Correct or partially correct 15%
- Q is independent of path 23%
- Q is higher because pressure is higher . . . 7%
- Other explanations 18%

  $Q_1 > Q_2$: 8%
  $Q_1 = Q_2$: 5%
  $Q_1 < Q_2$: 5%

- No response/no explanation 36%

Note: Only students who answered Work question correctly gave correct explanation for $Q_1 > Q_2$

Conclusions from Physics Diagnostic

- ≈ 25% believe that Work is independent of process.
- Of those who realize that Work is process-dependent, 30-40% appear to believe that Heat is ***independent*** of process.
- ≈ 25% of all students ***explicitly*** state belief that Heat is independent of process.
- There is only a partial overlap between those who believe that Q is process-independent, and those who believe that W is process-independent.
- ≈ 15% of these students appear to have adequate understanding of First Law of Thermodynamics.

Conjectures from Physics Diagnostic

- Belief that Heat is process-independent may not be strongly affected by realization that Work is ***not*** process-independent.

- Understanding the process-dependence of Work ***may*** strengthen belief that Heat is independent of process.

Results from Chemistry Diagnostic

[*Given in general chemistry course for science majors, Fall 2000, N =532]*

- 11% of students were able to use First Law of Thermodynamics to correctly compare Work done in different processes.

Preliminary Finding on Thermodynamics

Fewer than one in six students in both chemistry and physics introductory courses demonstrated clear understanding of First Law of Thermodynamics.

Second-law Concepts: Chemistry students

- Course covered standard topics in chemical thermodynamics:
  - Entropy and disorder
  - Second Law of Thermodynamics: $\Delta S_{universe}$ [= $\Delta S_{system} + \Delta S_{surroundings}$] ≥ 0
  - Gibbs free energy: $G = H - TS$
  - Spontaneous processes: $\Delta G_{T,P} < 0$
  - Standard free-energy changes

- Written diagnostic administered to 47 students (11% of class) last day of class.

- In-depth interviews with ten student volunteers

Student Interviews

- Ten student volunteers were interviewed within three days of taking their final exam.
- The average course grade of the ten students was above the class-average grade.
- Each interview centered on students “talking through” a six-part problem sheet.
- Responses of the ten students were generally quite consistent with each other.

Students' Guiding Conceptions (what they "know")

- *DH* is equal to the heat absorbed by the system.
- "Entropy" is synonymous with "disorder"
- Spontaneous processes are characterized by increasing entropy
- *DG = DH - TDS*
- *DG* must be ***negative*** for a spontaneous process.

Difficulties Interpreting Meaning of "ΔG"

- Students seem unaware or unclear about the definition of DG (i.e., $DG = G_{final} - G_{initial}$)

- Students often do ***<u>not</u>*** interpret "ΔG < 0" as meaning *"G is **decreasing**"*

- The expression "ΔG" is frequently confused with "G"
  - *"DG < 0" is interpreted as "G is negative," therefore, conclusion is that **"G must be <u>negative</u> for a spontaneous process"***

Student Conception: If the process is spontaneous, *G* must be ***negative.***

Student #4: Say that the Gibbs free energy for the system before this process happened . . . was a negative number . . . [then] it can still increase and be spontaneous because it's still going to be a negative number as long as it's increasing until it gets to zero.

Meaning of “*DG*”

Q: *Tell me what you remember about ΔG.*

Student #7*:* I remember calculating it, and then if it was negative then it was spontaneous, if it was positive, being non-spontaneous.

Q: *What does that tell you about G itself. Suppose ΔG is negative, what would be happening to G itself?*

Student #7: I don’t know because I don’t remember the relationship.

Students' confusion: apparently conflicting criteria for spontaneity

- $DG_{T,P} < 0$ criterion, and equation $DG = DH - TDS$, refer only to properties of the ***system****;*
- $DS_{universe} > 0$ refers to properties ***outside*** the system;

® *Consequently, students are continually confused as to what is the "system" and what is the "universe," and* ***which one*** *determines the criteria for spontaneity.*

Lack of awareness of constraints and conditions

- There is little recognition that ΔH equals *heat absorbed* ***only*** for constant-pressure processes

- There appears to be no awareness that the requirement that $\Delta G < 0$ for a spontaneous process only holds for ***constant-pressure, constant-temperature*** processes.

Overall Conceptual Gaps

- There is uncertainty as to whether a spontaneous process requires entropy of the ***system*** or entropy of the ***universe*** to increase.

- There is no recognition of the fact that change in *G* of the ***system*** is directly related to change in *S* of the ***universe*** (*universe* = *system* + *surroundings*)

- There is uncertainty as to whether $\Delta G < 0$ implies that entropy of the ***system*** or entropy of the ***universe*** will increase.

Preliminary Findings of Thermodynamics Research

- In our samples, the ***majority*** of students held incorrect or confused conceptions regarding ***fundamental*** thermodynamic principles following their introductory courses in physics and chemistry.

- The tenacity and prevalence of these conceptual difficulties suggest that instruction must focus sharply upon them to bring about significant improvements in learning.

Summary

- There is strong evidence that instruction based on research in physics education can lead to improved student learning.

- Research-based development of curricular materials and instructional methods holds great promise for continued improvements in instructional effectiveness.