Reforms and measurements in introductory physics

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Outline

1. Intro Physics at GT
2. Reform Implementation
3. Assessment Efforts
4. Think Aloud Protocols
5. Computational Homework Problems
6. Future Measurements
7. Closing Remarks
Introductory Physics @ Georgia Tech

Two Semester Sequence

- Semester 1 – Mechanics
- Semester 2 – Electromagnetism

Boundary Conditions for Intro Physics

- ~ 1600 students per semester
- 83% engineering, 17% science majors
- 3 hours of Lecture (150-250 students)
- 3 hour Lab/Recitation (25-40 students)
Intro Physics at GT

Shortcomings of Traditional Curriculum (TRAD)

Content unchanged for decades
- 19th century (or earlier) concepts
- Focus on analytic solutions of special cases

Difficulties at Tech
- GPA lower than other intro courses
- High D/F/W rate (as high as 25%)
- Unpopular with students
- External review criticized structure, outcomes
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Modern content
- Fundamental principles
- Atoms and structure of matter
- Relativity and quantum physics
- Macro/micro connections

Modern tools/techniques
- Computer modeling
Infrastructure Preparation

- Local expert: Hire post-doc (1/06-9/08)
- Train teaching assistants (Spring 06, on-going)
- Laboratory equipment purchase/construction (Spring 06, Fall 07, Spring 10)

Faculty Preparation: Apprenticeship Model

- Junior faculty
  - Pair with experienced instructor
  - Provide logistical support
- Senior faculty
  - Same plus financial incentive
### Gradual Implementation

#### Student Enrollment and Faculty Adoption

<table>
<thead>
<tr>
<th>Semester</th>
<th>M&amp;I Semester 1</th>
<th>M&amp;I Semester 2</th>
<th>Faculty w/M&amp;I experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 06</td>
<td>40 students</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>Fall 06</td>
<td>120 students</td>
<td>45 students</td>
<td>1</td>
</tr>
<tr>
<td>Spring 07</td>
<td>200 students</td>
<td>150 students</td>
<td>2</td>
</tr>
<tr>
<td>Summer 07</td>
<td>None</td>
<td>150 students</td>
<td>3</td>
</tr>
<tr>
<td>Fall 07</td>
<td>150 students</td>
<td>300 students</td>
<td>4</td>
</tr>
<tr>
<td>Spring 08</td>
<td>300 students</td>
<td>300 students</td>
<td>4</td>
</tr>
<tr>
<td>Summer 08</td>
<td>150 students</td>
<td>150 students</td>
<td>4</td>
</tr>
<tr>
<td>Fall 08</td>
<td>300 students</td>
<td>450 students</td>
<td>6</td>
</tr>
<tr>
<td>Spring 08</td>
<td>500 students</td>
<td>300 students</td>
<td>6</td>
</tr>
<tr>
<td>Summer 09</td>
<td>250 students</td>
<td>None</td>
<td>6</td>
</tr>
<tr>
<td>Fall 09</td>
<td>400 students</td>
<td>550 students</td>
<td>7</td>
</tr>
</tbody>
</table>
Is reform doing any good?

Compare student performance
- Traditional (control) vs M&I (reform)

In class measurements
- Concept inventories
- Common final exam problems
- Performance in follow-on courses

Out of class measurements
- Think aloud protocol studies
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Concept Inventory – Semester 2 (E&M)

Brief E&M Assessment (BEMA)

- 31 item multiple choice test covers all E&M
- Qualitative and short quantitative questions
- Items common to M&I and TRAD course
- Administer “pre-test” at beginning of course, “post-test” at end, measure gains

Topics

- Electrostatics (ES)
- DC Circuits (DC)
- Magnetostatics (MS)
- Faraday’s Law and Induction (FL)
Performance at 4 Institutions


M&I outperforms TRAD at all Institutions on the BEMA (E&M)

Computing $G$ and $g$

- Raw Gain, $G = \text{Post}\% - \text{Pre}\%$
- Normalized Gain, $g = G / (100\% - \text{Pre}\%)$
Pre-tests at GT and Purdue

Incoming BEMA scores similar

- Distributions similar (Wilcoxon test, $p \sim 0.30$)

Essential demographics similar

- Grade in Physics I, Calculus
- GPAs, SAT scores
Post-test at all Institutions

Outgoing BEMA scores favor M&I

- Higher means (Wilcoxon test, $p << 0.001$)
Focus on Large N – Georgia Tech

Pre and Post-test scores

Pre-test
\[ \bar{X}_{MI} = 25.9\%, \quad \bar{X}_{TRAD} = 24.8\% \]
\[ N_{MI} = 321, \quad N_{TRAD} = 1319 \]

Post-test
\[ \bar{X}_{MI} = 58.2\%, \quad \bar{X}_{TRAD} = 46.1\% \]
\[ N_{MI} = 612, \quad N_{TRAD} = 1246 \]

- Jagged distributions – Discrete scores
Large variation for TRAD (pedagogy, instructor)

\[ \bar{X}_{MI} = 58.2\% \quad \bar{X}_{TRAD} = 46.1\% \]

- No “instructor effect” for M&I (Kruskal-Wallis test)
- Significant “instructor effect” for TRAD (Kruskal-Wallis test)
Consider TRAD Instructors using Active Engagement

- Sections T3, T4, T8, T9, T10, T11

Instructors that use “clickers”

- TRAD instructors using “clickers”, $\bar{X}_{\text{TRAD}} = 51.3\%$
- Lower than M&I instructors, $\bar{X}_{\text{MI}} = 58.2\%$ (Wilcoxon test)
Performing an Item Analysis

Compare Performance per Question

- Performance is gauged by raw gain
  \[ G = \text{Post\%} - \text{Pre\%} \]
- Questions can be grouped by topic

Computing Fractional Differences

- Overall difference, \( \Delta G = G_{\text{MI}} - G_{\text{TR}} \)
- Item difference, \( \Delta G_i = G_{i,\text{MI}} - G_{i,\text{TR}} \)
- Fractional difference, \( \Delta G_i / \Delta G \)
Difference in Performance per Question

Fractional Difference identifies Strong Contributions to Performance

- Electrostatics (ES) 27.8%
- Magnetostatics (MS) 54.9%
- DC Circuits (DC) 11.8%
- Faraday’s Law (FL) 6.2%
Concept Inventory – Semester 1 (Mechanics)

Force Concept Inventory (FCI)

- 30 item multiple choice test covering force and motion
- Qualitative questions, emphasizes constant force motion
- Designed in context of a TRAD curriculum
- Administer “pre-test” at beginning of course, “post-test” at end, measure gains

Topics

- Kinematics
- Newton’s Laws (1st Law, 2nd Law, & 3rd Law)
- Force Identification
Assessment Efforts

Performance at Georgia Tech


TRAD outperforms M&I on the FCI: $\bar{x}_{TRAD} = 71.3\%$, $\bar{x}_{MI} = 59.3\%$

![Graph showing comparison between TRAD and M&I](image)

Other measures not statistically different

- GPAs, SATs, Incoming FCI, etc.
- Pedagogy (interactivity, presentation, etc.) very similar
Distributions of FCI scores

Pre and Post-test scores

- Data has been binned to reduce jagged appearance
Fractional Difference illustrates where M&I under-performs

- Experts’ *a priori* categorization
- Fraction a question contributes to overall difference (TRAD-M&I)
Underlying patterns to responses

Principal Component Analysis
- Mathematically sound
- Do clusters mean anything?

Factor Analysis
- Orthogonal vs. Non-orthogonal rotations?
- Controversy (Heller, 1995 & Hestenes 1995)
- “Best” method for binary measures?

Cluster Analysis
- Mathematically sound
- Distance measures clearly defined
- Consistent results with different measures
Cluster Analysis

Finding Patterns in Data

- Hierarchical Cluster Analysis

![Diagram showing 4 "Natural" Clusters, Individual Clusters, Pairs of Clusters, and Final Cluster.](image-url)
Cluster Analysis of the FCI

Binary Data Metric

- Hamming Distance
  \[ D_h = \frac{C_{tf} + C_{tf}}{N} \]
- ex. \([1001]\) and \([1010]\), \(D_h = 2\)

Linkage Criteria

- Mean linkage clustering
  \[ \bar{d} = \frac{1}{|A||B|} \sum_{a \in A} \sum_{b \in B} D_h(a, b) \]
Cluster Analysis of M&I data

Agglomerative categorization of problems (M&I)

- Students’ pattern of performance defines clusters
- Cluster [(5, 18), 11, (13, 30)] similar to a priori grouping
Cluster Analysis of TRAD data

Agglomerative categorization of problems (TRAD)

- Clusters are similar to M&I clusters
- Cluster [(11, 13), 18] similar to \textit{a priori} grouping
Pattern of Responses

\([ (5, 18), 11, (13, 30) ] \) Response Cluster (M&I)

- Jaccard Distance
  \[ D_j = \frac{C_{tf} + C_{tf}}{C_{tf} + C_{tf} + C_{tt}} \]
- Responses equally weighted (no \( C_{ff} \))
- Include fraction of students

- 2 dominant responses
  - Correct (green) and “Force in direction of motion” (red)
### Similar (Dismal) Performance

- Percentage of “Mostly Correct” Responses

<table>
<thead>
<tr>
<th>Question</th>
<th>TRAD.</th>
<th>M&amp;I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mech. 1</td>
<td>13%</td>
<td>26%</td>
</tr>
<tr>
<td>Mech. 2</td>
<td>29%</td>
<td>24%</td>
</tr>
<tr>
<td>Mech. 3</td>
<td>7%</td>
<td>8%</td>
</tr>
<tr>
<td>Mech. 4</td>
<td>21%</td>
<td>17%</td>
</tr>
<tr>
<td>Mech. 5</td>
<td>59%</td>
<td>49%</td>
</tr>
<tr>
<td>E&amp;M 1</td>
<td>10%</td>
<td>17%</td>
</tr>
<tr>
<td>E&amp;M 2</td>
<td>22%</td>
<td>39%</td>
</tr>
<tr>
<td>E&amp;M 3</td>
<td>20%</td>
<td>29%</td>
</tr>
</tbody>
</table>
Average GPA in Advanced Courses

Similar Performance

- **COE 2001 (Engineering Statics)** (Requires Mechanics Prerequisite)
  - TRAD: 2.79 (± 0.05) (N = 1695)
  - M&I: 2.81 (± 0.11) (N = 359)

- **ECE 3025 (Electromagnetics)** (Requires E&M Prerequisite)
  - TRAD: 2.93 (± 0.15) (N = 144)
  - M&I: 2.95 (± 0.28) (N = 24)

No significant difference

- Wilcoxon test, COE 2001 (p ~ 0.30)
- Wilcoxon test, ECE 3025 (p ~ 0.40)
Lessons Learned

More and Better Measurements are Needed

- Measurements are difficult
- Beware of over-reliance on particular measurements

Another E&M Concept Inventory: CSEM

CSEM scores (Fall 2009)

<table>
<thead>
<tr>
<th></th>
<th>PRE</th>
<th>POST</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRAD</td>
<td>N=428</td>
<td>N=282</td>
</tr>
<tr>
<td>M&amp;I</td>
<td>N=524</td>
<td>N=517</td>
</tr>
</tbody>
</table>

Average CSEM Score (%)

Error bounds (± 2 σ) are 95% Confidence Intervals

BEMA overlap (7 questions)

<table>
<thead>
<tr>
<th></th>
<th>CSEM</th>
<th>BEMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRAD</td>
<td>N=517</td>
<td>N=282</td>
</tr>
<tr>
<td>M&amp;I</td>
<td>N=612</td>
<td>N=1246</td>
</tr>
</tbody>
</table>

Average Score (%)
Assessment Efforts

Concept Inventories

Aren’t BEMA & CSEM Equivalent?

- Yes, (for same (Traditional) curriculum)

What about the FCI?

- Couched in TRAD language & examples
- M&I performance unaffected by prompting
  Caballero, unpublished (2008)
- FMCE? Similar differences in performance

Inventories equivalent for different curricula?

- More (and different) measurements needed
- Need variety
What are we doing now?

**Characterizing the observed FCI differences**
- Homework categorization, continuing cluster analysis

**Exploring students’ mechanics knowledge**
- FCI & Core Mechanics Think Aloud studies

**Developing computational knowledge**
- Computer modeling homework
- Evaluation of modeling skills

**Diversifying assessment**
- Qualitative - MIT Survey of Mechanics
- Attitudinal - CLASS, GT-designed “Attitudes about Modeling”
Think Aloud Study

Semester 1 Concept Inventory

- Audio and video record subjects solving subset of 10 FCI questions
- Subset had high contributions to the difference in scores
An Example from the Think Aloud Study

FCI Question #1

Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:
(A) about half as long for the heavier ball as for the lighter one.
(B) about half as long for the lighter ball as for the heavier one.
(C) about the same for both balls.
(D) considerably less for the heavier ball, but not necessarily half as long.
(E) considerably less for the lighter ball, but not necessarily half as long.

- Correct Response (C) - 90% TRAD, 57% M&I
- Major distractors (A & D) - 10% TRAD, 36% M&I

<table>
<thead>
<tr>
<th>Solution</th>
<th>TRAD (%)</th>
<th>M&amp;I (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determined acceleration was constant</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>“mass doesn’t matter”</td>
<td>60*</td>
<td>21</td>
</tr>
<tr>
<td>use of kinematics equations</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>recall from previous exercise</td>
<td>20</td>
<td>0</td>
</tr>
</tbody>
</table>

*Half of these students also used kinematic equations
Suggestive Results from Transcript Analysis

Lessons from FCI transcripts

- M&I students fail to employ $\Delta \vec{p} = \vec{F}_{\text{net}} \Delta t$ (NO mention of momentum at all)
- M&I students confuse components of $\vec{F}_{\text{net}}$ and agent forces
- Many students revert to naive/incorrect notions
- Some recall (often, incorrect/incomplete) memory of HS physics
- Students select correct responses without a deep understanding

Core Mechanics problems

- Developed and implemented new problems (non-constant forces)
- Think aloud work on-going (transcription almost complete)
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### Computational Homework Problems

**The Matter and Interactions Mechanics Course**

M&I differs from a “typical” physics course

- Emphasizes a principles based approach
  - $\Delta \vec{p} = \vec{F} \Delta t$
  - $\Delta E = W + Q$
  - $\Delta \vec{L} = \vec{\tau} \Delta t$

- Introduces the ball and spring model of matter
  - Young’s modulus, Speed of sound
  - Statistical Mechanics, Temperature

- Uses modern tools (computer simulation)
  - Iterative view of motion (Non-constant forces)
  - Computer modeling laboratories
Why Computer Modeling Homework?

Why Computer Modeling?

- Third pillar of science and engineering
  - Theory, Experiment, Computation
- Explore “intractable” systems
  - Effects of air resistance
  - 3D spring with viscous drag
- Simulate “impossible” experiments
  - Elliptical orbit
  - 3 body problem
- Visualize the problem
  - Observing the motion, physical vectors
  - Plotting of energy-time series
Why Computer Modeling Homework?

On Homework Assignments?

- Large service course
  - Online homework system; no hand graded homework
  - Randomization does not deter “short-cuts” (MIT - Palazzo, et.al.)
  - Closed form solutions (Google, Yahoo! Answers, Wolfram|Alpha, etc.)
- Some never write programs
  - Programming “person” in lab group
  - Internal cost-benefit calculation
- Not a novelty
  - Another tool for solving problems
  - Visualization might help intuition
Method of Implementation

Based on Computer Modeling Labs

- Numerical integration and differentiation
- Must be solved numerically

Implementation facilitated by WebAssign

- Generate and store $\sim$ 400–800 realizations
- Randomize realization per student
- Receive 2 realizations
  - test case: solutions given
  - graded case: no solutions

- Numeric Questions
- Visualization Questions
A Typical Week

Lab Program

- Position data file $\rightarrow \vec{F}_{net}$
- Integrate, determine $\vec{r}_f$, $\vec{v}_f$
- Visualize $\vec{p}$, $\Delta \vec{p}$, and $\vec{F}_{net}$

Homework Assignment

- Reproduce work done in lab (new data file)
- Compute and visualize $\vec{F}_{net,\parallel}$ and $\vec{F}_{net,\perp}$
- Visualize $\vec{p}_f$, $\Delta \vec{p}$, $\vec{F}_{net}$
- Graded for correctness, not completion

Weather Balloon Trajectory
blue arrow represents $\vec{F}_{net}$
So...how did it go?

**Instructor Perspective**

- Relatively straight-forward implementation
- Minor hiccups caught early on:
  - Installation issues
  - Test cases
- Confirmed suspicions; Some students never write programs

**Student Perspective**

- Questions not treated as “special”
  - Questions tacked on to lab assignment
  - Questions appear on homework assignment each Monday
  - Similar weight as a single homework question
- Anecdotal evidence that students start homework earlier
So...how did they do?

Scores similar to average homework question

Homework Avg. (n=238): 84.60 %  Comp. Questions (n=10): 85.86 %
Computer modeling in a controlled environment

4th Hour Exam Extra Credit

- 15 minute (password-protected) extra credit problem
  - integrate a central force
  - randomized conditions, force law, syntax
  - compute $\vec{r}_f$ and $\vec{v}_f$

Challenges

- Logistical problems
  - tabbing issue, feedback
  - time constraint
- Physics/modeling problems
  - error in sign of force, overflow error
  - adding vectors & scalars, etc.
- Instructors struggled with implementation
Computer modeling in a controlled environment

Proctored Lab Assignment

- Logistical changes
- Feedback from test case
- Lowered time constraint (25 min)
- No TA help ("Read carefully...")

- Mean: 62.42 ± 0.32 %
- N = 469
- Most common “physics” mistake: sign error
- Other syntax errors: vector + scalar, etc.
- Analysis continues...
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Another Concept Inventory?

- Problems are more complex
- Cover most of mechanics
- Process and reasoning driven

- Validation and reliability testing (Summer 2010)
Attitudinal Surveys

Colorado Learning Attitudes about Science Survey
- No attitudinal data from GT
- Curricular differences?

GT designed Attitudes/Impressions of Computer Modeling
- Similar design to CLASS
- Validating survey (i.e., colleague & student review)
- Curricular differences?
- Correlation of beliefs with student performance
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Collaborators and Friends

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- Lin Ding (OSU Physics) – BEMA

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  - Discussions, FCI/BEMA/Exams
Closing Remarks

Future Work (Fall 2010 and beyond)

- Computer modeling skill development and measurement
- Attitudinal inventory development, measurements, & comparisons
- Full description (disclosure) of concept inventory measurements
- Comprehensive measurement of conceptual understanding using think aloud protocols
- Novel problem study based on Kohlmyer’s work
- Intervention (Precision Teaching) and measurement

More info?

- GT PER Group - www.physics.gatech.edu/gtper
- Contact me - caballero@gatech.edu