# Can technology really improve teaching introductory physics?

Joel A. Shapiro
shapiro@physics.rutgers.edu

Rutgers University

March 27, 2008 at the University of Florida

# Structure of this Talk

# Large Intro Courses

Basic problem: getting students to *engage* with fundamental physics principles and analyze physical situations.

- Here is where we brilliantly present these ideas.
- But the students aren't thinking about what I am saying!

# Large Intro Courses

Basic problem: getting students to *engage* with fundamental physics principles and analyze physical situations.

- Here is where we brilliantly present these ideas.
- But the students aren't thinking about what I am saying!

- And their attention is wandering.
- And they don't even come any more!

# Getting them active

How to get students actively intellectually involved in thinking about the fundamental ideas?
The answer is well known:

# Getting them active

How to get students actively intellectually involved in thinking about the fundamental ideas?
The answer is well known:

Expert human tutoring has been shown to raise performance by two standard deviations,
*i. e.* 16th percentile $\longrightarrow$ 84th percentile,
low C $\longrightarrow$ B+.

No other added teaching component comes close.

# The textbook

The fundamental concepts are also presented in the textbook.

But fundamental ideas aren't easily absorbed. How do texts address this? Chapter 8 of Sears and Zemansky (now Young and Freedman)

| | First Edition | 12th Edition |
|---|---|---|
| Title | Impulse and Momentum | Momentum, Impulse and Collisions |
| Size of page | $6'' \times 8\frac{1}{2}''$ (51 in$^2$) | $8\frac{3}{4}'' \times 10\frac{3}{4}''$ (94 in$^2$) |
| Number of pages | 11 (561 in$^2$) | 27 (2538 in$^2$) |
| Ratio $\frac{\text{examples}}{\text{exposition}}$ | 0.45 | 0.96 |
| End of Chapter | 19 problems | 26 discussion Q's<br>112 exercises<br>4 challenge P's |

# Textbook changes (cont.)

I haven't quantified the

- "Learning Goals"
- "test your understandings"
- "problem-solving strategies"
- "Activ Physics" links,
- pictures of football players and other "relevant" irrelevancies

which, of course, occur only in the 12th edition.

Does any of this work? I doubt it!

# Homework and Exams

Here is where a student must actively use the physics understanding, right?

- we give too many plug-and-chug (single formula problems)
- too many "just like the example" problems
- why?
  - students give up or get stuck on challenging problems, need to be graded on partial solutions.
  - too much grading for instructors
- So we settle for ungraded homework and multiple choice exams.

# How can technology help?

There have been some important technological breakthroughs:

# How can technology help?

There have been some important technological breakthroughs:

- stick and sand (Archimedes, 287-212 BC)
- Gutenburg (1455)

- blackboards (not Blackboard) (1801)

# Technology that can be used today

- Presentation: Web, PowerPoint, computer demos, ...
- Simulations.
- Computer interface in labs, demos

I am not going to talk about the above — I just don't know very much about them.
Uses I will talk about

- Clickers
- Course Management Systems
- Exams
- Homework Systems
- Tutorial Systems

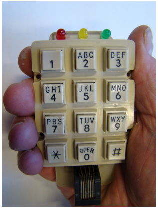
# Clickers can help!

Now we talk about clickers!
Uses:

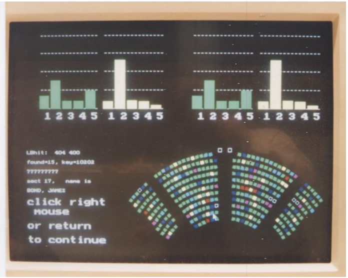
- promote active participation
- promote interaction
- give reading quiz at beginning of lecture
- real quizzes (dubious, I think)
- tells teacher if he needs to discuss something further.
- Improve attendance. Students will come to get even one point out of 1000.

# Some Clicker Systems

- Littauer: Built a five-button system at Cornell 1972 from discarded HEX equipment. Pushing a button discharged a capacitor to the appropriate charge counter!
- SRS: A system I built at Rutgers



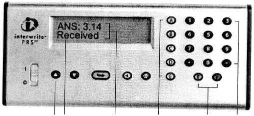

My keypad (normally in arm-rest)

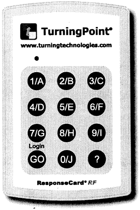



Computer screen after double session

Don't hire string theorists to build your electronics.

# Commercial Clickers

| PRS from GTCO CalComp | |
|---|---|
| IR | RF with screen |
|  |  |

| iclicker | e-Instruction CPS | Turning Point Response Card |
|---|---|---|
|  |  |  |

| Meridia | h-itt IR and RF | TI-84+ Calculator |
|---|---|---|

# Clicker issues

- hardwired, IR or RF?
  - Hardwired not available commercially, takes lots of work. But provides seat info.
  - IR came first, but student clicks can interfere, doesn't work reliably enough for grading in a large class.
  - RF seems completely reliable
- feedback: none, few LEDs, or screen?
  - Students don't trust their answer has been received without feedback. Some systems show student ID on projector, but that doesn't work well in a large class
  - Even one LED is enough to show response received. But this requires transmitter to receive info.
  - A multicharacter screen is enough for sophisticated interaction, but I don't know anyone who makes use of this.

# Course Management Systems

- Facilitates web posting (for novices)
- provides restrictive access
- provides discussion boards, chat rooms
- provides a gradebook
  - for your records
  - with student access to his/her own grades
  - Some systems:
    - BlackBoard
    - WebCT
    - Sakai
    - Moodle
    - Lon-Capa
- provides some homework grading/quiz facilities

# Exams

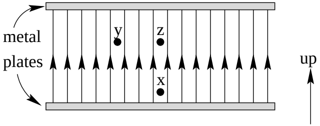
Most of us give computer-graded exams. In our department, we have a homemade system (grtex) which

- facilitates making up exams, with scrambling of answers and/or questions
- in LaTeX!
- I have been collecting such questions for years
- We have the ability to give numerical answer questions!

# A LaTeX question

1. The figure shows the electric field lines due to two charged parallel metal plates. We conclude that:

   a. the upper plate is positive and the lower plate is negative.
   b. a positive charge at X would experience the same force if it were placed at Y.

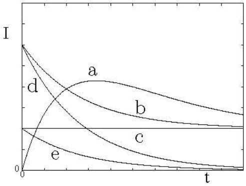



   c. a positive charge at X experiences a greater force than if it were placed at Z.
   d. a positive charge at X experiences less force than if it were placed at Z.
   e. a negative charge at X could have its weight balanced by the electrical force.

This question shows how flexibly figures can be included. Even when answers are permutted, the wrapping around the figure will work okay.

# Answers on the Figures

23. You also might want to have the figure on the right of the question, with the answers (a)—(e) appearing on the figure, as with mvaquest. This question is of that type. Note that the placement adjusted for one type is unlikely to work for the other. Note also that this format requires a width as well as the file name for the figure. This question ended with `\lmvaquest{2in}{mvapix.eps}`

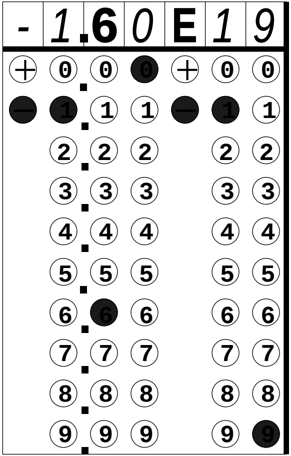



Here the five choices are shown on the figure, and are permuted in different exam versions.

# Numerical Answer Exam Questions

You can get special answer forms made. Ours has room for 15 numerical answer questions and 30 multiple choice. Here is one numerical answer and how it is entered.

What is the charge of an electron?



# Are Computer-Graded Exams Good?

Computer-graded exams are

- much less painful to grade!
- objective and consistent grading
- Questions must be more carefully written, clear and unambiguous, with well thought-out distractors
- Can they test deep understanding as well as open-ended written exams?
  Some studies show that they can grade as accurately as written exams.
- But possibly they fail to encourage deep-thinking studying. I don't really know.

# Homework Systems

Without computers, most homework in large intro courses goes ungraded. Not good for feedback or for motivation. So computer systems came into existence.

Non-science courses use MC or precisely specified short answers. Not good enough for us. Physicists have demanded randomization of problem parameters, algebraic expression answers. Systems which do that:

- Homework Service (Univ. of Texas at Austin)
- CyberProf (Univ. of Illinois Urbana-Champaign)
- WebAssign (evolved from North Carolina)
- Mastering Physics (evolved from MIT)
- Capa (Michigan State U)
- WebWork (mostly for math)

# Commercial vs. Open-source

- Commercial advantages/disadvantages
  - Excellent technical support
  - Publishers support extensively with their problems
  - Cost: Uncontrolled! Webassign cost $8.50/stud-sem in fall 2002, $32.00/stud-sem now, for Wiley problems, unless purchased with new textbook.
- Open-Source
  - less well supported with publisher's problems
  - need to run your own server
  - less polished CMS and ease of use
  - minimal tech support

Both systems allow teachers to write their own questions. At Rutgers, some of the younger faculty have taken up writing their own questions in WebAssign.

# Why what we have is not enough

Current homework and exam systems ask the students to present a single well-defined answer, quantitative or a symbolic expression, rather than present a full "show-your-work" solution.

My students get 95% on the WebAssign homework but 60% when asked simpler questions on the exam.

Old fashioned human grading of homework and exams could tutor on the ideas as well as the answer. But it is very expensive in terms of instructor's time. So we employ it less fully than would be ideal.

# What I would like

A computer-based "intelligent tutoring system" (ITS)

- present a complex problem to student
- understand student input including drawings, sets of equations, numerical quantities (with units).
- give feedback on
  - correctness of entries
  - explanation of what is wrong with entries
  - hints for making further progress
  - possibly summary of solution
- (Dream?:) Natural language dialog with students.

# Is this possible?

We won't get there by adding hints for each problem (as done in the tutorial problems in Mastering Physics)

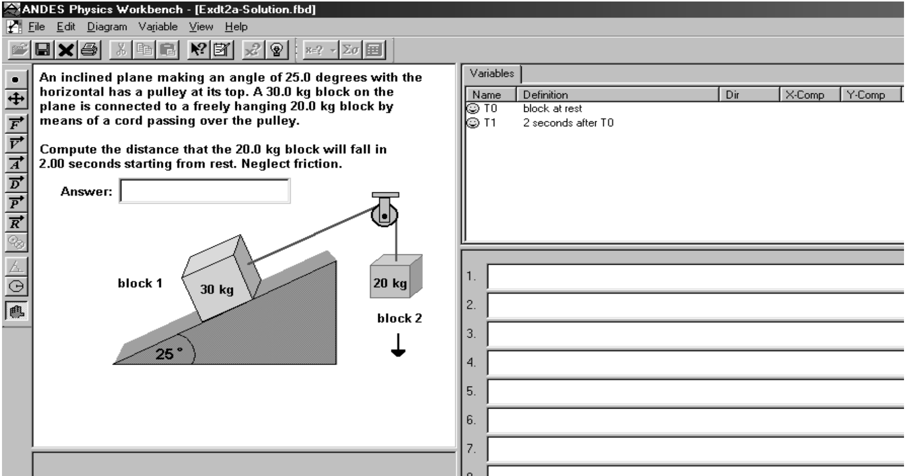
Sporadic efforts have been made: Plato, Andes

Such a system for high school algebra is rather successful, commercialized and used in many high-schools (from Carnegie-Learning)

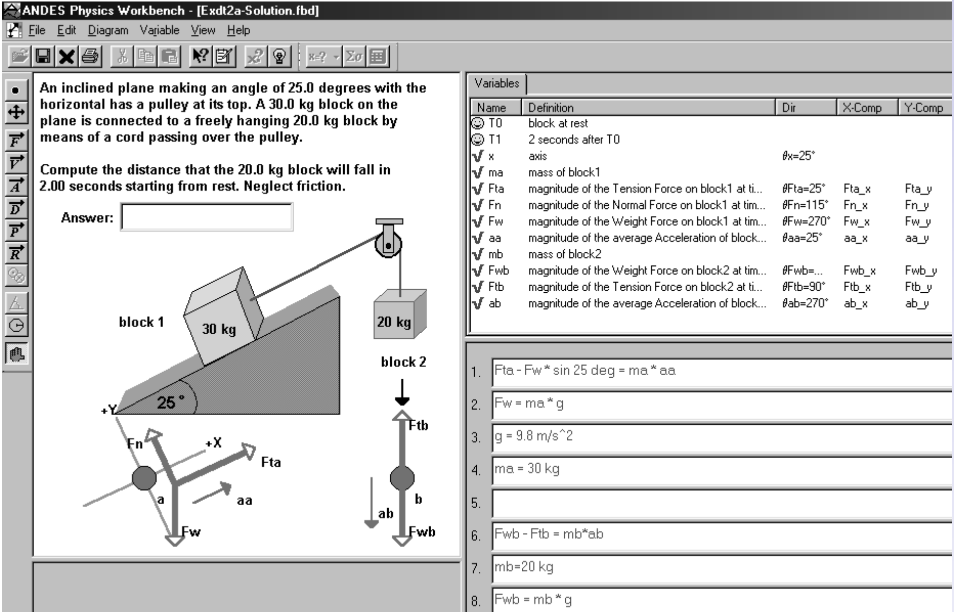
I believe Andes goes a good way towards developing a useful system, but is not really all there. Can it get there?

First, let's take a look at Andes

# Opening problem presentation



# Andes in mid-solution



# What does such a system need

- to *understand* the physics
- a problem specification language that it can understand
- the ability to solve the problem, in all possible ways
- the ability to match what the student inputs to features of a solution
- a model of what the student already understands about the problem
- the ability to match wrong entries to some remediation
- the ability to provide "what's next" help on request
- (hopefully) a model of what physics the student knows how to use.

# Needed components:
# 1. A user interface

- displaying text and graphics, including the problem statement
- accepting input in the form of
  - at least vectors and dots, maybe line segments, arcs, etc.
  - text: for variable names, properties, student turns in dialog.
  - equations (in symbolic form, with greek, exponents, subscripts, numbers *with units*, etc.)
  - help requests.
- display typeset-quality equations, summary of what's been done (variables defined, vectors drawn, etc)
- engaging in typed dialog with the student.
  Depending on how much natural language recognition it can handle, student input might be largely by pulldown menus and multiple choice.

# 2. A problem solver

Current homework systems do not understand any physics. The author writes the problem in a form that should be clear to the student, and gives the answer in a form the computer can compare to the student's answer. Maybe he gives specific wrong answers and accompanying hints. But complex problem solving does not consist of a well defined sequence of identifyable answers. The ITS needs

- production rules for making conclusions under appropriate conditions. These are physics principles and techniques for applying them
- a store of known conditions for the given problem
- the ability to know when all possible conclusions have been drawn, and when the problem has been solved.

Does this sound far-fetched? In fact, the strongest part of Andes is its ability to solve problems, given only a formal presentation of the problem.

# A problem specification

```
:soughts ((answer(at (mag (displacement block2))
        (during 1 2))))
:givens (
(time 1) (time 2) (time (during 1 2))
(given (duration (during 1 2)) (dnum 2 |s|))
(object block1)
(given (mass block1) (dnum 30 |kg|))
(supports plane block1 (during 1 2) (dnum 25 |deg|))
(tied-to string block1 (during 1 2) (dnum 25 |deg|))
(motion block1 (during 1 2) (straight speed-up
        (dnum 25 |deg|)))
(constant (accel block1) (during 1 2))
```

*falls how far?*
Problem statement
*specify times*
*2 sec apart*
*we have one block*
*with mass 30 kg*
*resting on a plane*
*tied to a string*
*will move at* $25^\circ$
*temporary cheat, shouldn't need*

```
(near-planet earth)                                  Hey, you just assumed this?
(object block2)                                      another object
(given (mass block2) (dnum 20 |kg|))                 with given mass
(tied-to string block2 (during 1 2) (dnum 90 |deg|))
                                                     hanging from string
(motion block2 1 momentarily-at-rest)                starts at rest
(motion block2 (during 1 2) (straight speed-up
        (dnum 270 |deg|)))                           moves downwards
(constant (accel block2) (during 1 2))               temp. cheat
                                                     as above
(motion block2 2 (straight NIL (dnum 270 |deg|)))
                                                     still v is down
))
```

Note formal definition has some things which shouldn't be needed, and much that is but which you might have assumed without stating it.

# What the Problem Solver provides

The problem solver provides the help system with

- a list of quantities which enter the problem
- solution paths, a graph of connected conclusions
- a list of equations, with justifications, the nodes of that graph. These are called the *canonical equations*
- the solution space for the problems (usually a set of values for each variable)
- Andes does not currently have, but could, a mal-rule generator which would give a list of wrong equations and remediation for each.

# The help system

The help system controls the interaction with the student. The problem solver has provided it with solution paths, including correct equations with their justifications, and list of variables involved in the problem.

Is a student entry correct or not?
For equations, a correct entry need not be among the *canonical equations*. But it should be derivable from them. A student equation could be judged correct

- if it is derivable from the canonical equations.
- if it is correct on the set of solutions to the canonical equations.

The second is much easier to check, especially on problems where that solution is a point with numerical coordinates in the space of all the variables. And it is equivalent to the first. Convincing the AI people of this is perhaps my biggest contribution to Andes.

# Help system, (cont.)

What does a correct equation tell us about what the student has understood and applied?

What about wrong equations? Can the system determine what the student was trying to do, and what he did wrong?

- left out a term?
- wrong projection for component of a vector?
- wrong concept?

# The algebra system

- Solves a system of equations.
- Checks the correctness of an equation.
- Determines whether a given equation is independent of a set of other equations. Needed
  - by the problem-solver to determine if a new production has supplied new information.
  - by the help system to determine which canonical equations a student equation entry entails.

The Andes tutor uses the solver not only to find the solution (which is needed to check the correctness of student equations) but also to provide a solving tool for the students. USNA professors offer the students this solving tool so they will focus on getting the basic equations, not on the algebraic manipulations on these equations to get the final answer.

# The student model system

Ideally the tutor would have a model of all the knowledge and abilities we want the student to learn, and keep a record of how well each student has learned them, based on the performance on all the problems he has worked on. Even listing all such knowledge is a long way off, and using performance to accurately judge how well the student possesses this knowledge is another very long range problem.

# What I would like to see happen

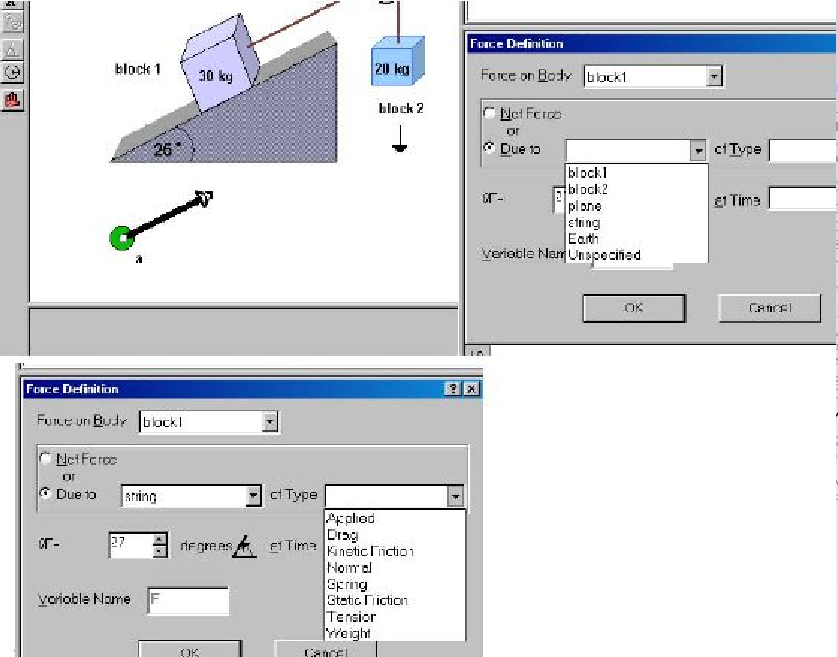
As I have mentioned, Andes is a step in the right direction. However

- It originally only ran on the students' identical PC's, not on the web.
- It has been partially web-ized, but needs to be done more completely.
- Currently has built in some onerous pedagogic requirements. In particular, every variable needs to be explicitly and exhaustively defined by the student, which may be useful at the beginning but becomes quite painful with experience.
- The help system needs a lot of improvement in better recognition of wrong equations, better what's next hinting, etc.
- it is being used at USNA, St. Anselm College, and by Sophia Gershman in Honors Physics at Watchung Hills Regional High School.

# Sophia Gershman's comments

Sophia sent me a long review of her use of Andes. She first praised it for emphasizing drawing bodies, coordinate systems, defining variables, and enabling the use of longer problems without having the students give up. But she continues:
"On the negative side, ANDES often clouds instead of illuminating the approach of starting from basic principles! The very issue that ANDES prides itself on gets destroyed by the computer limitations. Often, the student who gets scolded by ANDES for not using a "basic principle" simply didn't write the principle in the syntax or form that ANDES prefers. Students then spend an enormous amount of time trying to find just the right form of the expression instead of analyzing the phenomena and thinking about physics principles."
She says the weaker students benefit the most, while the best students get irritated and maybe even discouraged.

# Frustration: Defining a Force



# My Work

I spent my sabbatical year (2000-2001) with the Andes group, headed by Kurt VanLehn, at the Learning Research and Development Center, University of Pittsburgh, where I wrote the algebra component of AndesII.

Other than that, my work has been done jointly with

- Donald E. Smith, Computer Science, Rutgers
- Chun-Wai Liew, Computer Science, Lafayette College

This is the *Watchung* Group.
(The Watchung Mountains, about 10 miles west of Rutgers, reach a height of 500 ft above sea-level.)

We have concentrated at removing the requirement for the student to define each variable. Can a tutor know what the student equations refer to when the student chooses his own variable names and doesn't declare what they represent? Most of the time, yes!

# Why so little progress?

Progress has been disappointing. Why?

- Simple systems can be created by a few people in a short time, tempting not to embark on a very ambitious system. Look at all the simulation packages! At the early Homework Systems!
- The Artificial Intelligence (AI) community is more interested in systems of general applicability, *i.e.* no algebra! And they are fascinated with natural language.
- Many journals insist all developments be pedagogically tested for publication. This makes development of components difficult.
- Ditto for grant agencies. If you can't develop a working system in three years, they are not interested. Andes has been in development for more than a decade!

# What can we do?

I would like to see people work on components, much the way the Open-Software community has built Linux

- Someone should build an expression/equation slot, with robust ability to accept equations both in latex style and in Word style, or other reasonable form, and parse them and present them back in typeset (TEX) form, with facility for editing. And **with units!**
- Someone should work on a graphics buffer good for drawing free body diagrams and other diagrams of the kind we would like to see students draw.
- Someone should design an API for an interface, including the above components and the others I mentioned earlier, that could be united with a help system like Andes'.

(cont.)

- Someone should work on a more robust knowledge representation than what Andes has, although Andes is pretty advanced. Should it use real vectors (with vector equations, not just components)? Does it need variable functions (x(t))?
- My group has been working on variable recognition without explicit declaration. A major problem with Andes is how long it takes to do a problem because of this excessively demanding scaffolding. We have been reasonably successful, but have no way of testing our methods on real students.

# References

If you go to my Home Page `http://www.physics.rutgers.edu/~shapiro/`, and look under "Technology and Physics Teaching", you can find this talk, including a reference page. You can also find links to Andes, to my homemade clicker system (SRS), and to the Watchung Group home page, to our homemade exam system, and a few other things.

Warning: many of these pages are very obsolete (particularly the SRS).

# I am not a plagiarist

- Sleeping student image courtesy of `http://www.DailyClipArt.net`
- School of Athens, by Raphael `http://www.odu.edu/~mcarhart/hist102/slides/athens_school.htm`
- Gutenburg bible page from `http://commons.wikimedia.org/wiki/Image:Gutenberg_detail.jpg`
- clicker pictures of PRS and Turning Point from their sales literature

# Summary

In this talk, I have

- explained why improvements need to be made in our teaching of introductory physics
- told you some of the technological aids you could use now
- told you what I think an intelligent tutor might do in the future, and how it would need to function.
- encouraged you to jump in. But I am not responsible for the results!

Thank you for your attention. Perhaps one of you would like to work on inventing a piece of my dream system.