Assessing student learning and teaching effectiveness in intermediate mechanics

Bradley S. Ambrose, Dept. of Physics, Grand Valley State University, *ambroseb@gvsu.edu*

Part of the Targeted Poster Session
Formative and Summative Assessment in Upper-Level Physics

2011 Physics Education Research Conference
August 4, 2011, Omaha, NE

Context of research and development:
Intermediate Mechanics Tutorials[1,2] (Ambrose and Wittmann)

Project website: http://perlnet.umephy.maine.edu/imt

Overview of tutorial approach and materials:[3]

- Pretests (ungraded quizzes)
  - To **assess students' prior understanding** and create student interest
- Tutorial worksheets (small-group work)
  - Teaching is done by questioning, not telling
  - Focus on conceptual underpinnings and math-physics connections
  - **Formative assessment** during tutorial through instructor checkpoints
- Tutorial homework
  - Students review, apply, and extend findings from tutorial
- Examination questions (post-tests)
  - To **assess student learning after instruction** and **assess effectiveness of tutorials**

Special acknowledgements:

- Stamatis Vokos, John Lindberg *(Seattle Pacific University)*
- Juliet Brosing *(Pacific University),*
  Maja Krcmar *(Grand Valley State University),*
  Dawn Meredith *(University of New Hampshire),*
  Carolyn Sealfon *(West Chester University of Pennsylvania)*
  Carrie Swift *(University of Michigan-Dearborn)*

1. Ambrose, Am. J. Phys. 72 (2004).
2. Supported by NSF grants DUE-0441426 and DUE-0442388, Ambrose and Wittmann (2005 – 2007).
3. Modeled after *Tutorials in Introductory Physics* (McDermott, Shaffer, and the P.E.G. at Univ. of Wash.) and *Activity-Based Physics* (Wittmann, Steinberg, Redish, and the P.E.R.G. at Univ. of Maryland.)

Designing assessments in intermediate mechanics

Which model of student thinking may be more appropriate?[4]


"Misconceptions"? or *"Knowledge pieces"?*

Stable, coherent
Context-independent

Plastic, mutually independent
Context-dependent

4. Adapted from a slide by Rachel Scherr; Scherr, Am. J. Phys. **75** (2007); Elby, Am. J. Phys. Suppl. 73 (2005).

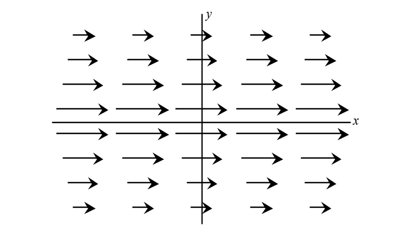
In what ways do students have difficulty with math-physics connections?

Both *qualitative* and *quantitative* problem solving skills are expected outcomes of instruction, particularly in upper division courses. *Yet:*

- Many students have difficulty using mathematics to express and apply physics ideas.
- Many students have difficulty extracting physical meaning from the mathematics.

Some assessments yield deeper insights administered on a *take-home basis* (not during class).

- *Example:* Tasks on higher level mathematics inherent to intermediate mechanics (see at right)
- *Example:* Paired qualitative and quantitative tasks (see **Observation #4** panel below)



Q1: Is curl zero at all locations?
Q2: Is force conservative or not?

Observation #1: Open-ended assessments can probe spectrum of student reasoning patterns

Example: Pretest on 2D oscillations

Inappropriate *"compensation arguments"* linking amplitude to frequency or force constant[5]

Original: GVSU (4 classes) and UME (1 class)

Consider a 2D oscillator with $U(x, y) = ½\, m\omega_1^2x^2 + ½\, m^2y^2$, or equivalently, $U(x, y) = ½\, k_1^2x^2 + ½\, k_2^2y^2$.

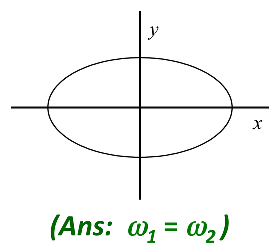
Q: Given the path of the oscillator, determine whether ω_1 is *greater than, less than,* or *equal to* ω_2. Explain.

(Note: Original version asked to compare k_1 and k_2.)

Typical incorrect responses:

"$k_1 < k_2$, the spring goes farther in the x-direction, so spring must be less stiff in that direction."

"$\omega_2 > \omega_1$. Since we now have an oval curve with x-axis longer, ω_2 must be greater to compensate.



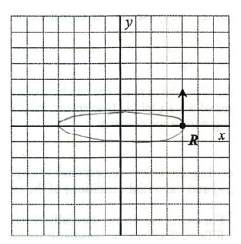
(Ans: $\omega_1 = \omega_2$)

More open-ended version: GVSU (1 class)

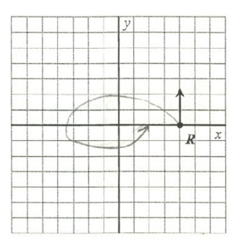
Consider a 2D oscillator: $\vec{F}_{net}(x,y) = \left(-k_x x\,\hat{i}\right) + \left(-k_y y\,\hat{j}\right)$

Q: For each case shown, draw a qualitatively correct trajectory with the given initial conditions. Explain.

Typical incorrect responses for the case $k_y = 4k_x$:



"An ellipse… because the spring forces are different."



"The object travels less in the y-direction because of the stiffer spring. The springs attempt to return the object to equilibrium."

- Few students **(0% – 15%)** answered pretest correctly in each class.
- Open-ended version of 2D oscillations pretest (i) verified presence of inappropriate linkage between amplitude and force constant and (ii) revealed "returning to equilibrium" intuition.

5. For evidence of this pattern of student thinking in the context of 1-D oscillators, see: Ambrose, PERC Proceedings, 2006, ed. L. McCullough, L. Hsu, and P. Heron, AIP Conference Proceedings.

Observation #2: Open-ended assessments can probe understanding of requisite concepts

Example: Pretest on damped oscillations

Underlying difficulties regarding behavior of amplitude of oscillator

Pretest: GVSU (1 class), SPU (1 class), WCUPA (3 classes)

An underdamped oscillator is released from rest at x = +1.00 m. After one full cycle the oscillator returns only to x = +0.80 m.

Q1: Is it possible to determine *the fraction of energy dissipated* by the retarding force during this first cycle?

If so, calculate it. If not, state what else you need to know. Explain.

Q2: Is it possible to predict the maximum displacement of the oscillator when it finishes its *second* full oscillation?

If so, determine it. If not, state what else you need to know. Explain.

In Q1: Only **~50%** of students correctly used relationship: $U = \frac{1}{2}kx^2 \propto x^2$

"We need the mass and spring constant."

"If 20% of the amplitude is lost, then one can deduce that 20% of the energy is lost."

In Q2: Only **~35%** of students recognized that the ratio of successive maxima is constant:

Ex.: Max. displacement after two cycles is x = 0.60 m (not x = 0.64 m) "because the retarding force is linear."

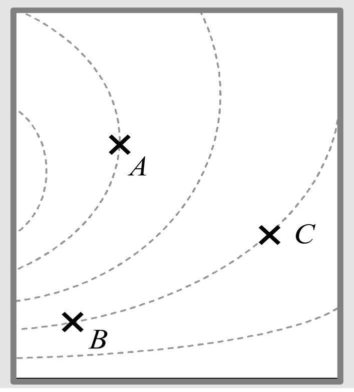
Example: Pretest on conservative forces and equipotential diagrams

Failure to discriminate between a quantity and its rate of change

Pretest: GVSU (7 classes) and numerous pilot sites

It is known for a certain test charge q_{test} that the potential energy at A is larger than that at B (that is, $U_A > U_B$).

Q: Rank the locations A, B, and C according to the *magnitude of the force* exerted on the test charge q_{test} at that location. Explain.



Examples of persistent difficulty discriminating between force and potential energy:

"A has the highest potential so it can exert a larger force on a test charge. B and C are on the same potential curve and thus have equal abilities to exert force."

"[$V_A > V_B = V_C$] … $F(x) = -\,dV/dx$
$\therefore F_C = F_B$ in magnitude and $F_A > F_C$."

Observation #3: Formative assessments can detect unanticipated student difficulties

Example: Tutorial checkpoint "Forced harmonic oscillations"

Student intuitions about power delivered by damping and driving forces

Q: When at steady-state, over the course of each oscillation, how does the work done by the damping force compare to the work done by the driving force?

- *Answer:* **Equal;** total energy is unchanged from cycle to cycle.

Q: When at resonance, is the power dissipated by the damping force relatively *large* or *small?*

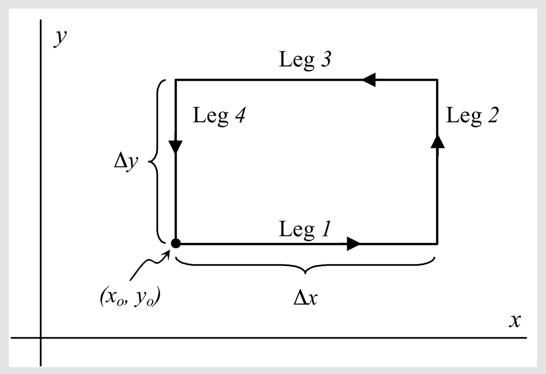
- *Answer:* **Relatively large;** damping force increases with velocity.
- *Implication:* At resonance, work done per cycle by driving force must also be relatively large.

A surprise for most students! Many hold *incorrect* intuition that damping force dissipates *very little power* at resonance.

Example: Tutorial checkpoint "Conservative force fields"

Guided derivation of (z-component of) vector curl

For a small rectangular loop in x-y plane (shown at right), students asked to express work around loop.



They then derive the z-component of the curl of the force by showing that in the $\Delta x \Delta y \to 0$ limit:

$$\frac{Work\ \ around\ \ loop}{Area\ \ subtended\ \ by\ \ loop} = \left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y}\right)\Bigg|_{(x,y)=(x_o,y_o)}$$

Even after scaffolding questions, *e.g.,* to help students approximate work around "leg 2" as:

$$W_{leg\,2} \cong F_y\left(x_o + \Delta x,\ y_o + \frac{\Delta y}{2}\right)$$

many students missed forming $\partial F_y/\partial x$ from $W_{\text{leg 2}}$ and $W_{\text{leg 4}}$ and instead "subtracted":

$$\text{"}\frac{F_y\left(x_o+\Delta x,\ y_o+{}^{\Delta y}\!/_2\right) - F_y\left(x_o,\ y_o+{}^{\Delta y}\!/_2\right)}{\Delta x} = \frac{F_y(\Delta x,\ 0)}{\Delta x}\text{"}$$

Observation #4: Summative assessment strategies extend effectively from intro to upper level

Example: Paired qualitative and quantitative post-tests

Do students exhibit consistency in their reasoning and recognize need for it?

Homework or take-home exam on orbital mechanics:

Students analyze elliptical transfer (Hohmann) orbits in two ways.

Q1: Describe *qualitatively* the maneuvers of a probe upon entering and leaving the transfer orbit. That is, must the probe *increase* or *decrease* its speed:

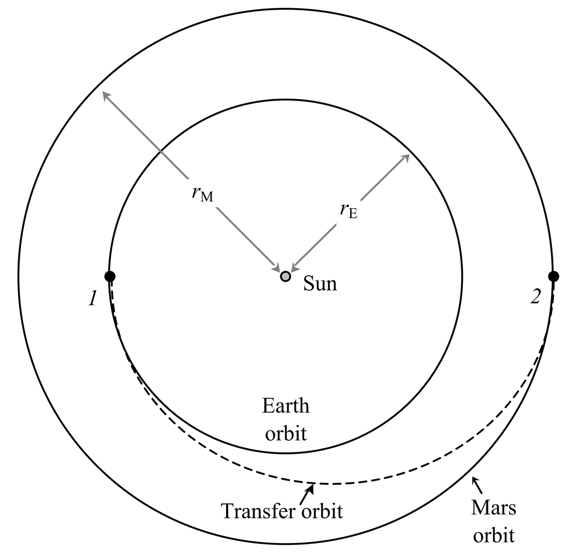
(i) upon entering the transfer orbit at point *1?* Explain.

(ii) upon entering Mars orbit at point *2?* Explain.

Q2: Now *calculate* the following quantities, showing all work:

(i) the change in speed of the probe entering the transfer orbit at *1*

(ii) the change in speed of the probe entering Mars orbit at *2*



Many students answer ***Q2*** (quantitative) correctly **but** in ***Q1*** (qualitative) inconsistently predict a *decrease in speed* from transfer orbit to Mars orbit (at point *2*)

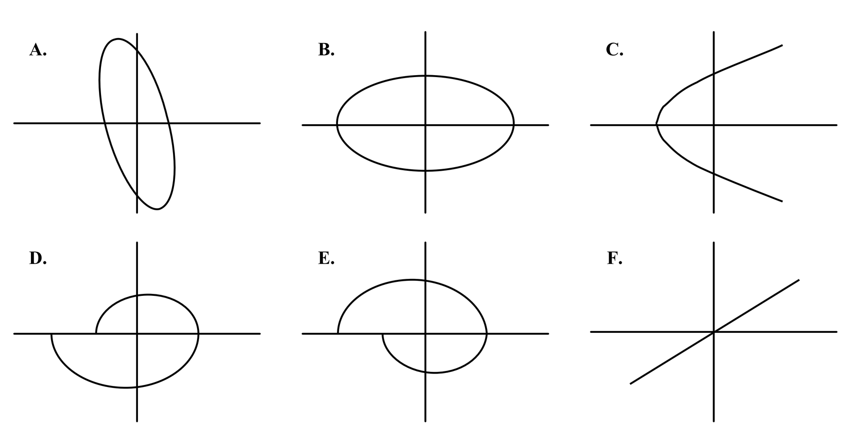
Example: Post-tests that require discrimination between related concepts

How coherently organized is student knowledge after instruction?

In-class post-test on oscillations:

Identify which diagram(s) at right, if any, could be:

- phase space plot of a simple harmonic oscillator
- phase space plot of an underdamped oscillator
- phase space plot of a forced oscillator at steady state
- trajectory of an isotropic 2-D oscillator
- trajectory of a 2-D oscillator for which $k_y > k_x$
- trajectory of a 2-D oscillator for which $k_y < k_x$



In-class post-test on oscillations:

Q1: Is the damping constant for oscillator #1 (blue) *greater than, less than,* or *equal to* that for oscillator #2 (pink)? Explain.

Q2: Is the quality factor of oscillator #1 *greater than, less than,* or *equal to* that for oscillator #2? Explain.

Q3: Using the information in the graph for oscillator #1, deduce the parameters a and b that describes its equation of motion:

$$\ddot{x} + a\dot{x} + b = 0$$