Because physics majors encounter conceptual difficulties too:

Refining an inquiry-based approach to teach intermediate mechanics

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From previous research at the introductory level

Many students have difficulty discriminating between a **quantity** and its **rate of change:**

- position *vs.* velocity, and velocity *vs.* acceleration *
- height *vs.* slope of a graph **
- electric field *vs.* electric potential †
- electric (or magnetic) flux *vs.* change in flux
- …*and many other examples*

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* Trowbridge and McDermott, Am. J. Phys. **48** (1980) and **49** (1981).
** McDermott, Rosenquist, and van Zee, Am. J. Phys. **55** (1987).
† Allain, Ph.D. dissertation, NCSU, 2001; Maloney *et al.*, Am. J. Phys. Suppl. **69** (2001).

As a *physics education researcher* teaching intermediate mechanics

The following research questions arise:

- To what extent have students developed a functional understanding of fundamental concepts in mechanics?
- What difficulties arise when students encounter topics in intermediate mechanics? To what extent do those difficulties have their roots in fundamental concepts?

What we teach **about conservative forces**

in intermediate mechanics

A force $\vec{F}(\vec{r})$ is conservative if and only if:

- the work by that force around any closed path is zero
- the vector curl of the force is zero at all locations
- a potential energy function $U(\vec{r})$ exists so that $\vec{F} = -\vec{\nabla} U$

(generalization of $\vec{E} = -\vec{\nabla} V$ from electrostatics)

"Equipotential map" task

Intermediate mechanics, GVSU

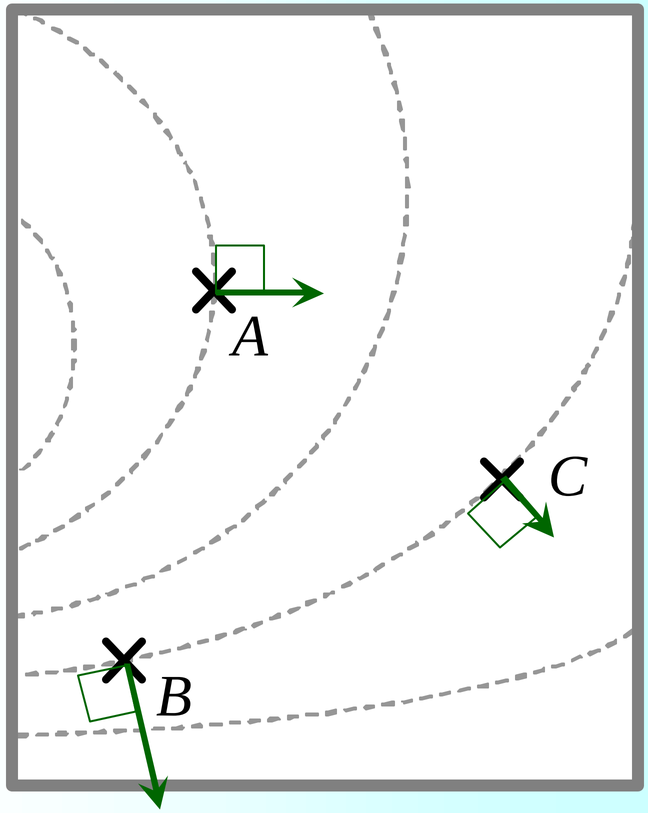
After all lecture instruction in introductory E&M

In the region of space depicted at right, the dashed curves indicate locations of *equal potential energy* for a test charge $+q_{test}$ placed within this region.

It is known that the potential energy at location *A* is *greater than* that at *B* and *C*.

A. At each location, draw an arrow to indicate the direction in which the test charge $+q_{test}$ would move when released from that location. Explain.

B. Rank the locations *A*, *B*, and *C* according to the magnitude of the force exerted on the test charge $+q_{test}$. Explain your reasoning.



(Qualitatively correct force vectors are shown.)

Equipotential map task: Results

Intermediate mechanics, GVSU (N = 43, 6 classes)

After all lecture instruction in introductory E&M

Percent correct *with correct reasoning:*
(rounded to nearest 5%)

Part A (Directions of force vectors)	50%	(22/43)
Part B (Ranking force magnitudes)	20%	(8/43)
Both parts correct	**10%**	**(5/43)**

Similar results have been found elsewhere with similar student populations (e.g., U. Maine, Seattle Pacific U.)

Equipotential map task: Results

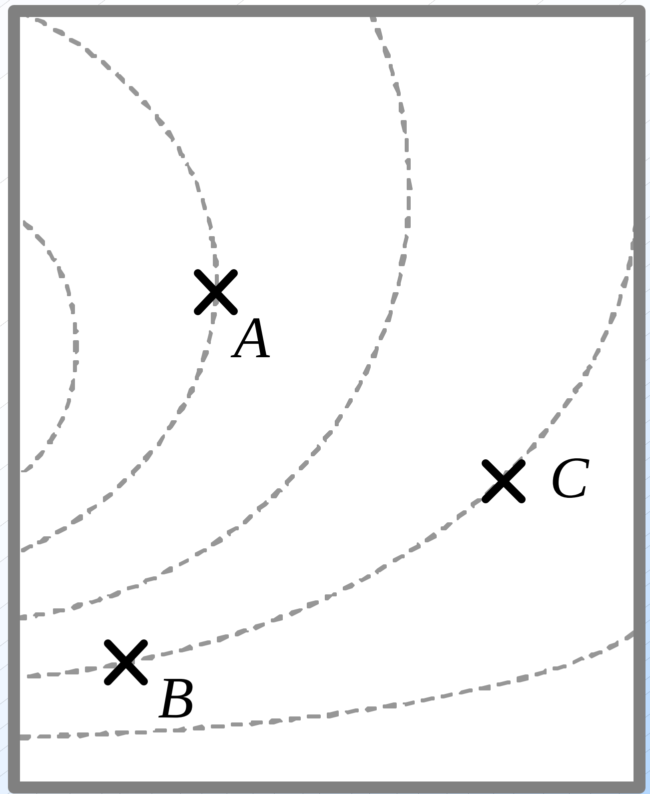
Intermediate mechanics, GVSU

After all lecture instruction in introductory E&M

Most common *incorrect* ranking: $F_A > F_B = F_C$

Example: "The amount of force exerted on q_{test} is dependent on the size of the potential at the point q_{test} is placed."

Example: "Since *F* is proportional to *V*, higher *V* means higher *F*."



Failure to discriminate between a quantity *(potential energy U)* ***and its rate of change*** *(force $\vec{F} = -\vec{\nabla}U$)*

Using research to improve student learning: *Tutorials in Intermediate Mechanics*

- Collaborative NSF-CCLI project at GVSU (Ambrose) and U. Maine (Wittmann)
- Modeled after *Tutorials in Introductory Physics*

  (by McDermott, Shaffer, and the Physics Education Group at the University of Washington, Prentice Hall, 2001)
- Research-based targeted-inquiry activities
  - Address specific conceptual difficulties
  - Connect concepts to real world and to mathematical formalism

Topics from *Tutorials in Intermediate Mechanics*

In development at GVSU*

- **Simple harmonic motion** (1 tutorial)
- **Newton's laws and velocity-dependent forces** (1 tutorial)
- **Damped harmonic motion** (2 tutorials)
- **Driven harmonic motion** (1 tutorial)
- **Phase space diagrams** (3 tutorials)
- **Conservative force fields** (1 tutorial)
- **Harmonic motion in two dimensions** (1 tutorial)
- **Accelerating reference frames** (3 tutorials)
- **Orbital mechanics** (2 tutorials)

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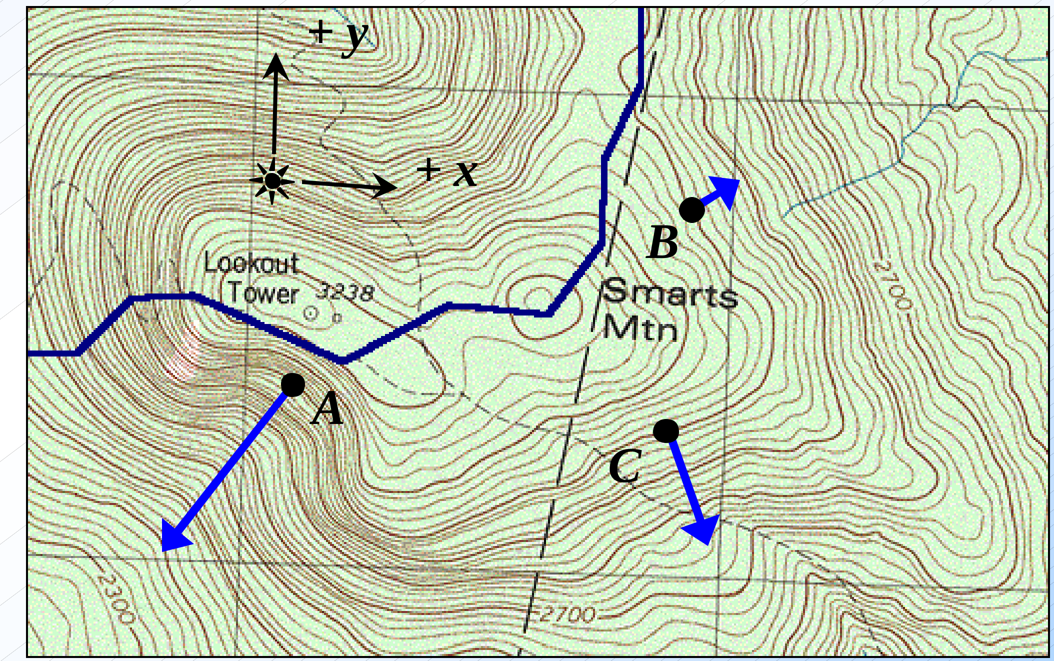
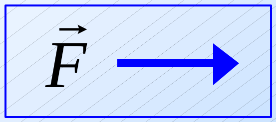
* Ambrose, "Investigating student understanding in intermediate mechanics: Identifying the need for a tutorial approach to instruction," *Am. J. Phys.* **72** (2004).

Overview of tutorial: *Conservative forces and equipotential diagrams*

For the three labeled locations *(A – C)*, students:

- Rank locations according to ***slope***
- Rank locations according to ***net force*** (neglecting friction)
- Determine ***direction*** of net force

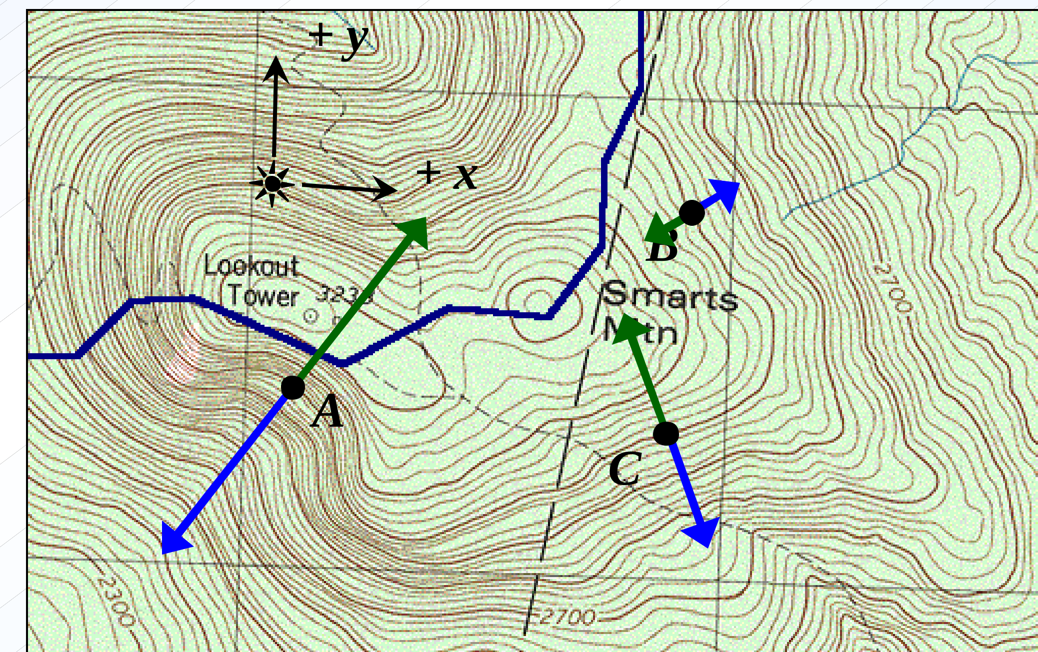


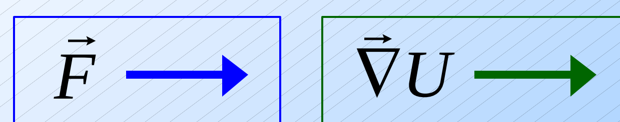


Overview of tutorial: *Conservative forces and equipotential diagrams*

For the three labeled locations *(A – C)*, students answer:

- *In words*, how would you calculate $\frac{\partial U}{\partial x}$ and $\frac{\partial U}{\partial y}$?
- Is $\frac{\partial U}{\partial x}$ pos, neg, or zero?
- Is $\frac{\partial U}{\partial y}$ pos, neg, or zero?
- Compare $\left|\frac{\partial U}{\partial x}\right|$ and $\left|\frac{\partial U}{\partial y}\right|$.
- Draw $\vec{\nabla}U = \left(\frac{\partial U}{\partial x}\hat{i} + \frac{\partial U}{\partial y}\hat{j}\right)$.

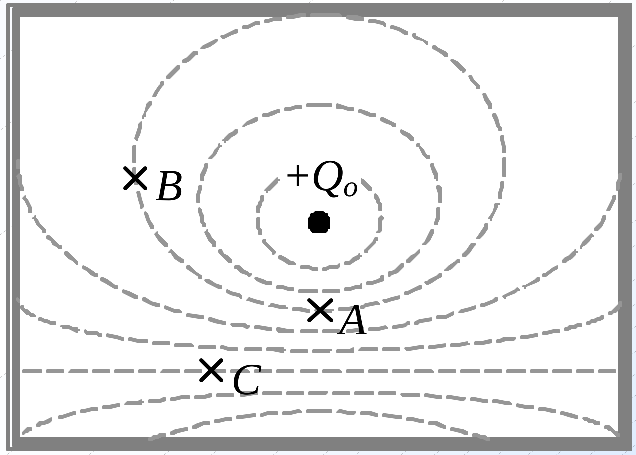




Examples of assessment questions

On written exams after tutorial instruction

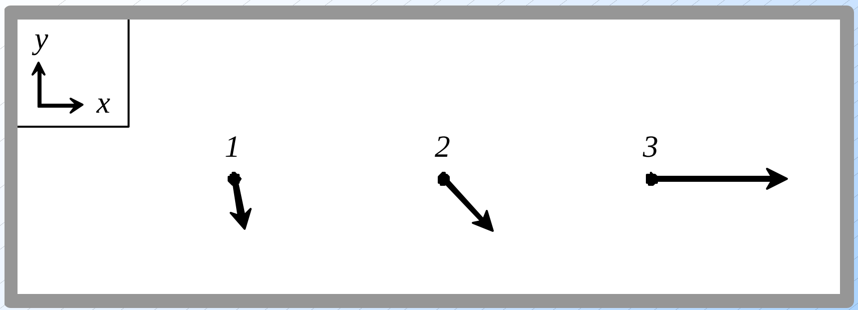
Task: Given equipotential map, predict directions and relative magnitudes of forces.



GVSU: **6/8 correct** (Fa 2004)

SPU: **7/11 correct** (Wi 2006)

Task: Given several forces, sketch a possible equipotential map and rank points by potential energy.



GVSU: **4/7 correct** (Fa 2005)

Role of tutorial homework

Students explicitly *reflect upon* and *apply* results from tutorial

Effectiveness of tutorial was enhanced by adding this HW problem:

Consider the following statement:

"For a conservative force, the magnitude of the force is related to potential energy. The larger the potential energy, the larger the magnitude of the force."

Do you *agree* or *disagree* with this statement?

- If you agree, state so explicitly. Explain your reasoning.
- If you disagree, use your results from this tutorial to provide **at least three (3)** specific counterexamples. Explain your reasoning.

Implications for instruction

- Advanced students often experience persistent conceptual and reasoning difficulties in physics.
  - Students often fail to discriminate between a quantity and its (temporal or spatial) rate of change.
- Student difficulties must be addressed *explicitly* and *repeatedly.*
  - Students must be guided to recognize what "$\overline{\nabla} U$" *means* and what it *doesn't* mean.
- A guided inquiry tutorial approach to instruction can enhance conceptual understanding and reasoning ability.

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