Research in physics education:
A resource for improving student learning

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New Physics and Astronomy
Faculty Workshop
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Physics Education Group at the University of Washington

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Coordinated program of research, curriculum development, and instruction supported in part by grants from the National Science Foundation.

Summary of workshop

- Overview of research and curriculum development by UW Physics Education Group
- Direct experience with curriculum
  (a *Tutorial* from *Tutorials in Introductory Physics*)
- Discussion of impact on student learning
- Generalizations on the teaching and learning of physics

Goals of UW Physics Education Group

- Conduct research on learning and teaching of physics concepts and reasoning (differs from research in Colleges of Education)

- Develop instructional procedures that:
  - are effective at helping students learn (concepts and reasoning)
  - yield similar results when used by faculty at other institutions

- Document impact and procedures in journals that are read by physics faculty (written in language accessible to physicists)
  - To help all faculty improve the effectiveness of instruction whether or not they are engaged in physics education research.

- Strengthen the preparation of K-12 teachers to teach physics and astronomy by inquiry

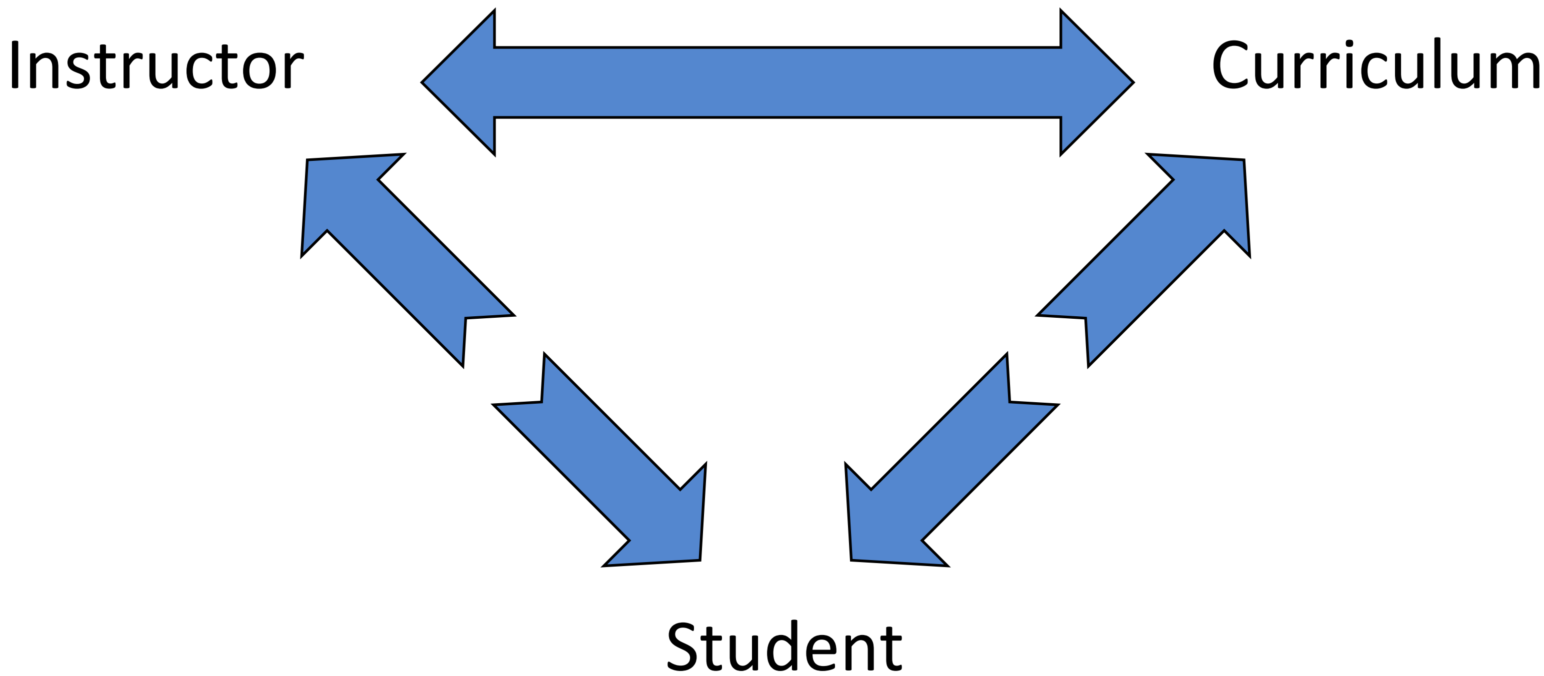
In working toward these goals, we have come to an important generalization:

On certain types of qualitative questions, student performance is essentially the same over a wide range of student ability:

- *before and after standard instruction*
- *in calculus-based and algebra-based courses*
- *with and without standard demonstrations*
- *with and without standard laboratory*
- *in large and small classes*
- *regardless of popularity of the instructor*

Hearing lectures, reading textbooks, seeing demonstrations, doing homework, and performing laboratory experiments often have little effect on student learning.

Evidence from research indicates gap



Gap greater than most instructors realize

- ◊ Teaching by telling is an ineffective mode of instruction for most students.

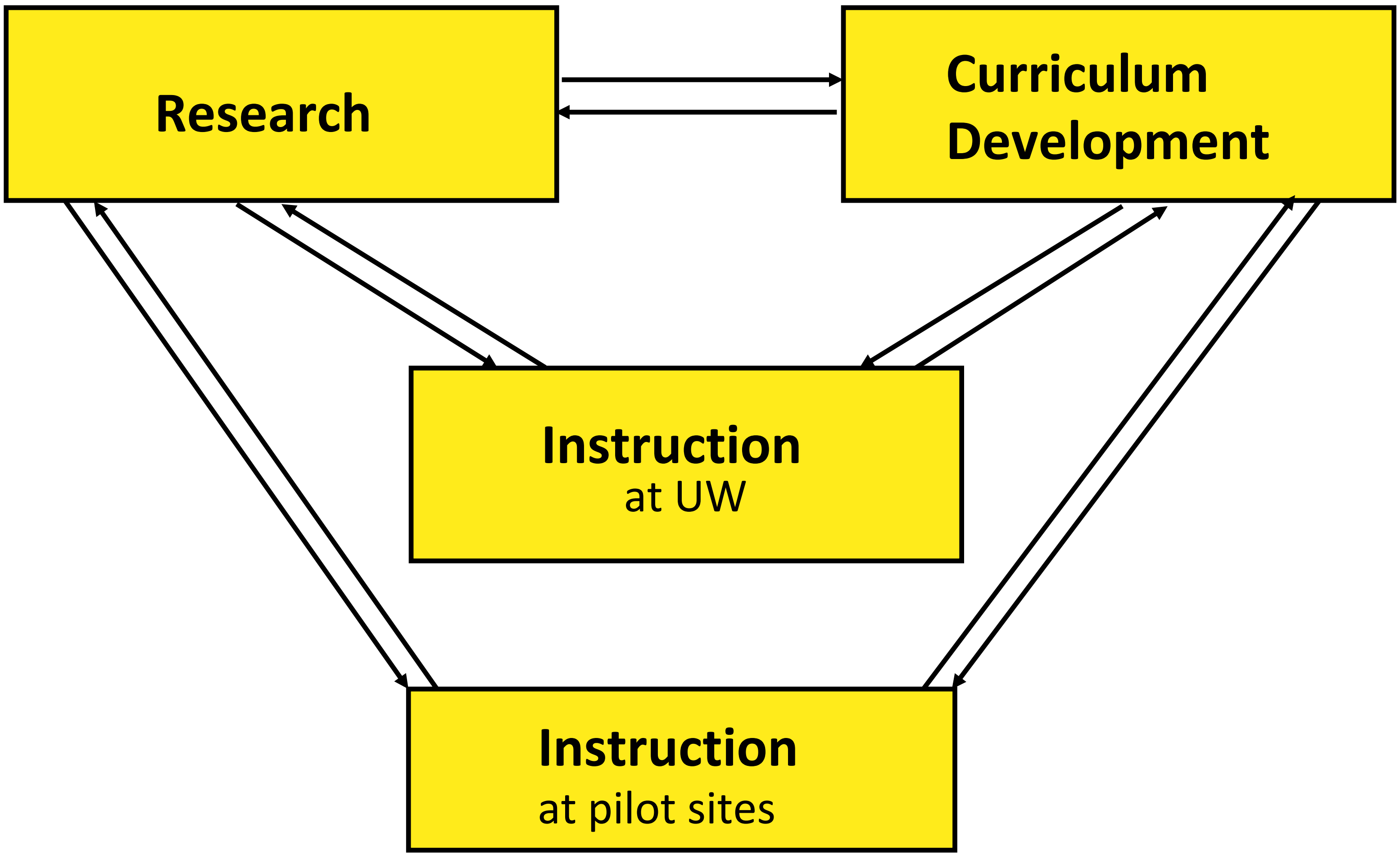
Teaching by questioning can be more effective.

Students must be intellectually active

Systematic investigations of student learning (at the beginning, during, and after instruction)

- **individual demonstration interviews**
  - for probing student understanding in depth
- **written questions with explanations** (pretests and post-tests)
  - for ascertaining prevalence of specific difficulties
  - for assessing effectiveness of instruction
- **descriptive studies during instruction**
  - for providing insights to guide curriculum development

Application of research to development of curriculum



Research-based ≠ Research-validated

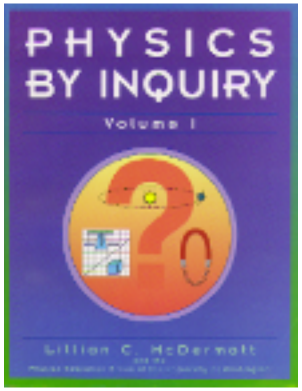
Research-based curriculum development

Preparing precollege teachers to teach physics and physical science

– Physics by Inquiry –

(John Wiley & Sons, Inc., 1996)

Self-contained, laboratory-based, no lectures

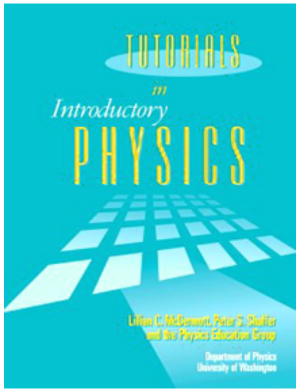


Improving student learning in introductory physics

– Tutorials in Introductory Physics –

(Prentice Hall, 2002)

Supplementary to lecture-based course



Tutorials respond to the research question:

Is standard presentation of a basic topic in textbook or lecture adequate to develop a *functional understanding*?

(*i.e.,* the ability to do the reasoning necessary to apply relevant concepts and principles in situations not explicitly studied)

If not,

what needs to be done?

Primary context (at UW) for tutorials

Calculus-based physics:

Weekly:

- 3 lectures (50 minutes)
- 1 laboratory (2-3 hours)
- 1 tutorial (50 minutes)

However, tutorials can be used in lectures or labs depending on constraints.

In either case, a crucial requirement is TAs who are well-prepared in both the content and instructional method.

Tutorial Components

- **weekly pretests**
  - *given usually after lecture on relevant material but before tutorial*
- **tutorial sessions**
  - *small groups (3-4) work through carefully structured **worksheets***
  - *tutorial instructors question students in semi-Socratic manner*
- **tutorial homework**

Additional critical components

- **examination questions based on tutorials**
  - *so students take seriously the emphasis on understanding*
- **required weekly seminar for tutorial instructors**
  - *graduate and undergraduate instructors, etc.*
  - *preparation in content and instructional method*
  - *TAs take pretest, work through tutorial, and discuss student responses.*

Example of tutorial: *Dynamics of rigid bodies*

- Pretest
  - Please complete on your own; take no more than about 5 minutes to answer.

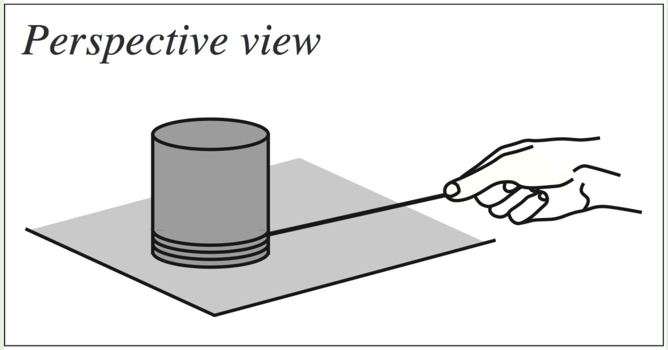
- Tutorial
  - Work in small groups followed by full-workshop discussions
    (Full group discussions not typical of student tutorial sessions)

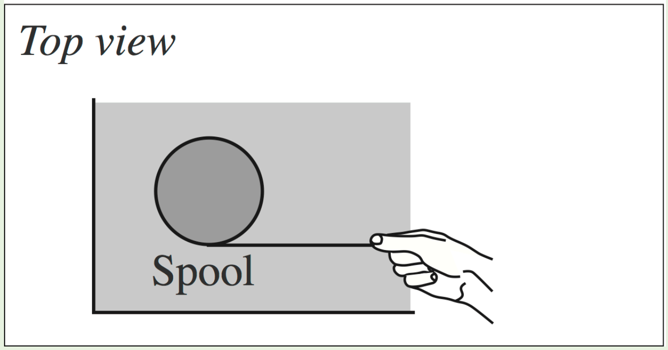
- Discussion of impact of tutorial and generalizations on method

Small group activity: page 1, Part A

A spool is pulled across a frictionless table as shown. The hand pulls horizontally. The thread has been wrapped many times around the bottom of the spool.

- ***Predict*** whether the spool will rotate. Explain.
- ***Predict*** whether the center of the spool will move and if so, in which direction. Explain.





As instructors, discuss answers that students might give and what the answers might indicate about student thinking.

Large group activity (Parts B and C)

Test your answers by observing the experiment on a table *with* friction.

What do your observations suggest would happen if the table were frictionless?

Spool on various tables (varying friction)

Spool on air table (negligible friction)

Examples of student responses to spools question from page 1 (*e.g.,* when given as pretest)

The spool will <u>rotate and not translate</u>

- "The force of the string will cause torque. ... There is no force ***applied directly to the spool*** to make it go forward."

➡ ***Belief that force not at center of mass results in rotation only.***

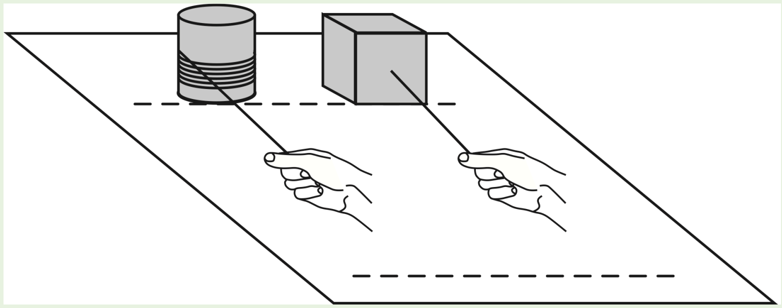
The spool will <u>translate and not rotate</u>

- "There is no friction so the … particles on the other side [of the spool] have no force keeping it put - so the spool will not rotate."
- "on a frictionless surface … tension will not generate rotation because there is no force in the opposite direction … for rotation … there must be a force in the positive and negative direction on the spool and … there is no negative force."

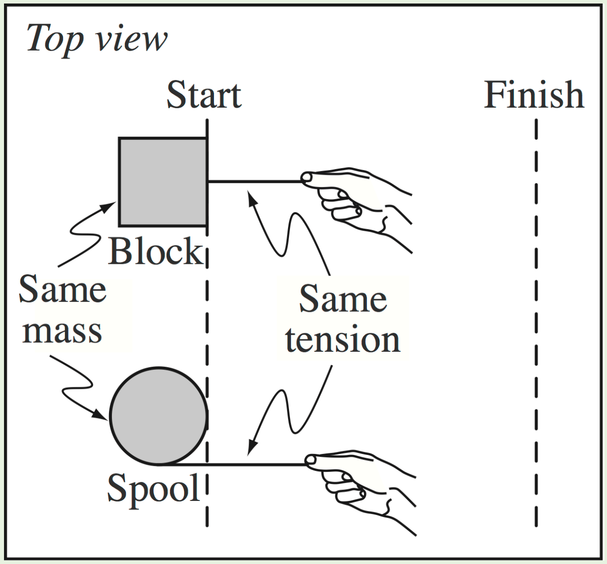
➡ ***Belief that force not at center of mass results only in translation of entire object -- unless another force acts to rotate object***

Small group activity: page 2

A block and spool are each pulled across a level, frictionless surface by a string.



- ***Predict*** the order in which they cross the finish line.



- Three students discuss the experiment.
  1. The spool rotates and **both finish at the same time** … same mass and net force so the centers have the same acceleration. The tensions have the same effect on translational motion.
  2. The **spool crosses after the block**. Some tension is used to rotate the spool. When a force causes rotation, it has less effect on translation.
  3. I agree the spool rotates and crosses later, but I was thinking about **energy**. They have the same total kinetic energy at the finish line. Since the spool has some rotational KE, it must have less translational KE.

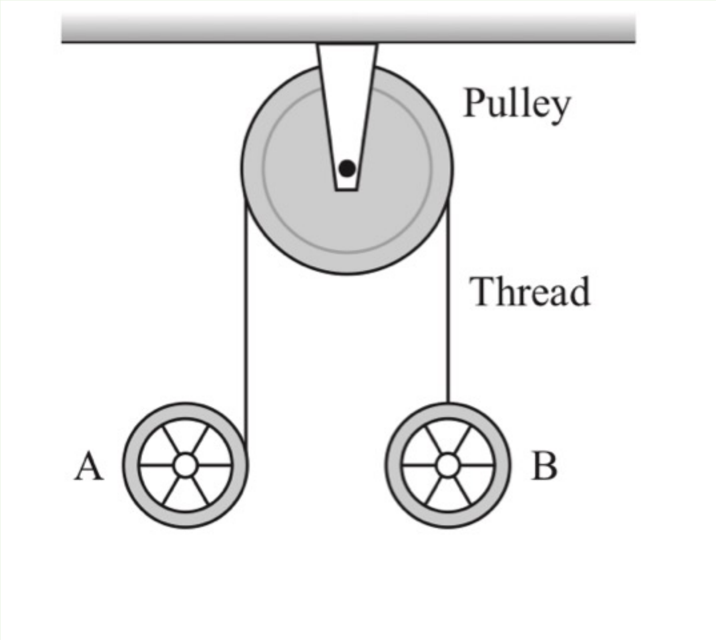
With which student do you agree?

Continue to page 3 when you and your partners are ready.

Small group activity: page 3

Two identical spools are connected by a thread that runs over an ideal pulley. The thread is wrapped around spool A many time, but is attached to a fixed point on spool B.

The spools are released from the same height at the same time.



- *Predict* whether spool A will hit the floor *before, after,* or *at the same time as* spool B.

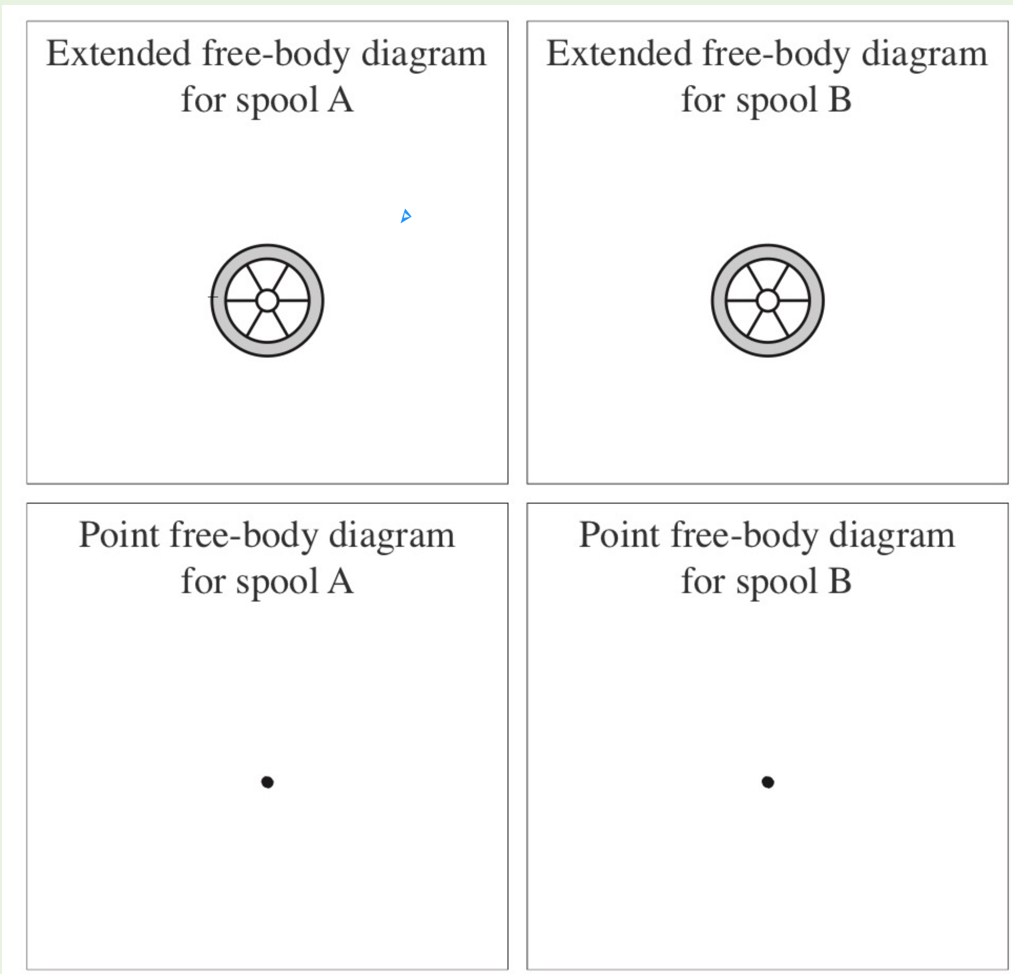
- Draw the following diagrams for each spool, corresponding to a time shortly after release:
  - an extended free-body diagram
  - a (point) free-body diagram

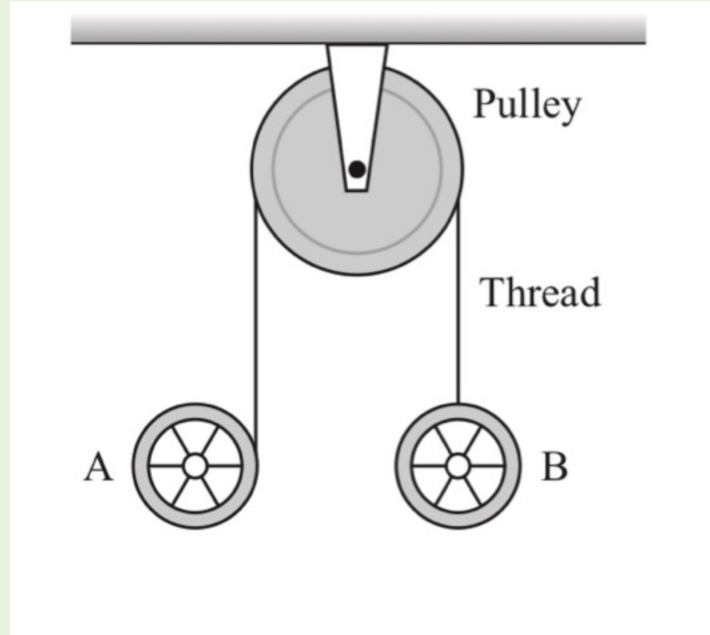
- What would each student on the previous page predict?

We will discuss the answers and observe a video as group.

Dynamics of rigid bodies, page 3

- Draw for each spool:
  - an extended free-body diagram
  - a (point) free-body diagram





Dynamics of rigid bodies, page 3

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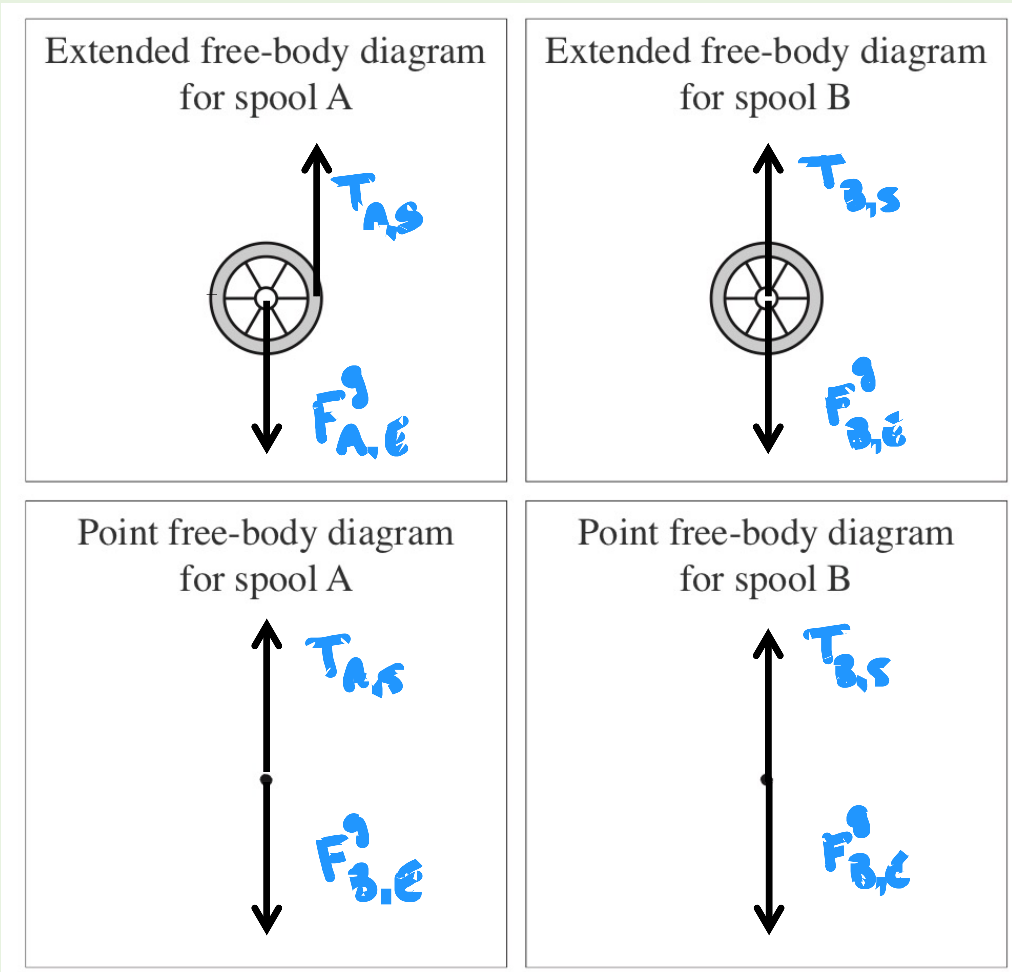
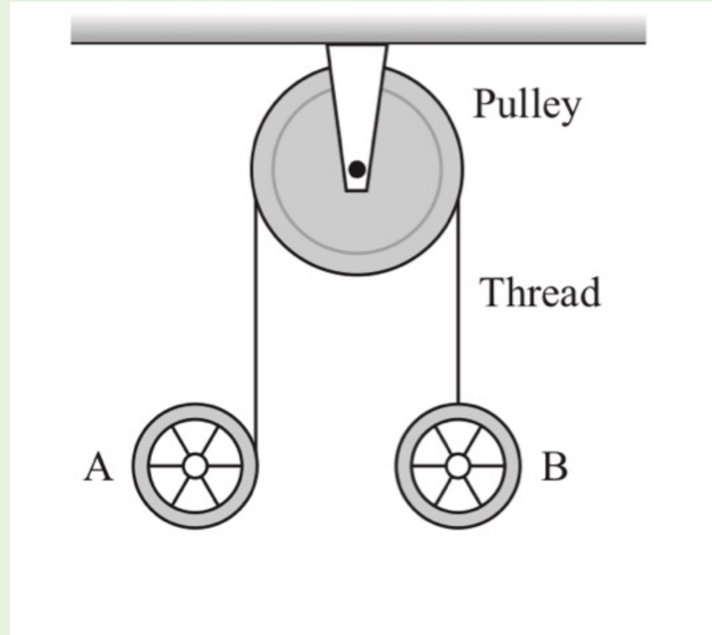
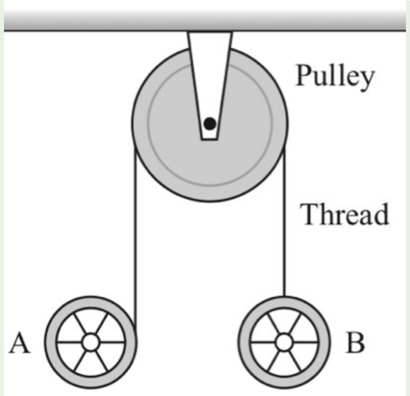




Dynamics of rigid bodies, page 3



- What would each student on the previous page predict?

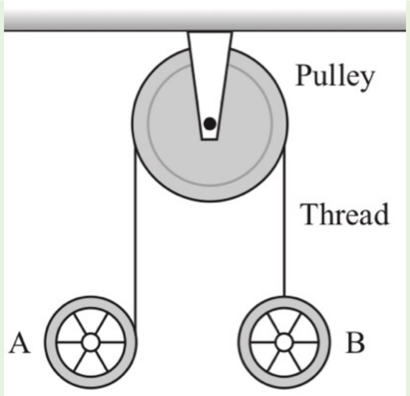
1. They have the same mass and same net force so the centers of mass have the same acceleration. The tensions have the same effect on translational motion.

   Same forces, same mass → **A lands at same time as B**

2. Some tension is used to rotate the spool. When a force causes rotation, it has less effect on translation.

3. I was thinking about energy. They have the same total kinetic energy at the finish line. Since the spool has some rotational KE, it must have less translational KE.

Dynamics of rigid bodies, page 3



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   T has less effect on A so A has larger net force down → **A lands before B**

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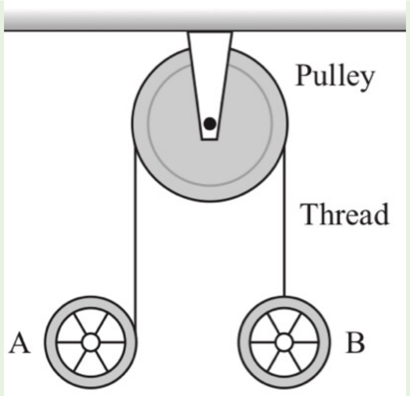
Dynamics of rigid bodies, page 3



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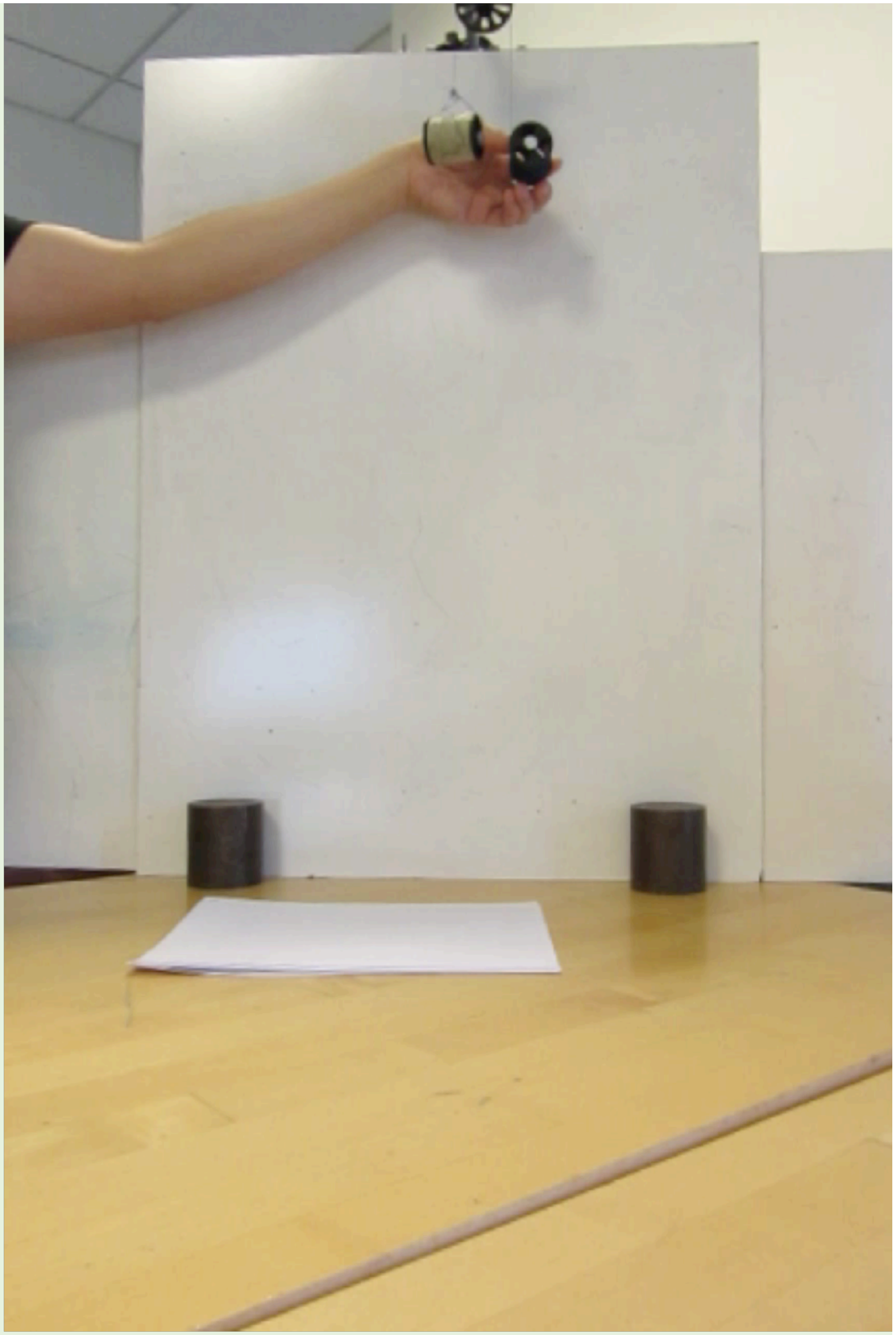
   T has less effect on A so A has larger net force down → **A lands before B**

3. I was thinking about energy. They have the same total kinetic energy at the finish line. Since the spool has some rotational KE, it must have less translational KE.

   Same total energy, A has rotational and kinetic → **A lands after B**

Three different predictions

Spools connected by string



Small group activity: page 4

F. Suppose you want to decide how a given force affects the translational motion of the center of mass of an object. Should you consider:

- where on the object the force is exerted?
- how the force is affecting the rotational motion of the object?

In the *Tutorial homework,* students reconcile their results with work and energy

Assessments of student learning

- **Pretests**: After all lecture & textbook instruction but **before tutorial**.
  - Provide motivation for tutorial and yield insights into student reasoning
  - Many versions used to test aspects of student understanding

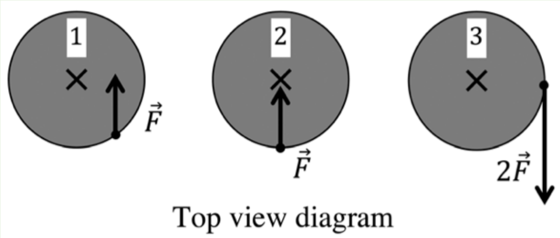
- **Post-tests:** After all instruction including *Tutorial* and *Tutorial Homework.*
  - Typically somewhat more difficult or in different context than pretests

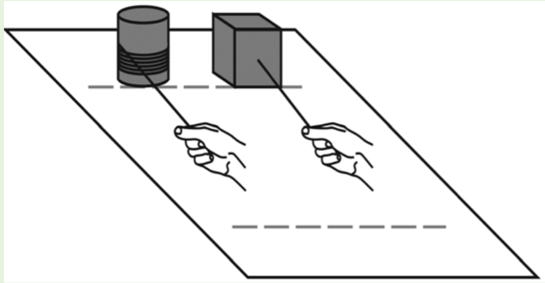
Note: Results are usually independent of instructor or textbook
with variations of *about* $\pm$*5% from class to class.*

"Student understanding of the application of Newton's second law to rotating rigid bodies," H.G. Close, L.S. Ortiz, and P.R.L. Heron, *Am. J. Phys.* **81** (6) 2013

Results from many Pretests & Post-tests

Sample questions:



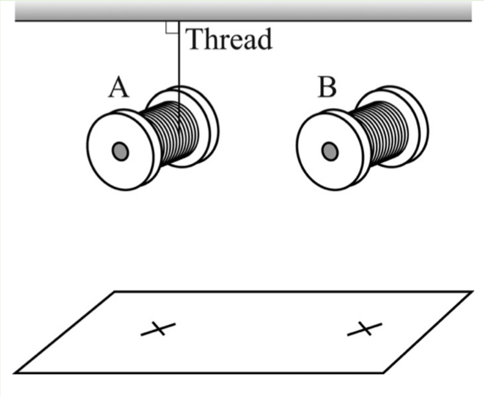


	Various post-tests	
	Pretest	Post-test
Correct (net force independent of point of application)	5%	80%
Treating translation as reduced if a force also results in rotation	80%	< 10%

Many years of research required to obtain satisfactory results:

- **Version 1:**
  - ‘Unconnected spools’
  - Student dialogue (but without having students apply each student’s reasoning to new case)

    → ***some improvement: 20% to 40% correct***



- **Versions 2 & 3**
  - ‘Unconnected spools’
  - Added questions to address directly the idea that the effect of a force on translation is decreased if the force also causes rotation.

    → **only small additional gains (**students could state ‘translation is independent of point of application’, yet answer many questions incorrectly.

- **Version 4:**
  - ‘Connected spools’ experiment developed to target key idea directly (since the forces on both spools are the same).

    → ***~ 70% to 80% correct***

Practical criterion for effectiveness of a tutorial:

Post-test performance of introductory students
matches (or surpasses)
pretest performance of graduate students.

(Graduate TAs ~30% correct on circular pucks question)

Reflections on successful implementation

Initially, students often ‘resist’ working in groups or being asked questions in response to their own questions. (“Just tell me the answer,” or “I don’t learn this way.”)

By the end of the quarter, students rate the tutorials as one of the most important components to their learning and performance in the course.

Critical components:

- Preparation of TAs
  - ~1 hour session in which TAs take pretest; work through tutorials; examine student pretests; and discuss questions to ask of students
  - Requires environment in which TAs are comfortable expressing their reasoning and can make errors without judgement
- Course assessments that match instructional goals
  - Written questions that assess student explanations
    - on homework (for practice and feedback)
    - on exams

Generalization based on findings from research:

It is insufficient for the instructor to

- give clear explanations
- show demonstrations
- assign problems and provide solutions
- be informed about student difficulties

Active mental engagement
by the students, themselves, is necessary.

Caution:

“active learning”
does not always lead to
“intellectual engagement”

Documented research is necessary
to determine the depth of understanding.

Assessments of student learning
at UW and beyond on many topics

Effect of tutorials on student performance

On qualitative problems:

- *much better*

On quantitative problems (e.g., end of chapter):

- typically somewhat better
- sometimes much better

On retention:

- sometimes much better

despite less time devoted to solving standard problems

The tutorials are <u>one</u> example of how, with a small time allotment, a research-based curriculum can help:

- make physics meaningful to students
- provide a foundation for quantitative problem solving
- develop scientific reasoning ability

even under constraints of large class size,
breadth of coverage, fast pace, limited time

The perspective that teaching is a science, as well as an art, is an effective approach for:

- setting high (yet realistic) standards
- assessing the extent to which meaningful learning takes place
- helping students meet expectations