


Metacognition and instructional design:

Theory-driven goals and methods in a large university physics class

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Outline

- Introduction
 - A Theoretical Frame for Education
 - The Impact on Goals and Methods
- Constraints
 - A Large-Lecture College Physics Class
- Preliminary Results
 - Understanding the meta-issues
 - Some first steps
- The Next Steps
 - Giving a voice to epistemology
 - Building independent thinking in laboratories


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The University of Maryland Physics Education Research Group

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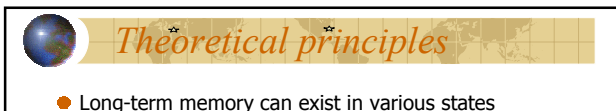
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A Theoretical Frame for Education

- To choose theoretical principles we rely on a triangulation from three independent research disciplines.
 - *Ecological*: observations of normal behavior, in educational environments, (mostly carried out by educational researchers)
 - *Psychological*: responses to simplified experiments designed to get at fundamental cognitive structures, (mostly carried out by psychologists)
 - *Neurological*: studies of the structure and functioning of the brain, (mostly carried out by neuroscientists)


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Theoretical principles

- Long-term memory can exist in various states of activation including (at least):
 - inactive,
 - primed (ready for use), and
 - active (immediately accessible).
- Memory is associative and productive.
 - Activating one element leads, with some probability, to the activation of associated elements.
 - The activation of a memory often contains data, reasoning elements, and mappings of the memory elements onto input structures.
- Activation and association are context dependent.
 - What is activated and subsequent activations depend on the context, both external and internal (other activated elements).

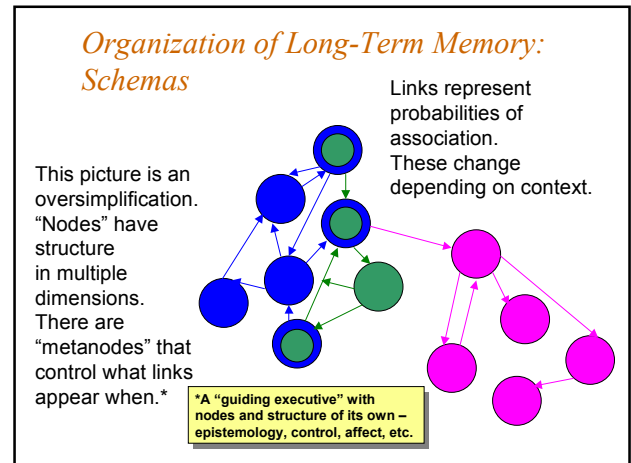
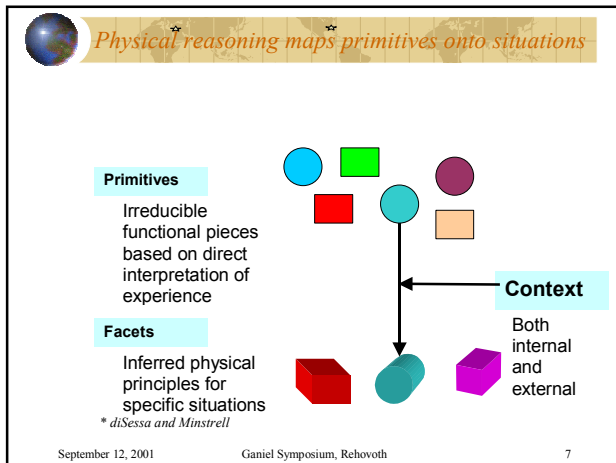
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Some structures in LTM

- Reasoning primitives
 - abstract general reasoning tools
- Facets
 - mappings of primitives into real-world situations to generate principles of how the world works
- Schemas
 - associational groups of elements
- Mental models
 - robust schemas useful in a variety of situations
- Ontological (physical) models
 - mental models based on objects, their properties, and interactions

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- Implications**
- This model leads to an understanding of what students bring into a classroom that we call *fine-grained constructivism*.
 - Student misconceptions are often
 - productive (created on the spot)
 - structured
 - context dependent.
 - The knowledge and associations students bring in to class are the *resources* from which their new knowledge must be built.
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- The Impact on Goals and Methods**
- Goals need to focus not only on the correctness of elements of knowledge but on their associational structure.
 - *Develop effective functionality.*
 - *Create strong mental models.*
 - Instructional methods can be more effective if they can identify existing student resources.
 - *Remap don't replace.*
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- The "Meta" Level**
- The above structures sit in a "frame" that governs and controls these structures.
 - "Executive function" in cognitive models.
 - Of great importance for situations involving conscious thought and "cognitively rich" processes.
 - Little is available from cognitive or neurological sources. Driven by ecological observations.
 - Triangulate with
 - Sociology
 - Anthropology
 - Linguistics
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- Meta-Learning**
- Metacognition
 - self-knowledge, assessment, and control decisions
 - Epistemology
 - how students access and create knowledge
 - Expectations
 - what students think is appropriate for a physics course
 - Linking to reality
 - making the connection between what students experience and what they learn in a physics course
 - Mental models
 - a coherent organizational structure providing executive functions of access and guiding activation
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The Meta-Level is also Structured.

- In different situations, people rely on different ways of knowing.
 - "A friend told me."
 - "I made it up."
 - "I read it in the newspaper."
- Students use different resources in different environments
 - "Working with someone on homework is cheating."
 - "In lab we don't have to make sense of what we're doing, we just have to get the numbers."

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Epistemological Resources: Expectations and Frames

- Identify the explicit resources students use to access and create knowledge.
 - memory
 - working it out using math
 - asking a friend
 - interpreting in light of personal experience
 - ...
- The set of resources a student thinks is appropriate for a particular environment is an *epistemological frame (e-frame)*.

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Implications

- The e-frames students bring to the educational environments we offer them do not necessarily match the ones we expect them to be using.
- The activities we choose for them not only send messages about the content we want to use but (often un-intended) *meta-messages* about the e-frames they should use.

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The Instructional Environment

- Algebra-based physics
- 3 hours/week of large class (N=100-200) lectures with a professor
- 3 hours/week of small class (N=20-30) recitation/lab with a GA
- Two 14 week semesters
- One Graduate Assistant (20 hrs/wk) for each 40-50 students

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The Constraints

- Additional personnel are not available.
- Students have a range of abilities but
 - many are weak in math (or think they are)
 - many are hostile to physics
- Almost all students are taking the class because it is required.
- A wide range of majors are included
 - mostly biology (40-80%)
 - many health-care pre-professionals (~40%)
 - architects, computer scientists, some engineers
- Most traditional topics must be "covered".

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The tools we have used so far

- In lecture
 - Interactive Lecture Demonstrations
 - Modified cognitive conflict
 - pairing correct and incorrect elements of student conceptions and refining intuition for consistency.
- In recitation
 - UW Tutorials
- Out of class
 - Modified homework problems

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Some First Steps

- Changing the classroom discourse
 - Adding epistemology to Interactive Lecture Demonstration
 - Understanding what makes a Tutorial work.
- A more complex view of problem solving
 - Building the physics problem
 - Adding reality to representations

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Changing the Nature of Classroom Discourse: Adding Epistemology to ILDs

- ILDs (Interactive Lecture Demonstrations) have proven effective in helping students build strong concepts in a large lecture environment.
- However, the “meta-message” sent by an ILD does not support our meta-learning goals.

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Interactive Lecture Demonstrations

- Present students with a series of demonstrations
 - Usually make use of MBL data collection
 - Students have 2 copies of the worksheet
- Structure
 - Instructor shows demo without collecting data
 - Students make prediction (on worksheet 1)
 - Students discuss among themselves
 - Brief whole-class discussion
 - Instructor does demo
 - Students put correct answer on worksheet 2
 - Students hand in worksheet 1 and keep worksheet 2

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The Trouble with ILDs

- ILDs send a number of inappropriate meta-messages.
 - “We are seeking the right answers and only the right answers.”
 - “Your initial (probably wrong) answer and your intuition are not valuable.”

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Modifying the Meta-Message in an ILD

- Before data is collected, ferret out more answers.
 - Give “your roommate’s answer” — be creative!
 - Meta-message: “We are interested not just in the right answer but in the range of all possible answers and in understanding why an answer is right or wrong.”
- After data is collected, discuss what was right in the various answers as well as what was wrong.
 - Meta-message: “Your intuitions are valuable. They may need to be refined, but you can build on them.”

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The Impact

- Asking for “your roommate’s answer” or “to be creative” seemed to remove the stigma from giving what they feared might be a wrong answer.
- Many more students were willing to become involved in the discussion — even in a large lecture. (~40% of a class of 100)

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Understanding Tutorials

- The UW Tutorial package has a strong epistemological character.
 - Students are guided to use qualitative reasoning to
 - decide the implications of a belief or principle
 - expose contradictions in their personal knowledge and beliefs
 - Analyzing student behavior in tutorials using an epistemological filter helps understand why they work for some students and not for others.
 - The Tutorial e-frame has to be negotiated.

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The trouble with traditional "end-of-chapter" problems

- Traditional problem solving sends a number of inappropriate meta-messages.
 - "The important part of solving a problem is finding the right equation to use and the subsequent mathematical manipulations."
 - "What matters in solving a problem is getting the correct numerical answer."

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A More Complex view of Problem Solving

- Problem solving involves not just mathematical manipulations. It involves many meta-learning elements.
 - Calling on intuition for setting up a problem
 - Extracting, viewing, and developing knowledge that is represented in a variety of ways.
 - Calling on personal real-world experience for evaluating and interpreting the result

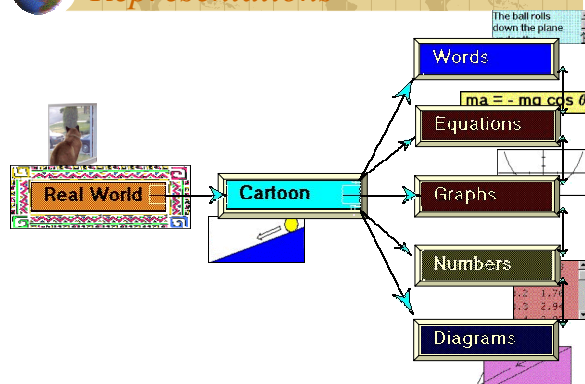
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Representations



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Building the Physics Problem

- Given a real-world situation (*creating the cartoon after choosing a channel on Cat-TV*), building a physics problem that can be solved by mathematical manipulation is one of the more difficult components of solving physics problems.
- Traditional end-of-chapter exercises often bypass this step, providing the student with clues (like a "keyword" analysis) that allow them to create the problem trivially by symbol mapping.

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Adding reality to representations

- Students often see graphs and equations as end products rather than as tools for creating knowledge.
 - Equations are ways to calculate a number, not a way to represent relationships.
 - Graphs are something to create to satisfy the instructor, not as a way of storing, codifying, or extracting knowledge about the real world.
- Changing this expectations requires new kinds of activities and new kinds of tests.

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Some Non-Traditional Physics Problems

- If we want students to think about the relation of physics to their real-world experience we need to expand the class of problems we ask students to solve.
 - Representation translation problems
 - Estimation problems
 - Conceptual and essay questions
 - Context-based reasoning problems
 - Problems without an answer

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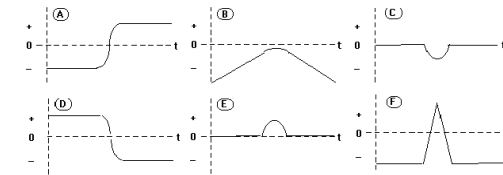
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A representation translation problem

Two carts on an air track are pushed towards each other. They bounce off each other elastically. The graphs describe some of the variables associated with the motion as a function of time. For each item in the list below, identify which graph is a possible display of that variable as a function of time. If none apply, write N (for none).

- the momentum of cart 1
- the force on cart 2
- the force on cart 1
- the position of cart 1.
- the position of cart 2



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Some estimation problems

Early in the semester

Later in the semester

Estimate the number of blades of grass a typical suburban house's lawn has in the summer.

According to Newton's law of universal gravitation, the earth's gravity gets weaker as we go further from the earth. But when we drop a ball near the top of the lecture hall it doesn't seem to fall any differently than we drop it near the floor.

Let g_t stand for the gravitational acceleration observed at the top of the lecture hall and g_b for it at the bottom. Estimate how much Newton's universal gravitation theory predicts g_t will be less than g_b . (Hint: It's easier if you estimate the fractional change, $g_b/g_t - 1$.)

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A real-world conceptual problem

In public restrooms there are often paper towel dispensers that require you to pull downward on the towel to extract it. If your hands are wet and you are pulling with one hand, the towel often rips. When you pull with both hands, the towel can be extracted without tearing. Explain why.



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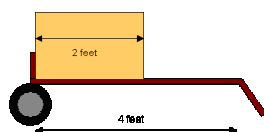


A context-based reasoning problem

You are working as a staff person on the call-in internet program "Ask Dr. Science." The following e-mail message comes in and needs a quick answer.

My wife just called me at the office and asked the following question. We had a large computer monitor delivered to her home office this morning. The delivery person was kind enough to put the box on our hand truck but he put it on while the truck was lying flat. My wife has some back problems and doesn't want to have to exert more than 50 pounds of force. The monitor in its box weighs about 85 pounds. She's having a business meeting at the house later and would like to get the box out of the front room. What I want to know is, can she stand the truck upright safely without hurting her back?

Is it safe for his wife to pull the handtruck upright so she can roll the box into the backroom? Be sure to explain why you think so.



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A problem without an answer

Five clocks are being tested in a laboratory. Exactly at noon, as determined by the time signal from Greenwich, on successive days of a week, the clocks read as in the following table. Rank the 5 clocks according to their relative value as good timekeepers, best to worse. Justify your choice.

Clock	Sun.	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.
A	12:36:40	12:36:56	12:37:12	12:37:27	12:37:44	12:37:59	12:38:14
B	11:59:59	12:00:02	11:59:57	12:00:07	12:00:02	11:59:56	12:00:03
C	15:50:45	15:51:43	15:52:51	15:53:39	15:54:37	15:55:35	15:56:33
D	12:03:59	12:02:52	12:01:45	12:00:38	11:59:31	11:58:24	11:57:17
E	12:03:59	12:02:49	12:01:54	12:01:52	12:01:32	12:01:22	12:01:12

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The Impact

- We interviewed students and asked:
"What that you are learning in physics class do you expect to be useful to you in two years?"
 - Traditional students
(N=10, middle of first semester)
 - Students in the "meta-learning" class
(N=13, end of second semester)

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Responses of traditional students

No (6 / 10)

"physics has nothing to do with my major, I know I'm just going to take the class, and that's about it.... I know it's not going to help me in my later career, but biochem, at least it has some applications"
Beach

It's possible (1 / 10)

"like biomechanics, with the torque around your wrists and the pressure that you put on a bone that causes it to break.... I could see how this could be relevant if I know it, but since I don't, I'm just praying that it's not going to be relevant."
Liz

They tell me I will (1 / 10)

"So I believe that people that planned the physics, they know that one day these people are going to use physics, that's why it's there. So I think it will be very helpful, because they've planned it like that."
Uta

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Responses of our "new and improved" students

Content Useful (7 / 13)

"a lot of things I learned here that are biology related obviously have immediate benefits....the homework problem we just returned this week with the radioactive nuclei of the gold, the cancer, I can see how that relates and I can understand from the physics there and the biology that I've learned..."
Thomas

Problem Solving (7 / 13)

"I now have the ability to look back at different problems and divulge more, to kind of step back from them and overall look at it and see if there's a way I can solve it using what I know, not having to ask for help.... Because I was actually able to solve problems in other classes..."
Arnold

"My friends in the other classes they sit there and memorize formulas and I would just look at something and try to understand what's behind it and I find that I do better on the [MCAT] diagnostic tests than they are, and they're just like whoa, because I used to be really bad at physics..."
Joshua

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Quantitative Results

- Maryland Physics Expectations Survey (MPEx)

- A 34 item Likert scale survey testing what students think they need to do to succeed in physics class
- Traditional classes and reformed concept-building classes show consistent pre-post losses on all categories.

- Force Concept Inventory (FCI) and Force-Motion Concept Evaluation (FMCE)

- Multiple-choice surveys in common speech with research-based distractors.
- Traditional classes show small pre-post gains that depend strongly on the lecturer.
- Concept-building reform classes show larger pre-post gains that are less dependent on the lecturer.

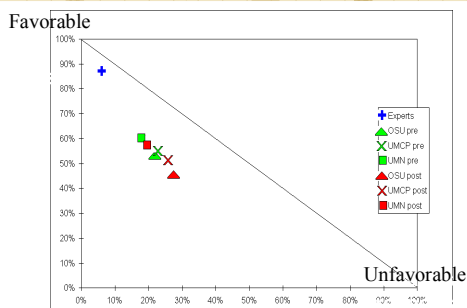
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Overall Results: Large Universities (M)



- Introductory mechanics (C) at 3 large research universities: ~500 each
- Initial distribution far from ideal.
- Result of instruction is a loss.

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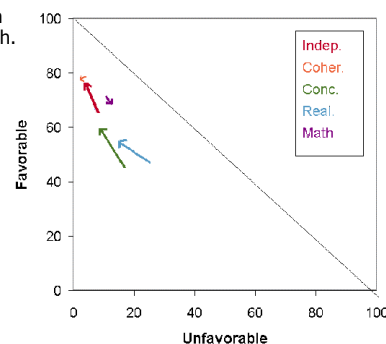
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


MPEx Results in Metaclass Trial

- Coherence and math started high and remained high.
- Strong improvements in independence, coherence, and reality.
- Improvements represent both increases in favorable and decrease in unfavorable responses.



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 *Some notable MPEX gains*
(N = 60; F = disagree)

- "Problem solving" in physics basically means matching problems with facts or equations and then substituting values to get a number. (#4)
- My grade in this course is primarily determined by how familiar I am with the material. Insight or creativity has little to do with it. (#13)
- Learning physics is a matter of acquiring knowledge that is specifically located in the laws, principles, and equations given in class and/or in the textbook. (#14)
- The most crucial thing in solving a physics problem is finding the right equation to use. (#19)


	Favorable	Neutral	Unfavorable
Pre	66%	30%	4%
Post	91%	9%	0%

	Favorable	Neutral	Unfavorable
Pre	57%	40%	3%
Post	79%	19%	2%

	Favorable	Neutral	Unfavorable
Pre	36%	53%	11%
Post	64%	34%	2%

	Favorable	Neutral	Unfavorable
Pre	45%	45%	10%
Post	72%	26%	2%

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 *Algebra-based ('00)* *Calc-based ('95)*

	F	N	U
Pre	66%	30%	4%
Post	91%	9%	0%

	F	N	U
Pre	60%	21%	19%
Post	77%	13%	10%

	F	N	U
Pre	57%	40%	3%
Post	79%	19%	2%

	F	N	U
Pre	54%	24%	22%
Post	49%	23%	28%

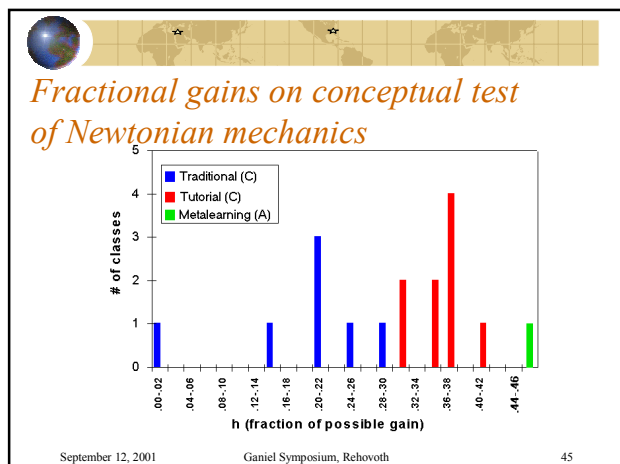
	F	N	U
Pre	36%	53%	11%
Post	64%	34%	2%


	F	N	U
Pre	39%	28%	33%
Post	37%	24%	39%

	F	N	U
Pre	45%	45%	10%
Post	72%	26%	2%

	F	N	U
Pre	43%	32%	25%
Post	46%	26%	28%


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 *The Next Steps*

- Giving a voice to epistemology
- Building independence in the laboratory

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 *Giving Voice to Epistemology*

- In addition to focusing on teaching content, we will develop names for the various
 - "epistemic games"
 - "epistemic forms"
 and explicitly discuss how we develop and evaluate knowledge.

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 *Examples of epistemic games*

- Restricting
- Sense-making
- Shopping for ideas
- Refining intuition
- Checking consistency
- Creating foothold ideas
- ...



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Building independence in the lab

- Laboratories are deeply epistemological activities.
 - Students investigate how we know and why we believe what we know.
- Laboratories are deeply rhetorical activities.
 - Uncertainty (error) analysis is about convincing and communicating with others about what we have learned.

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A radical reformation

- This year, we are attempting a redesign of our lab based on epistemological analysis.
 - Students are given equipment and a task without explicit instructions.
 - The lab is structured into planning, discussion, experimental, and evaluation segments.
 - Specific discussion of knowledge games will take place.
 - Students will have to present and discuss their results to the class.

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Conclusion

- Learning concepts is an essential part of learning physics — but only a part.
- The hidden meta-messages that we send our students can have important (often un-intended) consequences on what they learn.
- Understanding how students seek knowledge in different contexts can help us better understand and design our instruction.

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