Teaching Physics Sensemaking to Physics Majors

Dr. Elizabeth Gire
("Jeery")
Oregon State University
She, Her, Hers

Oregon State University PER Physics Education Research

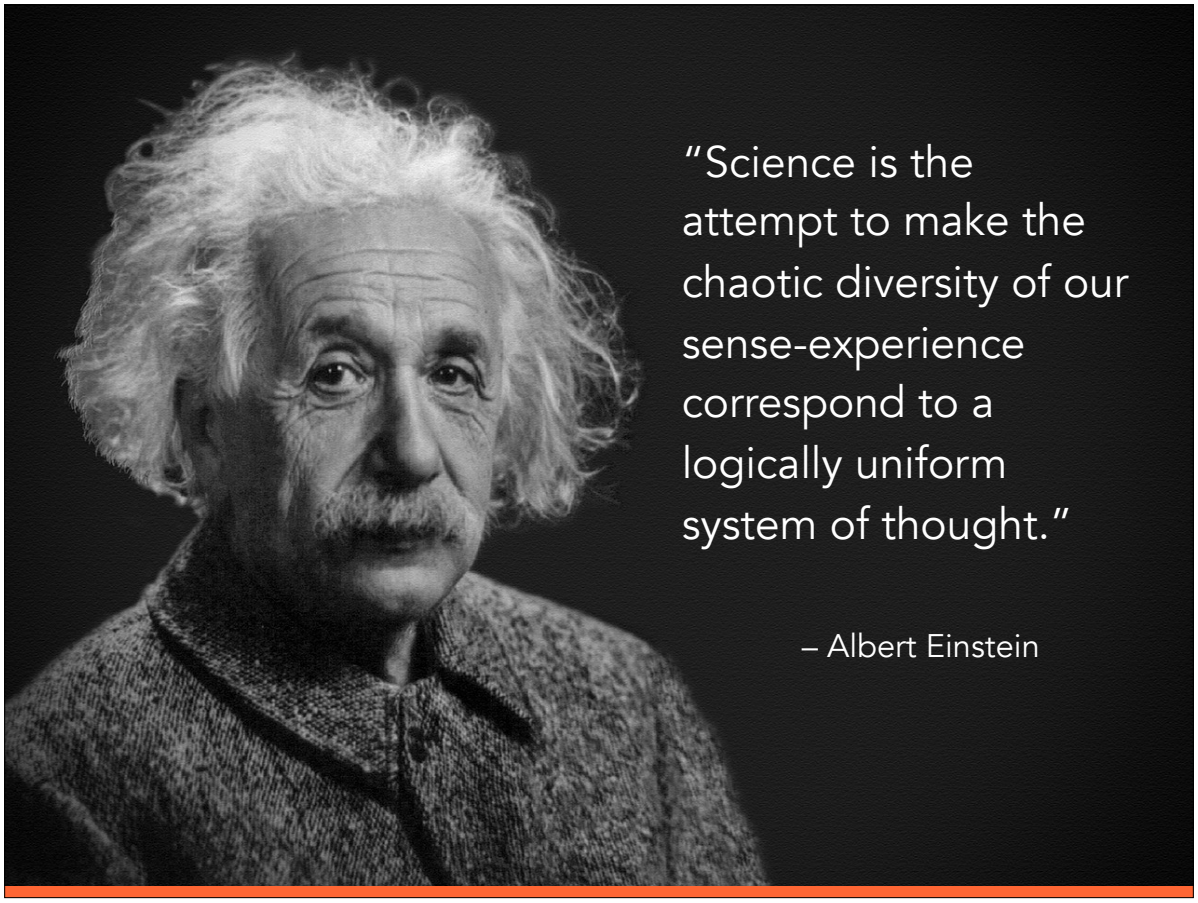
Kelby Hahn

MacKenzie Lenz

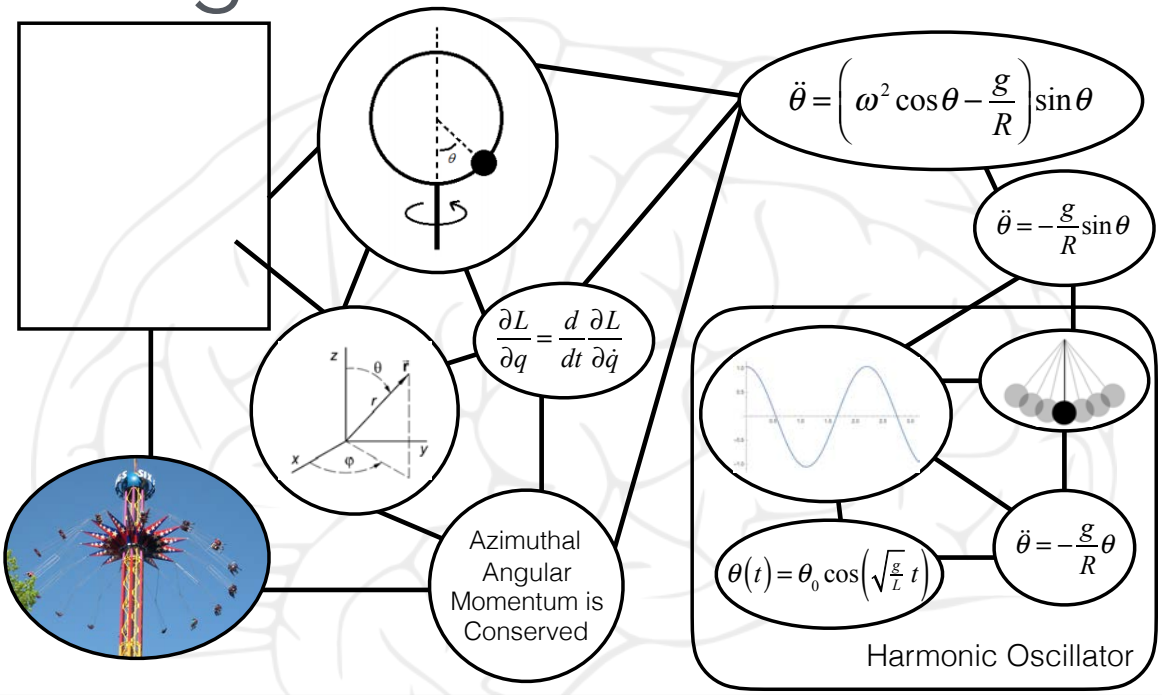
Paul Emigh

Some Big Questions

- What is "physics sensemaking"?
- How can learning to do physics sensemaking be supported in instruction?

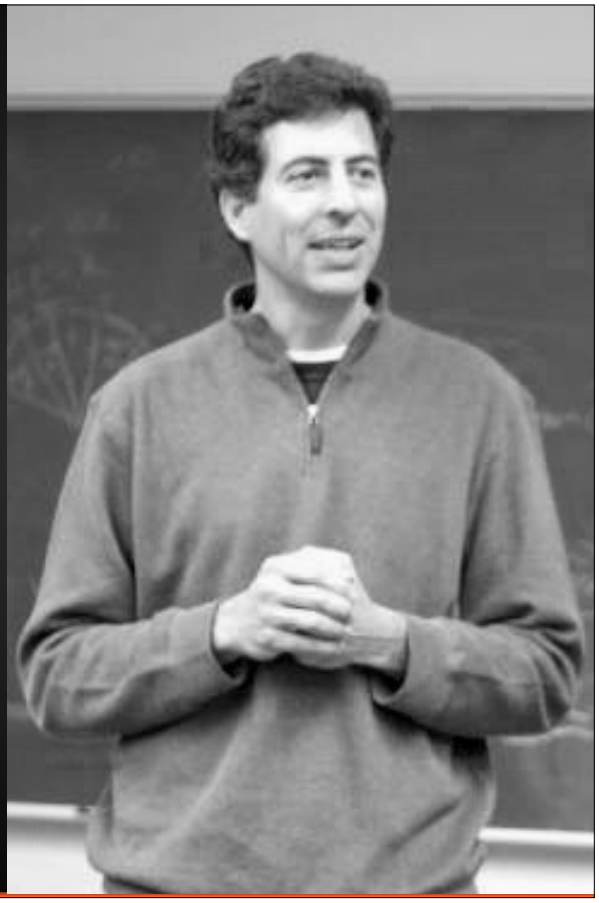


Cognitive Science



"Physicists are representation junkies."

– Charles de Leone



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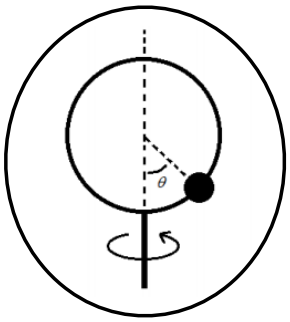
Physics Sensemaking

seeking meaning or coherence
between representations of physics knowledge



$$\ddot{\theta} = \left(\omega^2 \cos\theta - \frac{g}{R}\right)\sin\theta$$

Azimuthal Angular Momentum is Conserved

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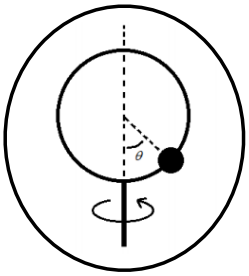


Real World Observations

5	3			7				
6			1	9	5			
	9	8					6	
8				6				3
4			8		3			1
7				2				6
	6					2	8	
			4	1	9			5
				8			7	9

Physics Problem

Physics Concepts

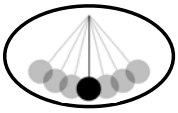
Azimuthal Angular Momentum is Conserved

Equations

$$\frac{\partial L}{\partial q} = \frac{d}{dt}\frac{\partial L}{\partial \dot{q}}$$

Related Problems

Intuitions

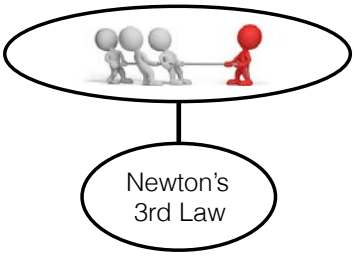


9	7	4	1	6	8	5	3	2
5	3	2	9	4	7	1	8	5
6	1	8	5	3	2	7	9	4
1	6	7	2	5	3	8	4	9
4	5	9	7	9	6	3	2	1
2	8	3	4	9	1	6	7	5
3	4	5	6	7	9	2	3	8
7	9	1	8	2	5	4	6	3
8	2	6	3	1	4	9	5	7

Not finding coherence is an opportunity for learning.

Sensemaking in PER

Physics Concepts & Everyday Experiences



e.g. Tutorials in Physics Sensemaking

Scherr, Elby, Redish, & Hammer, 2001

Equations & Conceptual Relations

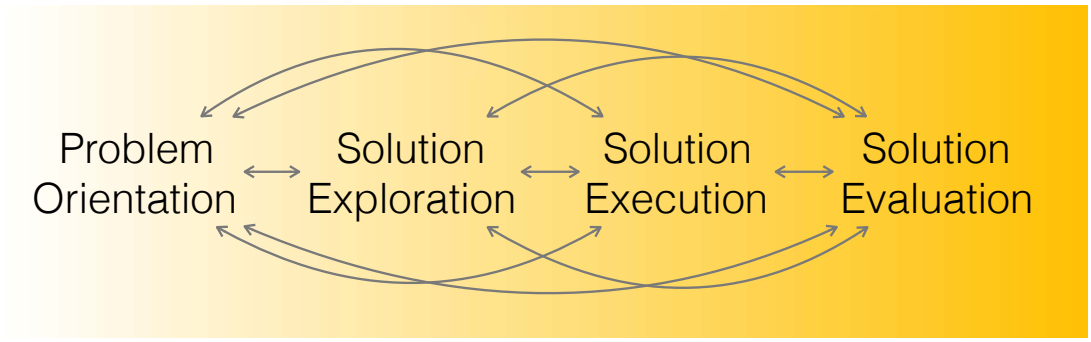
$$\ddot{\theta} = \left(\omega^2 \cos\theta - \frac{g}{R}\right)\sin\theta$$

Competing Terms

e.g. Symbolic Forms

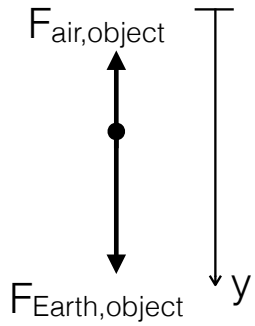
Sherin, 2001

Sensemaking & Problem Solving



Object falls near earth with a quadratic air resistance

$$v = \sqrt{v_T^2 - \left(v_T^2 - v_0^2\right) e^{-2gy/v_T^2}}$$



Does this equation describe the speed of the object after it has fallen a distance *y* ?

Sensemaking: Evaluation

- "Beasts"
  - Balancing "Beasts"
  - Appropriateness for Situation
- Answer Contextualization/Comparison
  - Problem/Answer Simulation
  - Reasonable Number
  - Multiple Solution Paths

Beasts

Beasts

- Scalars, Vectors, Matrices

$$\begin{bmatrix} \hbar/2 & 0 \\ 0 & -\hbar/2 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \frac{\hbar}{2}\begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

- Constant, Parameter, Variable

$$V(s,\phi,z) = \int_0^{2\pi} \frac{k\lambda R\, d\phi'}{\sqrt{s^2 + R^2 - 2sR\cos(\phi - \phi') + z^2}}$$

- Extensive vs. Intensive

$$dU = T\,dS - p\,dV$$

- Infinitesimal vs. "Large"

$$dU = T\,dS - p\,dV$$

A Hypothetical Learning Progression for Units & Dimensions

Checking Fundamental Units

kg, m, s

Checking Fundamental Dimensions

Mass, Length, Time

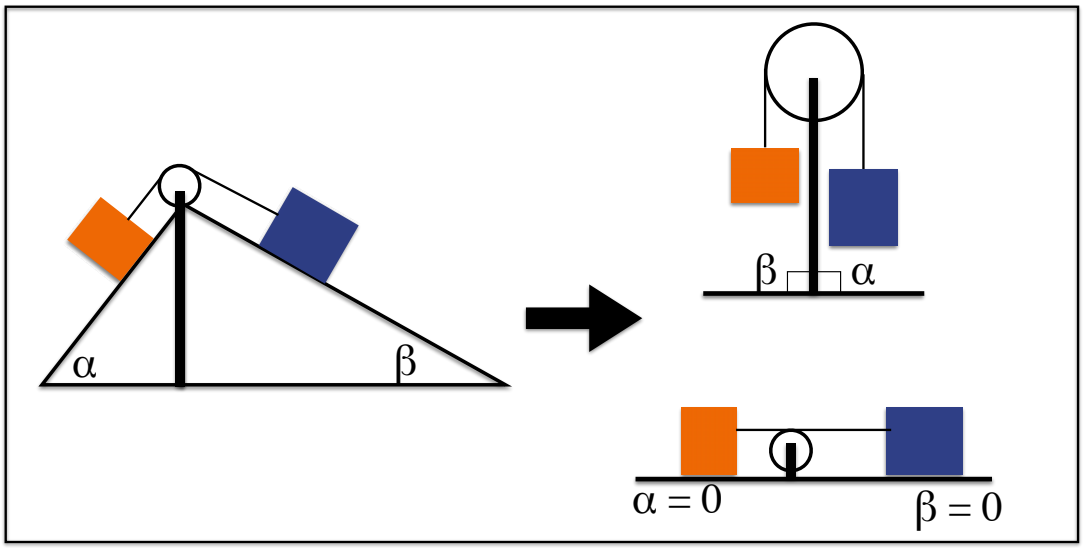
Checking Compound Dimensions

$$\frac{kQ}{R}, \quad IR, \quad E\Delta x$$

Generative Dimensional Analysis

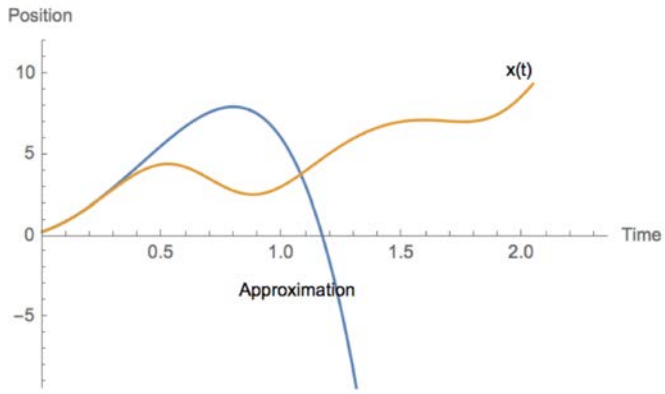
Street Fighting Physics, Mahajan, 2010

Answer Contextualization/Comparison



Problem/Answer Simulation

- Special Cases
- Limiting Cases & Approximations
- Functional Dependence & Behavior



How we teach physics sensemaking: Dimensional Analysis

- Demonstration

"I'll try to point out when there are ways of checking the answer by checking the dimensions… I haven't written problems that instruct them on how to do it properly or do it at all."

- Grading Practices

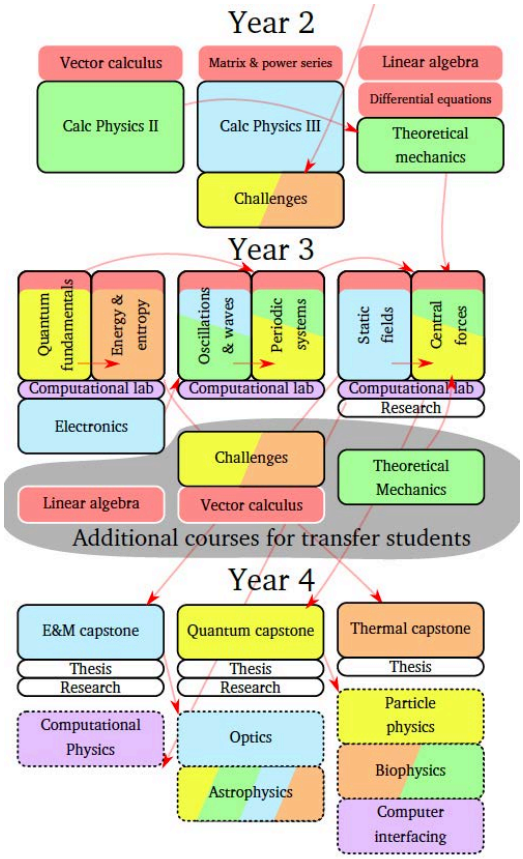
"It's something I remember my freshman professor pointing out that, he's like, 'you get hardly anything off if you just make a little mistake somewhere in your math but if your units don't match up, or your dimensions, then you get a lot off. It means you have no idea what you're doing."

Lenz & Gire, 2016

"If you don't assess what's important, what's assessed **becomes** important."

– Lauren Resnick

Paradigms 2.0



What is needed for Mathematical Problem Solving?

- Resources → Math Concepts & Definitions
- Heuristics → Problem Solving Strategies
- Control → Metacognition
- Beliefs → Epistemologies

Schoenfeld, 1985

Instructional Implications?

• Know what to do	➡ Physics Laws & Concepts	→ Intermediate Level
	➡ Sensemaking strategies	→ Explicit discussion/tags
	➡ Relevant knowledge/ experiences	→ Review idealized systems (projectiles, harmonic oscillator)
• Know when to do it	➡ Metacognition	→ Metacognitive prompting → Modeling & Scaffolding/Fading
• Know its something *they* should do	➡ Beliefs & Epistemic Framing	→ "Professional practice" → Active engagement
• Value it	➡ Reward	→ Reward structure

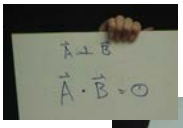
Ph335: Teaching Physics Sensemaking

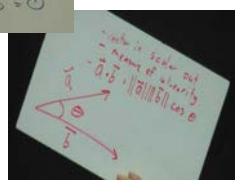
Mechanics Topics	Math Topics	Sensemaking
Velocity Dependent Forces	ODE's by Separation	Units/Dimensions
Lagrangian Mechanics	Generalized/Curvilinear Coordinates	Functional Behavior
Undetermined Lagrange Multipliers	Power Series	Signs/Directions
Intro to Hamiltonian Mechanics	Partial Derivatives	Special Case Analysis
Special Relativity	Matrix Algebra	Power Series Approximation
	Circle/Hyperbola Trig	Conceptual Connection
		Relate to Prior Knowledge
		Visualization
		Predict the Form of the Answer

Pedagogy

- Small Whiteboard Questions
- Small Group Problem Solving
- Whole Class Discussions About Sensemaking Strategies
- Metacognitive Prompting
  - What are you doing? (precisely)
  - Why are you doing it? (fit in solution)
  - How is it useful? (do with result)

  (Schoenfeld, Handbook for Research on Mathematical Teaching and Learning, 1992)
- Sensemaking-Enhanced HW
- Computer Visualization with Mathematica





Student-Generated Sensemaking Strategies List

- Dimensional Checking
- Direction/Sign of Answer
- Reasonableness of Answer
- Graphical Analysis
- Limiting/Special Cases
- Compare to what you know
- Plug answer back into start
- Proportionality
- Assumptions/Idealizations

Enhanced HW - Year 1

Early Assignments → Strategies Prescribed

Linear & Quadratic Air Resistance (*modified from Taylor 2.40*) Consider an object that is coasting horizontally (positive x direction) subject to a drag force $f = -bv - cv^2$.

(a) Write down Newton's 2nd Law for this object and solve for v by separating variables.

(b) *Sense-Making: Visualization* Plot $v(t)$ and describe how the shape of this plot makes sense.

(c) *Sense-Making: Consider a Limiting Case* Explain the time dependence for large t (Which force term is dominant when t is large?).

Later Assignments → Generic Sensemaking Prompt

(b) Use at least three different sense-making strategies to evaluate your answer.

Some Research Questions

- When you ask students to "make sense" of a physics equation, what do they do?
- Do students get better at physics sensemaking?
  - More proficient?
  - More productive?
  - More often? Unprompted?
- How do students experience the course?
  - New strategies?
  - Getting better at using strategies?
  - Using strategies when unprompted?
  - Find strategies useful?
  - Use strategies outside of class?

Sensemaking from open-ended prompts on homework

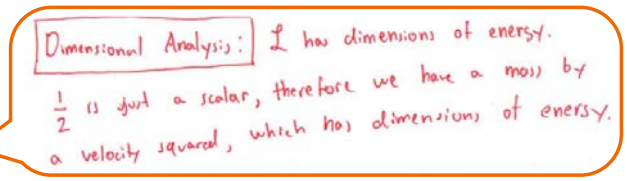
825 instances of sensemaking from n=29 students

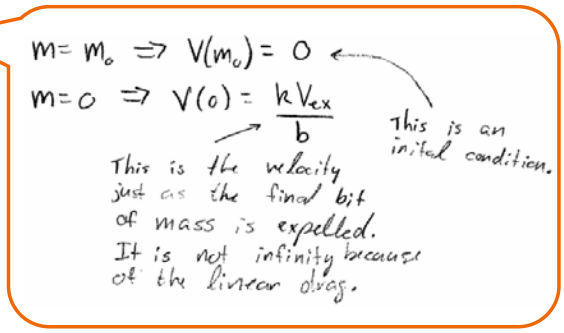
25% Dimension Checking

22% Special/Limiting Case

18% Conceptual Connection

14% Functional Dependence





Hahn, et al., PERC 2017

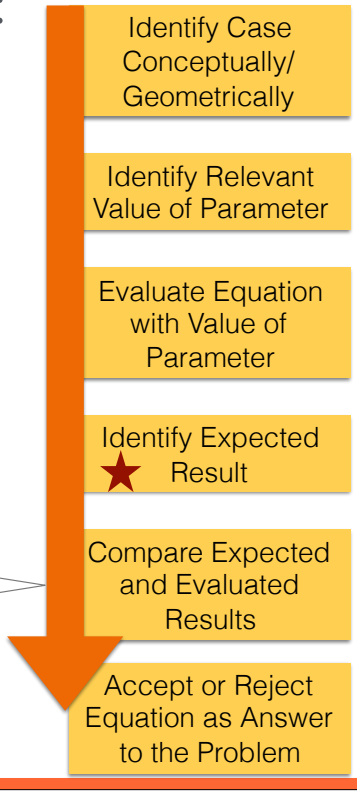
Evidence From Homework: Special Case Analysis

If Strategy Was Prescribed:

- compared conclusion to a "known result"
- related conclusion to the physical set up

If Strategy Was Not Prescribed

- related the variables to the real world
- related conclusion to a fundamental physics concept



Hahn, in preparation

Enhanced HW - Year 2

i. **Anticipate:** Discuss what you expect the answer to look like. Your discussion should include:
- the kind of "beast" (mathematical entity) it is,
- the dimensions of the answer,
- any functional behavior you expect,
- any special cases you could use to check your answer at the end

ii. **Do:** Find the position vector of the particle and write the components in terms of ω and t.

iii. **Evaluate:** Does your answer match your expectations you listed in 2(a)i?

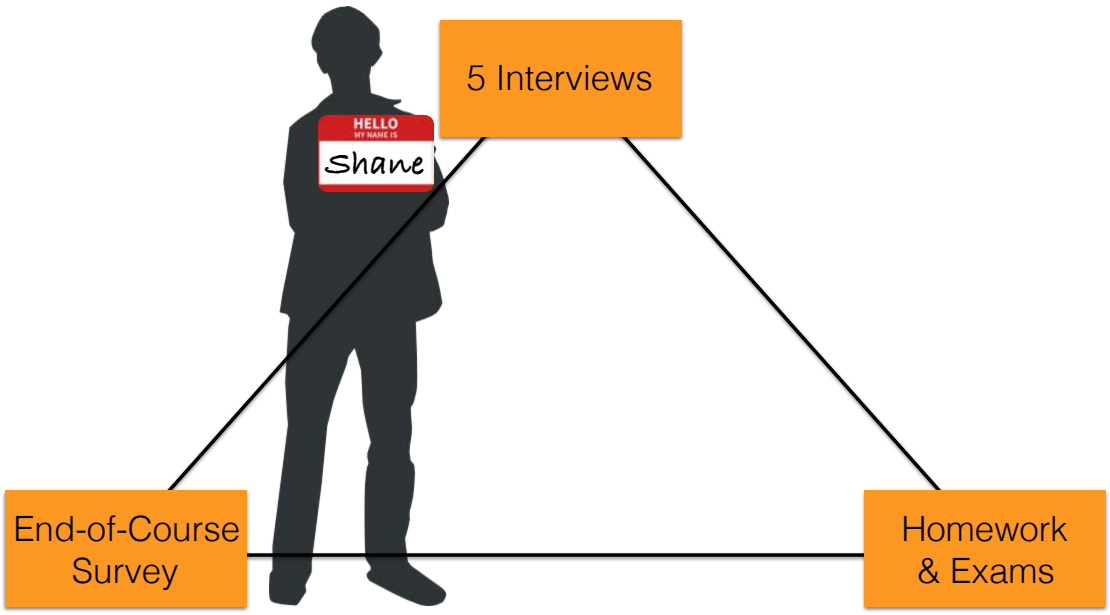
A. What "beast" is your answer? Is this appropriate?

B. What are the dimensions of your answer? Are they appropriate? (Are all the terms dimensionally consistent? Are the arguments of special functions dimensionless?)

C. Describe the functional behavior of your result, including major features of the behavior, and explain why it is or is not reasonable for this problem situation using diagrams and/or conceptual arguments. Plot the x and y components as the particle goes around the circle once.

D. What are the values of your answer for the special cases you identified in 2(a)i?

Case Studies of Student Experience



Lenz, et al., 2017

Case Studies of Student Experience

Started with informal knowledge of strategies

"I wouldn't say I've learned anything new or if there was anything really outstanding for me"

"I've learned, kind of, new ways to apply the [sense-making strategies] I already knew." (when talking about relativity)

Lenz, et al., 2017

Case Studies of Student Experience

Use of strategies became more formalized and sophisticated

"[Sensemaking strategies] were never talked about in the general physics series. I didn't really exercise the more complicated sense-making strategies. But this class actually creating a list [on next slide] of sense-making strategies brought them together."

"I didn't know that solving the question two different ways was an official sense-making strategy for this class."

Lenz, et al., 2017

Case Studies of Student Experience

Talked about doing unprompted sensemaking in this course and others

"Well I definitely do unprompted sensemaking on the homework where like halfway through my solution I'll actually use a different color... so I'll circle the arguments of some kind of logarithmic function or exponential and I'll just check that its dimensionless, like in the middle of the question."

$$\frac{k}{b}\ln\left(\frac{b}{k}v - v_{ex}\right) - \frac{k}{b}\ln\left(-v_{ex}\right) = \ln(m) - \ln(m_0)$$

$$\frac{k}{b}\ln\left(\frac{\frac{b}{k}v - v_{ex}}{-v_{ex}}\right) = \ln\left(\frac{m}{m_0}\right)$$

arguments are now unitless ✓

Lenz, et al., 2017

Take Home Messages

- Physics sensemaking is central to doing physics
- Teaching physics sensemaking is an equity issue
- Not adequately supported by typical instruction
- We're learning about
  - identifying kinds of sensemaking
  - how students & professionals engage in sensemaking
- A course with a holistic approach toward physics sensemaking can help foster physics sensemaking practices

OSUPER Group

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Paradigms in Physics
DUE- 1323800

Raising Physics to the Surface
DUE-1612480