# Making a Science out of Science Education

Transforming undergraduate physics classes using research in physics education

*University of California, Merced*
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Charles Baily
Physics Department
University of Colorado at Boulder
charles.baily@colorado.edu

PER@C

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**Faculty:**
Michael Dubson
Noah Finkelstein
Valerie Otero
Kathy Perkins
Steven Pollock
Carl Wieman

**Postdocs/ Scientists:**
Stephanie Chasteen
Kelly Lancaster
Laurel Mayhew
Rachel Pepper
Noah Podolefsky

**Grad Students:**
Charles Baily
Kara Gray
Lauren Kost
May Lee
Ben Spike
Robert Talbott III
Chandra Turpen

**Staff:**
J.Blanco,
M Frankel,
K. Kidder
T. Loeblein,
C. Malley,
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L. Wellman

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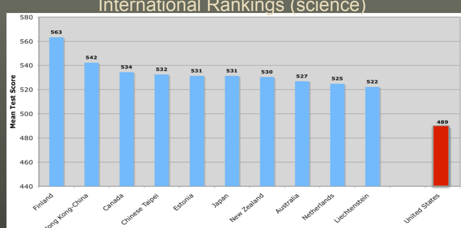
The Kavli Foundation · American Association of Physics Teachers · Physics Teacher Education Coalition · American Institute of Physics · APS · National Math + Science Initiative

# A Crisis in US Education

We need: Better education

U.S. ranks:
21 out of 30 in science
25 out of 30 in math
- PISA 2006

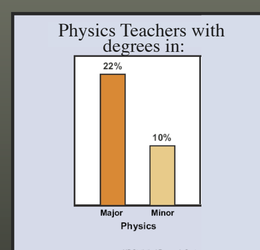
International Rankings (science)




# A Crisis in US Education

We need: Better education
More and better teachers

2/3 Physics Out of Field




# APS/AAPT Doubling Initiative Mission Statement (2007)

We advocate doubling the number of bachelor degrees in physics to address critical national needs including K-12 education, economic competitiveness, energy, security, and an informed electorate.

A call for increases in:

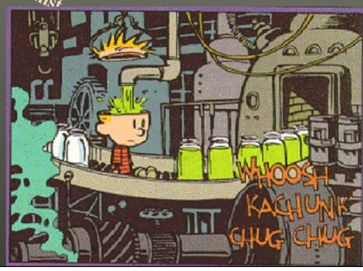
- QUALIFIED HIGH SCHOOL PHYSICS TEACHERS
- WOMEN & UNDER-REPRESENTED MINORITIES
- UNDERGRADUATE PROGRAMS SUPPORTING A VARIETY OF CAREER CHOICES

*How might this happen?*

## Traditional Model of Education

transmissionist

Individual ← Instruction via transmission — Content (e.g. circuits)



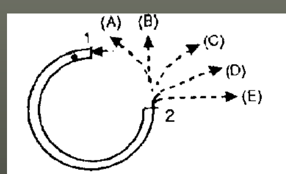

## A possible "tipping" point

- **Force Concept Inventory***
- Multiple choice survey (pre/post)
- Experts (especially skeptics!)

a necessary (not sufficient) indicator of conceptual understanding.

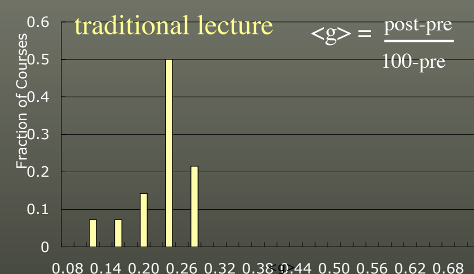
* Hestenes, Wells, Swackhamer, Physics Teacher 20, (92) 141, 1992

## Sample question



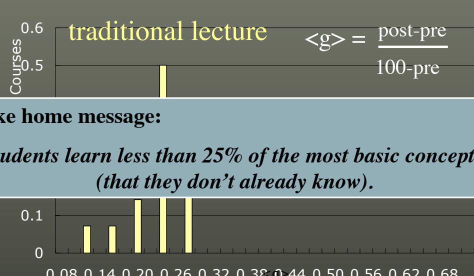

Looking down at a track (flat on table), a ball enters at point 1 and exits at point 2. Which path does it follow as it exits (neglect all friction)?

## We are not teaching students




R. Hake, "…A six-thousand-student survey…" AJP **66**, 64-74 ('98).

## We are not teaching students



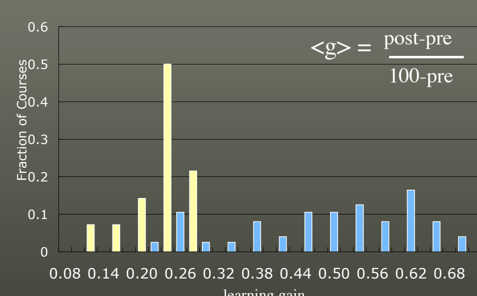

**Take home message:**

***Students learn less than 25% of the most basic concepts (that they don't already know).***

R. Hake, "…A six-thousand-student survey…" AJP **66**, 64-74 ('98).

## Engagement Improves Learning

traditional lecture — interactive engagement




Pollock & Finkelstein, Physical Review, 4, 010101 (2008).

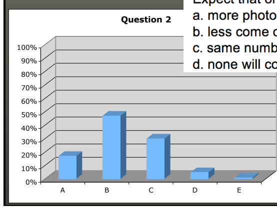
## Overview of PER

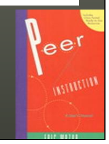
- Far more to our classes than what is traditionally evaluated
  - students are not learning what we want
  - learning some things we would not expect
- Physics education research develops:
  - Tools for assessment
  - Models of student learning
  - curricula / approaches in class

## Personal Response System

Consider ***this*** glass tube full of atoms, discharge lamp

Expect that on average
a. more photons will come out right hand end of tube
b. less come out right
c. same number as go in
d. none will come out.




**U. Washington Tutorials**
50 min/wk, 30 students, 1 grad TA
+ **undergrad Learning Assistant**

**Online HW System**
CAPA or BB

**Phys lecture**
3-600 students
3 lectures/wk
(No lab)

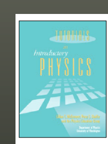
**Text**
trad or PER based

**Interactive Lectures**
Peer Instruction, clickers

## Tutorials in Introductory Physics

**Reconceptualize Recitation Sections**

- Materials
- Classroom format / interaction
- Instructional Role




## Tutorial Materials

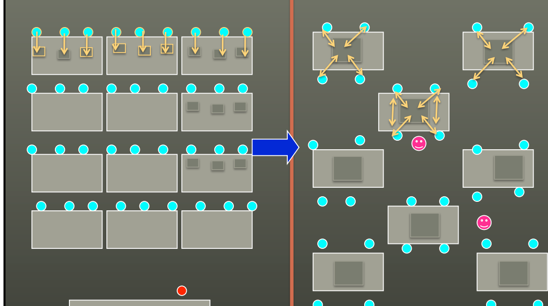
Hands-on, Inquiry-based, Guided, Research-based

**Assignment 11M:** Name ______
**Buoyancy** Tutorial section______

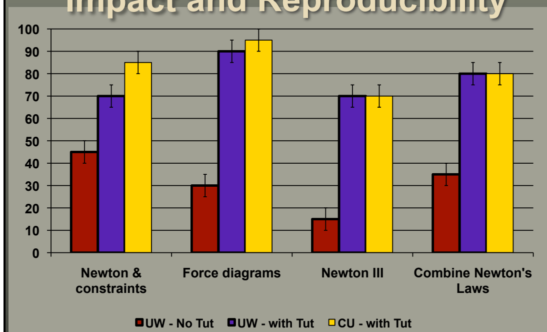
1. Three objects are at rest in three beakers of water as shown.
   a. Compare the mass, volume, and density of the objects to the mass, volume, and density of the displaced water. Explain your reasoning in each case.

| Object floats on top | Object floats as shown | Object sinks |
|---|---|---|
| Is $m_{object}$ (> < =) $m_{displaced\ water}$? Explain | Is $m_{object}$ (> < =) $m_{displaced\ water}$? Explain | Is $m_{object}$ (> < =) $m_{displaced\ water}$? Explain |

## Trad'l Recitation *vs* Tutorial



## Impact and Reproducibility




Trowbridge and McDermott, *Am. J. Phys*. **49** (3), 242 (1981).
Finkelstein and Pollock, (2005). *Phys Rev ST PER*, 1,1.010101

## The impact of recitation/pedagogy

**Physics 1, 300+ students,**
***Peer Instruction* in lecture, and:**

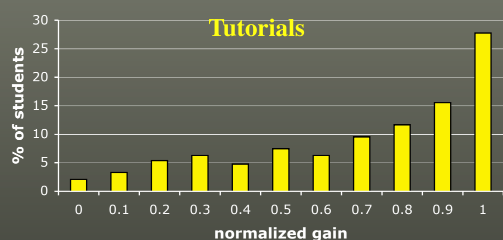
**1: "Tutorials" (Sp04) *Tutorials***

**2: "Workbook" (Fa04) *Knight Workbook***

**3: "Traditional" (Sp05) Mostly traditional**

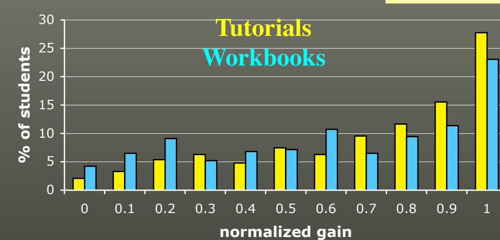
## Phys 1 normalized gains

gain <g>
= .66 +/-.02



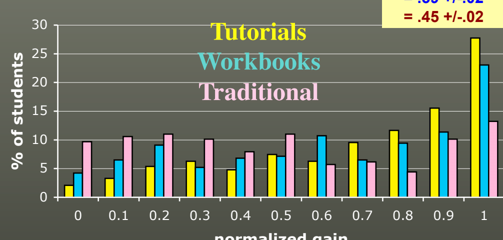

## Phys 1 normalized gains

gain <g>
= .66 +/-.02
= .59 +/-.02

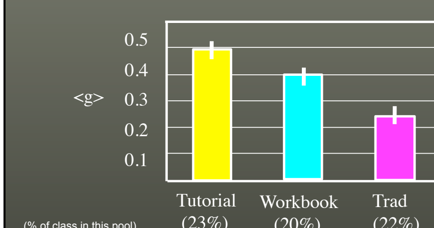



## Phys 1 normalized gains

gain <g>
= .66 +/-.02
= .59 +/-.02
= .45 +/-.02

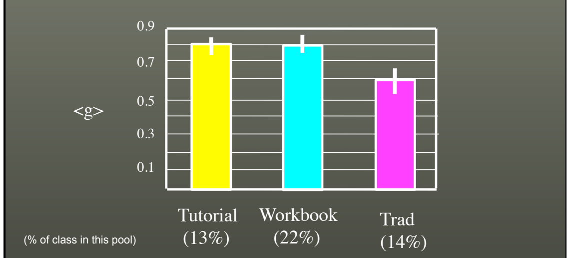



## Impact on different pretest populations: "low starters" pretest <=12.5%




**S. Pollock, 2005 *PERC proceedings***

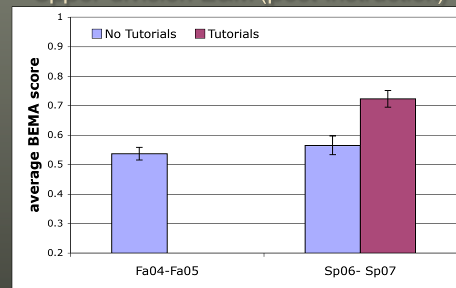
Impact on different pretest populations:
"high starters" 50<pre<93%




S. Pollock, 2005 *PERC proceedings*

## Long term impact of Tutorials

Upper-division E&M (post-instruction)




Red bins: students who had taken
Freshman physics *with* Tutorials (~2 years prior)

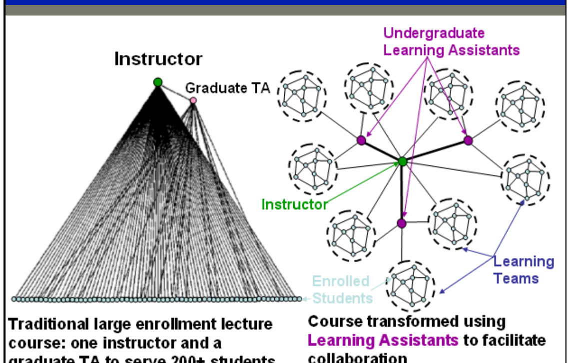
*Learning by Teaching:*
*the LA Story*

## CU Learning Assistant Model*

- Use UG's to implement PER-based materials
  - Help instructors make courses student-centered
  - Improve education for all students
  - Increase likelihood students engage in teaching
- Improve content mastery of future teachers

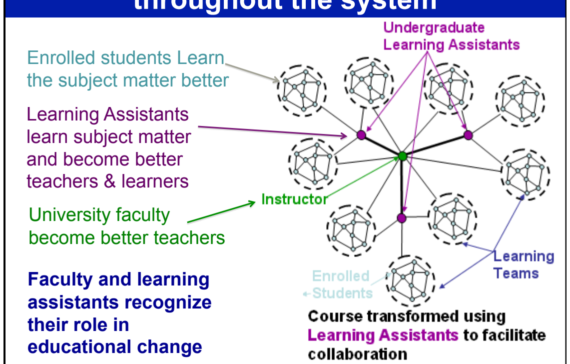
*V. Otero, N.D. Finkelstein, S.J. Pollock and R. McCray (2006). *Science*, **313**, 445

## Course Transformation with LAs

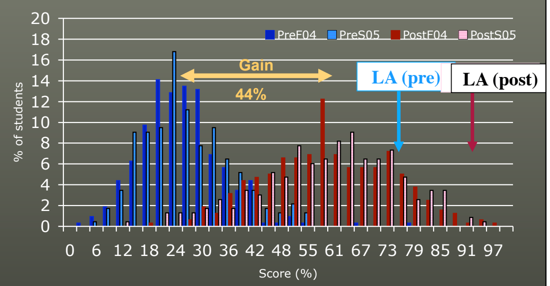



Otero et al, *Science* 2006

## In the LA Model: Learning is distributed throughout the system



## LA Program Impact on Content Knowledge

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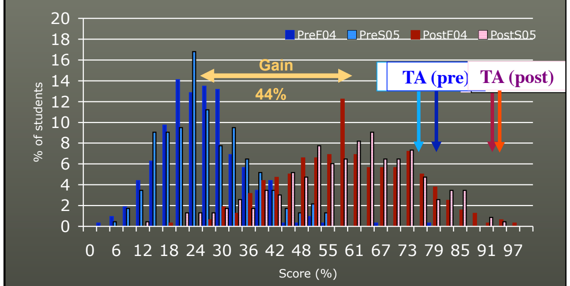
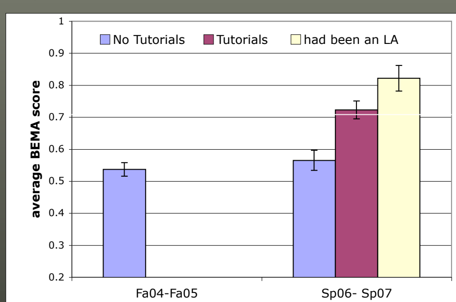
## LA Program Impact on Content Knowledge




V. Otero, N.D. Finkelstein, S.J. Pollock and R. McCray (2006). *Science*, **313**, 445

## Long term impact of LA experience




Yellow: students who had been Phys 2 LAs

*actively engaging is important*

*what people know affects what they learn*

*contexts shape what students learn (content and beliefs)*

*teaching is effective for instructor learning*

*actively engaging is important*

*what people know affects what they learn*

**It's not about our teaching, it's about creating environments supportive of student learning**

*teaching is effective for instructor learning*

Teaching
Quantum Interpretation
in a
Modern Physics Course

## COURSES STUDIED

- PHYS 2130 – General Physics III
  (modern physics for engineers)
- PHYS 2170 – Foundations of Modern Physics
  (for majors)

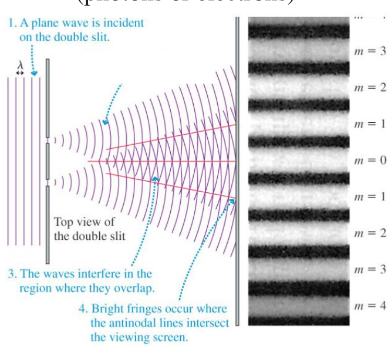
Typically, 1/3 Special Relativity, 2/3 Quantum Mechanics
All courses discussed today were large-lecture (N~100), and used interactive engagement (clickers, etc…).

## General Idea

Instruction in classical physics teaches and reinforces a *realist* perspective
- Deterministic/Local
- Intuitive

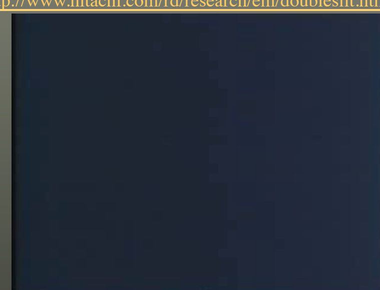
Topics from modern physics require students to develop a *quantum* perspective
- Probabilistic/Non-Local
- Non-intuitive

## Double-Slit Experiment (photons or electrons)




## Double-Slit Experiment with Single Electrons (1989)

http://www.hitachi.com/rd/research/em/doubleslit.html



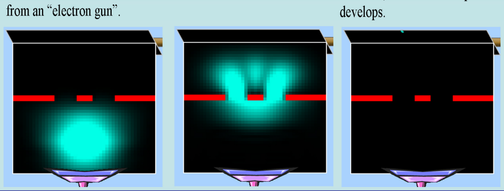
A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki and H. Ezawa, "Demonstration of Single-Electron Buildup of an Interference Pattern," Amer. J. Phys. 57 (1989) pp.117-120.

## The Double-Slit Experiment with Single Quanta

**1.** A blob (representing the probability density for a single electron) emerges from an "electron gun".

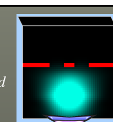
**2.** The blob passes through the two slits

**3.** A single electron is detected on the far screen. After many electrons, an interference pattern develops.



**http://phet.colorado.edu/**

*Three students discuss the* Quantum Wave Interference *simulation, in which a blob shown in the figure at right emerges from an electron gun, goes through two slits, and then a small dot appears on the screen, which is recognized as a "hit" of the electron. After a long time (many electrons) an interference pattern of "hits" is observed on the screen.*



- **[REALIST]** Each electron is a tiny particle that went through one slit or the other.
- **[QUANTUM]** Each electron went through both slits and interfered with itself.
- **[AGNOSTIC]** We can't say what the electron is doing between being emitted and detected.

## Comparisons between modern physics offerings:

ENG-R/S: Modern physics for engineers
- Taught from a realist/statistical perspective

ENG-Q: Modern physics for engineers
- Taught from a matter-wave perspective
- Revisions to 1st transformed curriculum

PHYS – C/A: Modern physics for majors
- Taught from an Copenhagen/Agnostic perspective.
- Similar to ENG-Q with a de-emphasis on interpretive themes.

ENGFA10: Modern physics for engineers
- 2nd transformed curriculum (no SR)

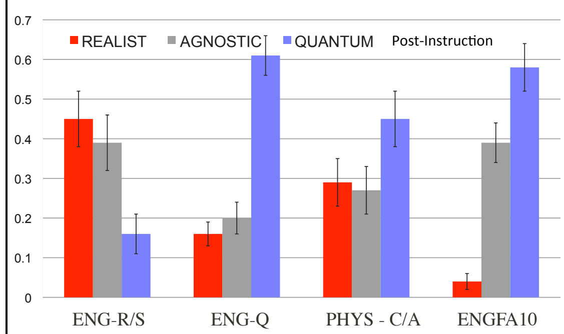
## Curriculum Development

- Make realist assumptions (determinism, locality) explicit.
- Construct operative notions of *model*, *theory* & *interpretation*.
- Expose students to ideas regarding interpretive themes from the historical development of QM.
  - Complementarity/wave-particle duality
  - Wave function collapse
  - Entanglement/non-locality
- Present canonical experiments on foundations of QM.
  - Single-quanta experiments
  - Distant, correlated measurements
- Introduce contemporary topics in quantum information theory.
  - Computing, cryptography, etc…

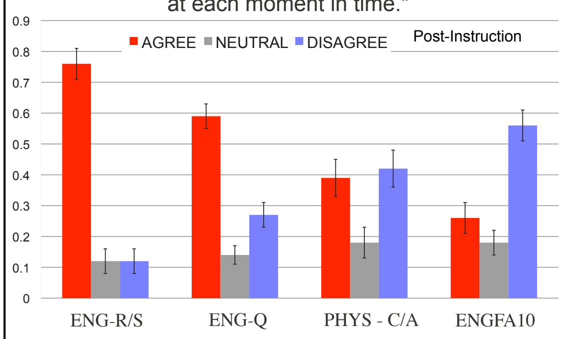
## Course Transformations

- New lecture materials
- Concept tests/homework & exam questions
- Undergraduate learning assistants (2)
- Problem-solving sessions (instructors and LA's)
- Tunneling tutorial (with LA's)
- Outside readings (Scientific American)
- Discussion board
  - Students pose/answer questions on readings
  - Additional topics according to student interest
- End-of-term essay assignment
  - Topic from quantum mechanics
  - Personal reflection on learning about QM

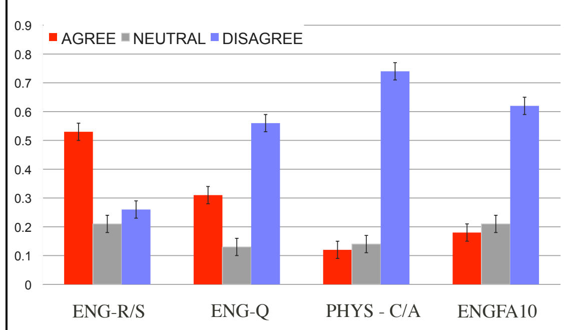
## Double-Slit Interpretation

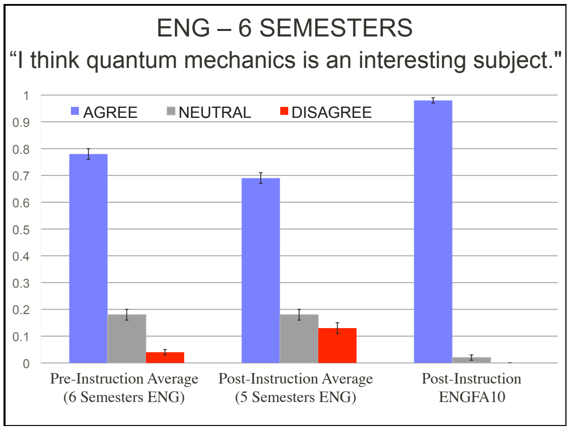


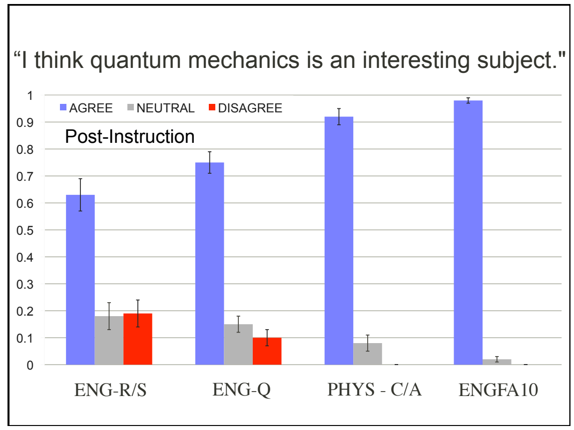

"When not being observed, an electron in an atom exists at a definite but unknown position at each moment in time."




"The probabilistic nature of quantum mechanics is mostly due to the limitations of our measurement instruments."






## Student Reflections

"I entered Physics 3 with a bitter taste in my mouth. Yet, some fragment of my mangled ego compelled me to continue down the path I was on. I have always found physics to be the most intriguing subject, and I was not about to let one class ruin it. I approached Physics 3 as the deal breaker: if this class was like its predecessor, then maybe mechanical engineering was a more apt major. […] Throughout the course, the almost magical results quantum mechanics attained reassured me that I am in the correct major. The teaching style in conjunction with the material made quantum physics attainable. I am not sure if it was the teaching that rejuvenated my passion or the material itself; either way I welcomed back my old friend, physics, with open arms and anticipation."

## Student Reflections

"Even in the world of professional physics, there isn't a unanimous consensus met (which you had talked about), but furthermore you didn't want us to be biased to either of your conclusions. I thank you for respecting us to make our own decisions, and thought it gave a whole new dynamic to the class. Your paper and teaching strategies in class also helped further solidify that there isn't necessarily a right or wrong when approaching this very complex subject, but rather a time and place in which we should use each of these different interpretations. Different scientists in different but related fields may have equally valid and useful but opposite interpretations which they use for their work, and I think that is one of the most important things to take from this course. There isn't necessarily a right or wrong interpretation, but it depends what abstraction works best to describe the work you do."

## Student Reflections

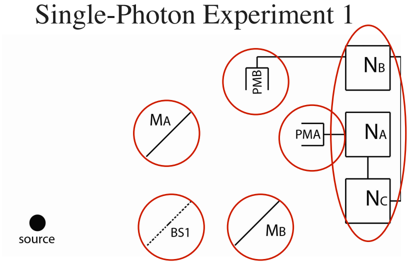
"My favorite topic [was] uncertainty, [which] would also include all of the possible interpretations, such as Many-Worlds, hidden variables and the Copenhagen interpretation, [and] all the experiments that followed. I really enjoyed this topic because it was something that could be debated, and each interpretation had a reasonable explanation for it. I was a little bit sad to learn that the hidden variable idea has been disproved, as I am most definitely a classical physics kind of a person, and the explanation of simply not knowing why some variable is unknown, rather than that variable being undefined at that particular moment still takes a lot to process and believe this."

## Student Reflections

Topic most cited by students as influencing their perspective on QM:

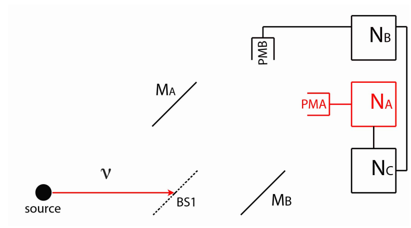
Single-Quanta Experiments

## Single-Photon Experiment 1




- $M_A$ and $M_B$ are mirrors.
- BS1 is a beam splitter.
- PMA & PMB are all photomultipliers.
- $N_A$, $N_B$ & $N_C$ are counters that record photon detections

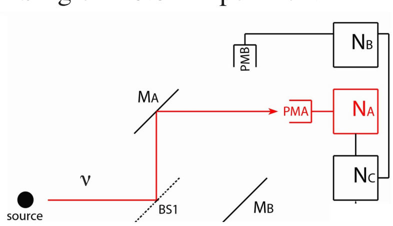
## Single-Photon Experiment 1




If the photon (ν) is detected by PMA, then the photon must have been…

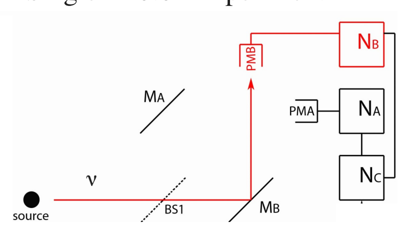
A) …reflected at BS1
B) …transmitted at BS1
C) …both reflected and transmitted at BS1
D) Not enough information.

## Single-Photon Experiment 1



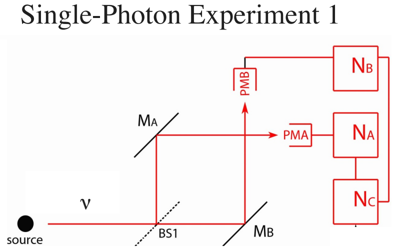

- If the photon (ν) is detected by PMA, then the photon must have traveled along Path A (via MA).

## Single-Photon Experiment 1



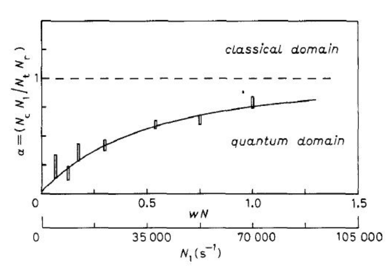

- If the photon (ν) is detected by PMB, then the photon must have traveled along Path B (via MB).

## Single-Photon Experiment 1




- If both PMA & PMB are triggered during w = 2τ, then the coincidence counter ($N_C$) is triggered.

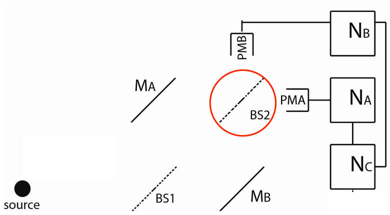
## Single-Photon Experiment 1




EM Waves → α ≥ 1     Quantum Particles → α ≥ 0

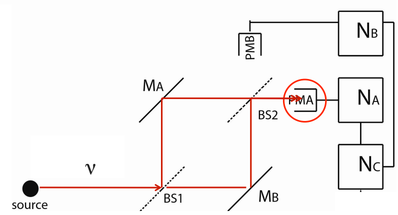
Photons take ***either*** **Path A** ***or*** **Path B**, but not both!!

## Single-Photon Experiment 2




- Use same experimental setup, but now insert a beam splitter. (BS2)
- Run experiment as before…

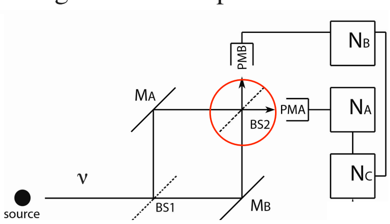
## Single-Photon Experiment 2




If the photon is detected in PMA, then it must have been…

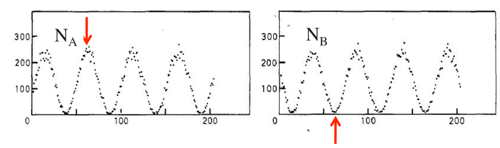
A) …reflected at BS2.
B) …transmitted at BS2.
C) …either reflected or transmitted at BS2
D) Not enough information.

## Single-Photon Experiment 2




- Whether the photon is detected in PMA or PMB, we have ***no information*** about which path (**A <u>or</u> B**) any photon took.
- What do we observe when we compare data from PMA & PMB?

## Single-Photon Experiment 2




Slowly change one of the path lengths (Move $M_B$, for example), and we observe interference!

- For some path length differences, all the photons are detected by PMA and none in PMB
- For some path length differences, there is an equal probability for either detector to be triggered.

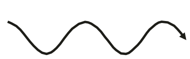
Each photon is somehow "aware" of ***both paths***!

## Single-Photon Experiments 1 & 2

- Photons in **Experiment 1** took **<u>only</u> Path A <u>or</u> Path B.** (which-path information – a particle encounters BS1 and takes either one path or the other)
- Photons in **Experiment 2** take **<u>both</u> Path A <u>and</u> Path B**. (no path information – a wave encounters BS1 and splits equally to take both paths)

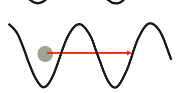
**Experiment One** says photons behave like ***particles***.

**Experiment Two** says photons behave like ***waves***.



Can a photon be ***both*** at once?

A) Yes B) No C) Maybe?



# Questions?

Much more at:

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