Quantum Mysteries

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Help from
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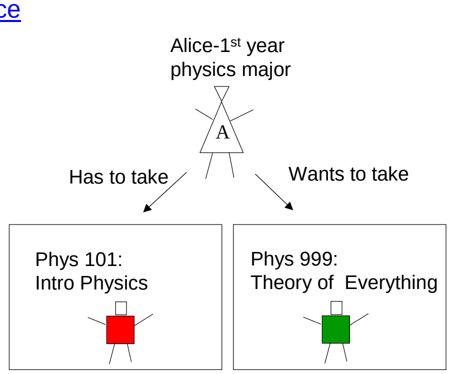
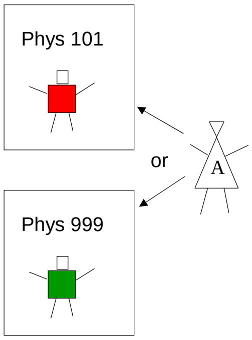
Thought Experiment

1) Describe the experiment
2) Describe some of the data we might collect during this experiment
   - Results from a particular set of measurements
3) Given these results, we'll *infer* what we would expect to see if we performed a different measurement
   - Logical implication
4) Describe what happens when we perform this other measurement
   - Was our inference correct?

Alice

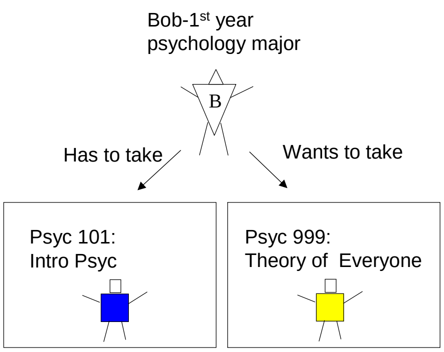


The Choice



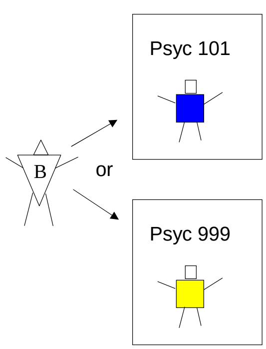
Half the time she attends 101, and half the time she attends 999

Bob

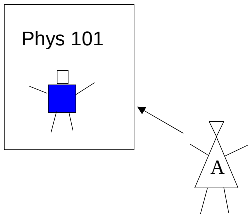


The Choice

Half the time he attends 101, and half the time she attends 999



Colors



On days she attends 101, the Prof. wears red, or blue.

Never any other color.

Choice appears random.

Colors

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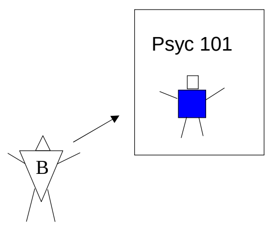
Never any other color.

Choice appears random.

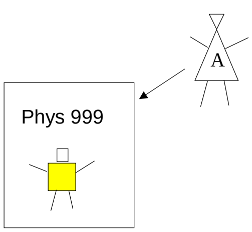


Colors

On days she attends 999, the Prof. wears green, or yellow.

Never any other color.

Choice appears random.

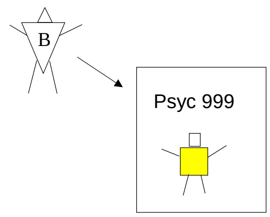


Colors

On days he attends 999, the Prof. wears green, or yellow.

Never any other color.

Choice appears random.



The Situation

Alice
- Randomly chooses Phys 101 or 999
  - 101
    - Prof wears red or blue
  - 999
    - Prof wears green or yellow

Bob
- Randomly chooses Psyc 101 or 999
  - 101
    - Prof wears red or blue
  - 999
    - Prof wears green or yellow

The Experiment

Every day Alice and Bob record which class they went to, and what color the Prof was wearing

Day	Alice		Bob	
1	101	B	101	B
2	999	G	999	Y
3	999	G	101	B
4	999	Y	101	B
5	101	R	999	G
6	101	B	101	B
7	999	Y	999	Y
8	101	R	101	R
9	999	G	101	R
10	999	Y	999	G

Day	Alice		Bob	
11	999	G	101	B
12	101	B	999	Y
13	999	Y	101	B
14	101	R	999	G
15	101	R	101	B
16	999	G	101	R
17	999	Y	999	G
18	101	B	101	B
19	101	B	999	Y
20	999	G	999	Y

Analyzing the data

On days where they both went to 101

They SOMETIMES see RR (9% of 101-101 visits)

Day	Alice		Bob	
1	101	B	101	B
2				
3				
4				
5				
6	101	B	101	B
7				
8	101	R	101	R
9				
10				

Day	Alice		Bob	
11				
12				
13				
14				
15	101	R	101	B
16				
17				
18	101	B	101	B
19				
20				

Analyzing the data

They SOMETIMES see RR (9% of 101-101 visits)

1) Alice R, Bob R OK [P(R,R)=0.09]

Analyzing the data

On days where they went to different classes:

If one measures R, the other ALWAYS measures G

Day	Alice		Bob	
1				
2				
3	999	G	101	B
4	999	Y	101	B
5	101	R	999	G
6				
7				
8				
9	999	G	101	R
10				

Day	Alice		Bob	
11	999	G	101	B
12	101	B	999	Y
13	999	Y	101	B
14	101	R	999	G
15				
16	999	G	101	R
17				
18				
19	101	B	999	Y
20				

Analyzing the data

On days where they went to different classes:
RY (or YR) NEVER occur

Day	Alice		Bob	
1				
2				
3	999	G	101	B
4	999	Y	101	B
5	101	R	999	G
6				
7				
8				
9	999	G	101	R
10				

Day	Alice		Bob	
11	999	G	101	B
12	101	B	999	Y
13	999	Y	101	B
14	101	R	999	G
15				
16	999	G	101	R
17				
18				
19	101	B	999	Y
20				

Analyzing the data

If one measures R, the other ALWAYS measures G

1) Alice R, Bob R OK [P(R,R)=0.09]
2) Alice R ➔ Bob G [P(R,Y)=0]
3) Bob R ➔ Alice G [P(Y,R)=0]

Clearly, the wardrobe choices of the faculty are NOT random.

Inference

On days where Alice and Bob both go to 101 and measure RR:
- We know that such days are possible
  - 1) Alice R, Bob R OK [P(R,R)=0.09]

If Bob changes his mind and goes to 999:
- He MUST measure G
  - 2) Alice R ➔ Bob G [P(R,Y)=0]

If Alice changes her mind and goes to 999:
- She MUST measure G
  - 3) Bob R ➔ Alice G [P(Y,R)=0]

Must be possible for Alice and Bob to measure GG
- P(G,G)≥0.09

Inference

Must be possible for Alice and Bob to measure GG
- P(G,G)≥0.09

The Data

Alice and Bob NEVER measure GG
- P(G,G)=0

Explanation?

The faculty are playing with Alice and Bob's minds
- Somehow the faculty are communicating
  - Cell phones?

Student Revenge

Alice and Bob decide to eliminate the possibility of communication
- Both come to class 5 minutes late
  - No time to change
- They choose and enter their classrooms at the exact same time
  - Leave no time for the faculty to communicate
  - Buy 2 atomic clocks to do this

With these improvements

They measure:

1) Alice R, Bob R OK [P(R,R)=0.09]
2) Alice R ➔ Bob G [P(R,Y)=0]
3) Bob R ➔ Alice G [P(Y,R)=0]

Same as before, so again they infer:

P(G,G)≥0.09

They measure:

P(G,G)=0

The changes made absolutely no difference.

What's going on?

Maybe I'm making up stories

- Half true

Do this experiment with real people

- Measure P(G,G)$\geq$0.09

Do an equivalent experiment with microscopic particles (electrons, photons)

- Measure P(G,G)=0

People are macroscopic and obey the laws of classical physics

Photons are microscopic and obey the laws of quantum mechanics

What is the microscopic experiment?

Faculty → Photons

Alice and Bob → Detectors

Choice of 101 or 999 → Choice of measurement

Color of faculty clothing → Polarization of photon

What's a Photon?

Great question. I wish I could answer it.

Photon is like a particle of light

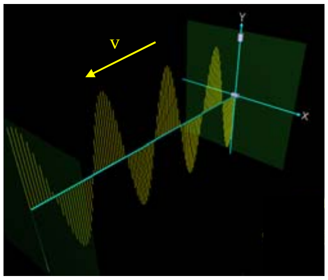
- Only problem is that light is not made of particles, it's an electromagnetic wave

Light has both wave-like and particle-like properties

- Sometimes wave-like properties are more evident
- Sometimes particle-like properties are more evident

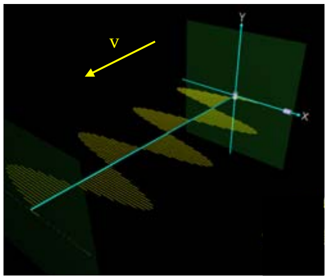
Polarization

Vertical



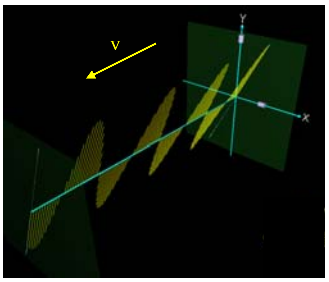
Polarization

Horizontal



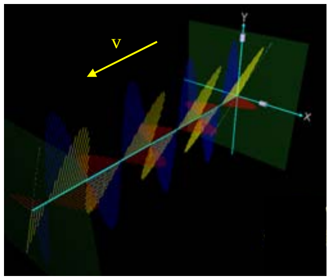
Polarization

General Linear



Polarization

General Linear has both vertical and horizontal components

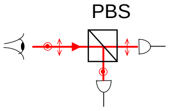


Polarizing Beamsplitters

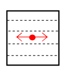
A Polarizing Beamsplitter (PBS) transmits or reflects light, depending on the polarization

Top View:

PBS



End View:



Horizontal Transmitted

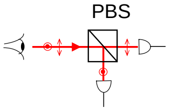
.... Transmission Axis

Polarizing Beamsplitters

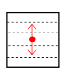
A Polarizing Beamsplitter (PBS) transmits or reflects light, depending on the polarization

Top View:

PBS



End View:



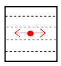
Vertical Reflected

.... Transmission Axis

Single Photon

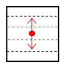
Single photon incident on a PBS

Horizontal



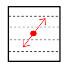
100%
Transmitted

Vertical



100%
Reflected

45º



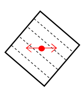
50%
Transmitted
50%
Reflected

Transmission
Axis

Single Photon

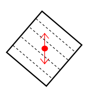
Single photon incident on a PBS--rotate the PBS

Horizontal



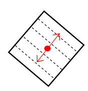
50%
Transmitted
50%
Reflected

Vertical



50%
Transmitted
50%
Reflected

45º

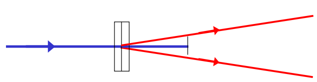


100%
Reflected

Transmission
Axis

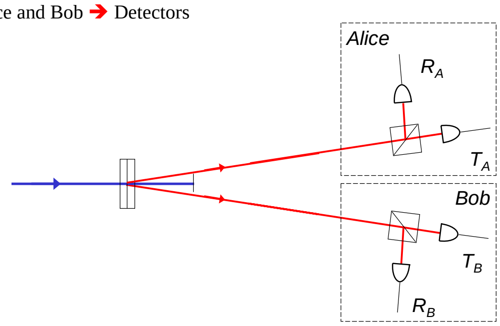
The Experiment

Faculty ➔ Photons



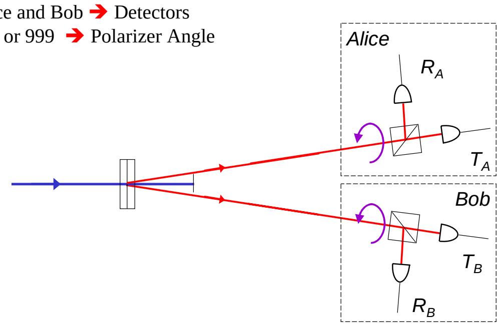
The Experiment

Faculty ➔ Photons
Alice and Bob ➔ Detectors



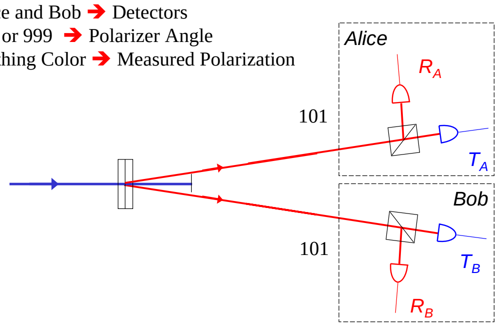
The Experiment

Faculty ➔ Photons
Alice and Bob ➔ Detectors
101 or 999 ➔ Polarizer Angle



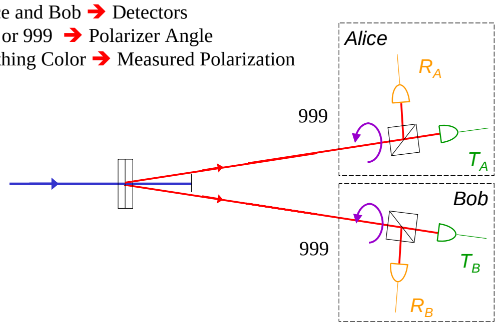
The Experiment

Faculty ➔ Photons
Alice and Bob ➔ Detectors
101 or 999 ➔ Polarizer Angle
Clothing Color ➔ Measured Polarization



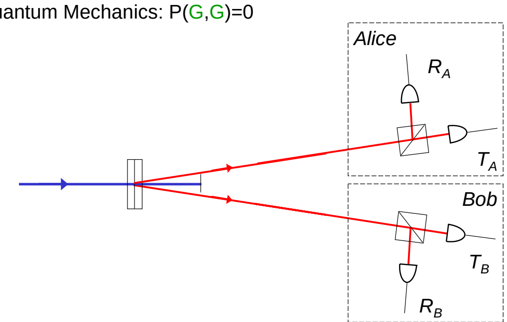
The Experiment

Faculty ➔ Photons
Alice and Bob ➔ Detectors
101 or 999 ➔ Polarizer Angle
Clothing Color ➔ Measured Polarization



The Results

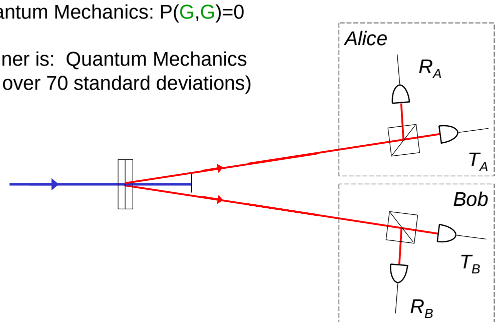
Classical Physics: P(G,G)≥0.09
Quantum Mechanics: P(G,G)=0



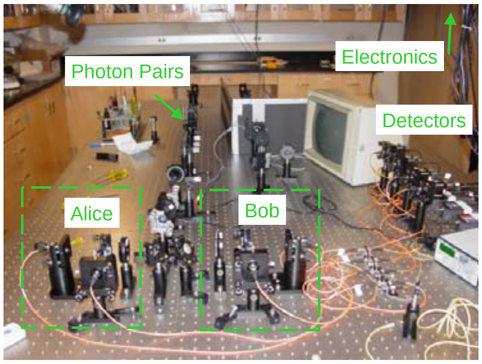
The Results

Classical Physics: P(G,G)≥0.09
Quantum Mechanics: P(G,G)=0

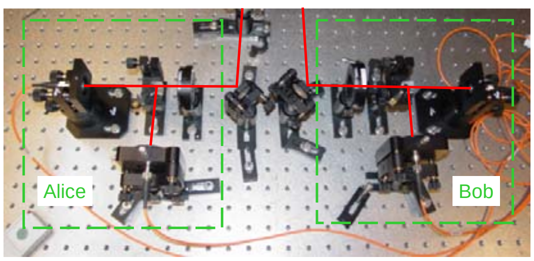
Winner is: Quantum Mechanics
(By over 70 standard deviations)



The Experiment



The Experiment



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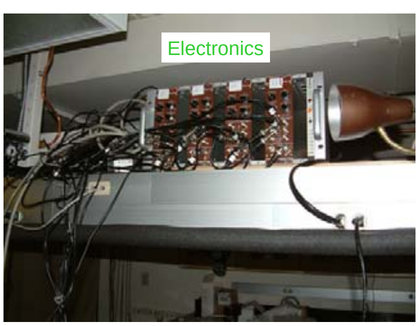
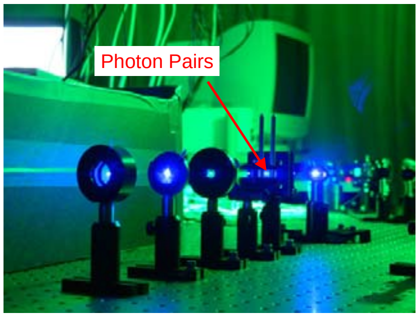


The Experiment



Conclusions

For certain experiments classical physics and quantum mechanics yield very different predictions

- QM is counterintuitive

Can experimentally test validity of QM

- We've done it here at Whitman

These experiments are suitable for an undergraduate laboratory

- Working on getting them into our curriculum

References

L. Hardy, "Nonlocality for two particles without inequalities for almost all entangled states," Phys. Rev. Lett. **71**, 1665 (1993).

N.D. Mermin, "Quantum Mysteries Refined," Am. J. Phys. **62**, 880 (1994).

P.G. Kwiat and L. Hardy, "The Mystery of the Quantum Cakes," Am. J. Phys. **68**, 33 (2000).