The Private Lives of Quantum Particles

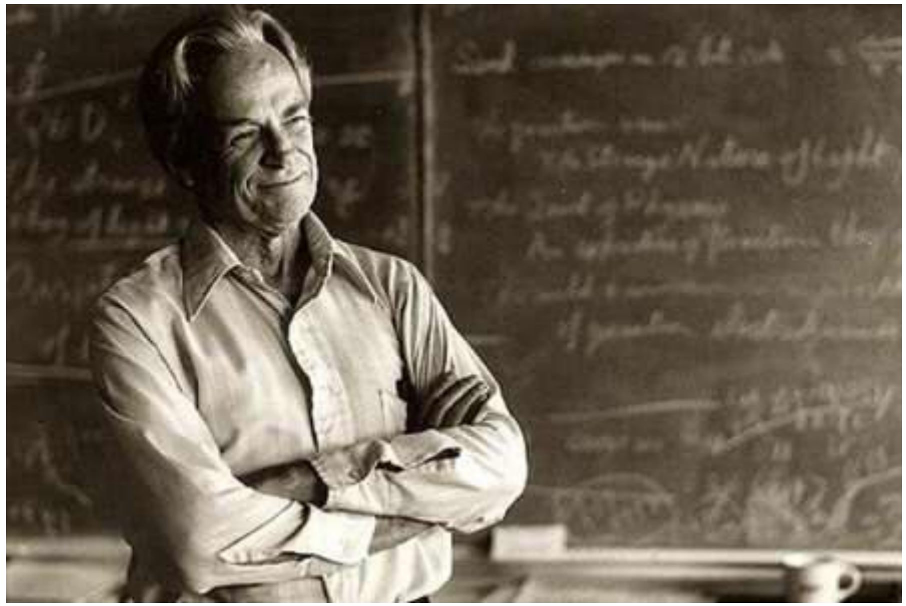
A Tale of Quantum Mystery and Romance

told by Benjamin Schumacher
of Kenyon College

What this talk is about

- Our **basic ideas** about how the world works -- the "pictures" we (try to) use to understand the meaning of physical theories.
- The strange nature of **quantum physics** -- especially the phenomena of quantum **interference** and **entanglement**.
- **Relationships** between particles -- and how a pair of quantum particles can share a relationship that can never be fully disclosed to the outside world.

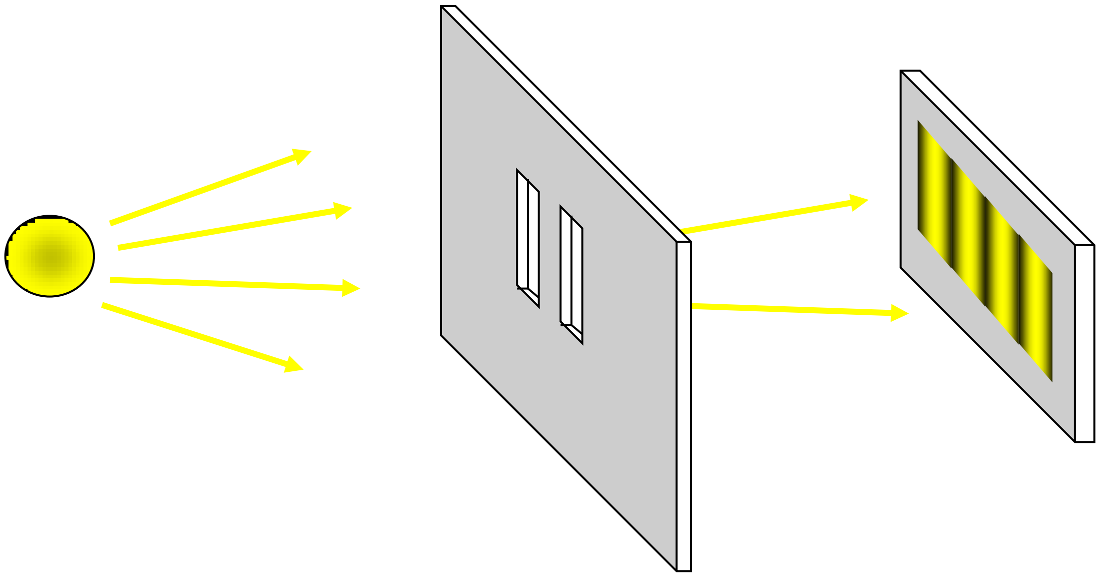
What this talk is about



“Nobody understands quantum theory.”
Richard Feynman

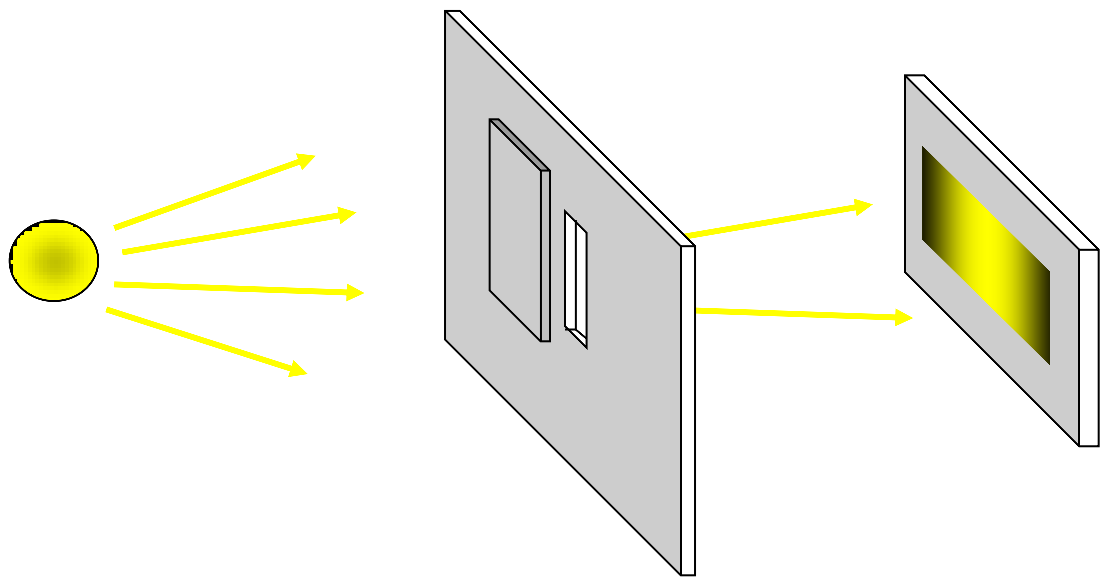
First Part:
A World of Shy Particles

Two-slit experiment



Light of a given wavelength passes through a pair of narrow slits. A pattern of light intensity registered on a distant screen.

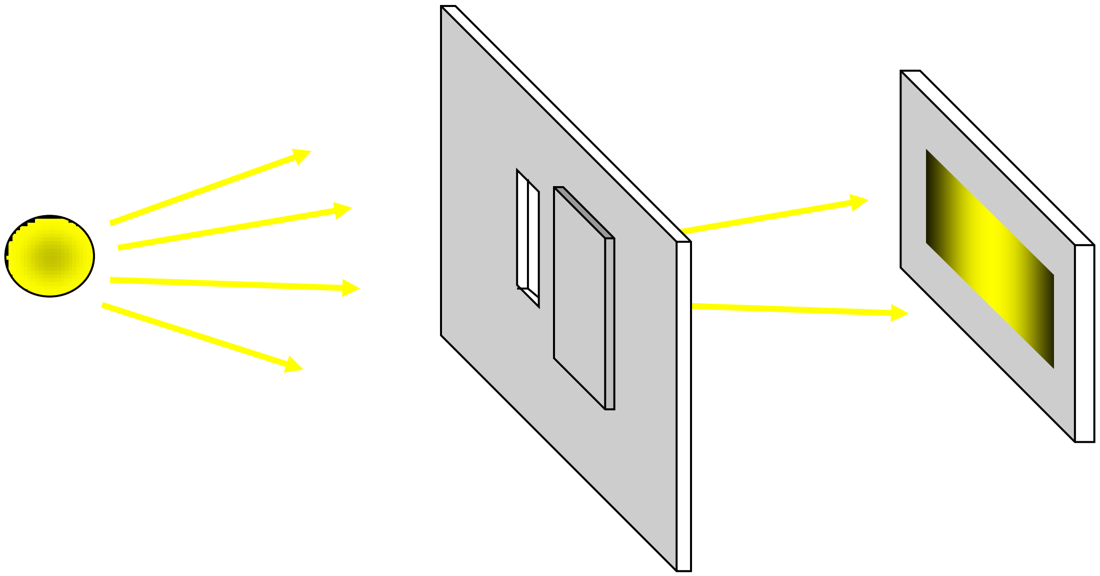
Two-slit experiment



Single-slit diffraction pattern from just the R slit.

R slit only

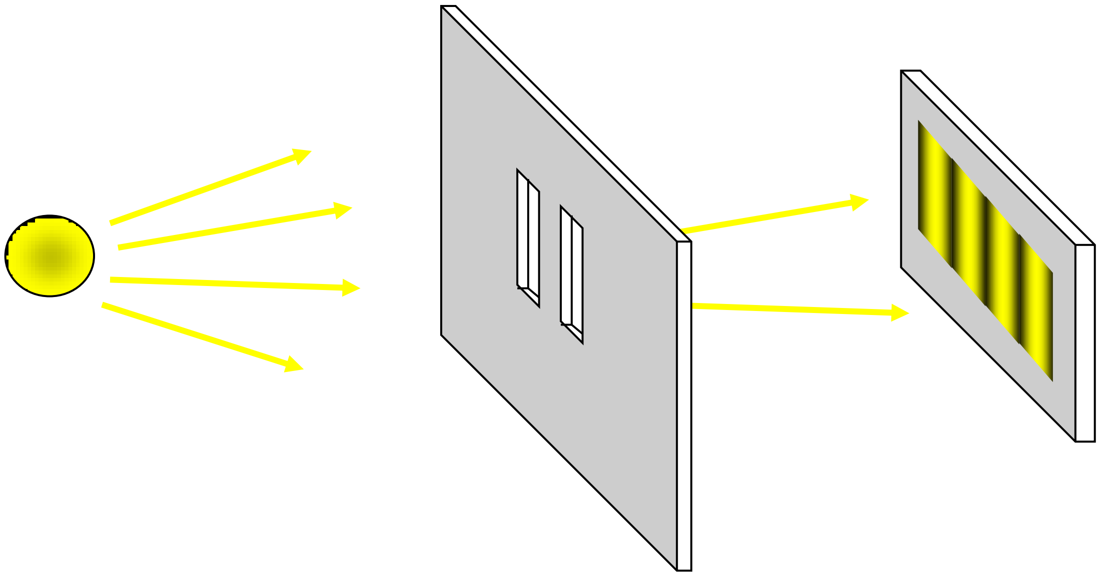
Two-slit experiment



Single-slit diffraction pattern from just the L slit.

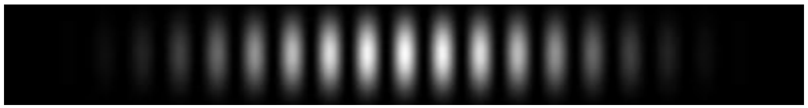
L slit only

Two-slit experiment



Both slits open:

Two-slit interference pattern appears!



Both slits

What is light? Waves!

Young (1803)

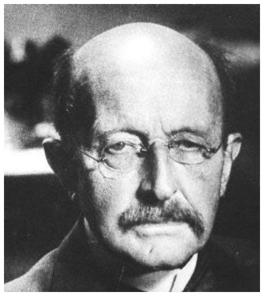
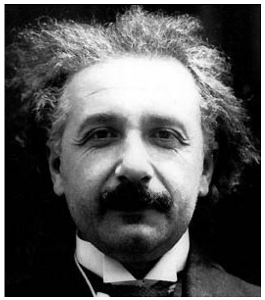
Light is composed of waves that can add up or cancel out (interference).

Maxwell (1859)

Light waves are moving disturbances in electric and magnetic fields.

Interference demonstration

Quantum troublemaking

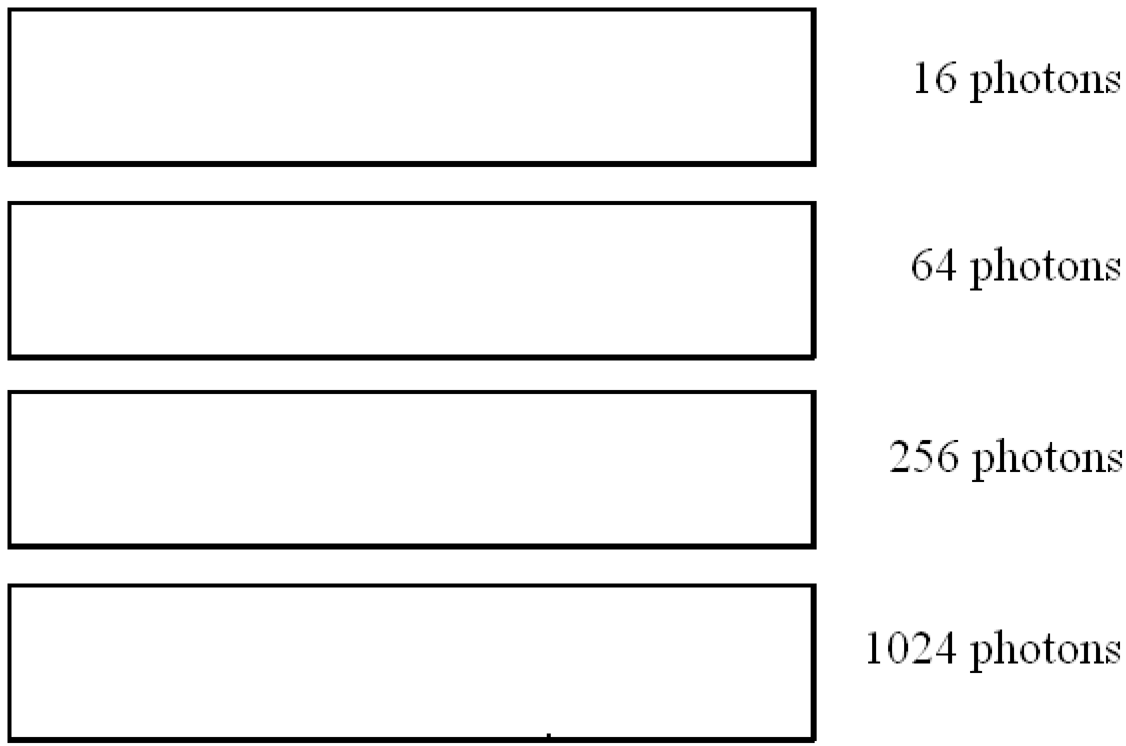
Planck (1900) and Einstein (1905)

Light can behave as a stream of particles (photons)!


De Broglie (1925) and Schrödinger (1926)

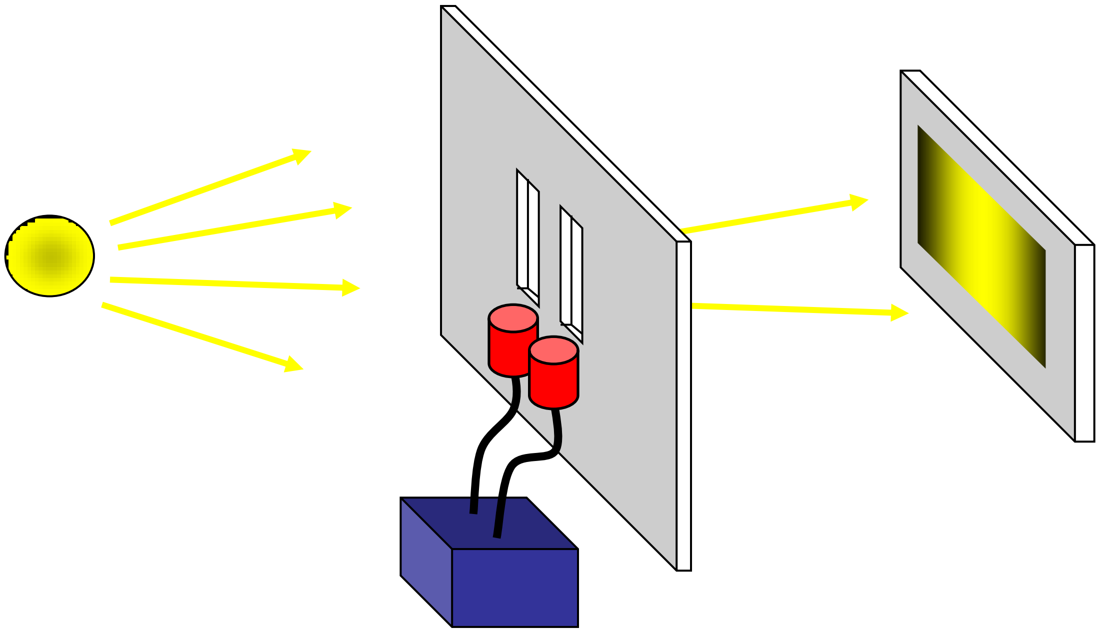
Particles of matter (electrons) can behave as waves!

One photon at a time



Wave intensity $\propto$ particle probability

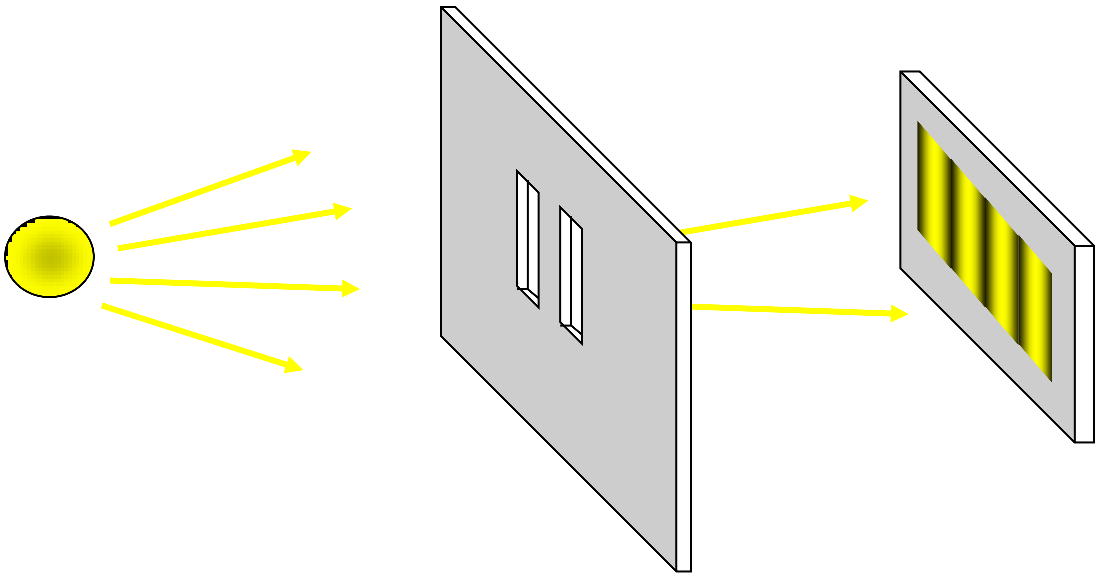
Two-slit experiment



Introduce device to measure which slit the photon passes through

Which slit?

Two-slit experiment



Quantum interference of photons can only occur if no measurement is made of "which slit" the photon passes through.

We can either do an "interference" experiment or we can do a "which slit" experiment -- but in a given instance, we can choose only one option.

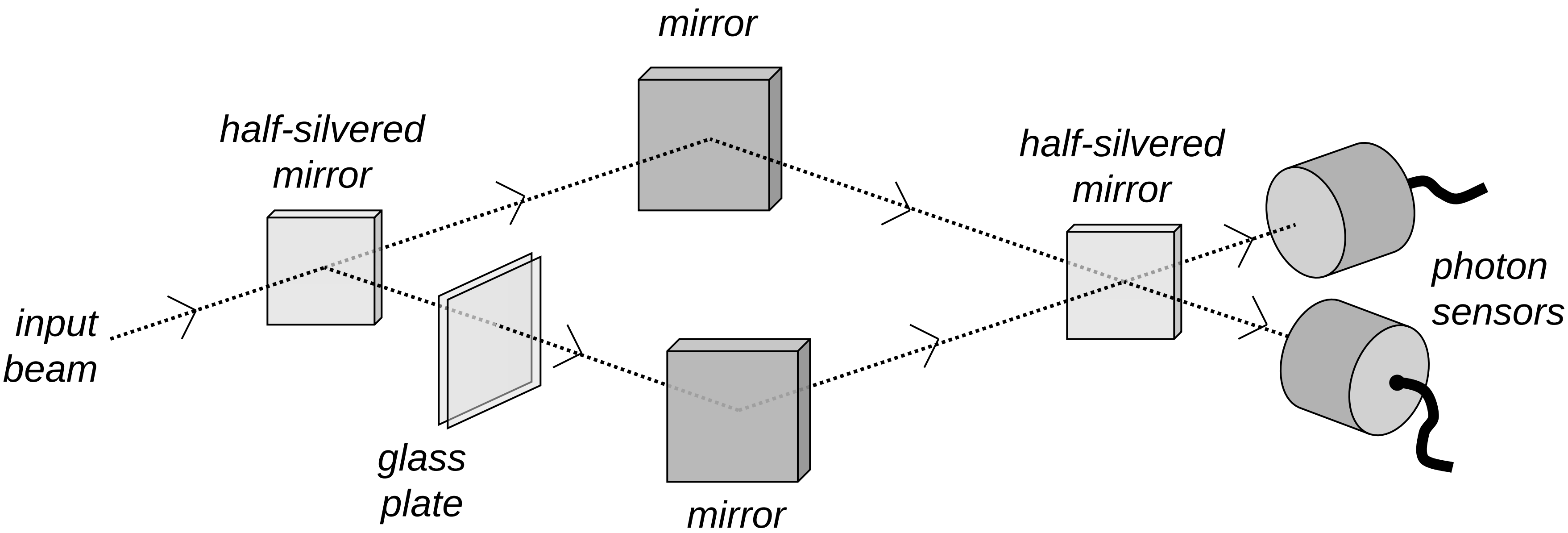
Later, we cannot say what *would have happened* if we had made another choice.

"Unperformed experiments have no results."
Asher Peres

Quantum physics is what happens when nobody is looking.

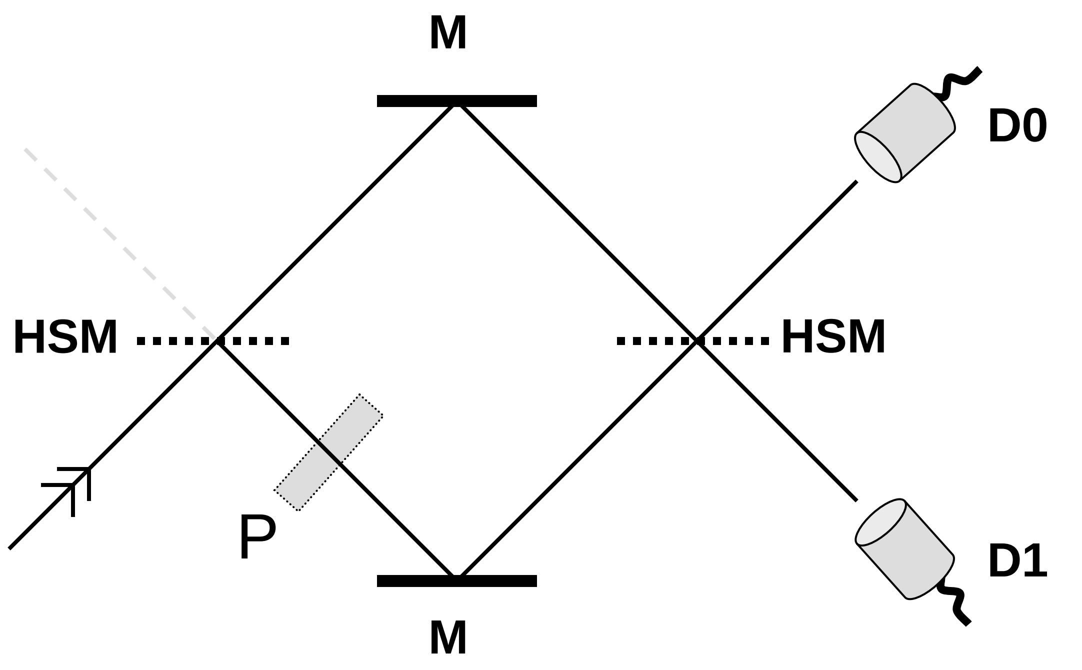
Second Part:
That Eerie Feeling...

A photon in an interferometer

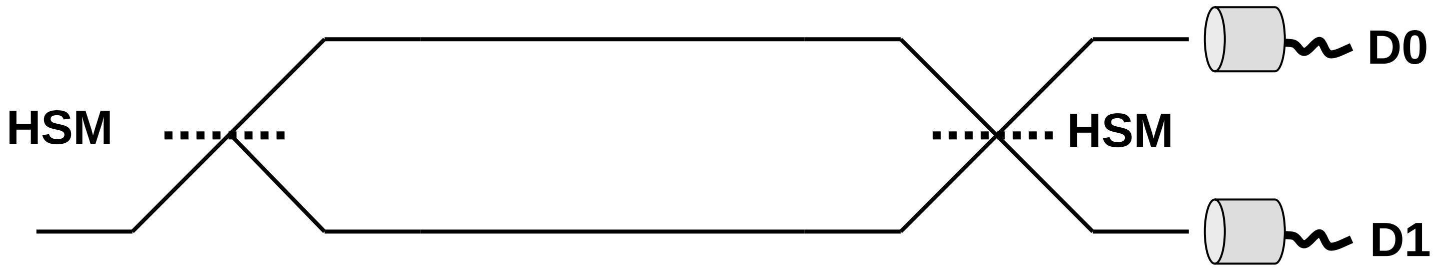


Send one photon at a time into the interferometer.

Where does the photon wind up? (Probabilities!)



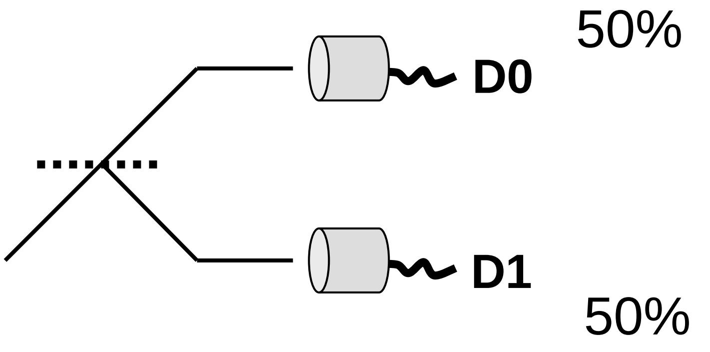
Interferometer (simplified)



Interferometer (schematic)

Experiment #1

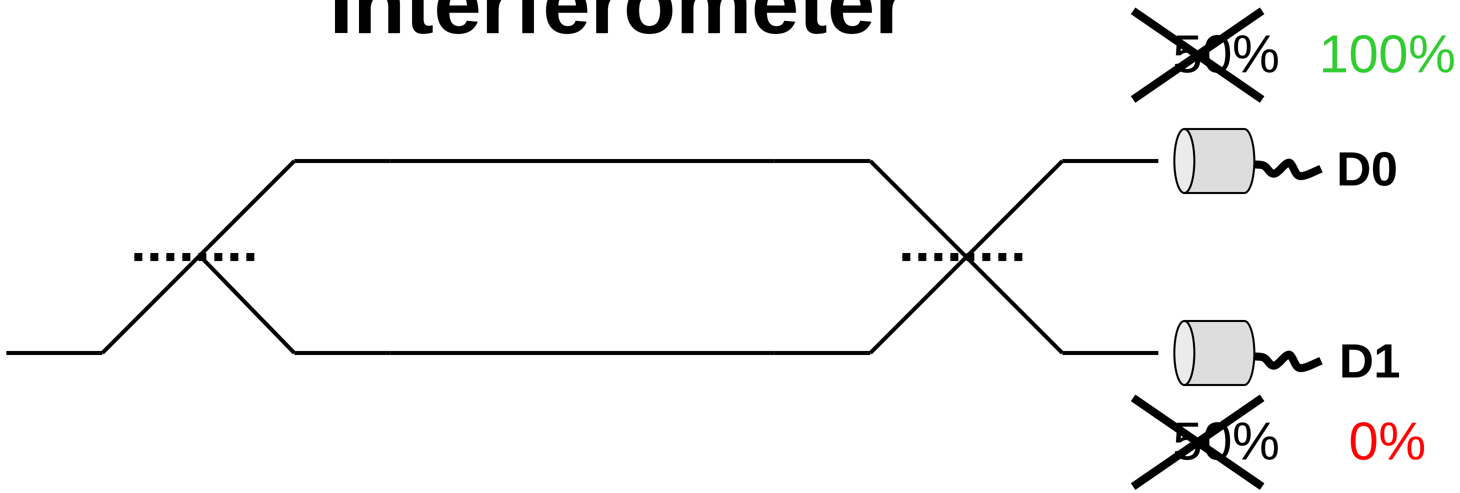
Half-silvered mirror



Result: Photon can reach either detector.

Experiment #2

Interferometer

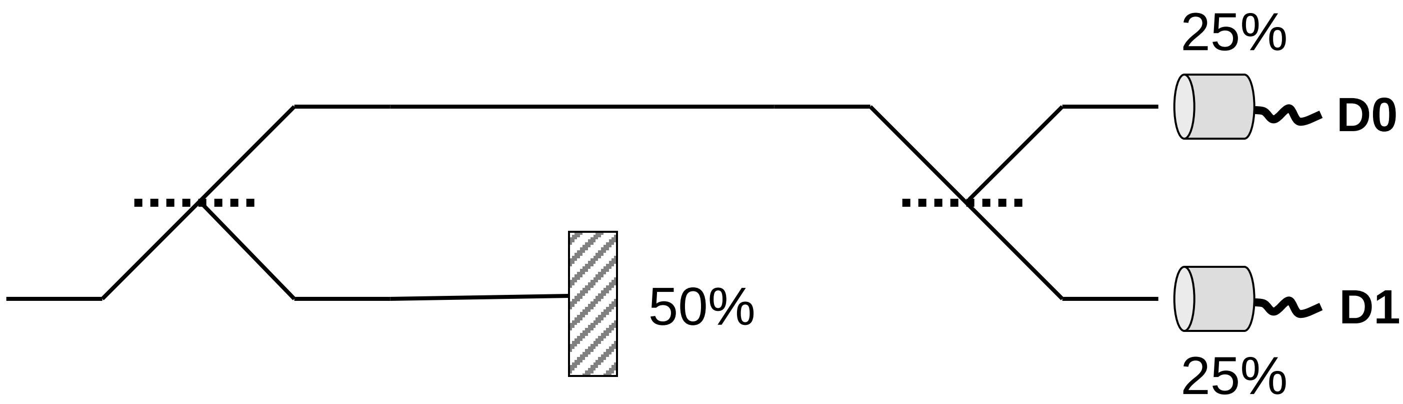


Particle thinking: Photon “flips a coin” at each mirror.

Actual result: Constructive and destructive interference!

Experiment #3

Block one beam



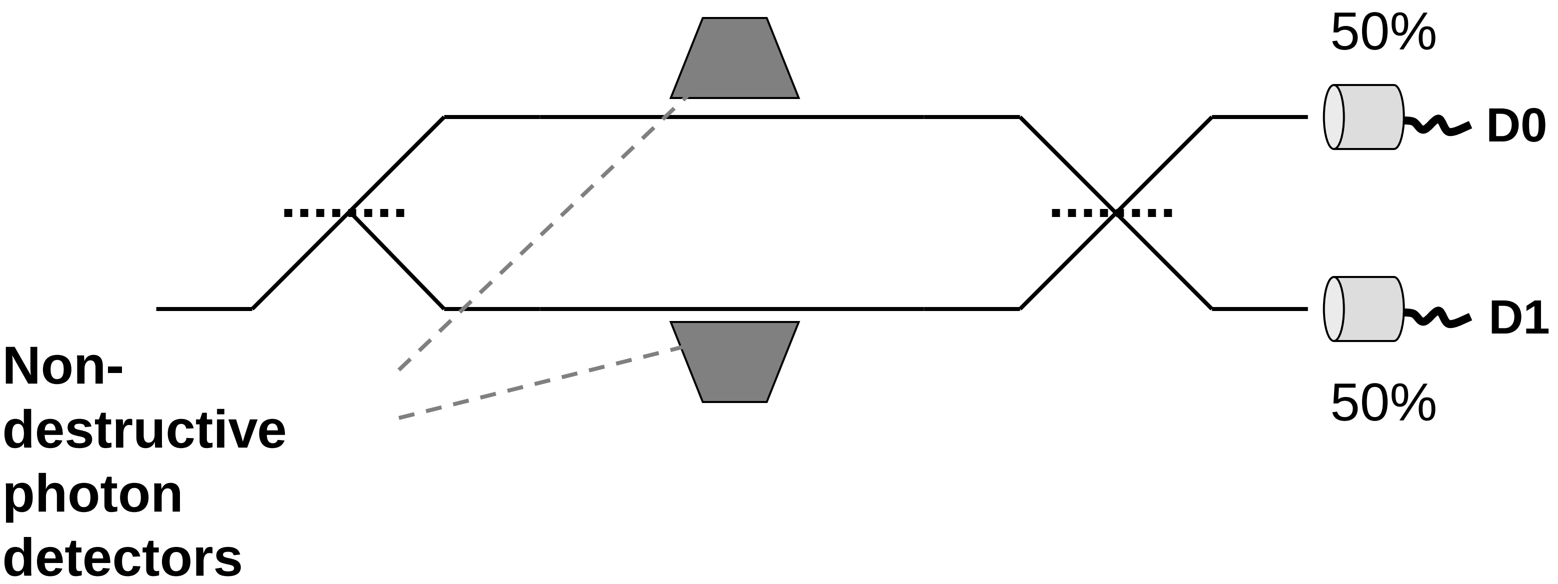
Half the time, the photon hits the block.

The rest of the time, the photon takes the other path.

Weird fact: By blocking one beam, we actually **increase** the amount of light that reaches D1.

Experiment #4

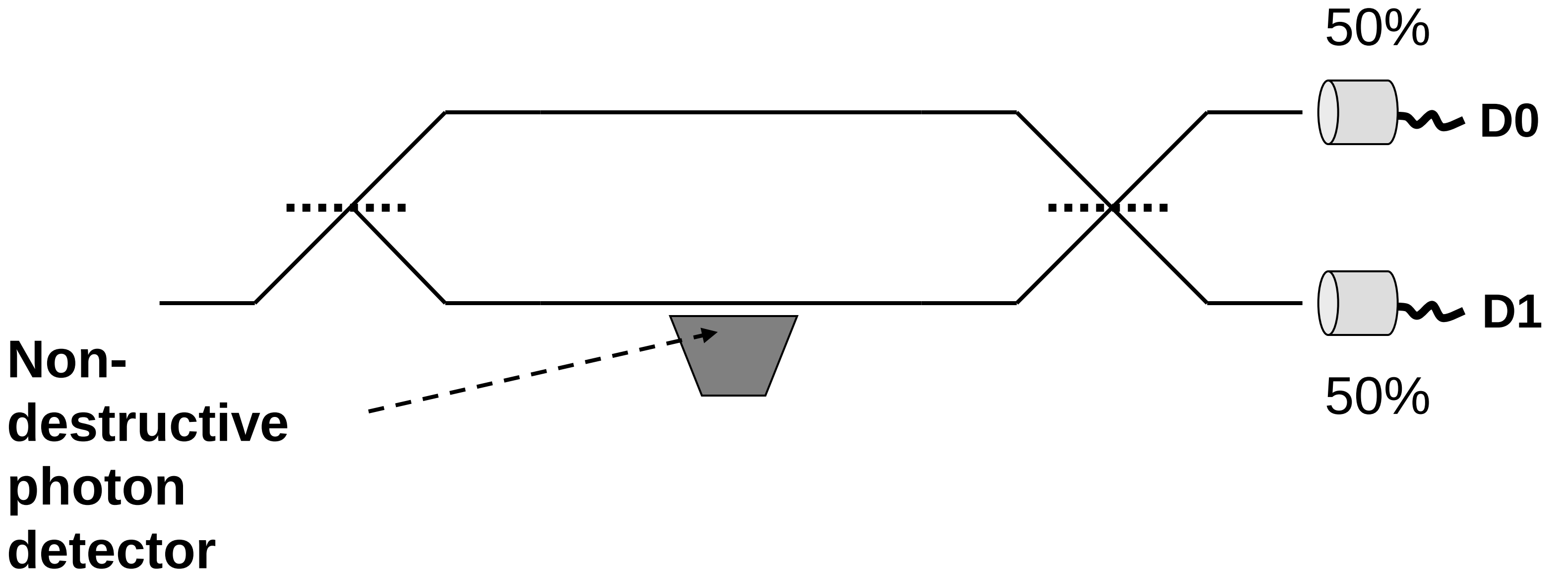
Observe the beams



Moral: If we **observe** which beam the photon travels, there is **no** interference.

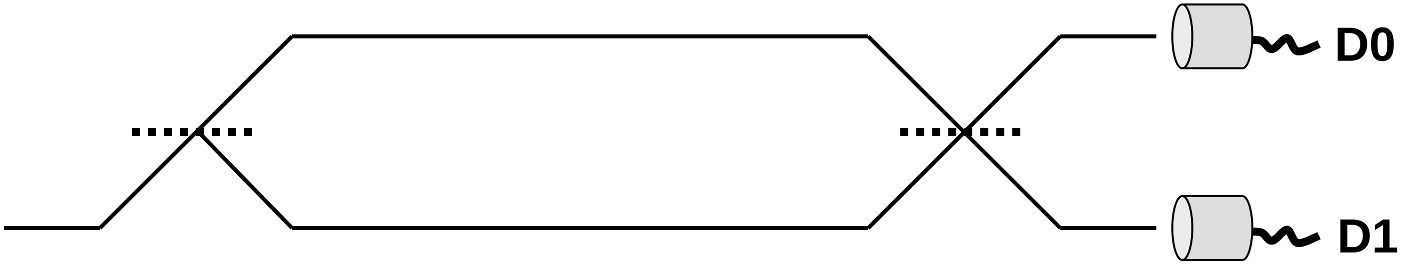
Experiment #4b

Observe one of the beams



Moral: A single detector is enough to determine "which path" the photon went.

The perfect crime



For interference, the photon must travel "**both ways"**, with no observation of which path it went.

“No observation of path” means **no physical record** of the path is made anywhere in the Universe!

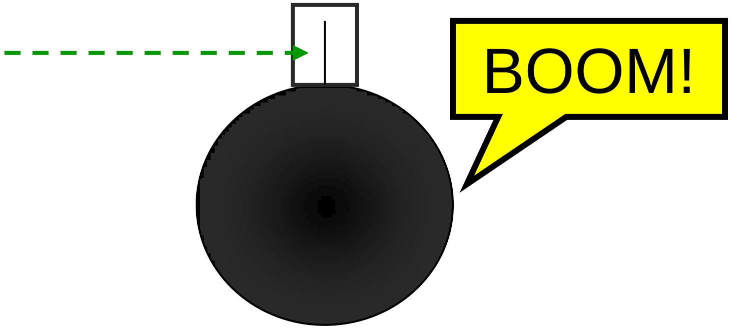
Observation is physical

Why should **observing** the photon destroy the quantum interference effects?

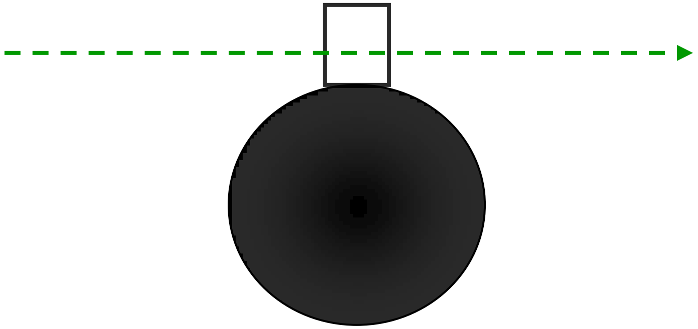
- A photon detector must **interact** with the photon -- i.e., the photon must be able to make a **physical change** in the detector.
- By a kind of “**action and reaction**” principle, the detector therefore makes a physical change in the photon.
- Observed photons act differently -- they have "that eerie feeling of being watched".
- Sometimes called "**quantum decoherence**".

Hair-trigger bombs

Imagine a bomb with a trigger mechanism so sensitive that *one photon* will set the bomb off.

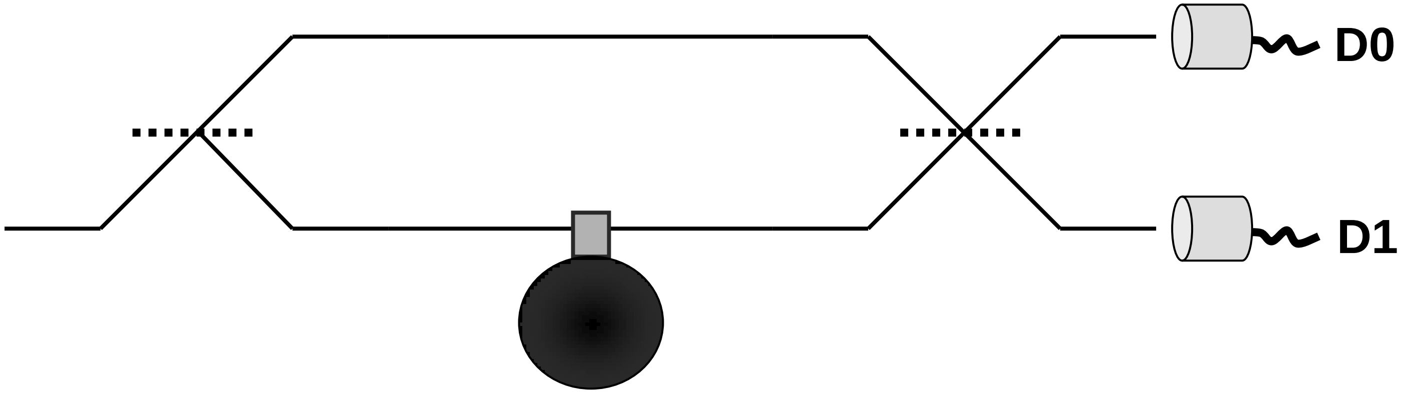


However, some bombs have defective triggers, and photons pass right through without setting the bomb off.



Puzzle: How can we insure that a particular bomb is in working order ***without blowing it up***?

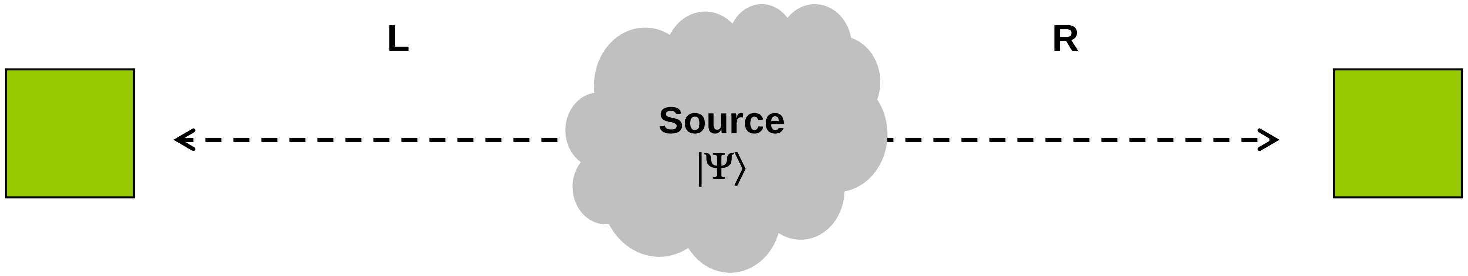
Quantum bomb testing



Defective bomb	Working bomb	
P(BOOM!) = 0%	P(BOOM!) = 50%	Wasted bomb
P(D0) = 100%	P(D0) = 25%	Inconclusive
P(D1) = 0%	P(D1) = 25%	**Success!**

Third Part:
Intimate Relationships That Cannot Be Shared

Quantum entanglement

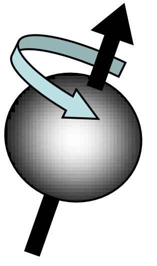


Theory: We can assign a quantum state $|\Psi\rangle$ to the pair, but not to the individual particles.

Experiment: Behavior of the two particles is strongly correlated.

Entangled spins

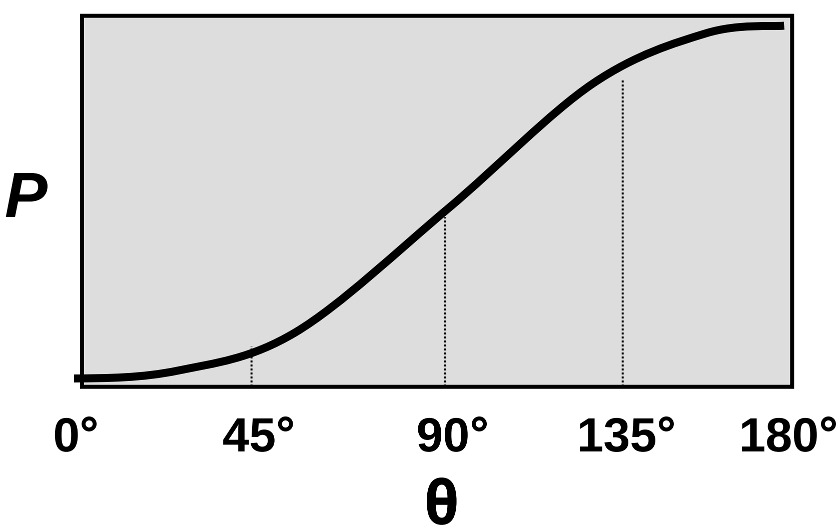
- Spin is an internal angular momentum of a quantum particle (e.g., an electron).
- We can measure the spin along any axis we choose. The result is always either +1 or -1 (in units of ħ/2).



- Entangled state of two spins: total spin zero (**TSZ**)
- (Sometimes called a "singlet state" of two spins.)

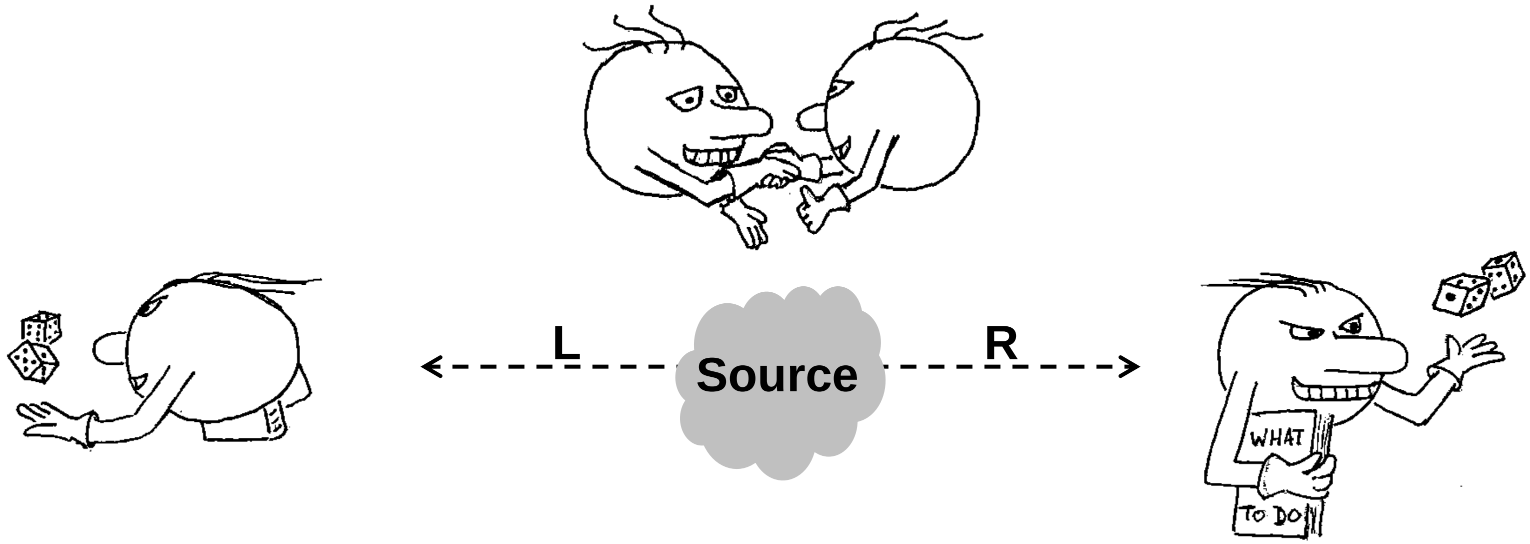
Total spin zero

Two axes are angle θ apart. How likely is it that the two results agree (both +1 or both -1)?



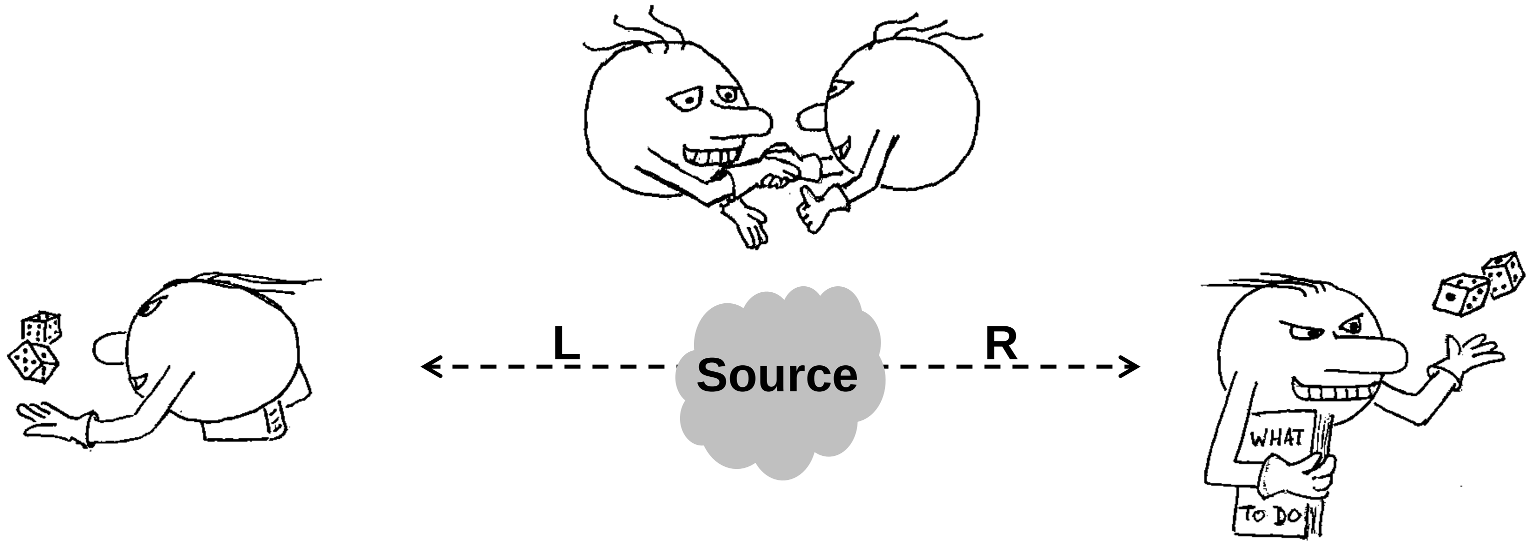
0°	**never agree (0%)**
45°	**agree 15% of time**
90°	**agree 50% of time**
135°	**agree 85% of time**
180°	**always agree (100%)**

Correlation and common sense



- When the pair is formed, the particles “make an agreement” about how to act.
- Particles go their separate ways with shared “instruction books”.
- Correlations between the particles are explained by prearranged agreement in the instructions.

Correlation and common sense



- When the pair i
  agreement” abo
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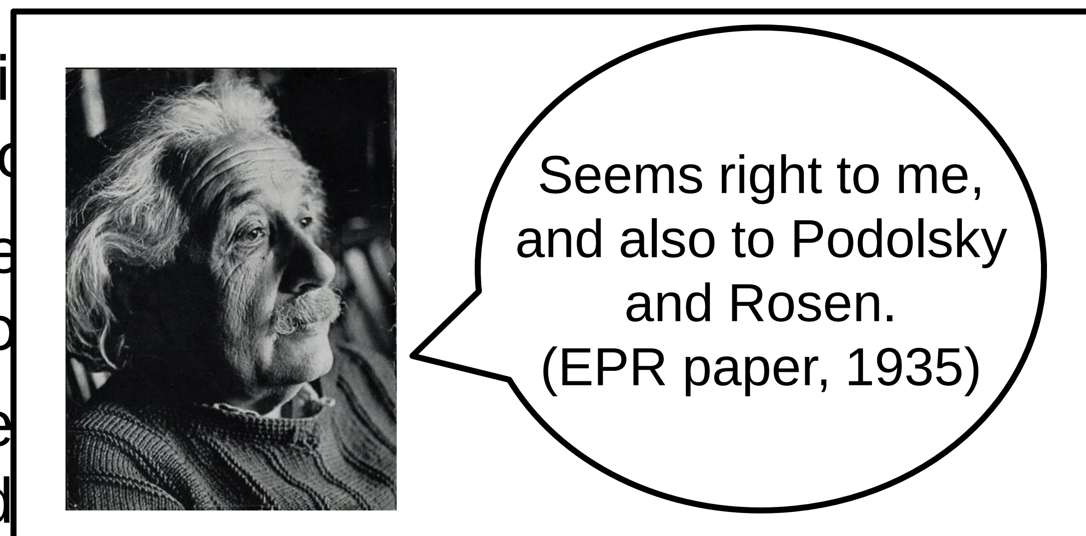


The Newlywed Game

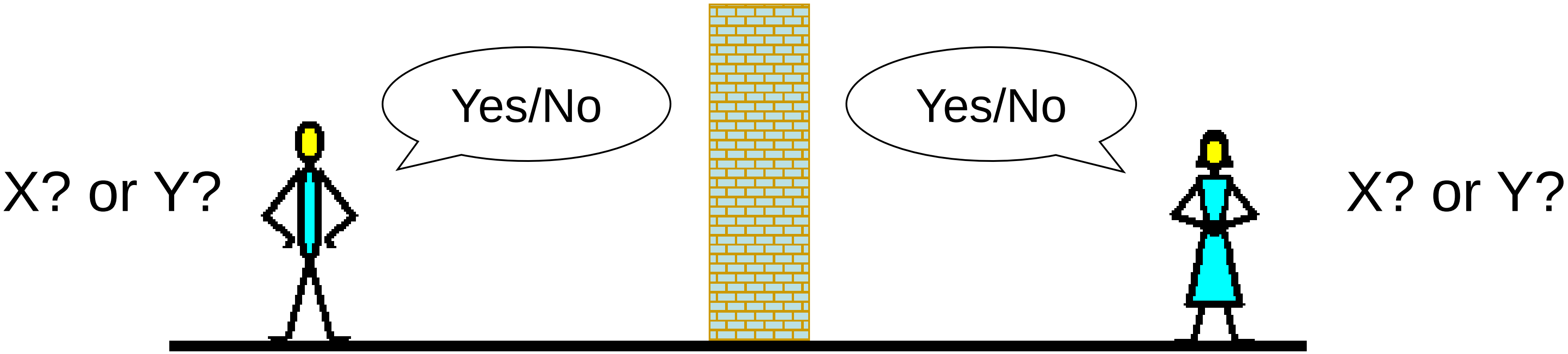
Alice and Bob have a relationship.

Interview them separately. Possible questions:

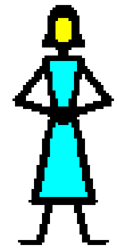
X? = Do you like to dance?

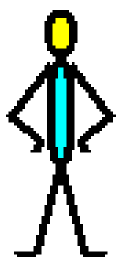
Y? = Do you like to eat oysters?

Individual answers are not predictable, but Alice and Bob give **correlated** answers.



A curious relationship

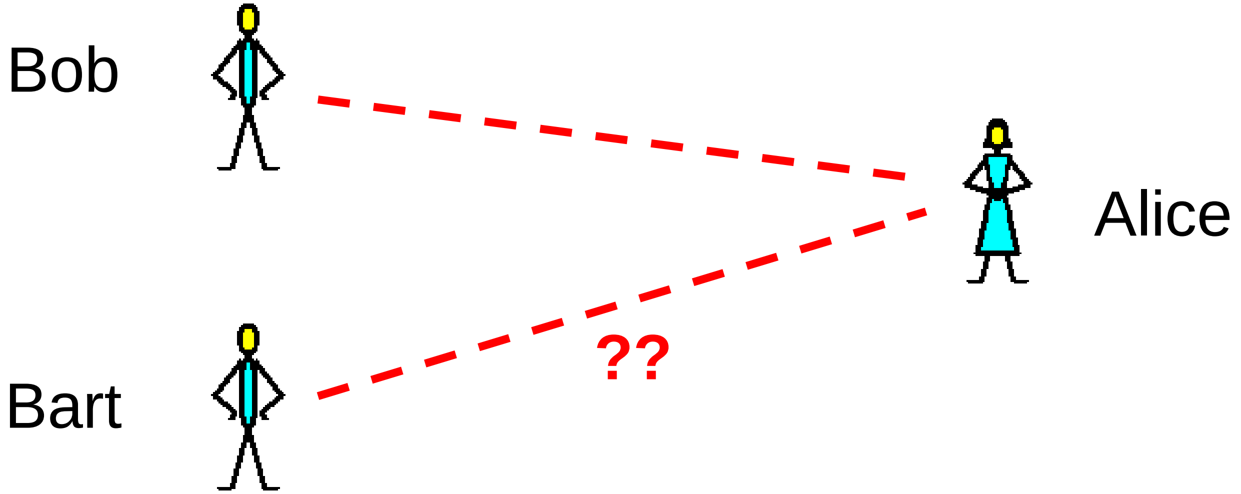




P(agree)	X?	Y?
X?	100%	0%
Y?	0%	0%

A monogamous relationship?

Could someone else (Bart) have the same relationship to Alice? That is, could Bart agree/disagree with Alice just as Bob does?



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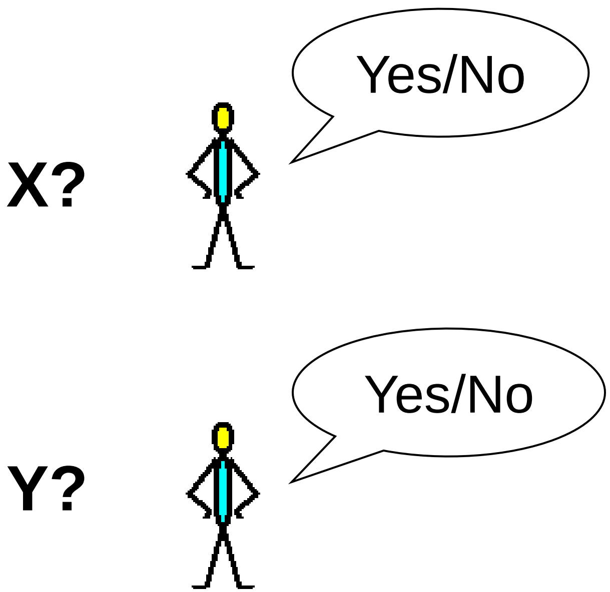
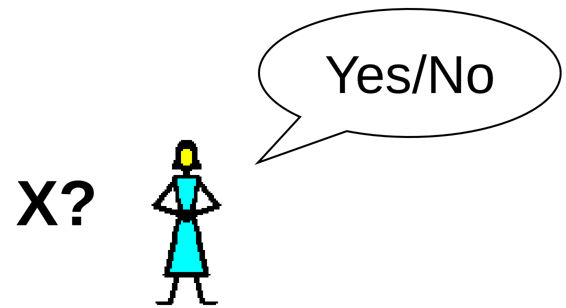
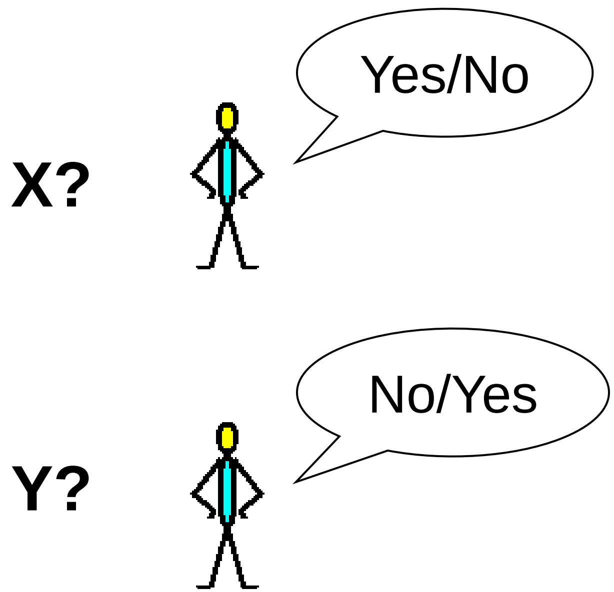


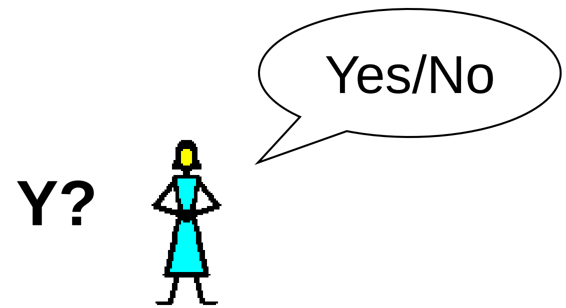


If Bob and Bart give the *same* answer, then Bart also agrees with Alice if we ask her X

A monogamous relationship?

Could someone else (Bart) have the same relationship to Alice? That is, could Bart agree/disagree with Alice just as Bob does?

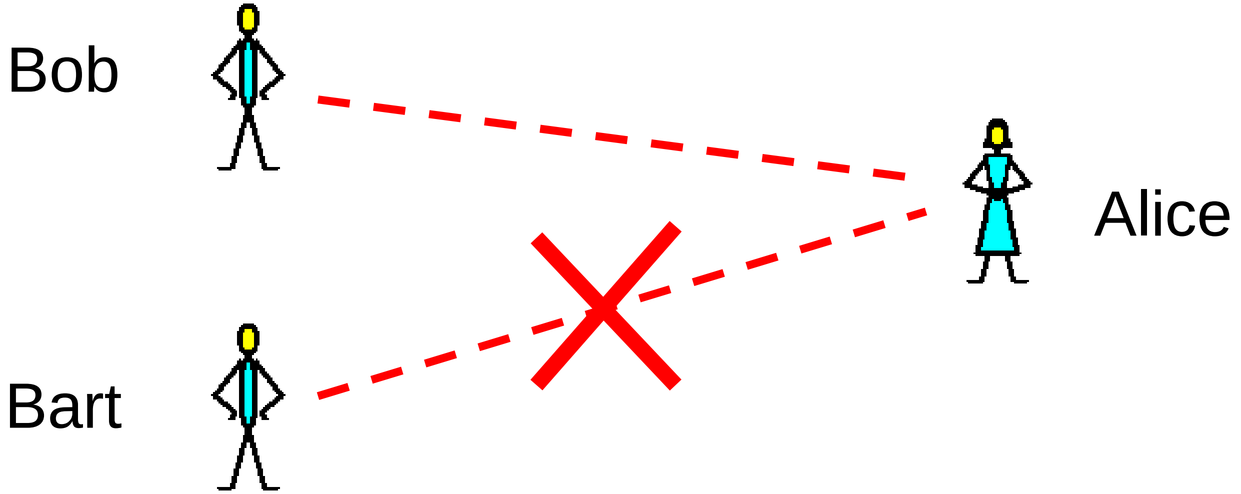


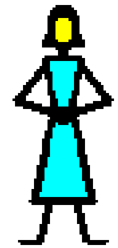


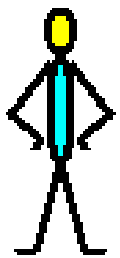
If Bob and Bart give *different* answers, then Bart must agree with Alice if we ask her Y

A monogamous relationship?

Could someone else (Bart) have the same relationship to Alice? That is, could Bart agree/disagree with Alice just as Bob does?

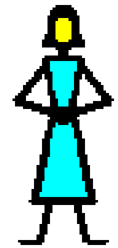


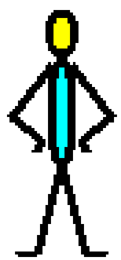




P(agree)	**X?**	**Y?**
X?	100%	0%
Y?	0%	0%

No third party can share in Alice and Bob’s relationship. It is *necessarily* **monogamous**!

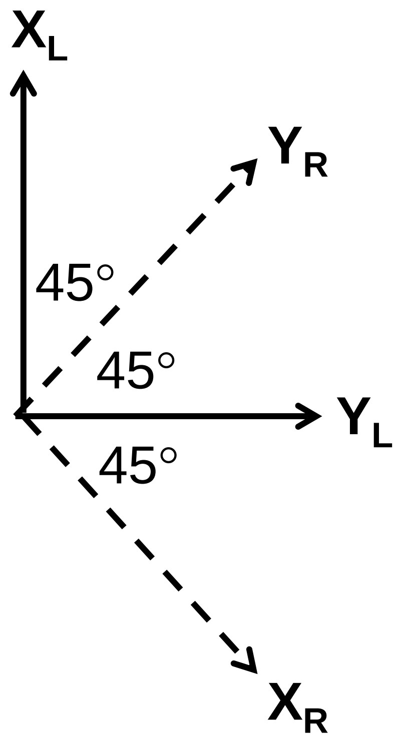




P(agree)	X?	Y?
X?	85% ~~100%~~	15% ~~0%~~
Y?	15% ~~0%~~	15% ~~0%~~

If the correlation is "noisy", the result still holds:
Alice and Bob's relationship is **monogamous**.

Quantum Newlywed Game



P(agree)	X_L	Y_R
X_L	85%	15%
Y_R	15%	15%

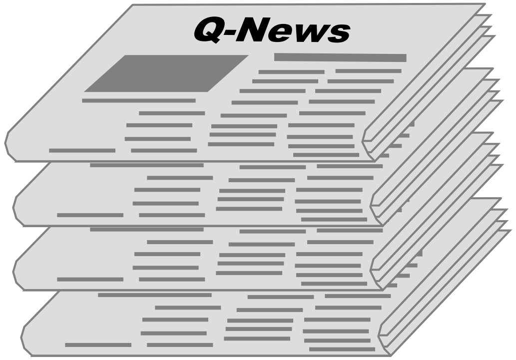
Quantum entanglement is monogamous!

Ordinary information can be shared

Newspaper #1

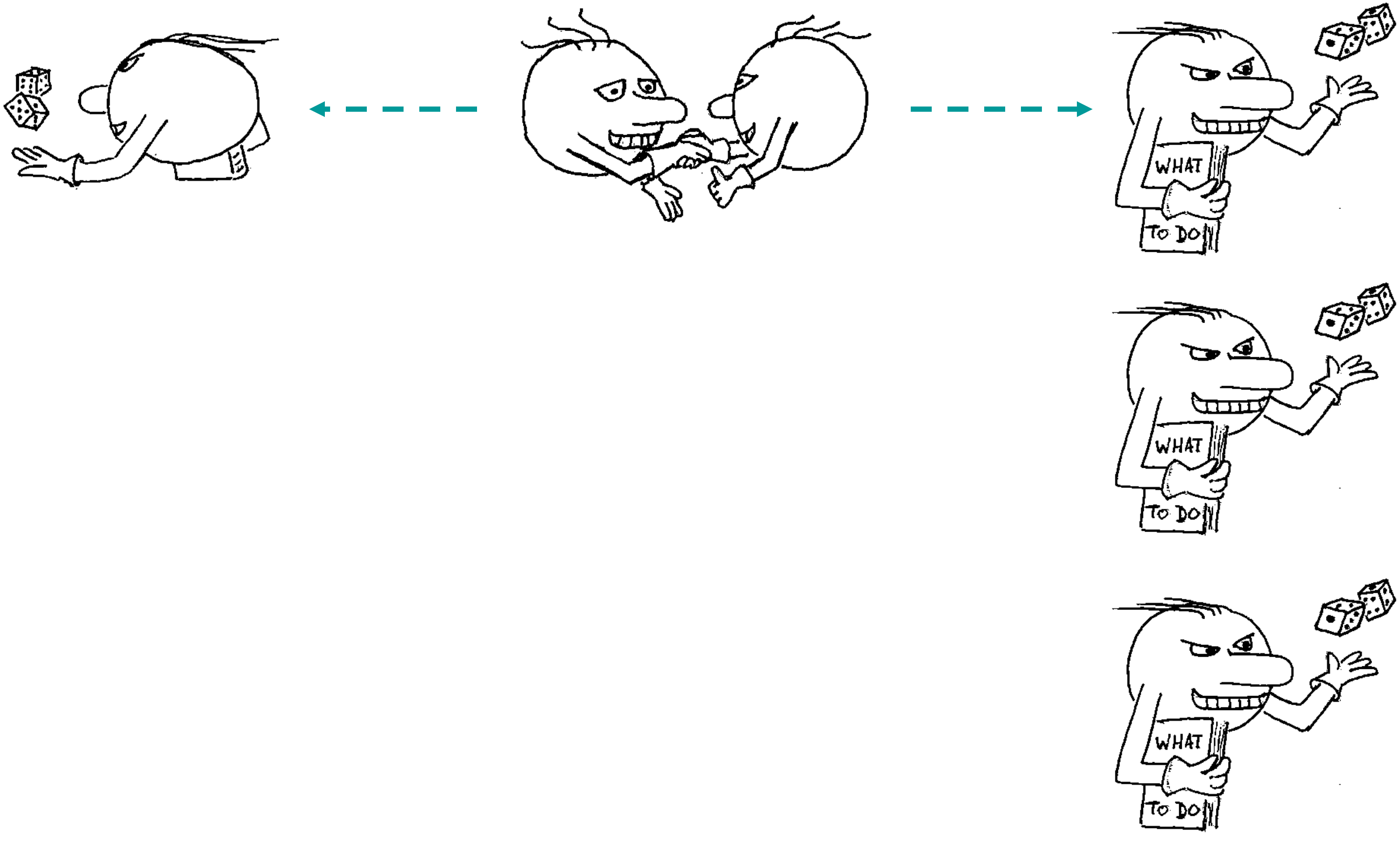
Newspaper #2

- Two copies of the newspaper are highly correlated.
- The same news! The same pictures! The same ads!
- Strong correlation between #1 and #2 does not prevent them from also being correlated with #3, #4, #5, etc.

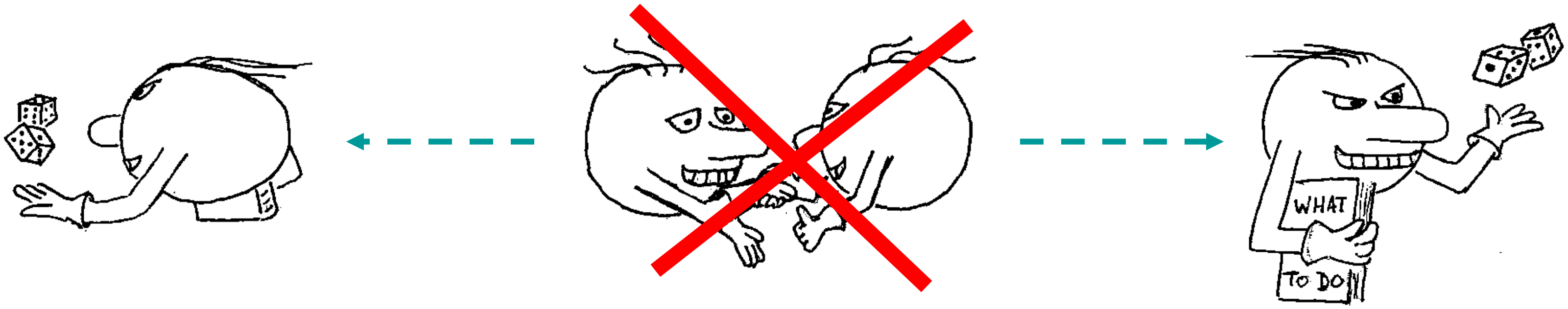


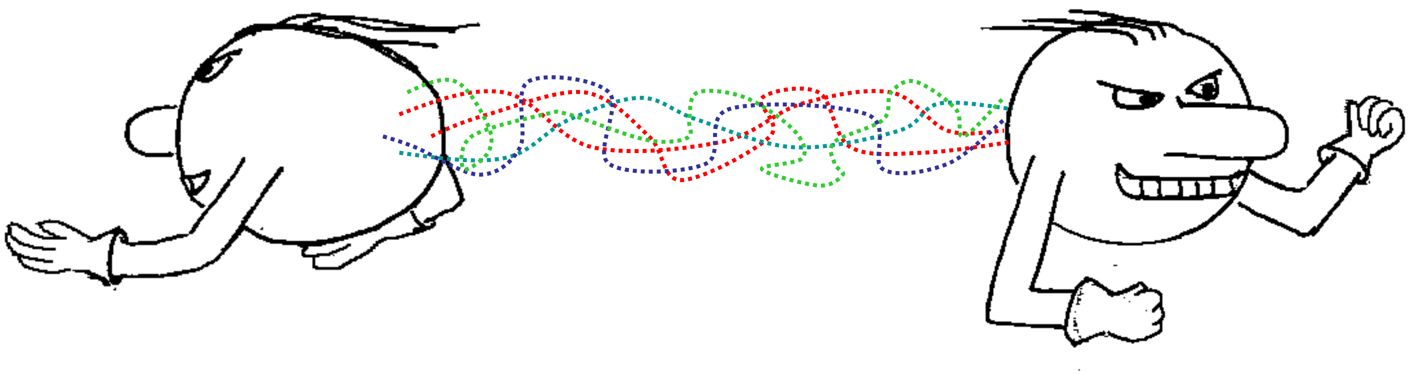
The correlation between two newspapers could be shared with any number of other copies!

Common sense ≠ monogamy



Entanglement ≠ common sense





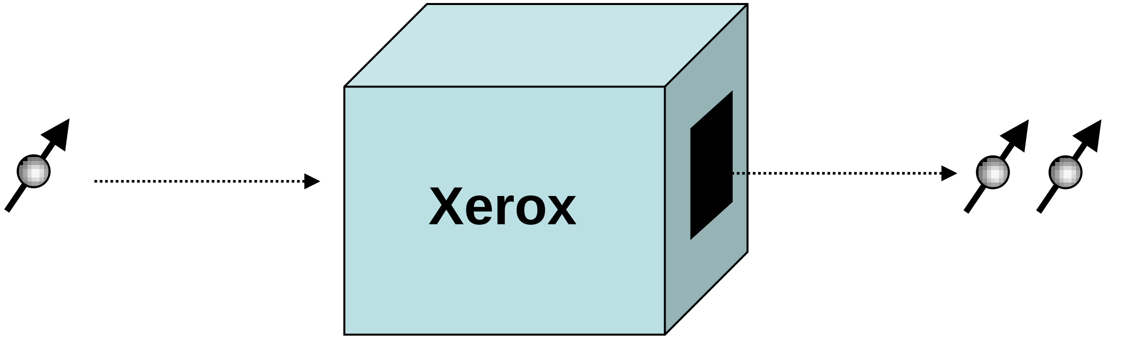
John Bell: No **local hidden variable** theory is consistent with quantum physics.

Abner Shimony: "Passion at a distance"

- Monogamy of entanglement is not just a "quantum" law -- it is a logical consequence of the *observed correlations* of the spins.
- Entanglement is not simply shared information.
- Any future (post-quantum) theories must include monogamous relationships between particles -- i.e., some version of entanglement.
- "Passion at a distance" is such a private, intimate relationship that **no other particles anywhere in the Universe can share in it**.

Fourth Part:
More Clandestine Habits of Quantum Creatures

No quantum cloning

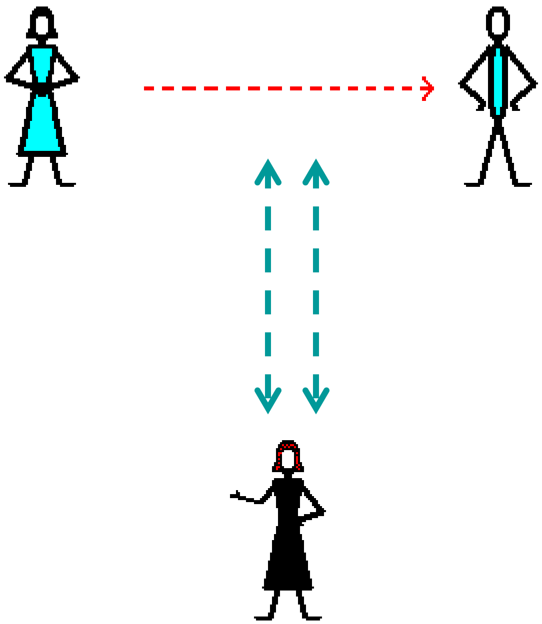


Q: Can we build a machine that could perfectly duplicate ("clone") a quantum spin, regardless of its initial state?

A: No! (The quantum **no-cloning theorem**)

Quantum information -- the type of information stored in quantum systems -- cannot be perfectly copied.

How to keep a secret



Alice sends secret data to Bob as a string of quantum particles

Eve cannot “eavesdrop” without disturbing the quantum information in some way (no quantum cloning!)

This idea is called **quantum cryptography**.

Lyrics to "*Alice et Bob*"

"Alice et Bob sur un canal public"
by Les Tchigaboux

Je suis atteint/D'une maladie Chronique
Un maudit microbe/Attendez que je vous explique
J'ai le beguin/Pour une fille angelique
Qui se derobe/Et prefere un drole de deux de pique
Elle, c'est Alice/Bob son pretendant
J'suis plus en lice/Pour gagner le coeur de l'enfant

Alice et Bob sur un canal public

Trop jaloux/V'la que je joue a la police
Dans les egouts/Sous l'appartement d'Alice
Taper la ligne/De son telephone
En bout de ligne/V'la tout ce que ca me donne:
Mes instruments/Reagissent de facon bizarre
J'entends du bruit blanc/Pis j'reste dans le noir

Alice et Bob sur un canal public

Voyant cela/J'ai utilise un modem
Pour jouir du son de la voix/De celle que j'aime
J'ai pu craquer facilement/Les protections du Bell
Mais suis reste impuissant/Face a celle de ma belle
Quelles sont donc les ficelles/De ce protocole
Quel est donc ce coeur rebelle/Que je cambriole?

Alice et Bob sur un canal public

J'me suis achete/Une antenne parabolique
Loue un *Cray*/Lu des traites d'algorithmique
Mais malgre mes efforts/Et tout ce temps de calcul
Je pitonne encore/Couvert de ridicule
Quelles sont donc les ficelles/De ce protocole
Quel est donc ce coeur rebelle/Que je cambriole?

Alice et Bob sur un canal public

The End