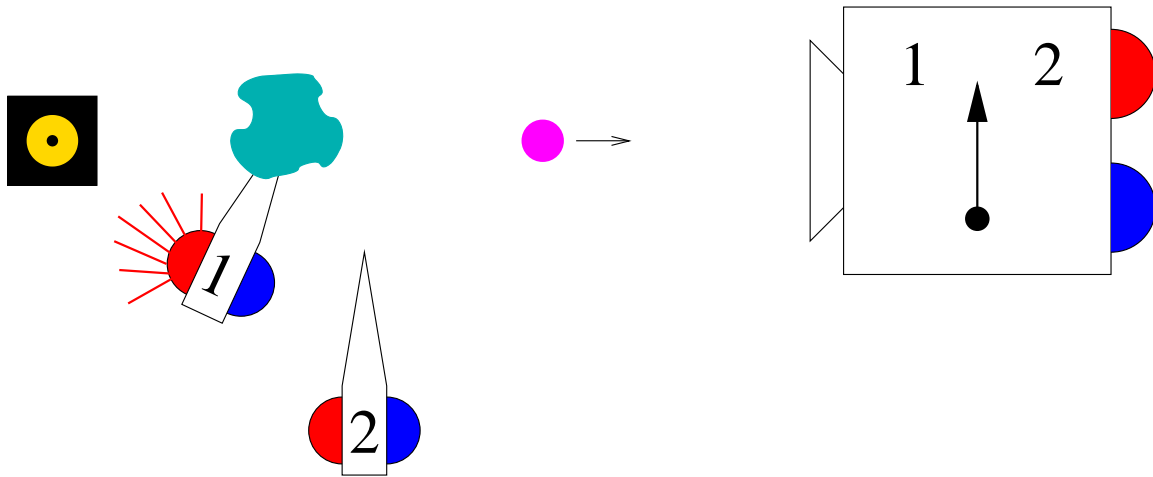


SPOOKY ACTIONS AT A DISTANCE?

Oppenheimer Lecture

Berkeley, **March 17**, 2008



THE QUANTUM THEORY

*The most accurate and successful theory
in the history of science*

The greatest intellectual achievement of the 20th century

But it is... quite strange.

Einstein on the Quantum Theory

*I cannot seriously believe in it because the theory cannot be reconciled with the idea that physics should represent a **reality** in time and space, free from **spooky actions at a distance**.*

— Einstein (to Max Born)

Einstein on the Quantum Theory

Most [physicists] simply do not see what sort of risky game they are playing with reality — reality as something independent of what is experimentally established.

— Einstein (to Erwin Schrödinger)

No reasonable definition of reality could be expected to permit this.

— Einstein, Podolsky, and Rosen

Bohr on the Quantum Theory

*I was strongly reminded of the importance of **utmost caution** in all questions of terminology and dialectics.*

— Bohr (on his debates with Einstein)

“Bohr” on the Quantum Theory

When asked whether the algorithm of quantum mechanics could be considered as somehow mirroring an underlying quantum world, Bohr would answer,

“There is no quantum world. There is only an abstract quantum physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.”

— Aage Petersen (in his obituary of Bohr)

Bohr on the Quantum Theory

Physics is to be regarded not so much as the study of something a priori given, but rather as the development of methods for ordering and surveying human experience.

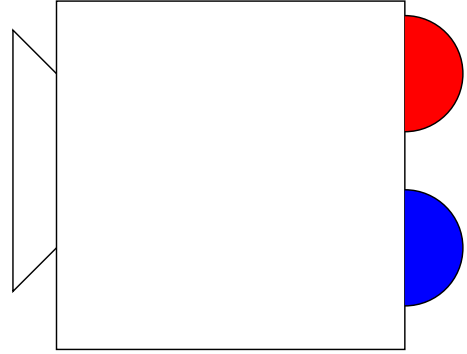
— Bohr

Part I.

Can a Thing Possess (Real) Properties?



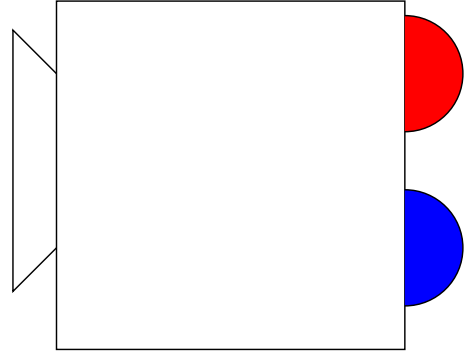
Source



Detector



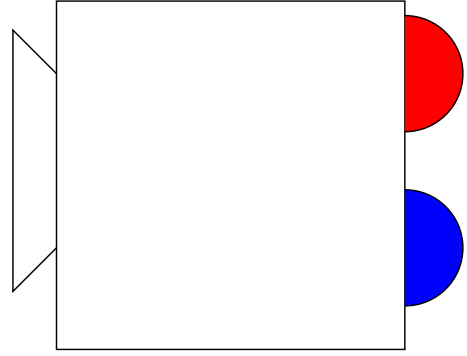
S



D



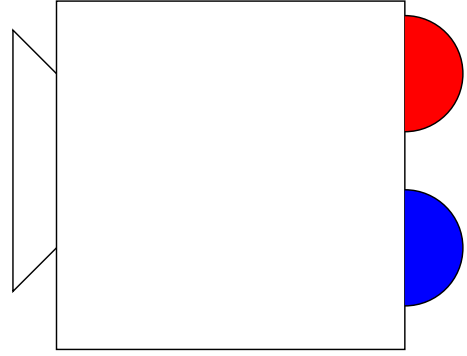
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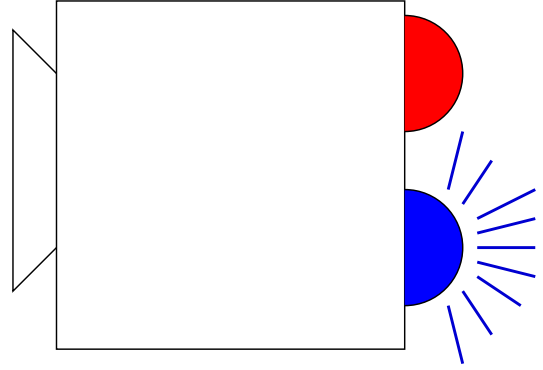
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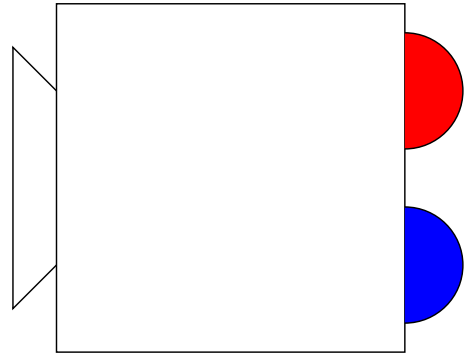
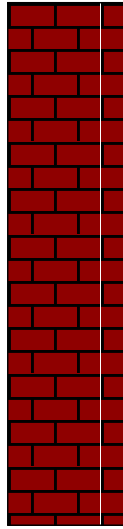
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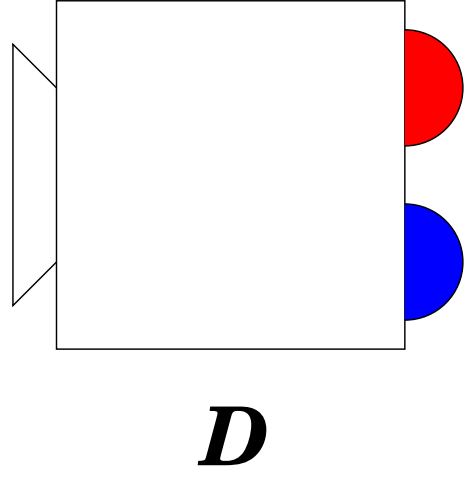
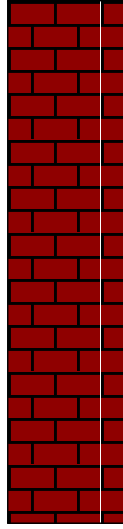
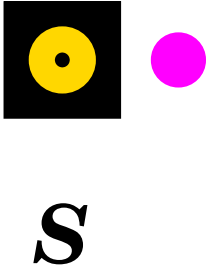
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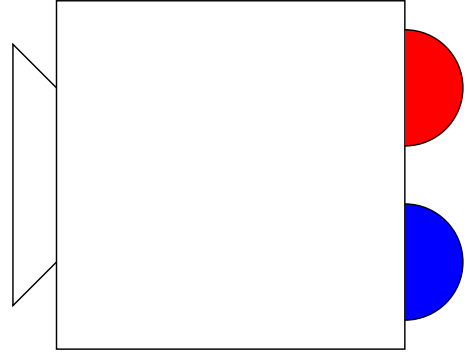
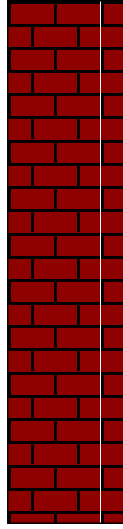


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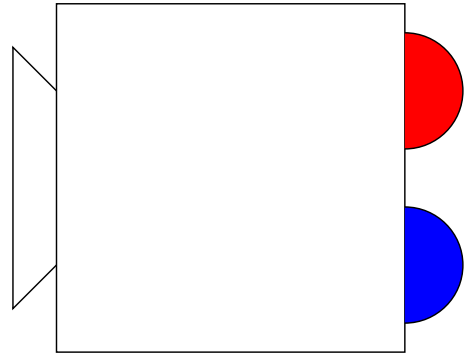
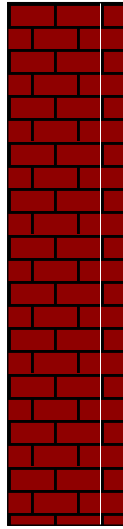
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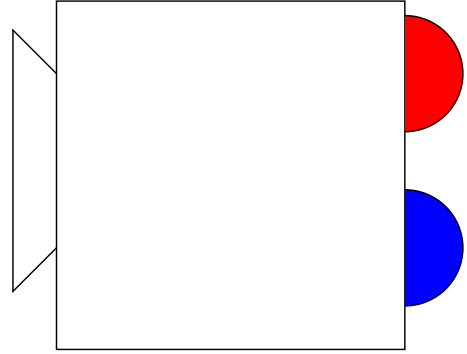
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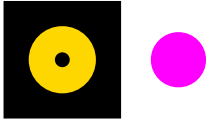
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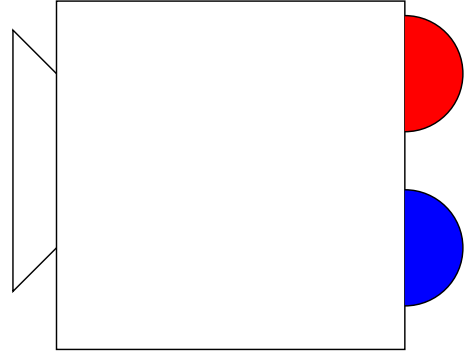
Source



Detector



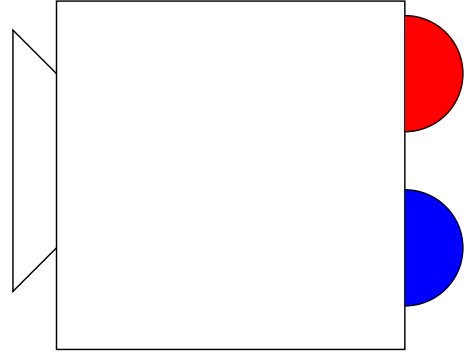
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D



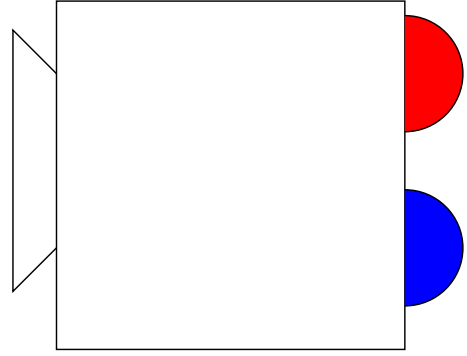
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D



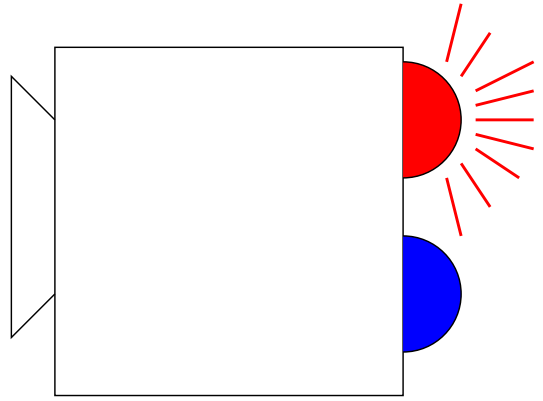
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D



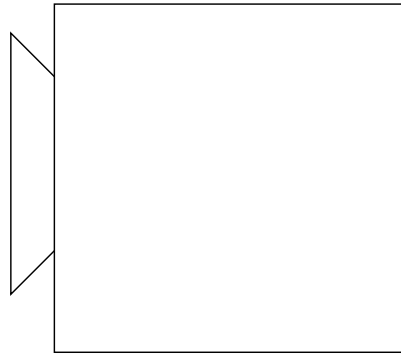
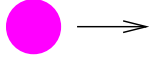
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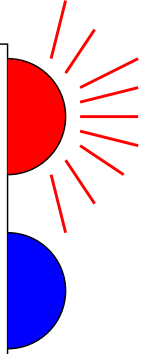
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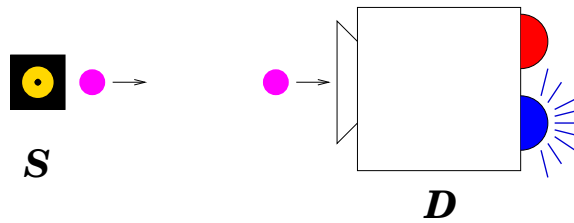


S



D



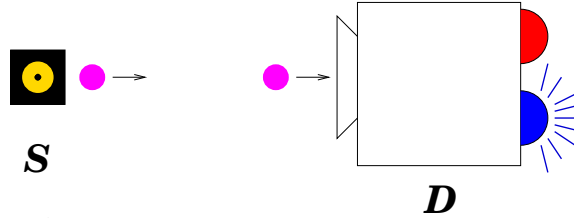


QUESTION:

Is the color flashed by D a response to a (real) property of the things from S ?

If so, call that (real) property “color”.

Things coming from S are of two types:
Those “colored” blue and those “colored” red.
 D detects which type of thing has entered it.



POSSIBLE EXAMPLES:

Things are hot or cold.

Detector flashes **red** for hot things,
blue for cold things.

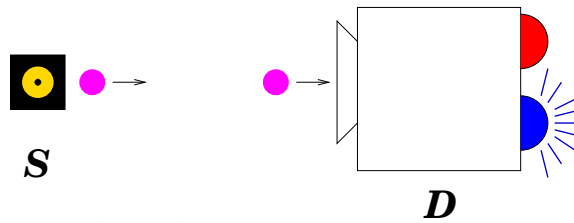
“Color” = Temperature

OR

Things are cubes or spheres.

Detector flashes **red** for cubes, **blue** for spheres.

“Color” = Shape

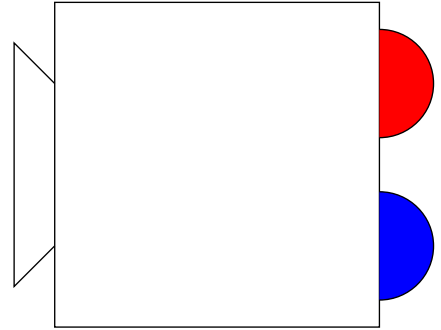
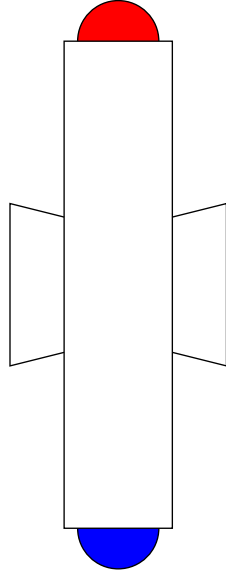


“COLORLESS” EXPLANATIONS:

- Things from S are identical. D decides which color to flash by tossing coin.
- D programmed to flash **red** or **blue** according to sequence on tape. Each thing from S triggers mechanism that moves tape to next position.
- Whether D flashes **red** or **blue** depends on time of day.



S

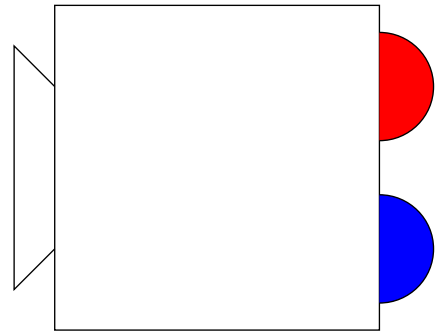
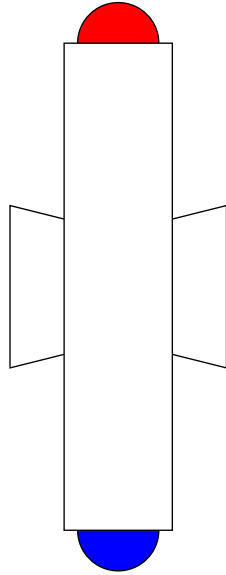


D

Testing device



S

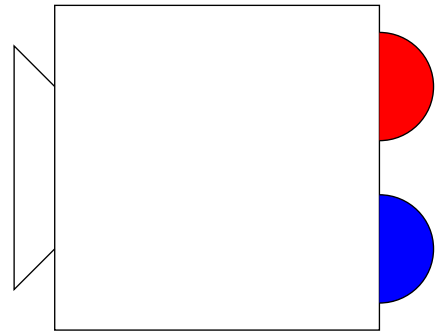
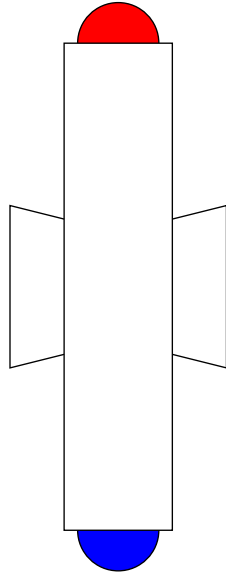


D

Testing device



S

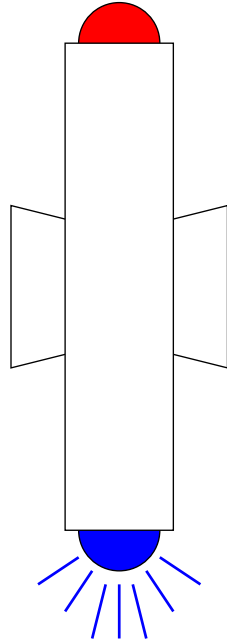


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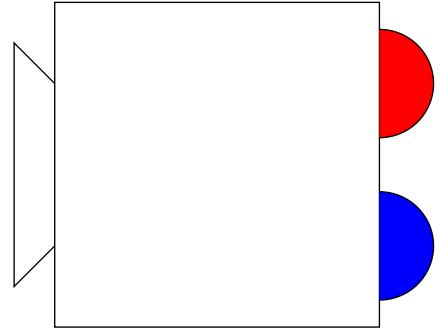
Testing device



S



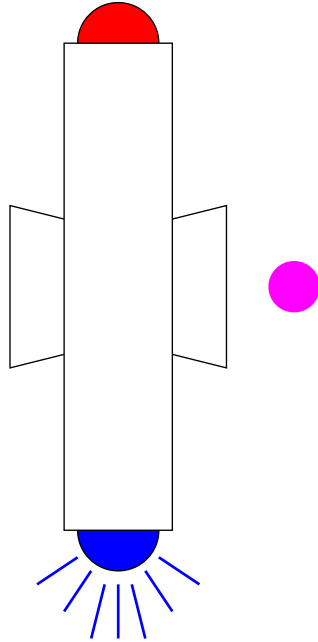
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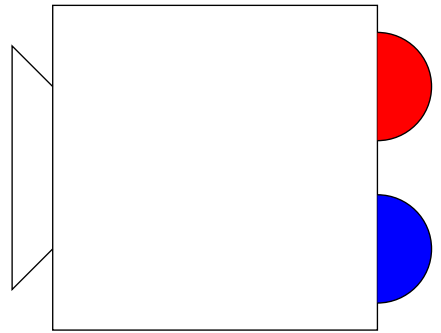
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S



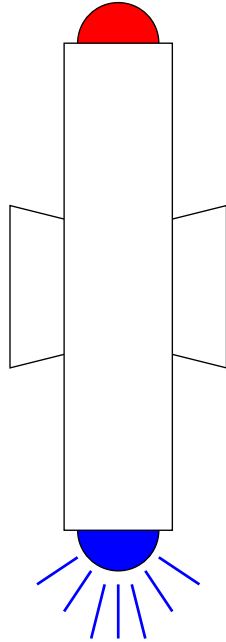
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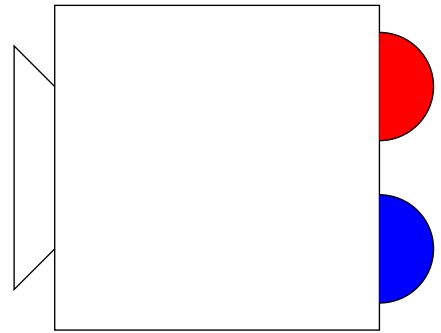
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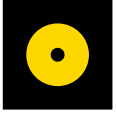
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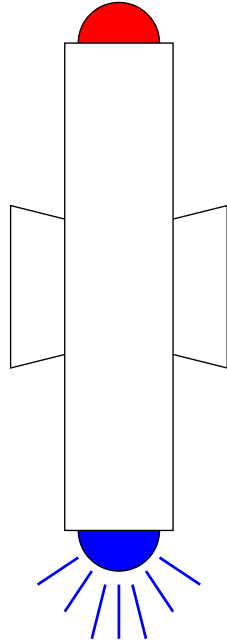
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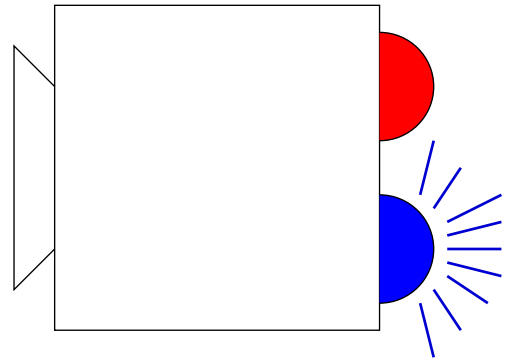
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S



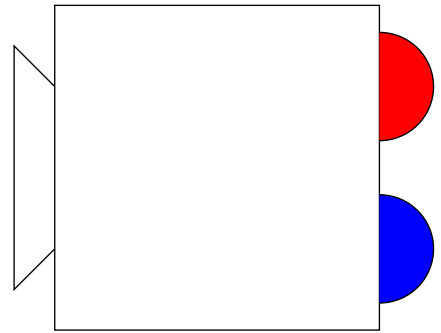
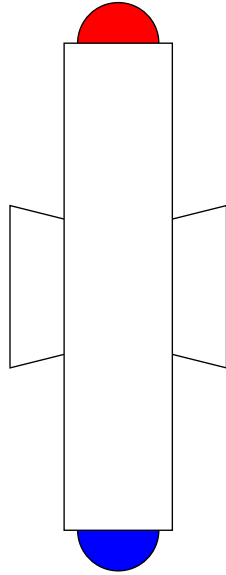
Testing device



D



S

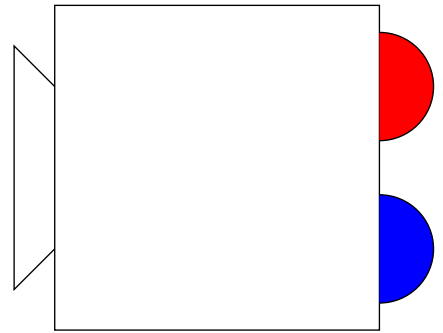
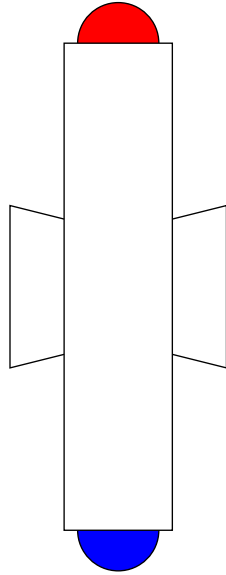


D

Testing device



S

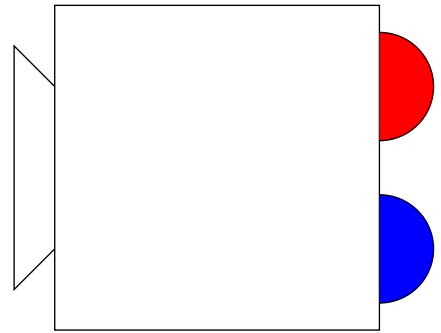
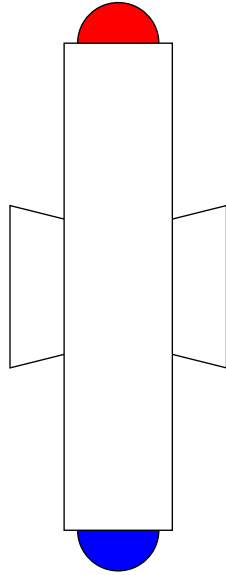


D

Testing device



S

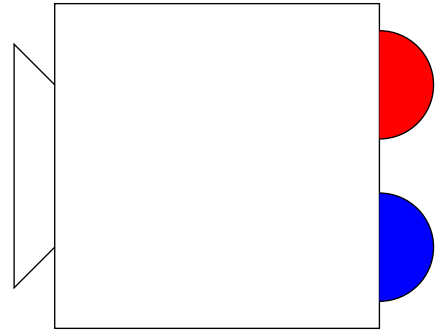
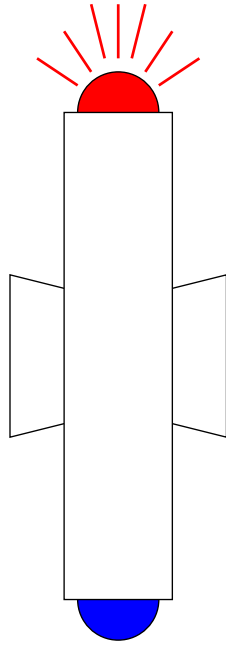


D

Testing device



S

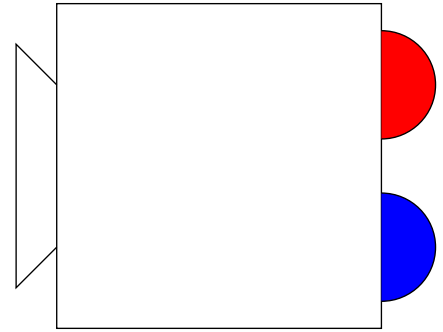
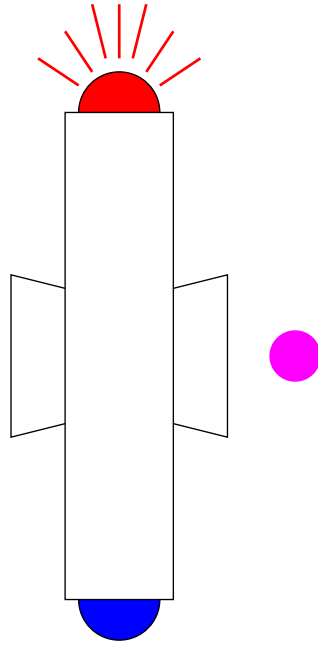


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Testing device



S

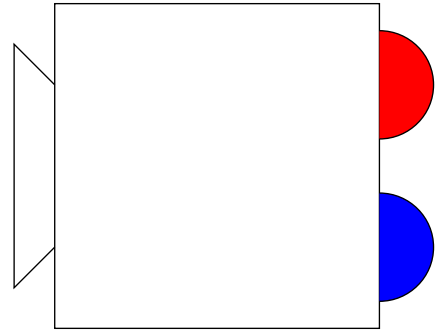
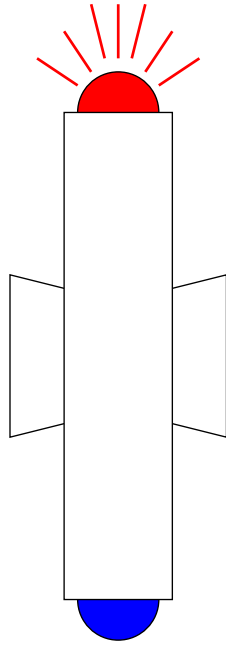


D

Testing device



S

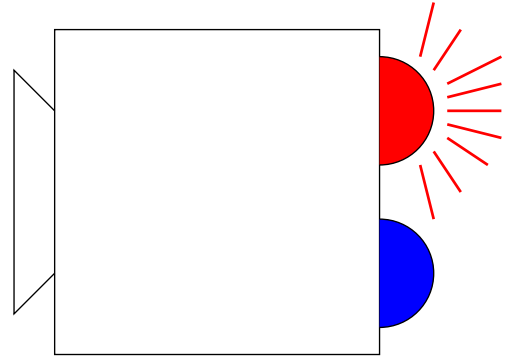
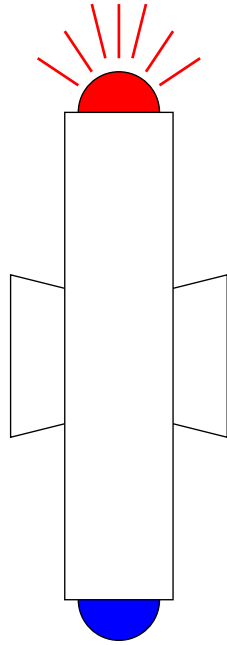


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Testing device

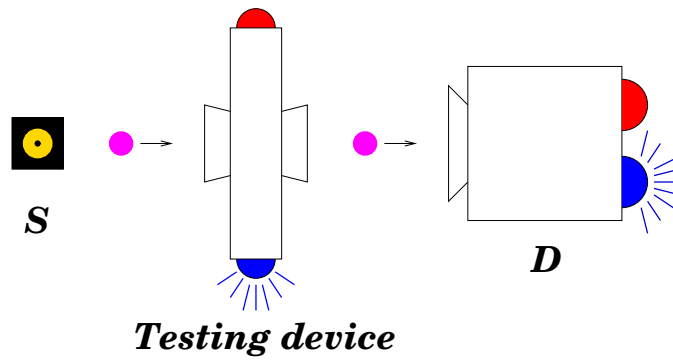


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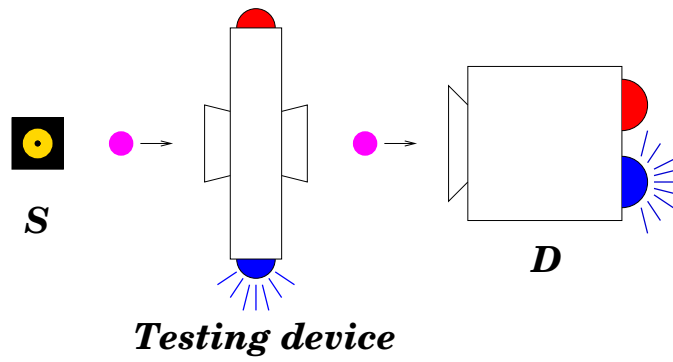
D

Testing device



When testing device inserted between S and D , testing device always flashes same color as D .

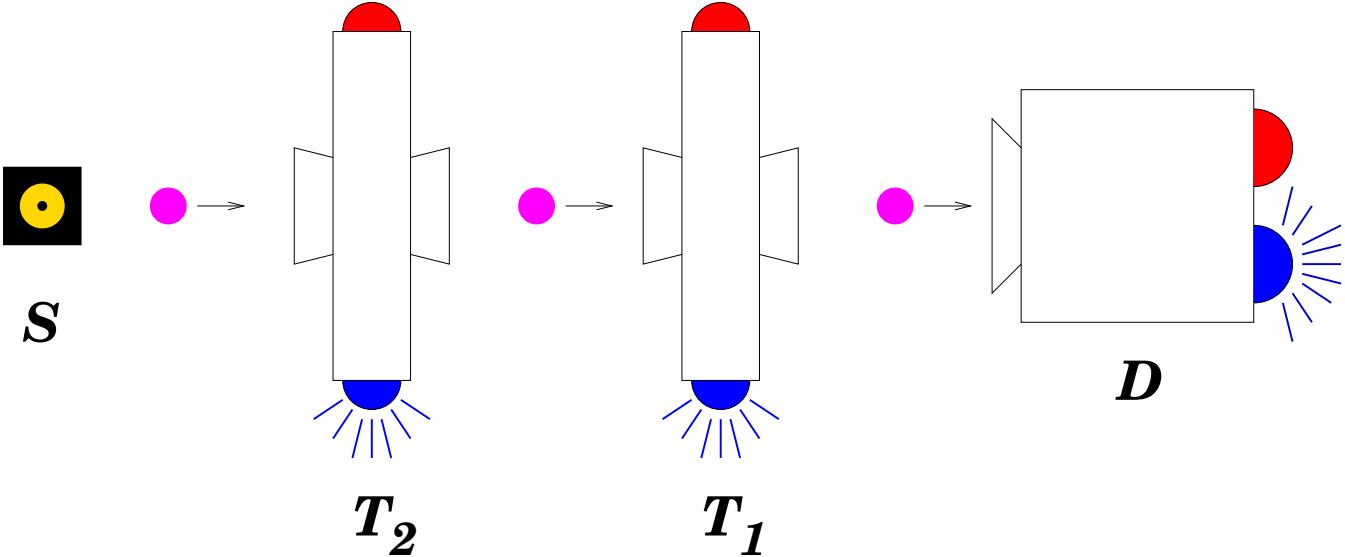
So thing emerging from testing device flashing blue (red) is surely “colored” blue (red).

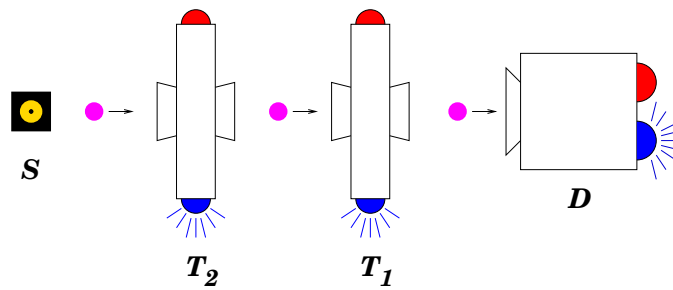


QUESTION:

Does thing *entering* testing device have “color”?
Or is “color” given to it by the testing device?

ANSWER WITH SECOND TESTING DEVICE:





Second testing device shows that first testing device correctly identifies “color” of things that have “color”.

But it fails to establish that *untested* things have “color”

QUESTION: Do untested things have “color”?

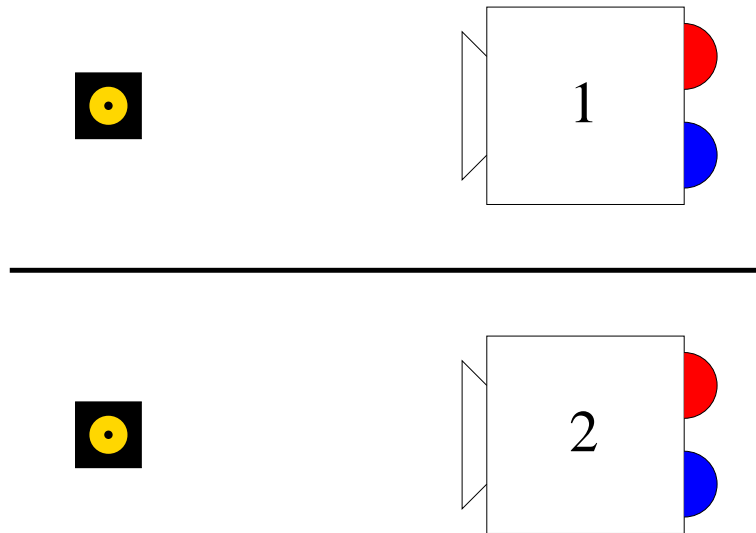
Is there a reality “*independent of what is experimentally established*”?

Part II.

Can a Thing Possess

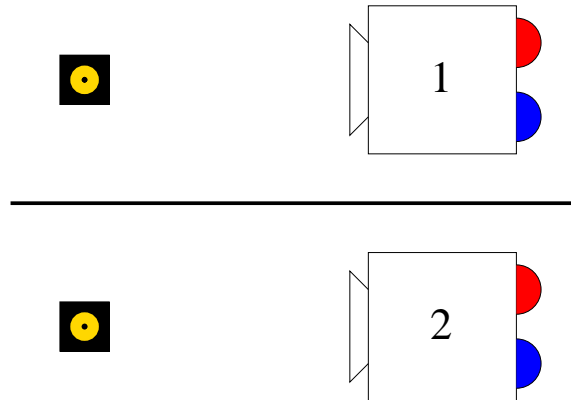
Two Different (Real) Properties?

TWO DIFFERENT KINDS OF DETECTORS



QUESTION:

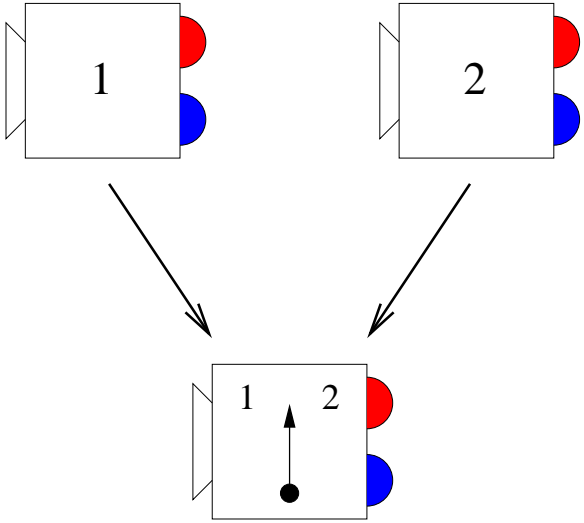
Can a thing have *both* 1-color *and* 2-color?



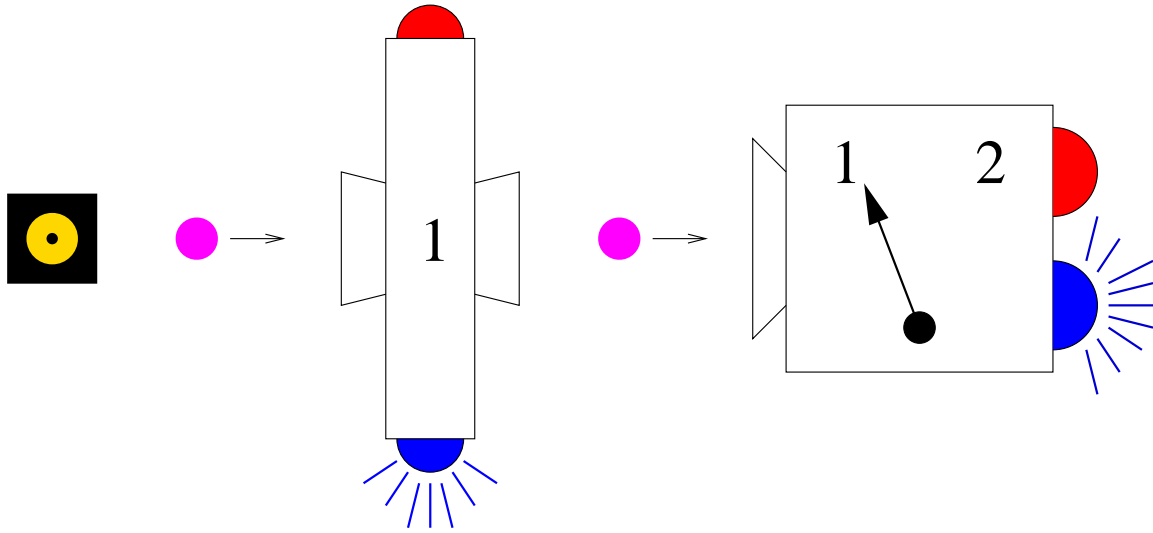
(1-color is property indicated by type-1 detector)

(2-color is property indicated by type-2 detector)

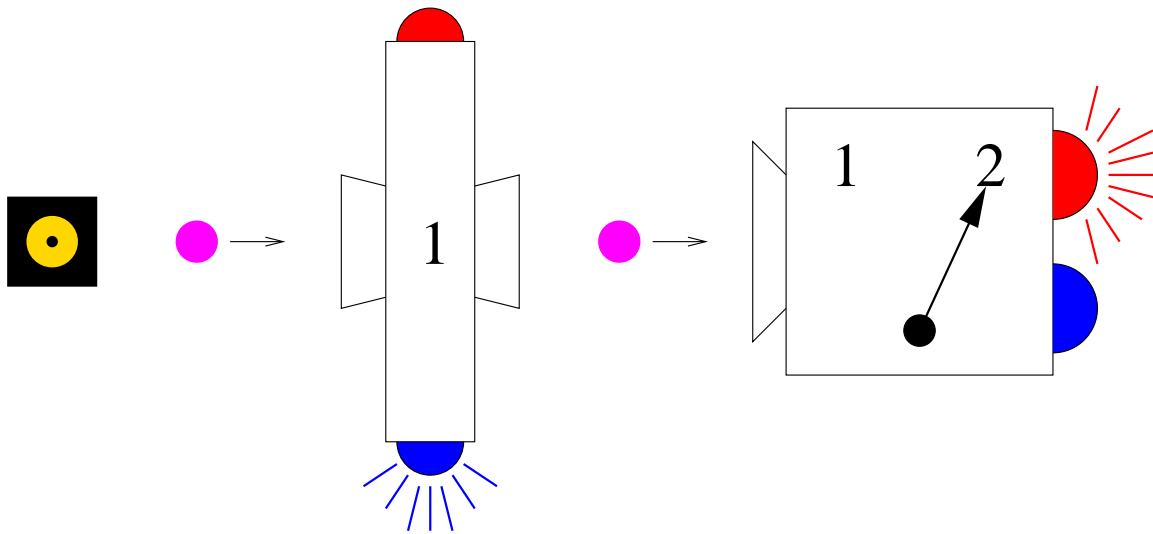
Convenient to package both kinds of detectors into single box with switch:



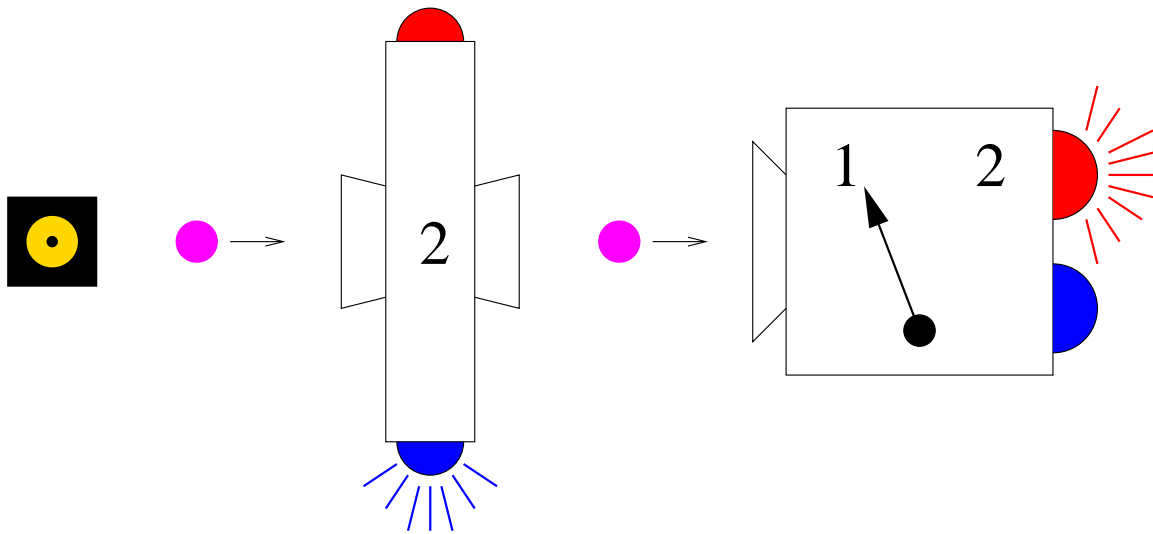
ALSO TWO KINDS OF TESTING DEVICES:



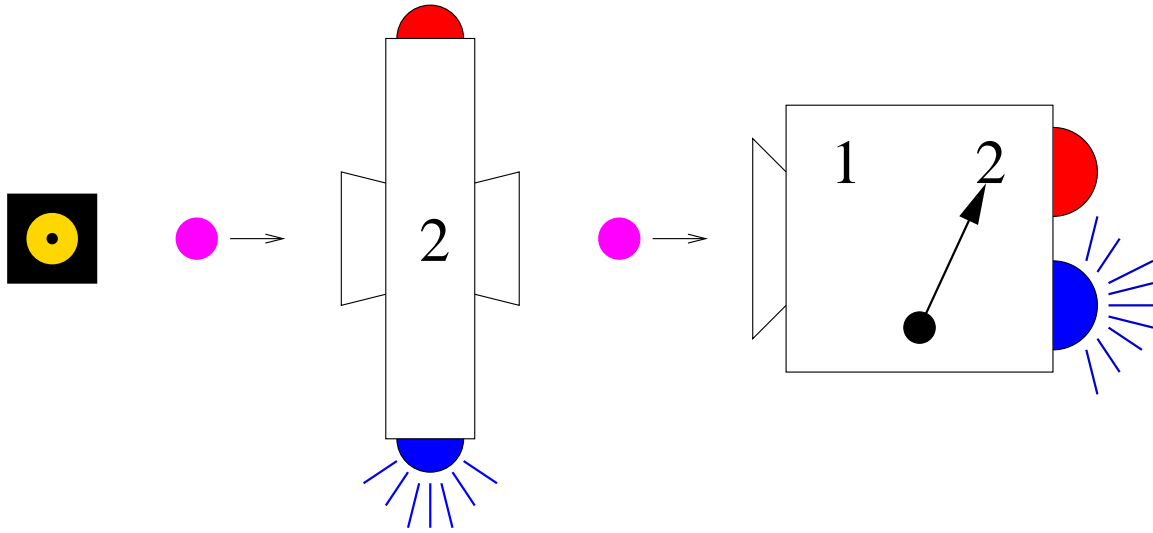
Type 1 testing device *always works* with type 1 detector.



But type 1 testing device is wrong half the time with type 2 detector.

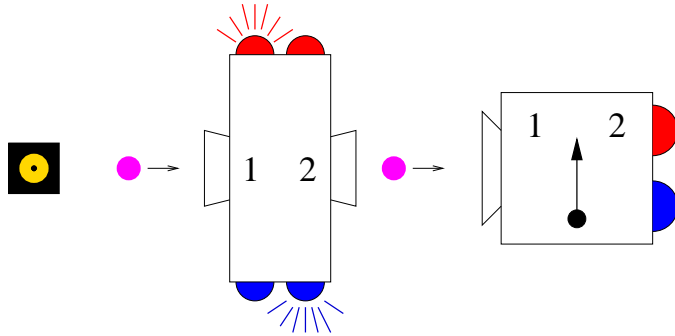


Type 2 testing device is wrong half the time with type 1 detector.



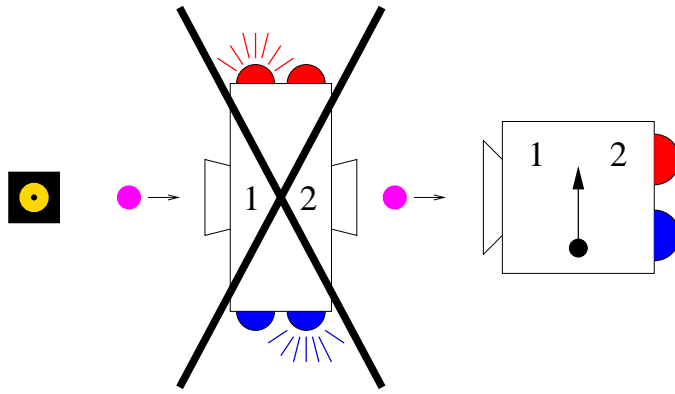
But type 2 testing device *always works* with type 2 detector.

QUESTION: Can a thing have *both* 1-color *and* 2-color?



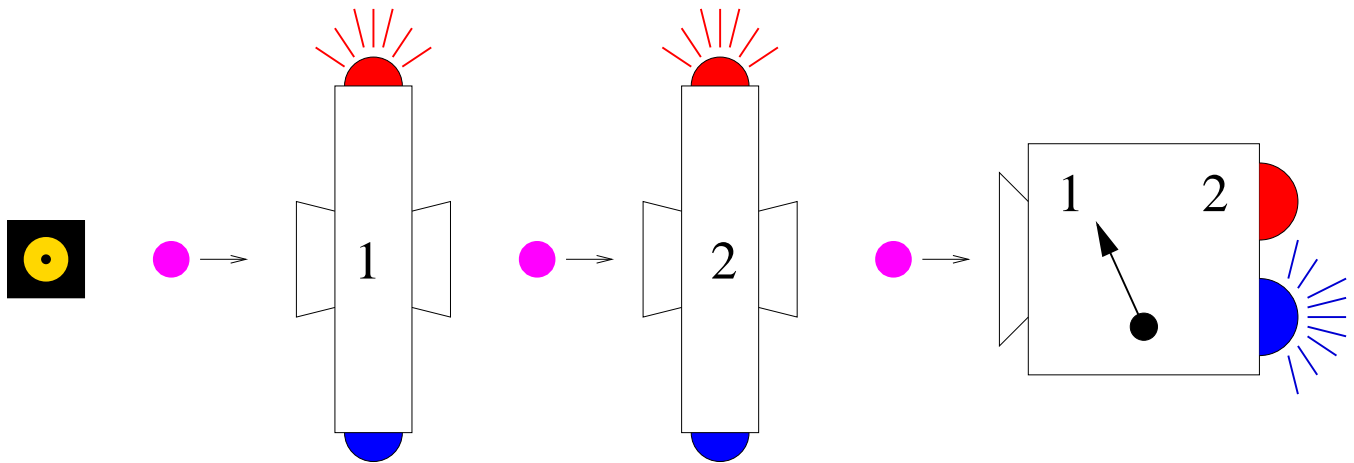
This could be established if there were a joint testing device that always worked, regardless of whether it was followed by a type 1 or a type 2 detector.

QUESTION: Can a thing have *both* 1-color *and* 2-color?



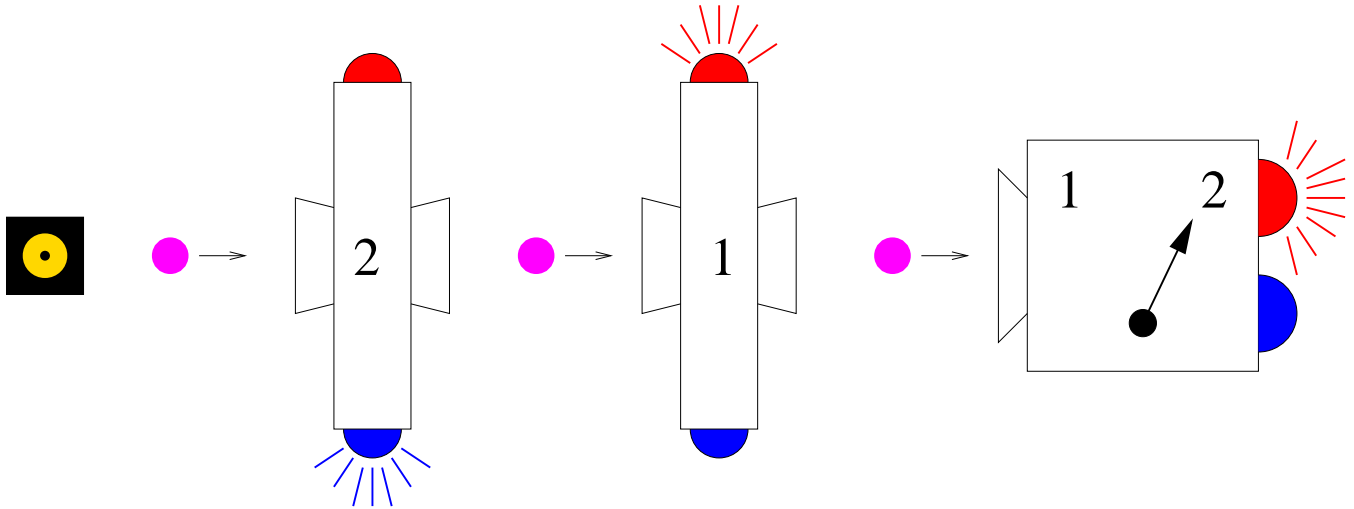
But no such joint testing device is known and we shall see at the end that no such device is possible.

Testing for 2-color *messes up* 1-color



If type 2 testing device comes between type 1 testing device and type 1 detector then type 1 testing device is wrong half the time at type 1 detector

And testing for 1-color *messes up* 2-color



If type 1 testing device comes between type 2 testing device and type 2 detector then type 2 testing device is wrong half the time at type 2 detector

QUESTION (EINSTEIN):

Even though there is no way
to learn what both of them are,
can a thing nevertheless have
both a 1-color and a 2-color?

*“...reality as something independent
of what is experimentally established.”*

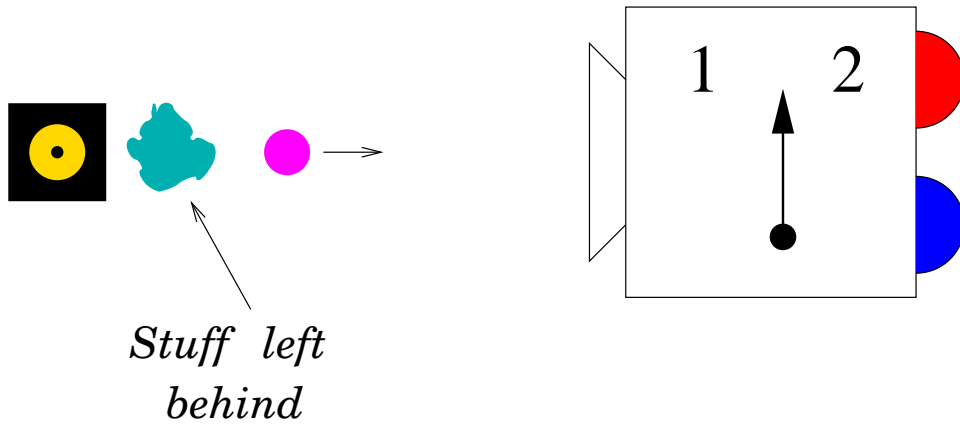
AN OBVIOUS ANSWER:

“One should no more rack one’s brain about the problem of whether something one cannot know anything about exists all the same, than about the ancient question of how many angels are able to sit on the point of a needle. But it seems to me that Einstein’s questions are ultimately always of this kind.”

— Wolfgang Pauli (to Max Born)

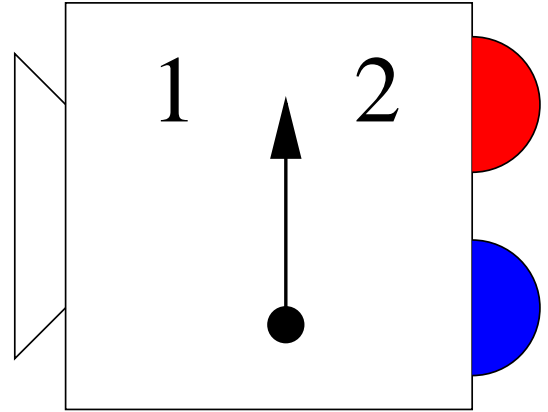
Part III.

Einstein's Neat Idea



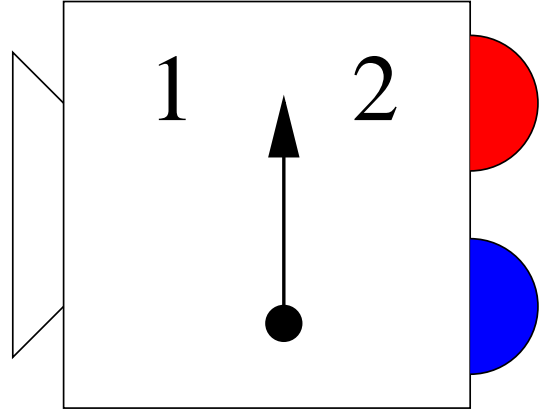
Don't test thing itself; test some stuff it leaves behind it!

Testing stuff it left behind can't mess up the *thing!*
It can only mess up the *stuff left behind.*



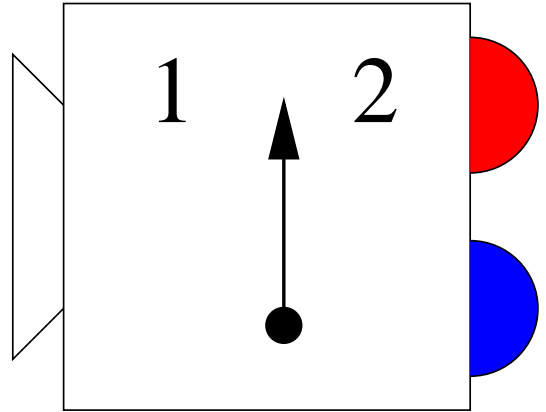


*Stuff
left
behind*



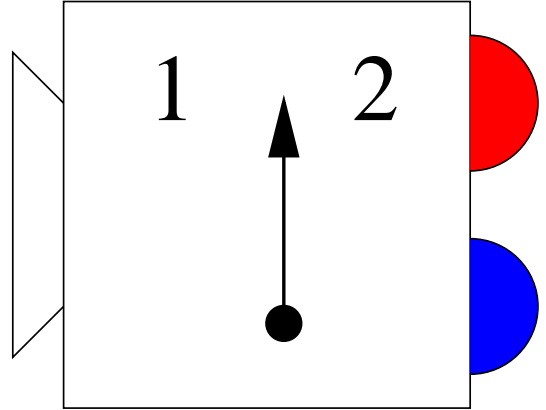


*Stuff
left
behind*



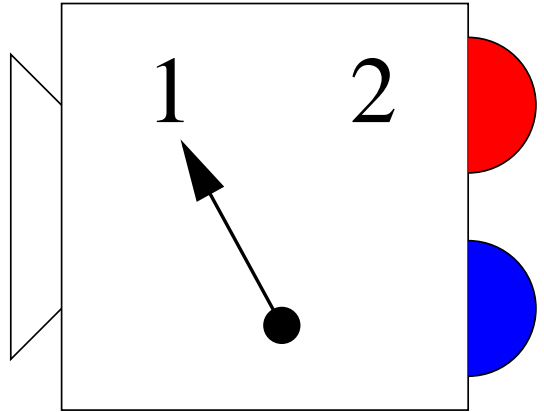


*Stuff
left
behind*



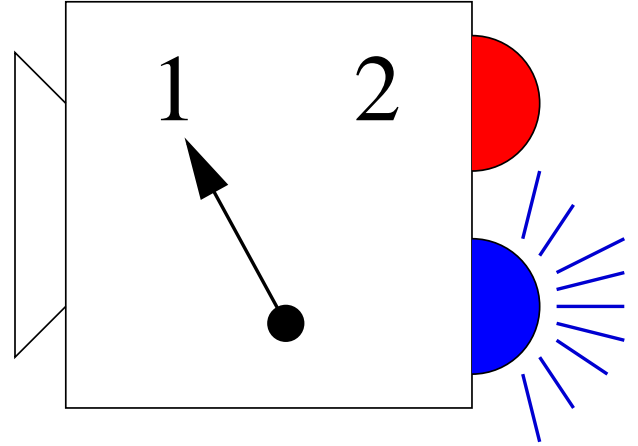


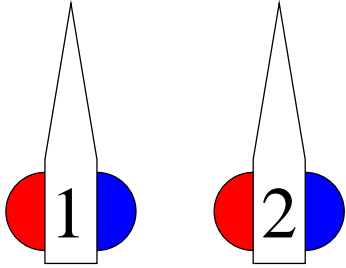
*Stuff
left
behind*



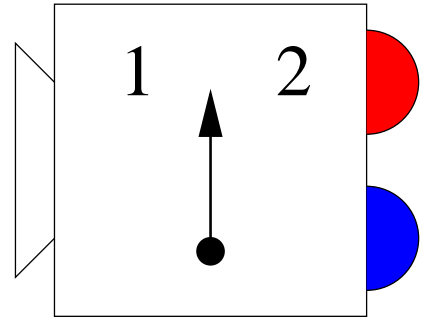


*Stuff
left
behind*

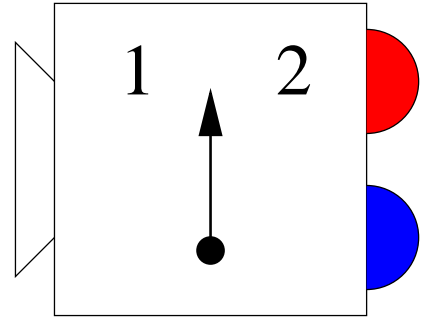
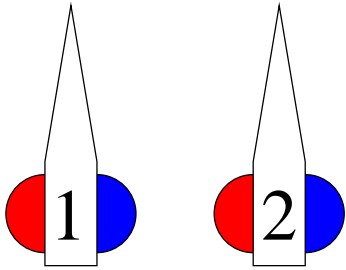


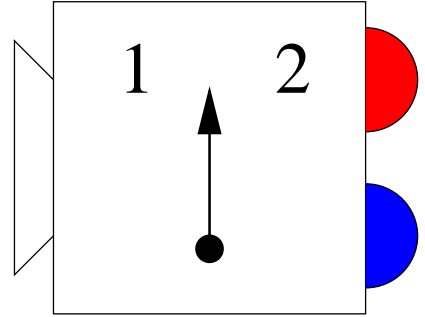
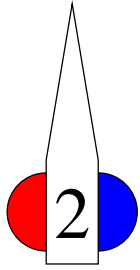
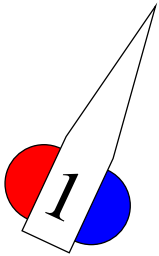


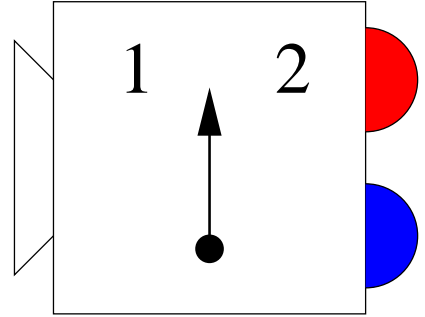
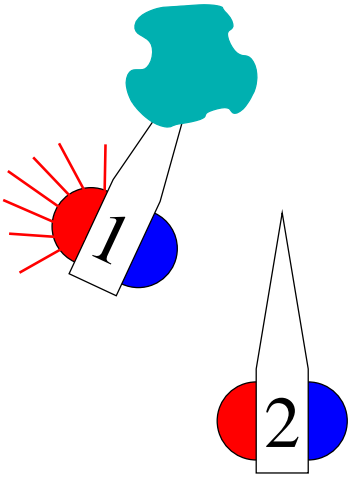
SLB testing devices

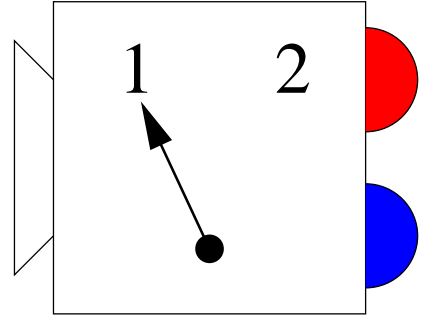
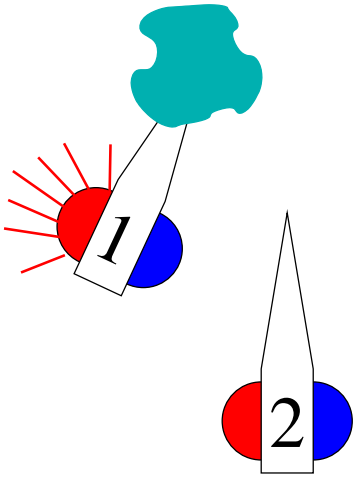


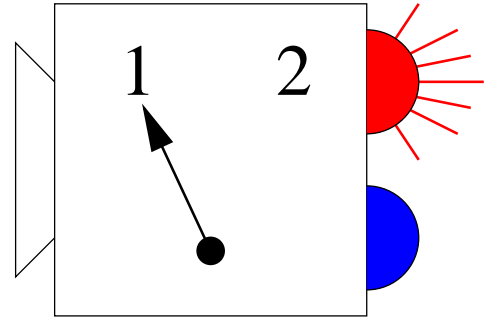
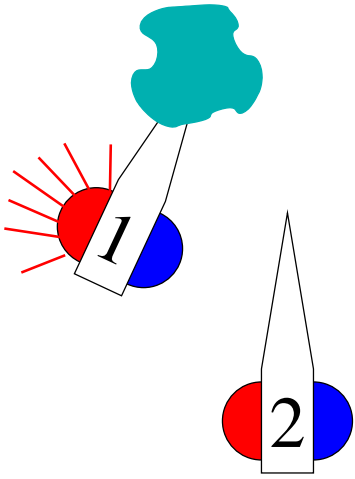
Testing Stuff left behind for 1-color.



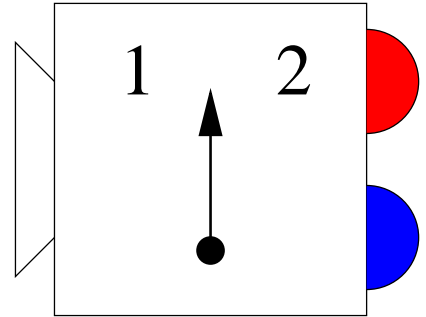
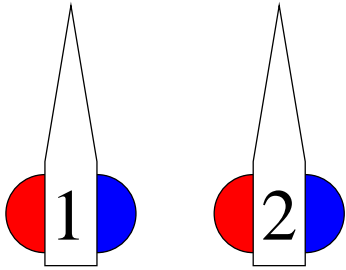


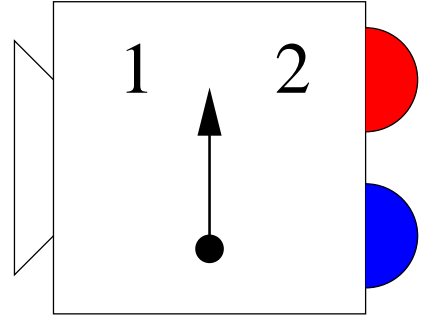
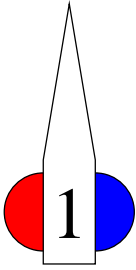


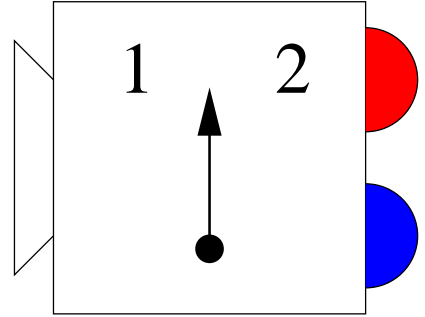
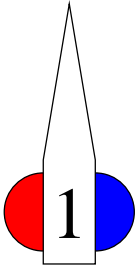
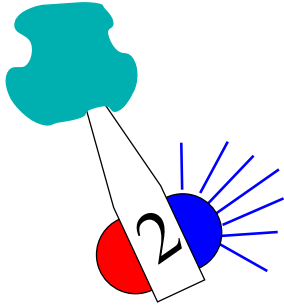


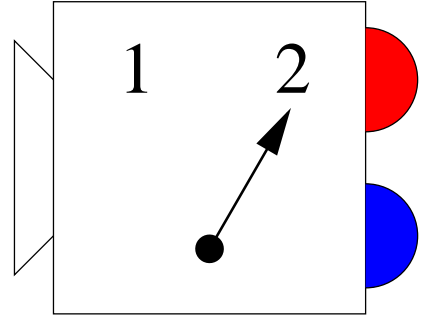
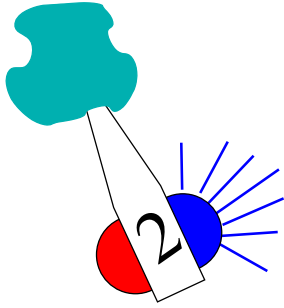
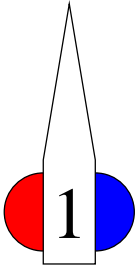


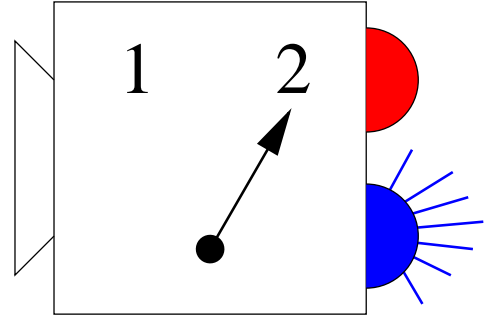
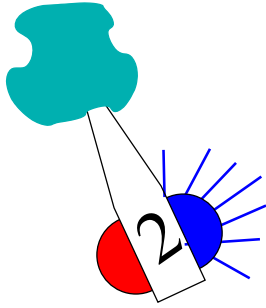
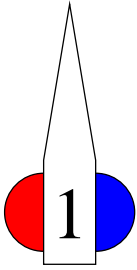
Testing Stuff left behind for 2-color.











EINSTEIN:

Can successfully test stuff left behind for 1-color without messing up the thing.

Can successfully test stuff left behind for 2-color without messing up the thing.

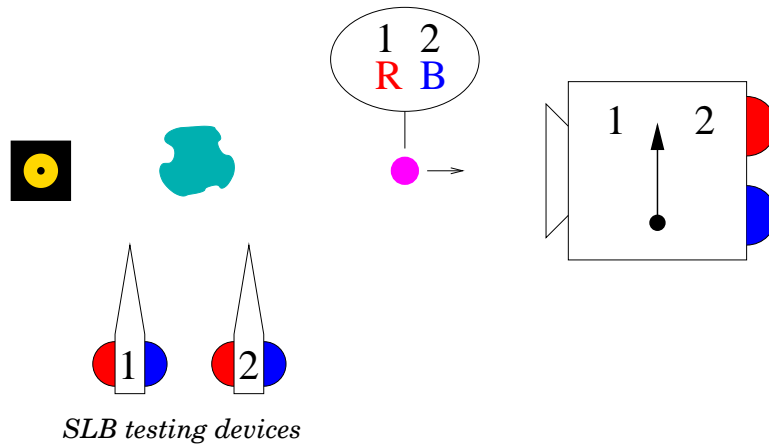
Therefore thing has both 1-color and 2-color!

Performing either test on stuff left behind messes up stuff left behind.

But it can't mess up the thing, because the thing isn't there any more.

EINSTEIN'S CONCLUSION:

*The thing has both 1-color and 2-color
(even though you can only learn one of them)*



“Every statement about [the thing] which we arrive at as a result of [testing the stuff it left behind] has to be valid for [the thing] even if no [test] whatsoever is carried out on [the stuff it left behind].”

BOHR'S OBJECTION:

All it *means* for the thing
to have 1-color (2-color)
is that 1-color (2-color) has been
indicated by a type-1 (type-2) test.

But you can't do *both* tests
on the stuff left behind because
either test messes up
the stuff left behind.

OBJECTION TO BOHR'S OBJECTION:

Yes, either test messes up the stuff left behind.

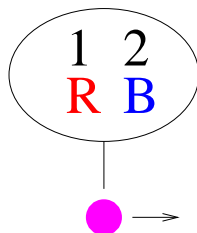
But in the absence of **spooky actions at a distance**
it can't mess up the thing!

BOHR'S REJOINDER:

It does mess up the thing, because it messes up

*“the very conditions which define the possible
types of predictions regarding the future behavior of”*
the thing.

JOHN BELL'S REACTION:

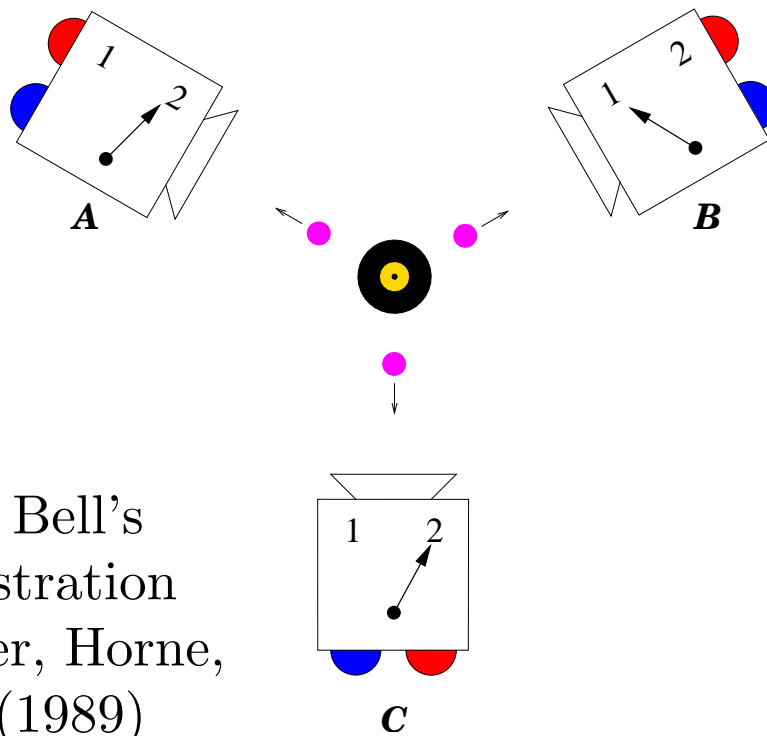


It is so reasonable to assume that the [things]... carry with them [properties]...telling them how to behave. ...I think that when Einstein saw that, and the others refused to see it, he was the rational man. The other people, ... were burying their heads in the sand. I feel that Einstein's intellectual superiority over Bohr, in this instance, was enormous — a vast gulf between the man who saw clearly what was needed, and the obscurantist.

Part IV.

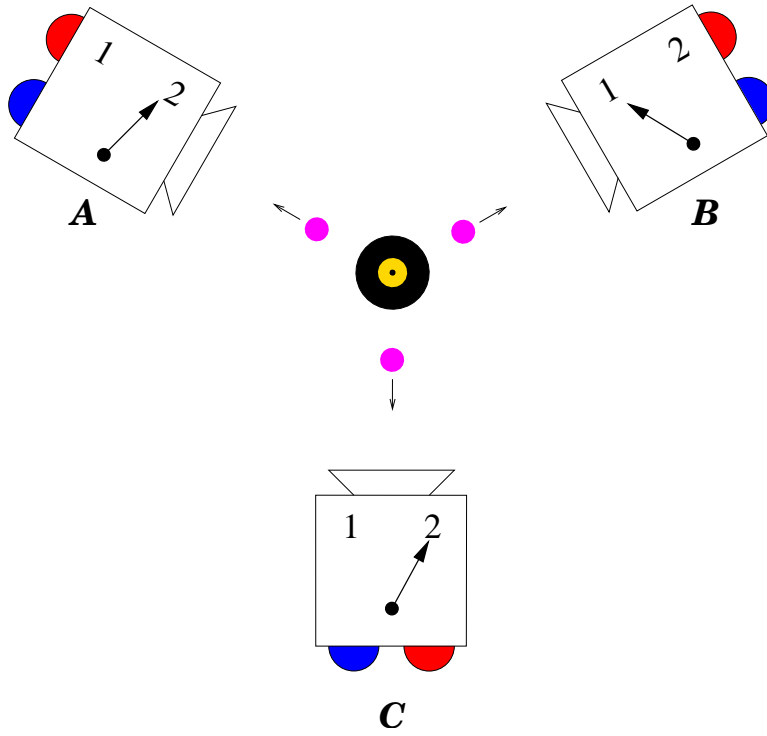
Why Einstein Was **Wrong**

DEMONSTRATION THAT BOHR WAS RIGHT!

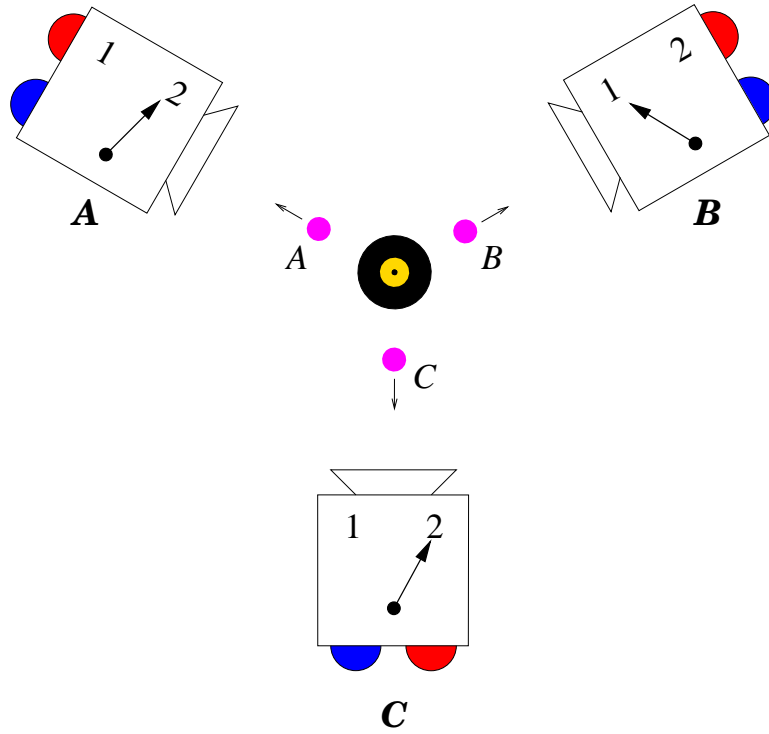


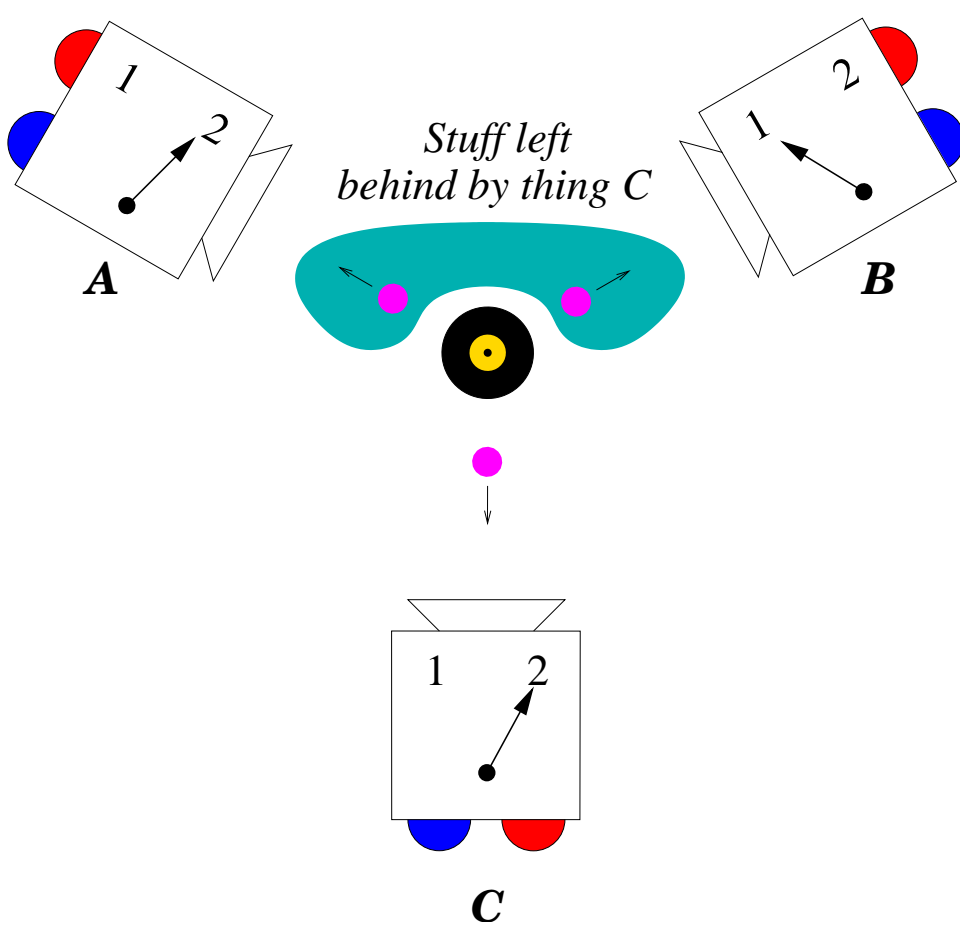
Refinement of Bell's
(1964) demonstration
by Greenberger, Horne,
and Zeilinger (1989)

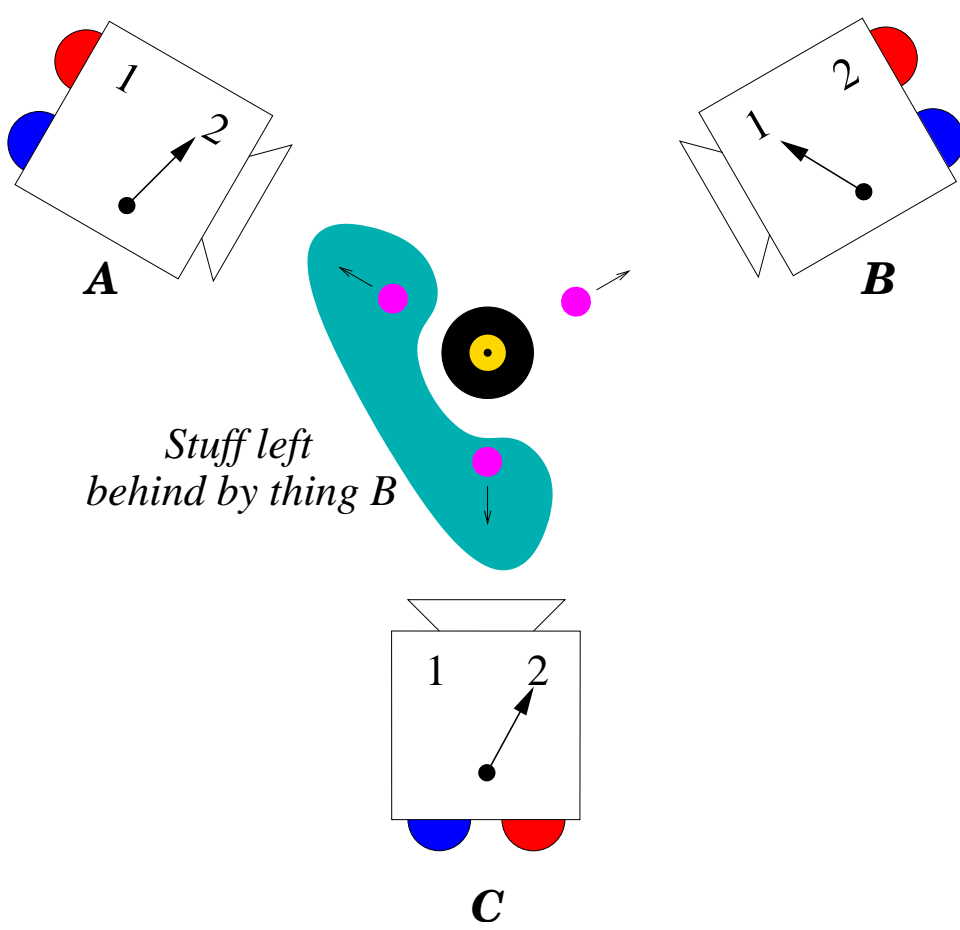
THREE THINGS THAT GO TO THREE DETECTORS

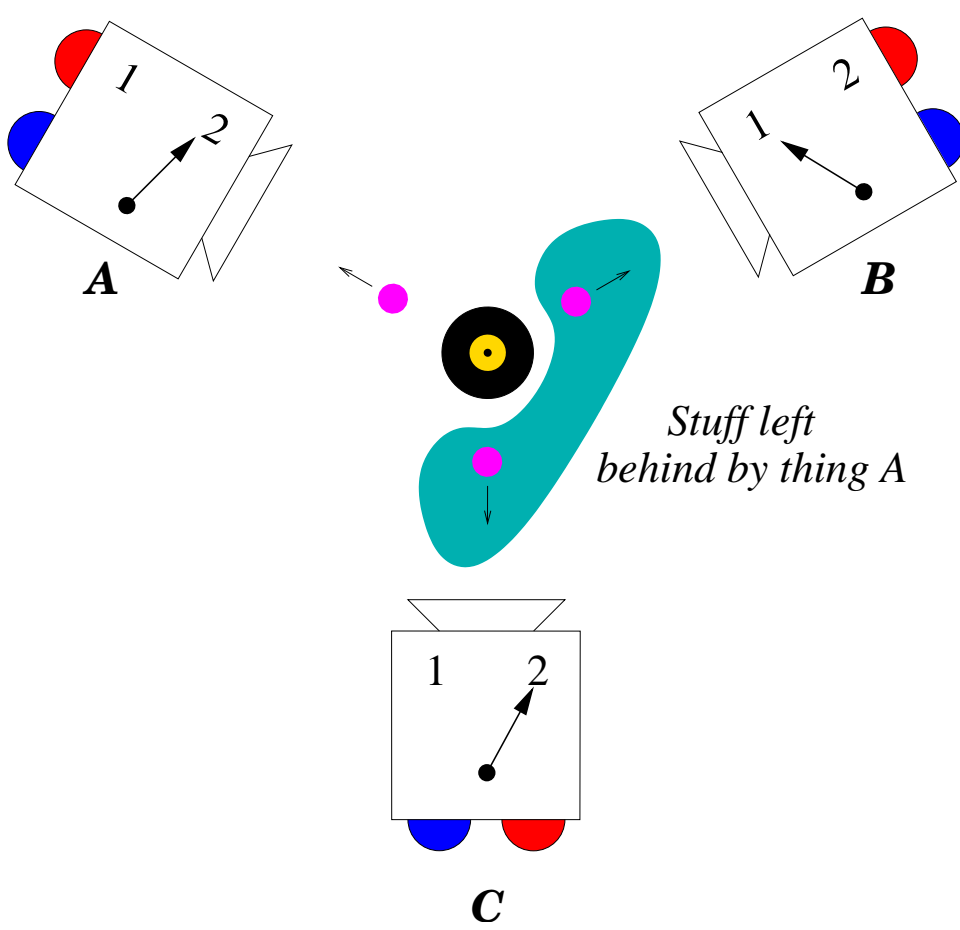


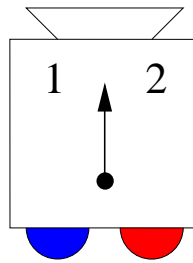
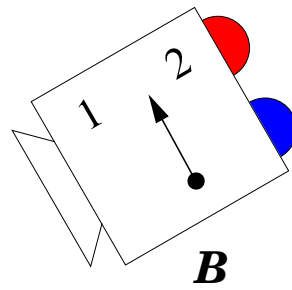
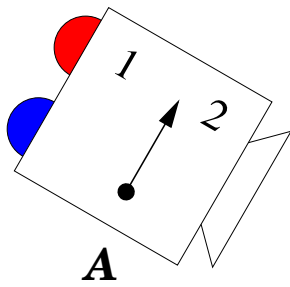
Label the three things by the three detectors they are going to.

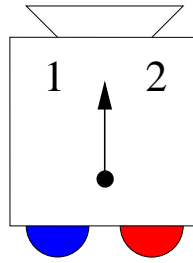
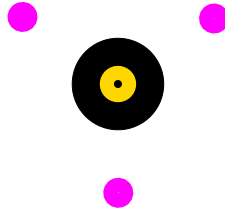
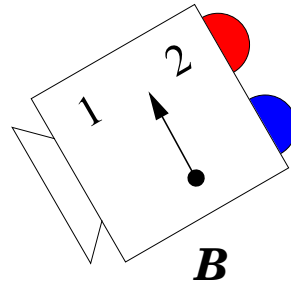
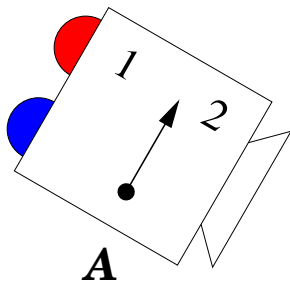




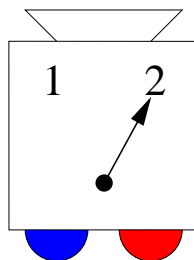
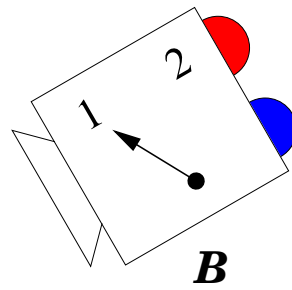
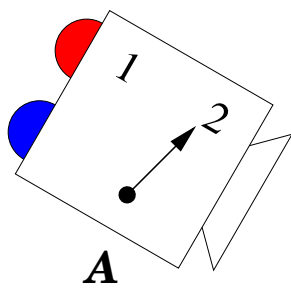


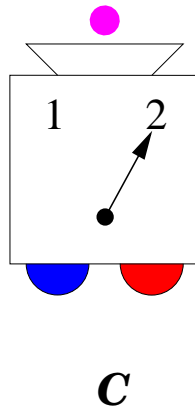
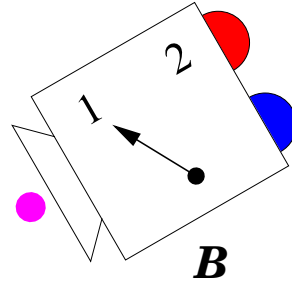
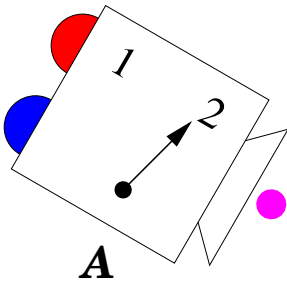


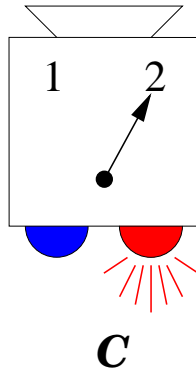
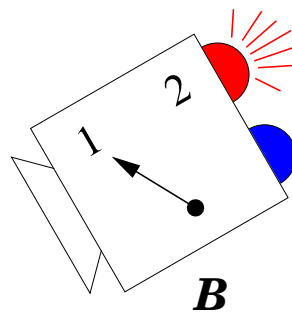
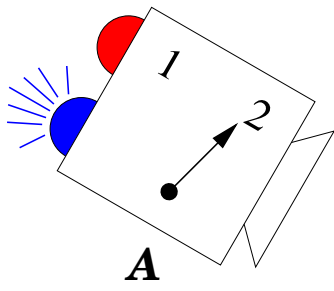


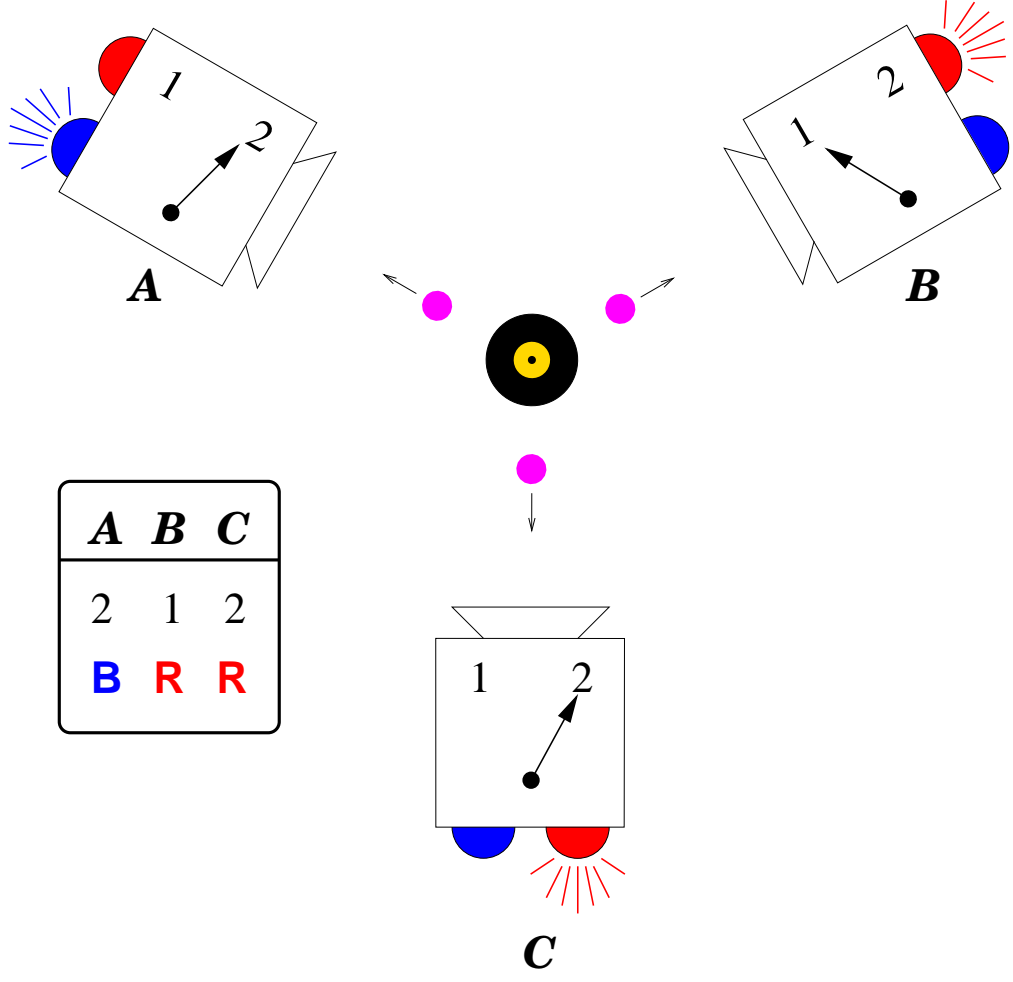


C

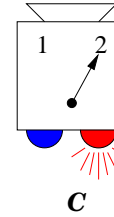
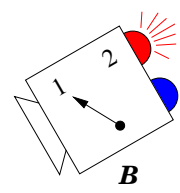
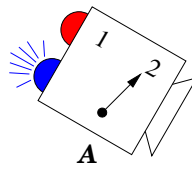






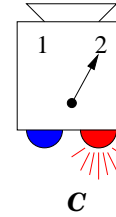
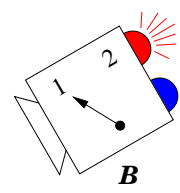
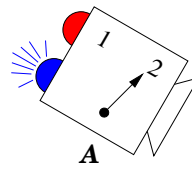


SOME CRUCIAL
FEATURES
OF THE DATA



A	B	C	Behavior of Lights
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

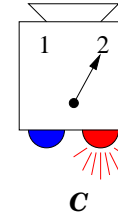
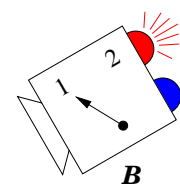
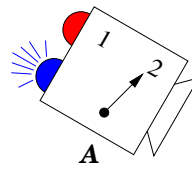
*SOME CRUCIAL
FEATURES
OF THE DATA*



<i>A</i>	<i>B</i>	<i>C</i>	<i>Behavior of Lights</i>
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

(Aside from these restrictions, behavior is random.)

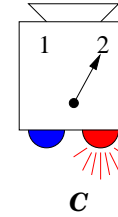
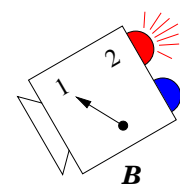
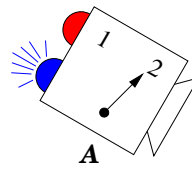
SOME CRUCIAL
FEATURES
OF THE DATA



A	B	C	Behavior of Lights
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

(Aside from these restrictions, behavior is random; e.g. in 212 run **BRR**, **RBR**, **RRB**, **BBB** are all equally likely.)

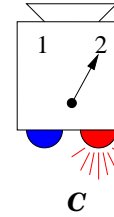
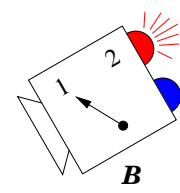
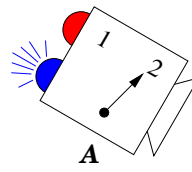
SOME CRUCIAL FEATURES OF THE DATA



A	B	C	Behavior of Lights
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

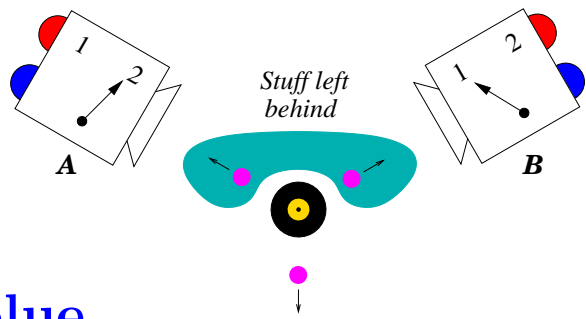
(e.g. in 222 runs all 8 outcomes, **RRR**, **RBB**, **BRB**, **BBR**, **BRR**, **RBR**, **RRB**, **BBB**, are equally likely.)

*SOME CRUCIAL
FEATURES
OF THE DATA*



A	B	C	<i>Behavior of Lights</i>
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

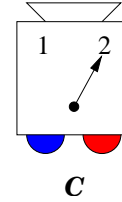
LEARNING 2-COLOR
OF THING GOING TO C
FROM THE STUFF
IT LEFT BEHIND



2 1 2: Odd number flash blue.

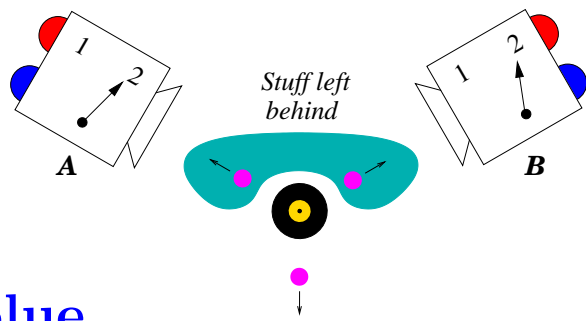
To learn 2-color at C send SLB to
type-2 at A and type-1 at B .

If both flash **blue** or both flash **red**,
thing going to C has 2-color **blue**.



If one flashes **blue** and other flashes **red**,
thing going to C has 2-color **red**.

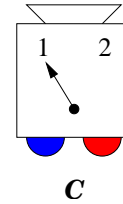
LEARNING 1-COLOR
OF THING GOING TO C
FROM THE STUFF
IT LEFT BEHIND



2 2 1: Odd number flash blue.

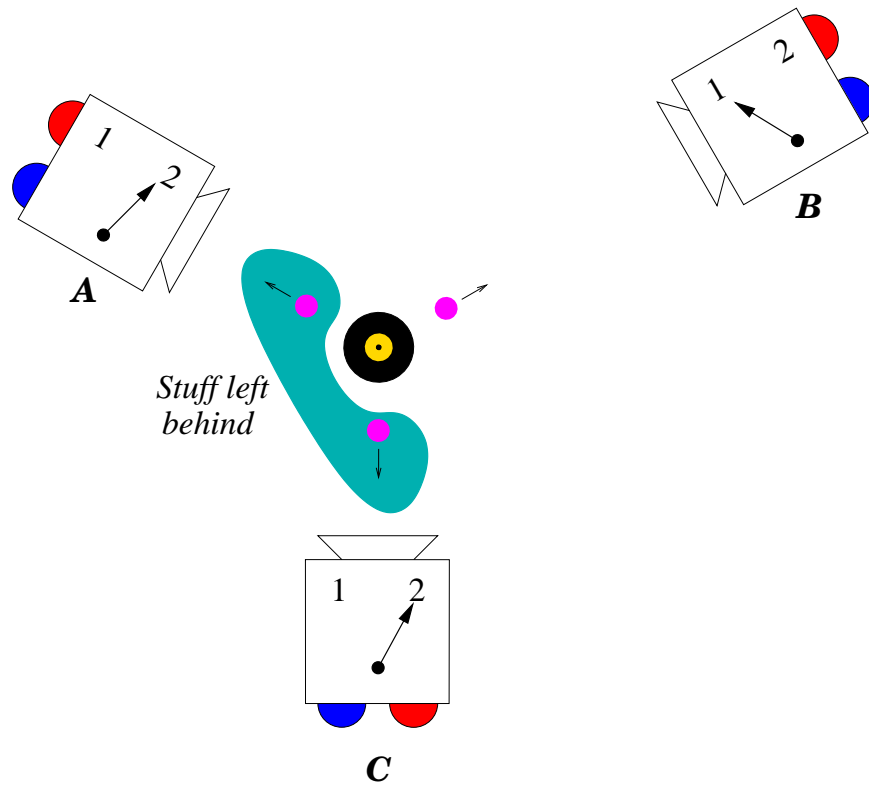
To learn 1-color at C send SLB to
type-2 at A and at B .

If both flash **blue** or both flash **red**,
thing going to C has 1-color **blue**.

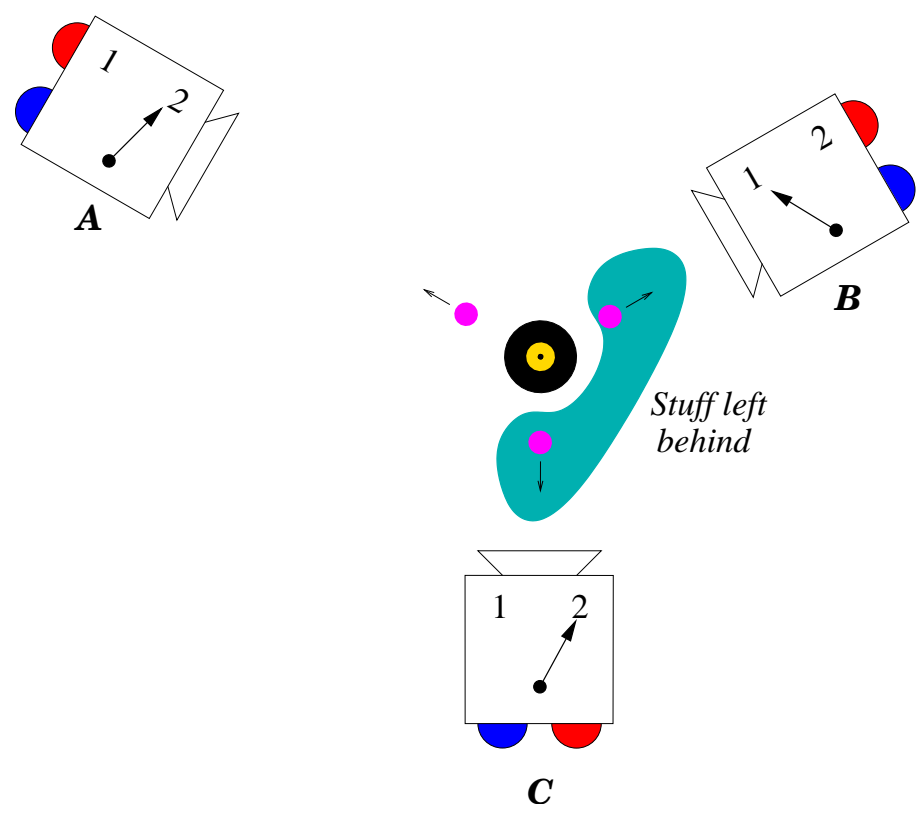


If one flashes **blue** and other flashes **red**,
thing going to C has 1-color **red**.

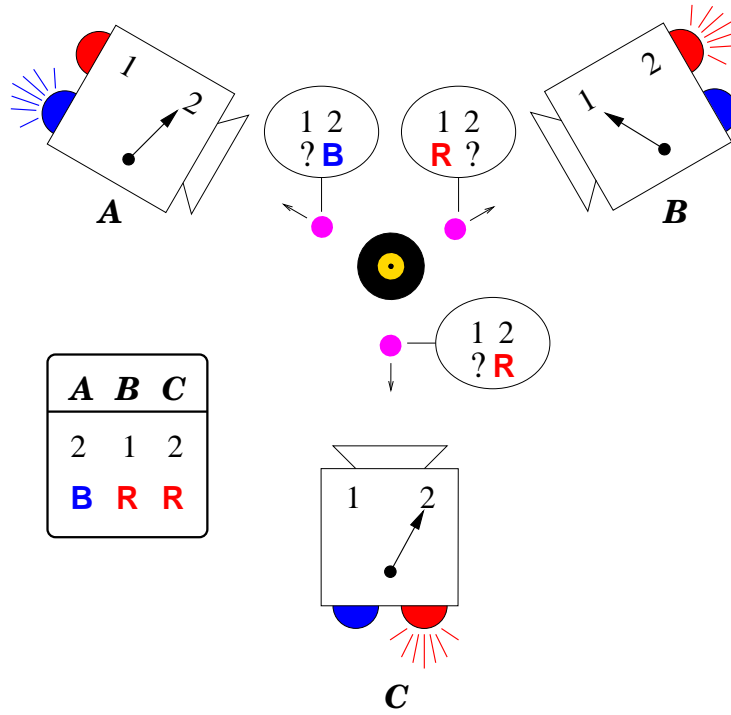
OR CAN LEARN 1-COLOR OR 2-COLOR OF THING GOING TO B, FROM THE STUFF IT LEFT BEHIND



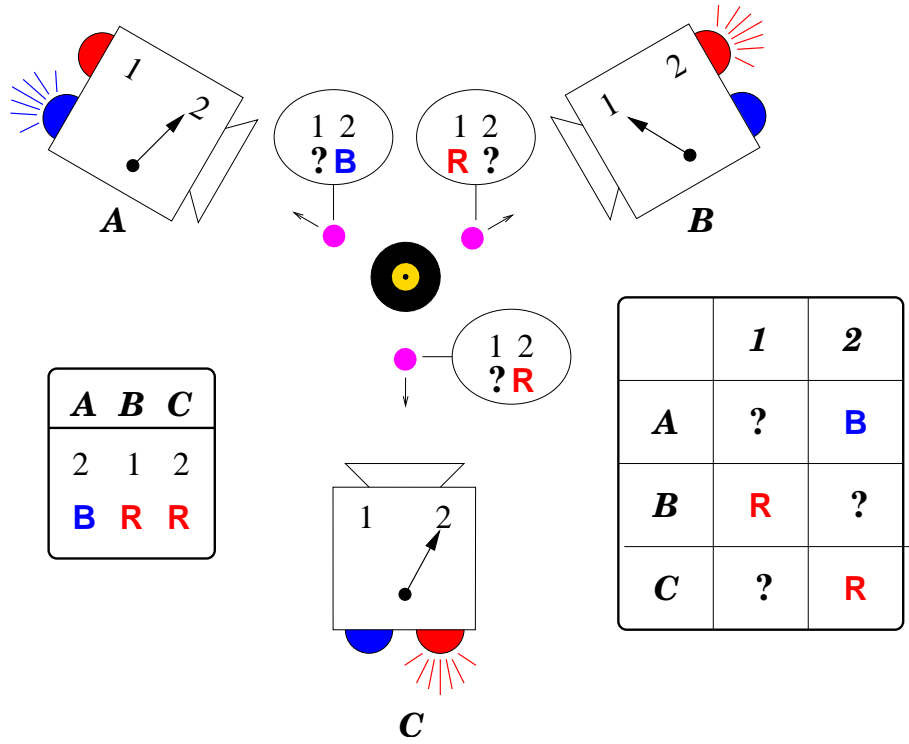
OR CAN LEARN 1-COLOR OR 2-COLOR OF THING GOING TO A, FROM THE STUFF IT LEFT BEHIND



*EINSTEIN'S CONCLUSION:
ALL THREE THINGS HAVE 1-COLOR AND 2-COLOR*



WHAT CAN WE LEARN ABOUT THE UNKNOWN 1-COLORS AND 2-COLORS?



<i>A</i>	<i>B</i>	<i>C</i>	<i>Behavior of Lights</i>
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

<i>A</i>	<i>B</i>	<i>C</i>	<i>Behavior of Lights</i>
<i>1</i>	<i>2</i>	<i>2</i>	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

<i>A</i>	<i>B</i>	<i>C</i>	<i>Behavior of Lights</i>
<i>1</i>	<i>2</i>	<i>2</i>	odd number always flash blue
2	1	<i>2</i>	odd number always flash blue
2	<i>2</i>	1	odd number always flash blue
<i>1</i>	1	1	odd number always flash red

<i>A</i>	<i>B</i>	<i>C</i>	<i>Behavior of Lights</i>
<i>1</i>	<i>2</i>	<i>2</i>	odd number always flash blue
<i>2</i>	<i>1</i>	<i>2</i>	odd number always flash blue
<i>2</i>	<i>2</i>	<i>1</i>	odd number always flash blue
<i>1</i>	<i>1</i>	<i>1</i>	odd number always flash red

<i>A</i>	<i>B</i>	<i>C</i>	<i>Behavior of Lights</i>
<i>1</i>	<i>2</i>	<i>2</i>	odd number always flash blue
<i>2</i>	<i>1</i>	<i>2</i>	odd number always flash blue
<i>2</i>	<i>2</i>	<i>1</i>	odd number always flash blue
<i>1</i>	<i>1</i>	<i>1</i>	odd number always flash red

	<i>A</i>	<i>B</i>	<i>C</i>	<i>Behavior of Lights</i>
odd number blue →	1	2	2	odd number always flash blue
odd number blue →	2	1	2	odd number always flash blue
odd number blue →	2	2	1	odd number always flash blue
even number blue →	1	1	1	odd number always flash red

	A	B	C	<i>Behavior of Lights</i>
odd number blue →	1	2	2	odd number always flash blue
odd number blue →	2	1	2	odd number always flash blue
odd number blue →	2	2	1	odd number always flash blue
even number blue →	1	1	1	odd number always flash red

↑ ↑ ↑
 even number
blue

It is so reasonable to assume that the [things]... carry with them [properties]... telling them how to behave. ...I think that when Einstein saw that, and the others refused to see it, he was the rational man. The other people, *although history has justified them*, were burying their heads in the sand. I feel that Einstein's intellectual superiority over Bohr, in this instance, was enormous — a vast gulf between the man who saw clearly what was needed, and the obscurantist. *So for me, it is a pity that Einstein's idea doesn't work. The reasonable thing just doesn't work.*

— John Bell

Part V

Where Does This Leave Us?

*DOES THIS MEAN
THAT QUANTUM MECHANICS IS WRONG?*

NO!

NO!

NO!

*IT IS THE MOST ACCURATE AND SUCCESSFUL
SCIENTIFIC THEORY IN HUMAN HISTORY!*

BUT WHAT IT TELLS US

(in my opinion)

IS SOMETIMES VERY PECULIAR

SPOOKY ACTIONS AT A DISTANCE?

1. One has the option of learning either the 1-color or the 2-color of any one of the three things by testing only stuff it leaves behind it.
2. But all three things cannot have both a 1-color and a 2-color.
3. So the act of testing the stuff it leaves behind it must confer 1-color or 2-color on a thing.

4. Is this action at a distance? Or is it no different from my wife's having our first baby in Ithaca, New York conferring fatherhood on me in Berkeley, California?

5. It is different. The thing can be tested by a detector that correctly reveals its 1-color or 2-color, but there is no test that can be performed on me in Berkeley to determine whether I am a father. (Asking me doesn't work unless I have spoken with my wife in New York on a non-spooky telephone.)

6. Is it really different? We can only be sure that our detector has *correctly* revealed the 1-color or 2-color until we talk to the people who have tested the stuff the thing left behind.

7. Yes, it is really different, because after doing it many times we find that the detector always agrees with the test on the stuff left behind, so we don't really need to check.

8.....

1. One has the option of learning either the 1-color or the 2-color of any one of the three things by testing only stuff it leaves behind it.
2. But all three things cannot have both a 1-color and a 2-color.
- ~~3. So the act of testing the stuff it leaves behind it — must confer 1-color or 2-color on a thing.~~
3. So a thing cannot have 1-color or 2-color unless an *actual* test reveals whether that color is **R** or **B**.

3. A thing does not have 1-color (2-color) unless an actual 1-color (2-color) test reveals whether that color is **R** or **B**.
4. Only one of the 4 tests 122, 212, 221, and 111 can *actually* be done.
5. It makes no sense to insist that the color revealed for thing C in an *actual* 122 test would be the same color in the *fictitious* world in which the test was a 212 test.

A thing does not have color unless an actual test reveals whether that color is **R** or **B**.

Unperformed experiments have no results.

— Asher Peres

What didn't happen *didn't happen*.

~~“Every statement about [the thing] which we arrive at as a result of [testing the stuff it left behind] has to be valid for [the thing] even if no [test] whatsoever is carried out on [the stuff it left behind].”~~

— Einstein

A thing does not have color unless a test reveals whether that color is **R** or **B** *even though the test only messes up the stuff the thing left behind it.*

BOHR:

Messing up the stuff left behind does mess up the thing, because it messes up *‘the very conditions which define the possible types of predictions regarding the future behavior of’* the thing.

Rhetorical Homework Problem:

Let H and V be polarization eigenstates for horizontally and vertically polarized photons, and let R and L be polarization eigenstates for two orthogonal “right” and “left” directions at 45° so that

$$H = \frac{1}{\sqrt{2}}(R + L), \quad V = \frac{1}{\sqrt{2}}(R - L). \quad (1)$$

Type-1 boxes contain a birefringent crystal and flash **red** if a photon is polarized horizontally and **blue** if it is polarized vertically. Type-2 boxes behave the same way with respect to photons polarized at 45° — i.e. they are given by simply rotating a type-1 box through 45° along the line joining it to the source of the three photons. The source produces three photons in the polarization state

$$\frac{1}{2}(HHH - VVH - VHV - HVV), \quad (2)$$

so if all boxes are type 1, an odd number of boxes must flash **red**. Show by appropriate substitutions of (1) into (2) that if only one box is type 1, then an odd number of boxes must flash **blue**.

Reference:

Albert Einstein, *Quantenmechanik und Wirklichkeit*
Dialectica 2, 320 (1948)
Reprinted in English in
The Born-Einstein Letters

For a link to all the figures shown in this lecture,
google mermin homepage and click on
“Spooky Actions at a Distance?”.