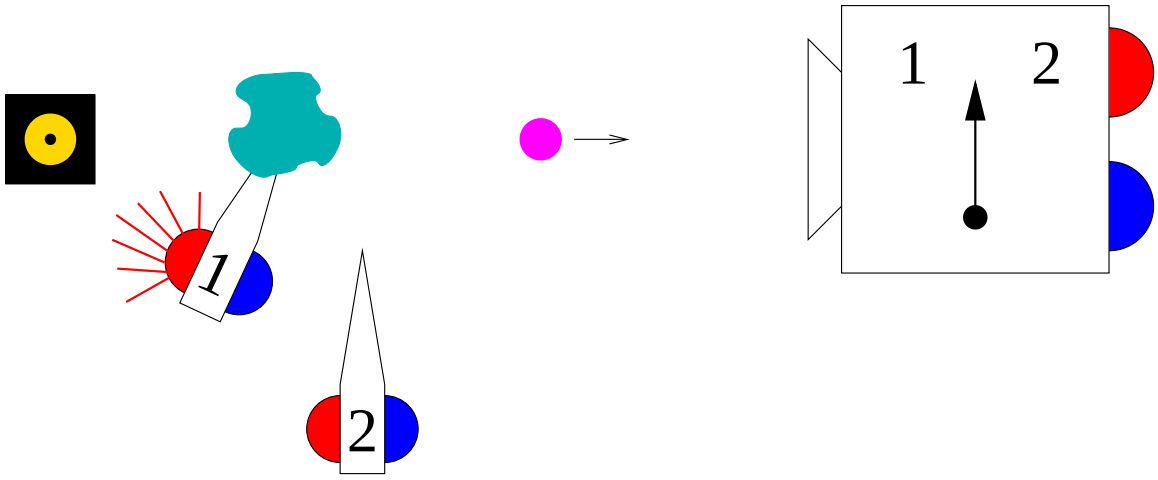
SPOOKY ACTIONS AT A DISTANCE?

Hofstadter Lecture, Stanford, April 4, 2011



THE QUANTUM THEORY

The most accurate and successful theory
in the history of science

The foundation of contemporary technology

The greatest intellectual achievement of the 20th century

But it is . . . quite strange.

Prologue.

The Vision of Einstein;
The Caution of Bohr.

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

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spukhafte Fernwirkungen

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

Niels Bohr on the Quantum Theory

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

— Bohr (remembering his debates with Einstein)

Niels Bohr on the Quantum Theory

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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 (*The Unity of Human Knowledge*)

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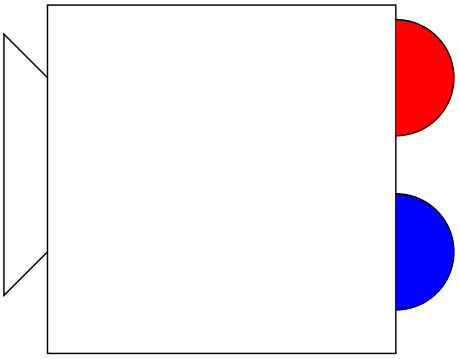
Part I.

Can a Thing Possess (Real) Properties?

Source



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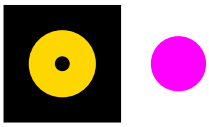

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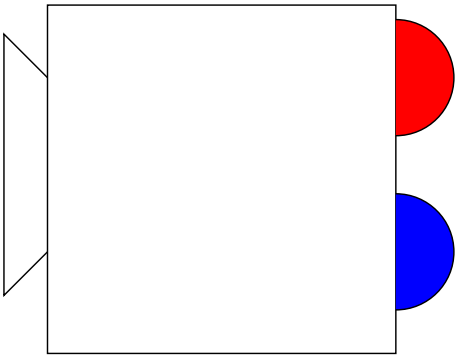

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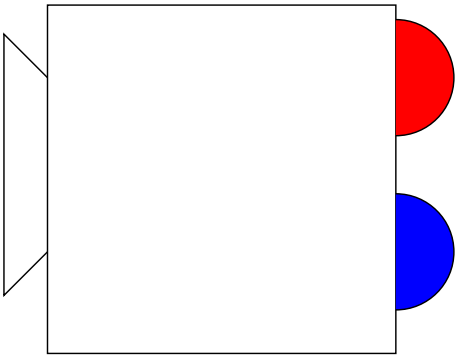

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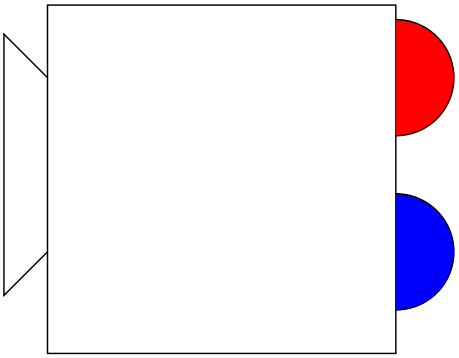

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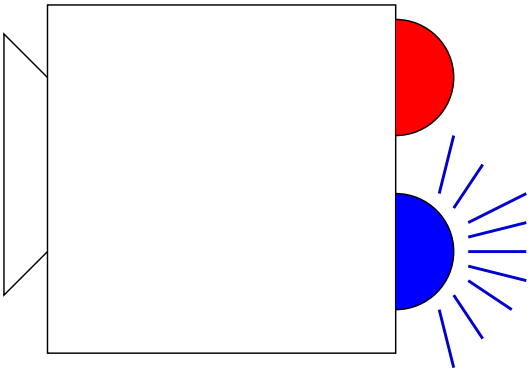

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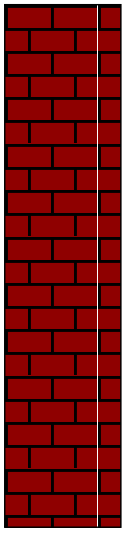

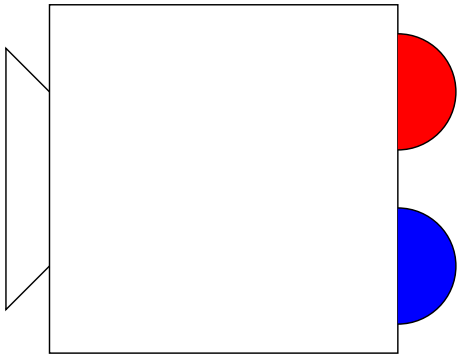

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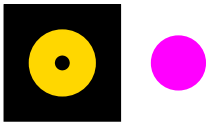

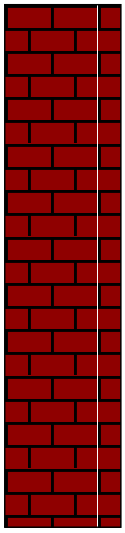

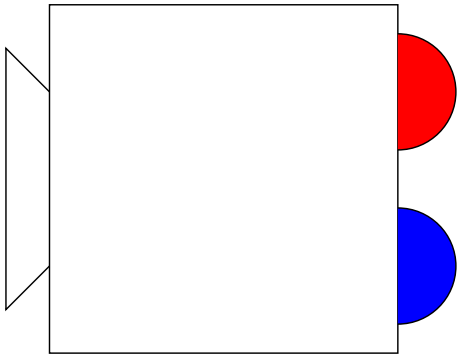

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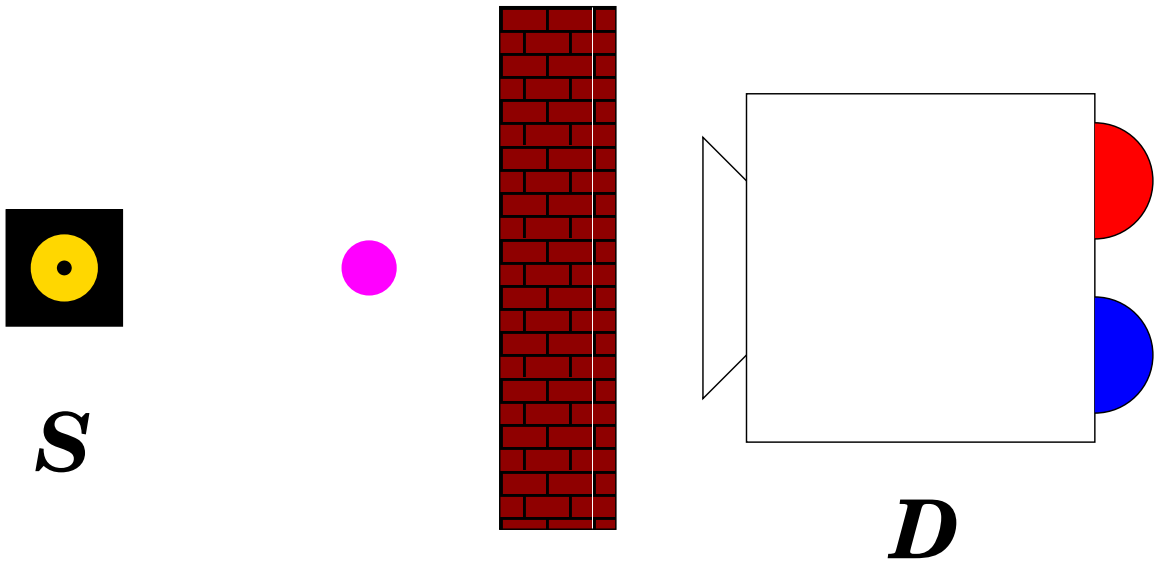
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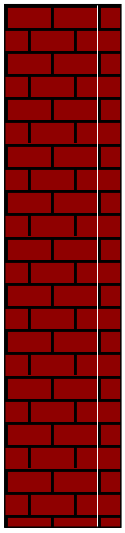

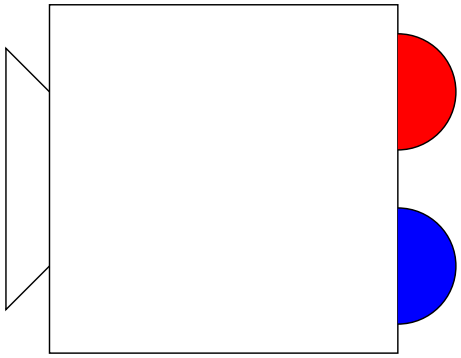

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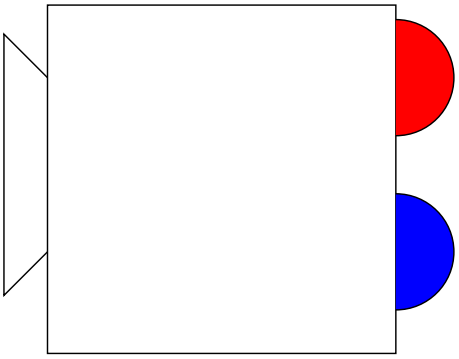

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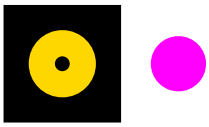

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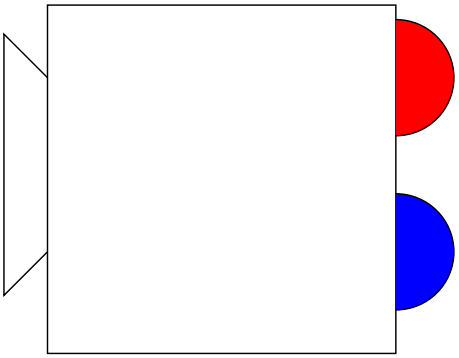

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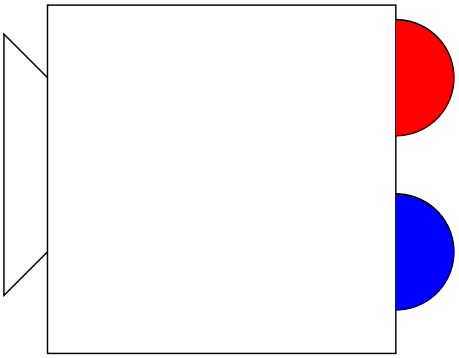

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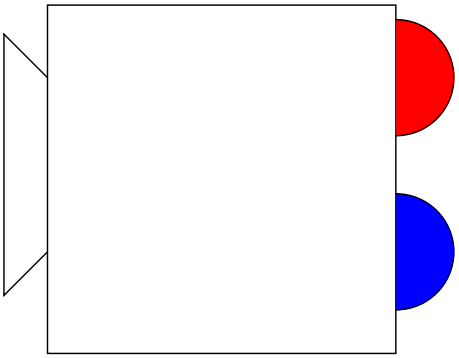

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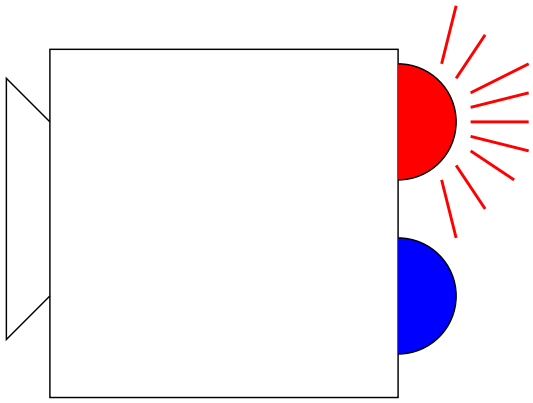

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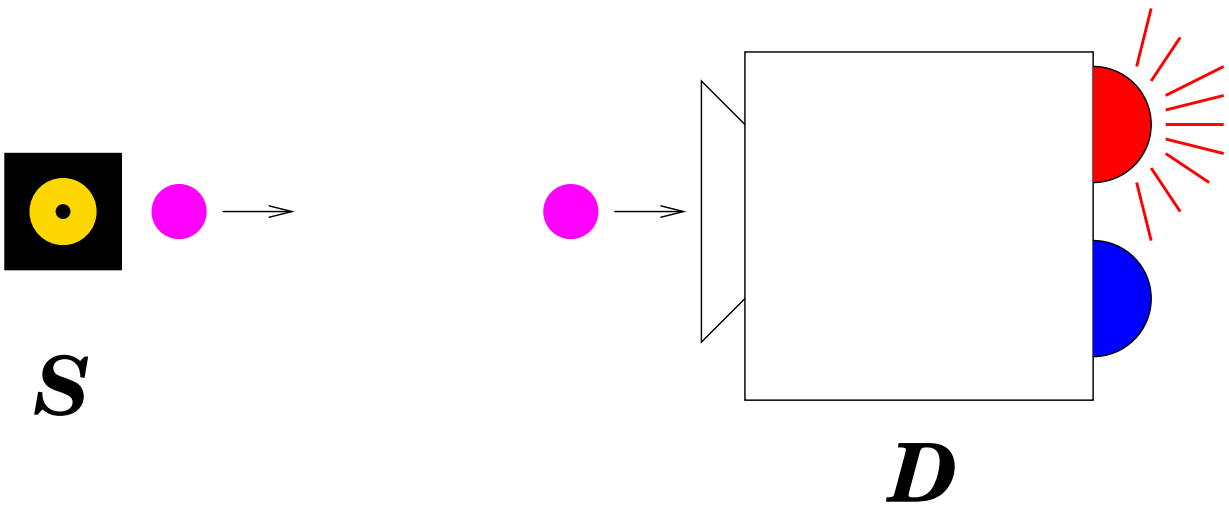
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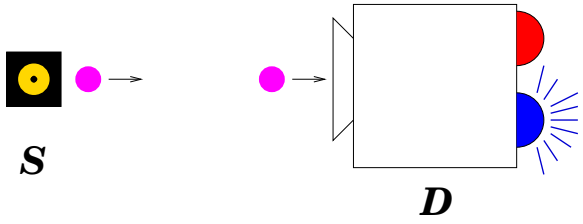


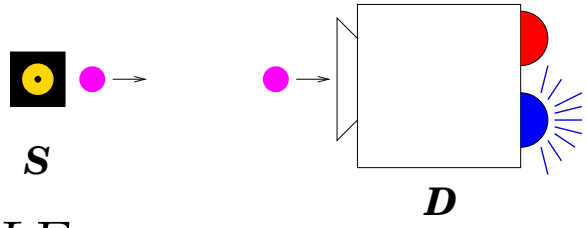
QUESTION:

Does the color flashed by D signify
a *(real) property* of the thing from S?

If so, name that (real) property "color".

Two types of things come out of S:
Those "colored" blue, and those "colored" red.

D detects which type of thing has entered it.

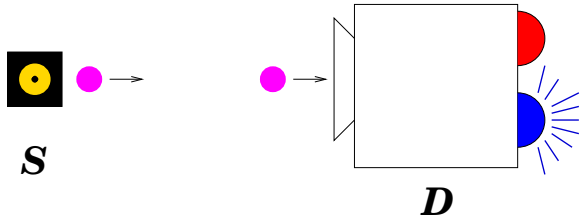


FOR EXAMPLE:

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

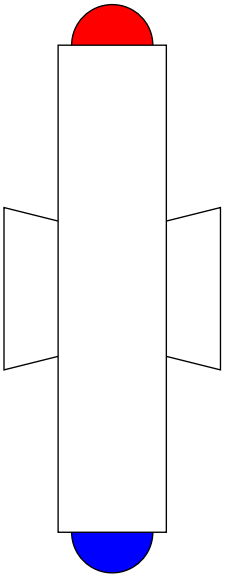


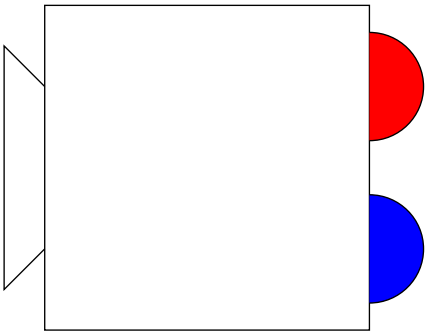
ALTERNATIVE "COLORLESS" EXPLANATIONS:

Things from S are all identical.

- D decides to flash red or blue by tossing a coin.
- Whether D flashes red or blue depends on the exact time the thing enters it.

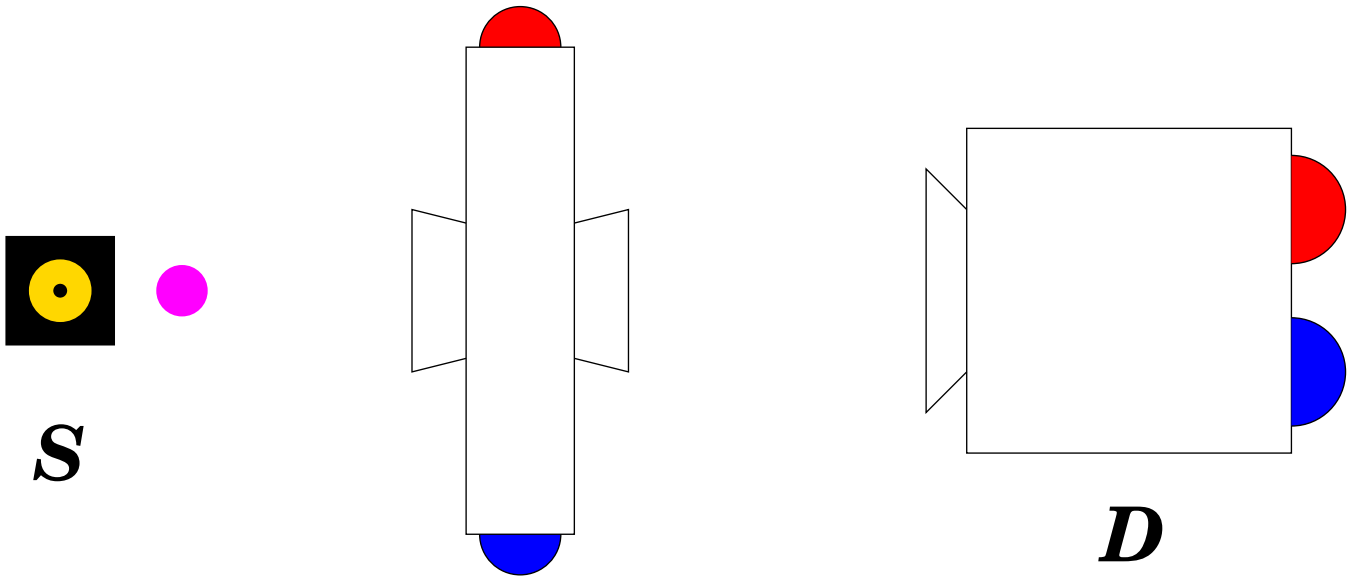
S





D

Testing device



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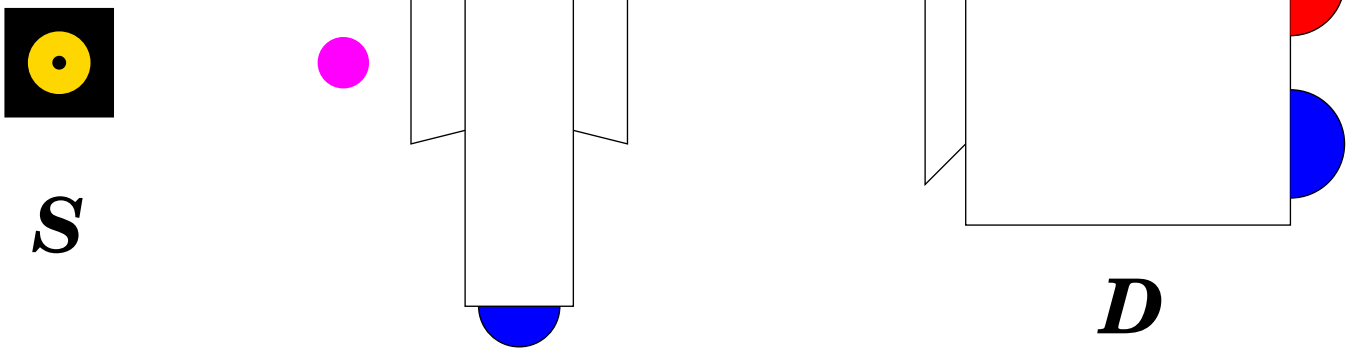

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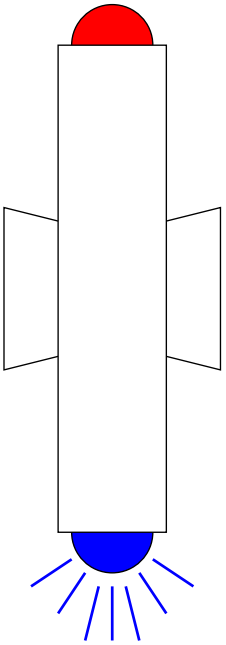

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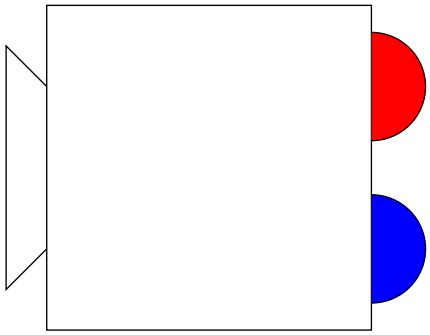

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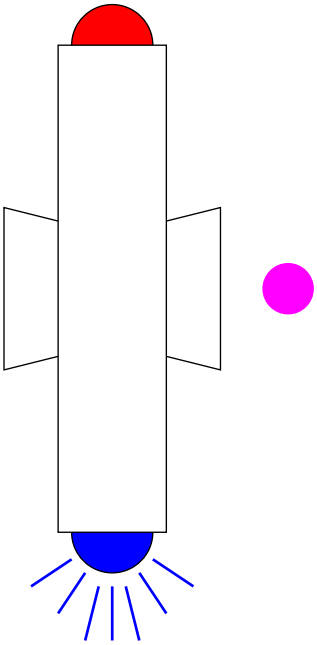

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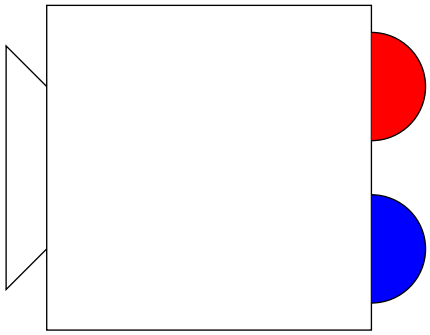

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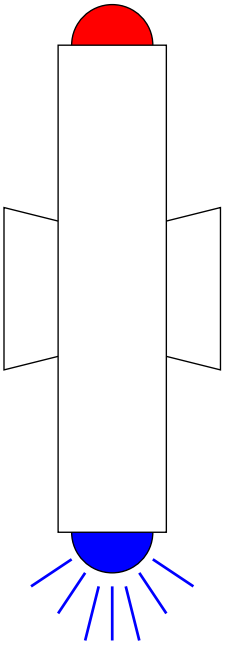

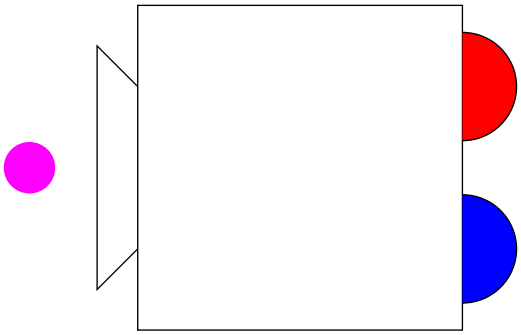

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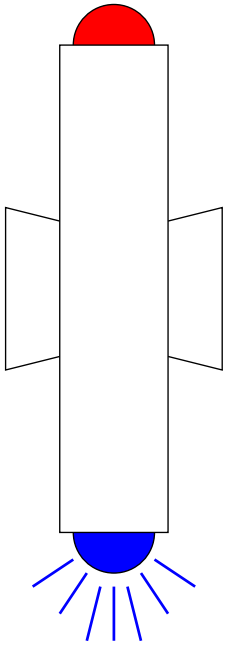

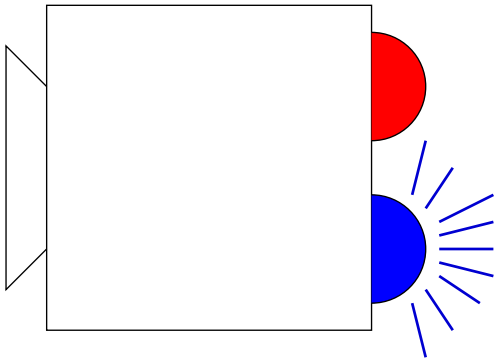

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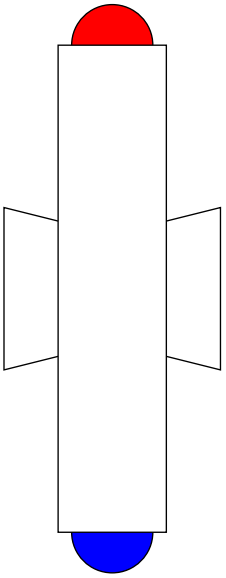

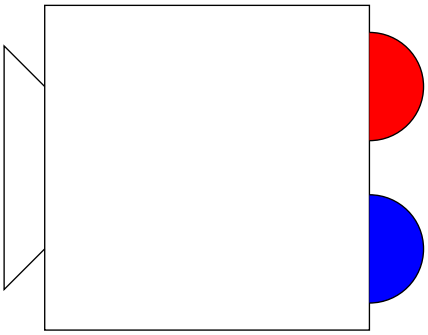

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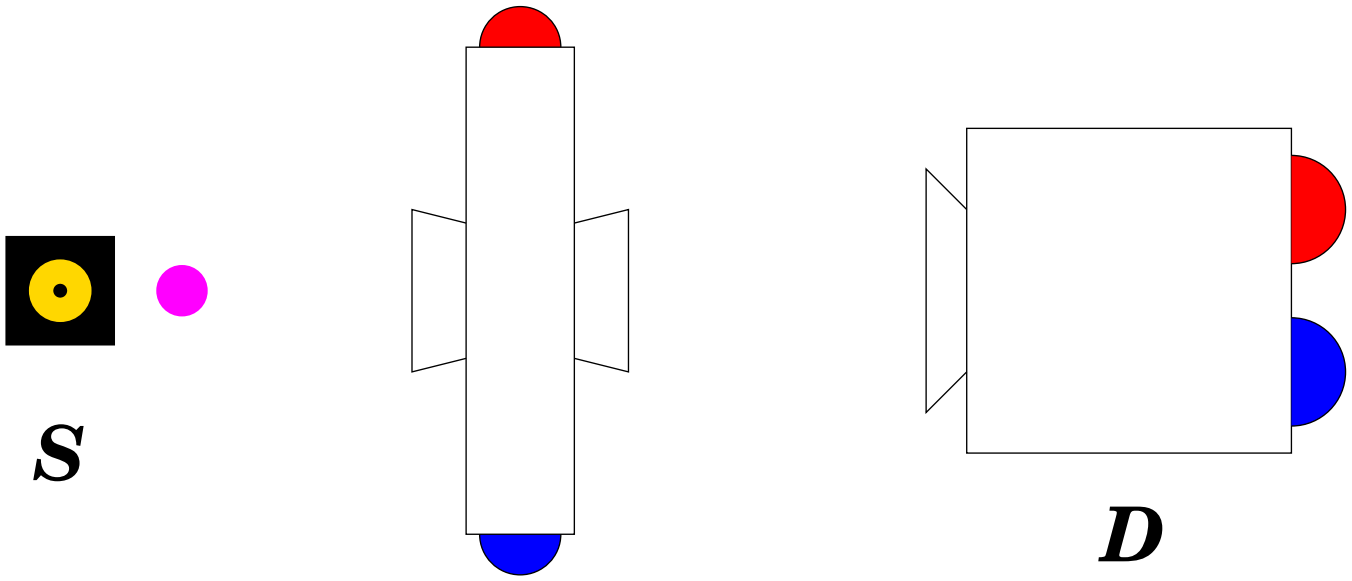

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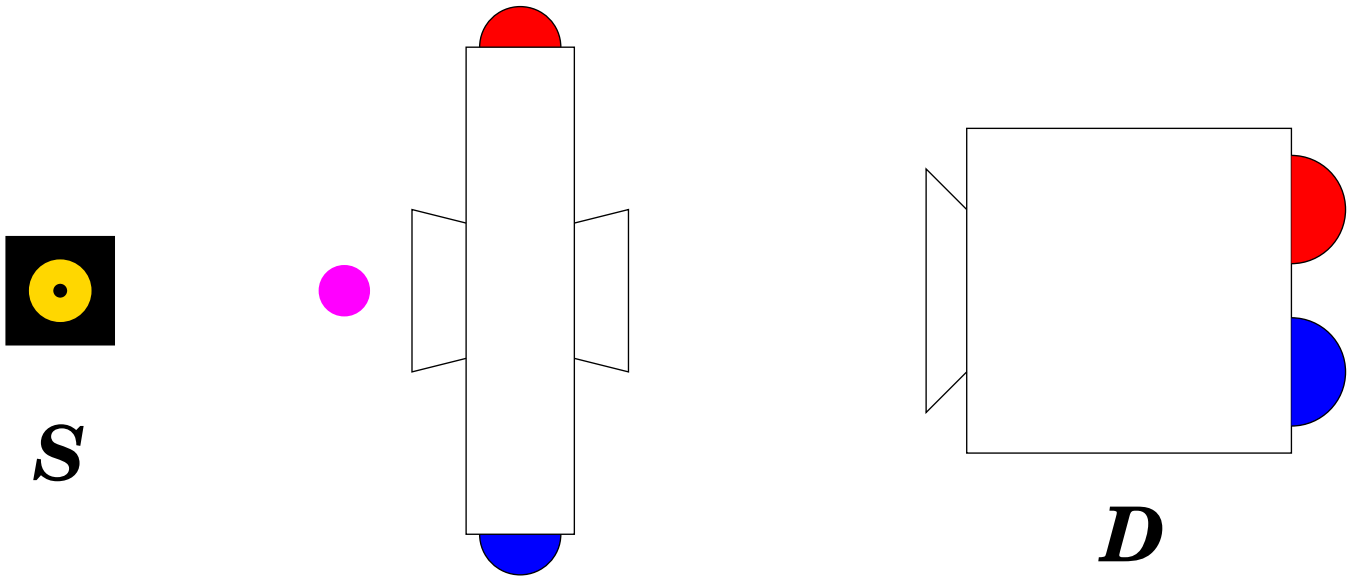

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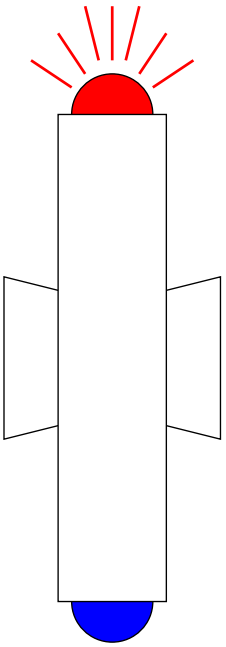

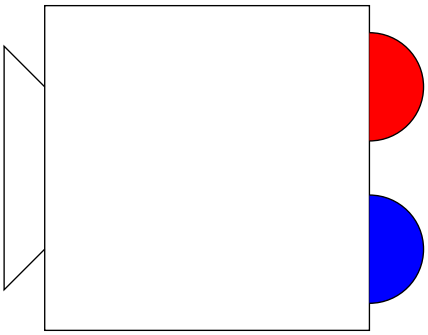

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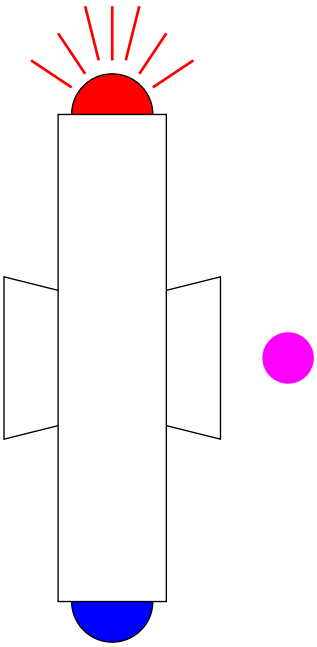

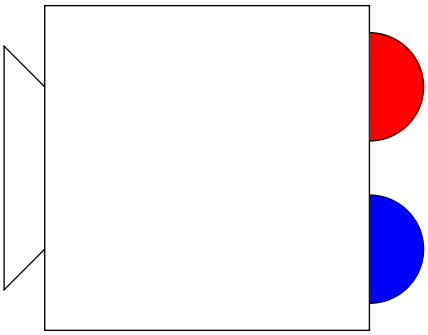

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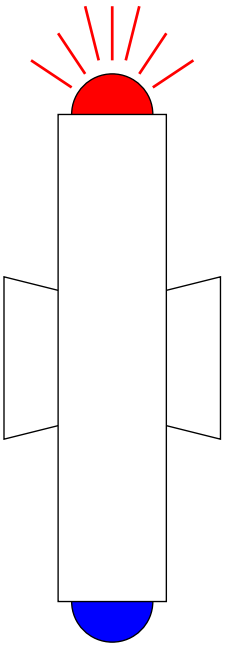

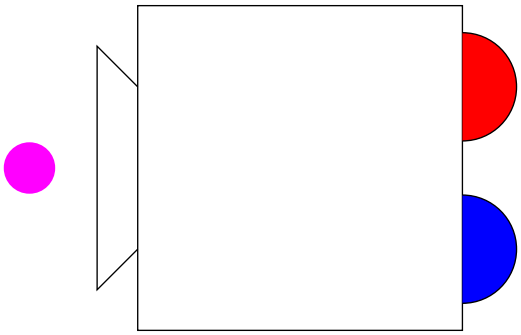

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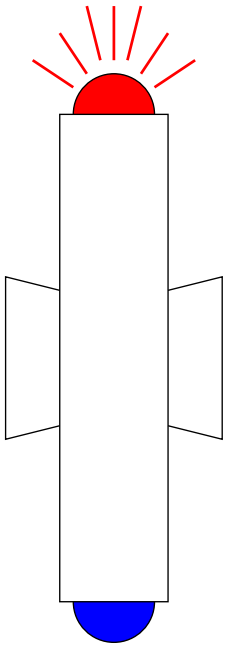

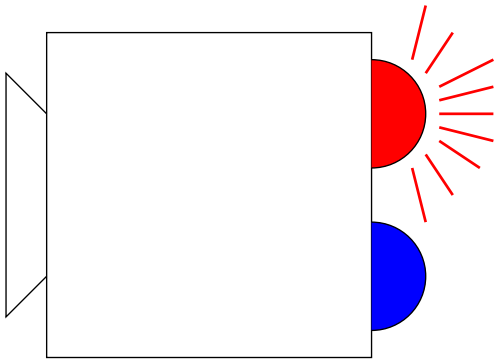

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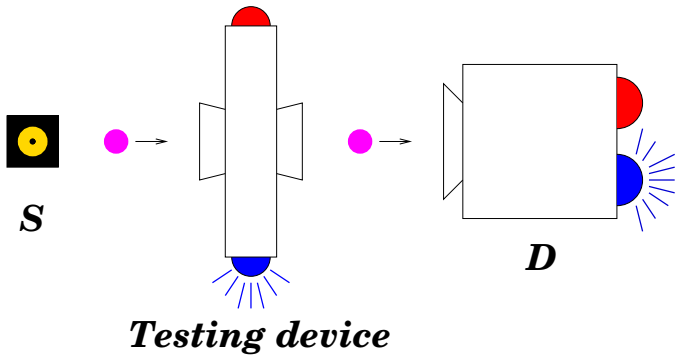
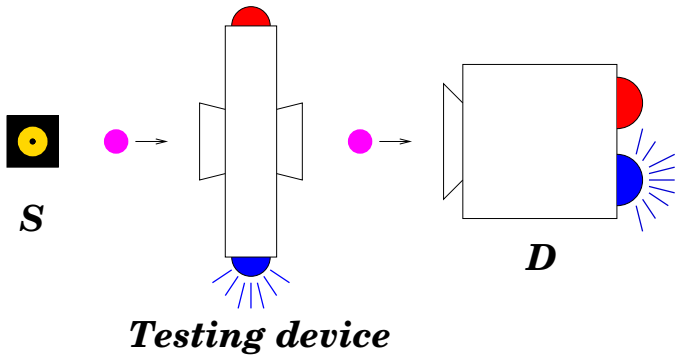


When testing device inserted between S and D, testing device always flashes same color as D.

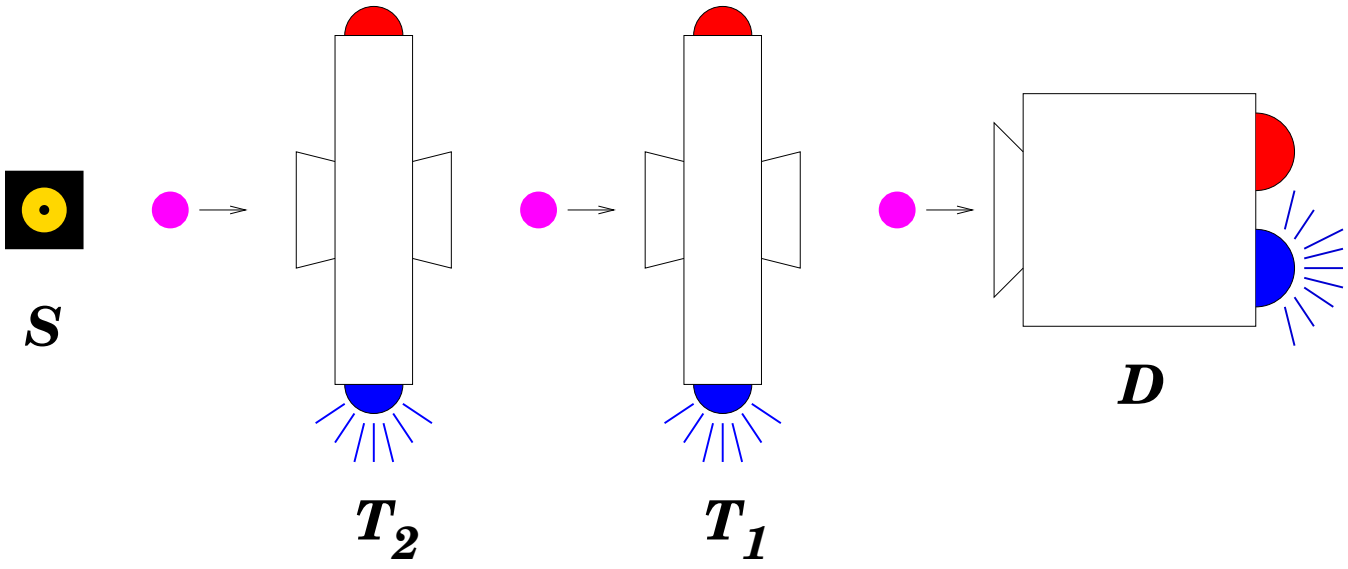
So thing emerging from testing device flashing blue (red) is surely "colored" blue (red).

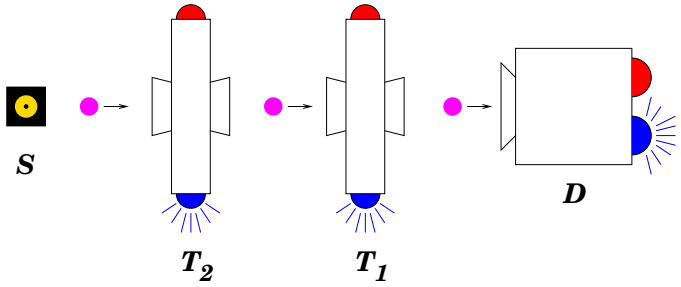


QUESTION:

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"

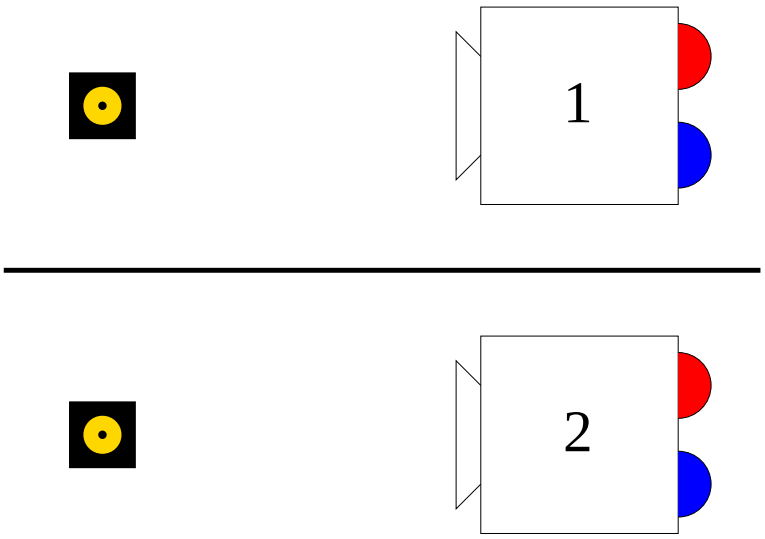
QUESTION: Do untested things have "color"?

Is there a *"reality. . .independent of what is experimentally established"?*

Part II.

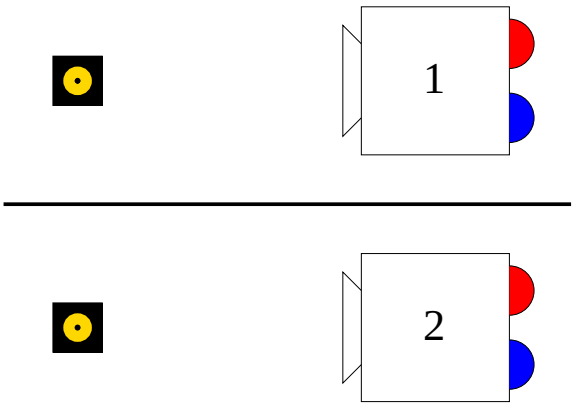
Can a Thing Possess
Two Different (Real) Properties?

TWO DIFFERENT KINDS OF DETECTORS



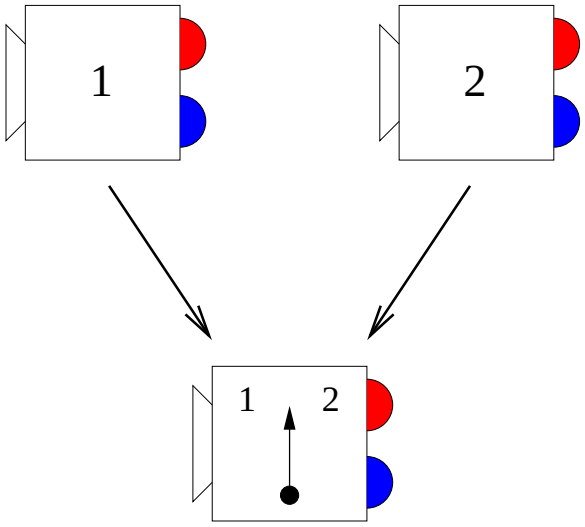
QUESTION:

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

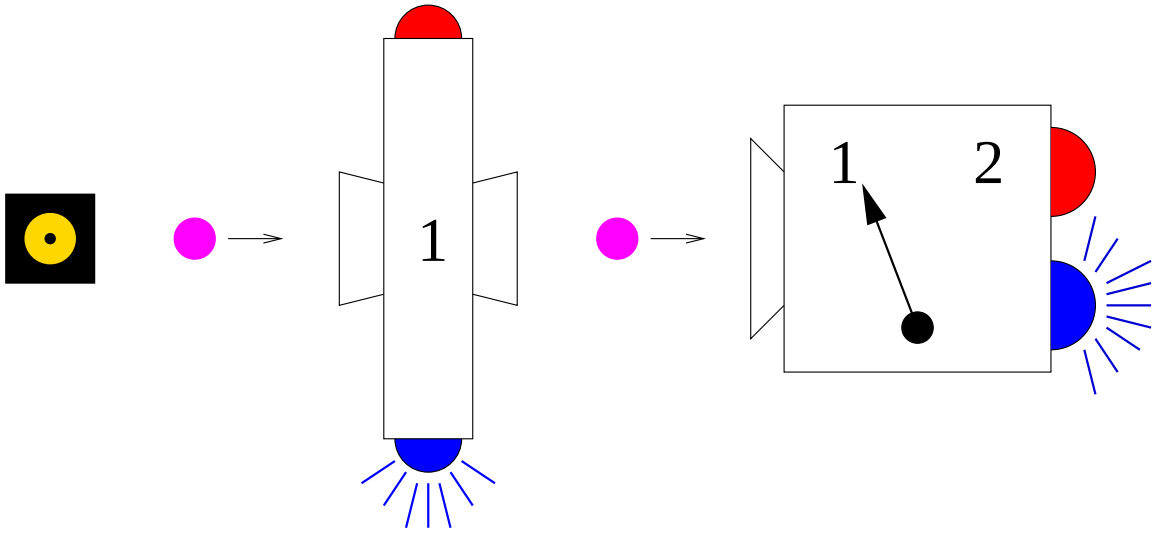


(1-color is property signified by type-1 detector)
(2-color is property signified by type-2 detector)

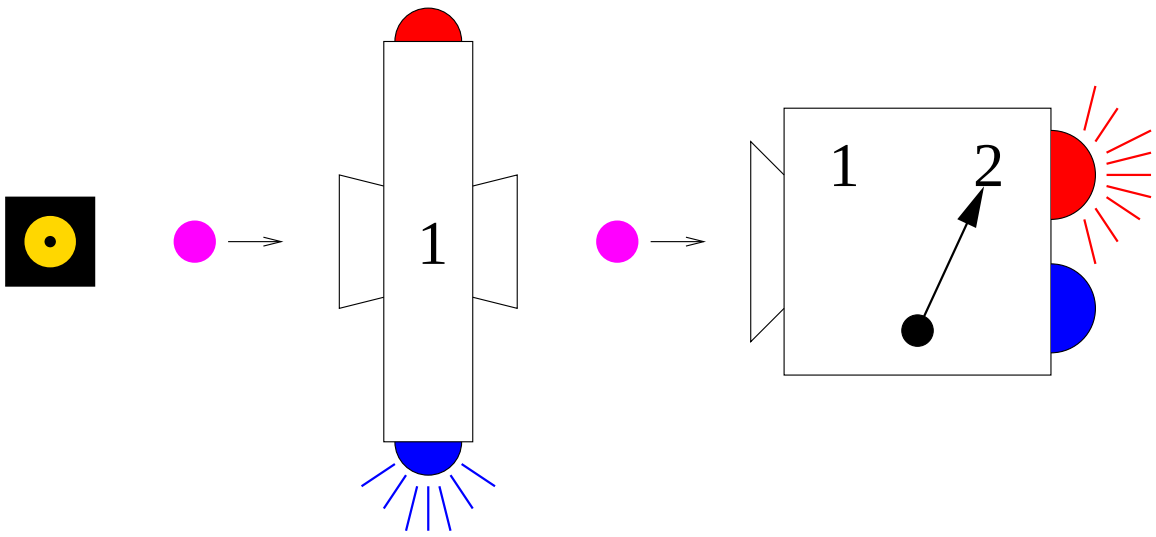
Convenient to package both kinds of detectors into single box with switch:



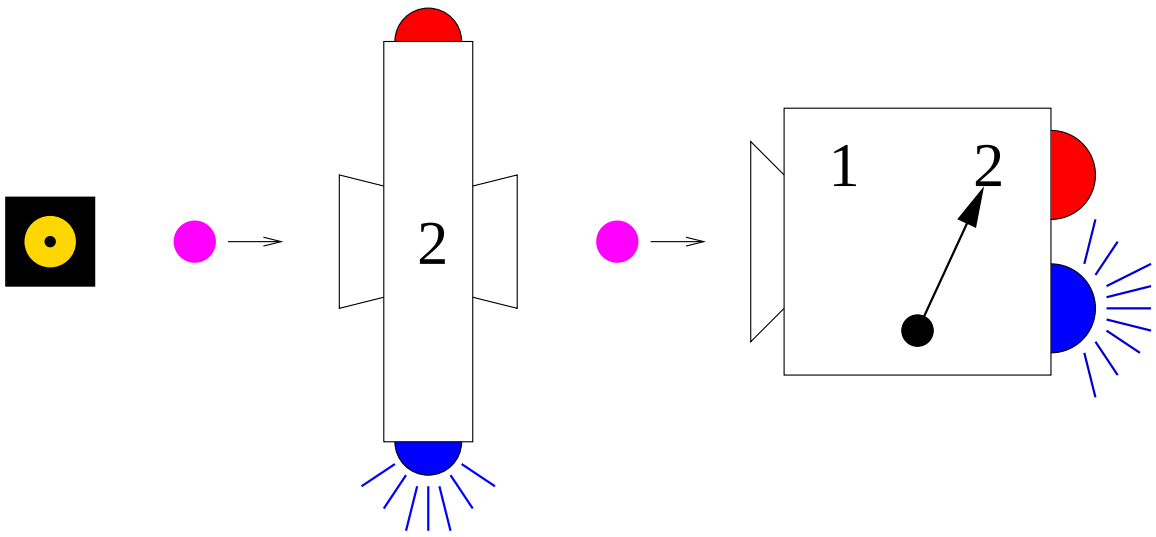
ALSO TWO KINDS OF TESTING DEVICES:



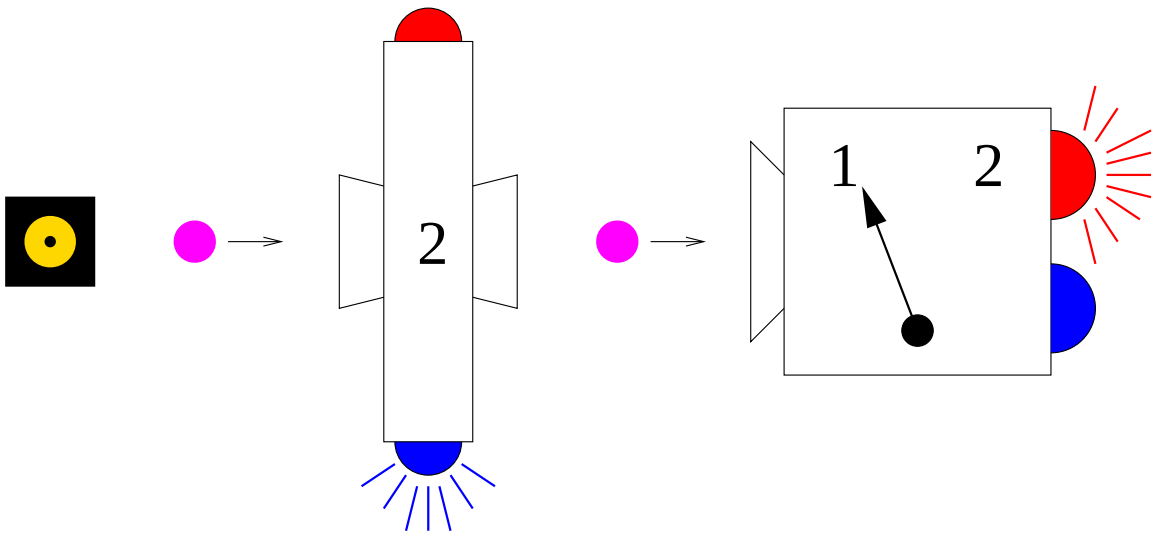
Type 1 testing device *always works* with type 1 detector.



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

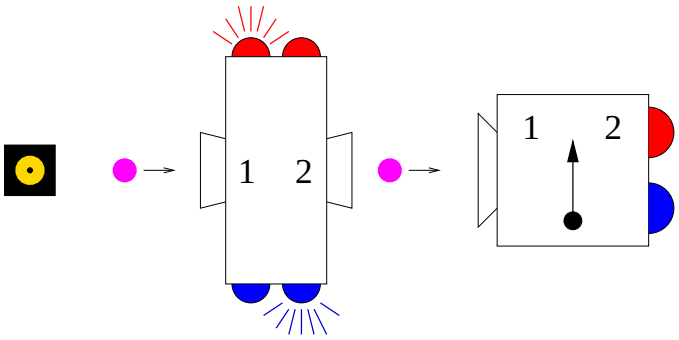


Type 2 testing device *always works* with type 2 detector.



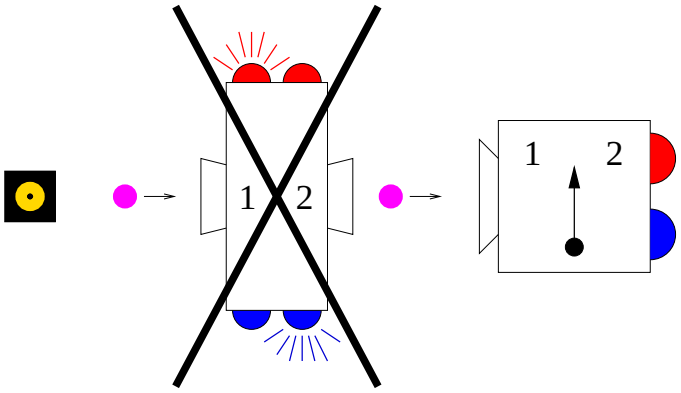
But type 2 testing device is wrong half the time with type 1 detector.

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



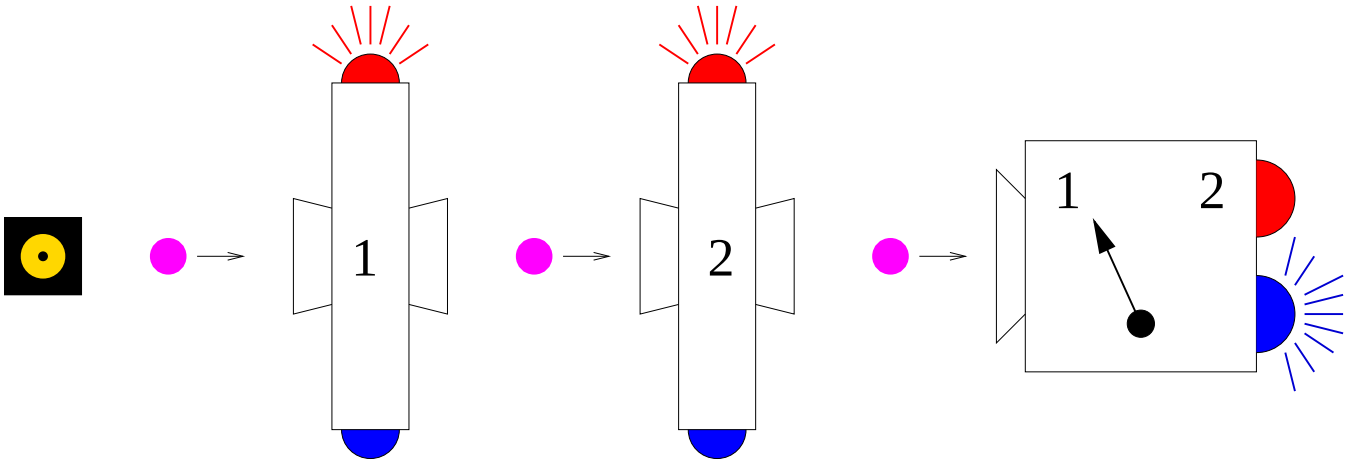
(This could be established if there were a joint testing device that always worked, regardless of whether it was followed by a type 1 or a type 2 detector.)

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



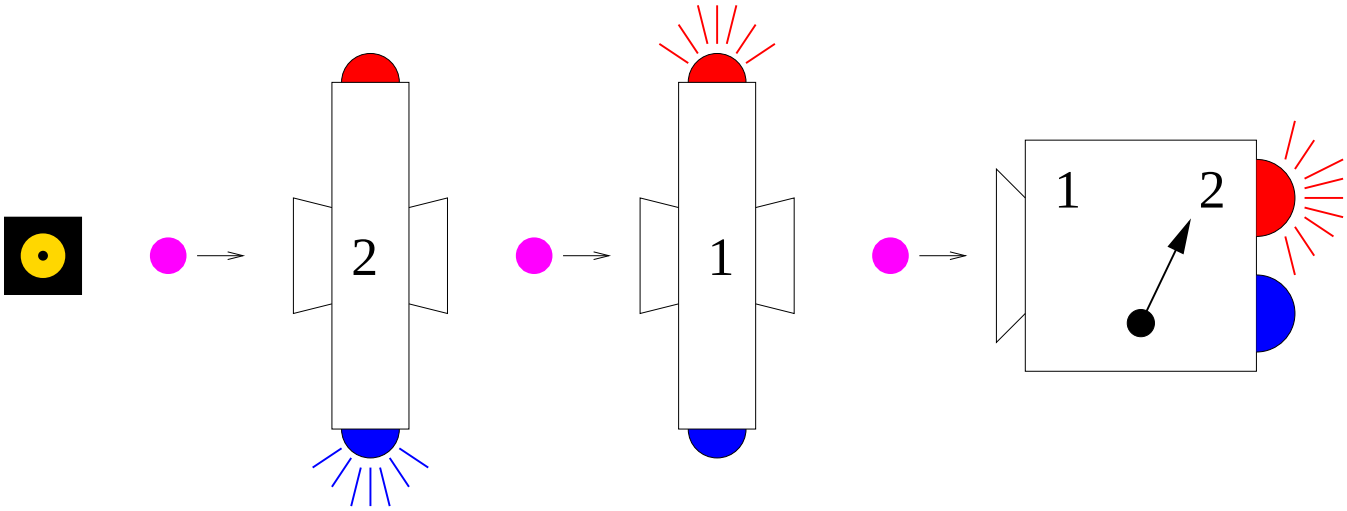
(But no such joint testing device has ever been made
and we shall see at the end of this lecture
that no such joint testing device is possible.)

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

EINSTEIN:

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

*"...reality as something independent
of what is experimentally established."*

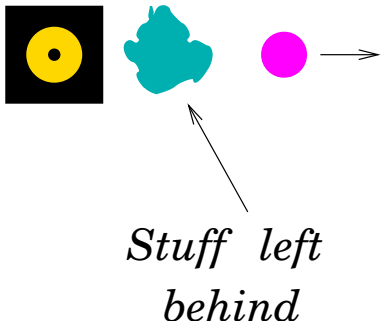
AN OBVIOUS REJOINDER:

"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."

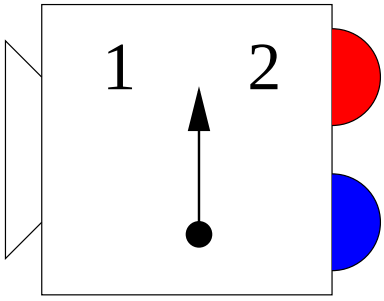
— Wolfgang Pauli (to Max Born)

Part III.

Einstein's Neat Idea

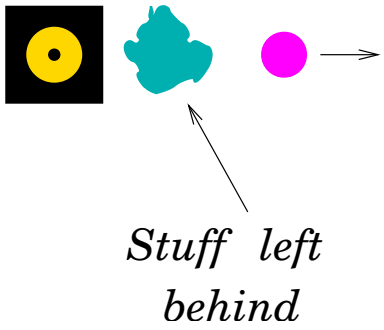


Stuff left behind

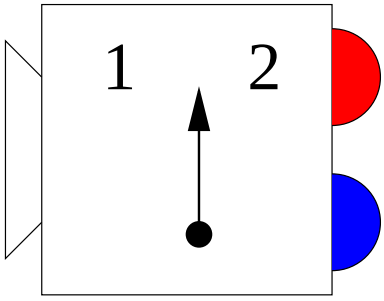


Don't test thing itself; test some stuff it leaves behind it!

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



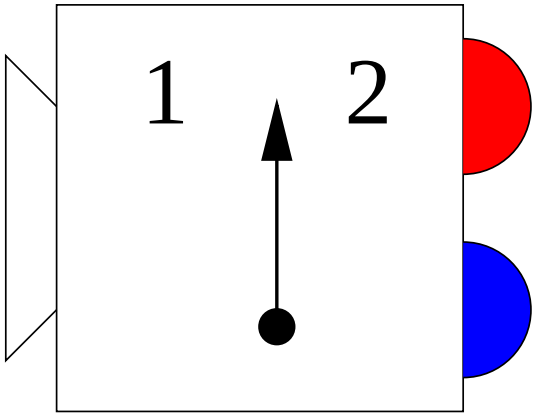
Stuff left behind

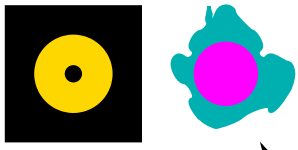


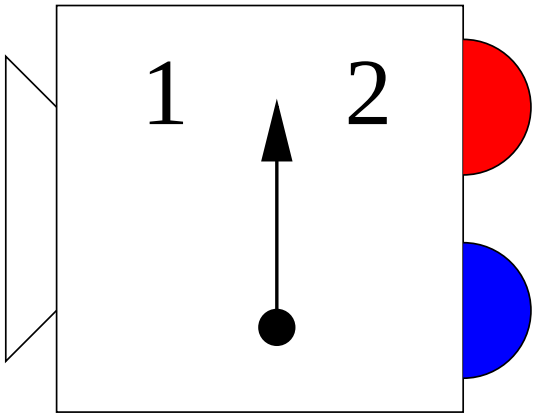
Don't test thing itself; test some stuff it leaves behind it!

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

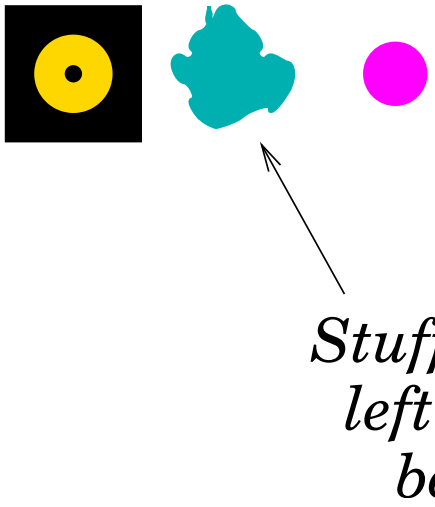
Paper in 1935 describes how this can actually be done.

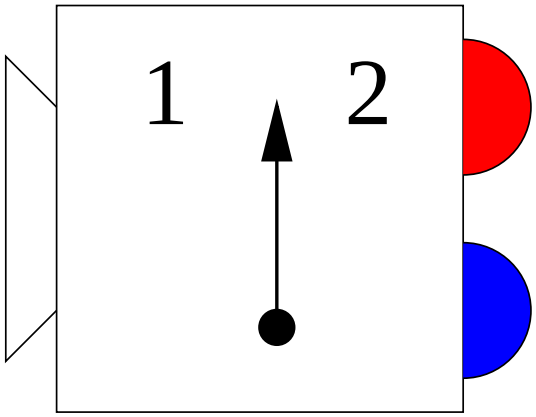

1
2

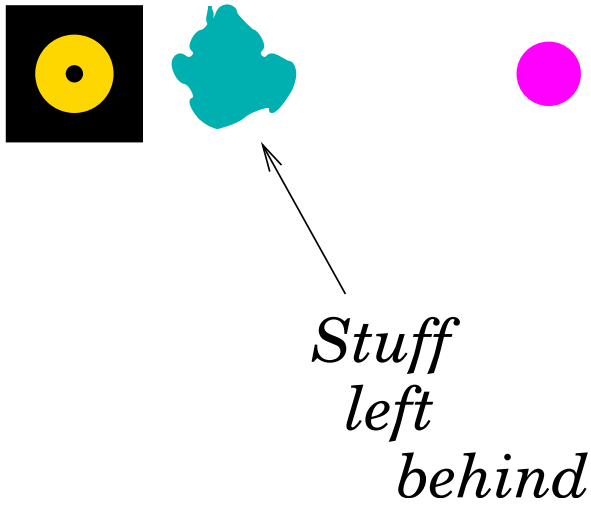


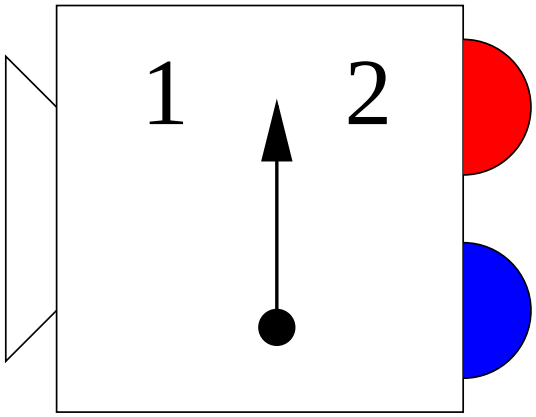


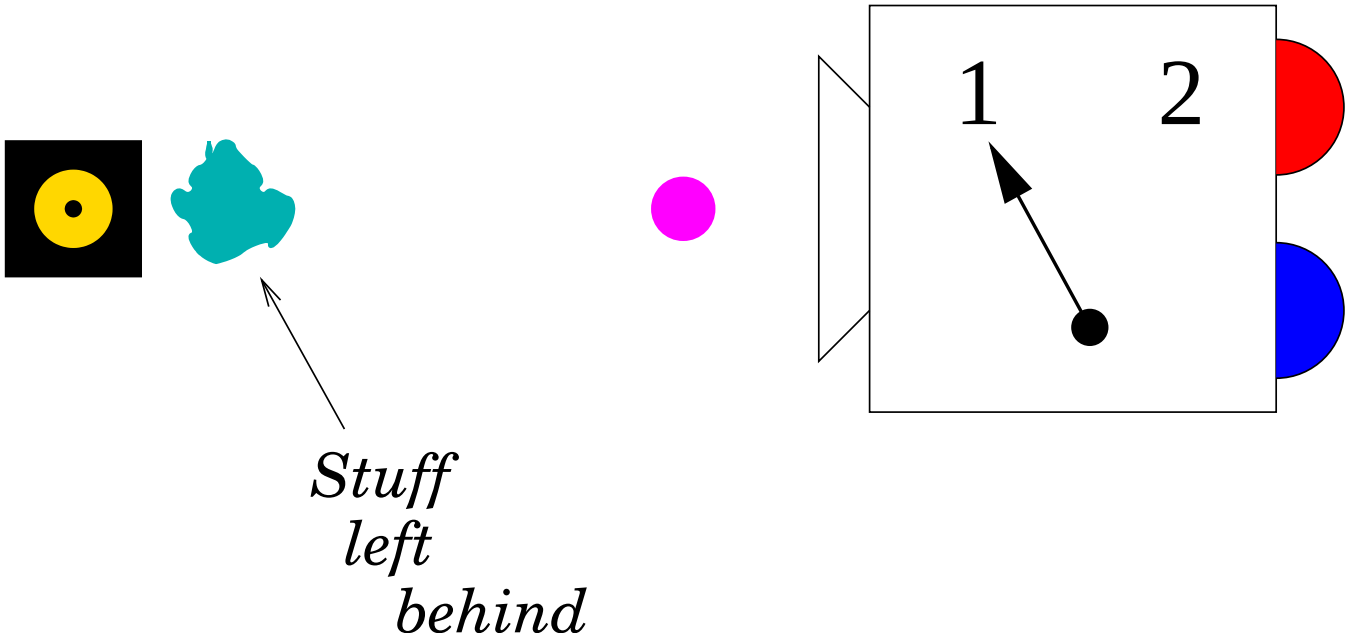
Stuff left behind


Stuff
left
behind

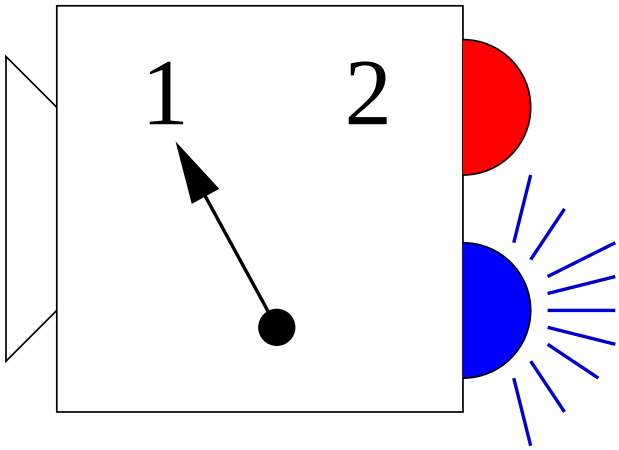

1
2

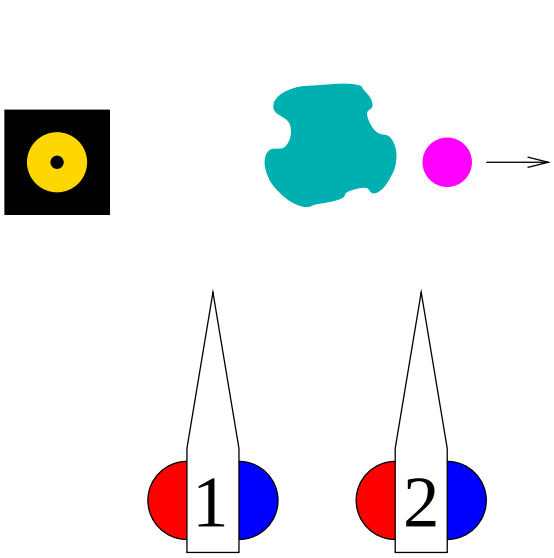

Stuff
left
behind

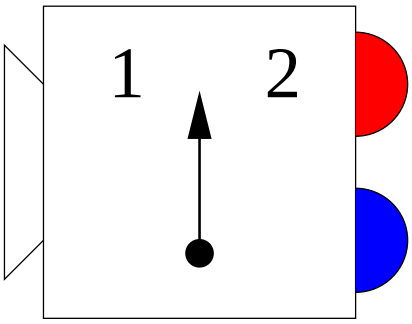

1
2


1
2
Stuff
left
behind

Stuff left behind

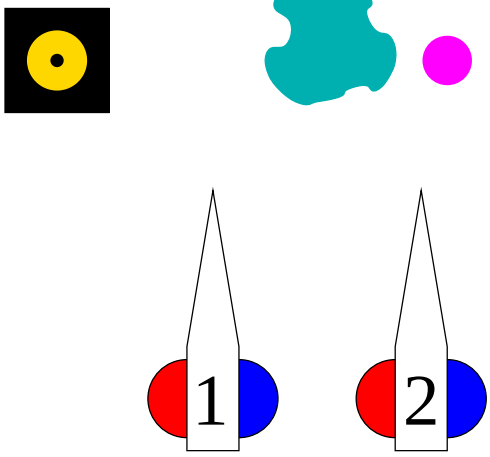


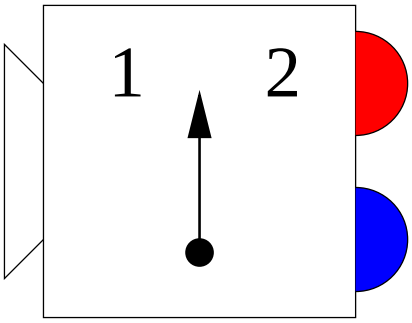


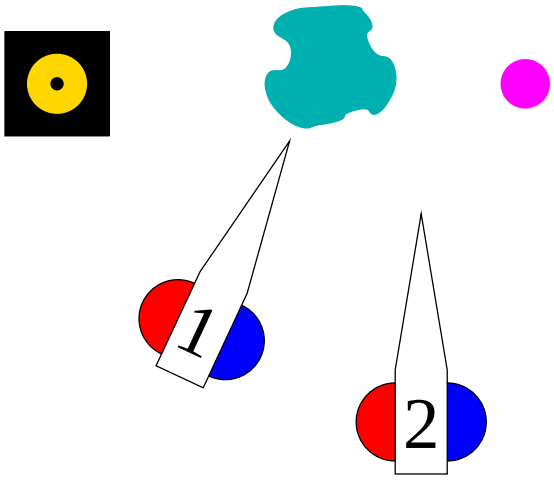


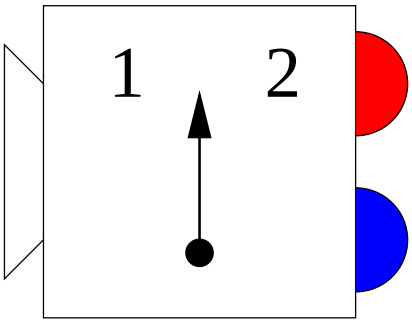
SLB testing devices

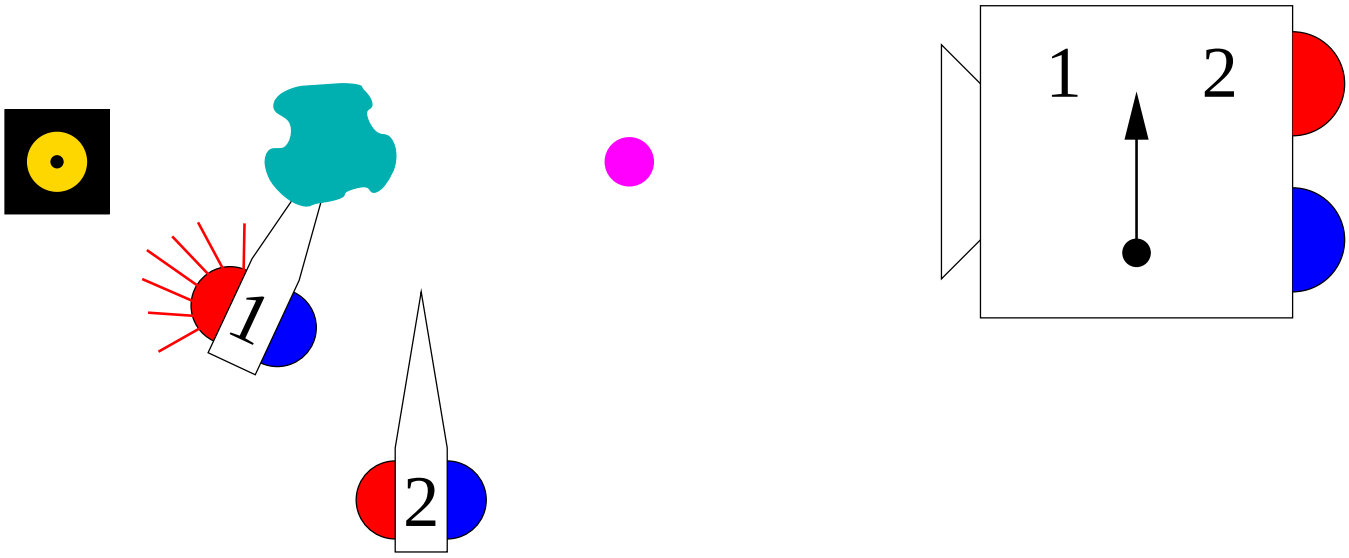
Testing Stuff left behind for 1-color.

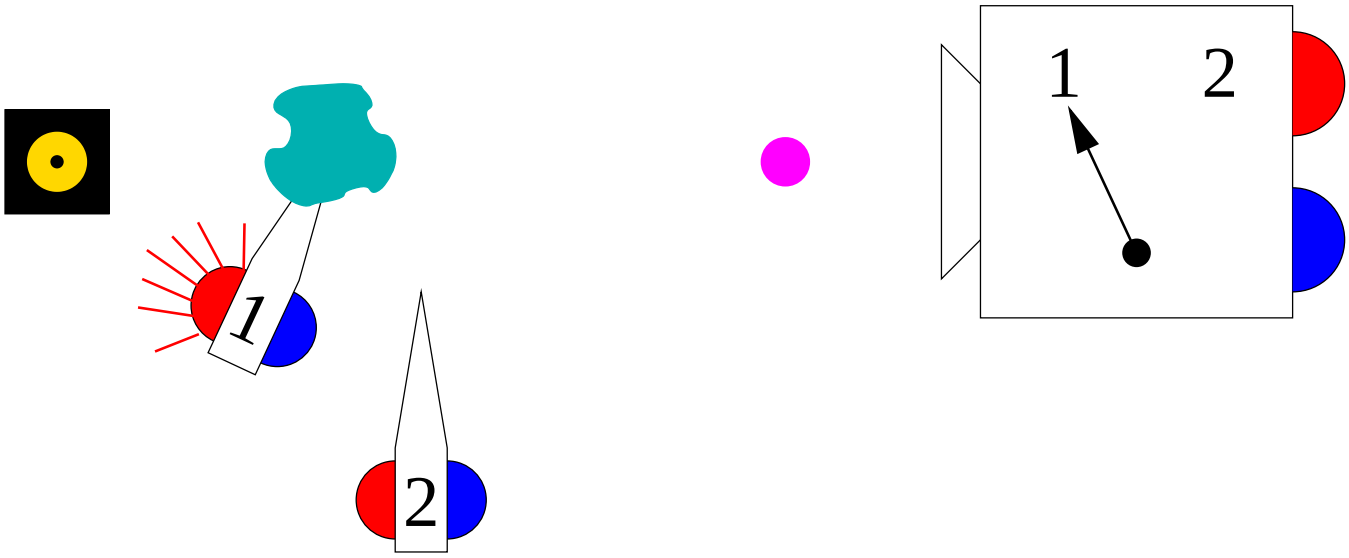


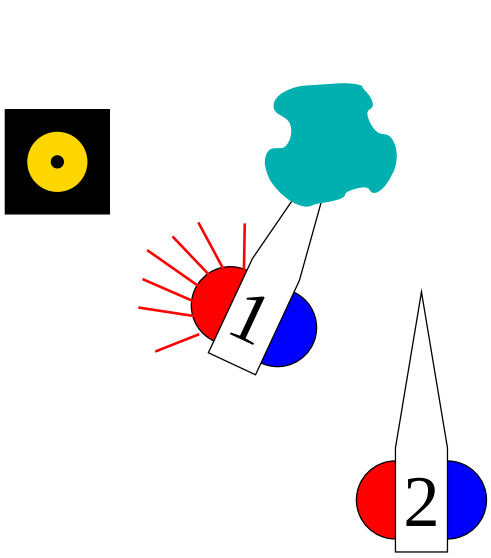


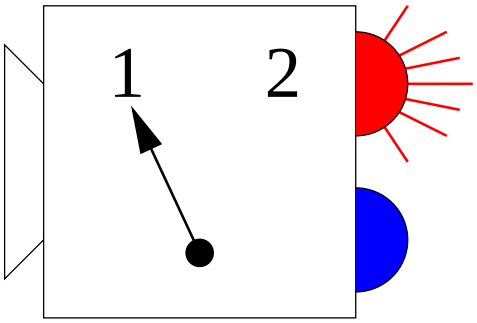

1
2


1
2

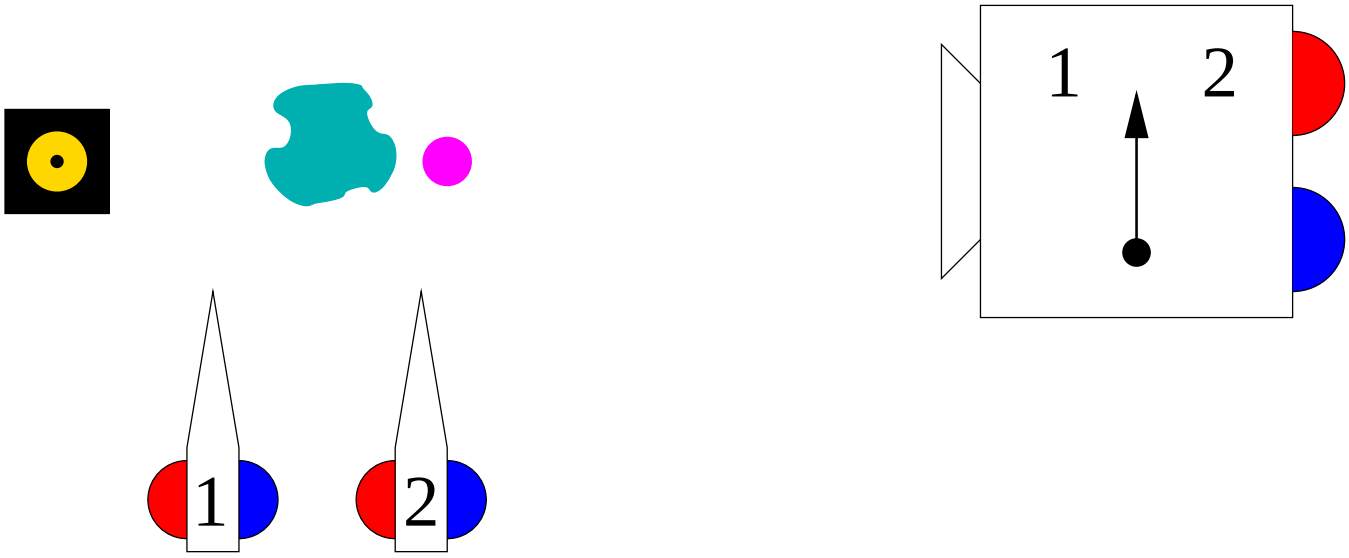

1
2
1
2

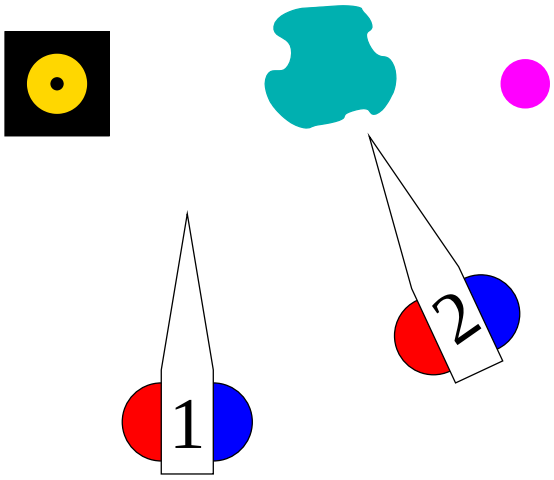

1
2
1
2

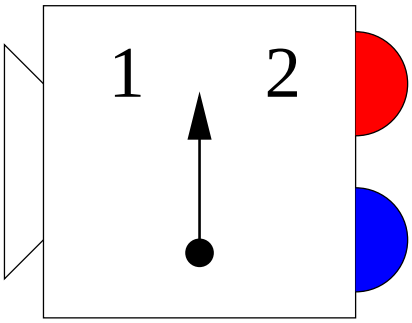

1
2

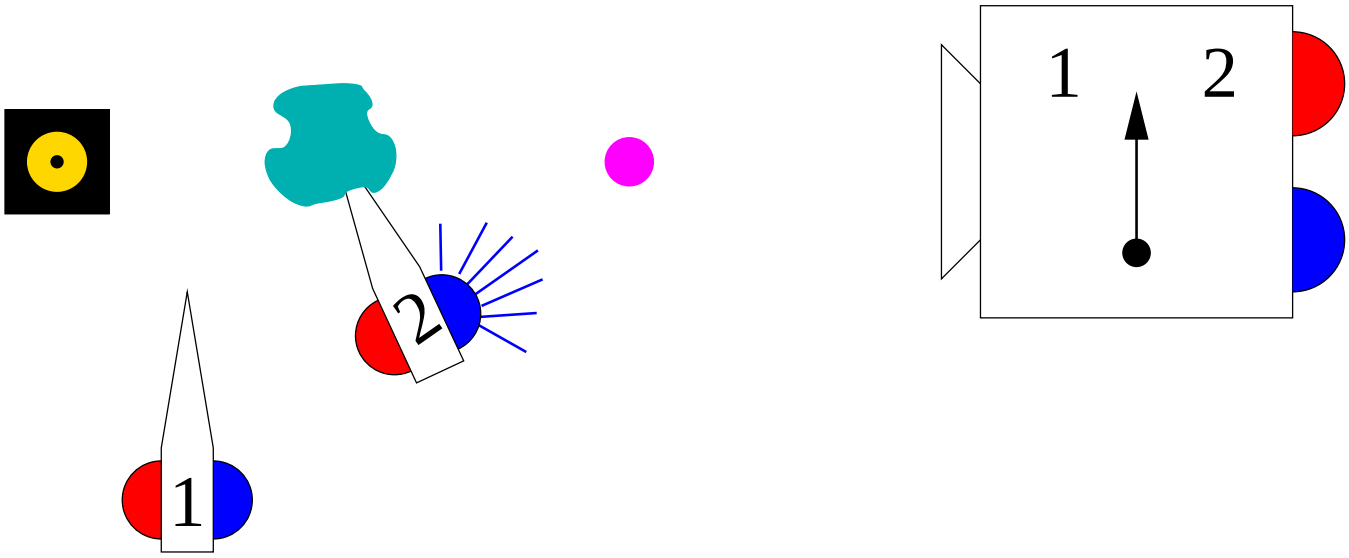

1
2

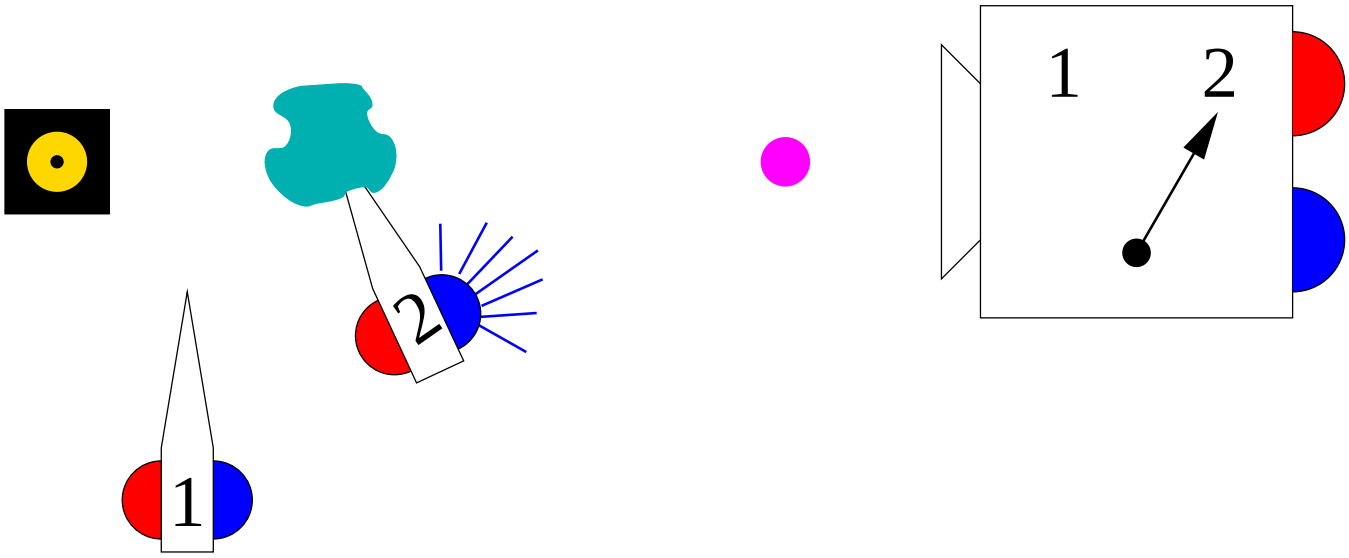
Testing Stuff left behind for 2-color.

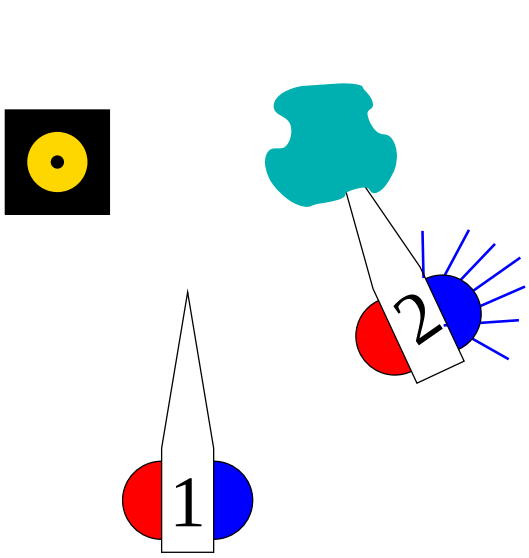


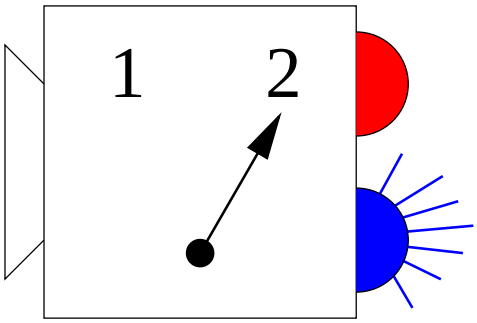

1
2


1
2


1
2
2
1


1
2
2
1


2
1


1
2

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.

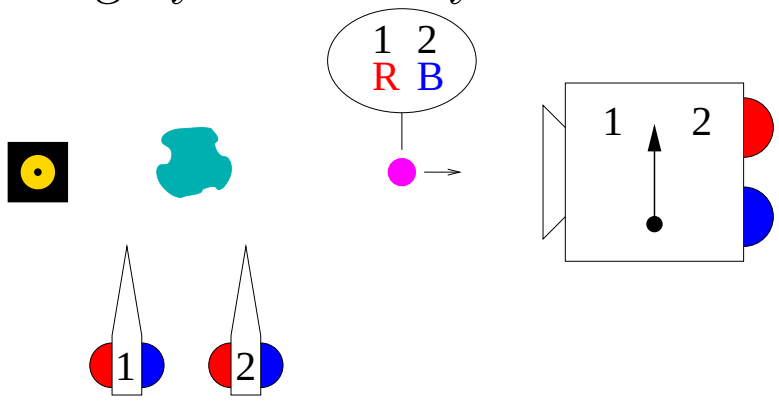
Therefore thing has both 1-color and 2-color!

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)



SLB testing devices

"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 (or 2-color)
is that 1-color (or 2-color) has been
indicated by a type-1 (or type-2) test.

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

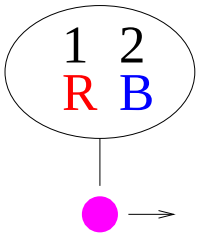
OBVIOUS OBJECTION TO BOHR'S OBJECTION:

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,
because the thing *isn't there* any more!

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:

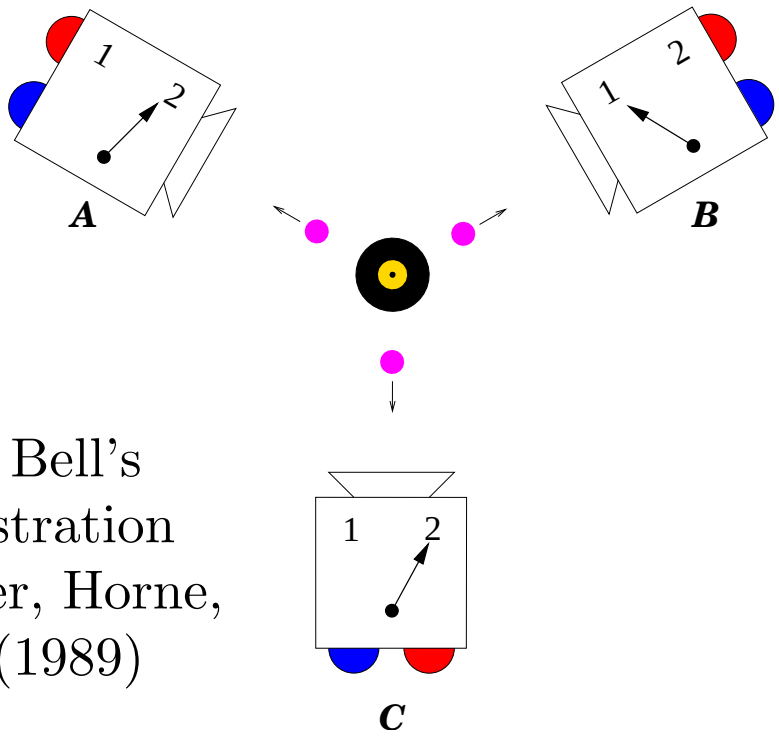


It is so reasonable to assume that the [things]... carry with them [properties]...telling them how to behave. ...I think that when Einstein saw that, and the others refused to see it, he was the rational man. The other people, ... were burying their heads in the sand. I feel that Einstein's intellectual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

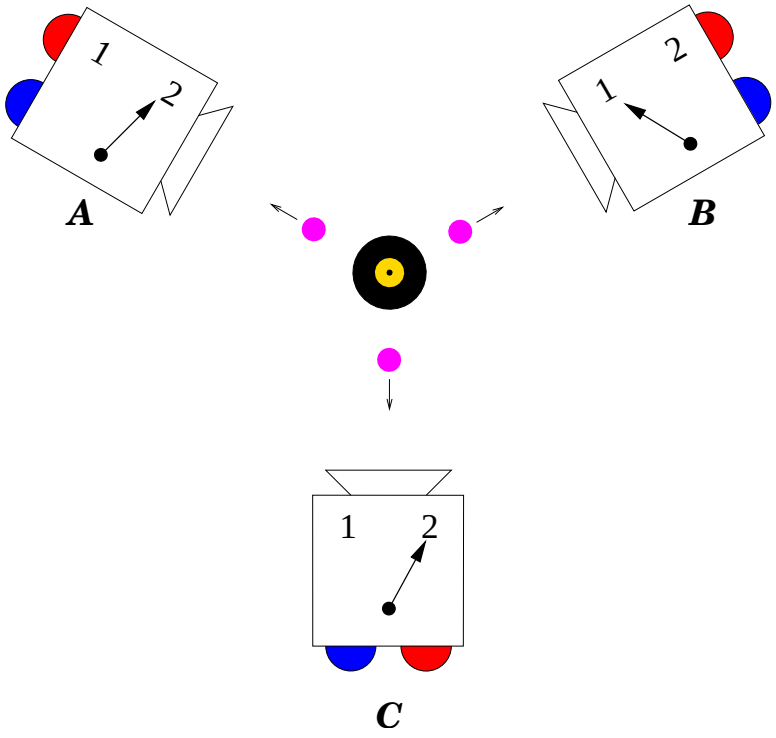
Part IV.

Why Einstein Was Wrong

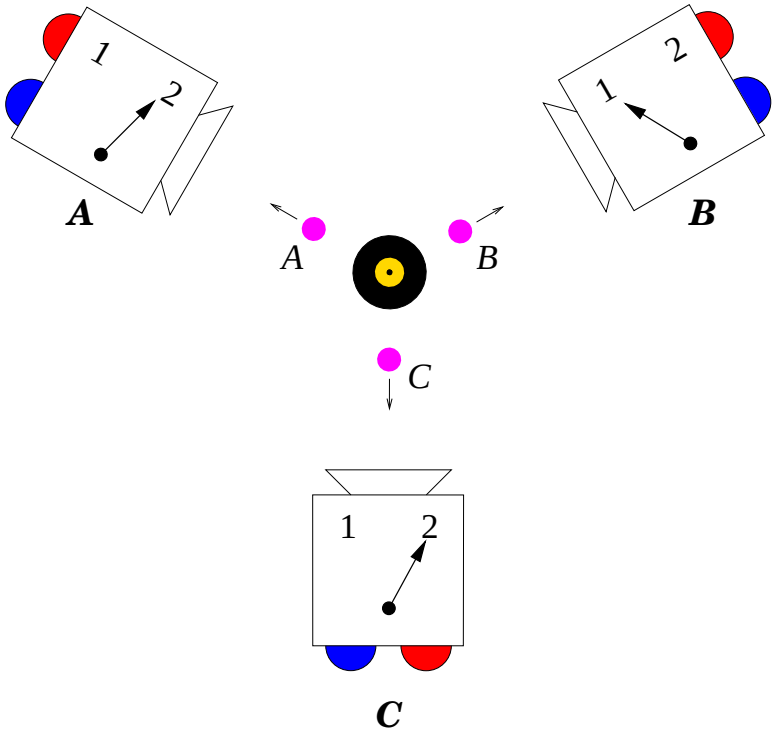
Refinement of Bell's (1964) demonstration by Greenberger, Horne, and Zeilinger (1989)

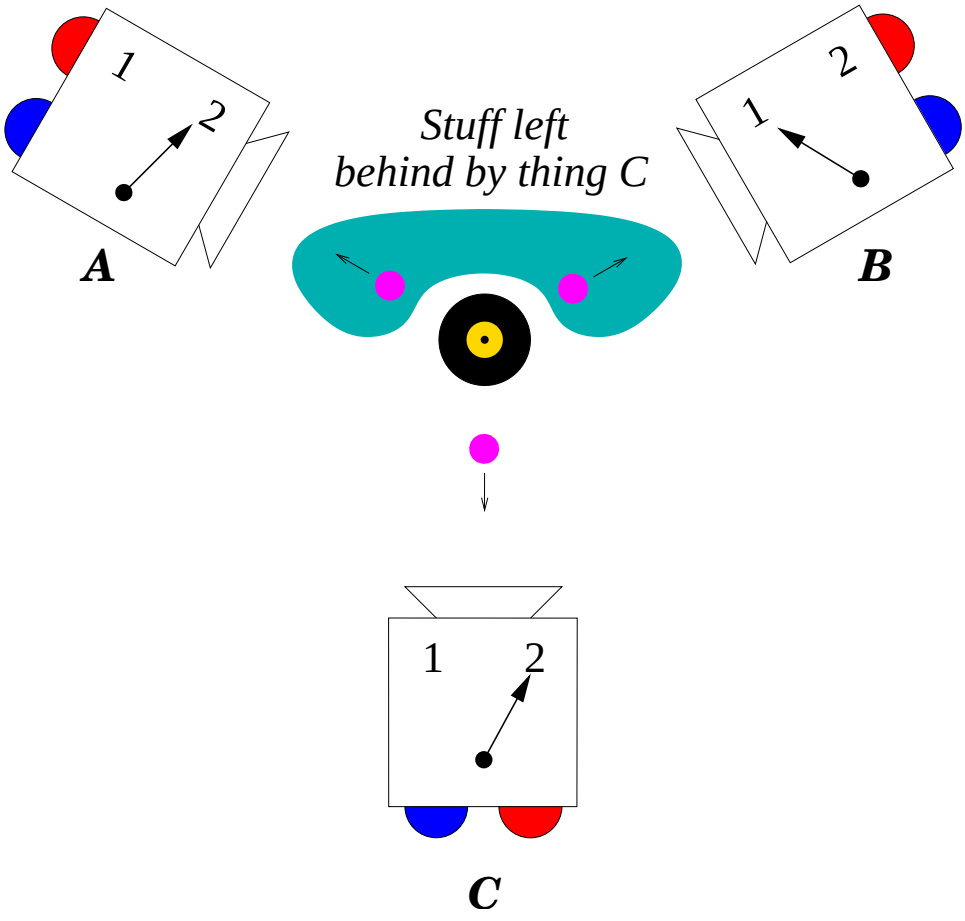


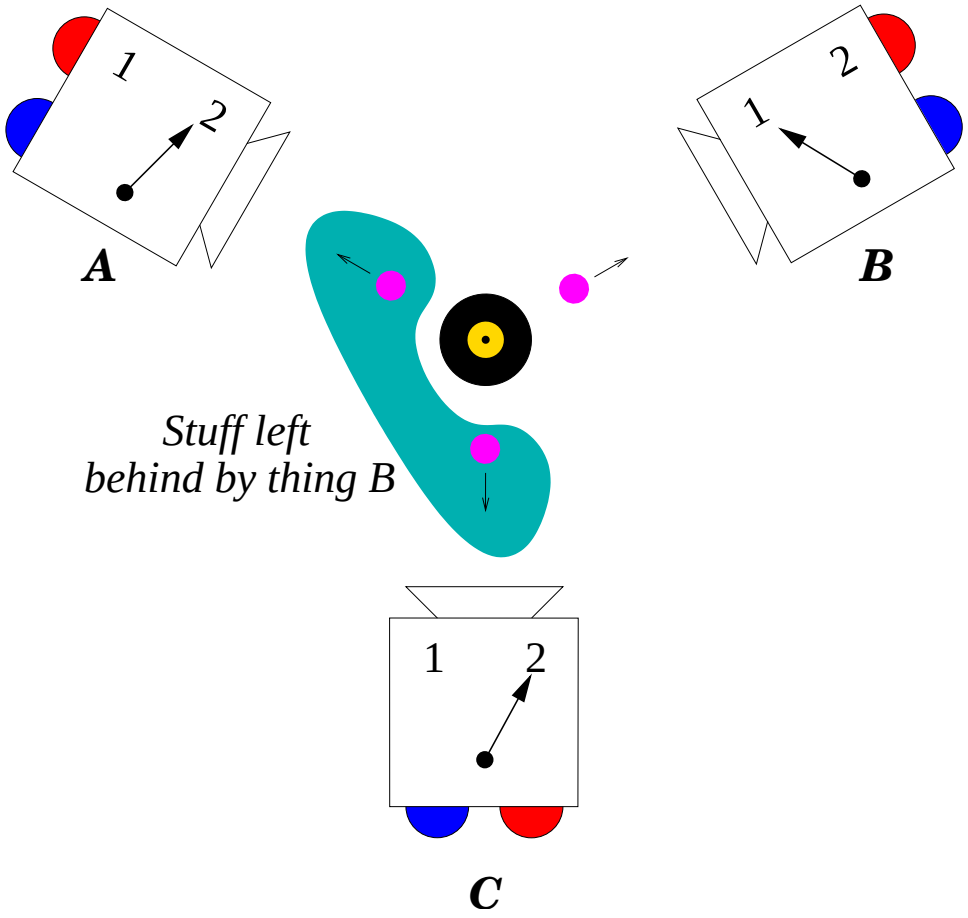
THREE THINGS
THAT GO TO THREE DETECTORS

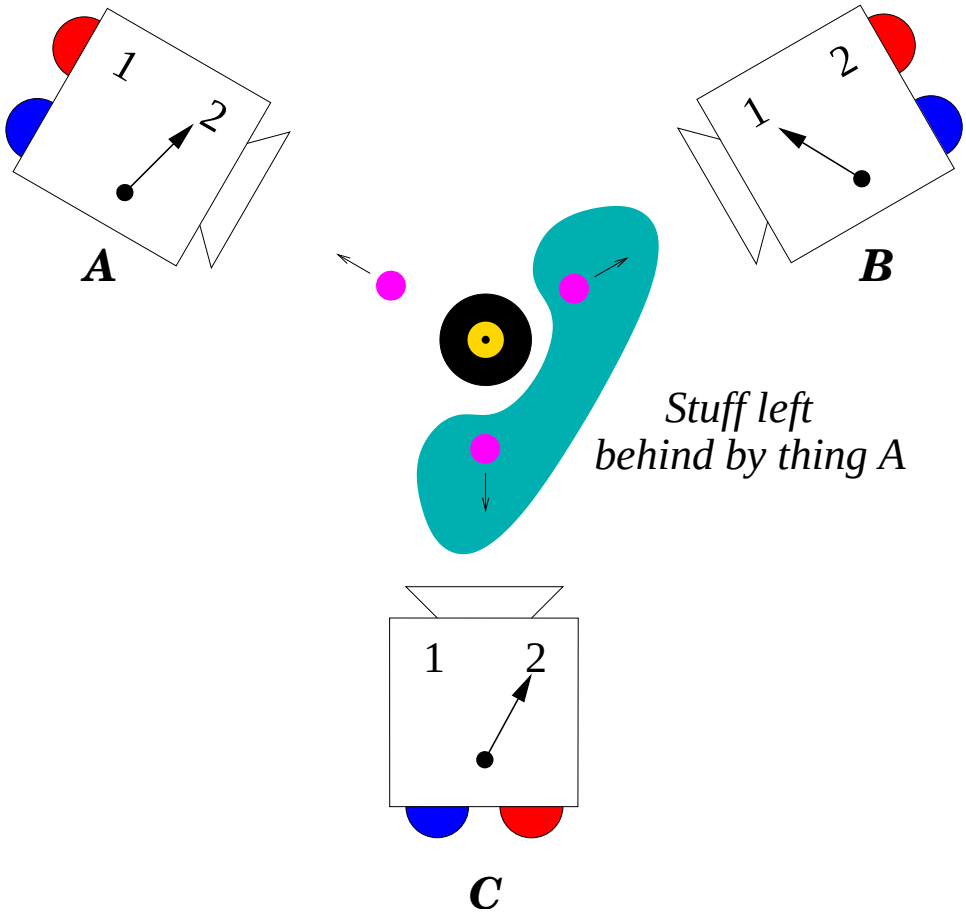


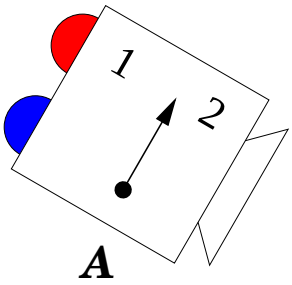
Label the three things by the three detectors they are going to.



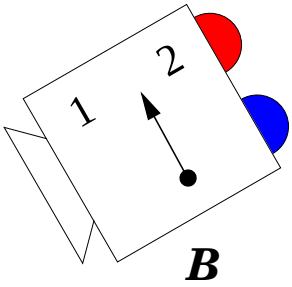

1
2
A
Stuff left
behind by thing C
2
1
B
1
2
C


1
2
A
2
1
B
Stuff left
behind by thing B
1
2
C

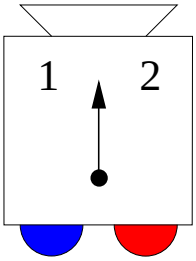

1
2
A
2
1
B
Stuff left
behind by thing A
1
2
C



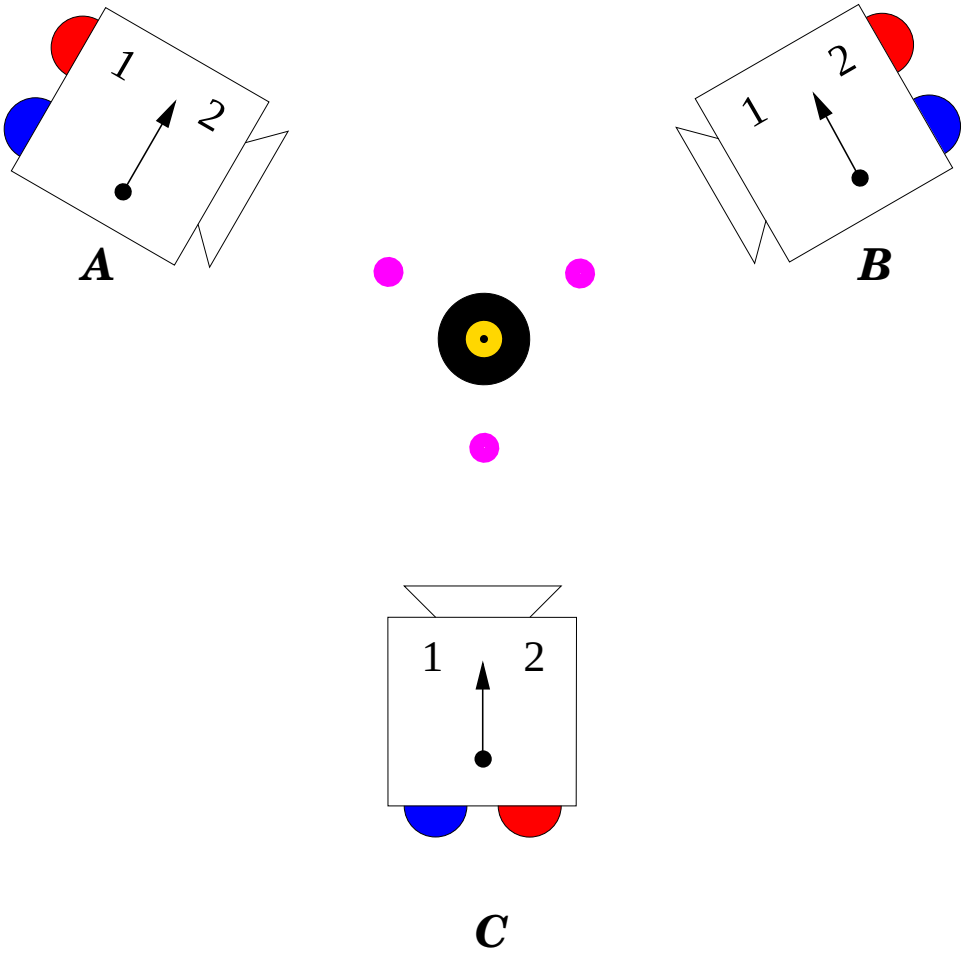
A

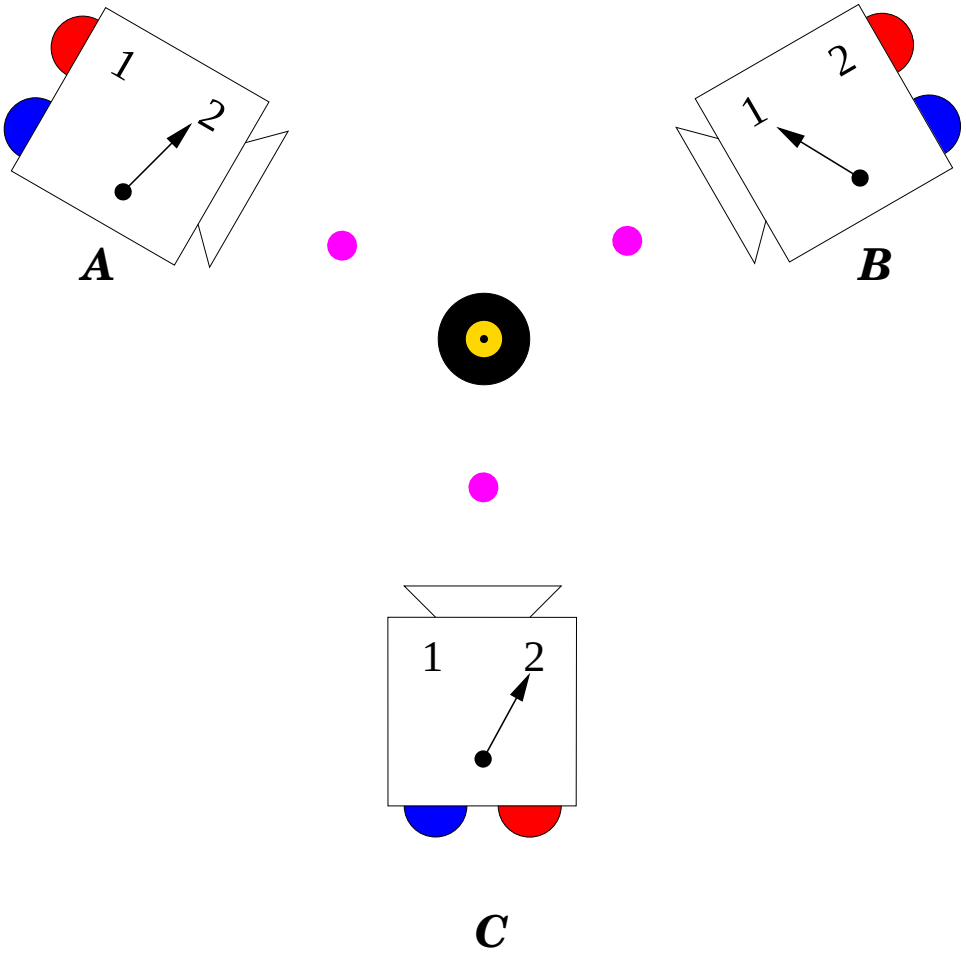


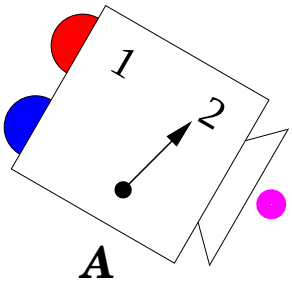
B



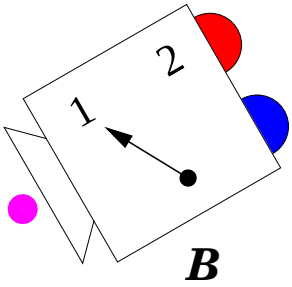
C


1
2
A
1
2
B
1
2
C

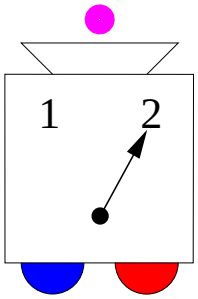

1
2
A
2
1
B
1
2
C



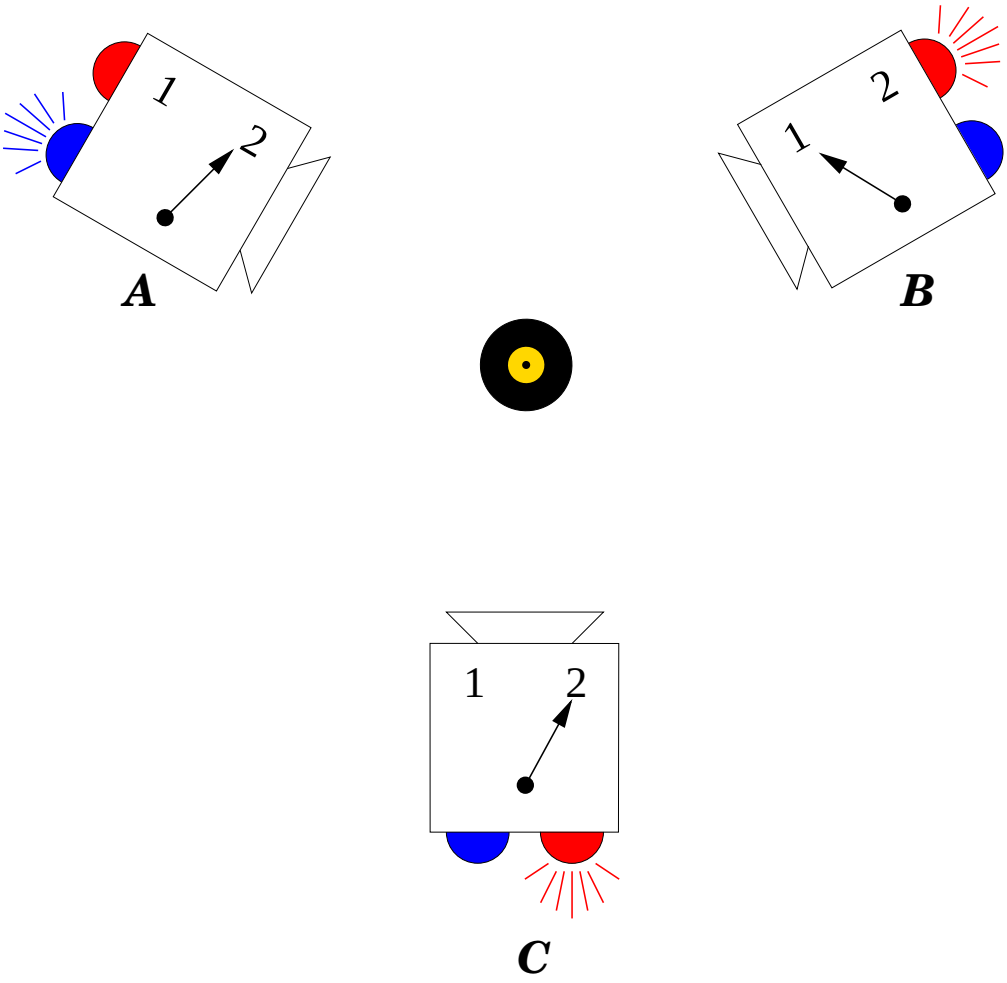
A

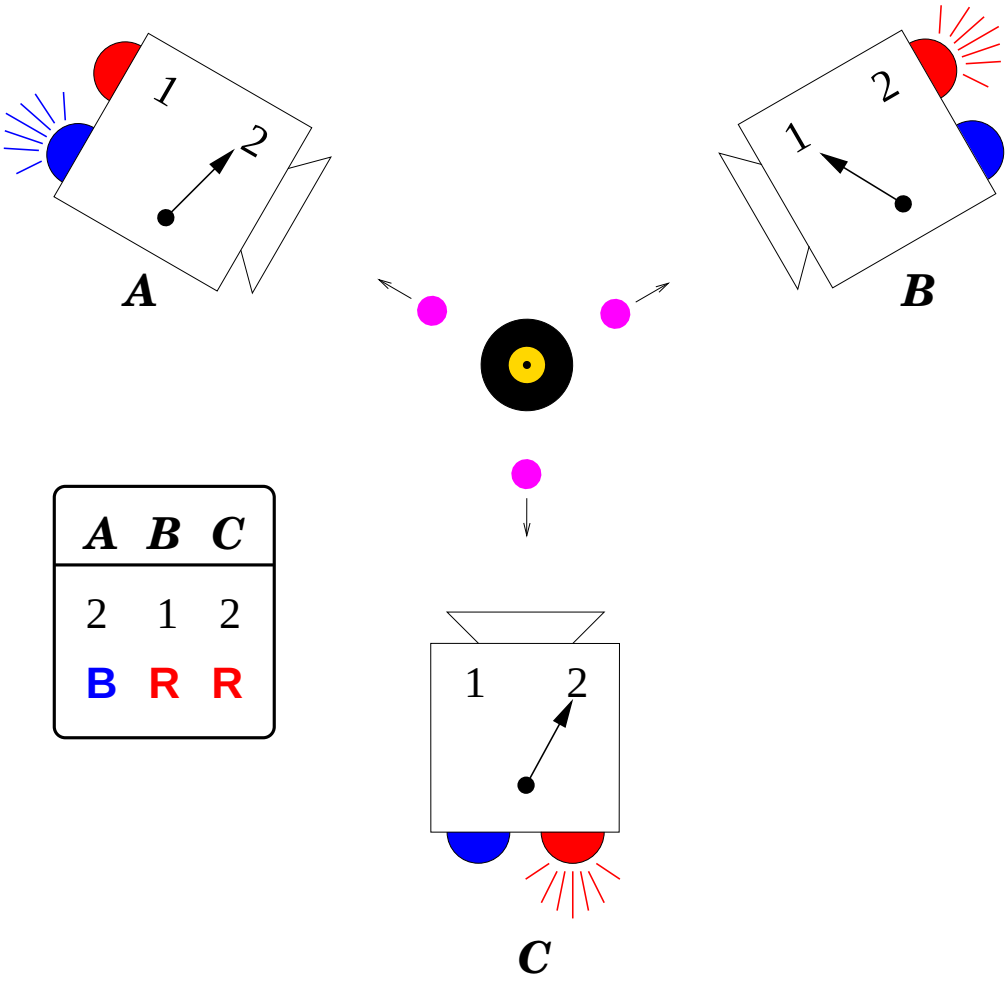


B



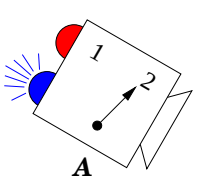
C

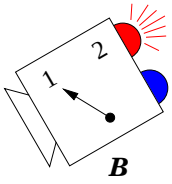

1
2
A
2
1
B
1
2
C



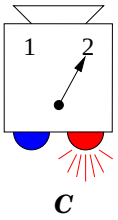
A	*B*	*C*
2	1	2
B	R	R

SOME CRUCIAL FEATURES OF THE DATA

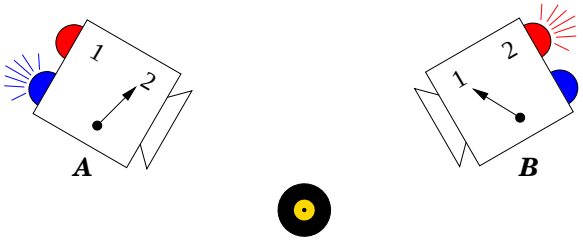




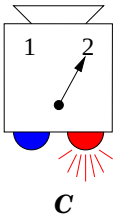
A	***B***	***C***	***Behavior of Lights***
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red



SOME CRUCIAL FEATURES OF THE DATA

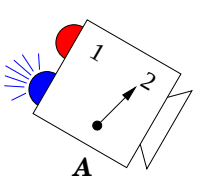


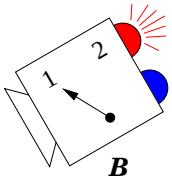
A	***B***	***C***	***Behavior of Lights***
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red



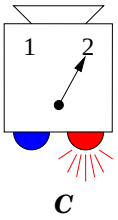
Paper in 1989 describes how this can actually be done.

SOME CRUCIAL FEATURES OF THE DATA



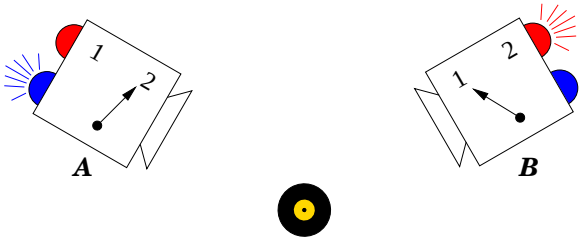


A	***B***	***C***	***Behavior of Lights***
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

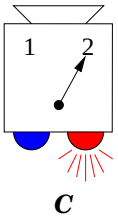


(Aside from these restrictions, behavior is random.)

SOME CRUCIAL FEATURES OF THE DATA

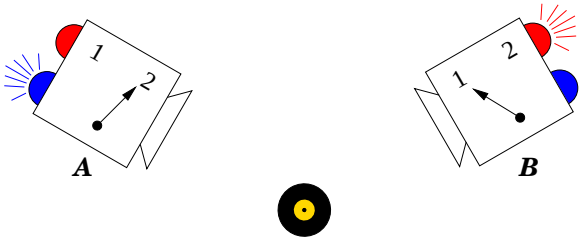


A	***B***	***C***	***Behavior of Lights***
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

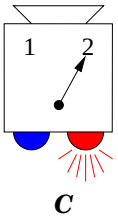


(Aside from these restrictions, behavior is random; e.g. in 212 run BRR, RBR, RRB, BBB are all equally likely.)

SOME CRUCIAL FEATURES OF THE DATA

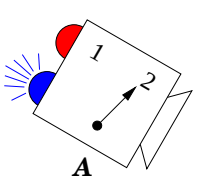


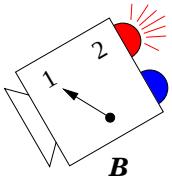
A	***B***	***C***	***Behavior of Lights***
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red



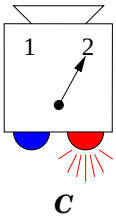
(Aside from these restrictions, behavior is random; e.g. in 222 runs all 8 outcomes, RRR, RBB, BRB, BBR, BRR, RBR, RRB, BBB, are equally likely.)

SOME CRUCIAL FEATURES OF THE DATA

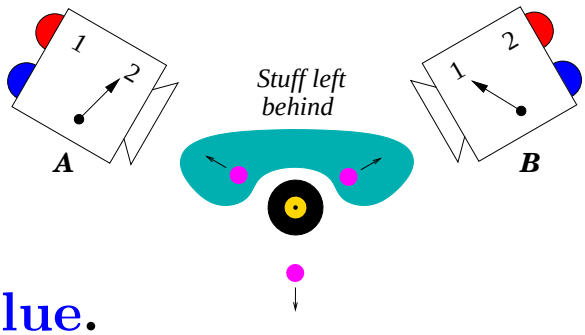




A	***B***	***C***	***Behavior of Lights***
1	2	2	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

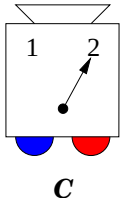


LEARNING 2-COLOR OF THING GOING TO C FROM THE STUFF IT LEFT BEHIND



2 1 2: Odd number flash blue.

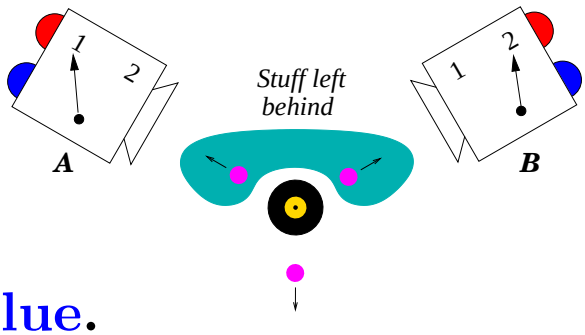
To learn 2-color at C send SLB to type-2 at A and type-1 at B.



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

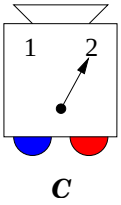
If one flashes blue and other flashes red, thing going to C has 2-color red.

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



1 2 2: Odd number flash blue.

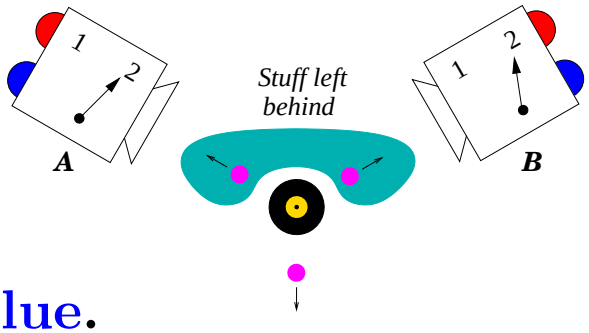
To learn 2-color at C send SLB to type-1 at A and type-2 at B.



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

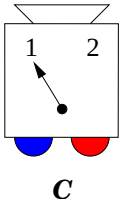
If one flashes blue and other flashes red, thing going to C has 2-color red.

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



2 2 1: Odd number flash blue.

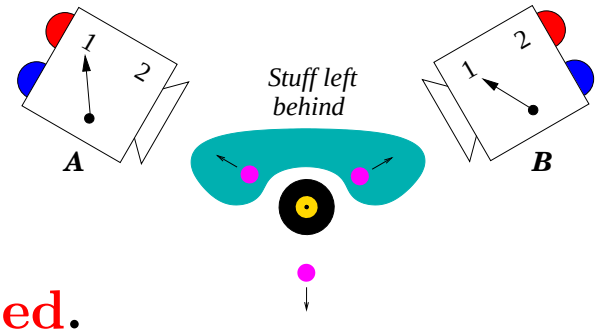
To learn 1-color at C send SLB to type-2 at A and at B.



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

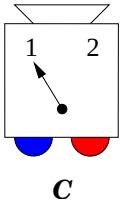
If one flashes blue and other flashes red, thing going to C has 1-color red.

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



1 1 1: Odd number flash red.

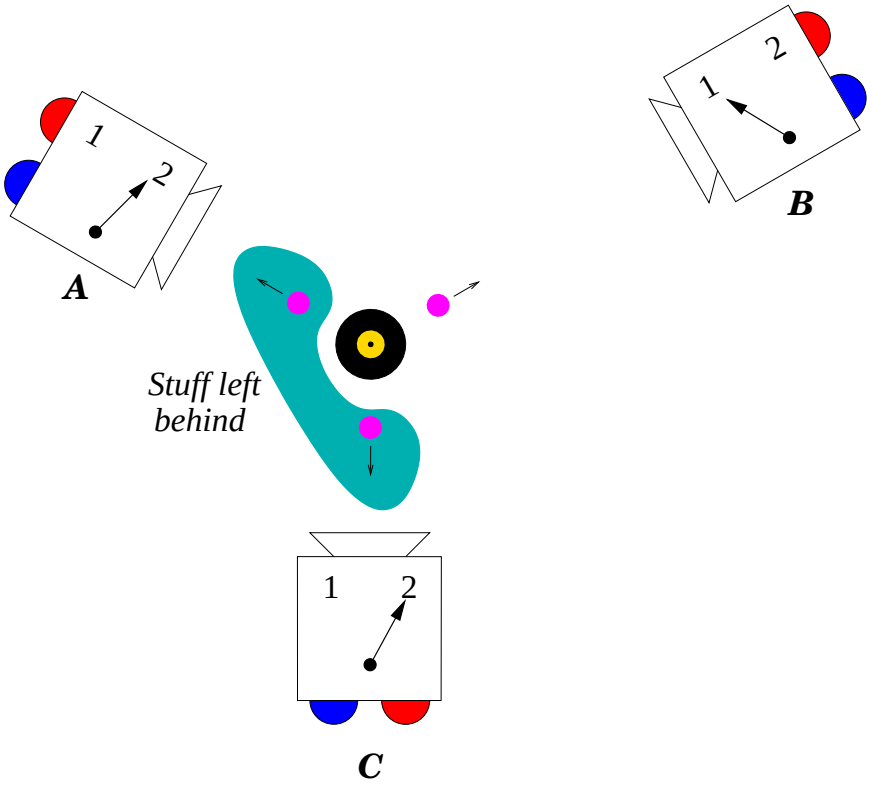
To learn 1-color at C send SLB to type-1 at A and at B.



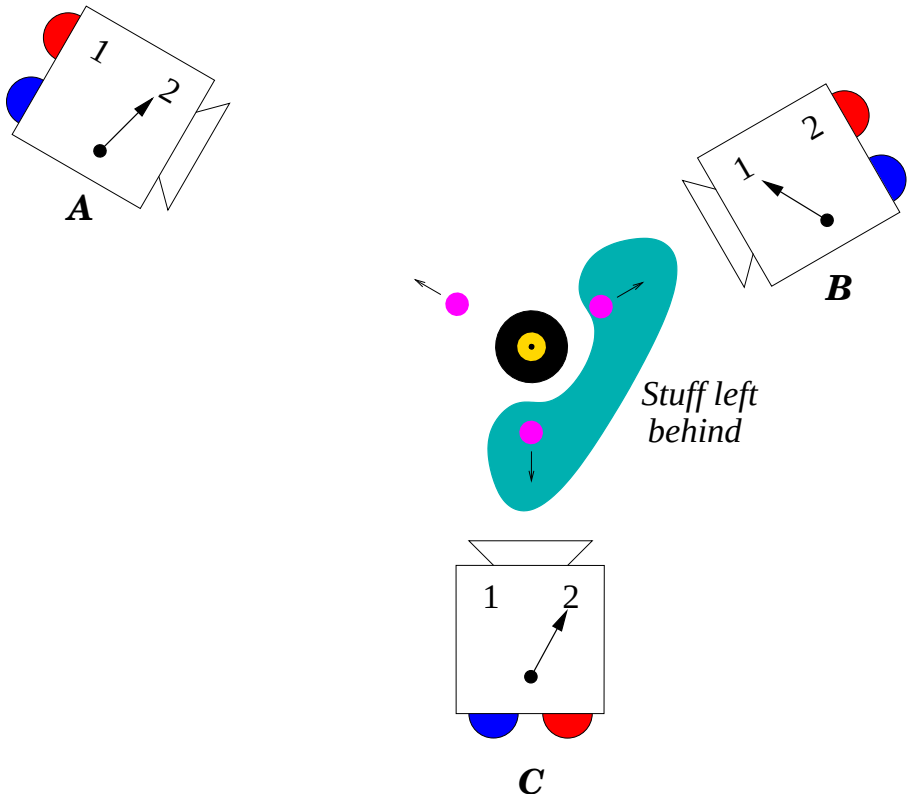
If both flash blue or both flash red, thing going to C has 1-color red.

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

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

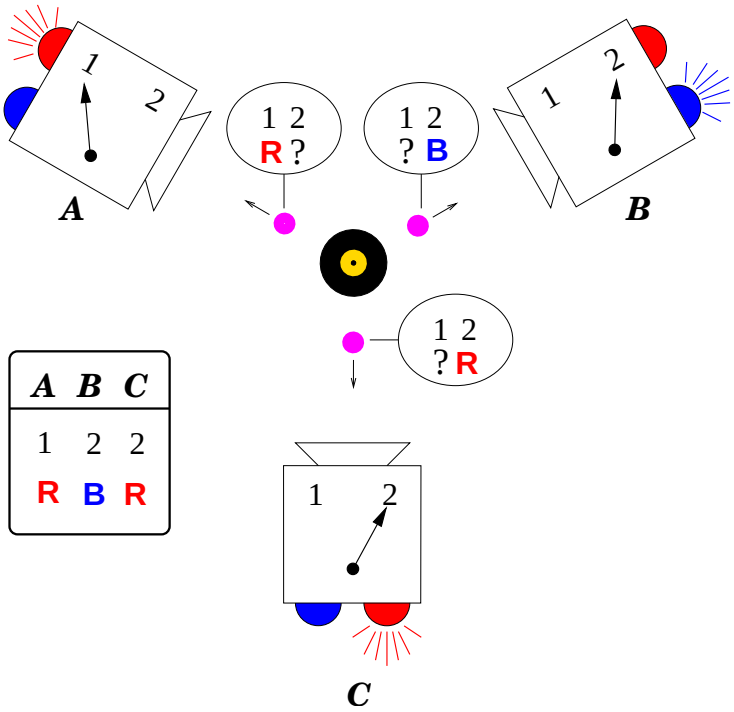


OR CAN LEARN 1-COLOR OR 2-COLOR OF THING GOING TO A, FROM THE STUFF IT LEFT BEHIND



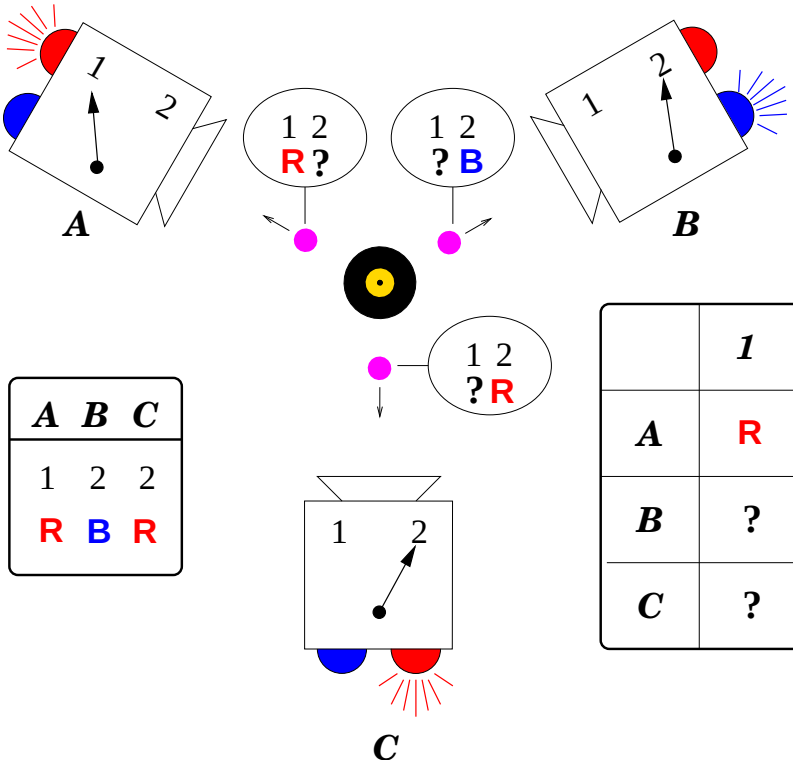
EINSTEIN'S CONCLUSION: ALL THREE THINGS HAVE 1-COLOR AND 2-COLOR

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] if no [test] whatsoever is carried out on [the stuff it left behind].



A	*B*	*C*
1	2	2
R	B	R

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



A	*B*	*C*
1	2	2
R	B	R

	1	*2*
A	R	?
B	?	B
C	?	R

Suppose we have a 122 run in which
A flashes red, B flashes blue, and C flashes red

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

Suppose we have a 122 run in which
A flashes red, B flashes blue, and C flashes red

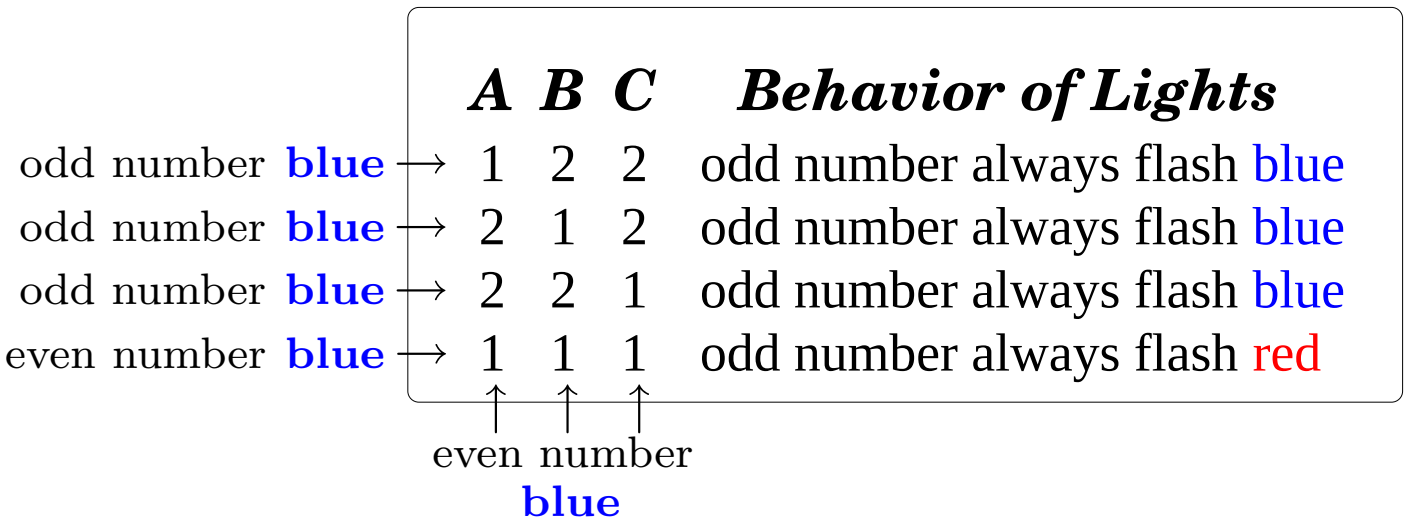
A	***B***	***C***	***Behavior of Lights***
1	***2***	***2***	odd number always flash blue
2	1	2	odd number always flash blue
2	2	1	odd number always flash blue
1	1	1	odd number always flash red

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

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

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

		A	*B*	*C*	***Behavior of Lights***
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
Behavior of Lights
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

Epilogue.

Where Does This Leave Us?

DOES THIS MEAN
THAT QUANTUM MECHANICS IS WRONG?

NO! **NO!** **NO!**

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

BUT THE BEHAVIOR IT DESCRIBES
(in my opinion)
IS SOMETIMES QUITE PECULIAR

1. One has the option of learning either the 1-color or the 2-color of any one of the 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 give a thing its 1-color or 2-color.

4. Is this *spooky action at a distance*? Or is it no different from my daughter-in-law having her first baby in Boston, Massachusetts, instantly making me a grandfather in Ithaca, New York?

4. Is this *spooky action at a distance*? Or is it no different from my daughter-in-law having her first baby in Boston, Massachusetts, instantly making me a grandfather in Ithaca, New York?

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 Ithaca to determine whether I have become a grandfather, if I have not spoken with Boston 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.

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.

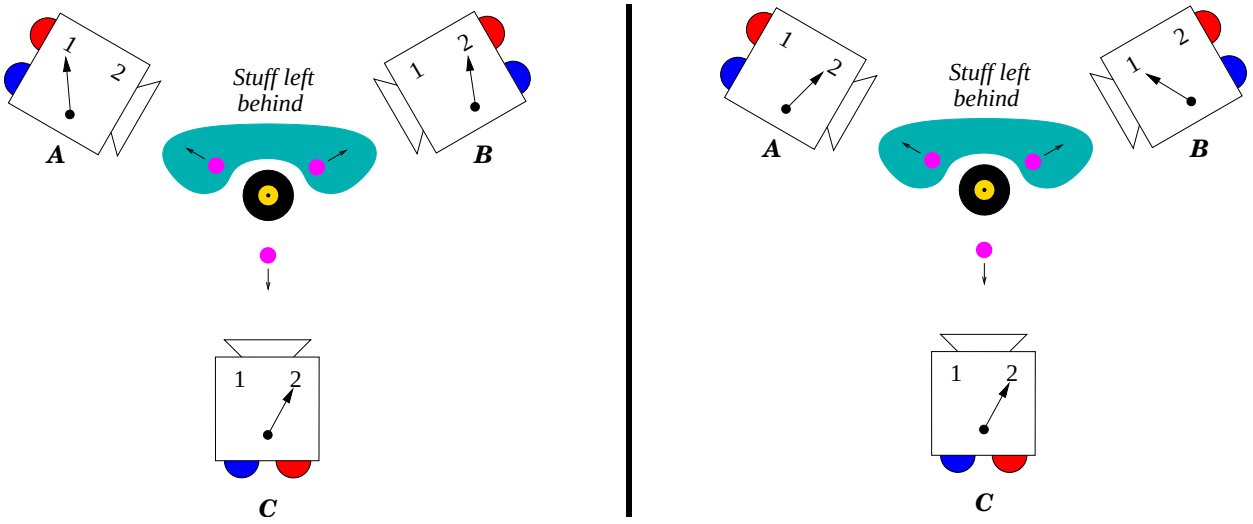
2. But all three things cannot have both a 1-color and a 2-color.

~~3. So the act of testing the stuff it leaves behind it must give a thing its 1-color or 2-color~~

3. So a thing cannot have 1-color or 2-color unless an *actual* test establishes that that color is R or B.

Thing C *does not have* a 2-color unless an *actual test* establishes that that color is R or B.

Thing C *does not have* a 2-color unless an *actual test* establishes that that color is R or B.



Only one of these tests can *actually* be done. Why should the 2-color of C in an *an actual* test be the same in a *fictitious* world where the test is different?

“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] whatseover is carried out on [the stuff it left behind].”

— Einstein

~~"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

~~"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 an *actual* test establishes that that color is R or B.

~~"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 an *actual* test establishes that that color is R or B.

Unperformed experiments have no results.

— Asher Peres

~~"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 an *actual* test establishes that that color is R or B.

Unperformed experiments have no results.

— Asher Peres

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

A thing does not have color unless an *actual* test establishes that 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.

Afterword.

A Rhetorical Homework Problem

Let H and V be polarization states for horizontally and vertically polarized photons, and let R and L be polarization states for two right and left 45° diagonal directions, so

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

Type-1 detectors measure polarization, flashing red if a photon is polarized horizontally and blue if it is polarized vertically. Type-2 detectors behave the same way with respect to diagonal photons — i.e. they are given by simply rotating a type-1 detector through 45° about the line joining it to the source of the three photons. The source produces three photons in the polarization state

$$\tfrac{1}{2}(HHH - VVH - VHV - HVV), \qquad (2)$$

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

Reference:

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

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