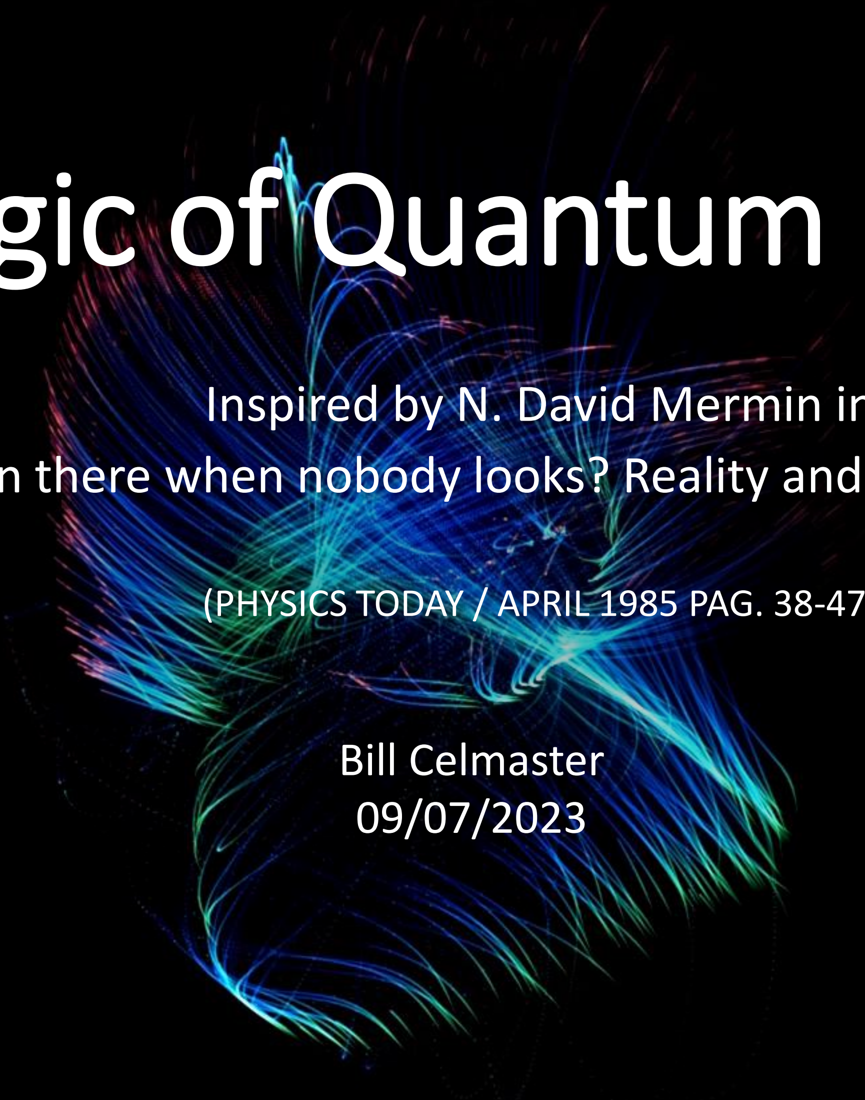
The Magic of Quantum Entanglement

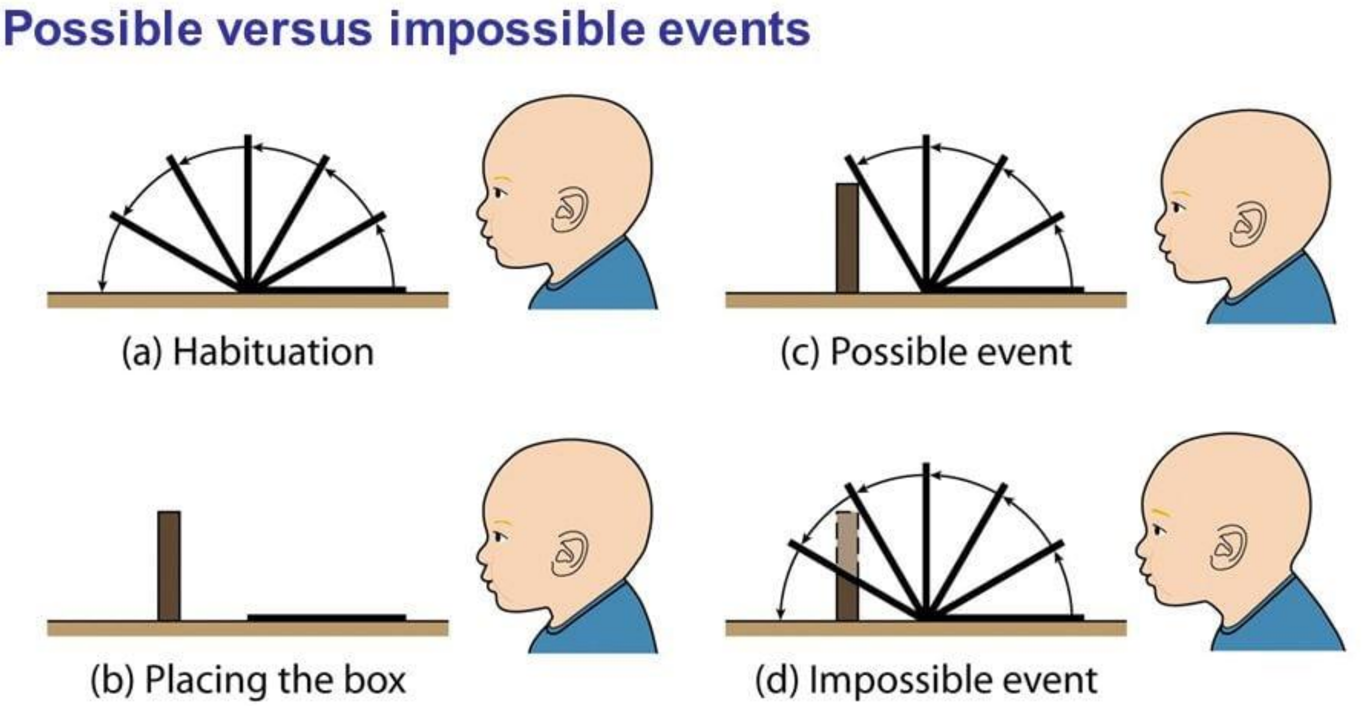


Inspired by N. David Mermin in
"Is the moon there when nobody looks? Reality and the quantum theory"

(PHYSICS TODAY / APRIL 1985 PAG. 38-47)

Bill Celmaster
09/07/2023

Piaget and “Object Permanence”



In a classic series of tests of object permanence, Renée Baillargeon and her colleagues first habituated young infants to the sight of a screen rotating through 180 degrees. Then a box was placed in the path of the screen. In the *possible event,* the screen rotated up, occluding the box, and stopped when it reached the top of the box. In the *impossible event,* the screen rotated up, occluding the box, but then continued on through 180 degrees, appearing to pass through the space where the box was. Infants looked longer at the impossible event, showing they mentally represented the presence of the invisible box. (From Baillargeon, 1987)

Impossibility and Magic

- Infant – it is ***awesome*** to encounter “object impermanence”
- Adult – it is ***awesome*** to encounter “magic”
  - E.g. Magician turns handkerchief into a bouquet of flowers
- Ingredients of magic
  - Set up the situation/experiment
  - Expectations based on habituation/experience
  - Defy expectations
- Magic vs. “magic trick”
  - “Magic trick” – there’s stuff we don’t know about the situation/experiment which would alter our expectations
    - However, if the trick is good we can’t guess what’s hidden
  - “Magic” – we know everything that can be known
    - *Even* יַהְוֹה *doesn’t known anything else*

Brief history of quantum magic through 1964

- 1900 – 1927: Basic mathematical rules of QM are inferred from experiments
- 1927 – 1935: The **Copenhagen** interpretation of *quantum foundations*
  - The Heisenberg Uncertainty Principle.
  - **Einstein argues that this looks like magic.**
  - **Bohr says "who cares?"**
- 1935: The EPR Paradox and Schrodinger's cat
  - Einstein, Podolsky and Rosen (EPR) illustrate an experiment that, according to QM looks like magic.
  - **Einstein doesn't believe in magic** (the Copenhagen view) **and says it must be *a magic trick***
    - Underlying QM must be a more complex theory involving ***hidden variables*** we don't know about
    - "God doesn't play dice"
    - "The theory looks like *spooky action at a distance"*, which Einstein doesn't accept
  - Schrodinger describes his cat experiment to show the absurdity of the Copenhagen interpretation
- 1935 – 1964: Much more data to support QM. But none rules out hidden variables.

Heisenberg uncertainty principle (1927)

- It isn’t possible to simultaneously know both the position and velocity of a moving object.
- If you know the object’s position, you can’t know its velocity and vice versa.
- If there are two identical situations where you measure a precise position ‘x’, then each time you measure the velocity ‘v’ you get a different answer. ***You get a probability distribution for ‘v’.***

- This is ‘explained’ by saying that when you try to measure the position, you need to bounce a photon (for example) off the object, so you change its velocity. Etc.
- How can you be sure the situations are identical? Only *if all possible information is the same for both situation.* ***No hidden variables***

Pascual Jordan:

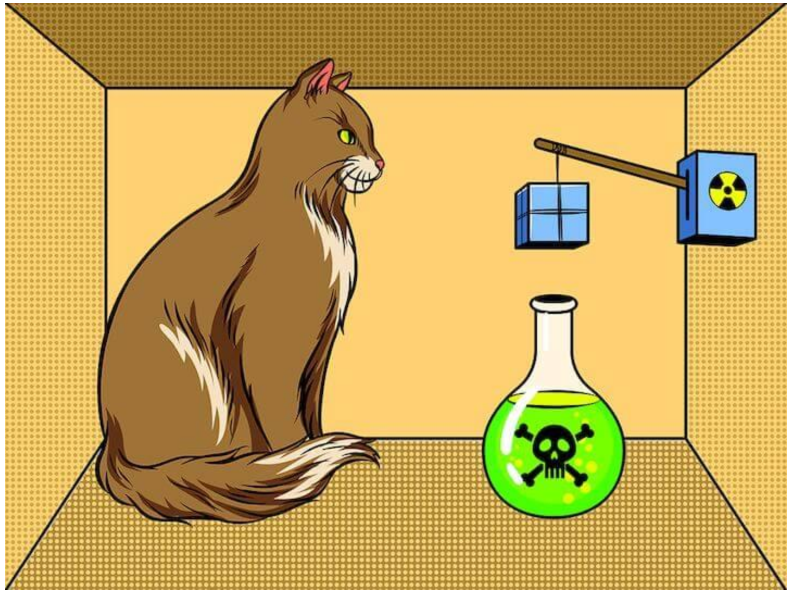
> “Observations not only disturb what has to be measured, they produce it….We compel [the electron] to assume a definite position…. We ourselves produce the results of measurements.”

THESE ‘EXPLANATIONS’ ARE MISLEADING

Schrodinger’s cat

Schrodinger: 1935

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter, there is a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer that shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts.



Doesn’t seem magical to me. More like semantics.

Dybbuk:

https://www.youtube.com/watch?v=EBbxphSNHko

Schrodinger’s cat:

https://www.youtube.com/watch?v=NbzWYjVrvpI

Setting up the Bell gedanken experiment

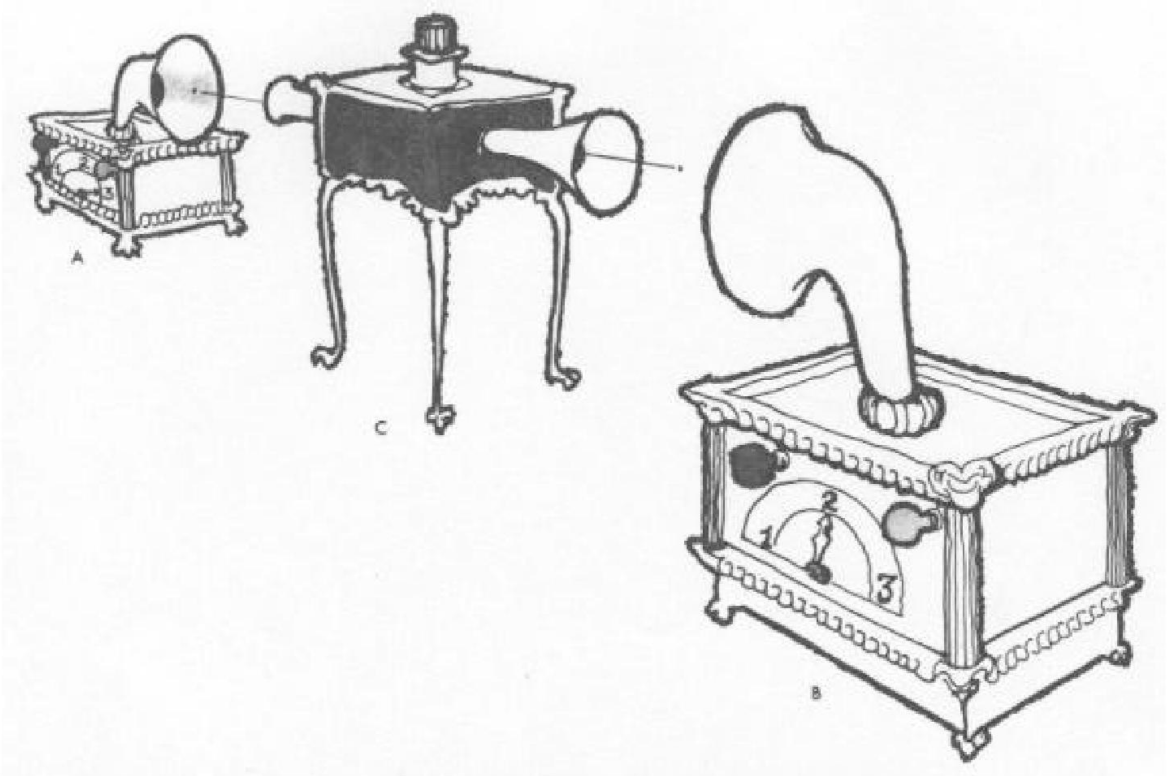
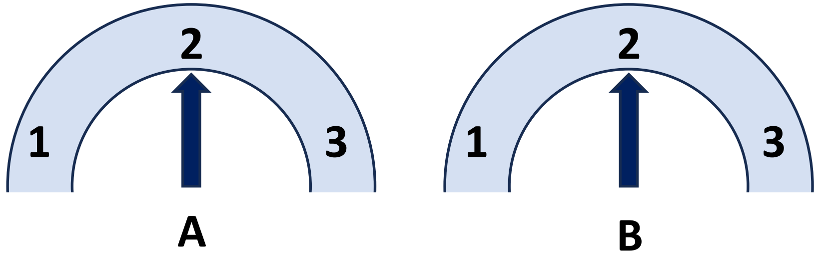


Figure 1 - An EPR apparatus.
The experimental setup consist of two detector, **A** and **B**, and a source of something ("particles" or whatever) **C**. To start a run, the experimenter pushes the button on **C**; something passes from **C** to both detectors. Shortly after the button is pushed each detector flashes one of its lights. Putting a brick between the source and one of the detectors prevents that detectors from flashing, and moving the detectors farther away from the source increases the delay between when the button is pushed and when the lights flash. The switch settings on the detectors vary randomly from one run to another. Note that there are no connections between the three parts of the apparatus, other than via whatever it is that passes from **C** to **A** and **B**.

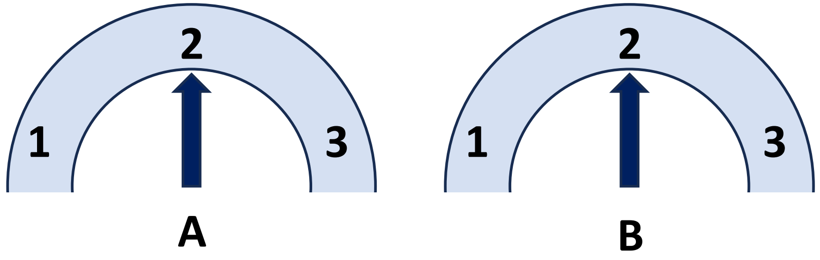
Experiment 1 (habituation): Both detectors set to ‘2’



- Source “C” on my desk
- Detector “A” near the moon
- Detector “B” on the other side of the earth

- Start: Press button at “C”
  - “A” flashes green
  - “B” flashes green
- Do it again: Press button at “C”
  - “A” flashes red
  - “B” flashes red
- Repeat a million times: “A” and “B” flash the same color, but the color is random between red and green.

Experiment 1 (habituation): Both detectors set to ‘2’



Guess the missing color

- Start: Press button at “C”
  - “A” flashes red
  - “B” flashes ?
- Do it again: Press button at “C”
  - “A” flashes ?
  - “B” flashes green
- Do it again: Press button at “C”
  - “A” flashes ?
  - “B” flashes red

Experiment 1: Interpretation

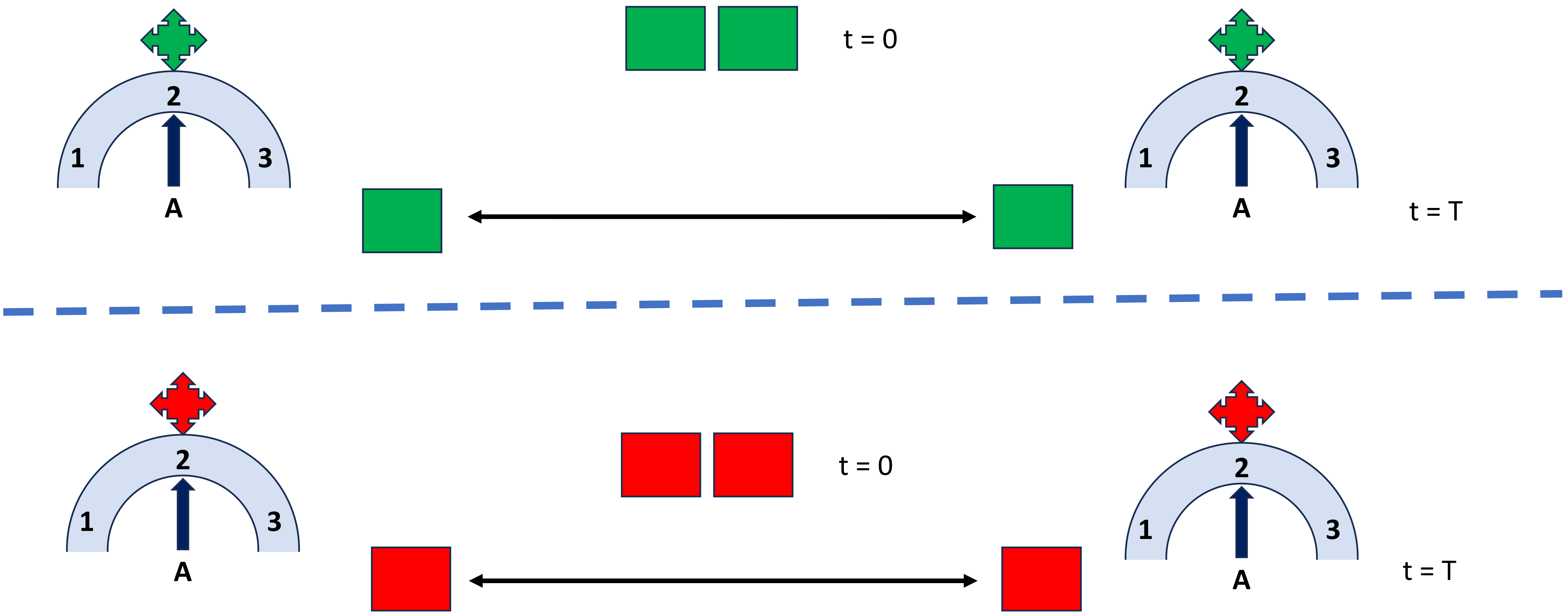
- First possibility (inspired by Heisenberg uncertainty principle) **X**

  Two objects are created and emitted by "C". When the first reaches "A", there is an interaction and "A" flashes red ***and also*** sends a signal to "B" so that "B" flashes red. Etc.

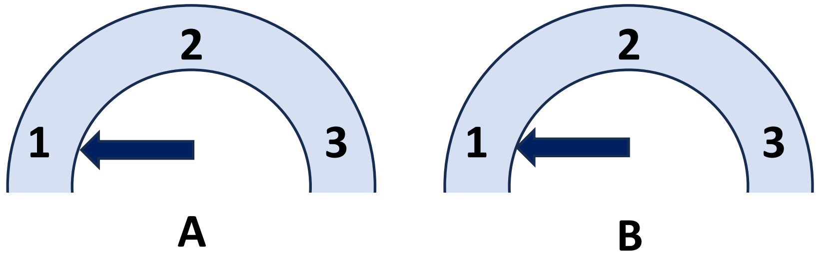
- Problem: **Information can't travel faster than light**

- Second possibility
  - Two objects are created by "C". Each carries the same information as the other.
  - The information determines the color of the detector.

Experiment 1: Predictions of *Second Possibility*



Experiment 2 (habituation): Both detectors set to ‘1’



- Start: Press button at “C”
  - “A” flashes red
  - “B” flashes red
- Do it again: Press button at “C”
  - “A” flashes red
  - “B” flashes red
- Do it again: Press button at “C”
  - “A” flashes green
  - “B” flashes green
- Repeat a million times: “A” and “B” flash the same color, but the color is random between red and green.

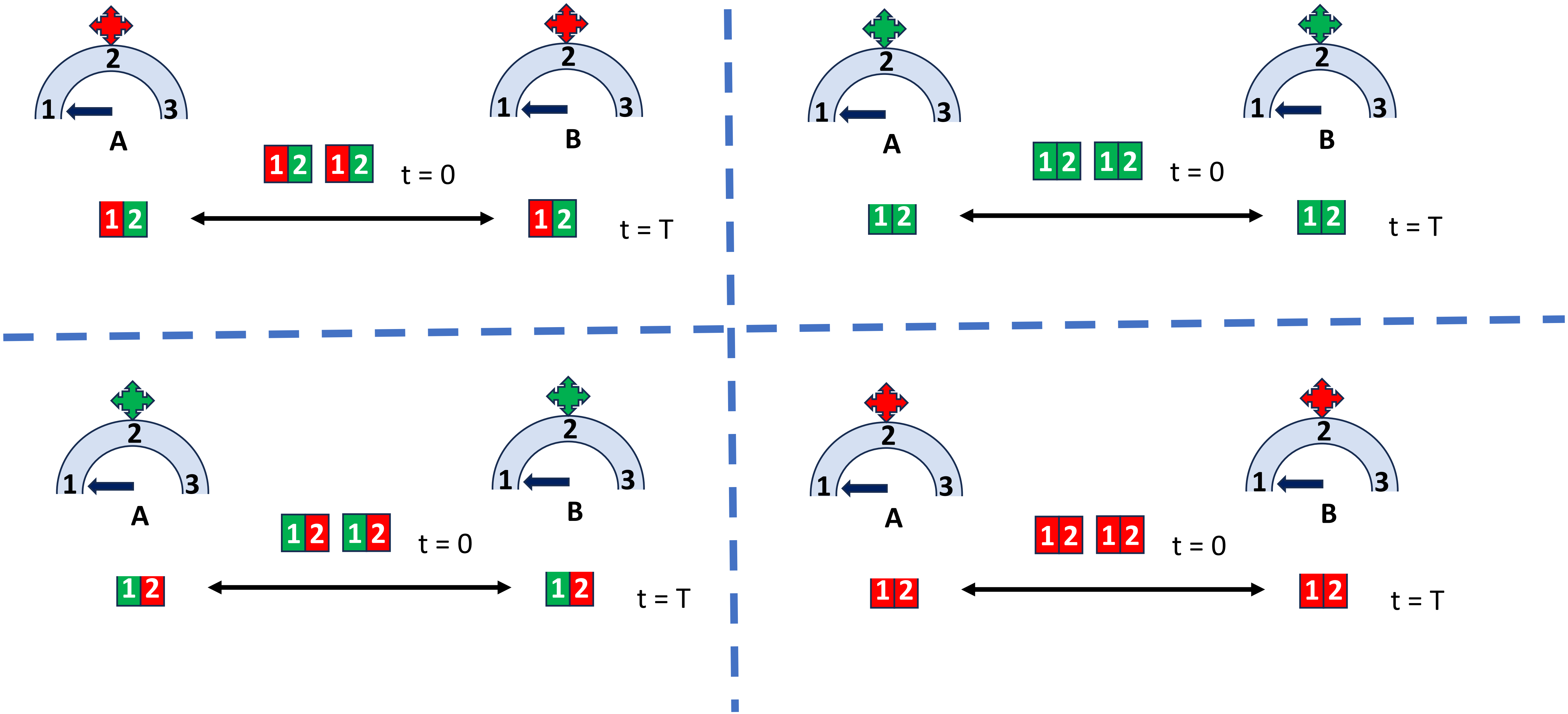
Experiment 2: Interpretation

- First possibility (same as before)

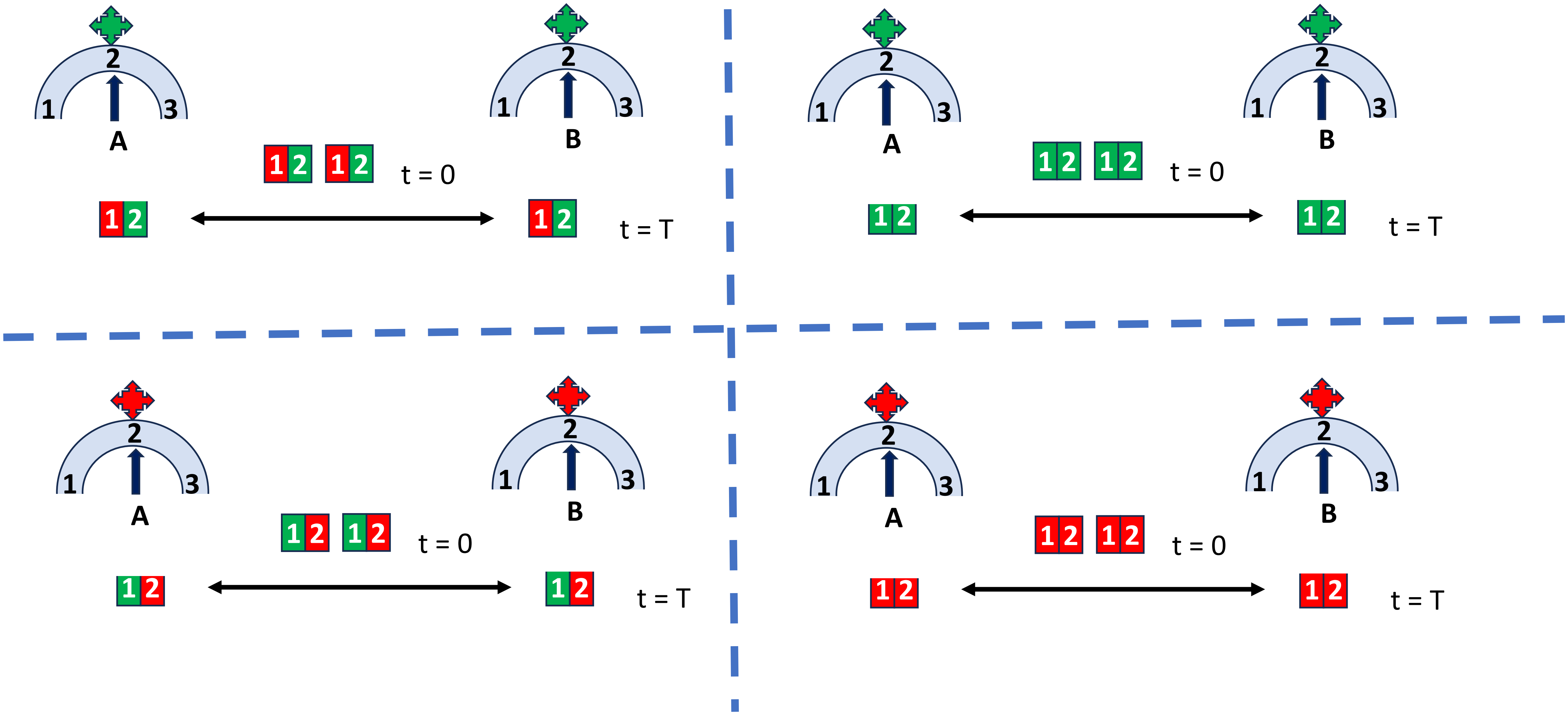
  Two objects are created by “C”. Each carries the same information as the other. The information determines the color of the detector.

- Second possibility
  - Two objects are created by “C”. Each carries the same information as the other.
  - However, each object now carries information for position 1 **and** information for position 2. The information for position 1 determines the color flashed in position 1 and the information for position 2 determines the color for position 2.

Experiment 2: Predictions of *Second Possibility*

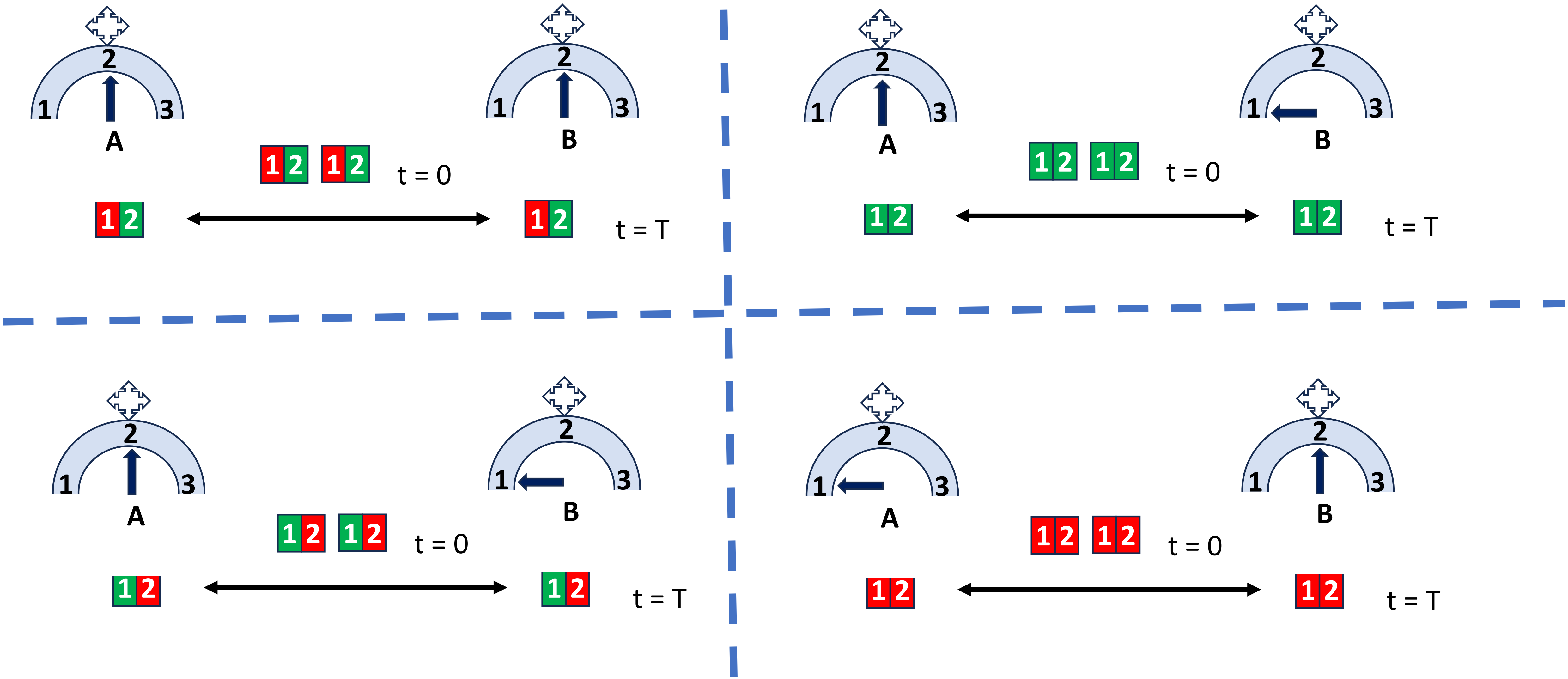


Experiment 2: More Predictions of *Second Possibility*



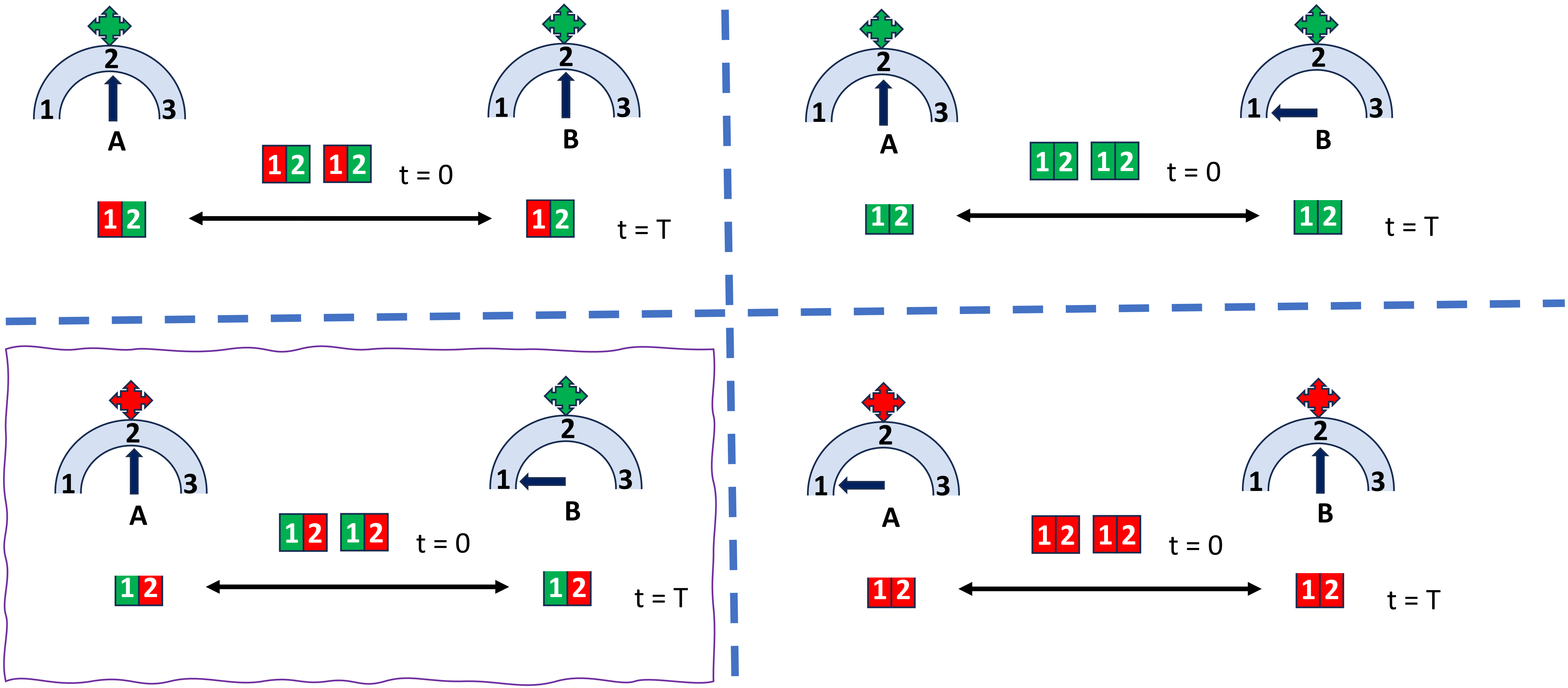
Experiment 3: Predictions of *Second Possibility*

Fill in the missing colors!



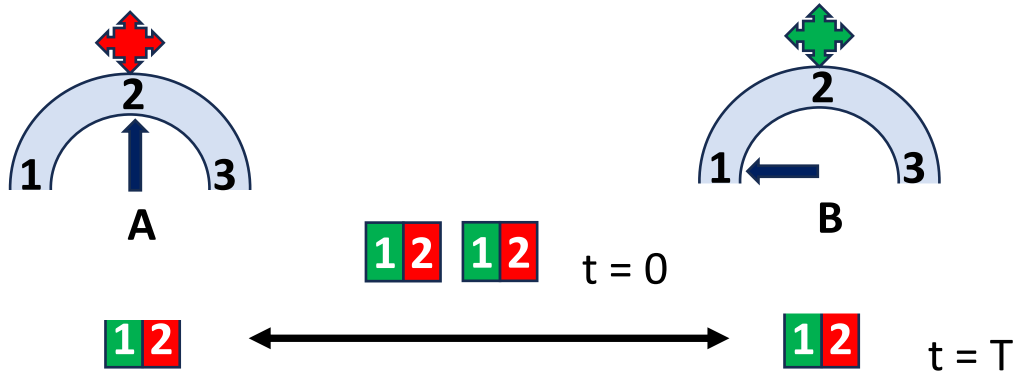
Experiment 3: More Predictions of *Second Possibility*

Answer



These are different colors. Not permitted with *first possibility.*

Experiment 3: Comment



- Sometimes when detectors are in *different positions,* they flash different colors
- So far, we don’t know how often that happens

Experiment 3: The Bell Chart *... fill in the blanks*

Y = 'both colors the same'
N = 'both colors different'

1 2

	A / 1	A/2
B /1	?	?
B/2	?	?

1 2

	A / 1	A/2
B /1	?	?
B/2	?	?

1 2

	A / 1	A/2
B /1	?	?
B/2	?	?

1 2

	A / 1	A/2
B /1	?	?
B/2	?	?

Experiment 3: The Bell Chart *… answer*

- For each particle color-pair, randomly set the positions of detectors A and B.
- P(Y) is the probability that both detectors flash the same color.

1 2

	A / 1	A/2
B /1	Y	Y
B/2	Y	Y

P(Y) = 4/4 = 1.0

1 2

	A / 1	A/2
B /1	Y	Y
B/2	Y	Y

P(Y) = 4/4 = 1.0

1 2

	A / 1	A/2
B /1	Y	N
B/2	N	Y

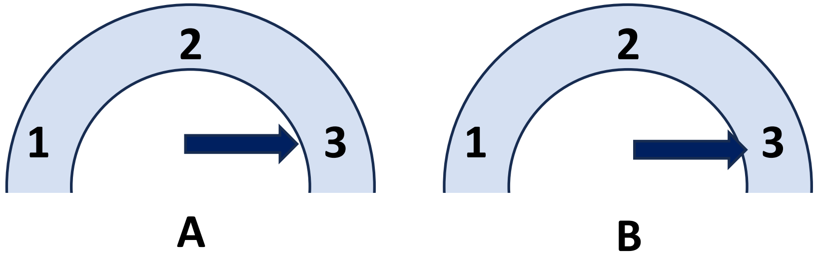
P(Y) = 2/4 = 0.5

1 2

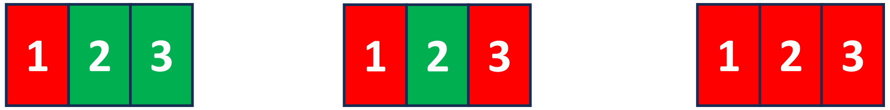
	A / 1	A/2
B /1	Y	N
B/2	N	Y

P(Y) = 2/4 = 0.5

Next Experiments – highlights



- Habituation: Both detectors at position 3.
  - As before, both flash the same color.
- Interpretation:
  - Two objects are created by "C". Each carries the same information as the other.
  - However, each object now carries information for position 1 **and** information for position 2 **and** information for position 3. The information for position 1 determines the color flashed in position 1, the information for position 2 determines the color for position 2, **and** the information for position 3 determines the color for position 3.
  - Examples:



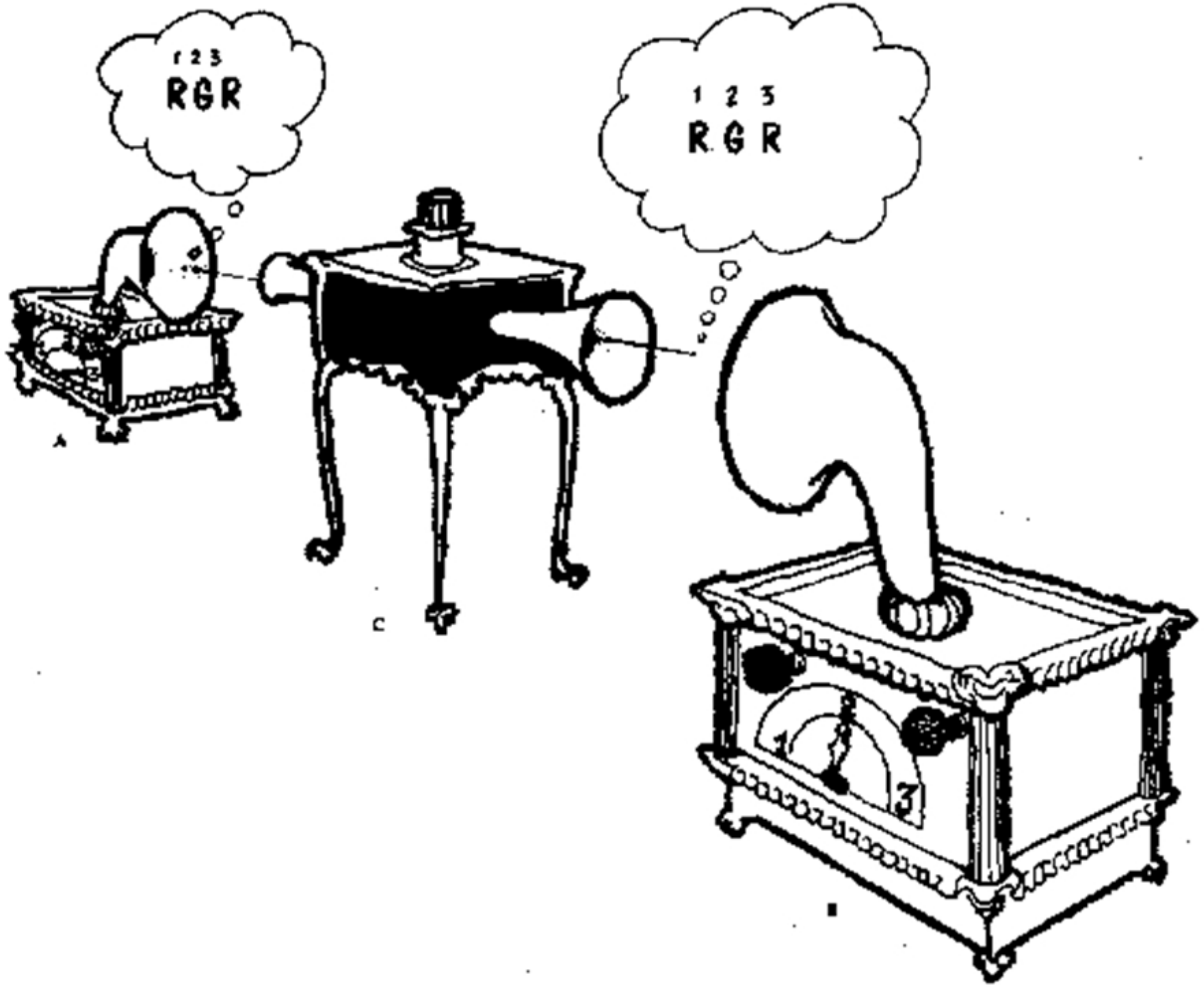
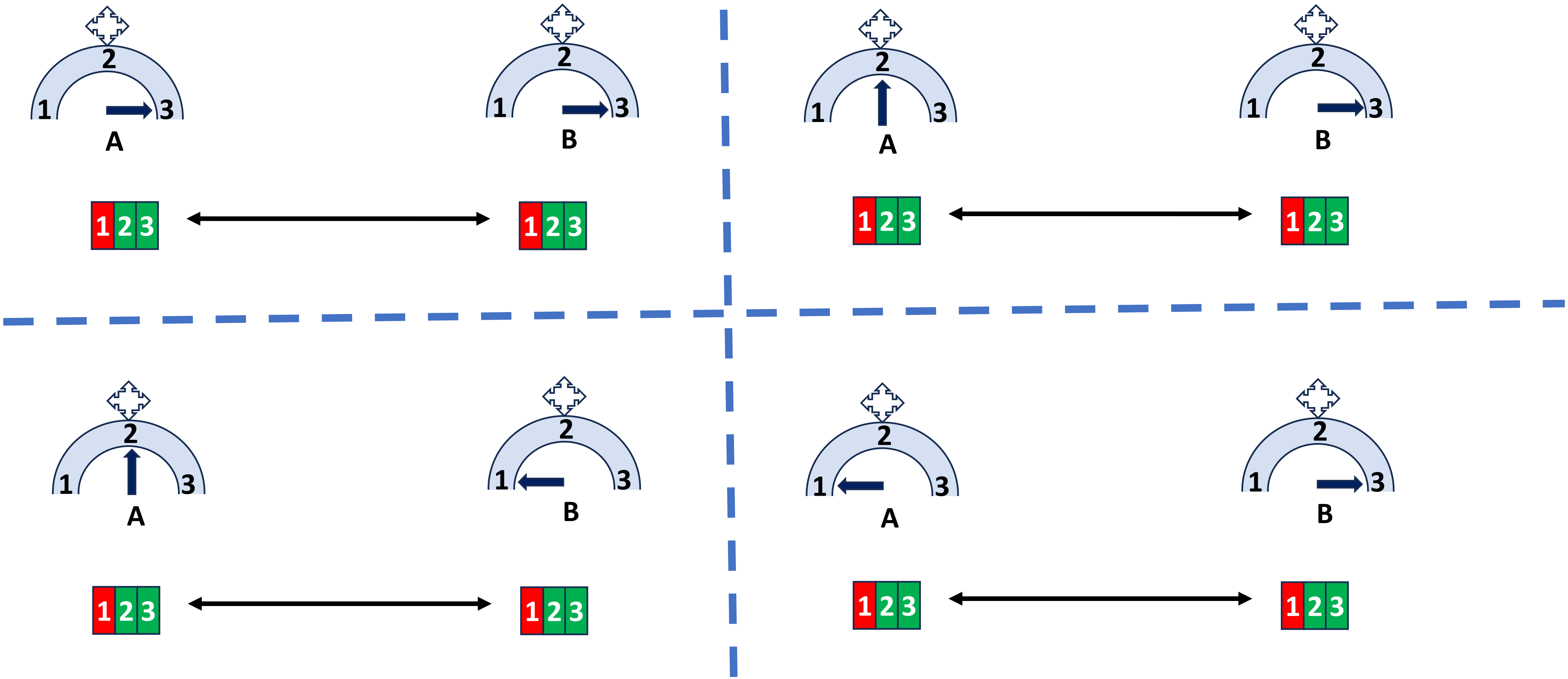


Figure 7 – Instruction sets.
To guarantee that the detectors of figure 6 flash the same color when the switches are set the same, the two particles must in one way or another carry instruction sets specifyng how their detectors are to flash for each possible switch setting. The results of any one run reveal nothing about the instructions beyond the actual data; so in this case, for example, the first instruction (1R) is “something one cannot know anything about”, and I’ve only guessed at it, assuming that “it exists all the same”.

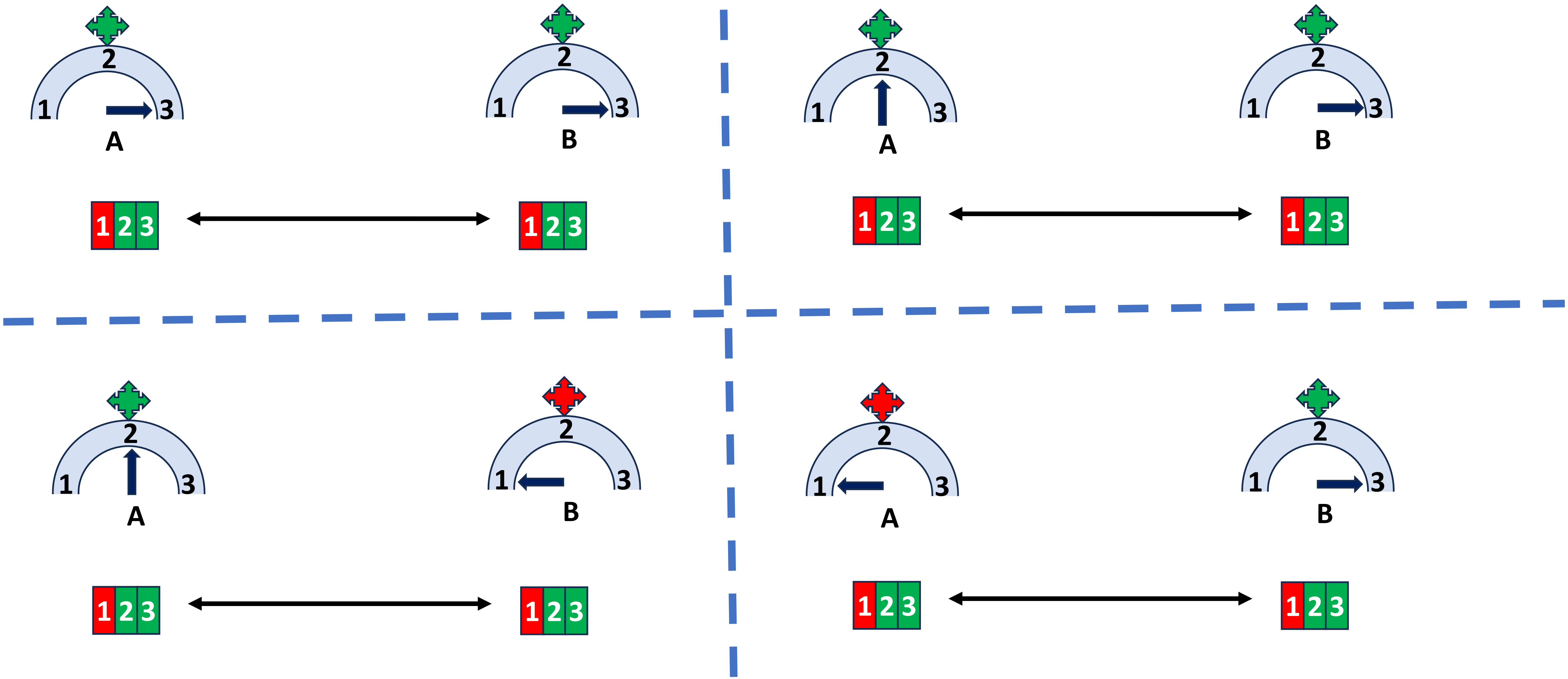
Next experiment: Some Predictions

Fill in the missing colors!



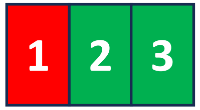
Next experiment: Some Predictions

Answers

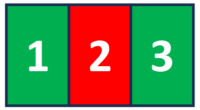


The Full Bell Chart *… fill in the blanks*

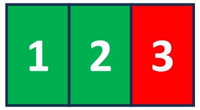
Y = 'both colors the same'
N = 'both colors different'



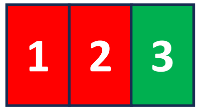
	A/1	A/2	A/3
B/1	?	?	?
B/2	?	?	?
B/3	?	?	?



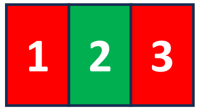
	A/1	A/2	A/3
B/1	?	?	?
B/2	?	?	?
B/3	?	?	?



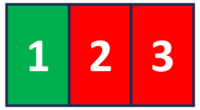
	A/1	A/2	A/3
B/1	?	?	?
B/2	?	?	?
B/3	?	?	?



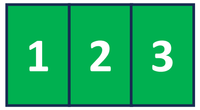
	A/1	A/2	A/3
B/1	?	?	?
B/2	?	?	?
B/3	?	?	?



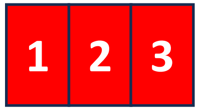
	A/1	A/2	A/3
B/1	?	?	?
B/2	?	?	?
B/3	?	?	?



	A/1	A/2	A/3
B/1	?	?	?
B/2	?	?	?
B/3	?	?	?



	A/1	A/2	A/3
B/1	?	?	?
B/2	?	?	?
B/3	?	?	?



	A/1	A/2	A/3
B/1	?	?	?
B/2	?	?	?
B/3	?	?	?

The Full Bell Chart *… answers*

- For each particle color-pair, randomly set the positions of detectors A and B.
- P(Y) is the probability that both detectors flash the same color.

1 2 3

P(Y) = 5/9

	A/1	A/2	A/3
B/1	Y	N	N
B/2	N	Y	Y
B/3	N	Y	Y

1 2 3

P(Y) = 5/9

	A/1	A/2	A/3
B/1	Y	N	Y
B/2	N	Y	N
B/3	Y	N	Y

1 2 3

P(Y) = 5/9

	A/1	A/2	A/3
B/1	Y	Y	N
B/2	Y	Y	N
B/3	N	N	Y

1 2 3

P(Y) = 5/9

	A/1	A/2	A/3
B/1	Y	Y	N
B/2	Y	Y	N
B/3	N	N	Y

1 2 3

P(Y) = 5/9

	A/1	A/2	A/3
B/1	Y	N	Y
B/2	N	Y	N
B/3	Y	N	Y

1 2 3

P(Y) = 5/9

	A/1	A/2	A/3
B/1	Y	N	N
B/2	N	Y	Y
B/3	N	Y	Y

1 2 3

P(Y) = 9/9

	A/1	A/2	A/3
B/1	Y	Y	Y
B/2	Y	Y	Y
B/3	Y	Y	Y

1 2 3

P(Y) = 9/9

	A/1	A/2	A/3
B/1	Y	Y	Y
B/2	Y	Y	Y
B/3	Y	Y	Y

Bell's Theorem

P(Y) ≥ 5/9

The results of the Bell gedanken experiment

- Of course, the point of a gedanken experiment is that you can’t do it.
- However, the experiment of Aspect et al. had all the key features of the Bell gedanken experiment.
- The Bell prediction is $P(Y) \geq 5/9$.
- The Aspect experiment finds $P(Y) \sim 1/2$.
- This violates the Bell inequality. **Quantum mechanics is *real* magic, not a magic trick.**

Recent history of quantum magic

- 1964: John Bell describes a class of experiments that can rule out hidden variables.
- 1964 – today: Aspect and others do the experiments and confirm they can't be explained by hidden variables. **i.e. the magic can't be done using a trick!**
- Regarded as a refutation of Einstein's statement that "*QM is necessarily an incomplete description of nature*"
- The phenomenon of correlations between apparently non-communicating particles is called **quantum entanglement.**

Quotation from Richard Feynman

We have always had a great deal of difficulty
understanding the world view
that quantum mechanics represents.

At least I do,
because I'm an old enough man
that I havent' got to the point
that this stuff is obvious to me.

Okay, I still get nervous with it….

You know how it always is,
every new idea,
it takes a generation or two
until it becomes obvious
that there's no real problem.

I cannot define the real problem,

therefore I suspect there's no real problem,
but I'm not sure
there's no real problem.