Could  have been right after all?

Gilles Brassard

Université de Montréal

Paul Raymond-Robichaud

ISI, Torino

Solstice of Foundations, ETH-Hönggerberg, 20 June 2019

Quantum theory can be local and realistic

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The New York Times | http://nyti.ms/1OIO2WJ

SCIENCE

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By JOHN MARKOFF OCT. 21, 2015

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Einstein-Podolsky-Rosen

Albert Einstein

Boris Podolsky

Nathan Rosen

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

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MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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Realism

The New York Times | http://nyti.ms/1OIO2WJ

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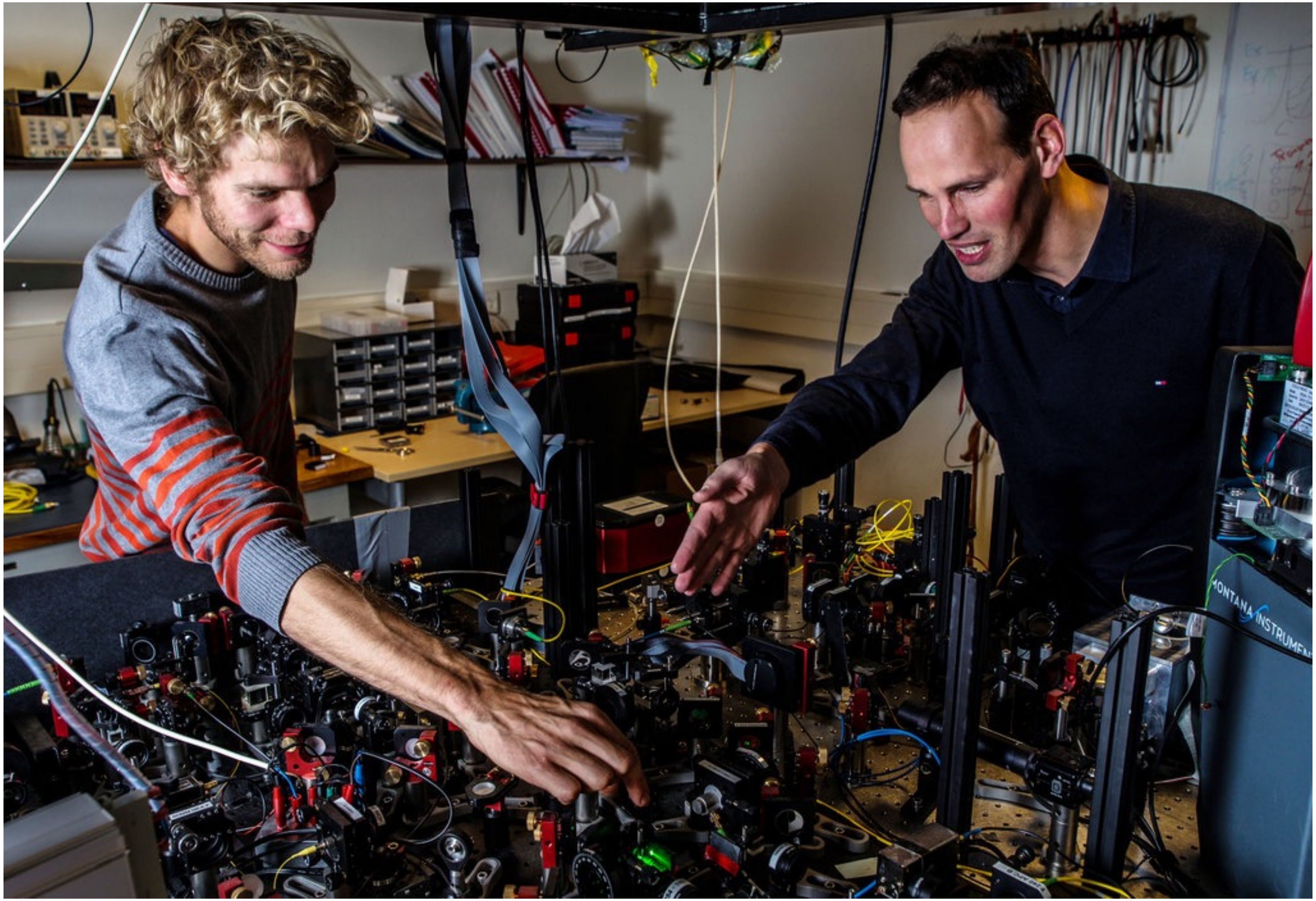
MONTANA

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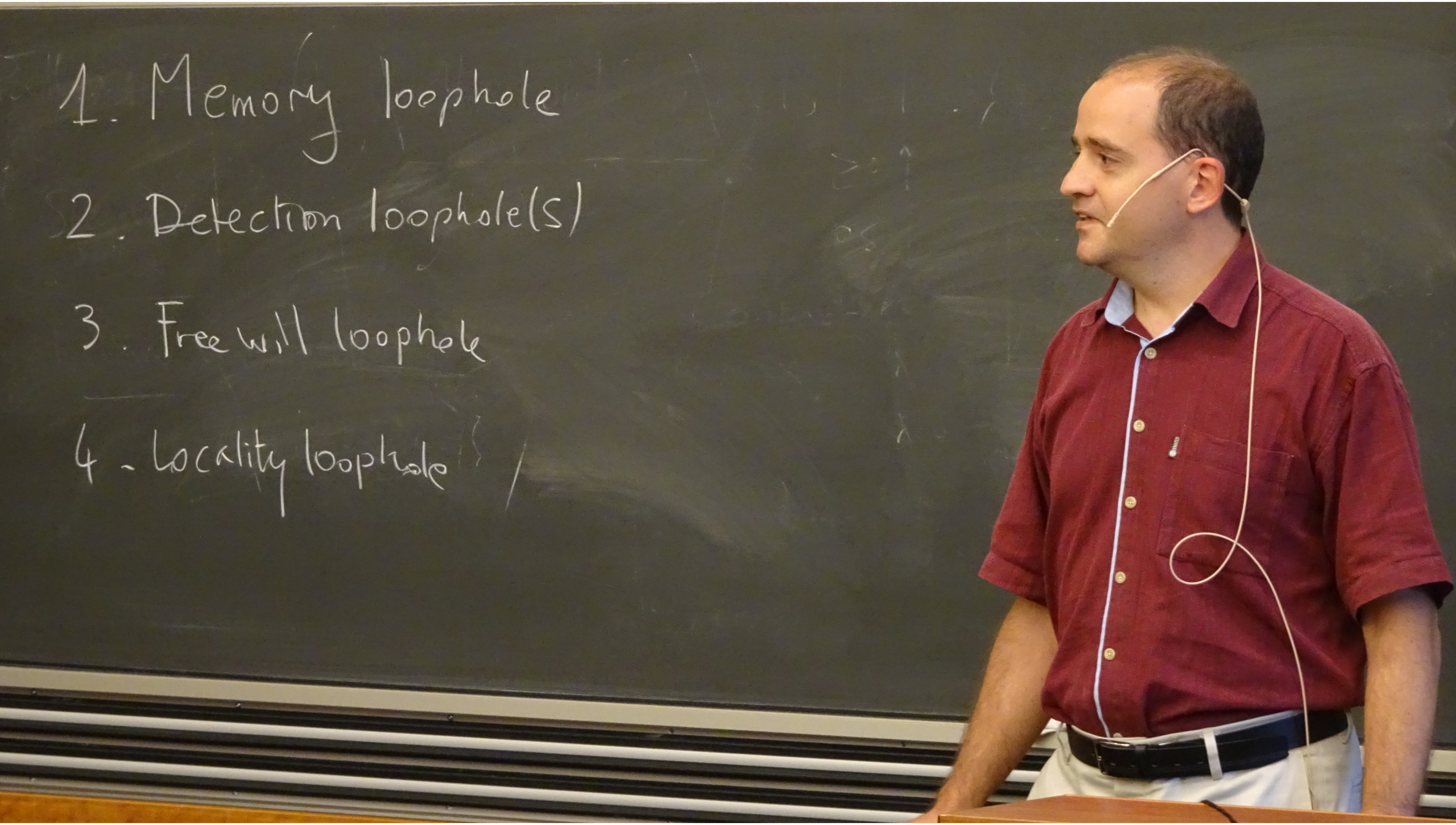
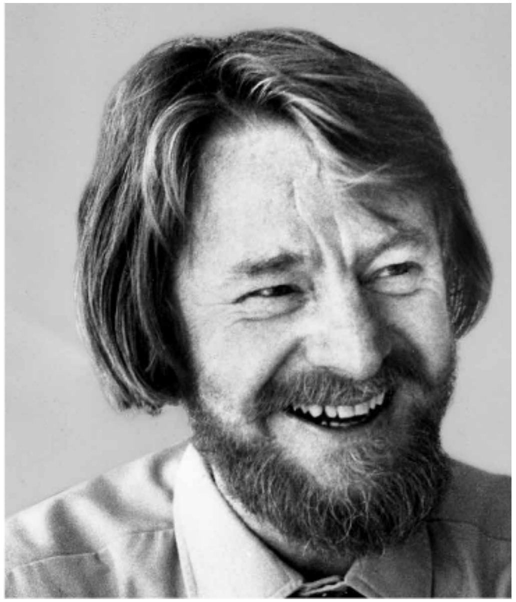

1. Memory loophole
2. Detection loophole(s)
3. Free will loophole
4. Locality loophole



John Bell

John Bell

Theorem: It is impossible for Nature to be local-realistic

John Bell

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(assuming quantum mechanics is correct in its observable predicitions)

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Theorem: It is impossible for Nature to be local-realistic (assuming quantum mechanics is correct in its observable predicitions)

What is proved by impossibility proofs is lack of imagination

John Bell

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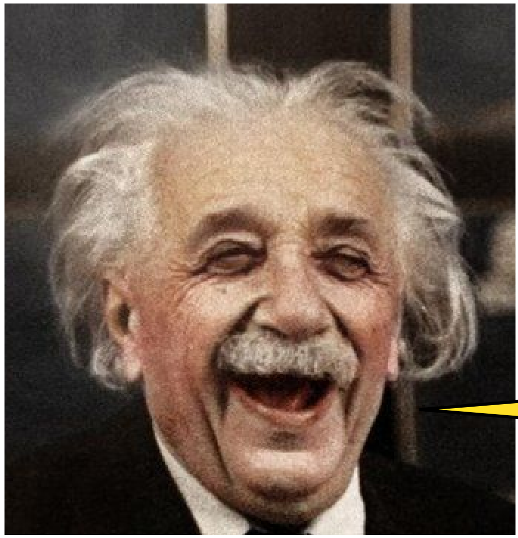

I am enough of the artist to draw freely upon my imagination.

Imagination is more important than knowledge.

For knowledge is limited, whereas imagination encircles the world.

1929

The usual argument

against local realism

The usual argument

against local realism

1. Quantum theory cannot be described by local hidden variables.

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* There exists an objectively real physical world, independent of observers (Matthew Leifer, this morning)

A theory can be

A theory can be

Local

A theory can be

Realistic

Local

A theory can be

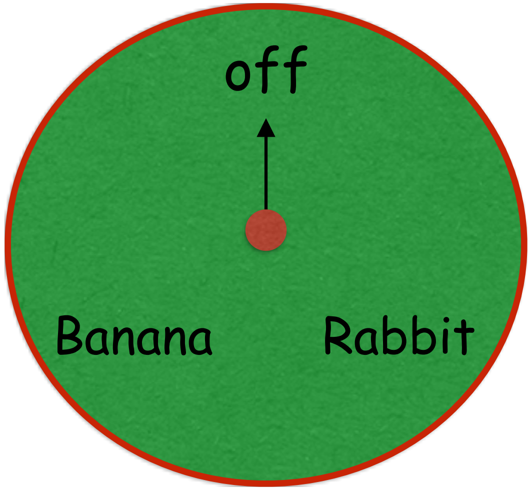
Realistic

Local

Non-Signalling

Signalling Theory

Signalling Theory



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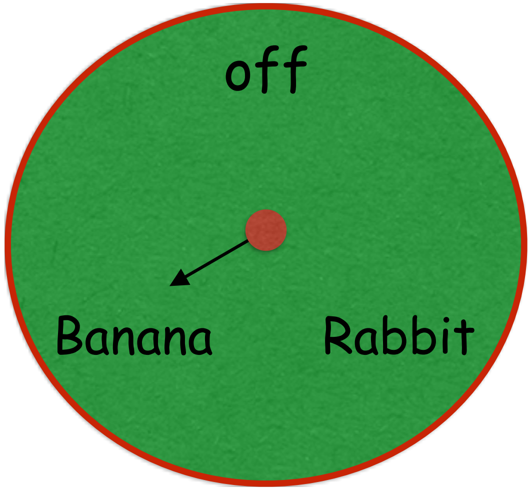

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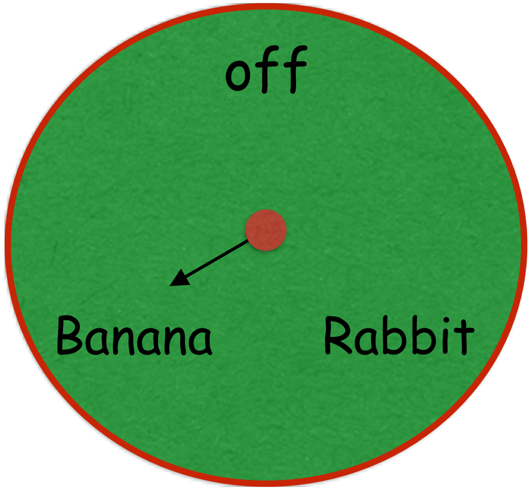

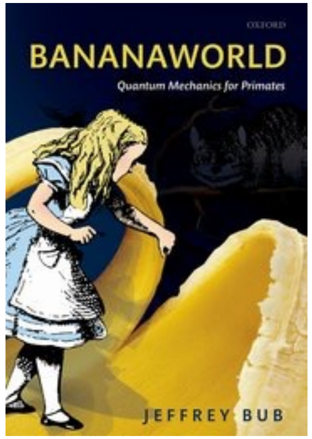

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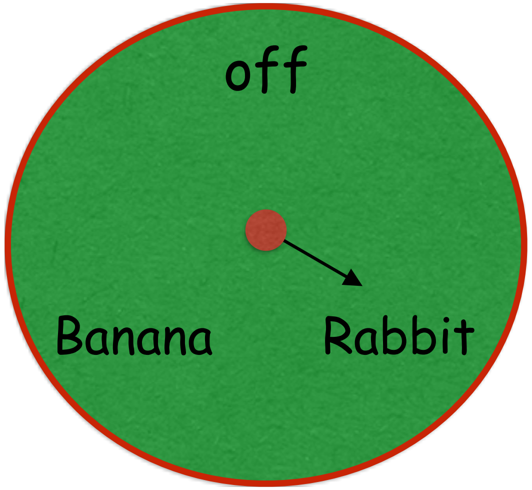

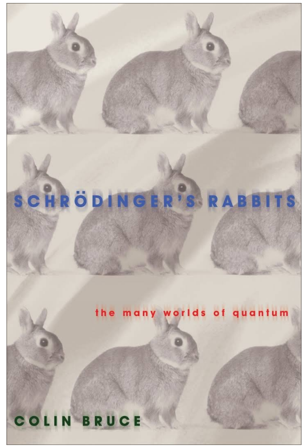

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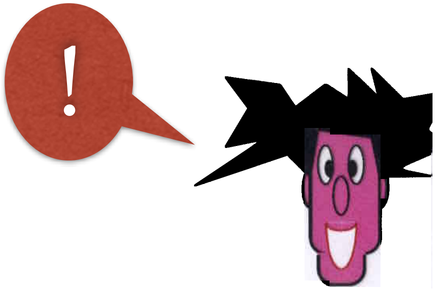
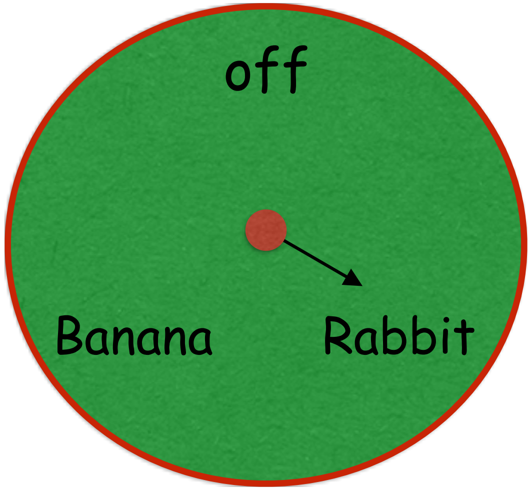
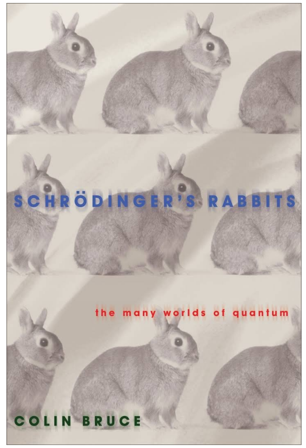
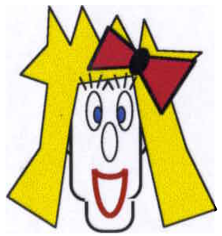
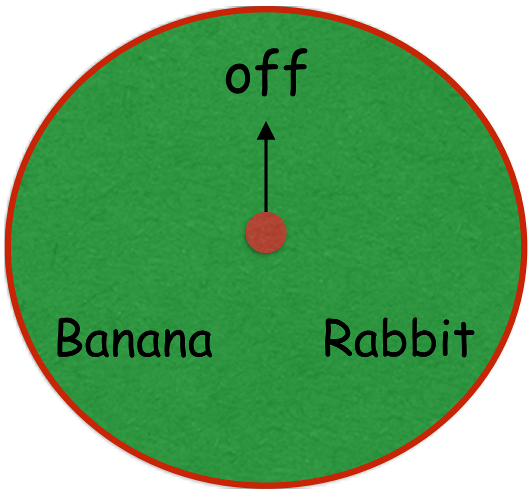






Non-Signalling Theory





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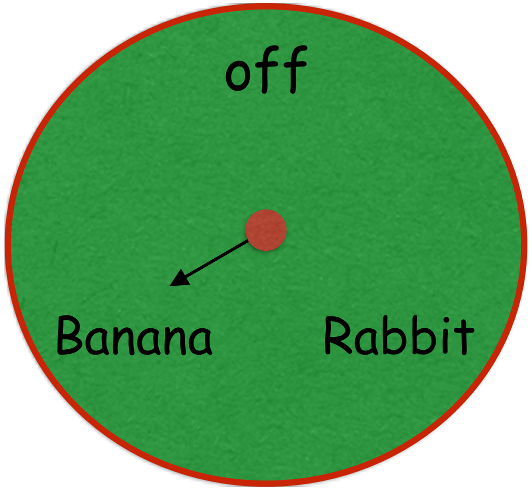

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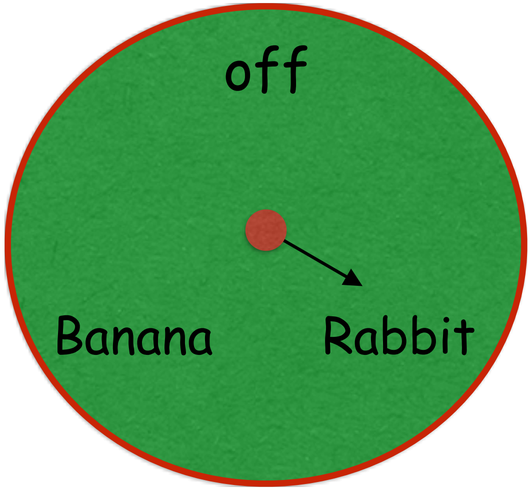

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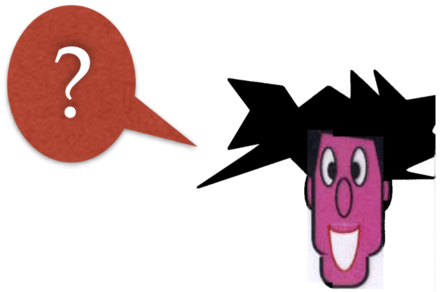

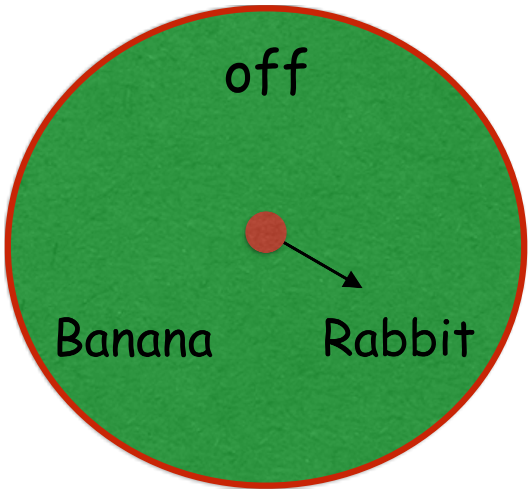

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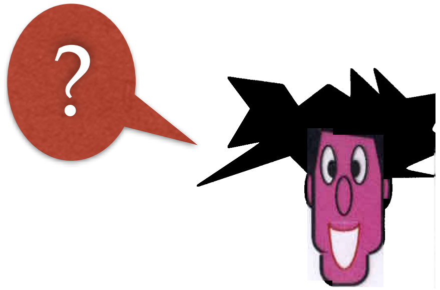
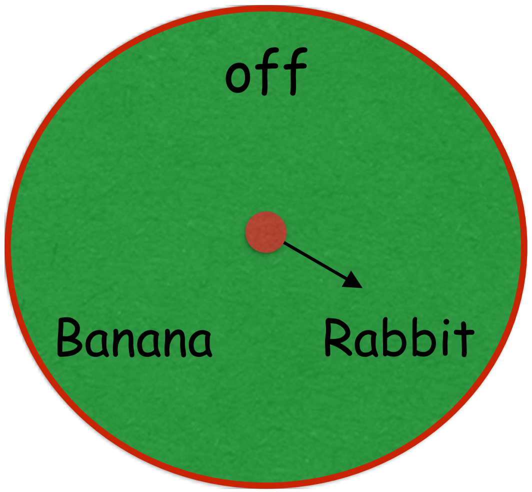
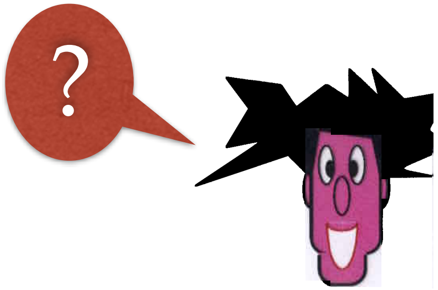
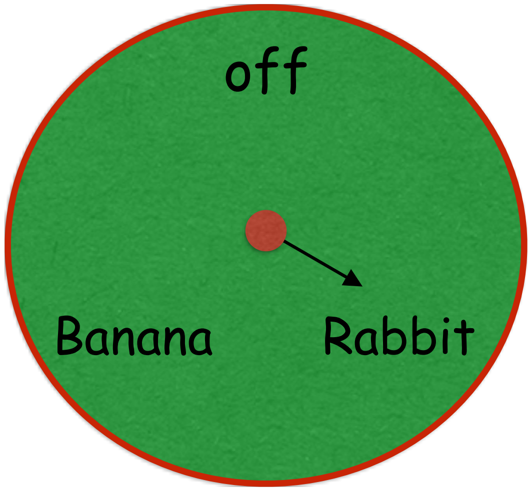




Spooky?

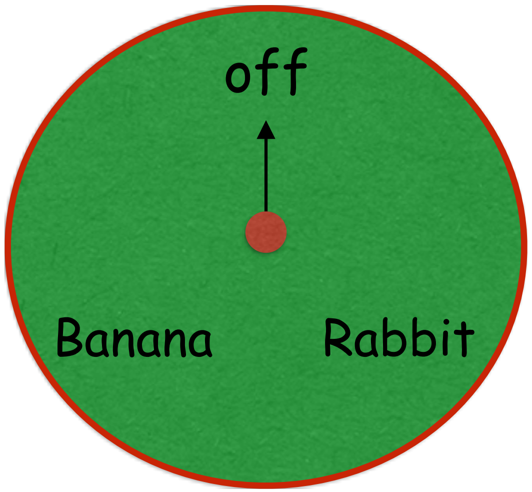
Non-Signalling Theory





This is the case of Quantum theory!

Local Theory



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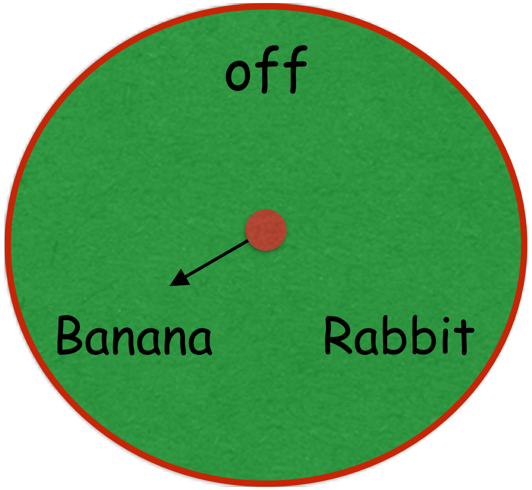

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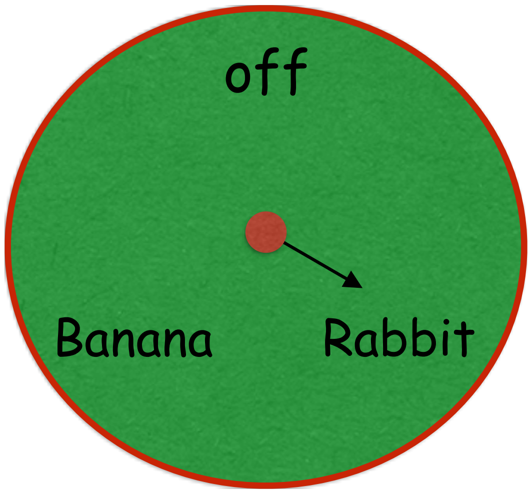

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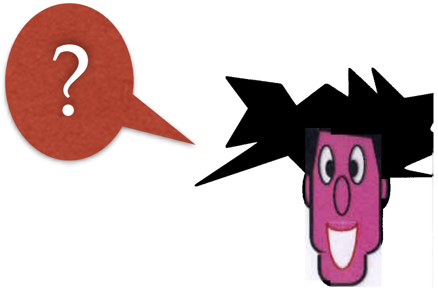

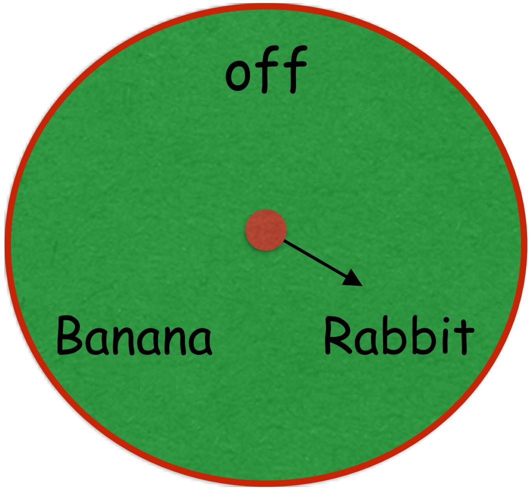

A theory can be

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Platonic / Kantian View

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Noumenal world

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Noumenal world

The objectively *real* physical world:
All that there is

Platonic / Kantian View

Noumenal world

The objectively *real* physical world: All that there is

Phenomenal world

Platonic / Kantian View

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The world of *perceptions*:

Platonic / Kantian View

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The world of *perceptions*:
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Platonic / Kantian View

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Platonic / Kantian View

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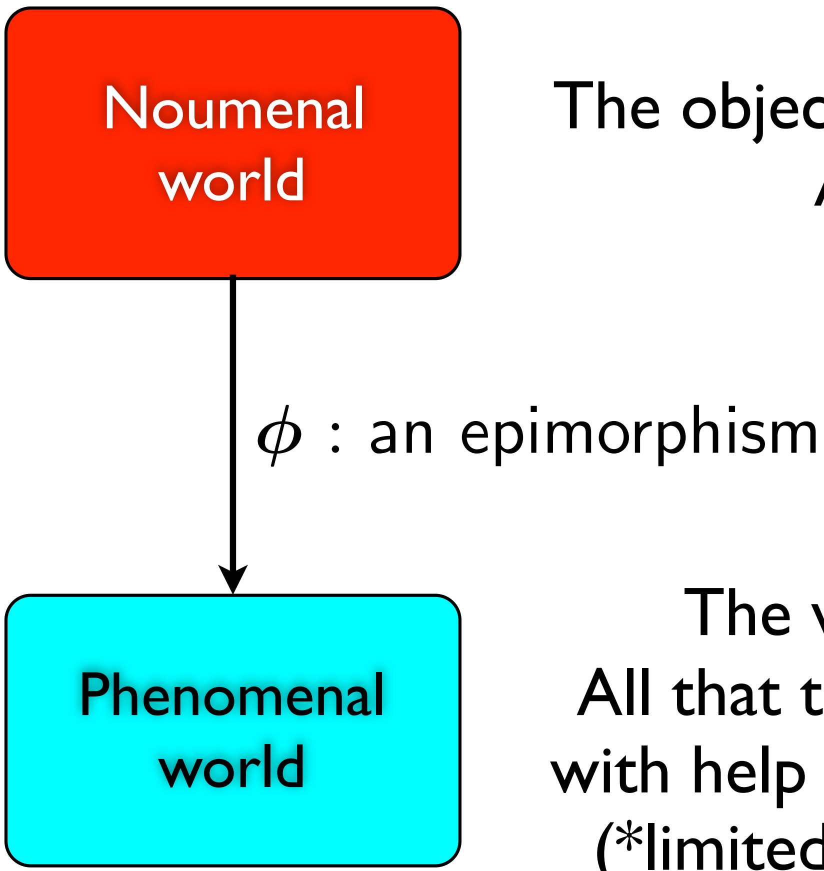
Platonic / Kantian View



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Platonic / Kantian View

$$\begin{tikzcd} \text{Noumenal world} \arrow[d, "\phi\ :\ \text{an epimorphism}"] \\ \text{Phenomenal world} \end{tikzcd}$$

Noumenal world: The objectively *real* physical world:
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ϕ : an epimorphism

Realm of
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Phenomenal world: The world of *perceptions*:
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Platonic / Kantian View

Realm of Philosophers

Noumenal world

The objectively *real* physical world:
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$$\text{Noumenal world} \xrightarrow{\phi\ :\ \text{an epimorphism}} \text{Phenomenal world}$$

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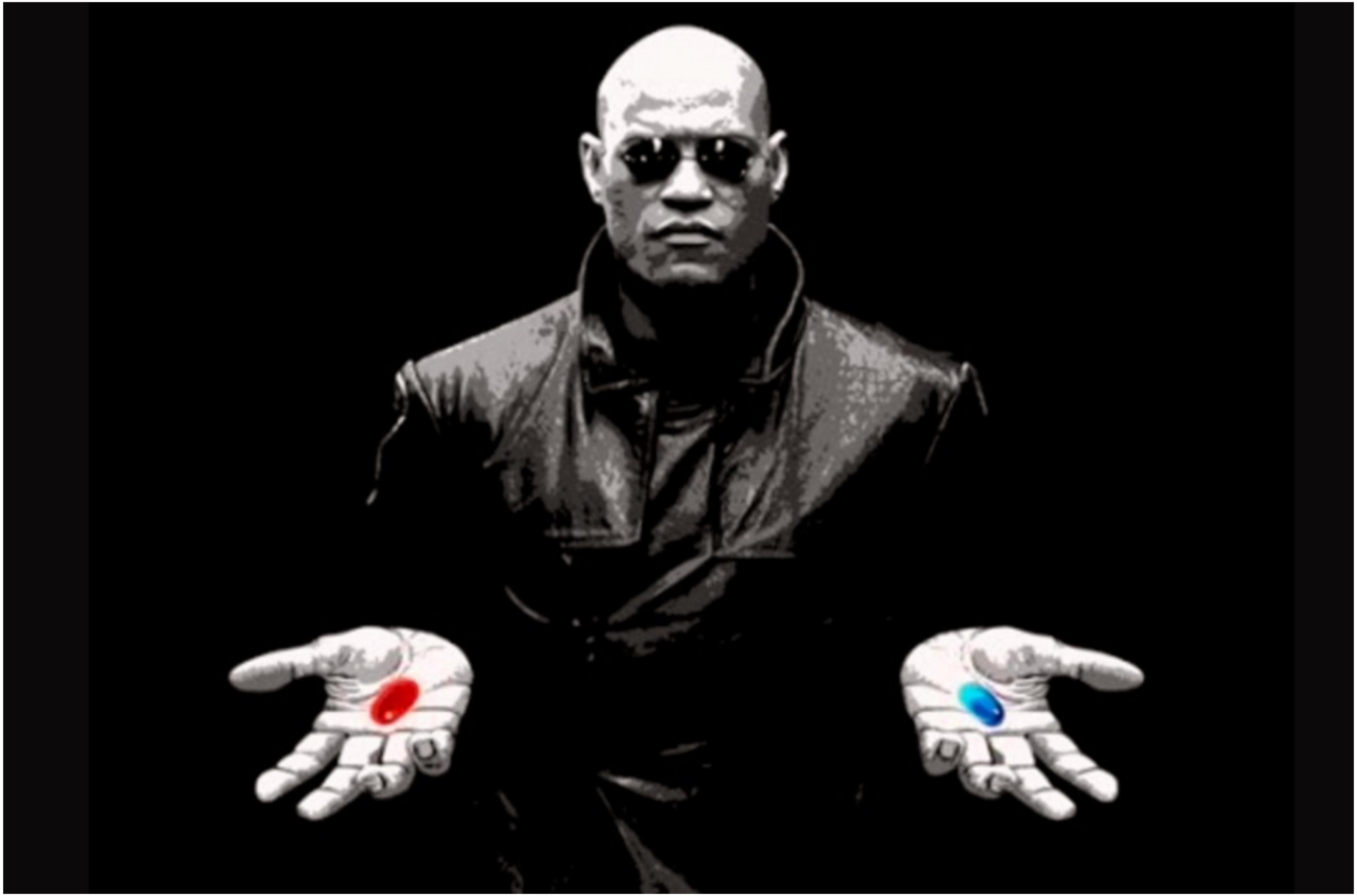

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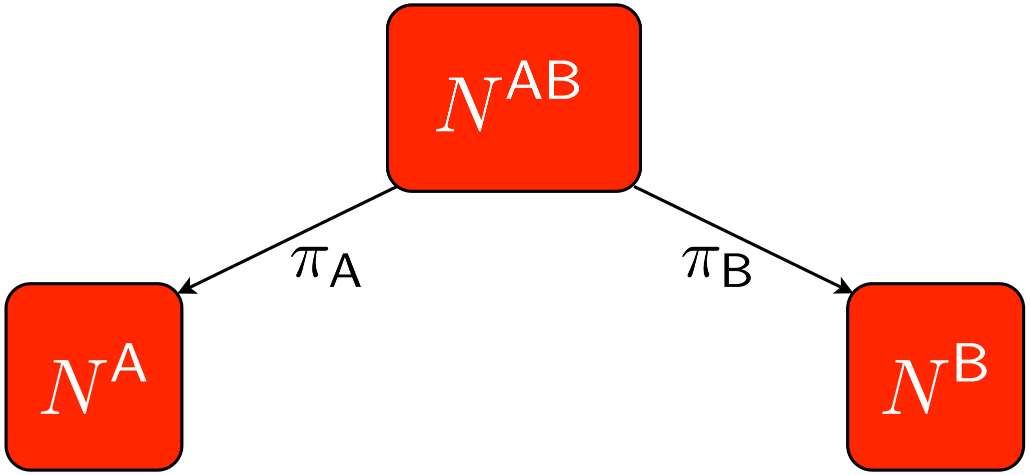
Splitting and Joining in a Local Universe

N^{AB}

Splitting and Joining in a Local Universe



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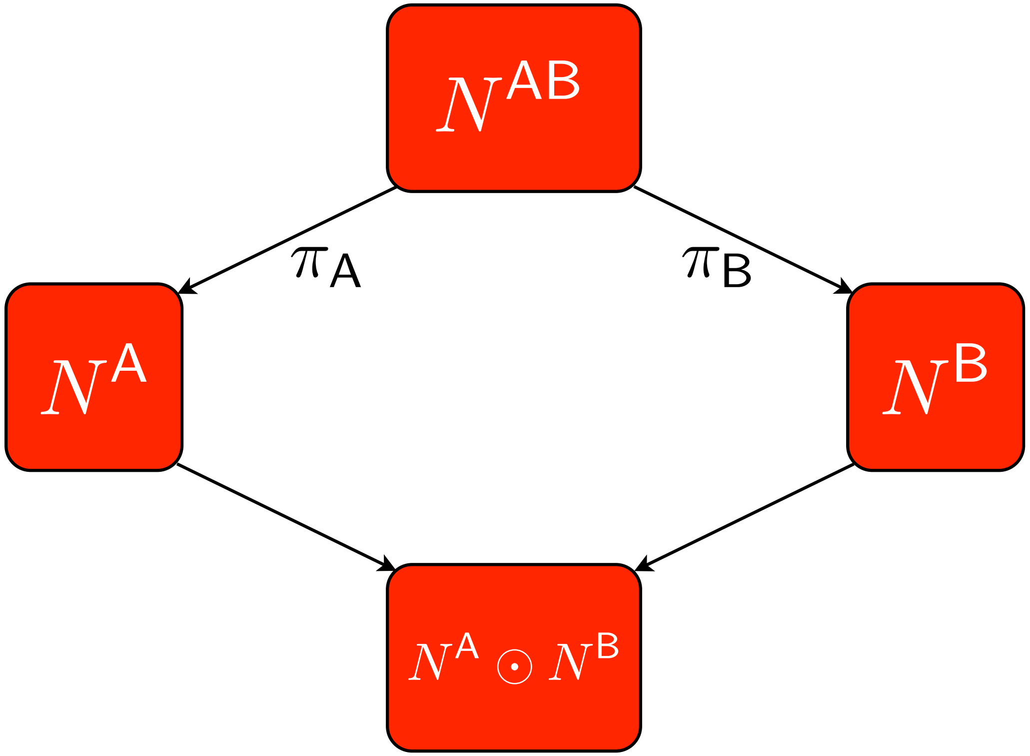

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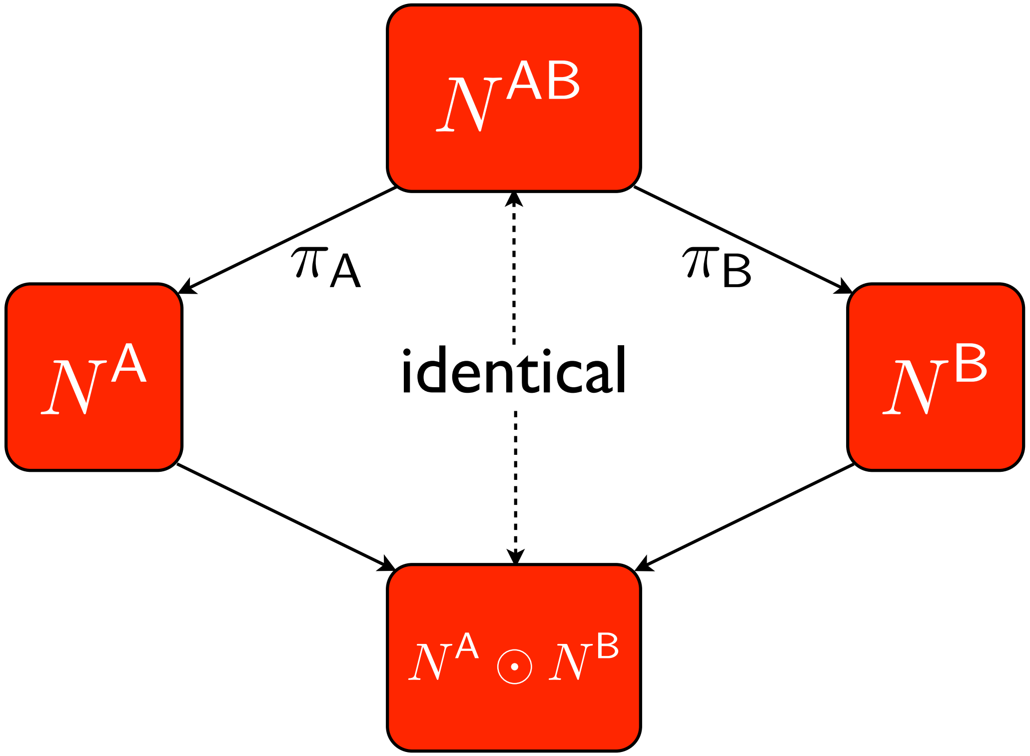

Splitting and Joining in a Local Universe

$$
\begin{tikzcd}
 & N^{\mathrm{AB}} \arrow[dl, "\pi_{\mathrm{A}}"] \arrow[dr, "\pi_{\mathrm{B}}"] \arrow[dd, leftrightarrow, dotted, "\text{identical}" description] & \\
N^{\mathrm{A}} \arrow[dr] & & N^{\mathrm{B}} \arrow[dl] \\
 & N^{\mathrm{A}} \odot N^{\mathrm{B}} &
\end{tikzcd}
$$

Not possible at the phenomenal level in quantum theory!

Principles

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Principle of **realism**: There is a real world whose state determines the outcome of all observations.

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Theorem: Local realism implies non-signalling.

Two Theorems

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1) All local-realistic theories are non-signalling.

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Proof:

$$
\begin{aligned}
&\pi_{\mathsf{A}}\Big(\,(U \times V)\,(\rho^{\mathsf{AB}})\Big)\\
&= \pi_{\mathsf{A}}\Big((U \times V)\big(\varphi(N^{\mathsf{AB}})\big)\Big)\\
&= \pi_{\mathsf{A}}\Big(\varphi\Big(\,(U \times V)\,(N^{\mathsf{AB}})\,\Big)\Big)\\
&= \varphi\Big(\pi_{\mathsf{A}}\Big(\,(U \times V)\,(N^{\mathsf{AB}})\,\Big)\Big)\\
&= \varphi\big(U\big(\pi_{\mathsf{A}}\big(N^{\mathsf{AB}}\big)\big)\big)\\
&= \varphi\big(U\big(N^{\mathsf{A}}\big)\big)\\
&= U\big(\varphi\big(N^{\mathsf{A}}\big)\big)\\
&= U\big(\rho^{\mathsf{A}}\big)\\
&= U\big(\pi_{\mathsf{A}}\big(\rho^{\mathsf{AB}}\big)\big)
\end{aligned}
$$

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2) All non-signalling theories are local-realistic.

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How could this be?

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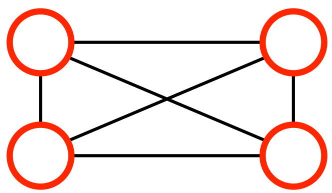

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Standard quantum theory is non-signalling,
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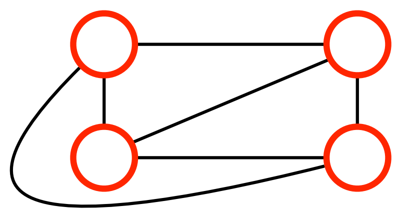

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But… doesn't Bell's Theorem precludes this?

John Bell

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(assuming quantum mechanics is correct in its observable predicitions)

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According to *La Nouvelle Cuisine* (1990)
not his original 1964 paper

John Bell

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That's different!

Local hidden variables is not the only way to be local and realistic

Another Local-Realistic Way?

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Two keys towards a solution:

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Smells of Everett's Many-Worlds?

Third Theorem

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Answer: No! (under the metaphysical assumption of locality)

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Question (EPR 1935): Can quantum-mechanical description of physical reality be considered complete?

Answer: No! (under the metaphysical assumption of locality)

Bell (1987): Either the wavefunction, as given by the Schrödinger equation, is not everything, or it is not right.

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Article

Parallel Lives: A Local-Realistic Interpretation of "Nonlocal" Boxes

Gilles Brassard [1,2,*] and Paul Raymond-Robichaud [1,*]

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2. Canadian Institute for Advanced Research, Toronto, ON M5G 1M1, Canada

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Received: 1 July 2018; Accepted: 11 January 2019; Published: 18 January 2019 *entropy*

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Editorial

Quantum Nonlocality

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Very subjectively—I find the most interesting contribution to be the work by Brassard and Raymond-Robichaud [11], "Parallel Lives: A Local-Realistic Interpretation of 'Nonlocal' Boxes".

PARALLEL LIVES: A LOCAL-REALISTIC INTERPRETATION OF "NONLOCAL" BOXES

GILLES BRASSARD AND PAUL RAYMOND-ROBICHAUD, UNIVERSITÉ DE MONTRÉAL

Abstract:

We show how local realism can be consistent with bipartite correlations that are usually considered to be nonlocal. For this purpose, we conduct a thought experiment in an imaginary world.

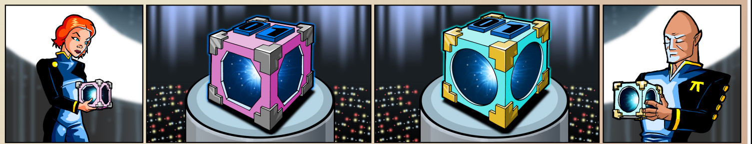
Imaginary World:

Our imaginary world follows the principles of Locality and Realism.

Principle of Locality: No action taken at some point can have any effect elsewhere at a speed faster than light.

Principle of Realism: There is a real world whose state determines the outcome of all observations.

This world has two inhabitants, Alice and Bob, who are each carrying a PR box, introduced by Popescu and Rohrlich.

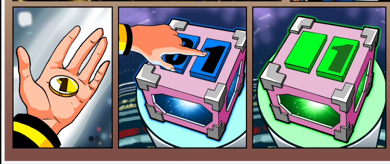


A PR box has a "0" and a "1" button. Whenever a button is pushed, it instantaneously flashes a green or a red light with equal probability. If Alice and Bob both push a button, they will discover when they meet that they have seen different colours precisely when they had both pushed the "1" button.

(Note that the PR box does not enable instantaneous communication between Alice and Bob)

Alice and Bob test their boxes with this protocol:

They travel far apart in their spaceships. Alice and Bob flip coins and push the corresponding buttons simultaneously.



Once a button is pushed, the box flashes either a green or a red light.

The experiment is performed with sufficient simultaneity that Alice's box cannot know the result of Bob's coin flip (hence the input to Bob's box) before it has to flash its own light, and vice versa.

After many experiments, they meet and realize that the boxes work perfectly.

The Einstein-Podolsky-Rosen Argument:

- Alice's pushing of a button cannot have any instantaneous effect on Bob's system by the principle of Locality.
- After Alice pushes her button, she can know with certainty what colour Bob will see depending on which button he pushes. *(For example, if Alice pushes "1" and sees green, she knows that if Bob pushes "0" he will see green)*
- Since it is possible for Alice to predict with certainty what colour Bob will see when he pushes a button, without influencing his system, it must be that his observations were predetermined.
- The observations of Bob should be described by local hidden variables B0 and B1.

B0 = 0 if Bob will observe green after pushing "0"
B0 = 1 if Bob will observe red after pushing "0"

B1 = 0 if Bob will observe green after pushing "1"
B1 = 1 if Bob will observe red after pushing "1"

- Likewise, Alice's system should be described by local hidden variables A0 and A1.

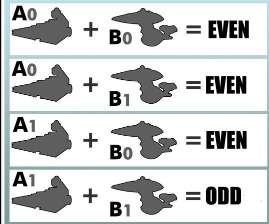
A0 = 0 if Alice will observe green after pushing "0"
A0 = 1 if Alice will observe red after pushing "0"

A1 = 0 if Alice will observe green after pushing "1"
A1 = 1 if Alice will observe red after pushing "1"

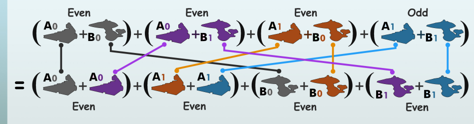
- A local hidden variable theory would give a local realistic explanation for this experiment.

Bell's Theorem: Local hidden variable theories can only produce PR boxes that work at most 75% of the time.

Proof: A local hidden variable theory of these boxes must satisfy the following 4 equations:



Summing these equations on both sides and rearranging the terms:



This implies: Odd = Even!

It is not possible for all four equations to be correct. At least one of the four possible choices of buttons pushed will give incorrect results.

Many people have concluded that any world that could produce PR boxes that work more than 75% of the time cannot be Local and Realistic. Remarkably, quantum mechanics enables PR boxes that work 85% of the time. Must we conclude that quantum mechanics cannot be Local and Realistic?

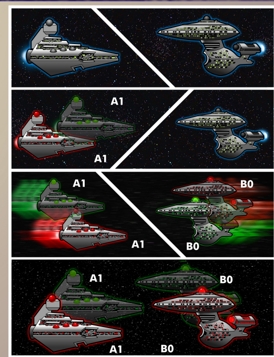
Here is how the seemingly impossible is accomplished:

Each spaceship resides inside a bubble.

When Alice pushes a button on her box (here "1"), her bubble splits into two bubbles. Each bubble contains a copy of its spaceship and its inhabitant. Inside one bubble, Alice has seen the red light flash; inside the other, she has seen the green light flash. From now on, the two bubbles are living parallel lives. They cannot interact in any way and will never meet again. Notice that this phenomenon is strictly local.

The same phenomenon takes place when Bob pushes a button on his box (here "0"). Let's see what happens when they travel toward each other.

Each of the two bubbles that contain Alice is allowed to interact with and see only a single bubble that contains Bob, namely the one that satisfies the equations described above.



Note that such a perfect matching is always possible. Furthermore, each bubble can "know" with which other bubble to interact provided it keeps a local memory of which button was pushed and which light flashed. Alice and Bob will be under the illusion of correlations that seem to emerge from outside space-time.

In our imaginary world, the Einstein-Podolsky-Rosen argument does not hold because whenever Alice pushes a button and can predict something about Bob, what she is really predicting is not what is happening simultaneously at Bob's place, but rather how their various lives will interact in the future.

Conclusion:

The virtue of our imaginary world is to demonstrate in an exceedingly simple way that local reality can produce correlations that are impossible in any classical theory based on local hidden variables.

In quantum mechanics, a theory analogous to this one can be traced back at least to Deutsch and Hayden.

Perhaps we live parallel lives?

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Brassard, G. and Raymond-Robichaud. P. (2017). Parallel lives: A local-realistic interpretation of "nonlocal" boxes. Available at: http://arxiv.org/abs/1709.10016.

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Poster art and design by Louis Fernet-Leclair (original version 2012, with slight corrections in 2018)

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This is the simplest possible proof that the violation of a Bell inequality does NOT rule out local realism!

The Imaginary World

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Several slides below are borrowed from Christoph Müller and Fabio Streun

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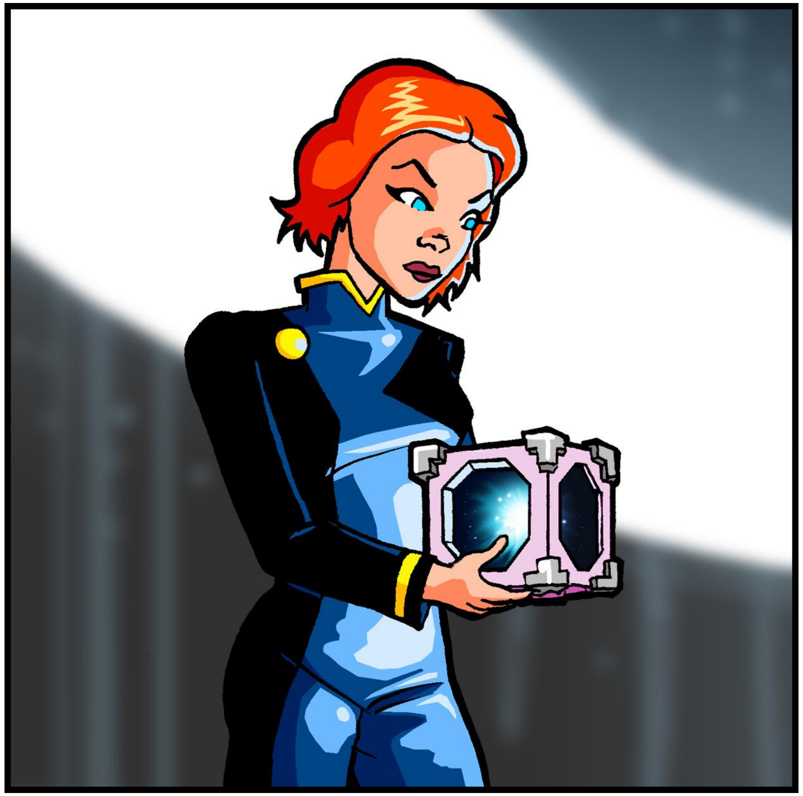
Earlier similar ideas by Colin Bruce in Schrödinger’s Rabbits (2004).

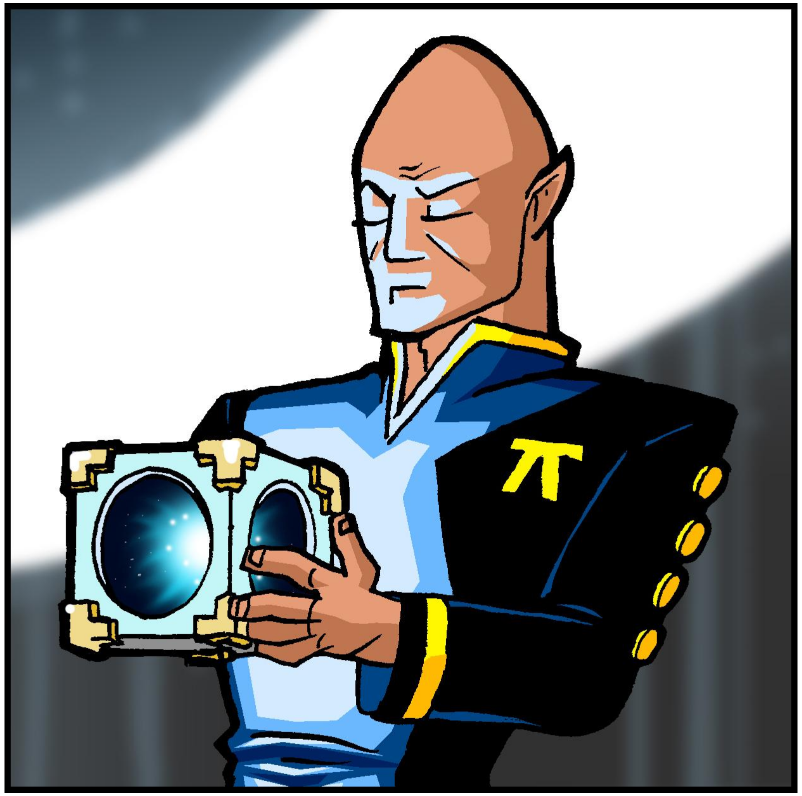
The Imaginary World



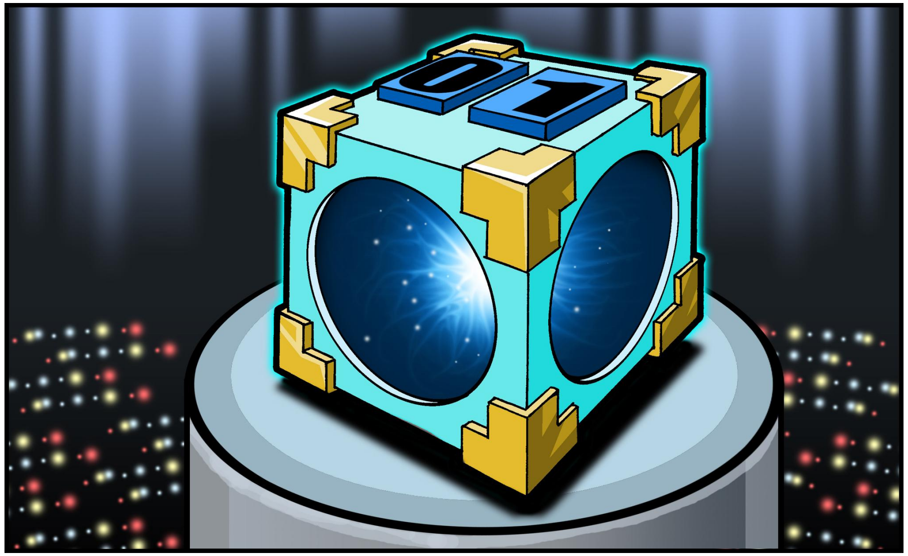
Alice and Bob

Spaceships

Nonlocal Boxes



Nonlocal Boxes



Invented by Sandu Popescu and Daniel Rohrlich, *Foundation of Physics*, 1994 (“PR-boxes”)

Nonlocal Boxes

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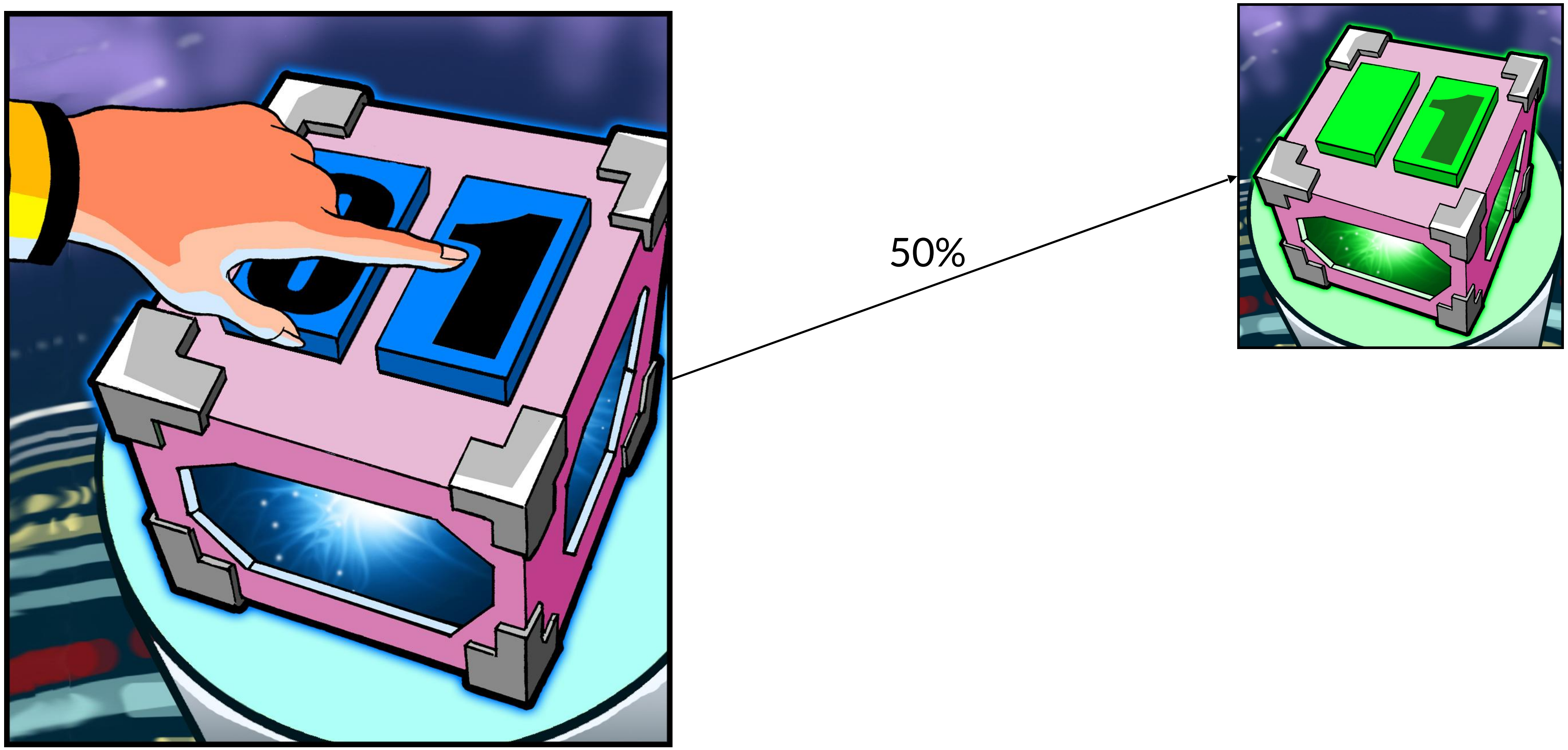

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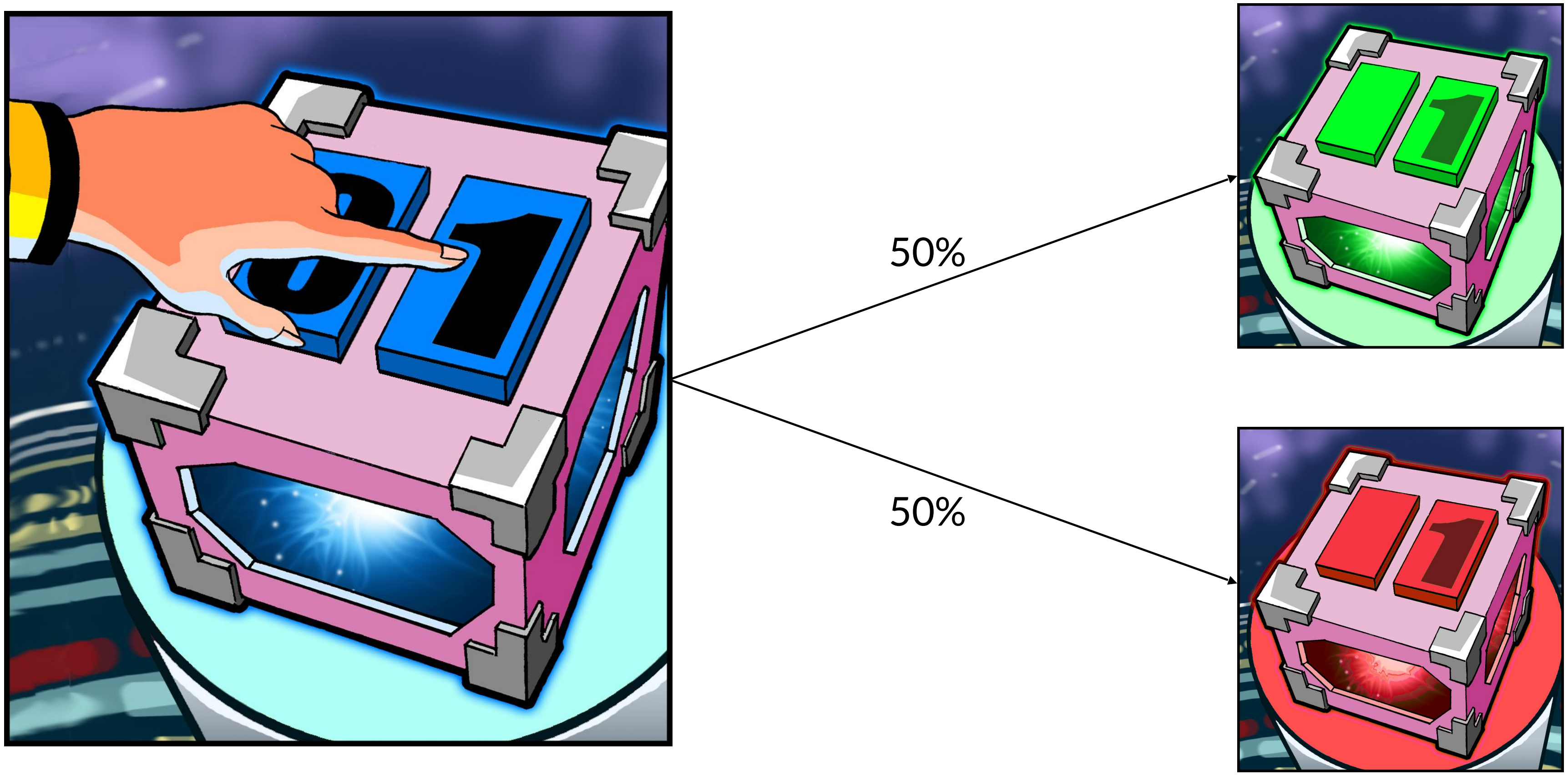
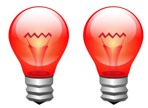
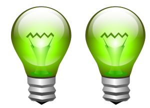


Alice’s Input	**Bob**’s Input	**Output** Colours
0	0	/
0	1	/
1	0	/
1	1	/

Magic Rule

Alice’s Input	**Bob**’s Input	**Output** Colours
0	**0**	/
0	**1**	/
1	**0**	/
1	**1**	/

Magic Rule

Alice’s Input	**Bob**’s Input	**Output** Colours
0	**0**	 /  (identical)
0	**1**	/
1	**0**	/
1	**1**	/

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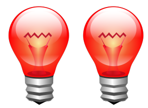
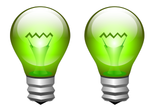
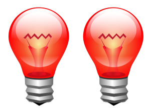
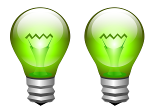
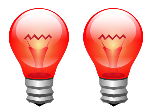
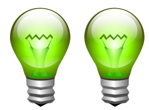
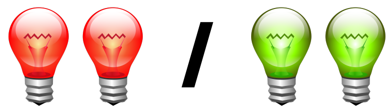
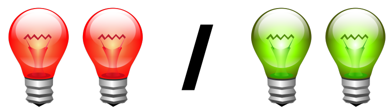
0	**0**	 / 	(identical)
0	**1**	 / 	(identical)
1	**0**	 / 	(identical)
1	**1**	/	

Magic Rule

Alice’s Input	**Bob**’s Input	**Output** Colours	
0	0		(identical)
0	1		(identical)
1	0		(identical)
1	1		(different)

Nonlocal Boxes: Summary

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Come in pairs

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Push button → 50 % **red**, 50% **green**

Nonlocal Boxes: Summary

Come in pairs

Push button → 50 % **red**, 50% **green**

Magic Rule

Nonlocal Boxes: Summary

Come in pairs

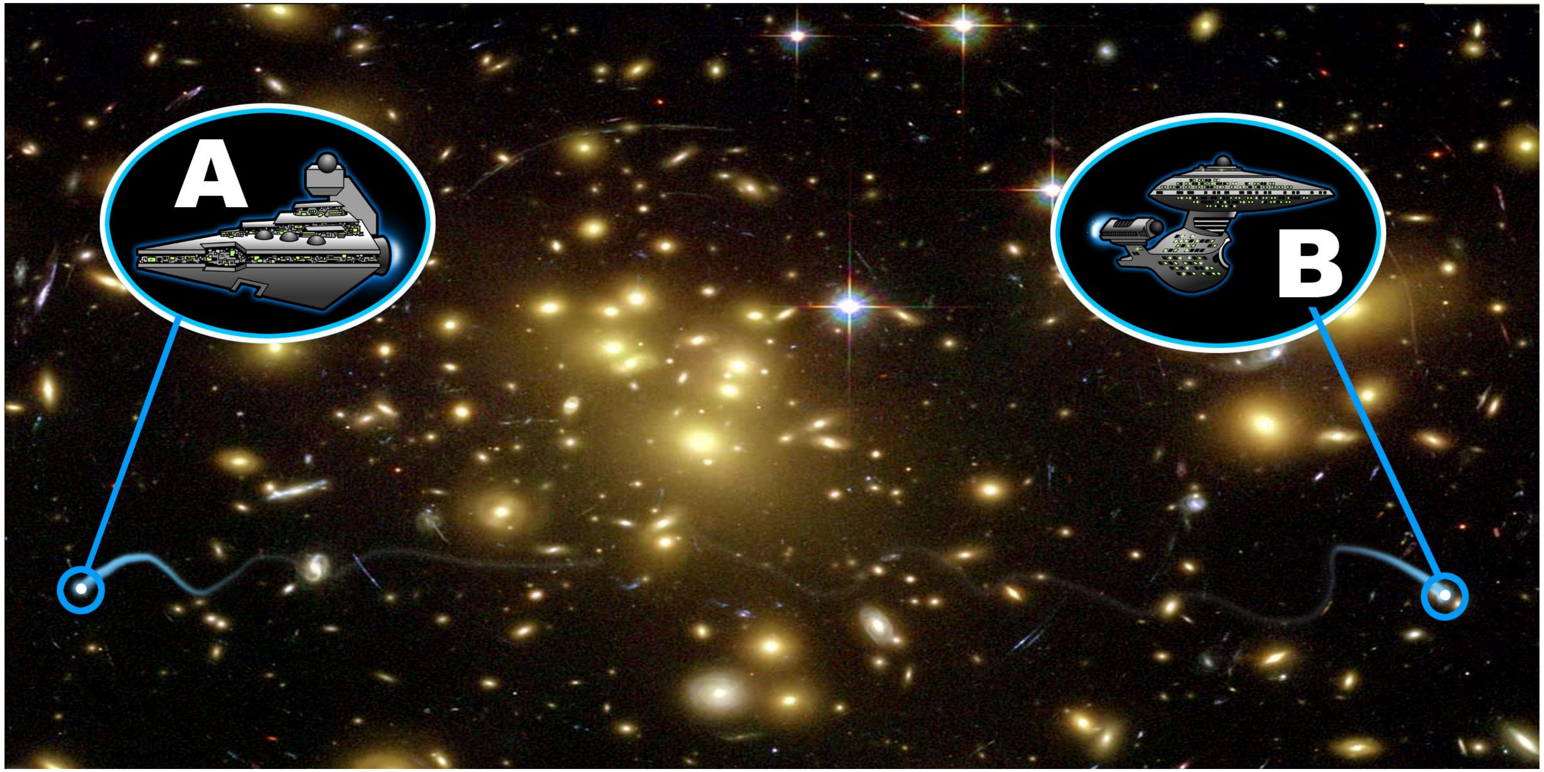
Push button → 50 % **red**, 50% **green**

Magic Rule

A	B	Output
0	0	/
0	1	/
1	0	/
1	1	/

Experiment with the boxes

Experiment with the Boxes



Experiment: Coin Flip

Simultaneous coin flip

Experiment: Use the Box

Alice

Experiment: Use the Box

Alice

Experiment: Use the Box

Alice

Alice knows that:

Experiment: Use the Box

Alice

Alice knows that:

If Bob pushes **0** he will see green.

Experiment: Use the Box

Alice

Alice knows that:

If Bob pushes **0** he will see green.

If Bob pushes **1** he will see red.

Experiment: Use the Box

Alice

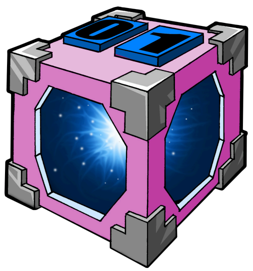
Alice knows that:

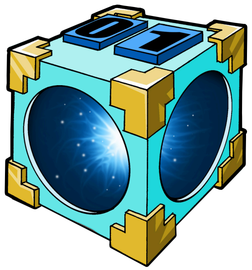
If Bob pushes **0**
he will see green.

If Bob pushes **1**
he will see red.

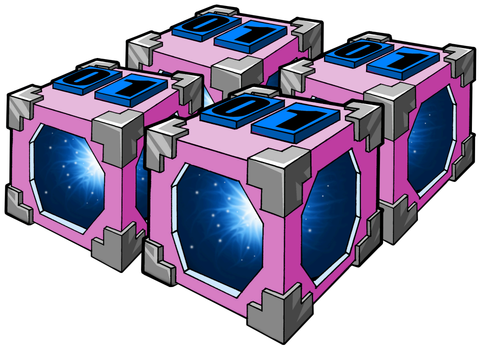
EPR Argument: the behaviour of Bob’s Box is predetermined

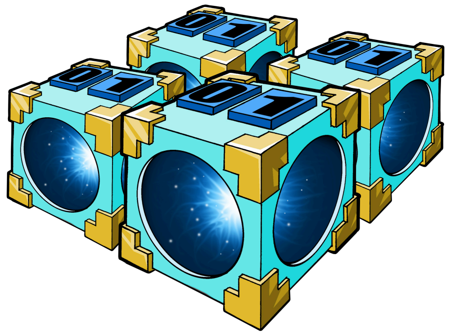
Experiment



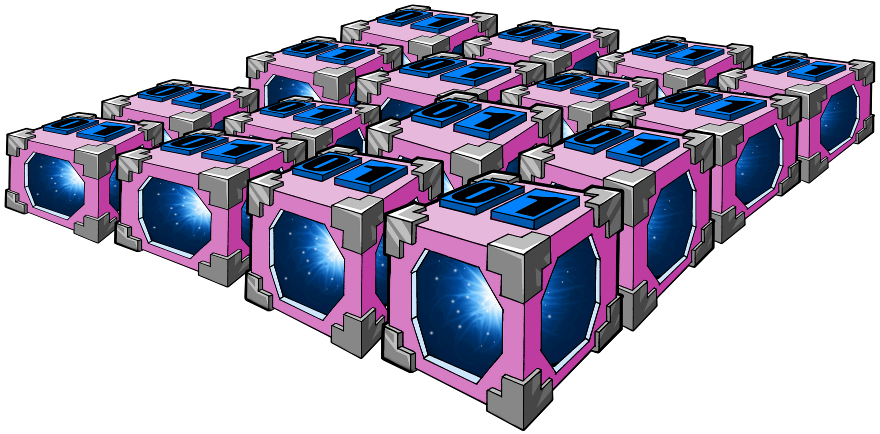


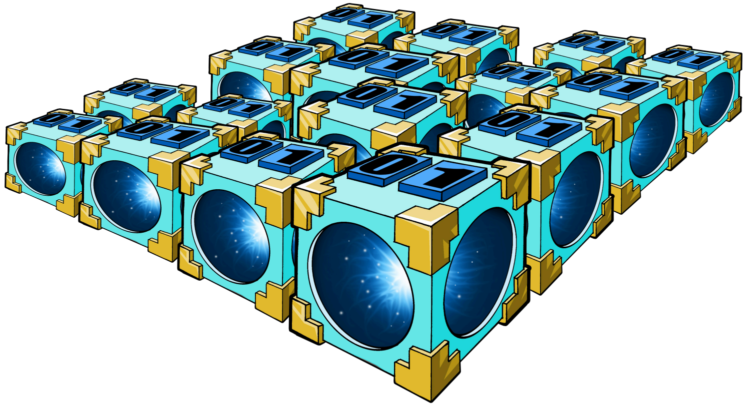
Experiment



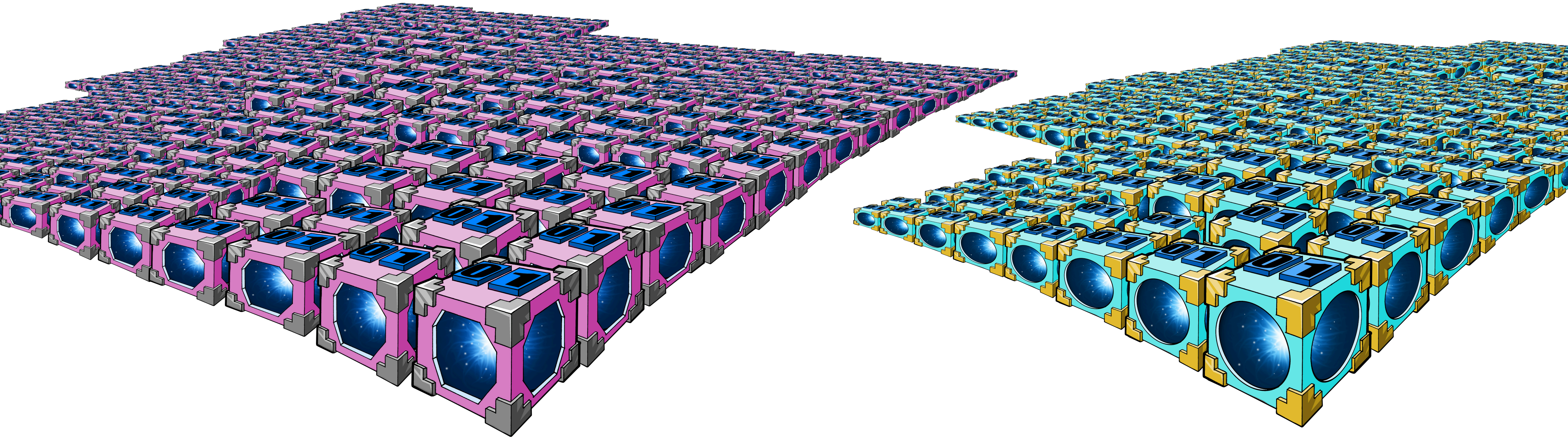


Experiment





Experiment



Testing the Boxes

A	B	Output
0	0	🔴🔴 / 🟢🟢
0	1	🔴🔴 / 🟢🟢
1	0	🔴🔴 / 🟢🟢
1	1	🔴🟢 / 🟢🔴

Result:

Boxes follow the **magic rule**
(colours don’t match ⇔ both pressed 1)

Testing the Boxes

A	B	Output
0	0	
0	1	
1	0	
1	1	

Result:

Boxes follow the **magic rule**
(colours don’t match ⇔ both pressed 1)

100% of the time! ⇒ perfect boxes

Testing the Boxes

A	B	Output
0	0	 / 
0	1	 / 
1	0	 / 
1	1	 / 

Result:

Boxes follow the **magic rule**
(colours don’t match ⇔ both pressed 1)

100% of the time! ⇒ perfect boxes

Possible only in imaginary world…

Imperfect Nonlocal Boxes

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Follow magic rule with probability *p*

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Disobeys it with probability $1{-}p$

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NOT SO FAST!

The usual conclusion from Bell's Theorem

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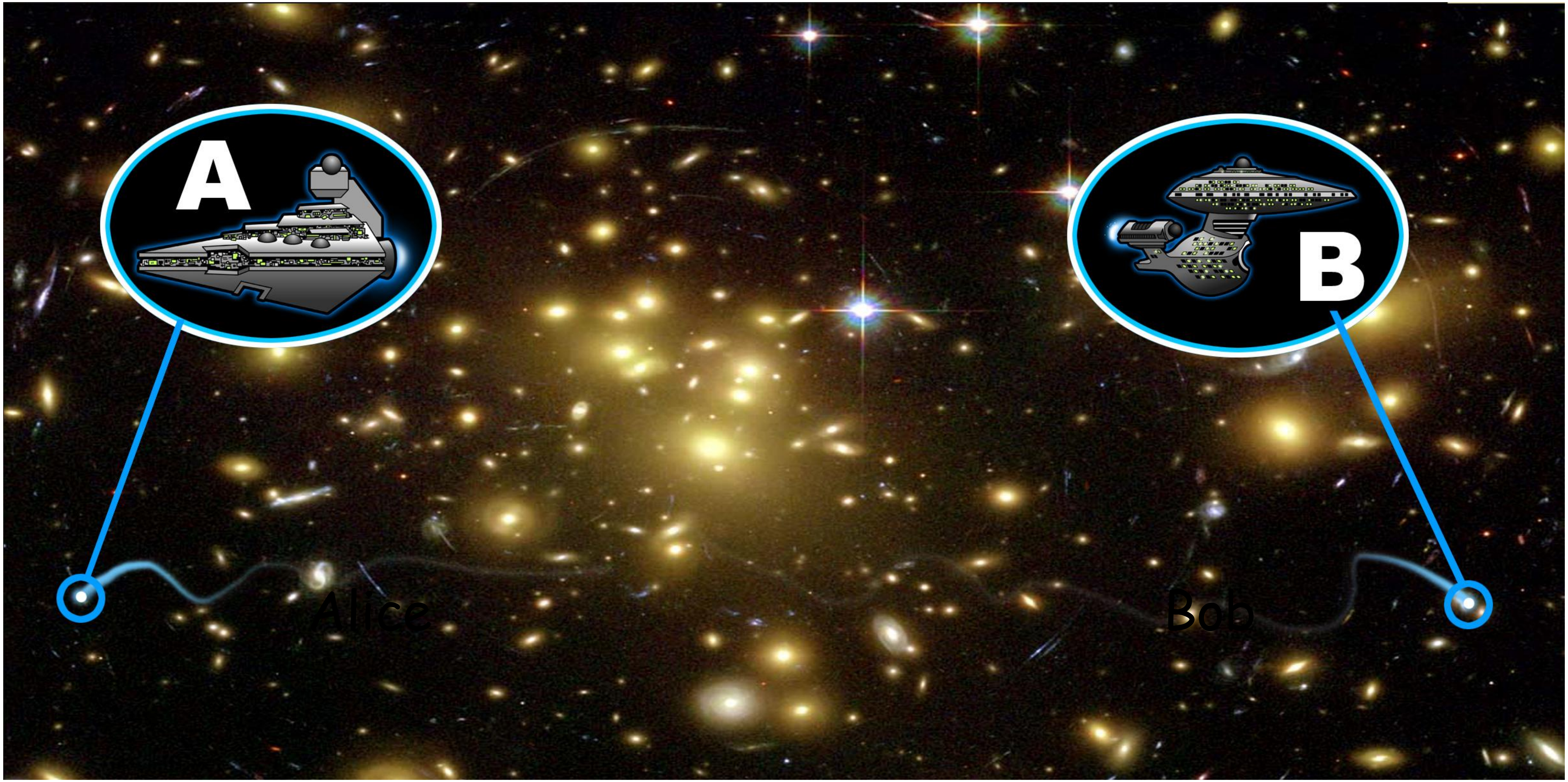
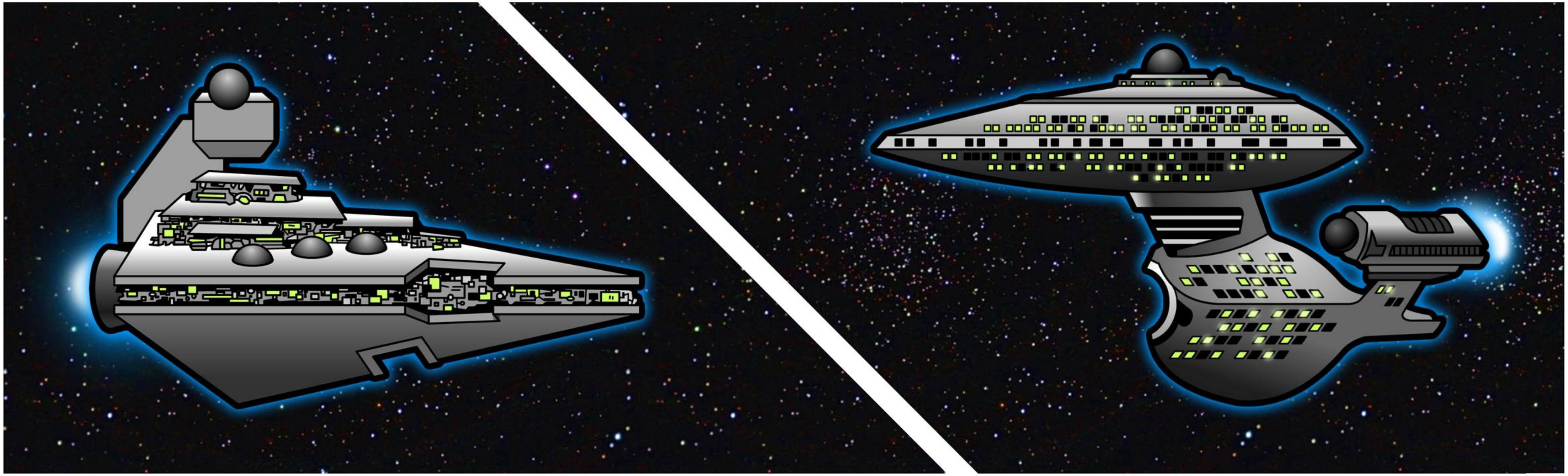
Any world containing nonlocal boxes that work with a probability better than 75% cannot be both local and realistic.

In particular the Quantum World

Yet, the seemingly impossible can be accomplished in a local-realistic world!

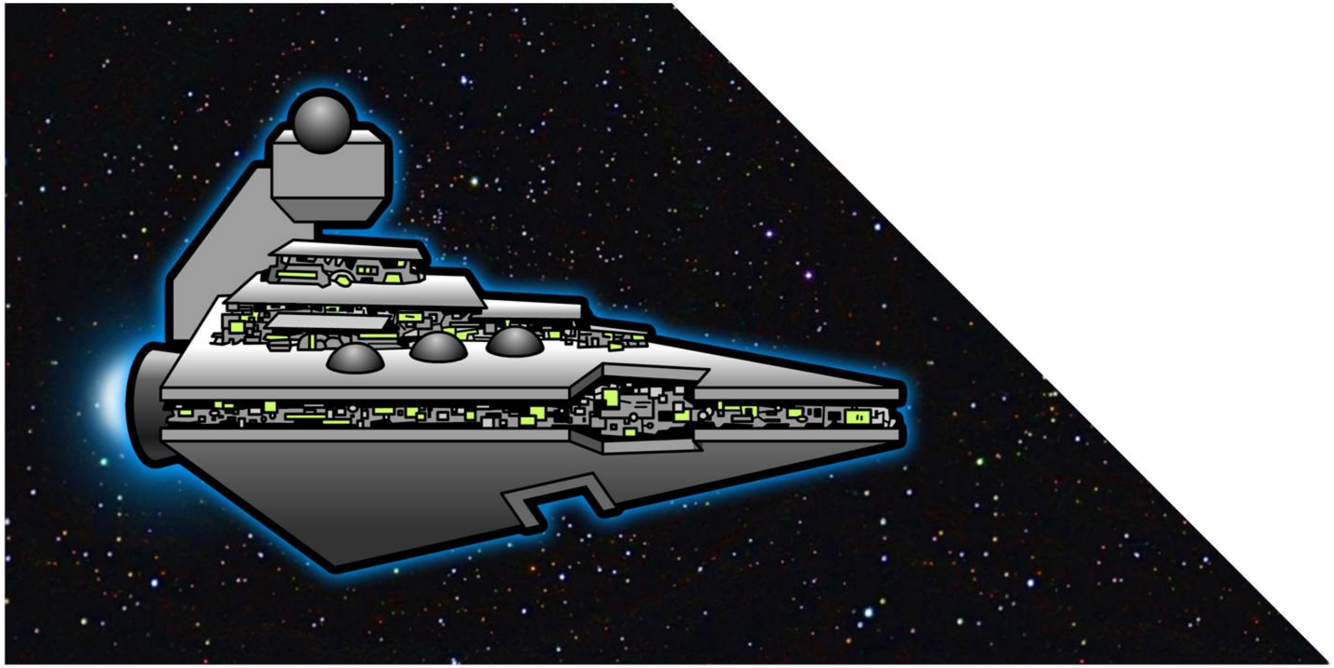
Parallel Lives


A
B
Alice
Bob

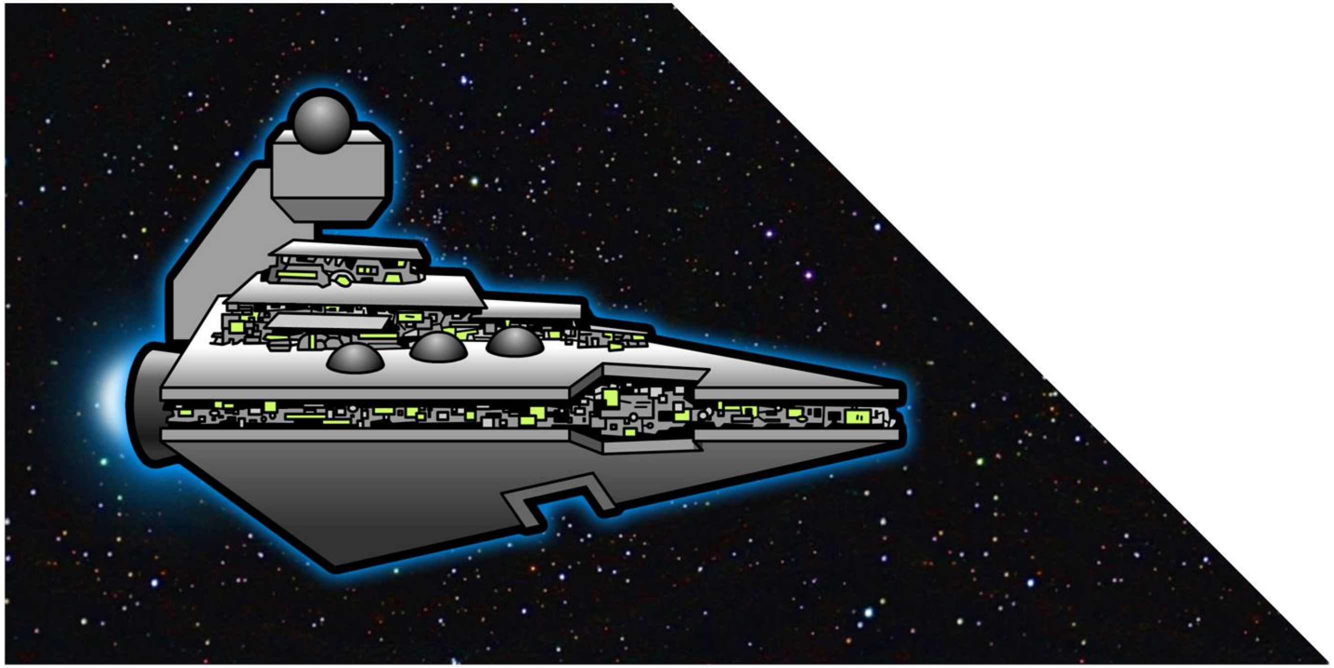


Alice

Bob

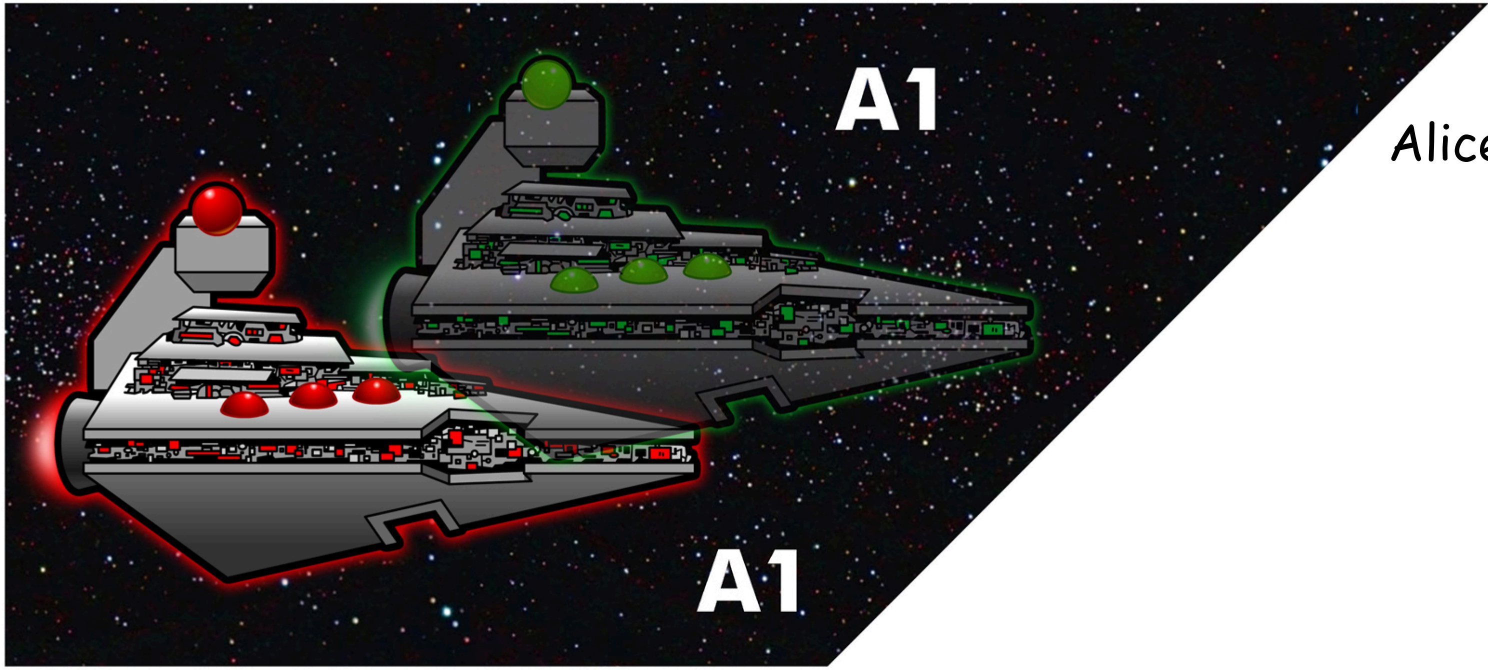


Alice



say Alice pushes button **1**

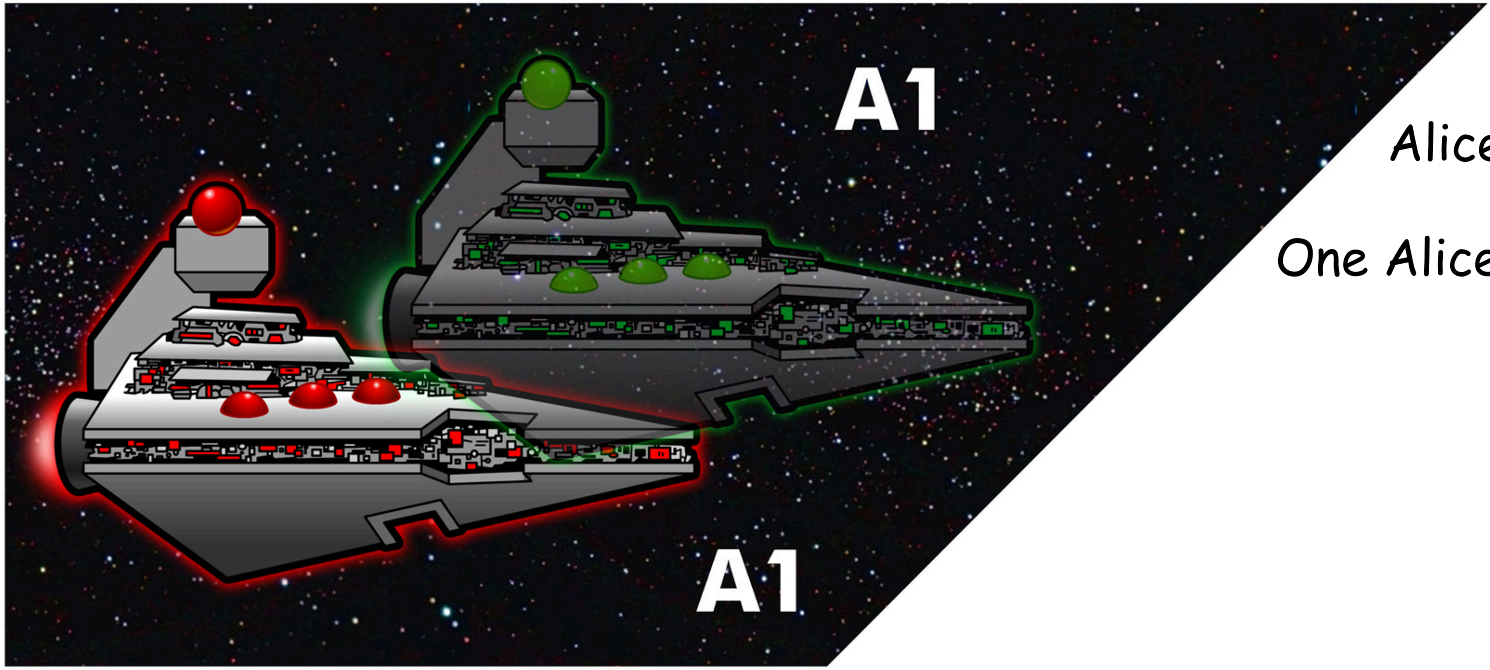
Alice



say Alice pushes button 1

Alice, box and spaceship split!

Alice

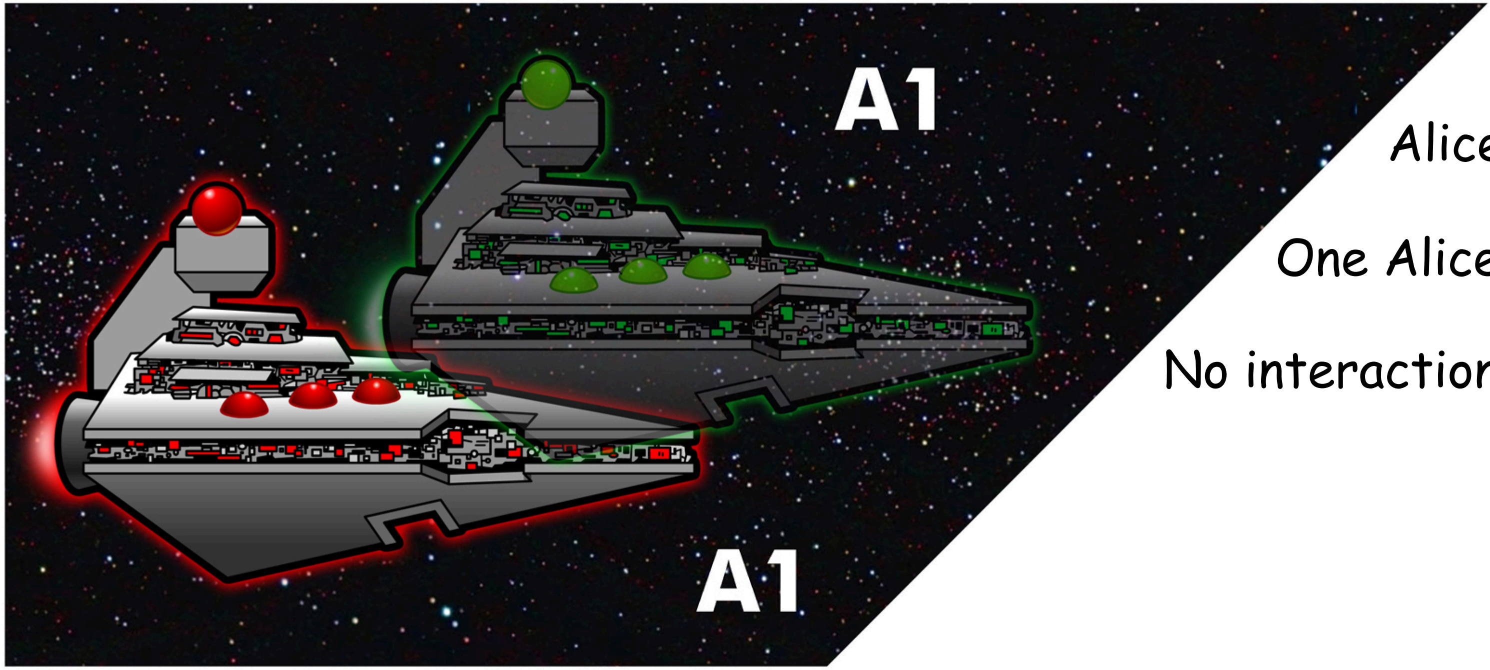


say Alice pushes button 1

Alice, box and spaceship split!

One Alice sees 💡, the other sees 💡

Alice



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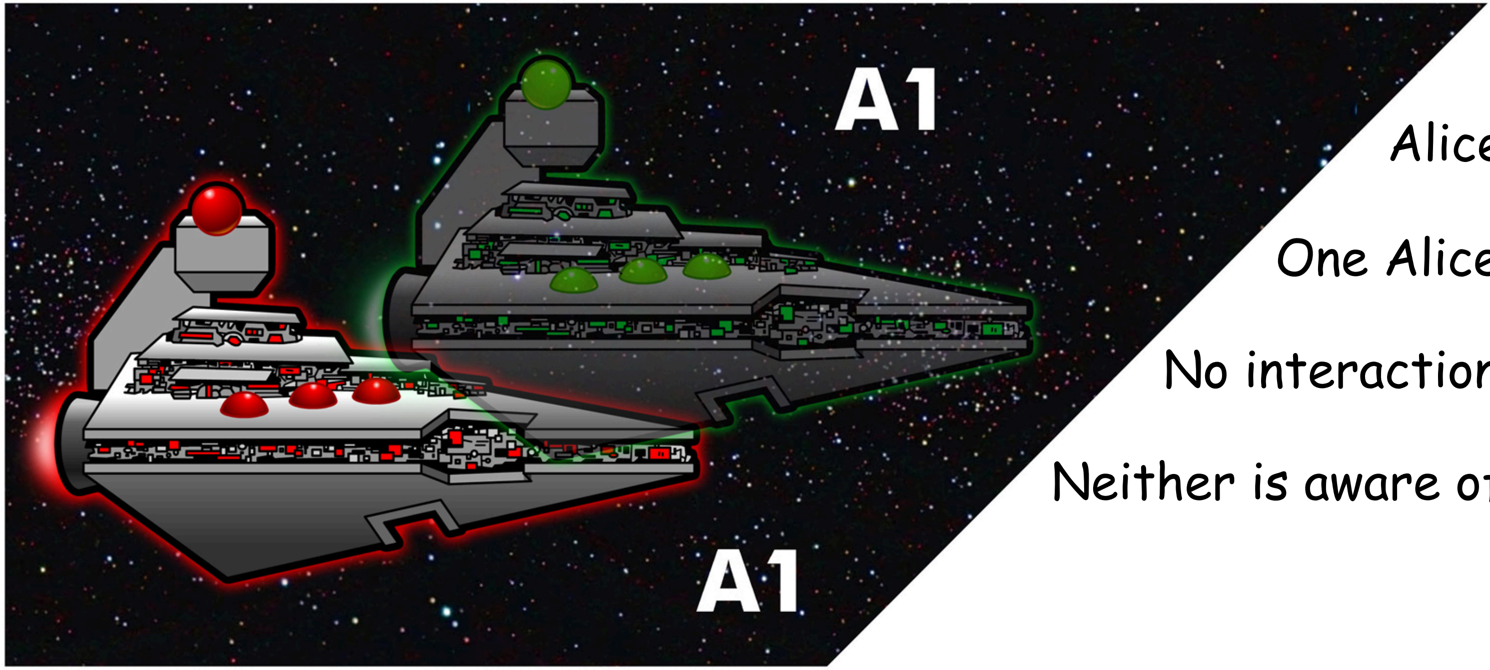

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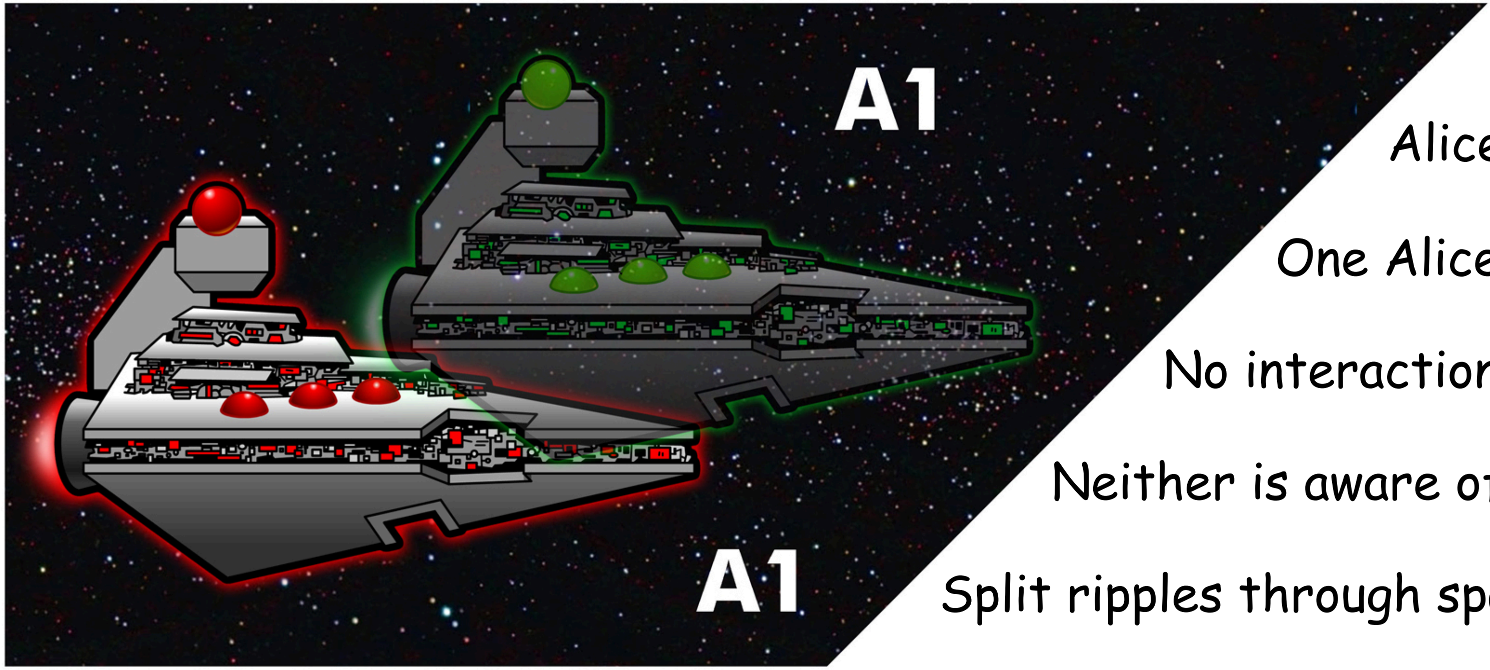

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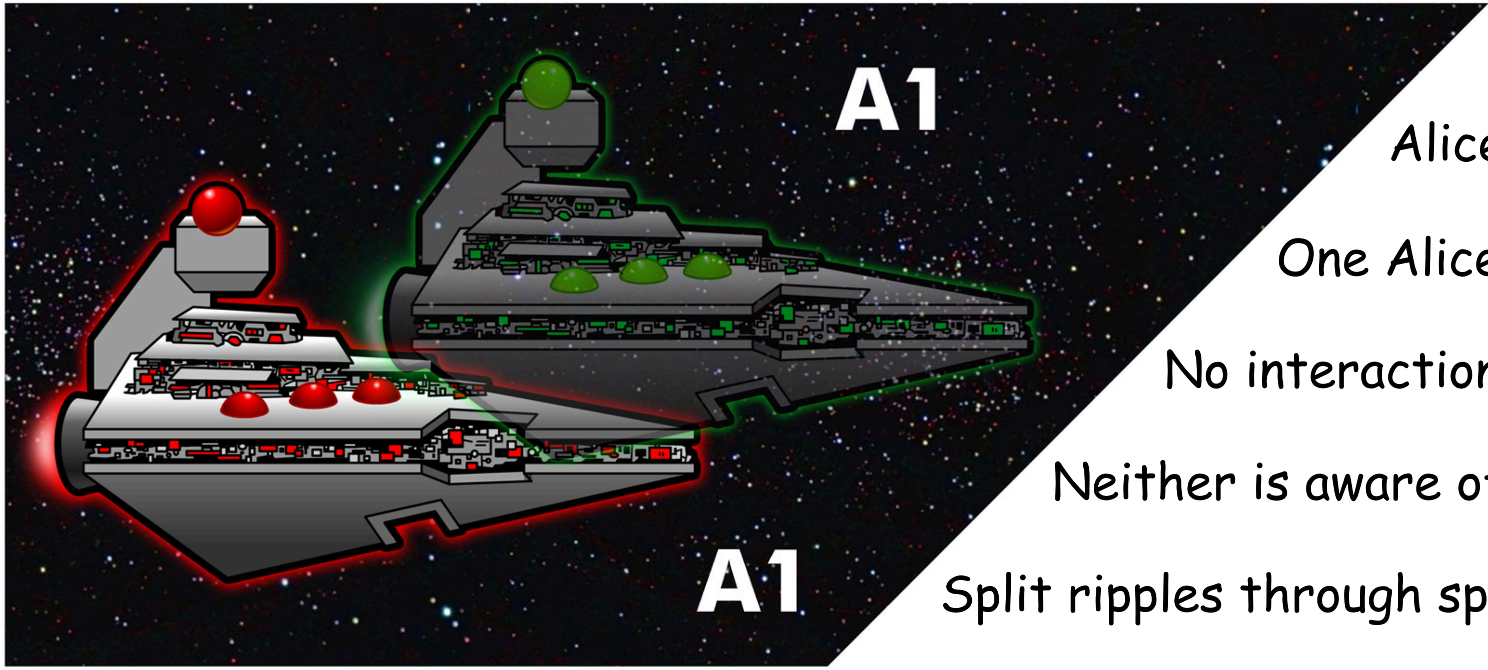

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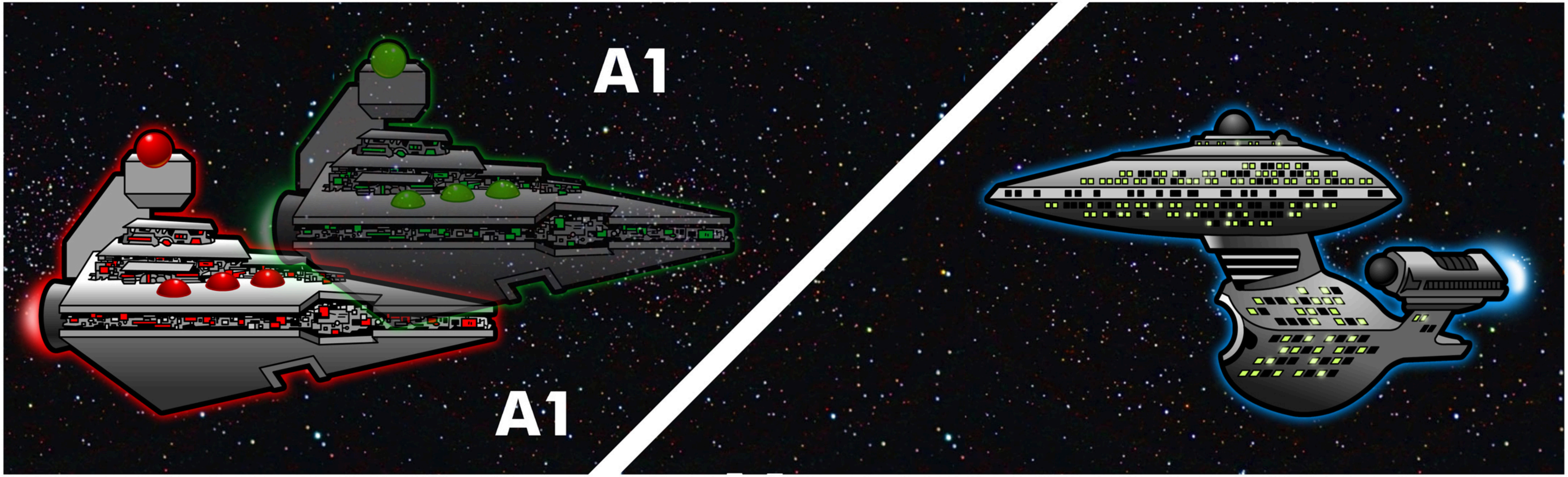

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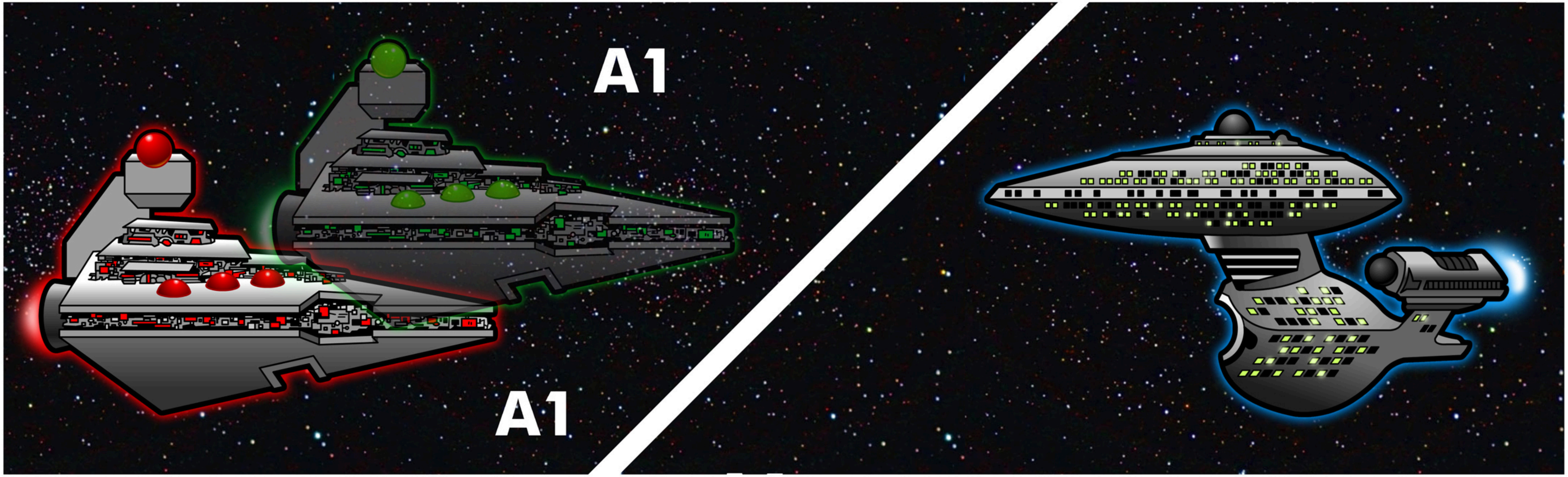

Alice

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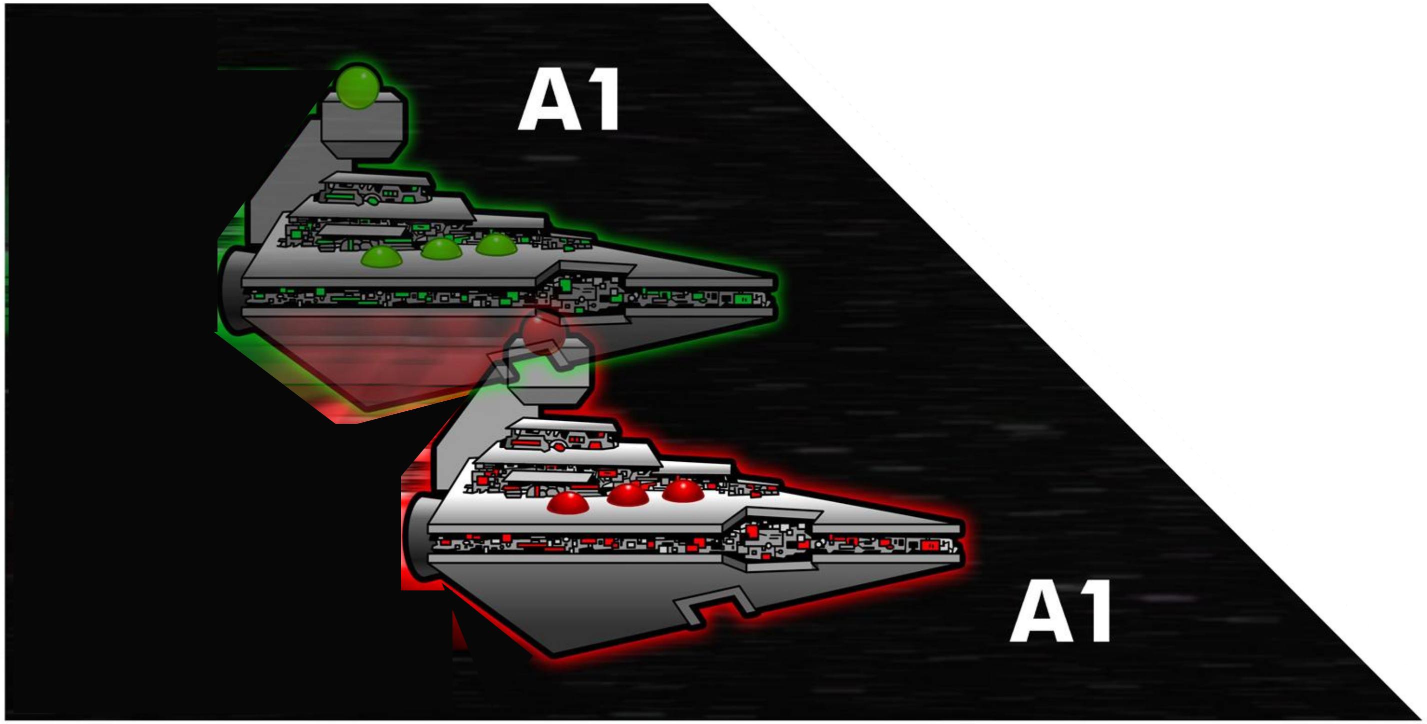
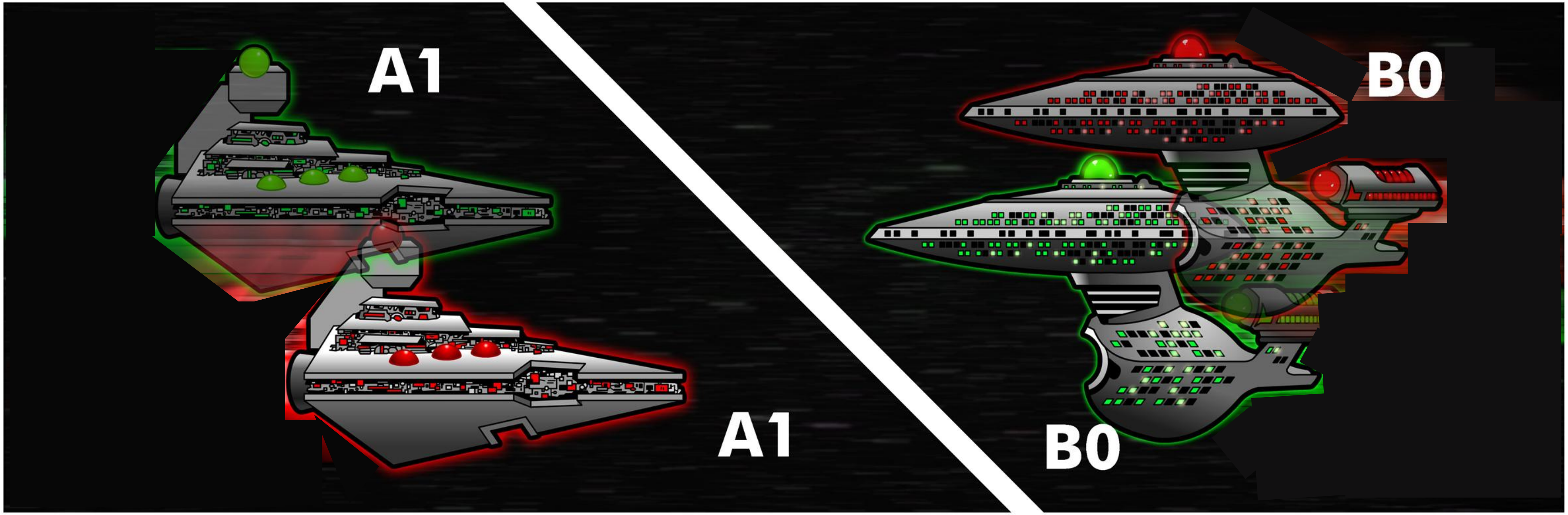
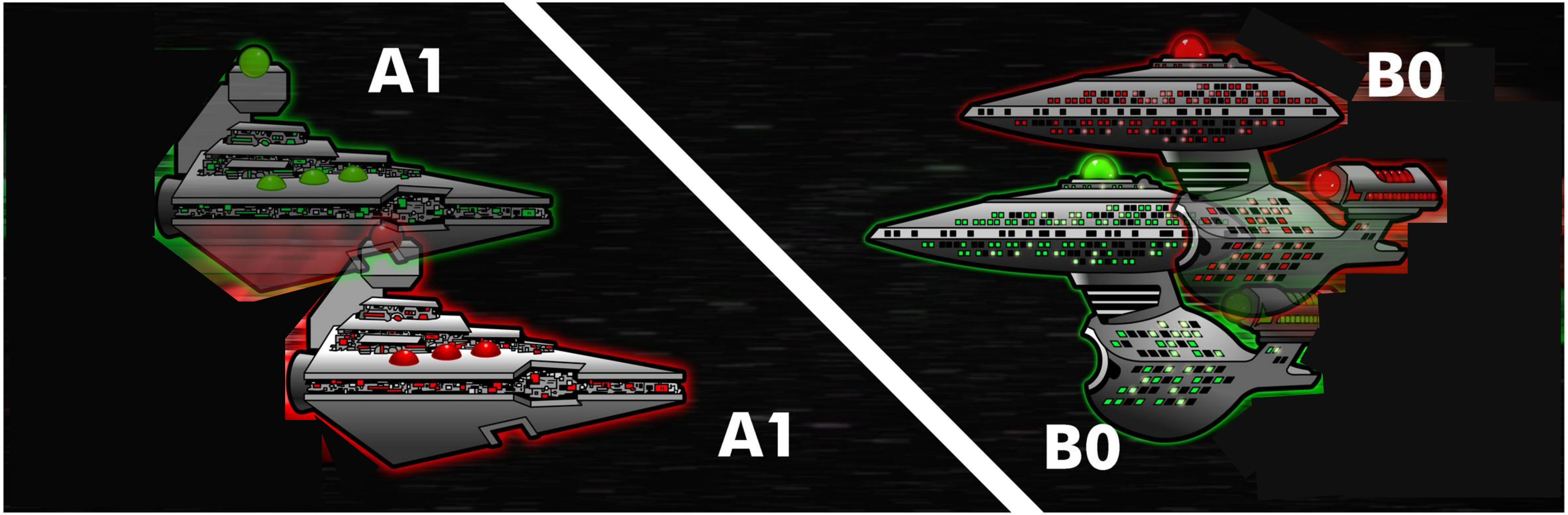
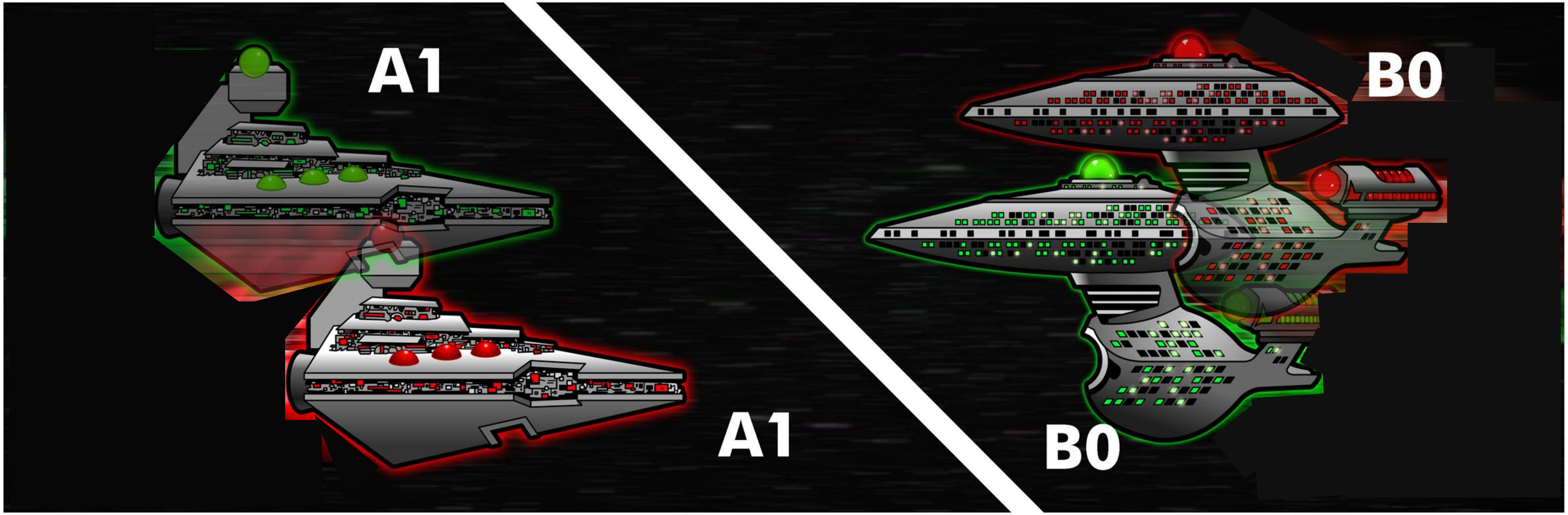
Say Bob pushes button **0**


A1
A1


A1
A1
B0
B0



There are now two Alices and two Bobs, all independent from one another



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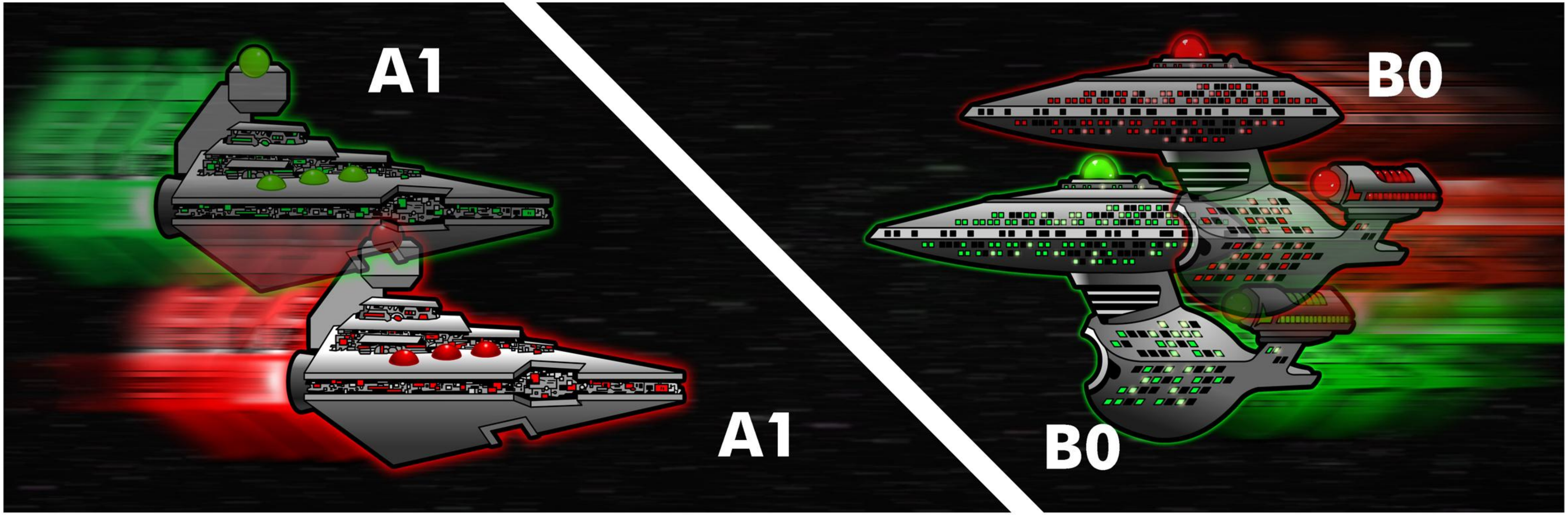

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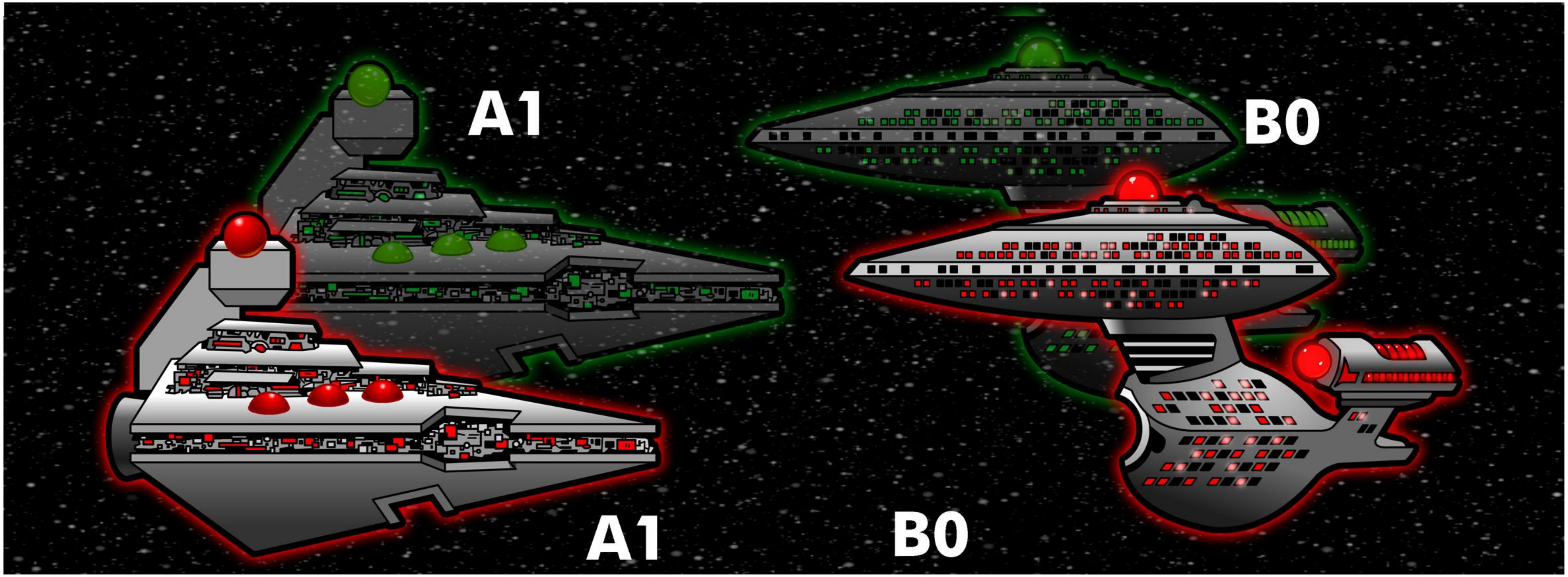

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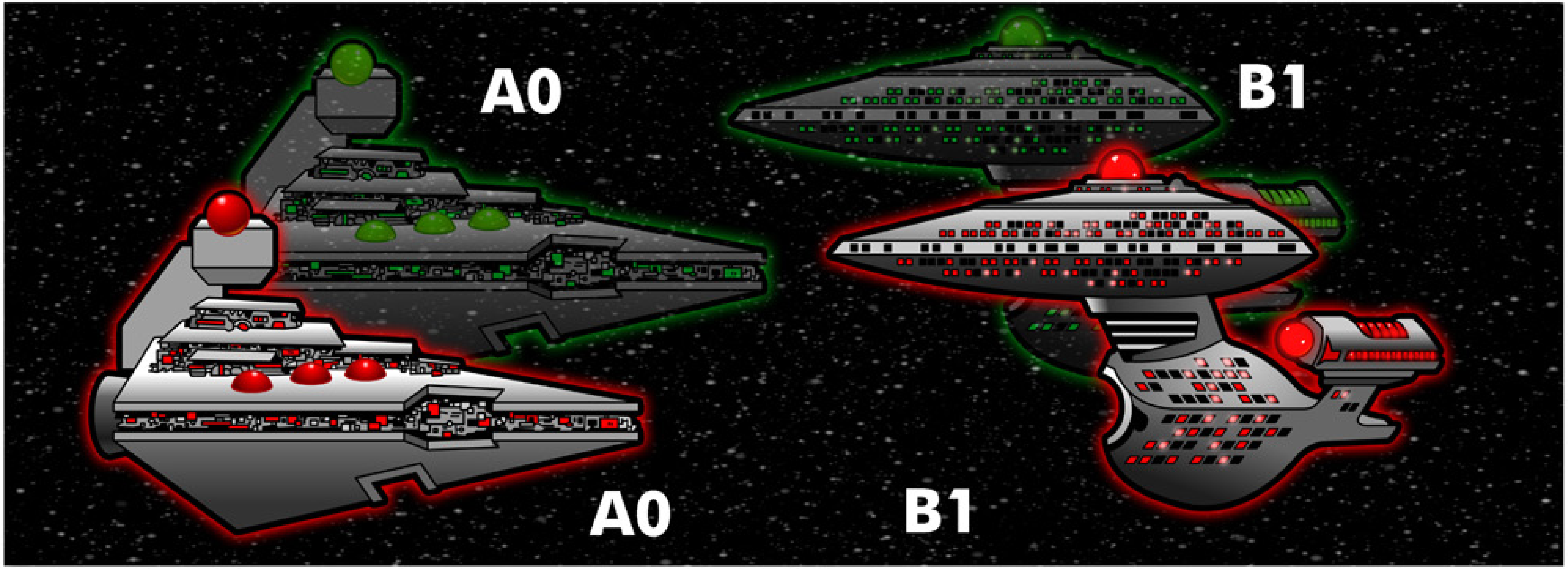

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The Key Idea

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In our imaginary world, the EPR argument does not hold because whenever Alice pushes a button and can predict something about Bob, she is really predicting not what is happening simultaneously at Bob's place but how their various lives will interact in the future.

This proves that

it is wrong to claim that

any world that violates
Bell inequalities
has to be nonlocal

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How about Quantum Theory?

10.1098/rspa.2000.0585

THE ROYAL SOCIETY

Information flow in entangled quantum systems

By David Deutsch and Patrick Hayden

Centre for Quantum Computation, The Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, UK

Received 4 June 1999; revised 3 November 1999; accepted 16 December 1999

All information in quantum systems is, notwithstanding Bell's theorem, localized. Measuring or otherwise interacting with a quantum system S has no effect on distant systems from which S is dynamically isolated, even if they are entangled with S. Using the Heisenberg picture to analyse quantum information processing makes this locality explicit, and reveals that under some circumstances (in particular, in Einstein–Podolsky–Rosen experiments and in quantum teleportation), quantum information is transmitted through 'classical' (i.e. decoherent) information channels.

Keywords: entanglement; non-locality; quantum information; Heisenberg picture; locally inaccessible information

Parallel Lives: Why quantum mechanics is a local realistic theory after all

Gilles Brassard and Paul Raymond-Robichaud

The Meaning and Non-Meaning of Bell's Thm

Conventional Wisdom: The violation of Bell's inequality is incompatible with local realism.

Fact: This is false!

Truth: The violation of Bell's inequality is incompatible with *local hidden variable theories*. That's different!

What about Quantum Mechanics? Can it be local realistic, Bell's Theorem notwithstanding?

Yes! It can! This was prophecised by Everett; explained by Frank Tipler to David Deutsch; published by Deutsch and Hayden (2000).

Can it be done in a simple way? YES!... See this poster!

Desiderata for Local Realism

- Systems should have local physical states.
- Systems should undergo local evolution.
- The whole should be fully described by its parts.
- All possible observations of a system should be determined by its physical state.

More Formally...

- For any system X, let M^X denote its **state**.
- **Separation:**

$$M^A = \mathrm{tr}_B\left(M^{AB}\right) \quad \text{and} \quad M^B = \mathrm{tr}_A\left(M^{AB}\right).$$

- **Merging:**

$$M^{AB} = M^A \odot M^B.$$

Even for *entangled* states!

- **Evolution:**

$$M_2^A = U\left(M_1^A\right).$$

- **Separate Evolution:**

$$(U \otimes V)\left(M^{AB}\right) = U\left(M^A\right) \odot V\left(M^B\right).$$

- **Predictions of Quantum Mechanics:**

$$\rho^A = f(M^A).$$

Commuting Diagrams

Observations commute with evolution and tracing out.

$$\begin{tikzcd} M^A \arrow[r, dash, "U"] \arrow[d, dash, "f"'] & U\left(M^A\right) \arrow[d, dash, "f"] \\ \rho^A \arrow[r, dash, "U"'] & U\left(\rho^A\right) \end{tikzcd} \qquad \begin{tikzcd} M^{AB} \arrow[r, dash, "\mathrm{tr}_B"] \arrow[d, dash, "f"'] & M^A \arrow[d, dash, "f"] \\ \rho^{AB} \arrow[r, dash, "\mathrm{tr}_B"'] & \rho^A \end{tikzcd}$$

$$U\Big(f(M^A)\Big) = f\Big(U(M^A)\Big) \qquad f\Big(\mathrm{tr}_B(M^{AB})\Big) = \mathrm{tr}_B\Big(f(M^{AB})\Big)$$

States

For a system A associated with a Hilbert Space of dimension n, its state M^A is described by an an $n \times n$ *evolution matrix* $\left[W\right]^A$, whose entries are matrices defined by

$$\left[W\right]_{i,j}^A = W^\dagger\left(\,|j\rangle\langle i| \otimes I^{\overline{A}}\right)W$$

for some unitary W on the global state, which corresponds to all that happened to the universe since the beginning of time.

Separation

$\mathrm{tr}_B\left[W\right]^{AB}$ is defined by:

$$\left(\mathrm{tr}_B\left[W\right]^{AB}\right)_{i,j} = \sum_k \left[W\right]_{(i,k),(j,k)}^{AB}$$

Theorem

$$\left[W\right]^A = \mathrm{tr}_B\left[W\right]^{AB}.$$

Merging

$\left[W\right]^A \odot \left[W\right]^B$ is defined by:

$$\left(\left[W\right]^A \odot \left[W\right]^B\right)_{(i,k),(j,l)} \stackrel{\text{def}}{=} \left[W\right]_{i,j}^A \left[W\right]_{k,l}^B$$

Theorem

$$\left[W\right]^{AB} = \left[W\right]^A \odot \left[W\right]^B.$$

Evolution

$U\left[W\right]^A$ is defined by:

$$\left(U\left[W\right]^A\right)_{i,j} = \sum_{m,n} U_{i,m}^\dagger \left[W\right]_{m,n}^A U_{n,j}$$

Theorem

$$U\left[W\right]^A = \left[(U \otimes V)W\right]^A$$

for any operation V applied to the rest of the universe.

Separate Evolution

Theorem

$$(U \otimes V)\left[W\right]^{AB} = U\left[W\right]^A \odot V\left[W\right]^B.$$

Predictions of Quantum Mechanics

$\left[W\right]^A |\psi\rangle$ is defined by:

$$\left(\left[W\right]^A |\psi\rangle\right)_{i,j} = \langle\psi|\left[W\right]_{i,j}^A|\psi\rangle$$

where $|\psi\rangle$ is a unit vector in the dimension of the global state.

Theorem

$$\left[W\right]^A |\psi\rangle = \mathrm{tr}_{\overline{A}}\left(W|\psi\rangle\langle\psi|W^\dagger\right)$$

Conclusion

- **Theorem:** The universal wavefunction cannot be the complete description of a local universe.
- It merely describes what can be observed.
- It is but a shadow of the real world!

References

- D. Deutsch and P. Hayden, "Information flow in entangled quantum systems", *Proceedings of the Royal Society of London* **A456**(1999):1759–1774, 2000.
- G. Brassard and P. Raymond-Robichaud, "Can free will emerge from determinism in quantum theory?", in *Is Science Compatible with Free Will? Exploring Free Will and Consciousness in the Light of Quantum Physics and Neuroscience*, A. Suarez and P. Adams (editors), Springer, pp. 41–61, 2013.

The Equivalence of Non-Signalling and Local Realism

Gilles Brassard and Paul Raymond-Robichaud

From Non-Signalling to Local Realism

Conventional Wisdom: Quantum theory is incompatible with local realism.

Truth: Quantum theory, *like any non-signalling theory* with a reversible dynamics, is compatible with local realism.

Appearance versus Reality

- The *phenomenal* state of a system describes everything that can be observed locally about the system.
- The *noumenal* state of a system is a complete description of the system.

Desiderata for Local Realism

- Systems should have local *noumenal* states.
- Systems should undergo local evolution.
- The whole should be fully described by its parts.
- The phenomenal state of a system should be determined by its noumenal state.

Non-Signalling Theory

- For any system X, let ρ^X denote its **phenomenal state**.
- **Splitting:**

$$\rho^A = \pi_A\left(\rho^{AB}\right) \text{ and } \rho^B = \pi_B\left(\rho^{AB}\right).$$

- **Evolution:**

$$\rho_2^A = U\left(\rho_1^A\right).$$

- **Non-Signalling:**

$$\pi_A\Big((U \times V)\left(\rho^{AB}\right)\Big) = U\left(\rho^A\right).$$

Local Realism: More Formally

- For any system X, let N^X denote its **noumenal state**.
- **Splitting:**

$$N^A = \pi_A\left(N^{AB}\right) \text{ and } N^B = \pi_B\left(N^{AB}\right).$$

- **Merging:**

$$N^{AB} = N^A \odot N^B.$$

Even for *entangled* states!

Local Realism: More Formally (continued)

- **Evolution:**

$$N_2^A = U\left(N_1^A\right).$$

- **Separate Evolution:**

$$(U \times V)\left(N^{AB}\right) = U\left(N^A\right) \odot V\left(N^B\right).$$

- **Predictions of the non-signalling theory:**

$$\rho^A = \phi\left(N^A\right).$$

Commuting Diagrams

Observations commute with evolution and projection.

$$\begin{tikzcd} N^A \arrow[r, "U"] \arrow[d, "\phi"'] & U(N^A) \arrow[d, "\phi"] \\ \rho^A \arrow[r, "U"'] & U(\rho^A) \end{tikzcd} \qquad \begin{tikzcd} N^{AB} \arrow[r, "\pi_A"] \arrow[d, "\phi"'] & N^A \arrow[d, "\phi"] \\ \rho^{AB} \arrow[r, "\pi_A"'] & \rho^A \end{tikzcd}$$

$$U\left(\phi(N^A)\right) = \phi\left(U(N^A)\right) \qquad \pi_A\left(\phi(N^{AB})\right) = \phi\left(\pi_A(N^{AB})\right)$$

Reversible Dynamics

Condition: Operations on a system form a *group*.

Equivalence Relation

Let A be a system and W, W' be operations on the global state. We define an equivalence relation:

$$W \equiv_A W' \overset{\text{def}}{\iff} (\exists V)\ W = \left(I^A \times V\right)(W')$$

where V is some operation that is applied on the rest of the universe and I^A is the identity operation on A.

States

For a system A, its *noumenal state* is defined by

$$N^A = [W]^A \overset{\text{def}}{=} \{W' \mid W' \equiv_A W\}$$

for some operation W on the global state that corresponds to all that has happened to the universe since the beginning of time.

Splitting

$$\pi_A\left([W]^{AB}\right) \overset{\text{def}}{=} [W]^A$$

Merging

$$[W]^A \odot [W]^B \overset{\text{def}}{=} [W]^{AB}$$

Evolution

$$U\left([W]^A\right) \overset{\text{def}}{=} [(U \times I)(W)]^A$$

where I is the identity operation applied on the rest of the universe.

Separate Evolution

Theorem:

$$(U \times V)\left([W]^{AB}\right) = U\left([W]^A\right) \odot V\left([W]^B\right).$$

Predictions of the Non-Signalling Theory

For a system A, its *phenomenal state* is

$$\phi\left([W]^A\right) \overset{\text{def}}{=} \pi_A\left(W(\rho_0)\right) = \rho^A$$

where ρ_0 is the phenomenal state corresponding to the global system at the beginning of time.

Commuting Relations

Theorem:

$$U\left(\phi\left([W]^A\right)\right) = \phi\left(U\left([W]^A\right)\right); \quad \pi_A\left(\phi\left([W]^{AB}\right)\right) = \phi\left(\pi_A\left([W]^{AB}\right)\right)$$

Conclusions

- **Theorem:** There is a local-realistic interpretation for *any* non-signalling theory with a reversible dynamics.
- **Corollary** There is a local-realistic interpretation for quantum mechanics!
- The observable quantum world *seems* to be non-local. Could it be but a *shadow* of the true local-realistic world?

References

- D. Deutsch and P. Hayden, "Information flow in entangled quantum systems", *Proceedings of the Royal Society of London* **A456**(1999), pp. 1759–1774, 2000.
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Quantum Physics

The equivalence of local-realistic and no-signalling theories

Gilles Brassard, Paul Raymond-Robichaud

(Submitted on 3 Oct 2017)

We provide a framework to describe all local-realistic theories and all no-signalling operational theories. We show that when the dynamics is reversible, these two concepts are equivalent. In particular, this implies that unitary quantum theory can be given a local-realistic model.

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(or arXiv:1710.01380v1 **[quant-ph]** for this version)

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New version coming soon!

"About your cat, Mr. Schrödinger—I have good news and bad news."