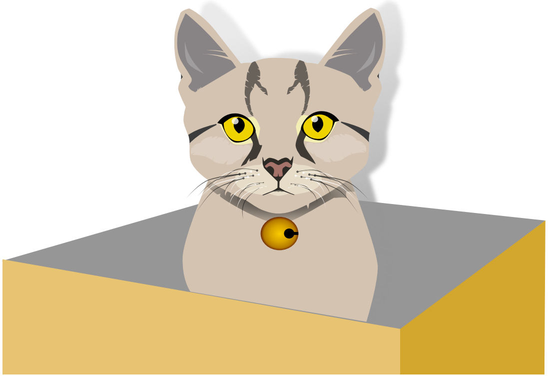
# Quantum Mechanics in Your Face for Anybody

Quantum Mysteries in Your Face for Anyone



Andrew Fowlie

MTH020. Modelling the Real World

# CONTENTS

## The Quantum World

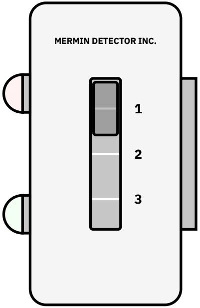
- Big, everyday objects behave in predictable and intuitive ways
- Small things — particles and atoms — obey a different set of rules, governed by *quantum mechanics*
- The quantum world is strange and counter-intuitive
- Mermin (1981) wanted everyone to see that strangeness without requiring any mathematical or physical concepts
- He created an experiment to show the difference between quantum physics and everyday life

Section 1

# Mermin experiment setup

# MERMIN DETECTOR

- This device is a *Mermin detector*
- It detects particles that strike its right-hand side
- It has a switch that can be in position **1**, **2** or **3**
- When it is struck by a particle, either the red light or the green light flashes



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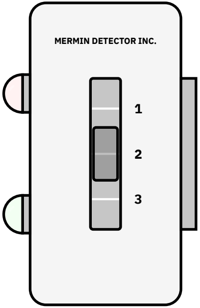

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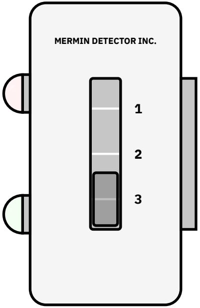

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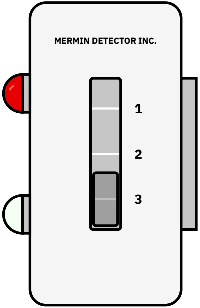

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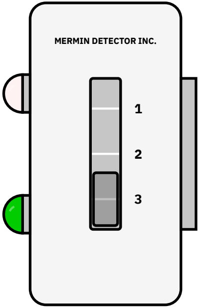
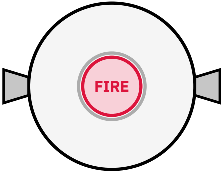


# PARTICLE EMITTER

- This device is a *particle emitter*
- You can press the button labelled **FIRE**
- Two particles are emitted from it in opposite directions



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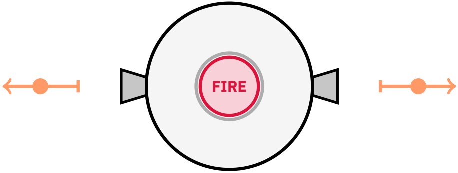
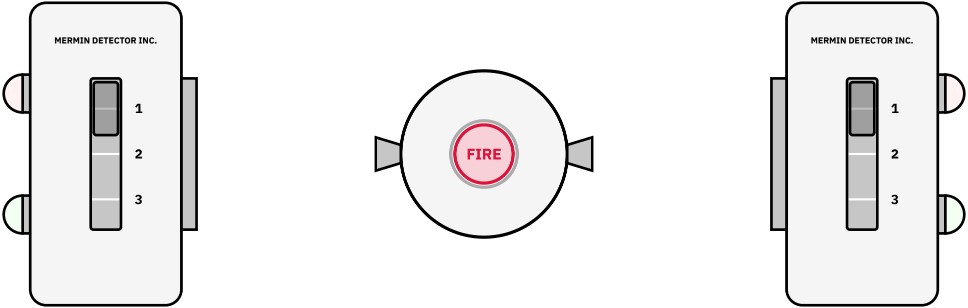


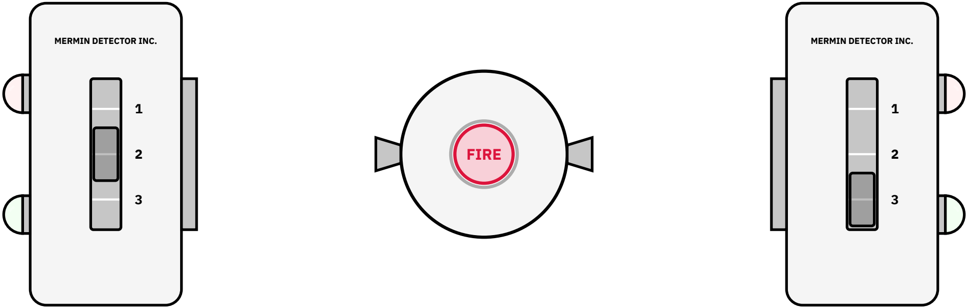
# EXPERIMENTAL SETUP

1. Place the particle emitter between two Mermin detectors



# EXPERIMENTAL SETUP

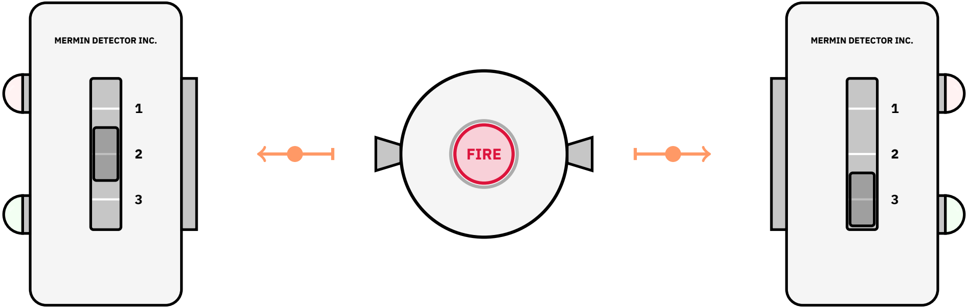
## 2. Randomly set the switches




There are 9 equally likely configurations: $\overset{\text{L}}{\mathbf{1}}\mathbf{:}\overset{\text{R}}{\mathbf{1}}$, $\overset{\text{L}}{\mathbf{1}}\mathbf{:}\overset{\text{R}}{\mathbf{2}}$, $\overset{\text{L}}{\mathbf{1}}\mathbf{:}\overset{\text{R}}{\mathbf{3}}$, $\overset{\text{L}}{\mathbf{2}}\mathbf{:}\overset{\text{R}}{\mathbf{1}}$, $\overset{\text{L}}{\mathbf{2}}\mathbf{:}\overset{\text{R}}{\mathbf{2}}$, $\overset{\text{L}}{\mathbf{2}}\mathbf{:}\overset{\text{R}}{\mathbf{3}}$, $\overset{\text{L}}{\mathbf{3}}\mathbf{:}\overset{\text{R}}{\mathbf{1}}$, $\overset{\text{L}}{\mathbf{3}}\mathbf{:}\overset{\text{R}}{\mathbf{2}}$ and $\overset{\text{L}}{\mathbf{3}}\mathbf{:}\overset{\text{R}}{\mathbf{3}}$. Here we have $\overset{\text{L}}{\mathbf{2}}\mathbf{:}\overset{\text{R}}{\mathbf{3}}$

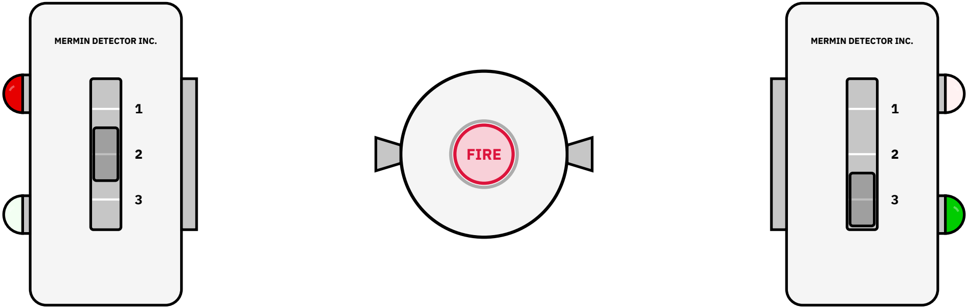
# EXPERIMENTAL SETUP

3. Press the **FIRE** button — two particles are emitted



# EXPERIMENTAL SETUP

4. The particles hit the detectors — observe which lights flash




Here we have **RED** and **GREEN**. We record this result as **23RG** — switches set at $\overset{L}{\mathbf{2}}:\overset{R}{\mathbf{3}}$ and flashes $\overset{L}{\mathbf{R}}:\overset{R}{\mathbf{G}}$

# REPEAT, REPEAT, REPEAT

- Repeat these 4 steps over and over again — I will show results from 10,000 repeats
- We choose the switch settings randomly each time
- We record each result in the format **[LEFT SWITCH][RIGHT SWITCH][LEFT COLOR][RIGHT COLOR]**, e.g., **23RG** every time

Section 2

# Mermin experiment results

# Notebook of first 100 results

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 12RR | 21RG | 22RR | 33RR | 12GR | 21GR | 33RR | 23RR | 31RG | 23RR |
| 22RR | 11RR | 22GG | 12GG | 32GG | 13RG | 23GR | 23RR | 23RG | 11RR |
| 31GR | 11GG | 21GR | 33GG | 12RR | 12RG | 22GG | 13RG | 21GR | 12RG |
| 31RR | 12GR | 32GR | 11RR | 23RG | 12GR | 11RR | 32RG | 12RR | 23RG |
| 32GR | 13GR | 32RR | 32GG | 11GG | 12GR | 11GG | 31RR | 13GG | 33RR |
| 33RR | 23RG | 32RG | 22GG | 31RG | 13RG | 23RR | 13GR | 21RG | 13RR |
| 13RR | 11RR | 22RR | 21RR | 12RR | 22GG | 23RG | 31RG | 12GR | 22RR |
| 23RG | 31GG | 33GG | 21RR | 32RG | 11GG | 31RG | 33GG | 12RG | 13GR |
| 33RR | 32GG | 31RG | 22RR | 23RG | 33GG | 22GG | 23GR | 31GR | 31GR |
| 33RR | 13GR | 22RR | 32RG | 13RG | 13GG | 23RG | 12RG | 23RR | 12GR |

# CASE (A)

Look at when the two detectors are in the same state, i.e. $\overset{L}{1}:\overset{R}{1}$, $\overset{L}{2}:\overset{R}{2}$ or $\overset{L}{3}:\overset{R}{3}$

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 12RR | 21RG | **22RR** | **33RR** | 12GR | 21GR | **33RR** | 23RR | 31RG | 23RR |
| **22RR** | **11RR** | **22GG** | 12GG | 32GG | 13RG | 23GR | 23RR | 23RG | **11RR** |
| 31GR | **11GG** | 21GR | **33GG** | 12RR | 12RG | **22GG** | 13RG | 21GR | 12RG |
| 31RR | 12GR | 32GR | **11RR** | 23RG | 12GR | **11RR** | 32RG | 12RR | 23RG |
| 32GR | 13GR | 32RR | 32GG | **11GG** | 12GR | **11GG** | 31RR | 13GG | **33RR** |
| **33RR** | 23RG | 32RG | **22GG** | 31RG | 13RG | 23RR | 13GR | 21RG | 13RR |
| 13RR | **11RR** | **22RR** | 21RR | 12RR | **22GG** | 23RG | 31RG | 12GR | **22RR** |
| 23RG | 31GG | **33GG** | 21RR | 32RG | **11GG** | 31RG | **33GG** | 12RG | 13GR |
| **33RR** | 32GG | 31RG | **22RR** | 23RG | **33GG** | **22GG** | 23GR | 31GR | 31GR |
| **33RR** | 13GR | **22RR** | 32RG | 13RG | 13GG | 23RG | 12RG | 23RR | 12GR |

# CASE (A)

**Case (A):** The two detectors are in the same state, i.e. $\overset{L}{\mathbf{1}}\mathbf{:}\overset{R}{\mathbf{1}}$, $\overset{L}{\mathbf{2}}\mathbf{:}\overset{R}{\mathbf{2}}$ or $\overset{L}{\mathbf{3}}\mathbf{:}\overset{R}{\mathbf{3}}$

1. This case occurs about one-third of the time as the detector states are randomly chosen — 3,301 times in 10,000 results
2. In this case, we only ever see $\overset{L}{\mathbf{R}}\mathbf{:}\overset{R}{\mathbf{R}}$ or $\overset{L}{\mathbf{G}}\mathbf{:}\overset{R}{\mathbf{G}}$
3. We see them with approximately equal frequency — 1,636 occurrences of $\overset{L}{\mathbf{R}}\mathbf{:}\overset{R}{\mathbf{R}}$ and 1,665 of $\overset{L}{\mathbf{G}}\mathbf{:}\overset{R}{\mathbf{G}}$

> **Case (A):** $\overset{L}{\mathbf{R}}\mathbf{:}\overset{R}{\mathbf{R}}$ or $\overset{L}{\mathbf{G}}\mathbf{:}\overset{R}{\mathbf{G}}$ occurs 100% of the time

# CASE (B)

Look at when the two detectors are in different states, i.e. $\overset{L\ \ R}{1:2}$, $\overset{L\ \ R}{1:3}$ $\overset{L\ \ R}{2:1}$ $\overset{L\ \ R}{2:3}$ $\overset{L\ \ R}{3:1}$ or $\overset{L\ \ R}{3:2}$

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 12RR | 21RG | 22RR | 33RR | 12GR | 21GR | 33RR | 23RR | 31RG | 23RR |
| 22RR | 11RR | 22GG | 12GG | 32GG | 13RG | 23GR | 23RR | 23RG | 11RR |
| 31GR | 11GG | 21GR | 33GG | 12RR | 12RG | 22GG | 13RG | 21GR | 12RG |
| 31RR | 12GR | 32GR | 11RR | 23RG | 12GR | 11RR | 32RG | 12RR | 23RG |
| 32GR | 13GR | 32RR | 32GG | 11GG | 12GR | 11GG | 31RR | 13GG | 33RR |
| 33RR | 23RG | 32RG | 22GG | 31RG | 13RG | 23RR | 13GR | 21RG | 13RR |
| 13RR | 11RR | 22RR | 21RR | 12RR | 22GG | 23RG | 31RG | 12GR | 22RR |
| 23RG | 31GG | 33GG | 21RR | 32RG | 11GG | 31RG | 33GG | 12RG | 13GR |
| 33RR | 32GG | 31RG | 22RR | 23RG | 33GG | 22GG | 23GR | 31GR | 31GR |
| 33RR | 13GR | 22RR | 32RG | 13RG | 13GG | 23RG | 12RG | 23RR | 12GR |

# CASE (B)

**Case (B):** the two detectors are in different states, i.e. $\overset{L}{1}:\overset{R}{2}$, $\overset{L}{1}:\overset{R}{3}$, $\overset{L}{2}:\overset{R}{1}$, $\overset{L}{2}:\overset{R}{3}$, $\overset{L}{3}:\overset{R}{1}$ or $\overset{L}{3}:\overset{R}{2}$

1. This case occurs about two-thirds of the time as the detector states are randomly chosen — 6,699 times in 10,000 results
2. In this case, we see all four outcomes: $\overset{L}{R}:\overset{R}{R}$, $\overset{L}{G}:\overset{R}{G}$, $\overset{L}{R}:\overset{R}{G}$ and $\overset{L}{G}:\overset{R}{R}$
3. In this case, we see matching colors, $\overset{L}{R}:\overset{R}{R}$ or $\overset{L}{G}:\overset{R}{G}$, about 25% of the time — 1690 times out of 6,699 cases

**Case (B):** $\overset{L}{R}:\overset{R}{R}$ or $\overset{L}{G}:\overset{R}{G}$ occurs 25% of the time

# SUMMARIZING OBSERVATIONS

We can summarize our results as follows:

- **Case (A)**: When detector states are the *same*, we see $\overset{L}{\mathbf{R}}{:}\overset{R}{\mathbf{R}}$ or $\overset{L}{\mathbf{G}}{:}\overset{R}{\mathbf{G}}$ 100% of the time
- **Case (B)**: When detector states are *different*, we see $\overset{L}{\mathbf{R}}{:}\overset{R}{\mathbf{R}}$ or $\overset{L}{\mathbf{G}}{:}\overset{R}{\mathbf{G}}$ 25% of the time

Section 3

# Hidden Instruction Model

# EXPLAINING OBSERVATIONS IN CASE (A)

**Q:** There are no wires or connections between the detectors. How can the detectors produce matching outcomes without communicating?

**A: Hidden instruction model**

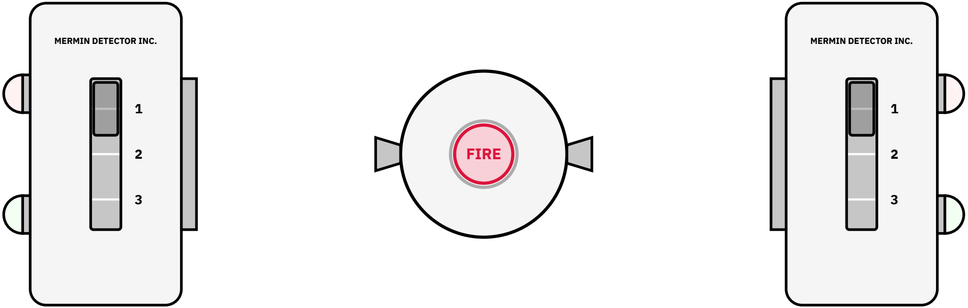
**PARTICLE CARRIES HIDDEN INSTRUCTIONS**

# Hidden Instruction Model

- The particles contain hidden instructions, e.g., if state **1**, show **RED**
- The instructions could be encoded in the form e.g., $\overset{1\,2\,3}{\mathbf{RGR}}$, which means
  - If state **1**, show **RED**
  - If state **2**, show **GREEN**
  - If state **3**, show **RED**
- There are 8 possible instruction sets: $\overset{1\,2\,3}{\mathbf{RRR}}$, $\overset{1\,2\,3}{\mathbf{RRG}}$, $\overset{1\,2\,3}{\mathbf{RGR}}$, $\overset{1\,2\,3}{\mathbf{GRR}}$, $\overset{1\,2\,3}{\mathbf{RGG}}$, $\overset{1\,2\,3}{\mathbf{GRG}}$, $\overset{1\,2\,3}{\mathbf{GGR}}$ and $\overset{1\,2\,3}{\mathbf{GGG}}$
- The coordination is explained if the emitter sends the *same* instruction to each detector

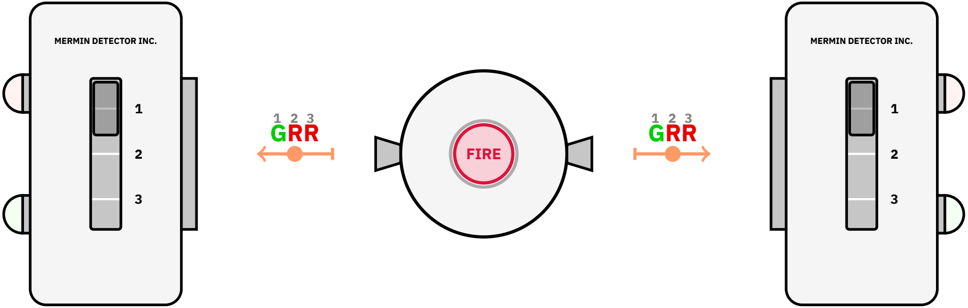
# EMITTER SENDS INSTRUCTIONS

1. The detectors are in the same state — $\overset{L}{1}:\overset{R}{1}$



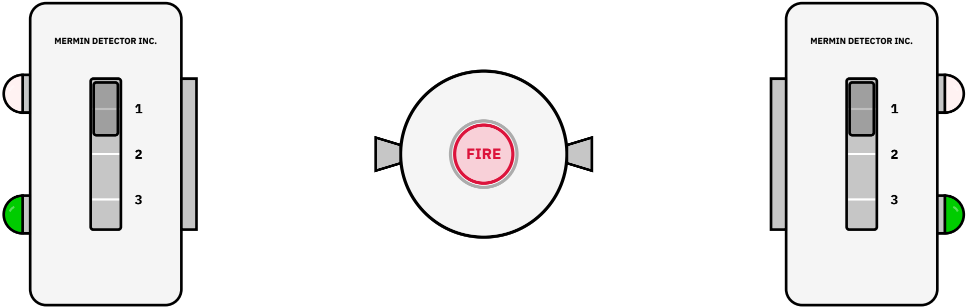
# EMITTER SENDS INSTRUCTIONS

2. We press **FIRE** and two particles are emitted carrying *identical instructions*, e.g., GRR (1 2 3)



# EMITTER SENDS INSTRUCTIONS

3. The detectors follow the instructions and thus show the same colour



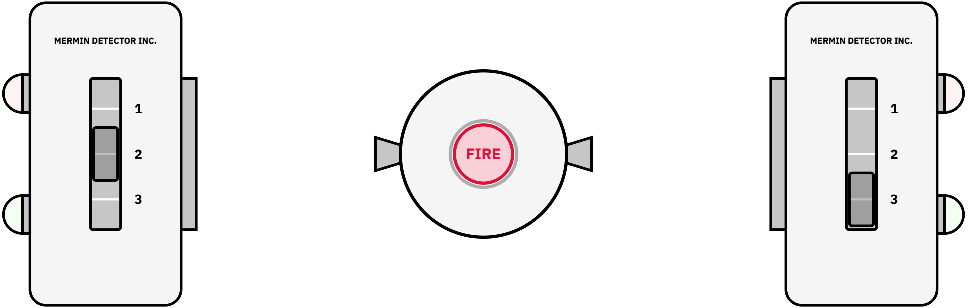

The detectors were in state **1** and received instruction $\overset{1}{\text{G}}\overset{2}{\text{R}}\overset{3}{\text{R}}$ and thus showed **GREEN**

## Hidden Instruction Model in Case (b)

- The emitter doesn’t know the detector settings — the hidden instructions it sends cannot depend on the detector settings
- Suppose the emitter again sends $\overset{1}{\mathbf{G}}\overset{2}{\mathbf{R}}\overset{3}{\mathbf{R}}$ but this time the switches are in different states, e.g., $\overset{L}{\mathbf{2}}:\overset{R}{\mathbf{3}}$

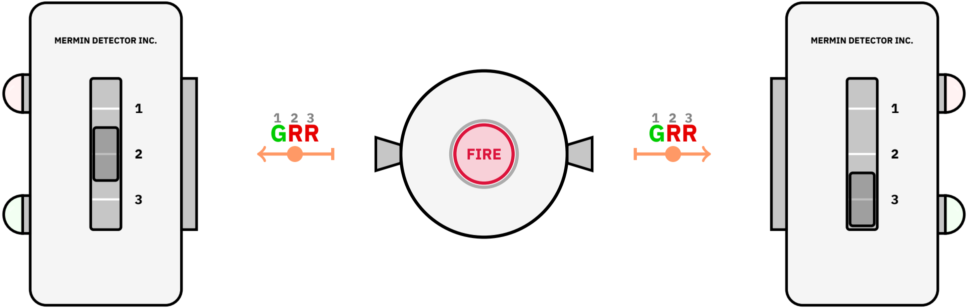
# EMITTER SENDS INSTRUCTIONS

1. The detectors are in different states — L:R 2:3



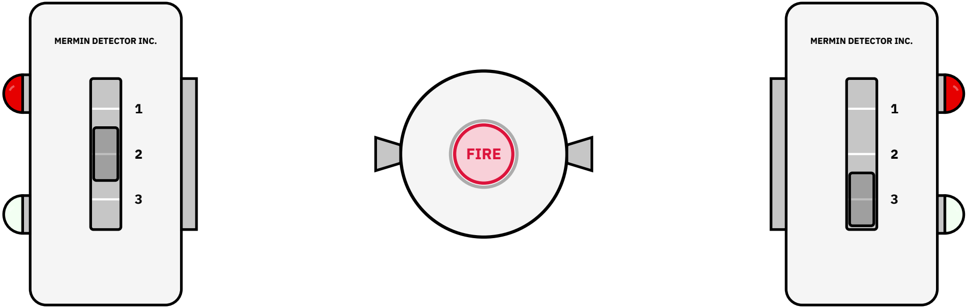
# EMITTER SENDS INSTRUCTIONS

2. We press **FIRE** and two particles are emitted carrying identical instructions, e.g., $\overset{1\,2\,3}{GRR}$



# EMITTER SENDS INSTRUCTIONS

3. The detectors follow the instructions




The detectors were in state **2:3** and received instruction **GRR**. They thus showed the colors corresponding to the second and third characters, both **RED**

# Hidden Instruction Model in Case (B)

For the code $\overset{1}{\mathbf{G}}\overset{2}{\mathbf{R}}\overset{3}{\mathbf{R}}$ and different detector states, how often will they flash the same colour?

- There are 6 equally probable switch settings: $\overset{L}{\mathbf{1}}:\overset{R}{\mathbf{2}}$, $\overset{L}{\mathbf{1}}:\overset{R}{\mathbf{3}}$, $\overset{L}{\mathbf{2}}:\overset{R}{\mathbf{1}}$, $\overset{L}{\mathbf{2}}:\overset{R}{\mathbf{3}}$, $\overset{L}{\mathbf{3}}:\overset{R}{\mathbf{1}}$ and $\overset{L}{\mathbf{3}}:\overset{R}{\mathbf{2}}$
- $\overset{L}{\mathbf{G}}:\overset{R}{\mathbf{G}}$ is impossible, as it would require setting $\overset{L}{\mathbf{1}}:\overset{R}{\mathbf{1}}$
- $\overset{L}{\mathbf{R}}:\overset{R}{\mathbf{R}}$ is possible for 2 switch settings: $\overset{L}{\mathbf{2}}:\overset{R}{\mathbf{3}}$ and $\overset{L}{\mathbf{3}}:\overset{R}{\mathbf{2}}$
- Thus they show the same colour with a frequency of 2/6, about 33%

The same reasoning applies to the 5 codes $\overset{1}{\mathbf{R}}\overset{2}{\mathbf{G}}\overset{3}{\mathbf{R}}$, $\overset{1}{\mathbf{R}}\overset{2}{\mathbf{R}}\overset{3}{\mathbf{G}}$, $\overset{1}{\mathbf{G}}\overset{2}{\mathbf{G}}\overset{3}{\mathbf{R}}$, $\overset{1}{\mathbf{G}}\overset{2}{\mathbf{R}}\overset{3}{\mathbf{G}}$ and $\overset{1}{\mathbf{R}}\overset{2}{\mathbf{G}}\overset{3}{\mathbf{G}}$

# EXPLAINING OBSERVATIONS IN CASE (B)

For the code $\overset{1}{\mathbf{R}}\overset{2}{\mathbf{R}}\overset{3}{\mathbf{R}}$, how often will they flash the same colour?

- $\overset{L}{\mathbf{R}}\mathbf{:}\overset{R}{\mathbf{R}}$ occurs for any switch setting, i.e., at a frequency of 100%

The same reasoning applies to the code $\overset{1}{\mathbf{G}}\overset{2}{\mathbf{G}}\overset{3}{\mathbf{G}}$. We have now considered all 8 codes

# Contradiction in the Hidden Instruction Model

- Our explanation for observations in **Case (A)** was that the particles carry the same instruction set to each detector — the hidden instruction model
- We have just shown that this predicts $\overset{L}{\mathbf{R}}:\overset{R}{\mathbf{R}}$ or $\overset{L}{\mathbf{G}}:\overset{R}{\mathbf{G}}$ should occur at least 33% of the time in **Case (B)**
- Observations showed that $\overset{L}{\mathbf{R}}:\overset{R}{\mathbf{R}}$ or $\overset{L}{\mathbf{G}}:\overset{R}{\mathbf{G}}$ occurred only 25% of the time in **Case (B)**

**Conclusion:** Identical hidden instructions cannot explain the data

Section 4

# BELL'S THEOREM

# What can explain the data?

There were 3 assumptions in our failed hidden instruction model

- **Locality:** the output from the left-hand side detector cannot depend on the right-hand side detector setting, and vice-versa
- **Realism:** the detectors are reacting to pre-existing instructions carried by the particles
- **No-conspiracy:** we were free to choose the detector settings — no conspiracy between our setting choices and the particles emitted

We could break one of these to explain the data

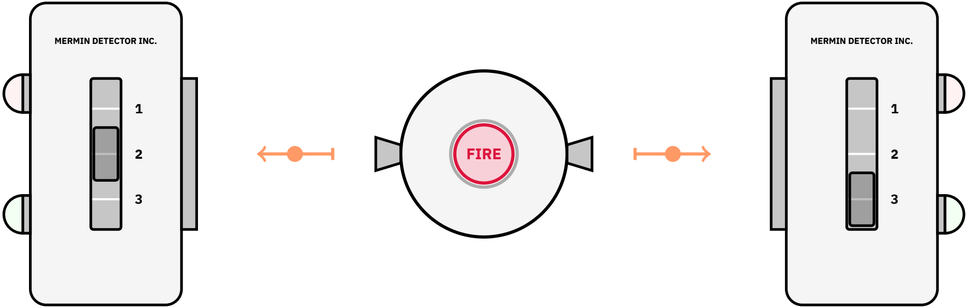
# LOCALITY

> **Locality:** the output from the left-hand side detector cannot depend on the right-hand side detector setting, and vice-versa

- In the hidden instruction model, the detector output depended *only* on the detector setting and the instruction
- E.g., detector setting **1** and instruction $\overset{1}{\mathbf{R}}\overset{2}{\mathbf{G}}\overset{3}{\mathbf{G}}$ always outputs **RED** regardless of the other detector setting
- Non-local instructions would depend on the states of *both* detectors. In a non-local hidden instruction model, each particle could carry an instruction for the colours of each detector in the 9 possible cases, e.g., $\overset{1:1}{\mathbf{RR}}\ \overset{1:2}{\mathbf{GR}}\ \overset{1:3}{\mathbf{GG}}\ \overset{2:1}{\mathbf{RG}}\ \overset{2:2}{\mathbf{RR}}\ \overset{2:3}{\mathbf{GR}}\ \overset{3:1}{\mathbf{RR}}\ \overset{3:2}{\mathbf{GR}}\ \overset{3:3}{\mathbf{GG}}$

# EXERCISE: CONSTRUCT INSTRUCTION SETS FOR A NON-LOCAL HIDDEN INSTRUCTION MODEL

# LOCALITY




**What happens in this detector ...**

**... cannot depend on this detector setting, arbitrarily far away**

# REALISM

**Realism:** the detectors are reacting to pre-existing instructions carried by the particles

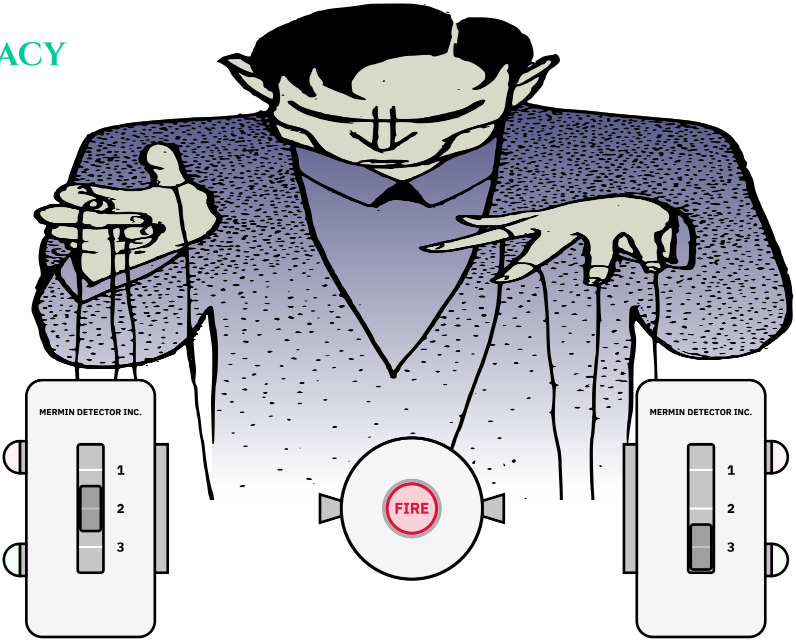
- In the hidden instruction model, the particles carried a pre-existing instruction, e.g., $\overset{1}{\mathrm{R}}\overset{2}{\mathrm{G}}\overset{3}{\mathrm{G}}$
- With detector setting **1**, we see **RED**. The instructions $\overset{2}{\mathrm{G}}\overset{3}{\mathrm{G}}$ for cases **2** and **3** existed, even though we didn't choose settings **2** or **3**

# No-conspiracy

**No-conspiracy:** we were free to choose the detector settings — no conspiracy between our setting choices and the particles emitted

- For any hidden instruction emitted, e.g., $\overset{1}{\mathbf{R}}\overset{2}{\mathbf{G}}\overset{3}{\mathbf{G}}$, we were free in principle to have chosen any of the 9 detector settings: $\overset{L}{\mathbf{1}}:\overset{R}{\mathbf{1}}$, $\overset{L}{\mathbf{1}}:\overset{R}{\mathbf{2}}$, $\overset{L}{\mathbf{1}}:\overset{R}{\mathbf{3}}$, $\overset{L}{\mathbf{2}}:\overset{R}{\mathbf{1}}$, $\overset{L}{\mathbf{2}}:\overset{R}{\mathbf{2}}$, $\overset{L}{\mathbf{2}}:\overset{R}{\mathbf{3}}$,$\overset{L}{\mathbf{3}}:\overset{R}{\mathbf{1}}$, $\overset{L}{\mathbf{3}}:\overset{R}{\mathbf{2}}$ or $\overset{L}{\mathbf{3}}:\overset{R}{\mathbf{3}}$
- A conspiracy would mean we were not free to choose the detector settings — we were fated to choose the ones we did given the instructions of the particles that were emitted

# CONSPIRACY



# CONSPIRACY

- Suppose that the puppetmaster picked a random row from this table
- The result was fated to be the one in that row
- We weren't free to choose the settings — we were fated to choose the settings in that row
- We would see R:R or G:G in 100% in **case (A)** and about 17% in **case (B)**
- That is less than the 33% bound we found before — with a bigger table, we could even arrange exactly 25%

| Setting | Case | Result | R:R or G:G |
|---|---|---|---|
| 1:1 | **A** | R:R | Y |
| 1:2 | **B** | R:R | Y |
| 1:3 | **B** | R:G | N |
| 2:1 | **B** | G:R | N |
| 2:2 | **A** | G:G | Y |
| 2:3 | **B** | R:G | N |
| 3:1 | **B** | R:G | N |
| 3:2 | **B** | G:R | N |
| 3:3 | **A** | R:R | Y |

## **EXERCISE:** CONSTRUCT A TABLE OF 18 ENTRIES THAT YIELDS A 25% PROBABILTY

# Bell's theorem

We have reached *Mermin's version* of *Bell's theorem* (Bell, 1964)

**Bell's theorem:** Without a *conspiracy*, no theory that is both *local* and *real* can explain this data

This is profoundly important: the data rule out any hidden instruction model and any local-real theory. Whatever is left will be weird and non-classical

# Which assumption should we break?

To explain the data, which assumption should we break?

- **Locality:** breaking it is in tension with *special relativity* and allows dependence at arbitrary distances
- **Realism:** breaking it means that properties of objects do not exist before they are measured
- **No-conspiracy:** breaking it means that our choices of measurement settings can never be truly free

Section 5

# Welcome to the Quantum World

# Welcome to the Quantum World

- **Quantum mechanics** can explain this data extremely successfully

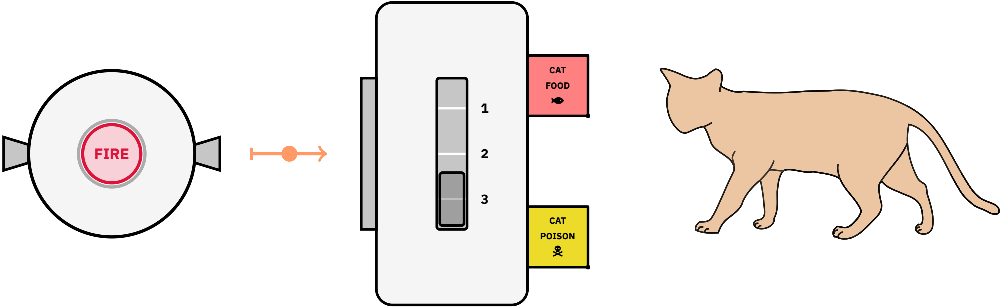
**Non-real:** Quantum mechanics breaks realism

- That means that some properties do not have definite values before we measure them
- Schrödinger's cat is a thought experiment that shows us just how weird that would be if it applied to everyday objects

**This is a thought experiment — I oppose any cruelty to animals**

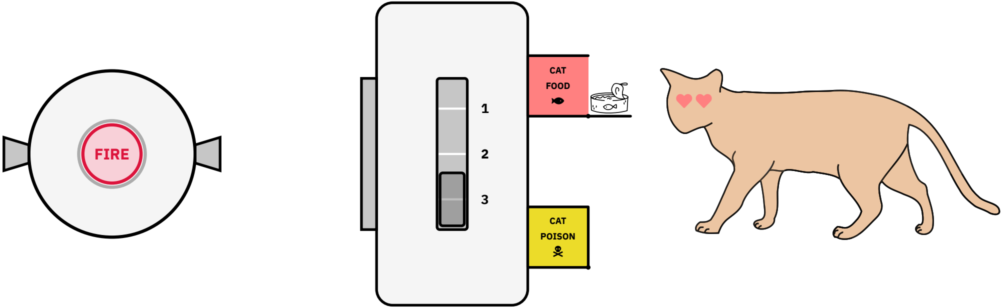
# SCHRÖDINGER'S CAT

Instead of red and green lights that can flash, this device has cat food and cat poison boxes that can open and a cat



# SCHRÖDINGER'S CAT

Instead of red and green lights that can flash, this device has **cat food** and cat poison boxes that can open and a cat



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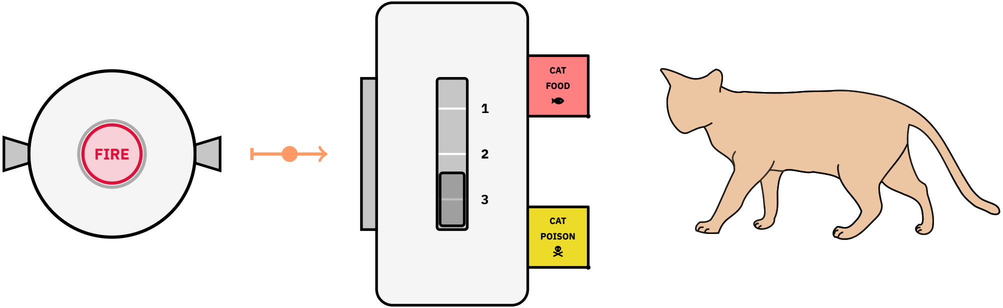

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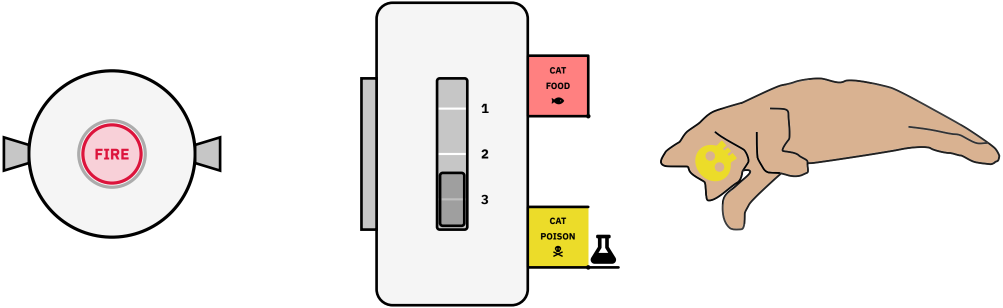
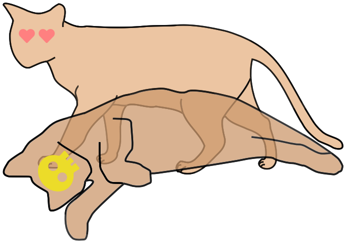


# SCHRÖDINGER'S CAT

- In quantum theory, some properties do not exist until they are observed
- If we press **FIRE**, but don't observe the cat or the detector, is the cat dead or alive?
- If quantum rules applied to everyday objects as well as small things, before the cat is observed, it must be in a strange state — **a superposition** — of dead **and** alive

**Superposition of dead and alive is weird** — resolving that weirdness is known as the *measurement problem*



# FURTHER READING

- Mermin's original paper (Mermin, 1981) and follow-up Mermin (1990)
- This simple proof of Bell's inequality (Maccone, 2013)
- The famous Einstein-Podolsky-Rosen (EPR) paper (Einstein et al., 1935)
- John Bell's book (Bell, 2004)

# CONCLUSIONS

- We described a simple experiment involving a particle emitter and two detectors
- We showed that the results could not be explained by a simple local realist theory
- To explain the results, we needed to give up at least one assumption
  - **Locality** — measurements cannot depend on things that are arbitrarily far away
  - **Realism** — measurements reveal pre-existing properties of objects
  - **No-conspiracy** — we are free to choose what measurements we make
- Quantum mechanics gives up realism — some properties do not have pre-existing values before we observe them
- Schrödinger's cat shows us just how weird quantum mechanics would be if it applied to everyday objects

# References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