Picturing Quantum Processes

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Chapter 1: Introduction

Under normal conditions the research scientist is not an innovator but a solver of puzzles, and the puzzles upon which he concentrates are just those which he believes can be both stated and solved within the existing scientific tradition.

Quantum theory: The standard line

- Quantum theory governs the behaviour of the microscopic world

- True, it has some 'bugs' from the p.o.v. of classical physics:
  - irreducible non-determinism
  - non-locality
  - incompatible observations
  - ...

- A century of effort went to answering: Why is quantum theory so weird, and can we fix its bugs?
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- You’ve probably heard from credible sources\(^1\) that it is **weird**, **spooky**, and defies our **natural, classical intuitions**.

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(Mermin, describing the Copenhagen interpretation)
Another, more interesting question

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  What if the **bugs** in quantum theory are actually **features**?
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- Enter:

  quantum teleportation, communication, cryptography

  quantum computation
From QT to teleportation

1932 - quantum theory
1992 - quantum teleportation

⇒

We'll see that teleportation is miraculous...but it's also totally obvious.
From QT to teleportation

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⇒

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Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels

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(Received 2 December 1992)
From QT to teleportation

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We’ll see that teleportation is **miraculous**...but it’s also **totally obvious**.
Q: Why did it take so long?
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Q2: Why is this so hard?
From QT to teleportation

**Q:** Why did it take so long?

**A:** It took 60 years to ask the right question.

**Q2:** Why is this so hard?

**A2:** QT needs a better language.
Low-level vs. high-level languages
Low-level vs. high-level languages

```
.LCO:
    .string "QUANTUM!"
    .text
    .globl main
    .type main, @function
main:
.LFB0:
    .cfi_startproc
    pushq  %rbp
    .cfi_def_cfa_offset 16
    .cfi_offset 6, -16
    movq  %rsp, %rbp
    .cfi_def_cfa_register 6
    subq  $16, %rsp
    movl  $0, -4(%rbp)
    jmp   .L2
.L3:
    movl  $.LCO, %edi
    movl  $0, %eax
    call   printf
    addl  $1, -4(%rbp)
.L2:
    cmpl  $4, -4(%rbp)
    jle   .L3
    leave
    .cfi_def_cfa 7, 8
    ret
    .cfi_endproc
```

```vs.
5. times do
    print "QUANTUM!"
end
```
Low-level vs. high-level languages
Low-level vs. high-level languages

\[
\frac{1}{4} \begin{pmatrix}
-1+i & 1+i & 1+i & -1+i & 1+i & 1-i & 1-i & 1+i \\
1+i & 1-i & 1-i & 1+i & -1+i & 1+i & 1+i & -1+i \\
1+i & 1-i & 1-i & 1+i & 1-i & -1-i & -1-i & 1-i \\
1-i & -1-i & -1-i & 1-i & 1+i & 1-i & 1-i & 1+i \\
1+i & 1-i & 1-i & 1+i & 1-i & -1-i & -1-i & 1-i \\
1-i & -1-i & -1-i & 1-i & 1+i & 1-i & 1-i & 1+i \\
-1+i & 1+i & 1+i & -1+i & 1+i & 1-i & 1-i & 1+i \\
1+i & 1-i & 1-i & 1+i & -1+i & 1+i & 1+i & -1+i
\end{pmatrix}
\]
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1+i & 1-i & 1-i & 1+i & 1-i & -1-i & -1-i & 1-i \\
1-i & -1-i & -1-i & 1-i & 1+i & 1-i & 1-i & 1+i \\
1+i & 1-i & 1-i & 1+i & 1-i & -1-i & -1-i & 1-i \\
1-i & -1-i & -1-i & 1-i & 1+i & 1-i & 1-i & 1+i \\
-1+i & 1+i & 1+i & -1+i & 1+i & 1-i & 1-i & 1+i \\
1+i & 1-i & 1-i & 1+i & -1+i & 1+i & 1+i & -1+i
\end{pmatrix}
\]
Quantum picturalism

Definition

Quantum picturalism refers to the use of diagrams to represent, reason about, and capture essential features and logic of interacting quantum processes.

\[
\begin{align*}
  \quad & = \\
  \quad & = 
\end{align*}
\]
Quantum theory: a warmup

• Typical quantum systems are photons, electrons, etc.
• You won't need any physics background for this course, so let's focus on an 'alternative' quantum system.
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- You won’t need any physics background for this course, so let’s focus on an ‘alternative’ quantum system
This is Dave.
This is Dave.

...he’s a dodo.
This is Dave.

...he’s a quantum dodo.
Bits vs. qubits

- Dave’s state is that of a *two-level system*, or a *qubit*, the simplest kind of quantum system.
Bits vs. qubits

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- Bits:
  1. admit two states, 0 and 1
  2. can be subjected *any* function
  3. can be read freely
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• Qubits:
  1. admit an *entire sphere* of states
  2. can *only be subjected to rotations* of the sphere
  3. can only be accessed by special processes called *quantum measurements*
Where’s Dave?

The rules:
1. we are only allowed to ask whether an animal lives at a specific location on Earth or its antipodal location,
2. all animals can talk, and will always answer 'correctly', and
3. predatory animals will refrain from eating the questioner.
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Process theories

- Dave (or rather, a qubit) is just one kind of *system*
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- systems undergo processes (e.g. rotations and measurements)
- if we wrap up all the processes which ‘fit together’ in a theory of physics/logic/computation/etc., we get a process theory
- The plan for this week:

Build the theory of quantum processes from scratch, and understand its behaviour using diagrams.