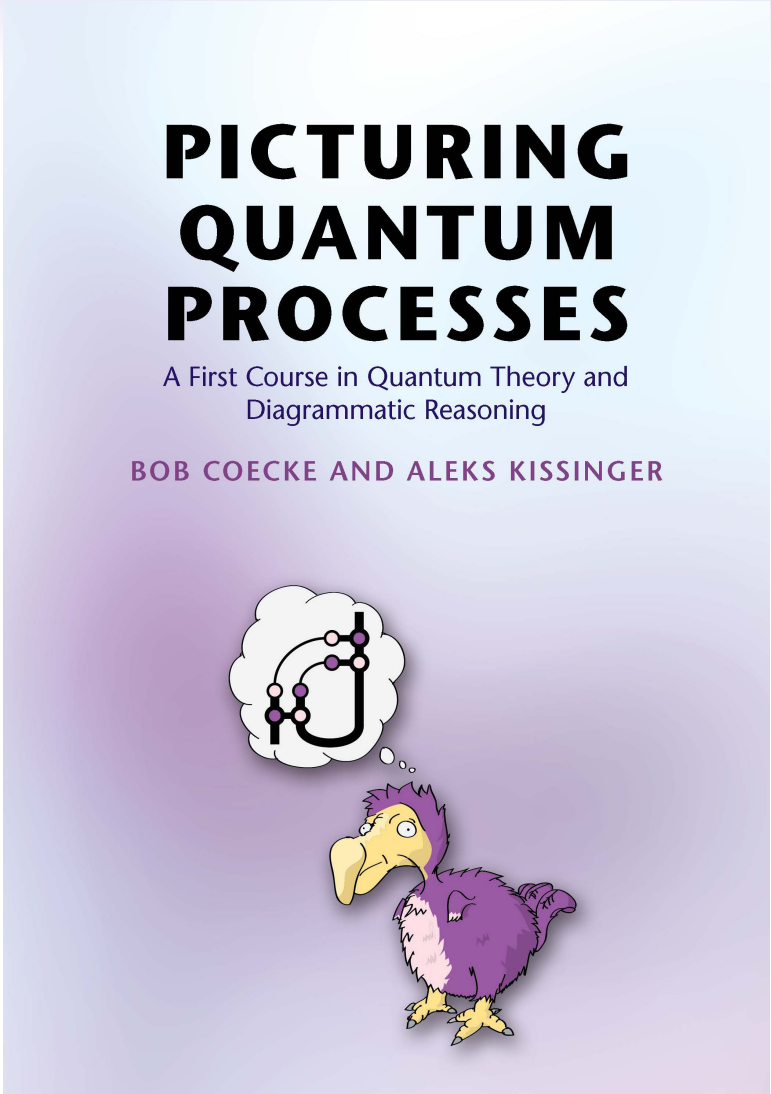
Picturing Quantum Processes

Aleks Kissinger and Bob Coecke

Radboud University and Oxford University

ESSLLI Toulouse 2017



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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.

— Thomas Kuhn, The Essential Tension, 1977.

Quantum theory: The standard line

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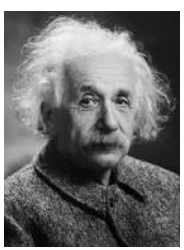
[1] e.g. 

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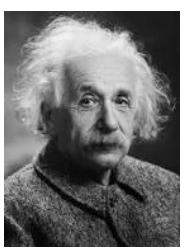
  - irreducible non-determinism
  - non-locality
  - incompatible observations
  - ...

[1] e.g. 

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- True, it has some 'bugs' from the p.o.v. of classical physics:
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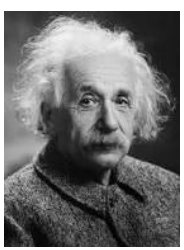
  - ...
- A century of effort went to answering:

  Why *is quantum theory so weird, and can we* **fix** *its bugs?*

[1] e.g. 

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(Mermin, describing the Copenhagen interpretation)

Another, more interesting question

- In the 1980s, a handful of people started to think like software engineers, and ask:

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

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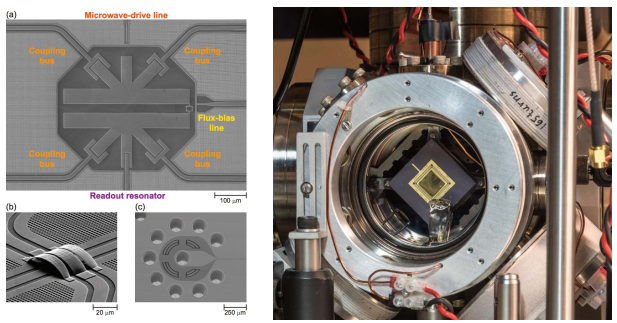
- Enter:

quantum teleportation, communication, cryptography

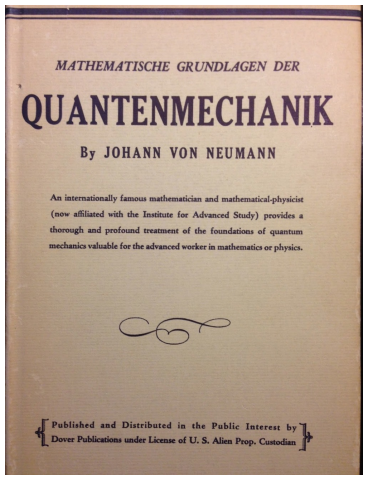


quantum computation

From QT to teleportation

From QT to teleportation

1932 - quantum theory



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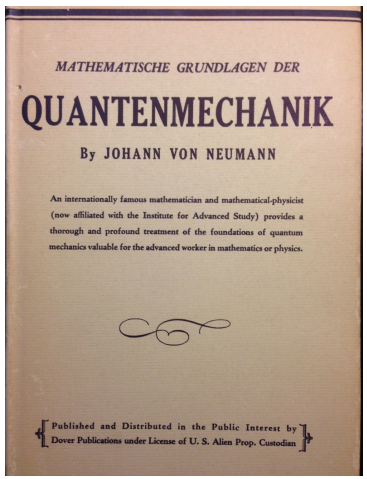

$\Rightarrow$

1992 - quantum teleportation

PHYSICAL REVIEW
LETTERS

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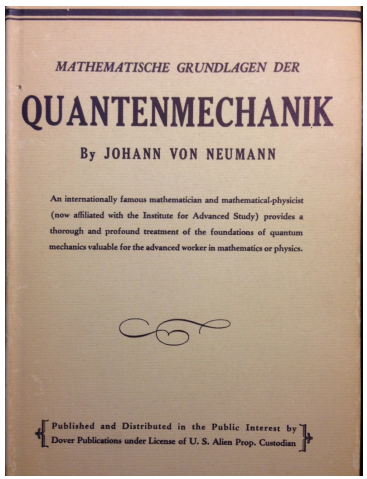
Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels

Charles H. Bennett,[1] Gilles Brassard,[2] Claude Crépeau,[2,3]
Richard Jozsa,[2] Asher Peres,[4] and William K. Wootters[5]
[1] *IBM Research Division, T.J. Watson Research Center, Yorktown Heights, New York 10598*
[2] *Département IRO, Université de Montréal, C.P. 6128, Succursale "A", Montréal, Québec, Canada H3C 3J7*
[3] *Laboratoire d'Informatique de l'École Normale Supérieure, 45 rue d'Ulm, 75230 Paris CEDEX 05, France*[a]
[4] *Department of Physics, Technion–Israel Institute of Technology, 32000 Haifa, Israel*
[5] *Department of Physics, Williams College, Williamstown, Massachusetts 01267*
(Received 2 December 1992)

From QT to teleportation

1932 - quantum theory



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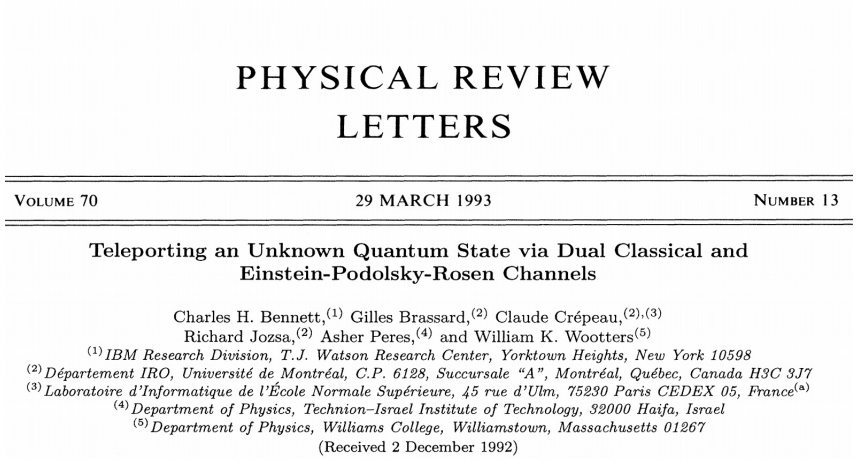

We'll see that teleportation is **miraculous**...but it's also **totally obvious**.

From QT to teleportation

Q: Why did it take so long?

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

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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

```
.LC0:
    .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    $.LC0, %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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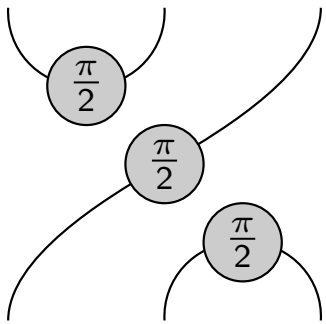
vs.



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.

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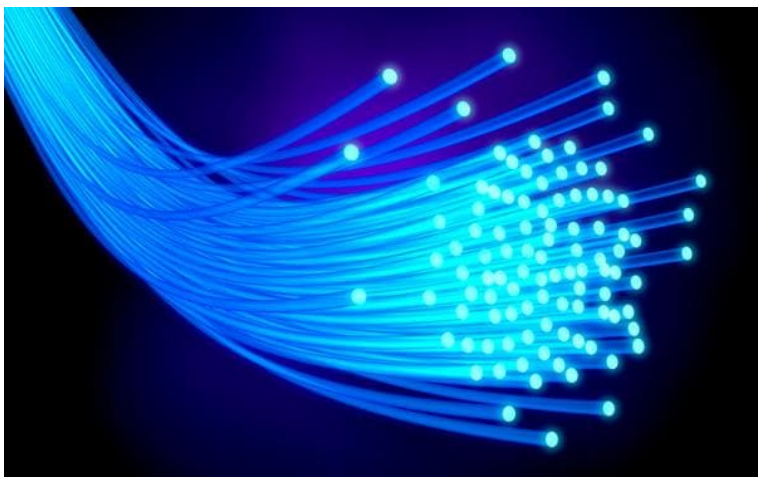

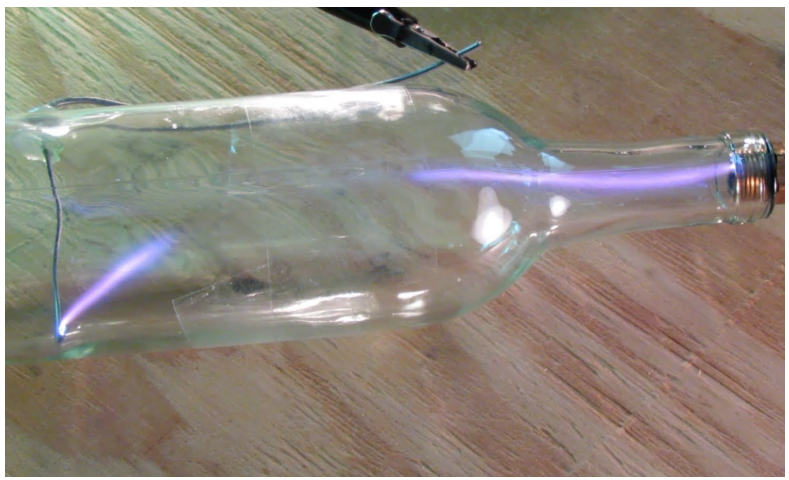

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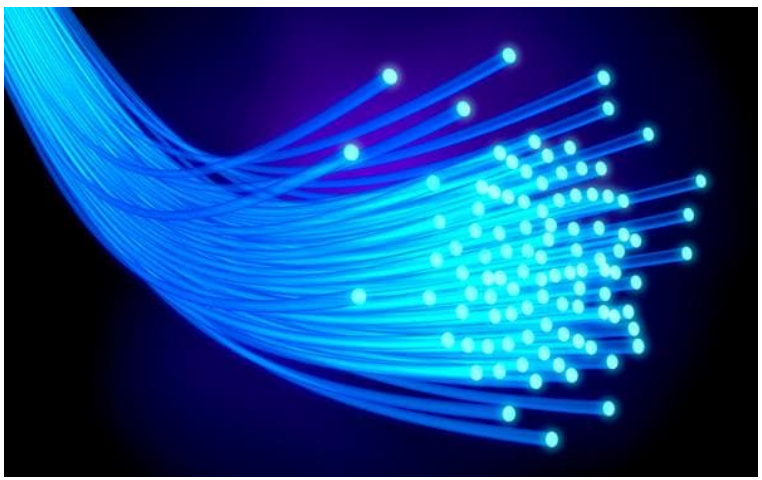
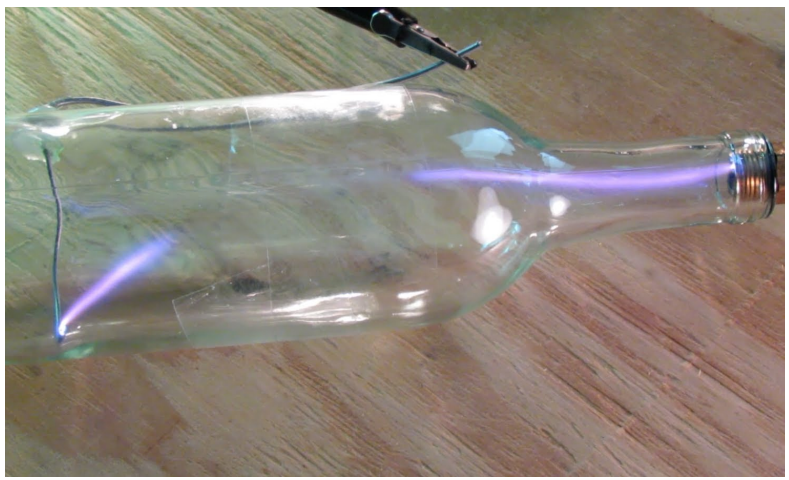
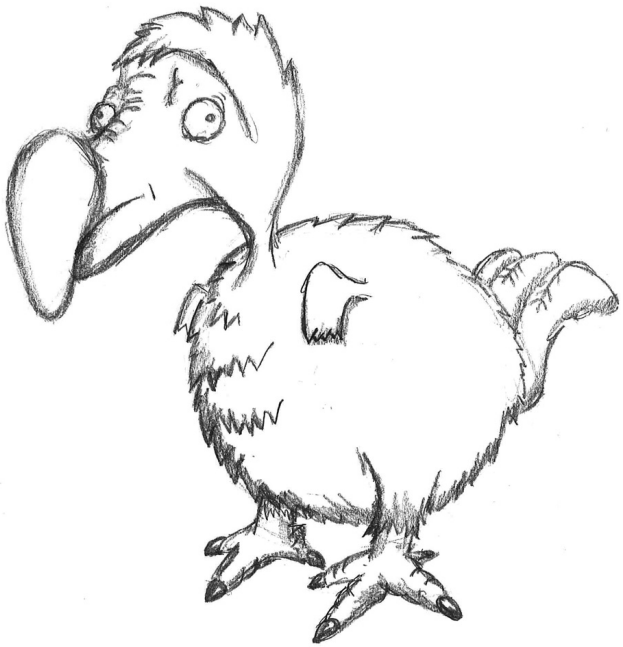




- You won't need any physics background for this course, so let's focus on an 'alternative' quantum system

This is Dave.



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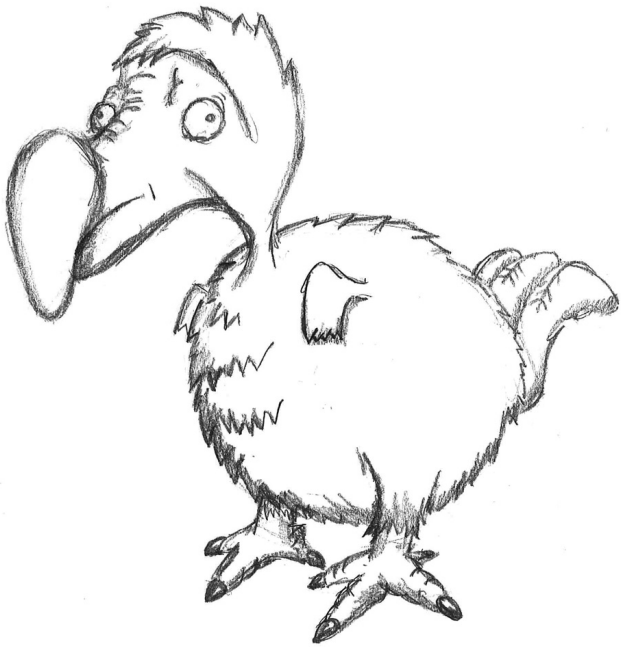

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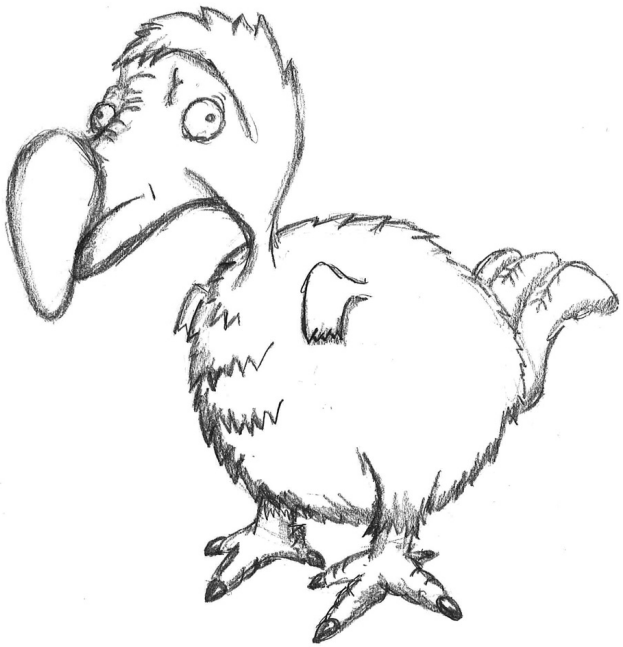

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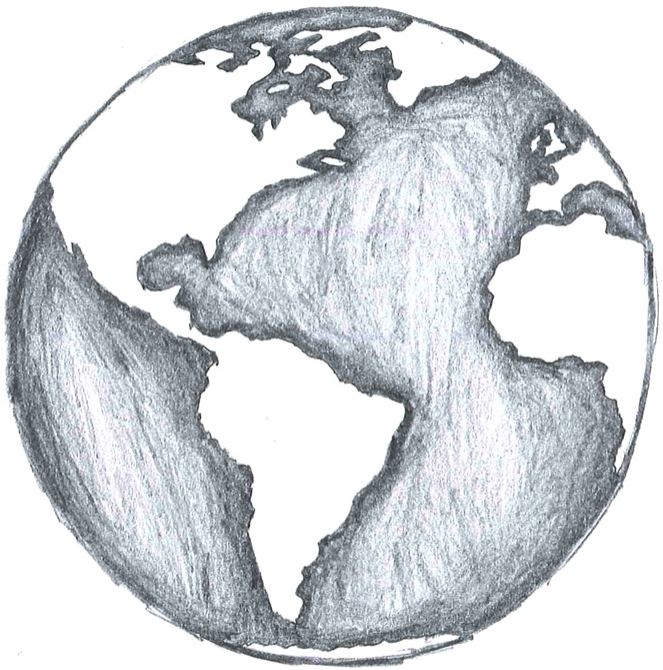
- Bits:
  1. admit two states, 0 and 1
  2. can be subjected *any* function
  3. can be read freely
- Qubits:
  1. admit an *entire sphere* of states
  2. can *only be subjected to rotations* of the sphere
  3. can only be accessed by special processes called *quantum measurements*



0
1

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2. all animals can talk, and will always answer 'correctly', and
3. predatory animals will refrain from eating the questioner.

South Pole

NORTH POLE

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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**.