Quantum Networks

for 5-year-old network researchers

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Network Theory Seminar @ LINCS

What to expect, what not to expect

At the end of this talk,

- You will not understand quantum physics;
- You will not understand quantum computing;
- You will only think you understand qubits (quantum bits) and Bell pairs;
- But you may hopefully get a feel for how quantum networks are expected to behave.

Also, since the objective is to oversimplify things to the point of making then intelligible, I will lie. A lot.

(I have a slide at the end quickly listing all the lies, if we ever get there)

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Why quantum networks?

Quantum networks are expected to be used in two fundamental ways:

- Transmitting qubits between distant quantum computers, e.g.
  - distributed quantum computers,
  - quantum cloud computing;
- Using the properties of qubits to improve classical distributed algorithms, e.g.
  - cryptography (cf. quantum key distribution, aka QKD),
  - consensus algorithms.

Quantum networks are not meant to replace classical networks:

- They are not efficient for simply transmitting classical bits;
- They require a classical network to operate.

It is best to consider quantum networks as a new tool for distributed algorithms, to be used alongside existing ones.

The main problem: losses

Qubits are sent by encoding their state inside single photons, but:

- 90% of photons are lost after going through only 50km of optical fiber, 99% after 100km, etc…
- We cannot duplicate qubits/photons encoding a specific quantum state, and therefore cannot amplify the signal.

Current solution for QKD: trusted nodes

Hot take: this is not really satisfactory, as it has limited application and is not very scalable…

We need to find another way of transmitting qubits along greater distances.

For this, we have a fundamental tool at our disposal: entanglement!

Entanglement allows us to transmit qubits without sending them through the network.

The aim of a quantum network is to distribute entanglement!

Outline

Qubits and entanglement

How do we transmit qubits without sending them?

What does "propagating entanglement" mean, and how do we do it?

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Qubits

"If you think you understand quantum mechanics, you don't understand quantum mechanics."

— Richard P. Feynman

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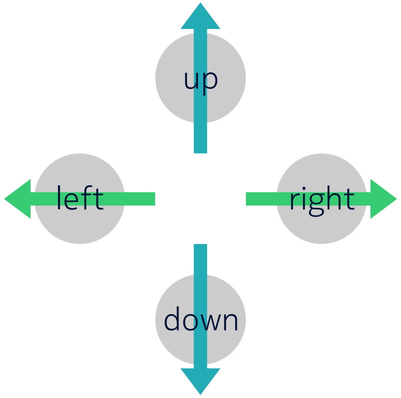
Classical bits (cbits) and quantum bits (qubits)

Classical bit
(2 states)

0 / 1

"Free" quantum bit
(4 states)



The state of a qubit can be encoded in
- the polarization of a single photon ("flying qubit", for transmission in optical fiber)
- the spin of a single electron ("matter qubit", for storage in quantum buffers)

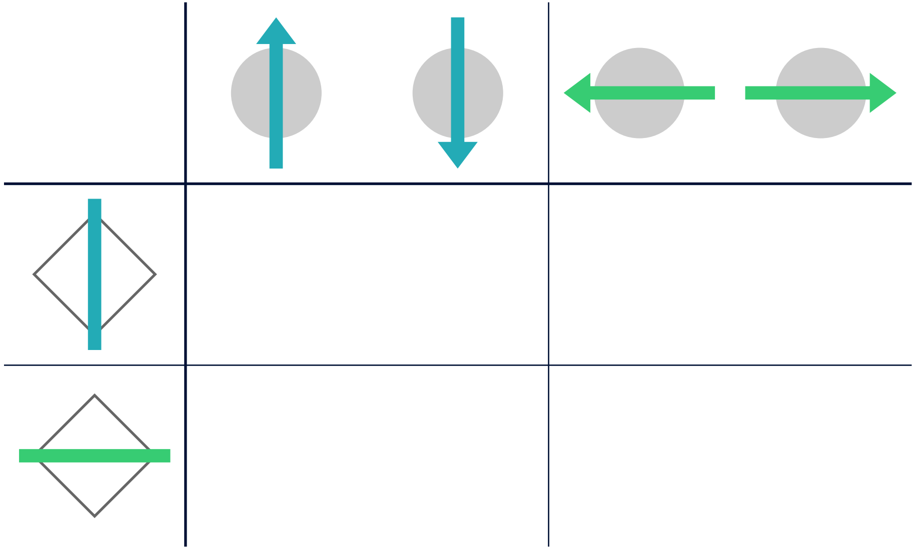
"Transduction" allows us to transfer between flying and matter qubits.

The state of a qubit cannot simply be "checked"...

.... it must be "measured"!

Measuring a qubit does 2 things:

- It changes the state of the qubit;
- It tells us the new state of the qubit.



There are 2 ways of measuring a qubit:

vertically and horizontally .

These are called the two "measurement bases".

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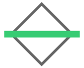
vertically  and horizontally .

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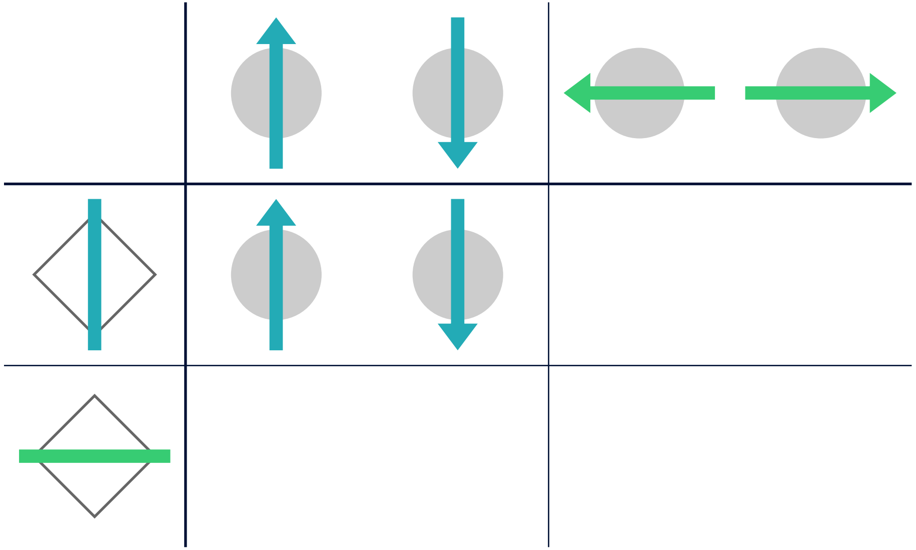

Vertically measuring a up or down qubit does not change its state.

The state of a qubit cannot simply be "checked"...

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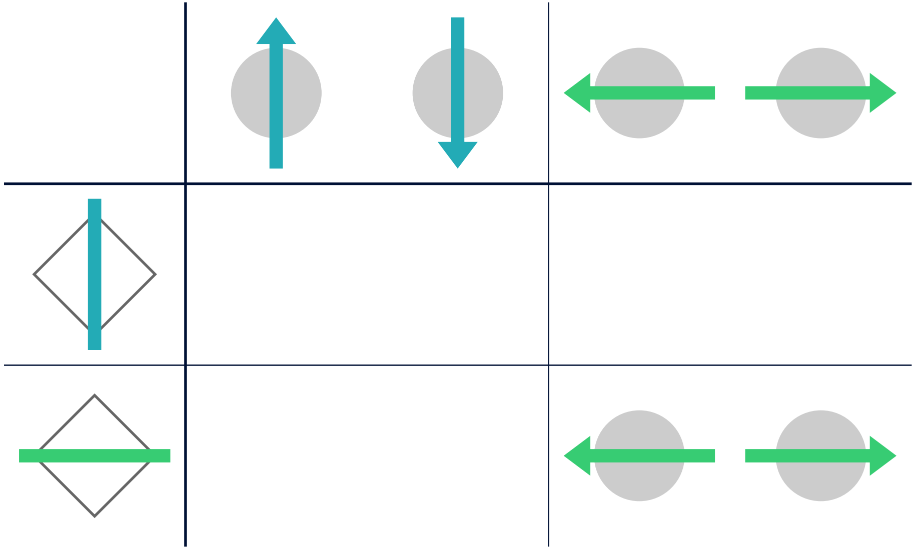

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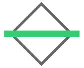
vertically  and horizontally .

These are called the two "measurement bases".

Horizontally measuring a left or right qubit does not change its state.

The state of a qubit cannot simply be "checked"...

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Measuring a qubit does 2 things:

- It changes the state of the qubit;
- It tells us the new state of the qubit.

There are 2 ways of measuring a qubit:

vertically and horizontally .

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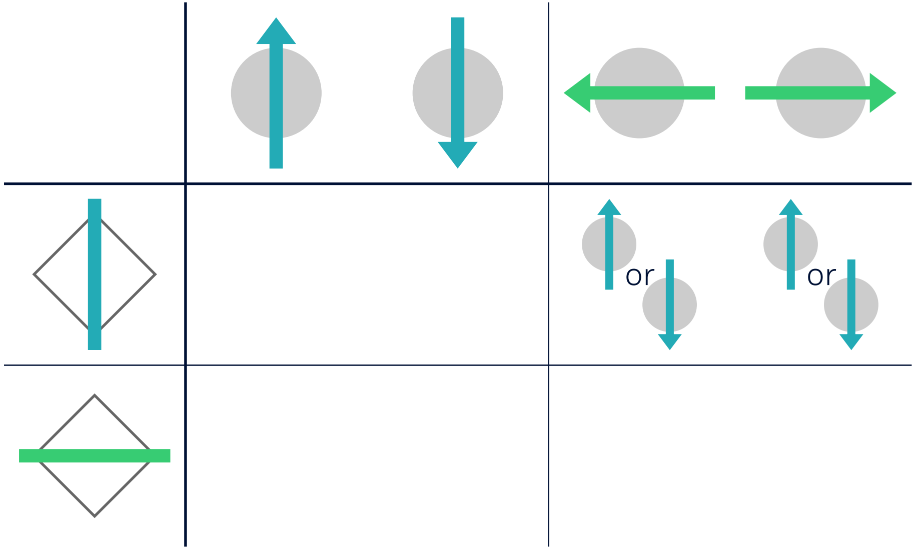

Vertically measuring a left or right qubit changes its state to either up or down (50/50 chance)

The state of a qubit cannot simply be "checked"...

.... it must be "measured"!

Measuring a qubit does 2 things:

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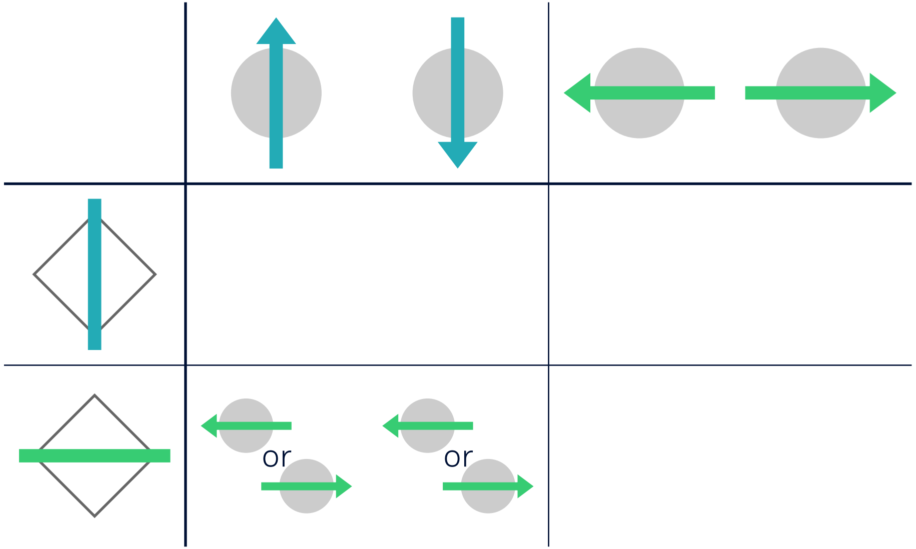

Horizontally measuring a up or down qubit changes its state to either left or right (50/50 chance)

The state of a qubit cannot simply be "checked"...

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Measuring a qubit does 2 things:

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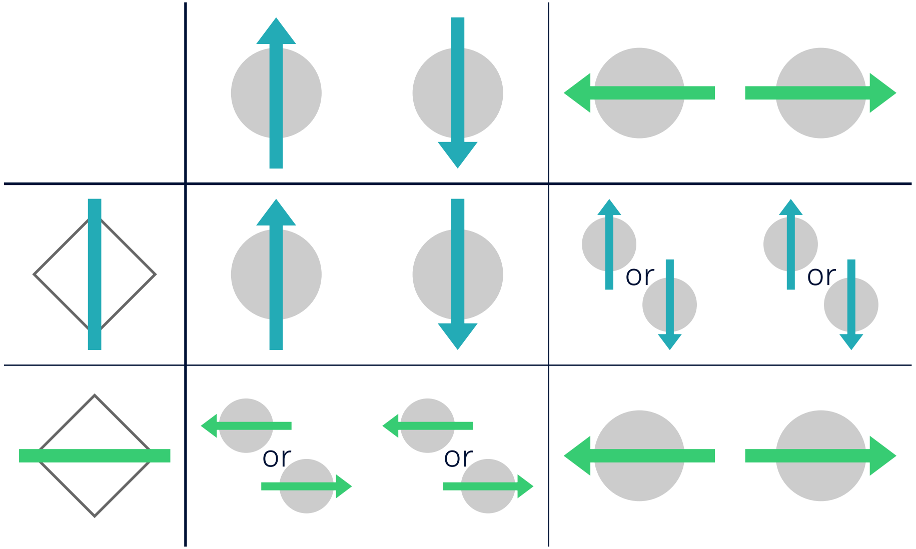

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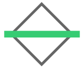
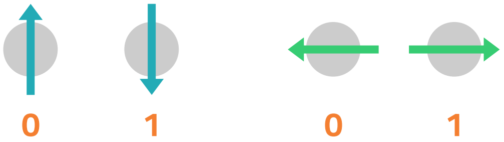
vertically  and horizontally  .

These are called the two "measurement bases".

Qubits cannot be cloned!

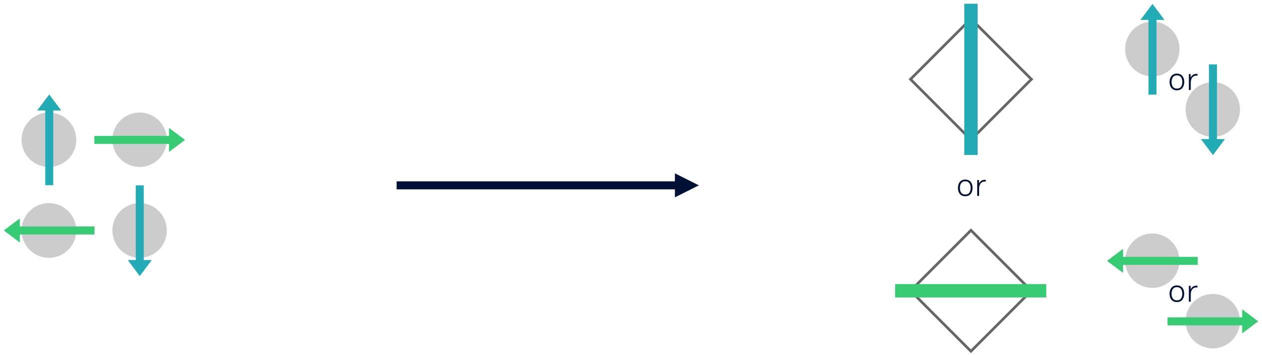
It is however possible to create qubits in any given state.

Up and left are generally interpreted as **0**, down or right as **1**.



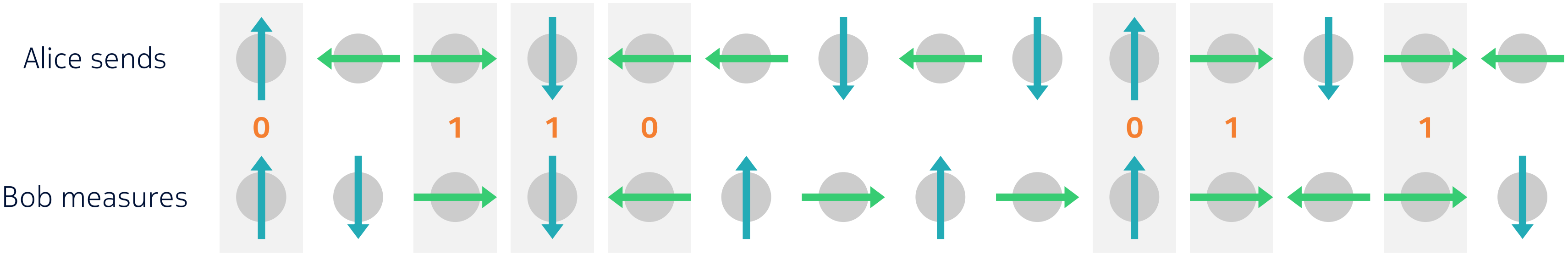
Example: quantum key distribution (QKD)

Alice selects a random qubit… … and sends it to Bob… … who measures it along a random axis



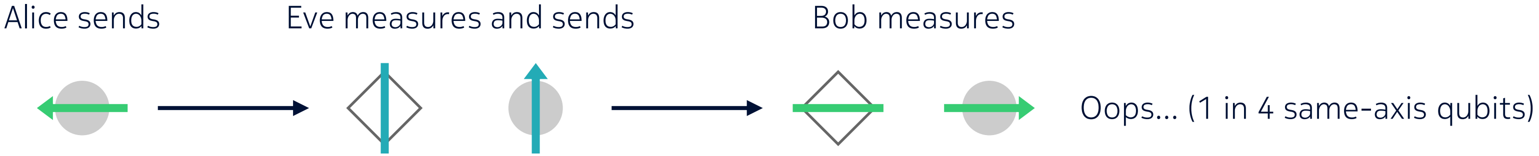
Alice and Bob then publicly announce their respective axes for each qubit!

Example: quantum key distribution (QKD)



If the axes match, then the qubits are necessarily in the same state!

But can an eavesdropper obtain the shared secret without being detected?



Alice and Bob can easily detect this eavesdropping by sacrificing part of the shared secret key!

Entanglement

"Spooky action at a distance"

— Albert Einstein

Entanglement and Bell pairs

Qubits are not always "free", they can be entangled!

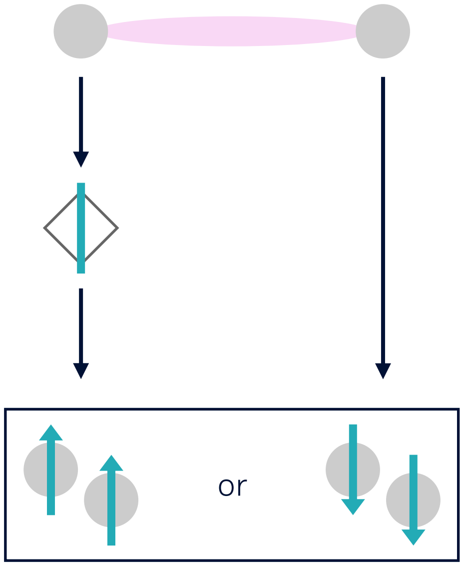
Entangled qubit (ebit) pairs, aka Bell pairs, differ from free qubits in two fundamental ways:

- Ebits don't have individual states, only the Bell pair has a state;
- When measuring ebits, the results are:
  - completely random;
  - not necessarily independent.

When measuring an ebit along an axis:

- Both ebits become free qubits, i.e. they are no longer entangled;
- The state of the measured qubit is random (50/50);
- The state of the second qubit is along the same axis;
- The state of the other qubit is completely correlated.

Measuring one ebit reveals the new state of both ebits!



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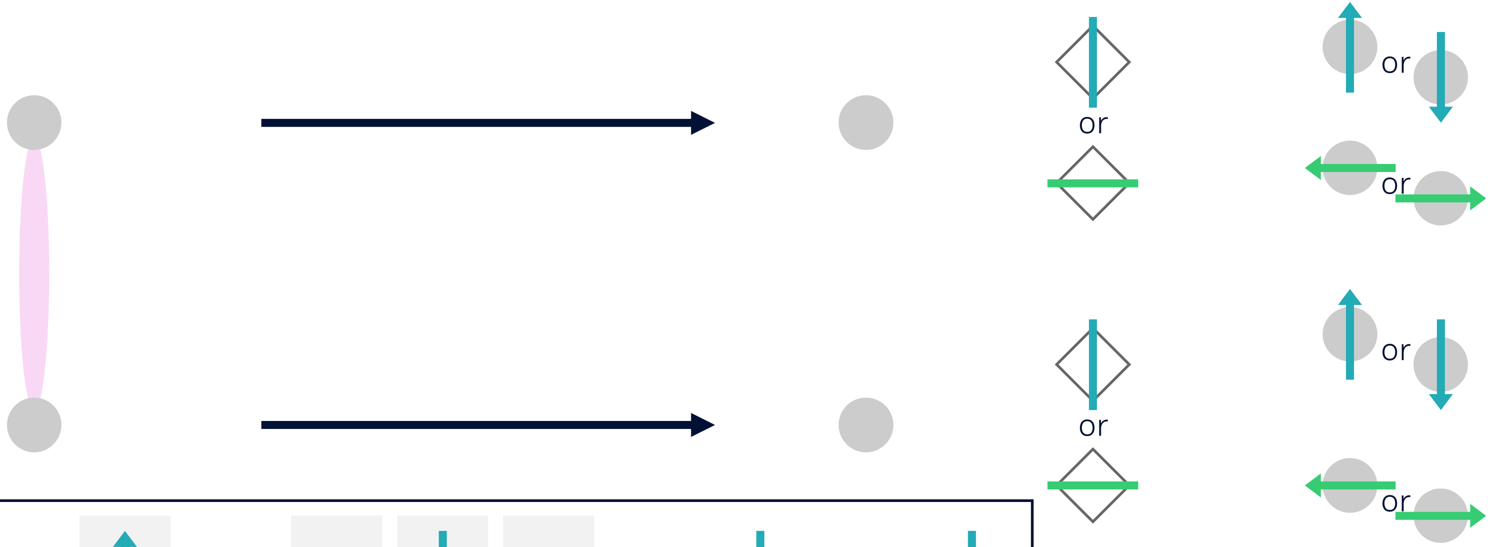
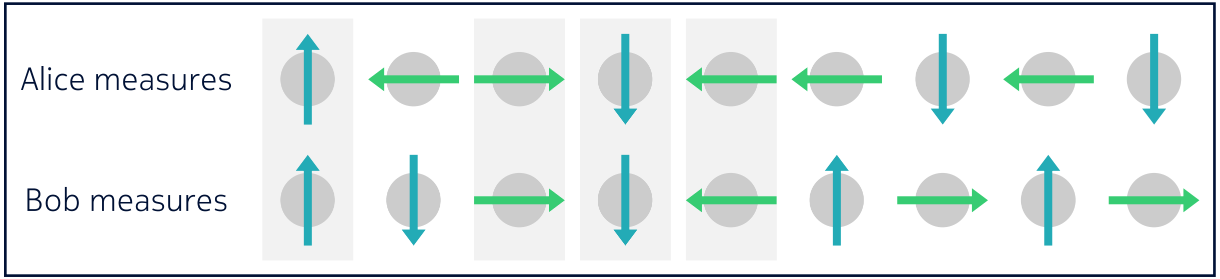
Example: QKD revisited

Generate a Bell pair… … and send the ebits to Alice and Bob… … who measure them along random axes

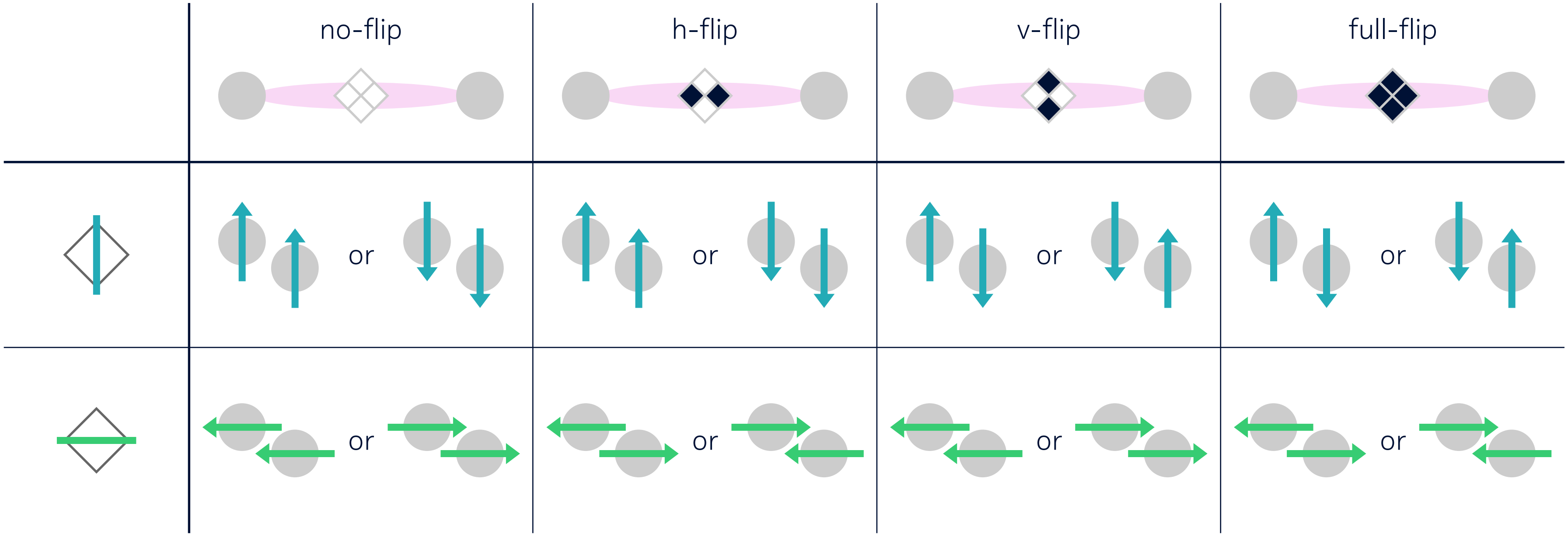




The four Bell states

After measurement, the state of both ebits is completely correlated… but not necessarily equal!

Depending on the Bell state and the measurement axis, they are either always equal, or always opposite.



If you know the state of a Bell pair, and measure one of its ebits, you know the new state of both ebits!

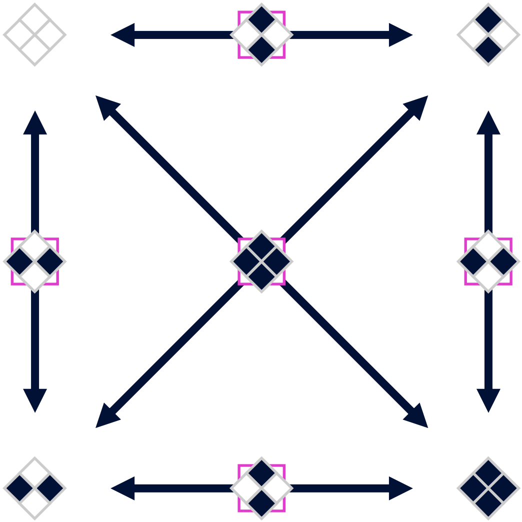
Working with Bell pairs

Pauli correction

Four simple operations on one ebit in a Bell pair.

Changes the state of the Bell pair.

- Which of the two ebits is modified is unimportant;
- Applying the same Pauli correction twice to an ebit is a no-op;
- Applying the same Pauli correction to both ebits is a no-op.



( is a no-op)

Working with Bell pairs

Bell state measurement

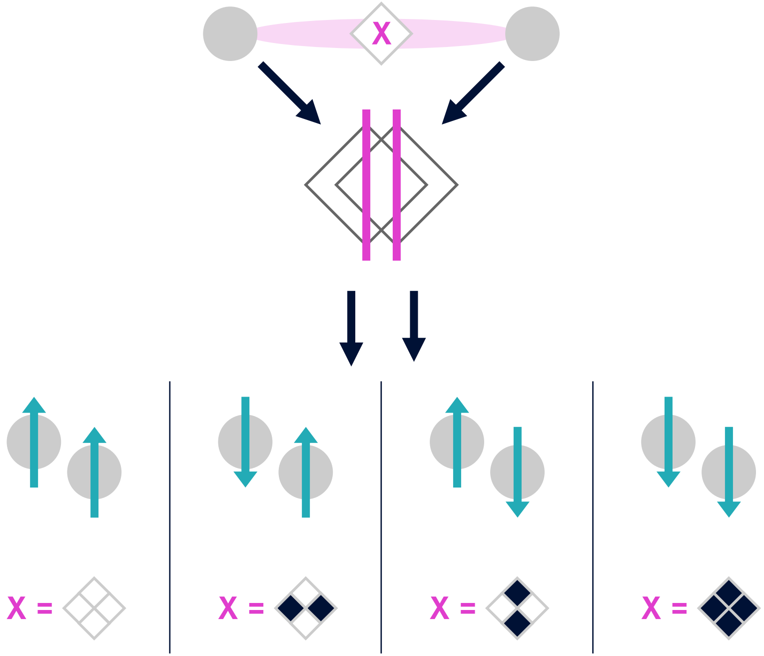
Special 2-qubit vertical measurement.

Must be done locally (both ebits must be in the same place).

When applied to ebits from an unknown Bell pair:

- The result is deterministic;
- The result encodes the state of the Bell pair.

Fun fact: if you send both ebits in a Bell pair through a link, an eavesdropper can successfully determine the state of the Bell pair while remaining undetected.



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Bringing it all together

"If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet."

— Niels Bohr

Why did we do all this again?

Looking back to my introduction…

"Entanglement allows us to transmit qubits without sending them through the network."

Quantum teleportation

"The aim of a quantum network is to distribute entanglement!"

Entanglement swapping

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Quantum teleportation

Alice and Bob share a Bell pair in the no-flip state.

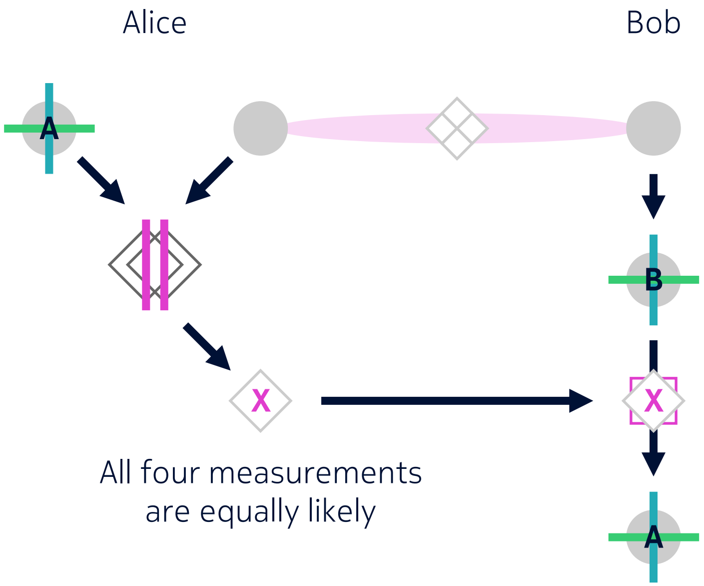
Alice has an arbitrary qubit in state **A**.

Now suppose that...

- Alice does a Bell state measurement of her 2 qubits;
- Alice sends the resulting measurements to Bob;
- Bob does a corresponding Pauli correction on his qubit...

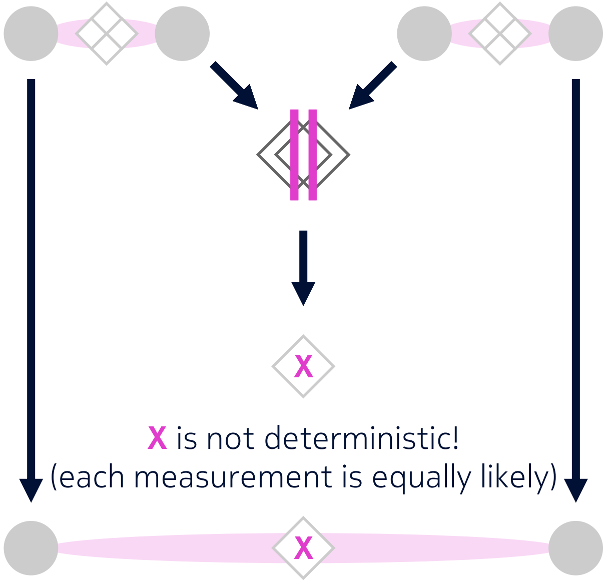
Bob's qubit is now in state **A**!

Since **A** is not transmitted as a qubit, it won't be lost!



Entanglement swapping

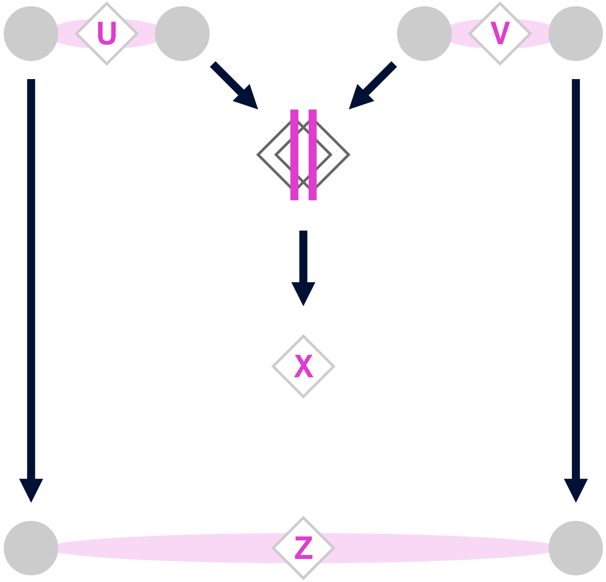
Bell state measurement applied to separate Bell pairs propagates entanglement!



Entanglement swapping

Bell state measurement applied to separate Bell pairs propagates entanglement!

Still works if the two Bell pairs in arbitrary known states.



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Entanglement swapping

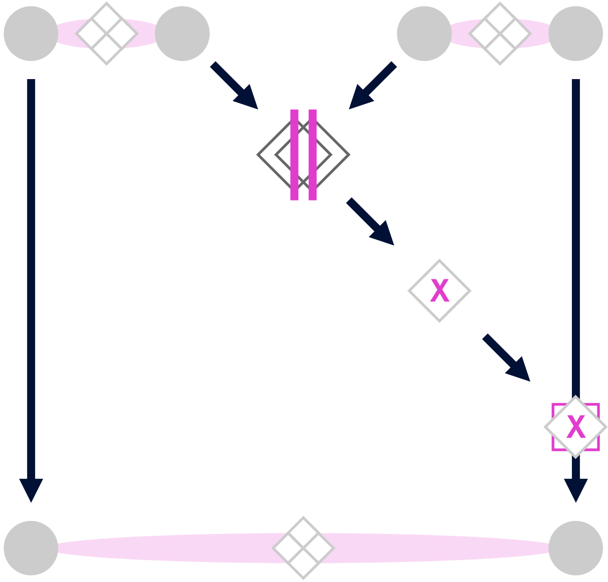
Bell state measurement applied to separate Bell pairs propagates entanglement!

Still works if the two Bell pairs in arbitrary known states.

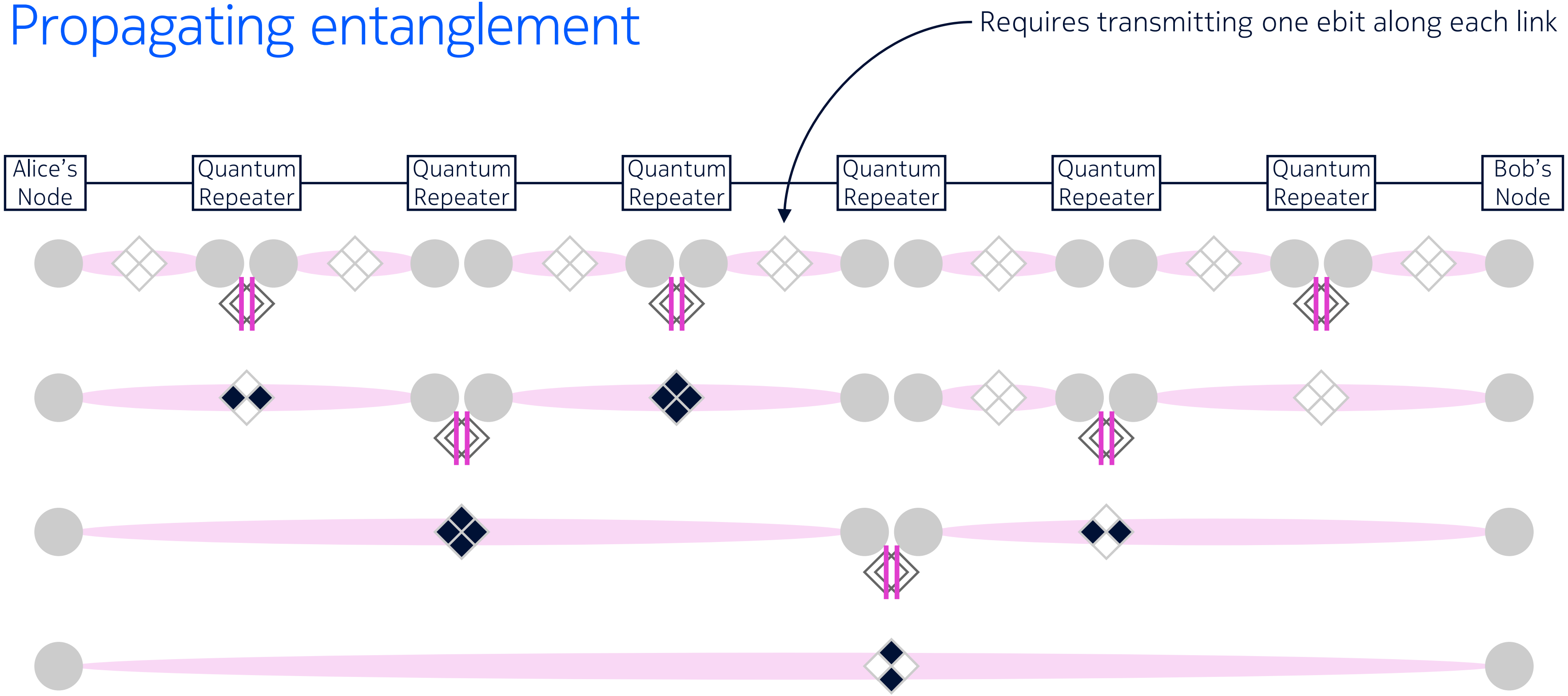
Combined with Pauli correction, we can fix the Bell state.

If you prefer, you can think of this as quantum teleporting an ebit, it's the same operations!

(note how the two operations are accomplished in different locations; this requires transmitting X, i.e. 2 classical bits)



Propagating entanglement



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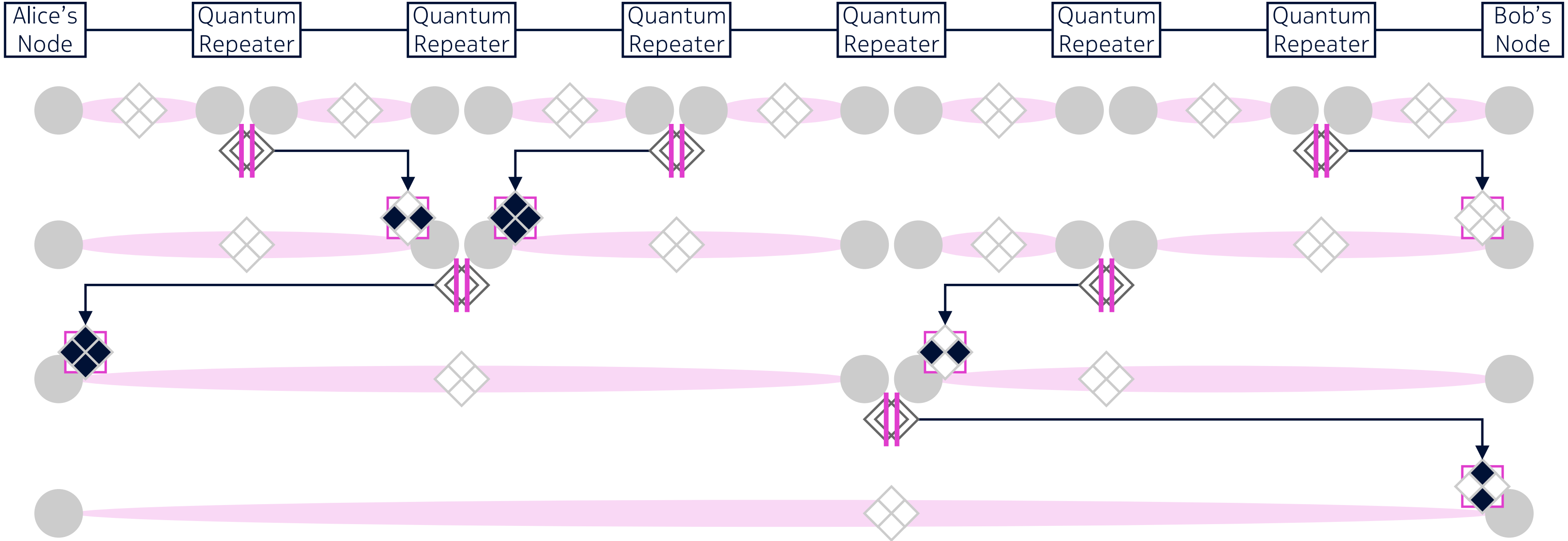
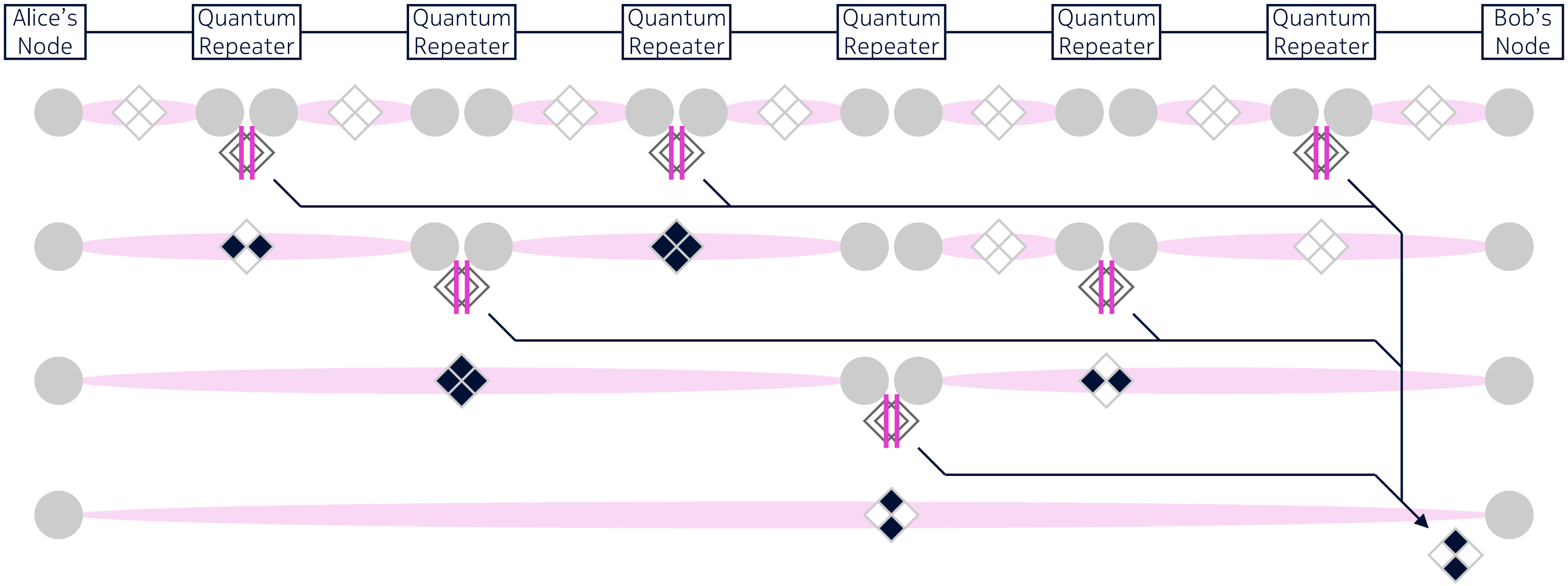


Propagating entanglement



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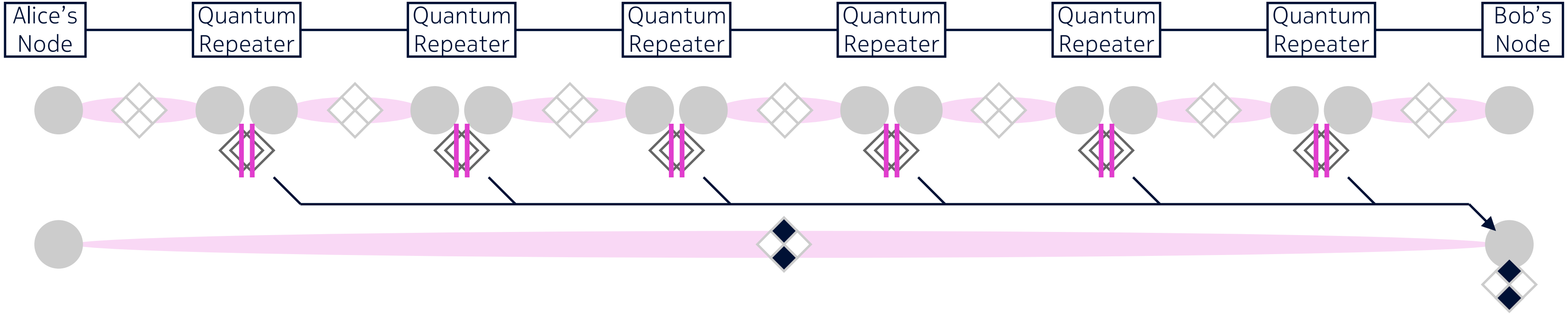
Propagating entanglement



Creating long-range entanglement is a complex distributed algorithm.

There is no linear propagation along a path!

This requires a whole new family of protocols which don't exist yet.

Wrapping it up

"Quantum mechanics makes absolutely no sense."

— Roger Penrose

Important things I've left out

Decoherence

Loss of fidelity (state becomes noisy) due to imperfect hardware.

Quantum error correction codes (QECR)

Entanglement distillation

Means of compensating for losses and decoherence.

Qudits

Continuous-variable quantum networks

We've only been considering qubits.

Research opportunities at LINCS

Quantum network routing feels both similar and very different:

- There are still "paths", but they are no longer traversed "from start to finish";
- Bell pairs are arbitrary, and therefore don't need to be pre-assigned to specific end-to-end paths at creation.

There is a strong queueing theory "vibe" to entanglement propagation, but it's very different from what we are used to!

- Choosing which Bell pairs to entangle plays an important role.

Determining hardware requirements for a viable quantum internet:

- Quantum buffer decoherence rate.
- Quantum operation decoherence/loss rates.

Other stuff, such as distributed quantum algorithms, general architecture for the quantum internet, protocol design, etc.

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The lies…

- A qubit can be in an infinite number of states (think "any 3-dimensional unit vector")
  (or you could say there are only two states, up and down, and infinitely many superpositions of these two states…)
- A qubit can be measured along an infinite number of axes (think "any direction in 3-dimensional space")
  (the more orthogonal the measurement axis and the qubit, the more "random" the measurement output)
- Two qubits can be partially entangled (non-Bell pairs)
  (think "partially correlated")
- Three or more qubits can be entangled
  (see namely GHZ and W states)

But there are still **only** four Bell states!

And it turns out my lies and over-simplification suffice to exploit the full potential of these Bell pairs!

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