The little

Quantum Pocket Guide

EN

by MCQST

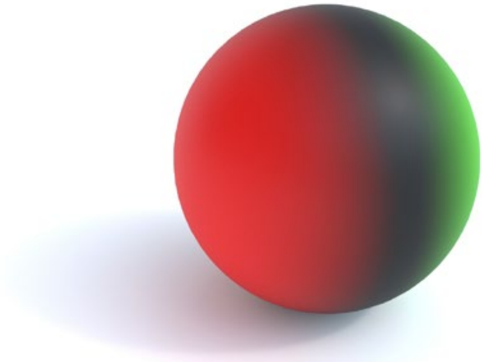
1

A **classical bit** is the smallest unit of information used in computers. It exists in one of two states: **0** or **1**.

Think of a bit as a card with a red side representing 0 and a green side representing 1.

In quantum computers, we use **qubits** instead of classical bits. Unlike classical bits, qubits can exist in **more than just two states**. Think of a qubit as a sphere with red and green poles.

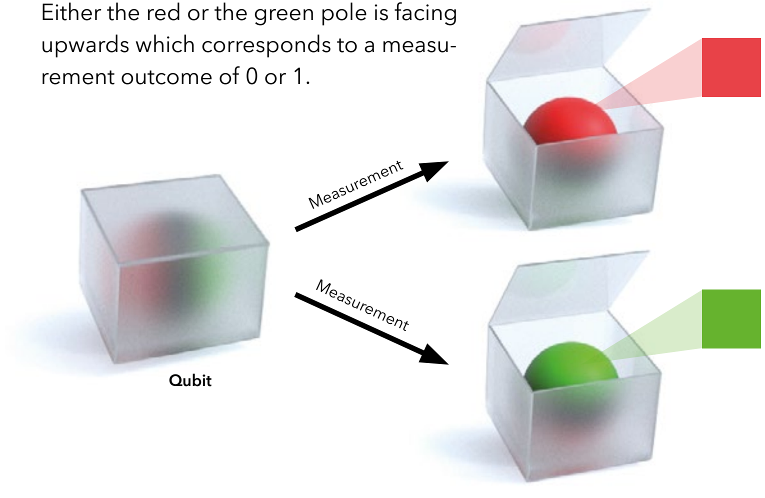
The orientation of the **qubit sphere** indicates the state of the qubit.



We put the qubit in a box. Only by opening the box can we see (measure) the state of the qubit.

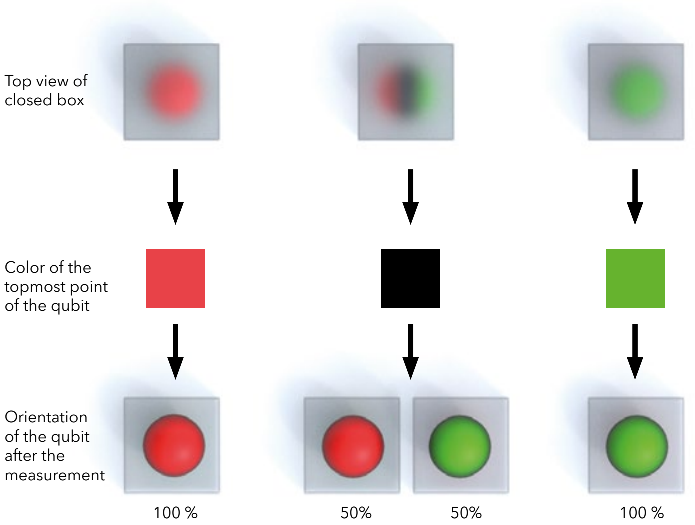
When we open the lid and **look inside (measurement)**, the sphere **snaps into one of two orientations**, even if the qubit was initially in a tilted orientation.

Either the red or the green pole is facing upwards which corresponds to a measurement outcome of 0 or 1.



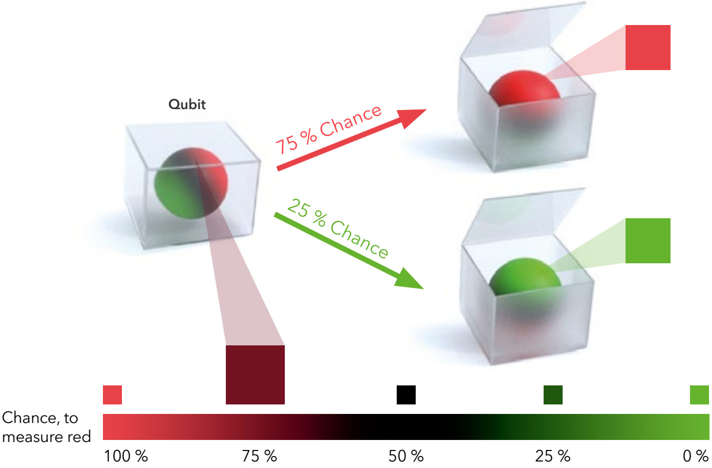
4

Before opening the box, **the color of the topmost point** of the qubit defines the chances of measuring red or green once the lid is opened.



A qubit in a **tilted** position is in a superposition state.

In the scenario shown below, the qubit in the closed box shows a **dark shade of red on top**, which tells us that the probability to measure red upon opening is 75% (see the color map at the bottom of the page). However, there is still a chance of about 25% to measure green instead.

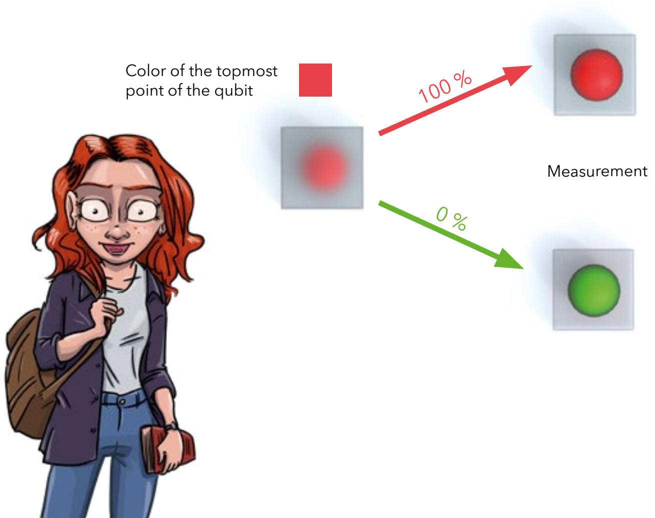


Meet Alice and Bob. They each receive a set of these boxes. All boxes contain **qubit spheres** with the **same orientation**. After opening the boxes and looking inside, their task is to guess the initial orientation of the qubits before the boxes were opened.

7

When opening each box, Alice **consistently** finds a qubit sphere with its **red pole facing upwards**.

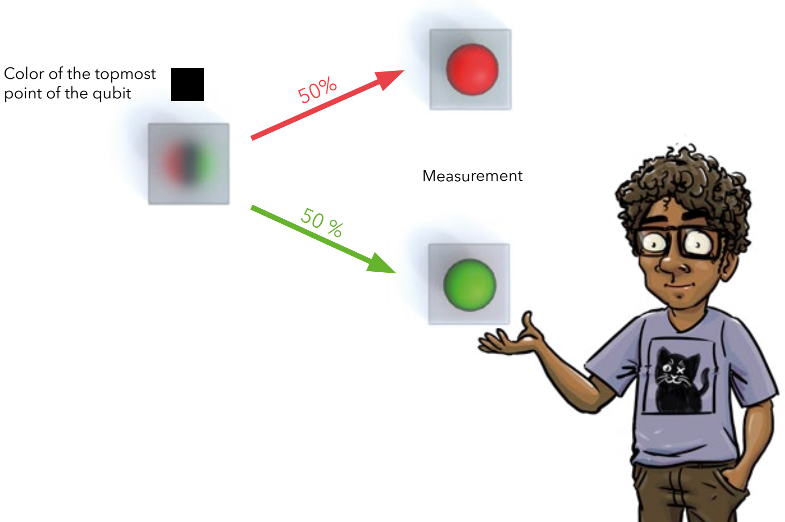
She concludes that all qubits initially had **their red pole on top** when the boxes were still closed, resulting in her always finding a red measurement outcome.



8

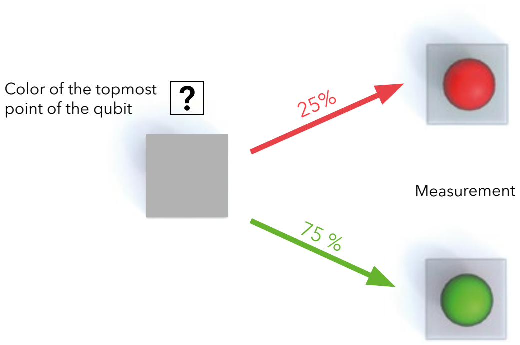
Bob examines another set of boxes, which again all contain qubits with the same orientation. Despite this, he observes an **the same number of „0“ (red) and „1“ (green)** results in his measurements.

This indicates that his qubits were in a state of **equal superposition** before the measurement



Let's solve a riddle:
Based on the measurement results we received, what color could the top side of our qubit sphere have been while inside the closed box?

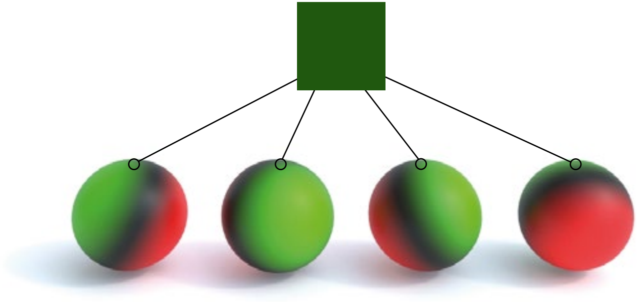
You can find the answer on the next page.



Solution to Page 9:

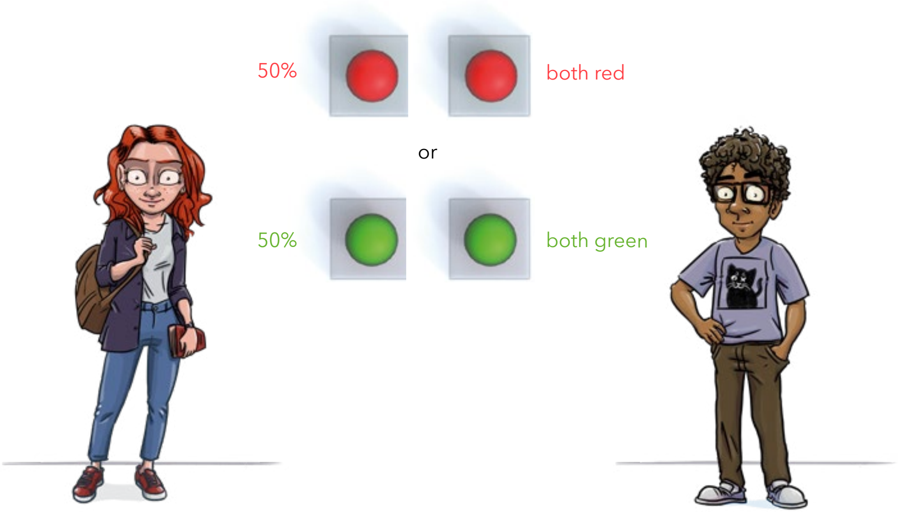
Our measurements reveal both red and green poles, indicating that the qubits were in a **superposition state** before the measurements. However, we observe **green more frequently** than red. Therefore, the color at the top of the sphere was initially a **darker shade of green** (refer to the color map at the bottom of page 5).

Below are some possible orientations of the qubit inside the closed boxes which would lead to this result.



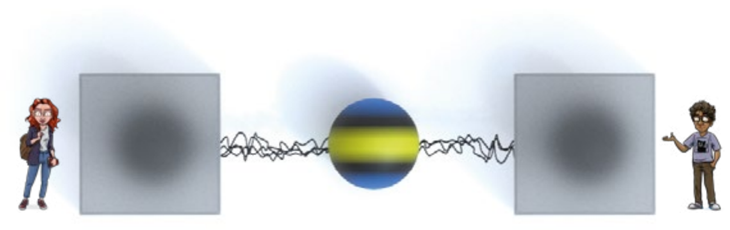
Now, Alice and Bob receive a set of identically prepared **qubit pairs**. For each pair of boxes, Alice unpacks one qubit, and Bob unpacks the other. Both Alice and Bob sometimes measure red and sometimes green, but **for each pair**, their **results are always the same**.

This suggests a special **connection** between their qubits.



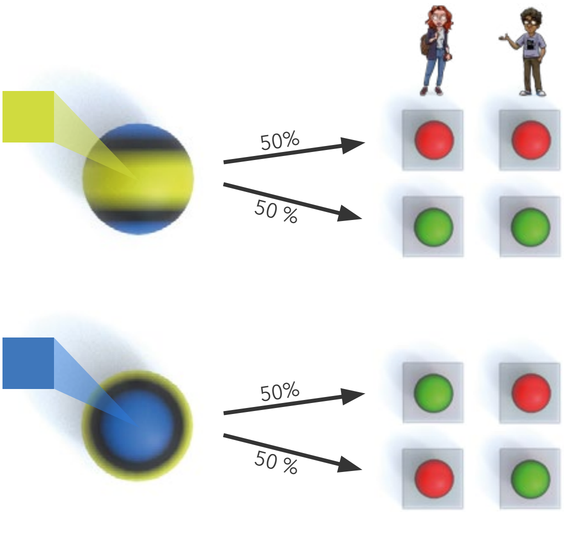
This special connection between qubits is known as **entanglement**. When qubits are entangled, the **measurement result of one qubit also determines the result of the other**.

We represent this connection with an additional sphere, which we call the **entanglement sphere**. If qubits are fully entangled, the qubit spheres are black before the measurement
(➛ 50:50 chance of measuring red or green for each individual qubit).



If the entangled sphere is oriented with the **yellow side up**, both qubits will give the **same result** when they are measured. (e.g., both red).

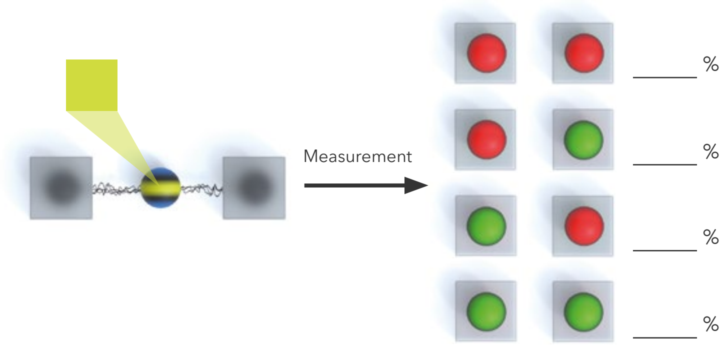
On the other hand, if the top of the entanglement sphere is **blue**, the qubits will always get **opposite results** (i.e., one red, one green).



Now, let's unravel some more riddles!

What are the **chances** of measuring the following pairs of results?

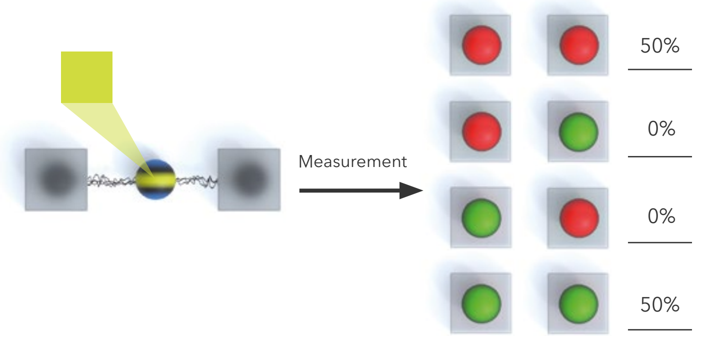
Find the correct solution on the next page.



Solution to page 14:

In this case, we see a blue-yellow entanglement sphere. The **topmost point of the entanglement sphere is yellow**. Consequently, upon measurement, both qubit spheres will align identically after the measurement.

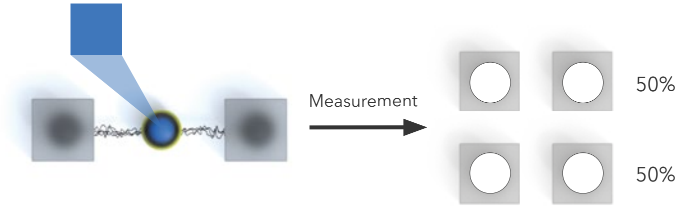
As the qubit spheres are initially black, we have a **50:50 chance** of obtaining red or green results. Measuring qubit pairs with opposite colors is not possible in this case.



Another riddle awaits:

Which **results** do we expect for the qubits below?

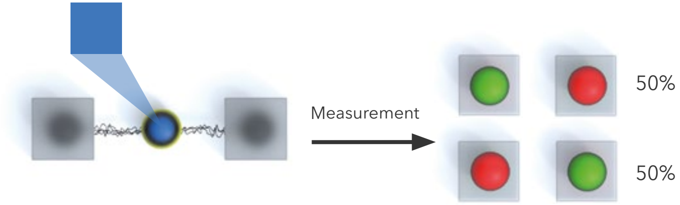
Use the empty circles for sketching your answer. The solution awaits on the next page.



Solution to page 16:

This scenario also represents an entangled state. Here, the entanglement sphere is **blue on top**. Consequently, both qubits adopt opposite states.

With the **qubit spheres being black**, we have an equal chance of obtaining **red/green** and **green/red** results at a 50:50 chance.



What did we learn?

Together with Alice and Bob, we took a first glimpse into the world of quantum bits. Unlike classical bits, which only can be an „either-or“, qubits introduce a „both-and“ scenario. They can exist in a state of superposition, where **0 and 1 can exist at the same time**, paving the way for new algorithms.

Furthermore, we observed that two quantum bits can exist in **entangled states**, where the measurement outcome of each individual qubit is random and unpredictable, yet **always identical** (or always opposite) to each other. The concept of entanglement can be visually represented using entanglement spheres with distinct coloring.

What can we do with this knowledge?

This fundamental understanding sets the stage for delving into more advanced topics:

- How can quantum bits be generated and entangled in laboratory settings?
- How can simple quantum operations be harnessed to construct entire quantum algorithms?
- How can the sensitivity of a quantum bit be leveraged for innovative sensor technologies?
- How can quantum information be transmitted and received over long distances?

These and other questions are points of interest for scientists across multiple disciplines and research institutions in Munich.
The **Munich Center for Quantum Science and Technology (MCQST)** brings all these groups together, fostering collaboration among individual researchers and promoting scientific exchange.

Website: www.mcqst.de

About the origin of „The Little Quantum Pocket Guide“:

This guide is the result of a close collaboration between the MCQST Office and the **research group of Prof. Steffen Glaser** (Technical University of Munich).

The visual representations are based on a one-to-one mapping of arbitrary quantum states onto colored spheres, dubbed „qubit beads“ and „entanglement beads“. Tangible models offer a remarkably simple and engaging approach to quantum mechanics, blending graphical representation with mathematical precision.

Dennis Huber, a member of Prof. Glaser‘s research group, co-authored „The Little Quantum Pocket Guide“ and in particular developed the unique and powerful QuBeads app. This is an easy to use, highly interactive, and versatile tool for teaching and research in quantum information theory. The QuBeads app is based on the SpinDrops-App (originally created by Niklas Glaser, Michael Tesch, and Steffen Glaser) that was geared towards the visualization of the dynamics of spin ensembles in magnetic resonance spectroscopy and imaging (www.spindrops.org).

Website of Glaser Research Group: www.ch.nat.tum.de/ocnmr

Get entangled with us!

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