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# Moderne Quantentechnologien

*Institut für Physik,  
Johannes Gutenberg-Universität Mainz*

Ferdinand Schmidt-Kaler, Peter van Loock

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# Quantentechnologie: IBM, Google ...


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Article | [Published: 23 October 2019](#)

## Quantum supremacy using a programmable superconducting processor

[Frank Arute](#), [Kunal Arya](#), [Ryan Babbush](#), [Dave Bacon](#), [Joseph C. Bardin](#), [Rami Barends](#), [Rupak Biswas](#), [Sergio Boixo](#), [Fernando G. S. L. Brandao](#), [David A. Buell](#), [Brian Burkett](#), [Yu Chen](#), [Zijun Chen](#), [Ben Chiaro](#), [Roberto Collins](#), [William Courtney](#), [Andrew Dunsworth](#), [Edward Farhi](#), [Brooks Foxen](#), [Austin Fowler](#), [Craig Gidney](#), [Marissa Giustina](#), [Rob Graff](#), [Keith Guerin](#), ... [John M. Martinis](#) 

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[Nature](#) 574, 505–510 (2019) | [C](#) Research



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### What is Quantum Volume?

Quantum volume (QV) is a single-number metric used to measure the power of a for near-term devices with a modest number of qubits, and measures the largest and [depth](#) that can be reliably run.

Visual demo

Click through these slides for a quick overview on quantum volume.



### Featured publications

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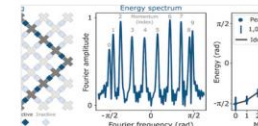
Quantum Supremacy Using a Programmable Superconducting Processor

On Oct 23, 2019, Google announced it performed a calculation on a quantum



Topological Quantum States

We experimentally explore topologically ordered quantum states, including simulating the braiding of elusive anyons and encoding logical qubit states we



Achieving Precision in Quantum Material Simulations

We outline a blueprint for achieving record levels of precision for the task of simulating quantum materials.



Demonstrating the Fundamentals of Quantum Error Correction

We outline in this paper how we use quantum repetition codes to demonstrate a new technique for

# Quantentechnologie: Amazon ...



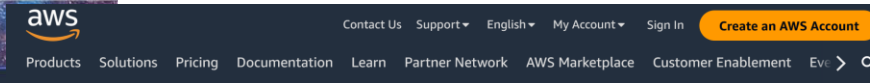
## Amazon Braket

Beschleunigung der Forschung im Bereich Quantencomputer

Erste Schritte mit Amazon Braket

### Eine Stunde freie Simulationszeit pro mit dem kostenlosen Kontingent

- Einfaches Arbeiten mit verschiedenen Arten von Quantencomputern und Schaltungssimulatoren unter Verwendung eines einheitlichen Satzes von Entwicklungswerkzeugen.
- Erstellen Sie Quantenprojekte in einer vertrauenswürdigen Cloud mit einfachen Preis- und Verwaltungskontrollen sowohl für Quanten- als auch für klassische Workloads.
- Schnelleres Starten hybrid-quantenklassischer Algorithmen mit vorrangigem Zugriff auf Quantencomputer und ohne Verwaltung klassischer Infrastruktur.
- Entwickeln Sie Innovationen fachkundiger und technischer Berater im Amazon Quantum Solutions zusammen.



## Amazon Braket

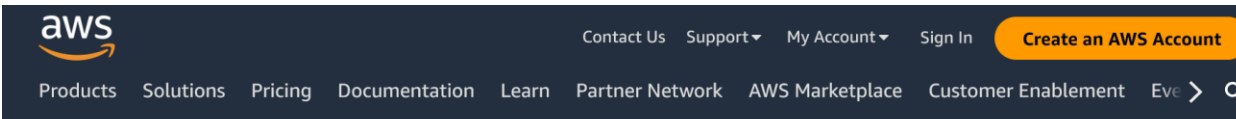

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## IonQ

IonQ is a leader in quantum computing. By making our quantum hardware accessible through the cloud, we're empowering organizations and developers to solve the world's most complex problems in chemistry and materials simulation, logistics and optimization, pharmaceutical and security applications.

Leveraging IonQ's nature-based approach, our systems provide both a viable technological roadmap to scale and the flexibility necessary to explore a wide range of application spaces in the near term.



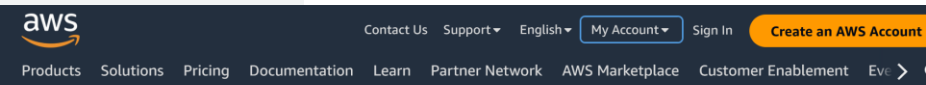
AWS Blog Home Topics Edition

## Announcing the AWS Center for Quantum Networking

by Denis Sukachev and Mihir Bhaskar | on 21 JUN 2022 | in [Amazon Quantum Solutions Lab](#), [Announcements](#), [AWS Quantum Technologies](#) | [Permalink](#) | [Share](#)

Over the last decade, governments and technology companies have invested heavily in research and development of the potential to [revolutionize](#) science and technology. While there is still a long way ahead, these investments in quantum computers: They have evolved from delicate laboratory systems accessible to only a few research institutions to commercial machines available to researchers, developers, and even quantum enthusiasts worldwide via cloud services.

While quantum computing continues to be a major area of investment and progress for academic and industry research, quantum networking is becoming a component of a broader class of quantum technologies. To unlock the full potential of quantum devices, they need a *quantum network*, similar to the way today's devices are connected via the internet. Despite not receiving the same attention as quantum computers, quantum networks have fascinating possible applications. One of them is enabling global communication with privacy and security levels not achievable using conventional encryption techniques. Quantum networks can be built and secure cloud quantum servers by connecting together and amplifying the capabilities of individual quantum processors.



## Amazon Braket

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## Xanadu

[Xanadu](#) is a photonic quantum technology company headquartered in Toronto, Canada. A leader in both quantum hardware and software, Xanadu leads the development of [PennyLane](#), an open-source software library for quantum computing and application development.



"Xanadu is on a mission to build quantum computers that are useful and available to people everywhere. We believe that photonics offers one of the most viable approaches to universal fault-tolerant quantum computing. We are proud to provide AWS customers access to Borealis, which our peer reviewed article in Nature shows to be the first programmable photonic quantum computer that has achieved quantum advantage."

# Quantentechnologie: PsiQuantum, Xanadu



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// Quantum Hardware

## Quantum computational advantage on Xanadu Cloud

Forbes

FORBES > INNOVATION > CLOUD

## PsiQuantum Has A Goal For Its Million Qubit Photonic Quantum Computer To Outperform Every Supercomputer On The Planet

Paul Smith-Goodson Contributor

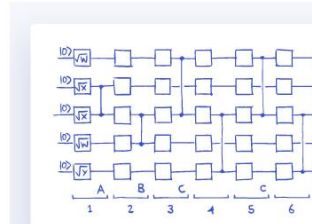
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## Your quantum playground

Xanadu Cloud provides you with hardware, software and applications for quantum computing. Sign up now!



Build

Software services for Strawberry Fields & PennyLane

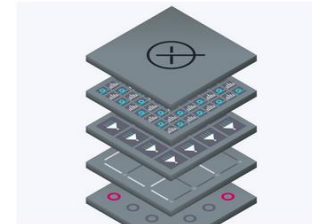
```
import pennylane as qml
from pennylane import numpy as np

# create a quantum device
dev = qml.device("default.qubit", wires=8)

# a quantum node
@qml.qnode(dev)
def circuit(phi1, phi2):
    qml.RX(phi1, wires=0)
    qml.RY(phi2, wires=0)
```

Experiment

Leverage high performance simulators



Execute

Exclusive access to photonic quantum computers

PsiQuantum

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# Building the first useful quantum computer

It takes 1,000,000+ qubits.

It takes error correction.

It takes fault tolerance.

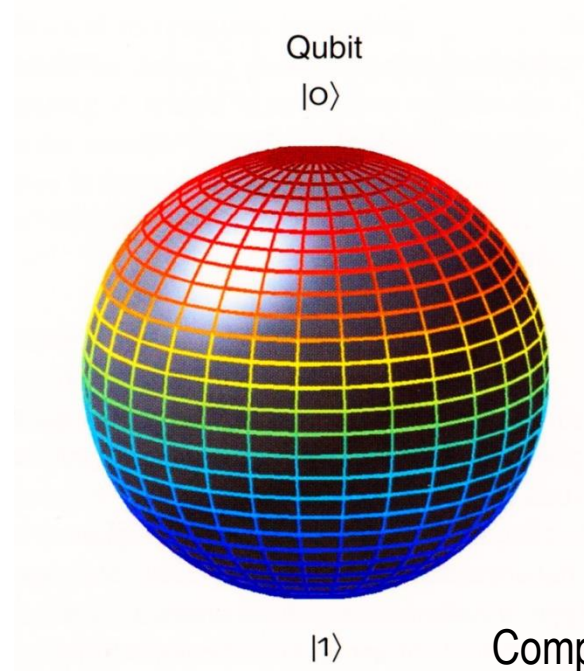
It takes photons.

# Klassische Bits versus Quantenbits (Qubits)

0 or 1



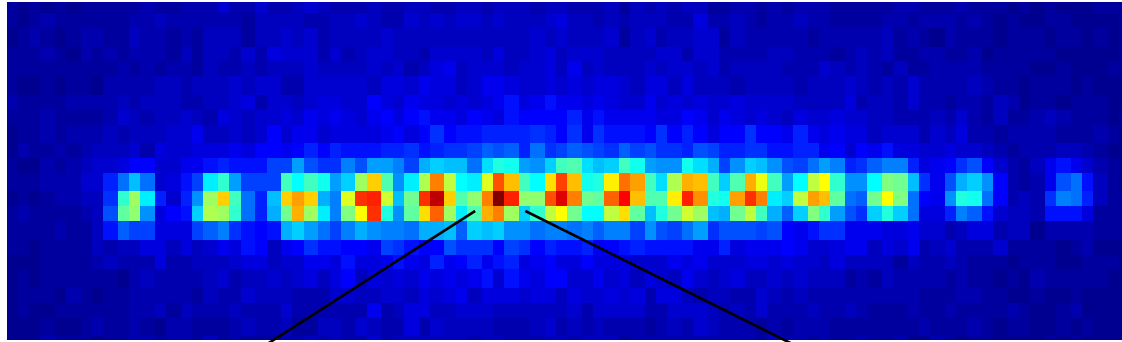
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



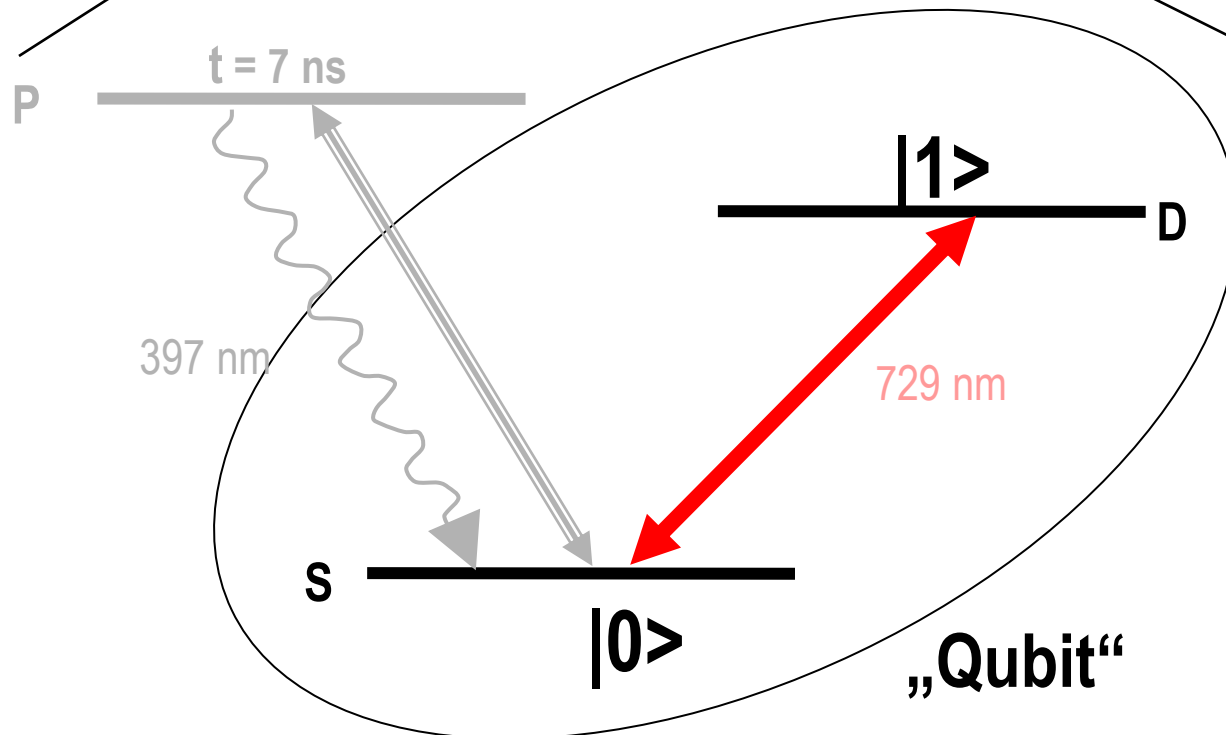
$\{|0\rangle, |1\rangle\}$

Computational Basis States

# Ion-Qubit



F. Schmidt-Kaler  
Group



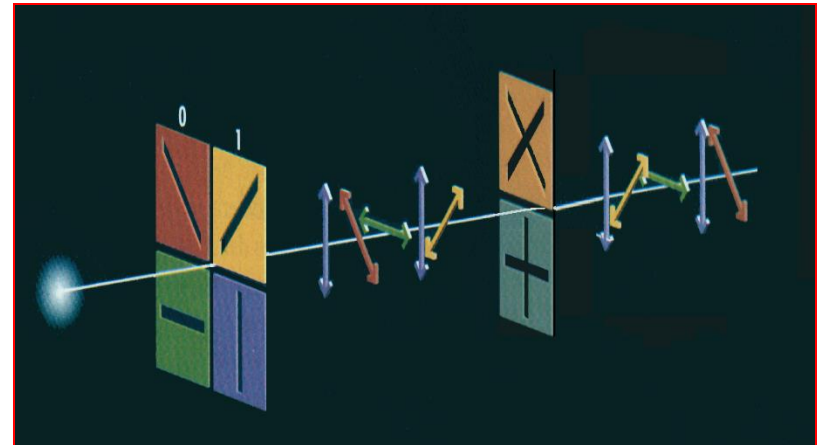
# Photonisches Qubit

Occupation-Number Qubit:  $\alpha |0\rangle + \beta |1\rangle$

Dual-Rail Qubit:  $\alpha |10\rangle + \beta |01\rangle$

e.g., **polarization** of a photon...

$$\alpha |\leftrightarrow\rangle + \beta |\updownarrow\rangle$$



# Quanteninformation

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No Communication  
Faster Than Light



Heisenberg  
Uncertainty Relation



Entanglement





# Verschränkung: ``EPR'', Schrödinger und Bell

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*“When two systems enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before. I would not call that one but rather the characteristic trait of quantum mechanics, the one that **enforces its entire departure from classical lines of thought**. By the interaction the two systems have become **entangled**.”*

Schrödinger (1935)

# Verschränkung: ``EPR'', Schrödinger und Bell



Entanglement

$$\int dx |x, x - c\rangle$$

Continuous Variables

$$|\Psi^+\rangle = (|01\rangle + |10\rangle) / \sqrt{2}$$

Discrete Variables

Einstein, Podolsky, and Rosen (1935)...

... [non-locality](#), non-realism, or hidden variables... QM incomplete

# Verschränkte Photonenpaare im Quantenoptik-Labor



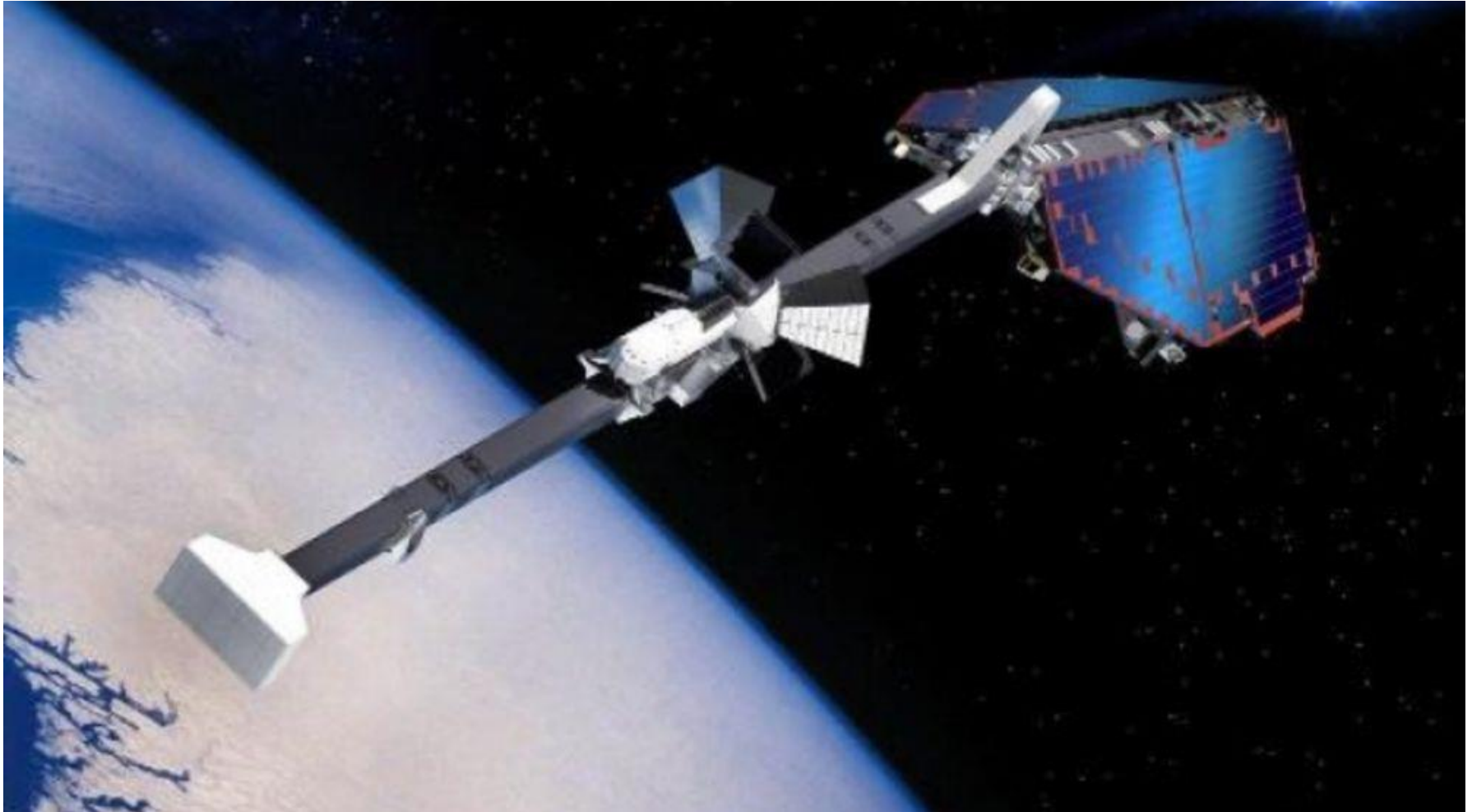
# Verschränkte Photonen über 144 km



Zeilinger (2007)

# Quantum Space Satellite (QUESS)

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# Quanteninformation

No Communication  
Faster Than Light



“No-Cloning”  
Theorem

Entanglement

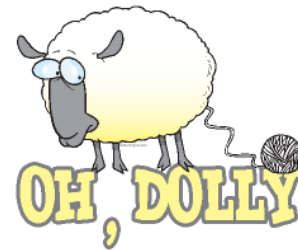
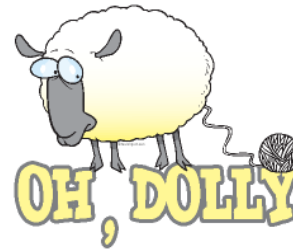
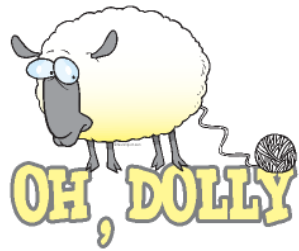


Heisenberg  
Uncertainty Relation



# Klonen

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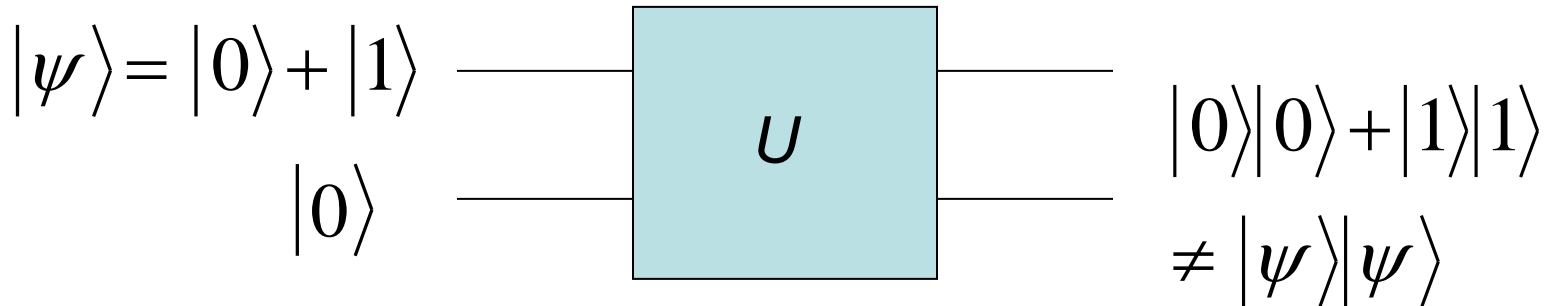
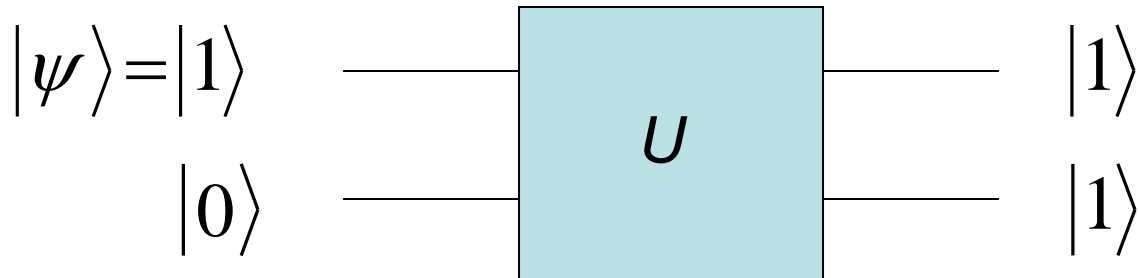
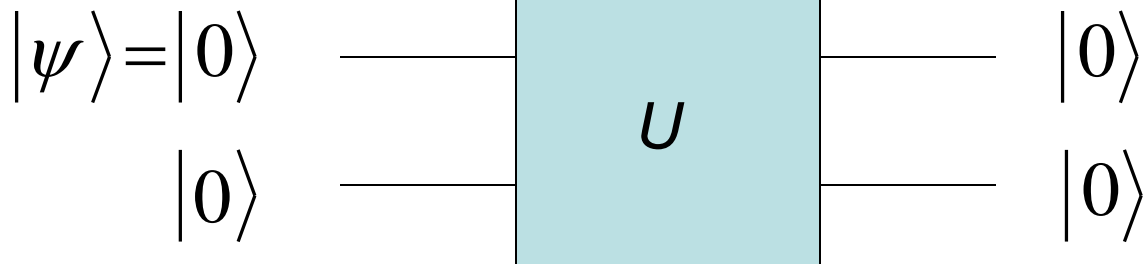
# Nicht-Klonen (``No-Cloning Theorem'')

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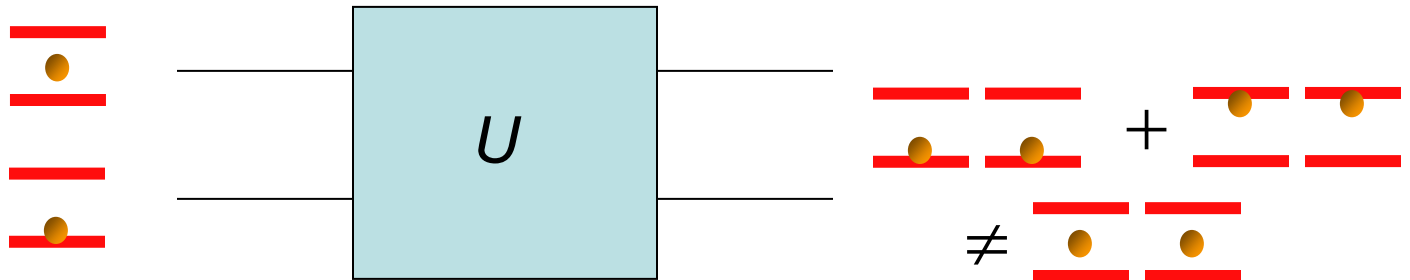
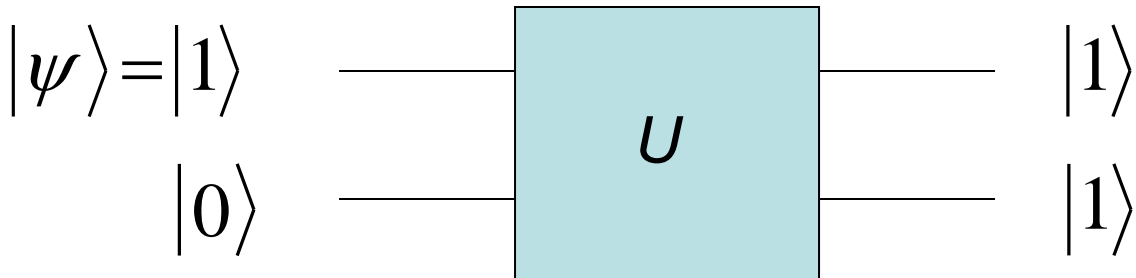
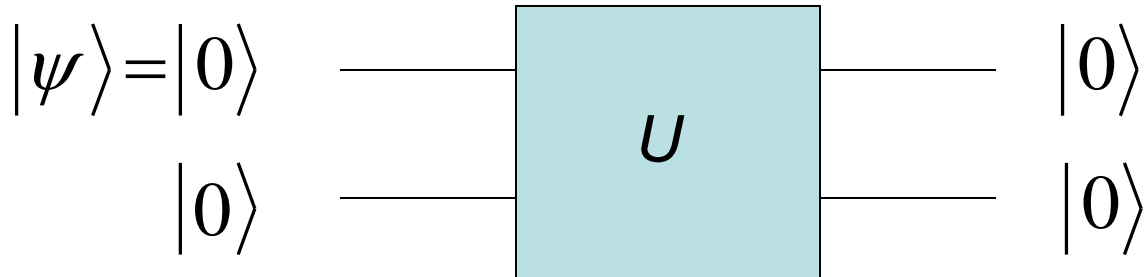
$$|\psi\rangle \not\rightarrow |\psi\rangle |\psi\rangle$$



# Nicht-Klonen



# Nicht-Klonen



# Quanteninformation

No Communication  
Faster Than Light



“No-Cloning”  
Theorem

Entanglement



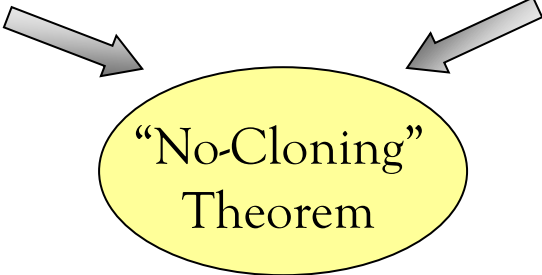
Heisenberg  
Uncertainty Relation



# Quanteninformation & Quantentechnologie

No Communication  
Faster Than Light

Heisenberg  
Uncertainty Relation

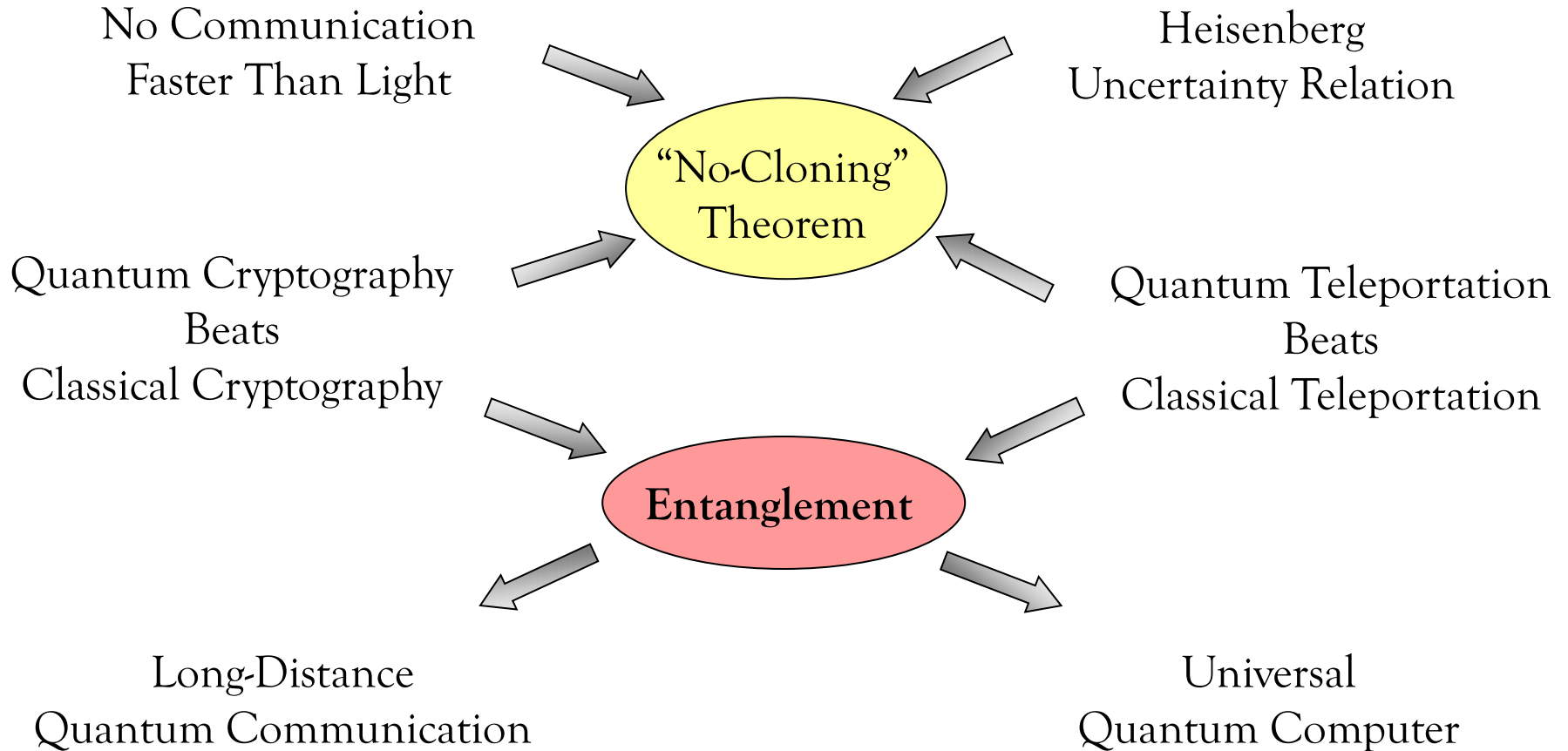


Long-Distance  
Quantum Communication

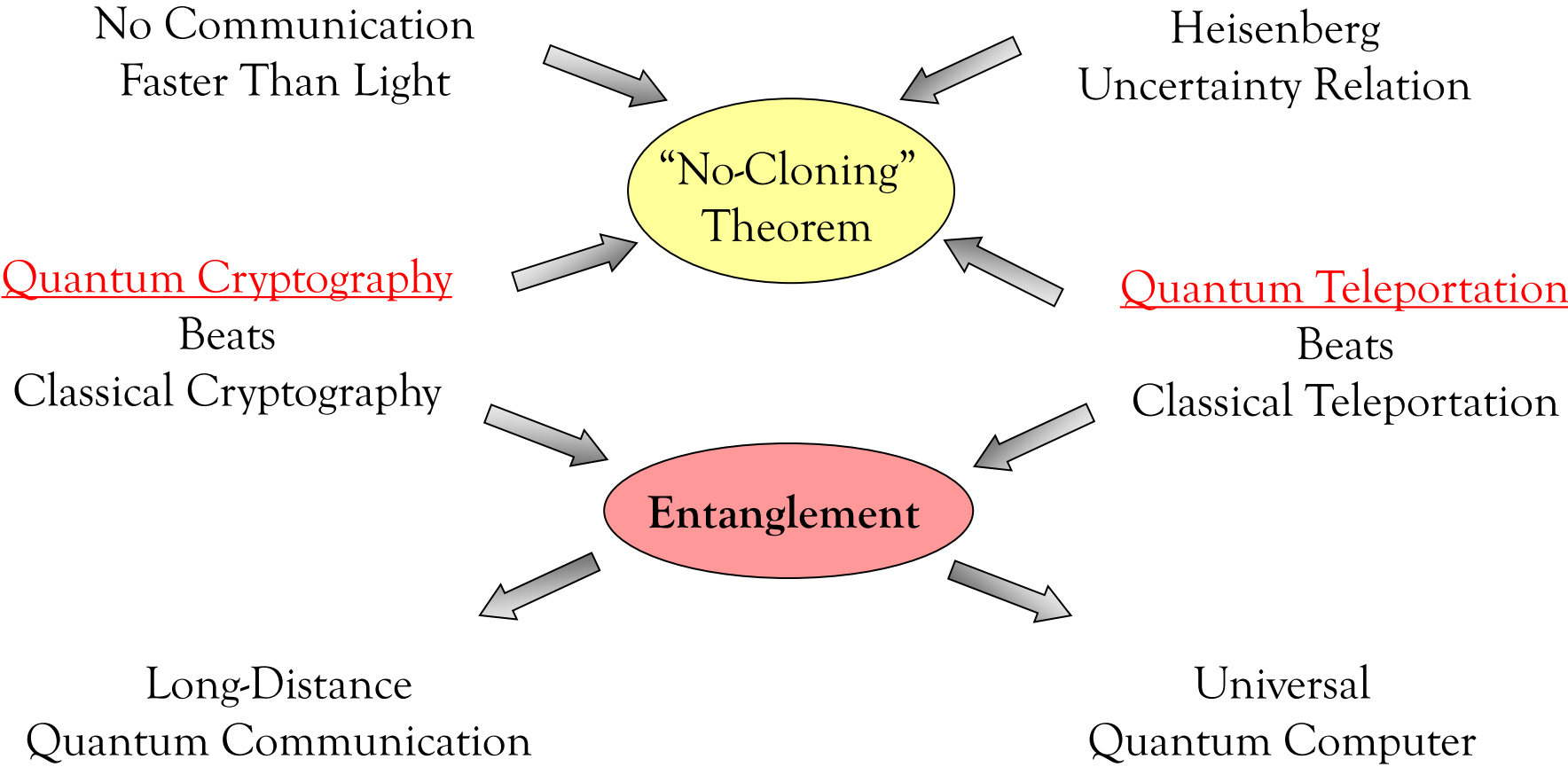
Universal  
Quantum Computer

# Quanteninformation & Quantentechnologie

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# Quanteninformation & Quantentechnologie



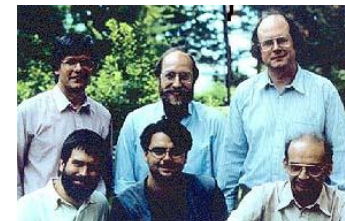
# Quantenkommunikation

**Reliable** Transmission  
of **Quantum** Information...  
(Quantum Teleportation)

**Secure** Transmission  
of **Classical** Information...  
(Quantum Cryptography)



# PHYSICAL REVIEW LETTERS



(top, left) Richard Jozsa, William K. Wootters, Charles H. Bennett. (bottom, left) Gilles Brassard, Claude Crépeau, Asher Peres. Photo: André Berthiaume.

VOLUME 70

29 MARCH 1993

NUMBER 13

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

Charles H. Bennett,<sup>(1)</sup> Gilles Brassard,<sup>(2)</sup> Claude Crépeau,<sup>(2),(3)</sup>  
Richard Jozsa,<sup>(2)</sup> Asher Peres,<sup>(4)</sup> and William K. Wootters<sup>(5)</sup>

<sup>(1)</sup> *IBM Research Division, T.J. Watson Research Center, Yorktown Heights, New York 10598*

<sup>(2)</sup> *Département IRO, Université de Montréal, C.P. 6128, Succursale "A", Montréal, Québec, Canada H3C 3J7*

<sup>(3)</sup> *Laboratoire d'Informatique de l'École Normale Supérieure, 45 rue d'Ulm, 75230 Paris CEDEX 05, France<sup>(a)</sup>*

<sup>(4)</sup> *Department of Physics, Technion-Israel Institute of Technology, 32000 Haifa, Israel*

<sup>(5)</sup> *Department of Physics, Williams College, Williamstown, Massachusetts 01267*

(Received 2 December 1992)

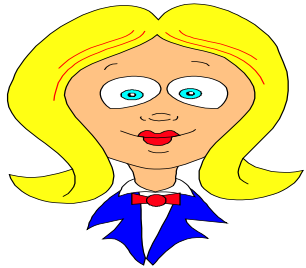
An unknown quantum state  $|\phi\rangle$  can be disassembled into, then later reconstructed from, purely classical information and purely nonclassical Einstein-Podolsky-Rosen (EPR) correlations. To do so the sender, "Alice," and the receiver, "Bob," must prearrange the sharing of an EPR-correlated pair of particles. Alice makes a joint measurement on her EPR particle and the unknown quantum system, and sends Bob the classical result of this measurement. Knowing this, Bob can convert the state of his EPR particle into an exact replica of the unknown state  $|\phi\rangle$  which Alice destroyed.

PACS numbers: 03.65.Bz, 42.50.Dv, 89.70.+c

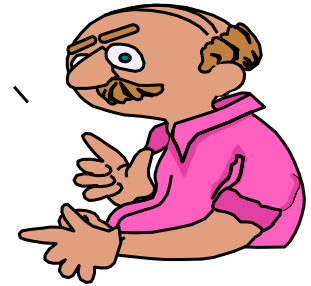
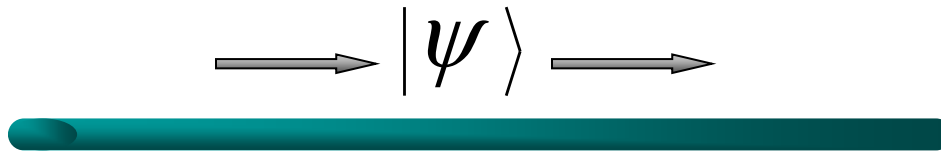


# Quantenteleportation

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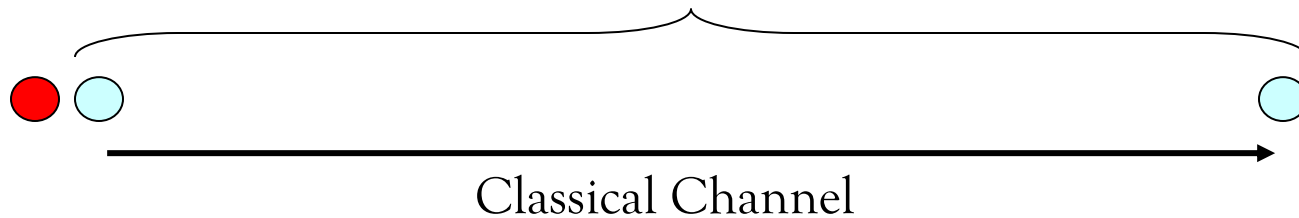
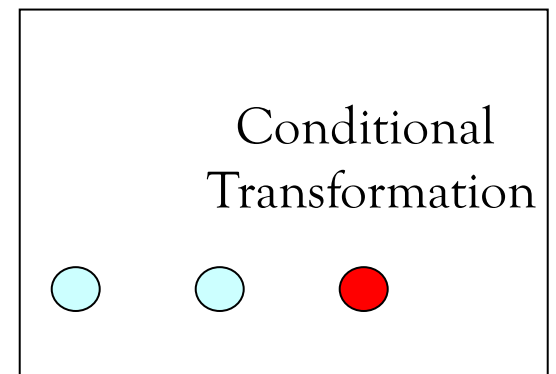
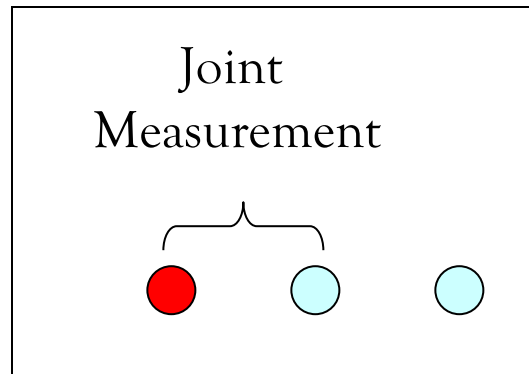
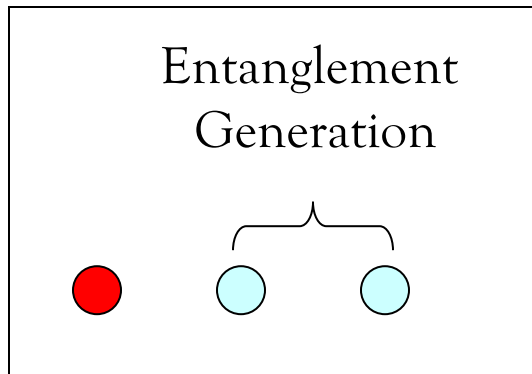


**Alice**

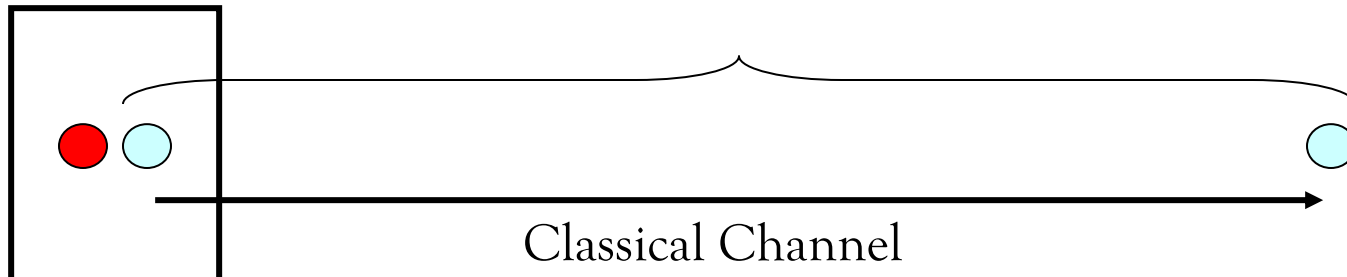
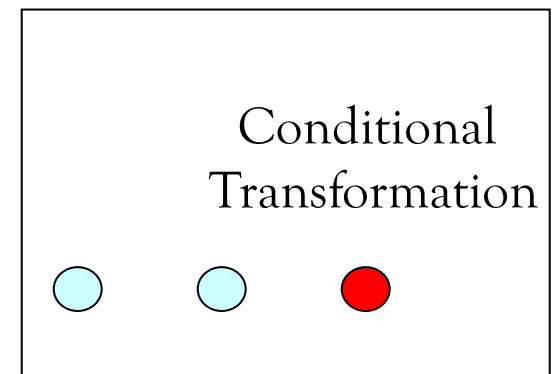
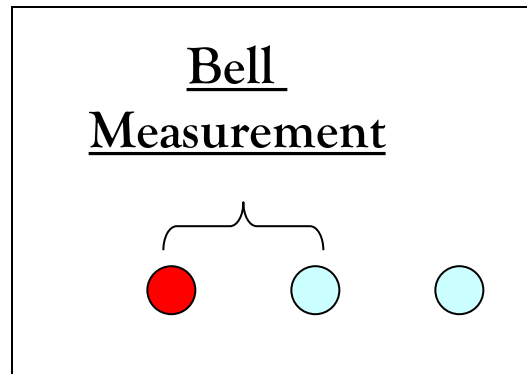
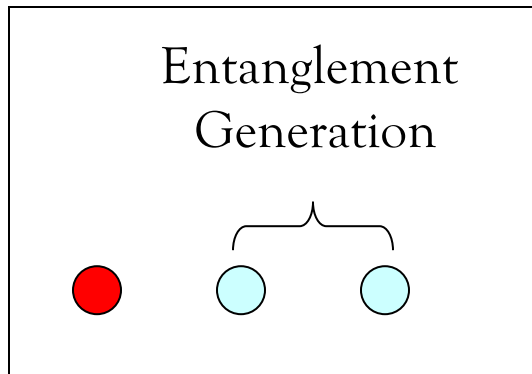


**Bob**

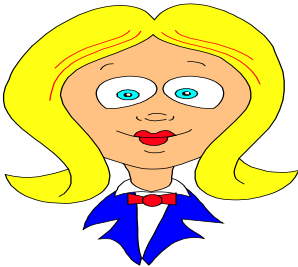
# Quantenteleportation



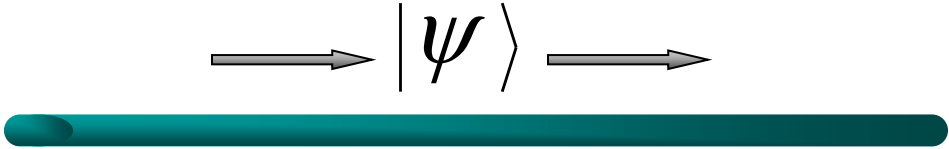
# Quantenteleportation



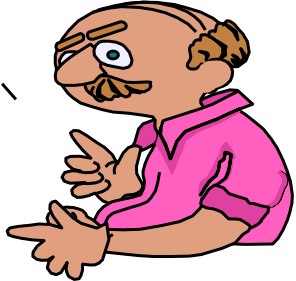
# Quantenkryptographie, Schlüsselverteilung



Alice



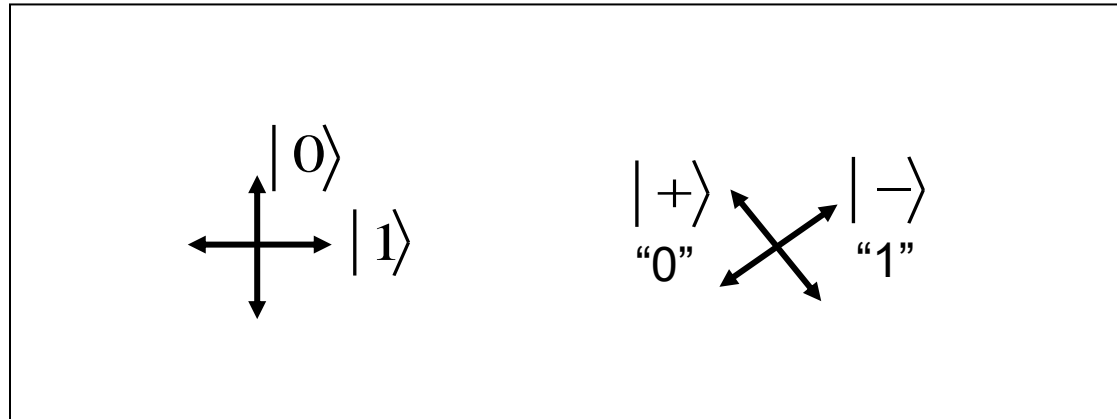
Eve



Bob

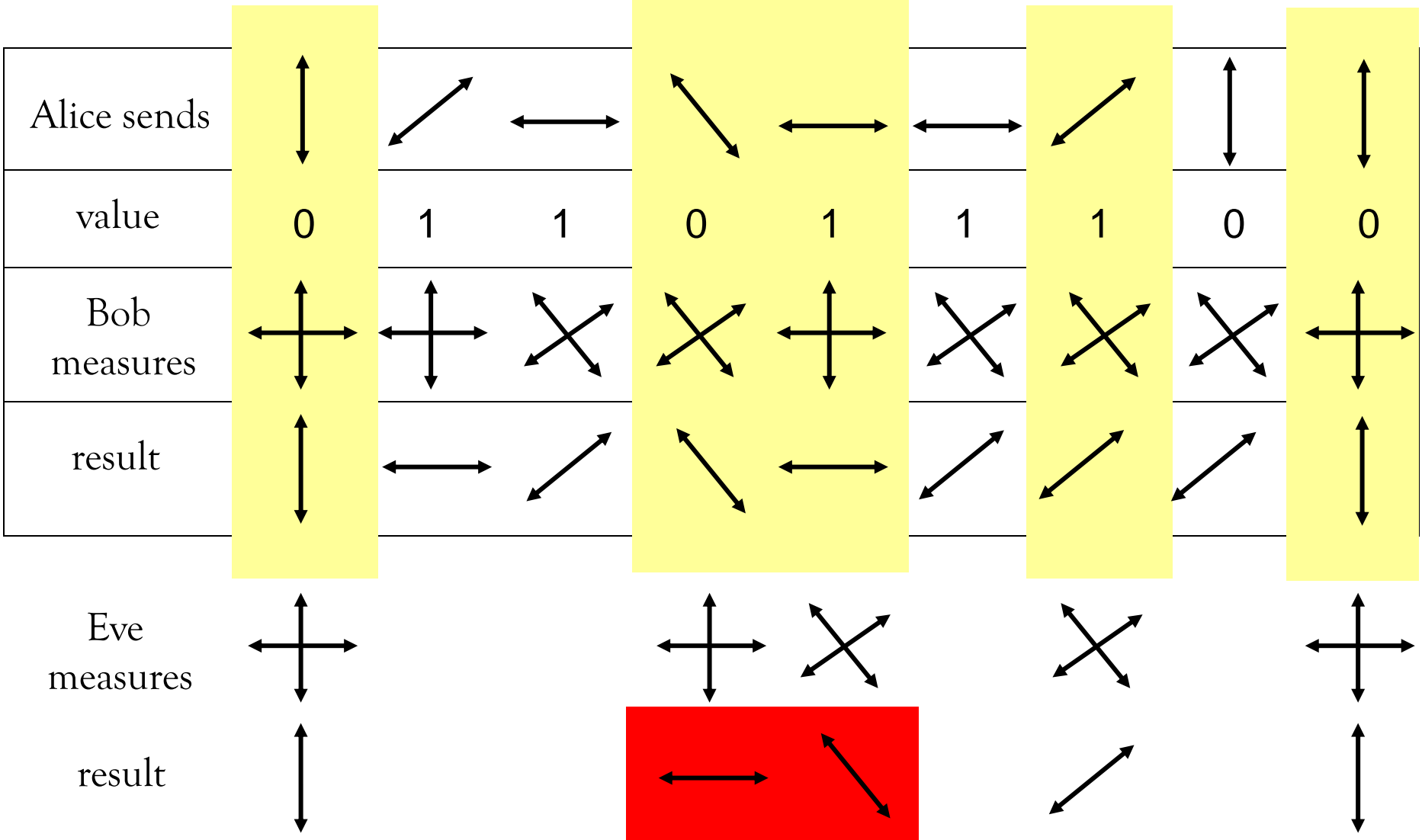
# Quantenkryptographie, Schlüsselverteilung

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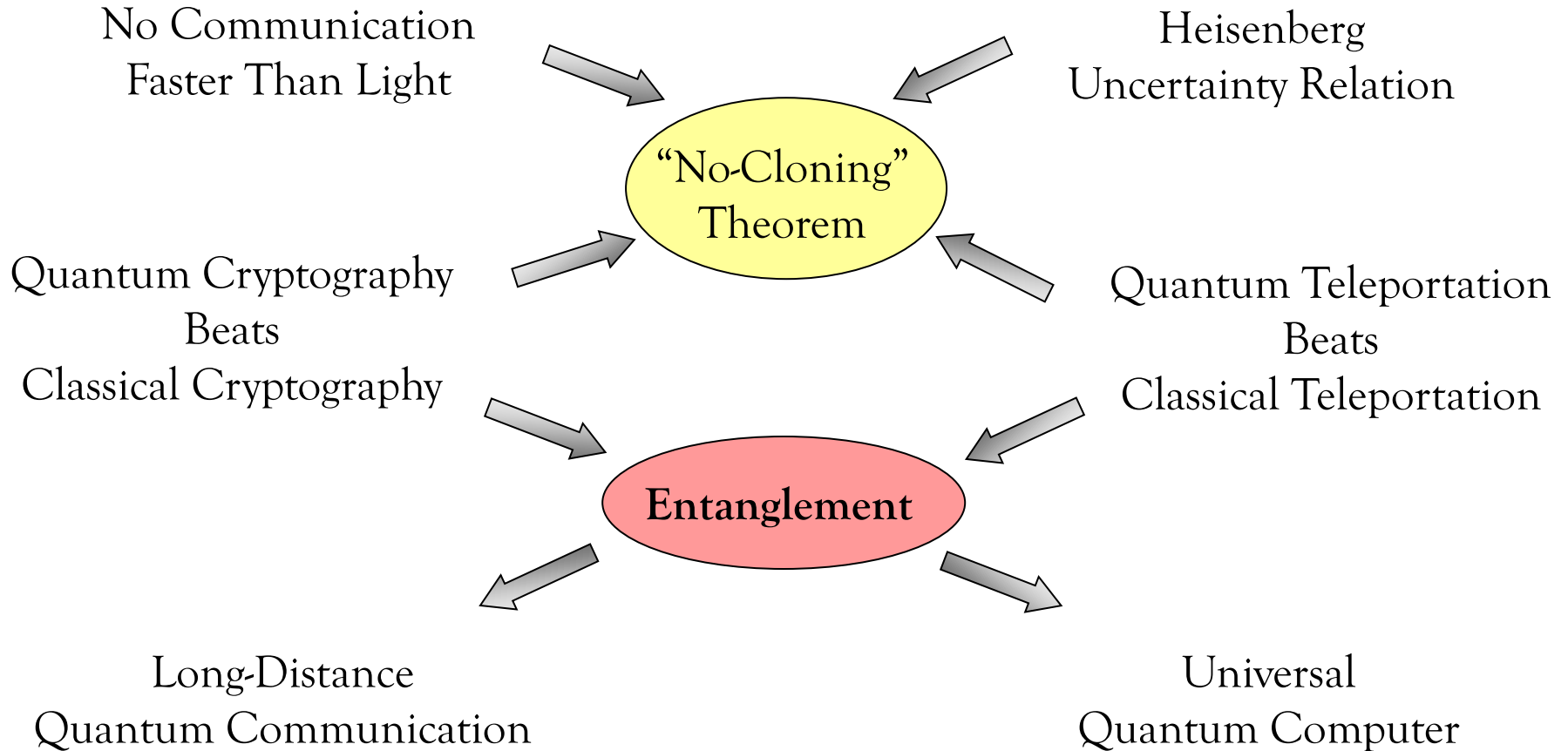
$$|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$$

# Quantenkryptographie, Schlüsselverteilung

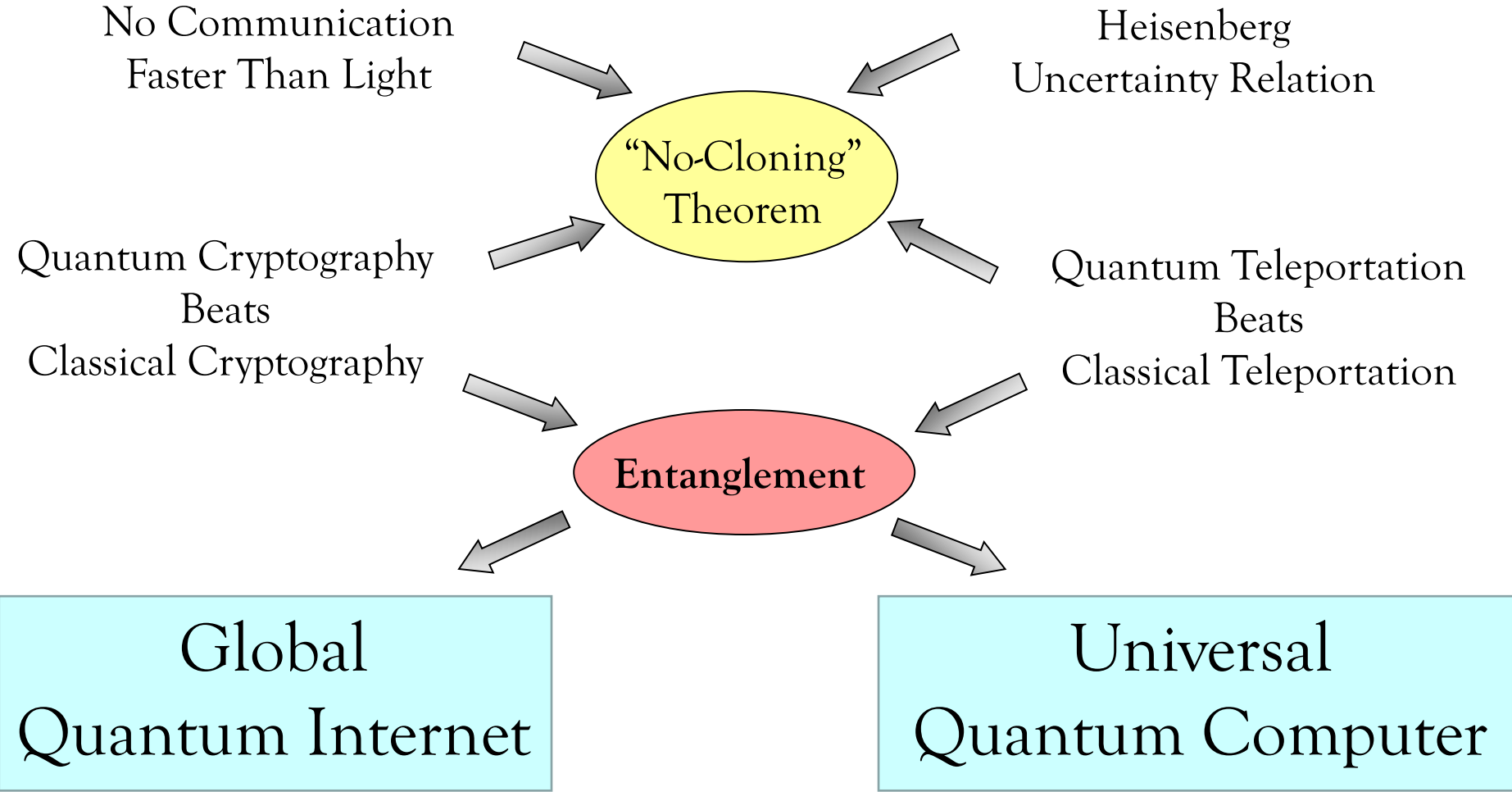


# Quanteninformation & Quantentechnologie

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# Quanteninformation & Quantentechnologie



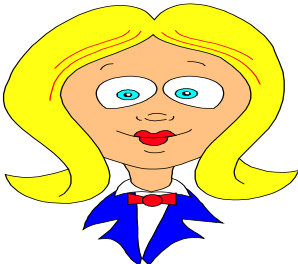


# Quanteninformation & Quantentechnologie

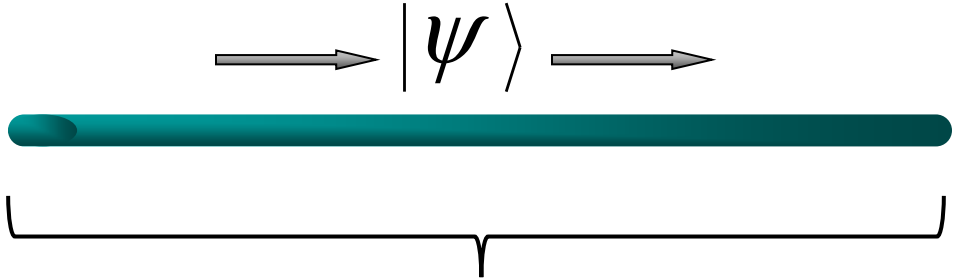
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Global  
Quantum Internet

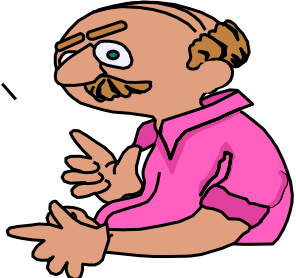
# Quantenkommunikation: Große Distanzen?



Alice



$\sim 1000 \text{ km}$

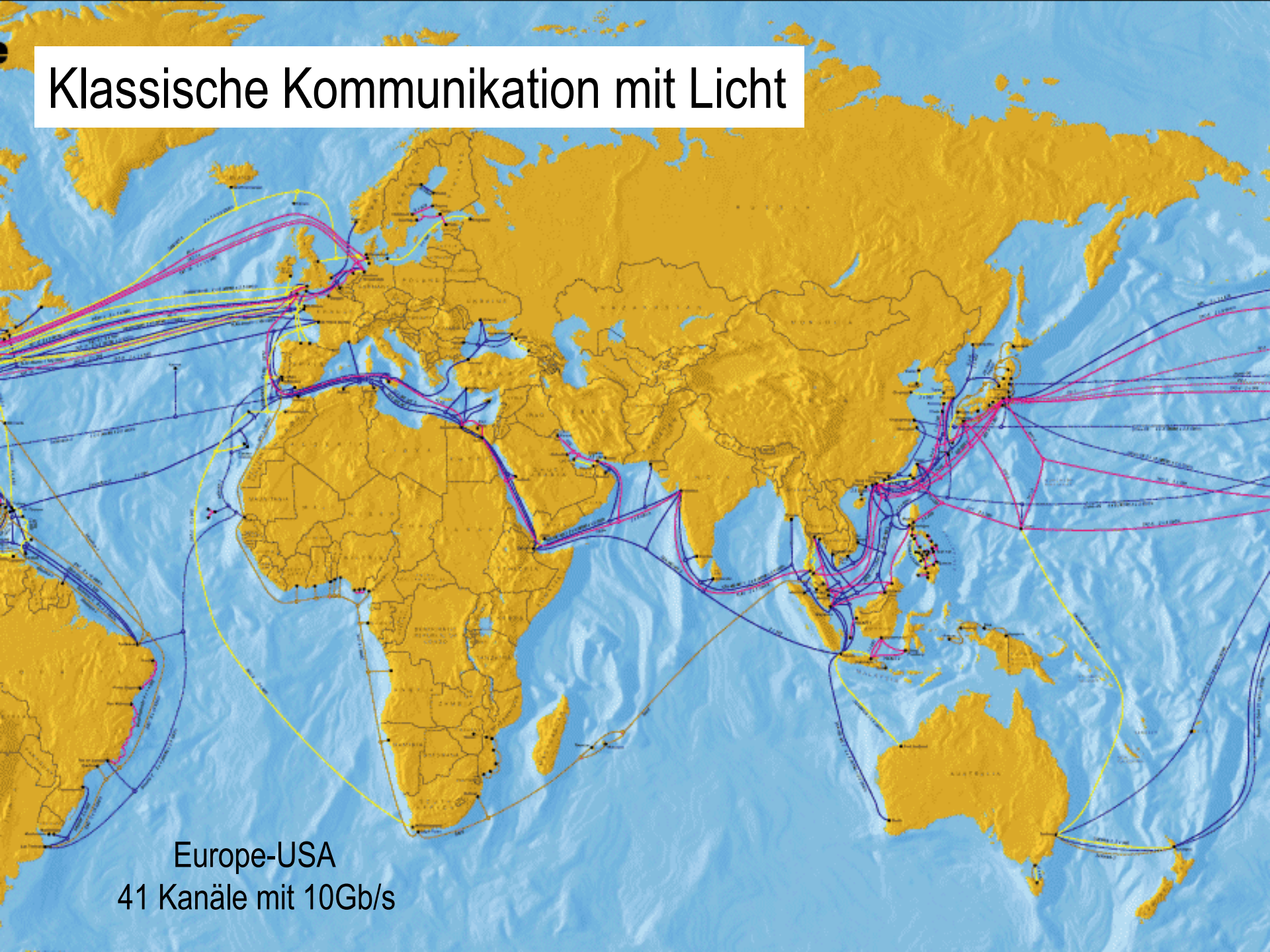


Bob



Eve

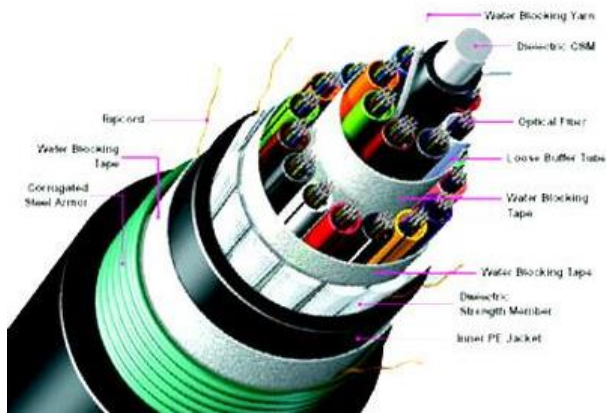
# Klassische Kommunikation mit Licht



Europe-USA  
41 Kanäle mit 10Gb/s

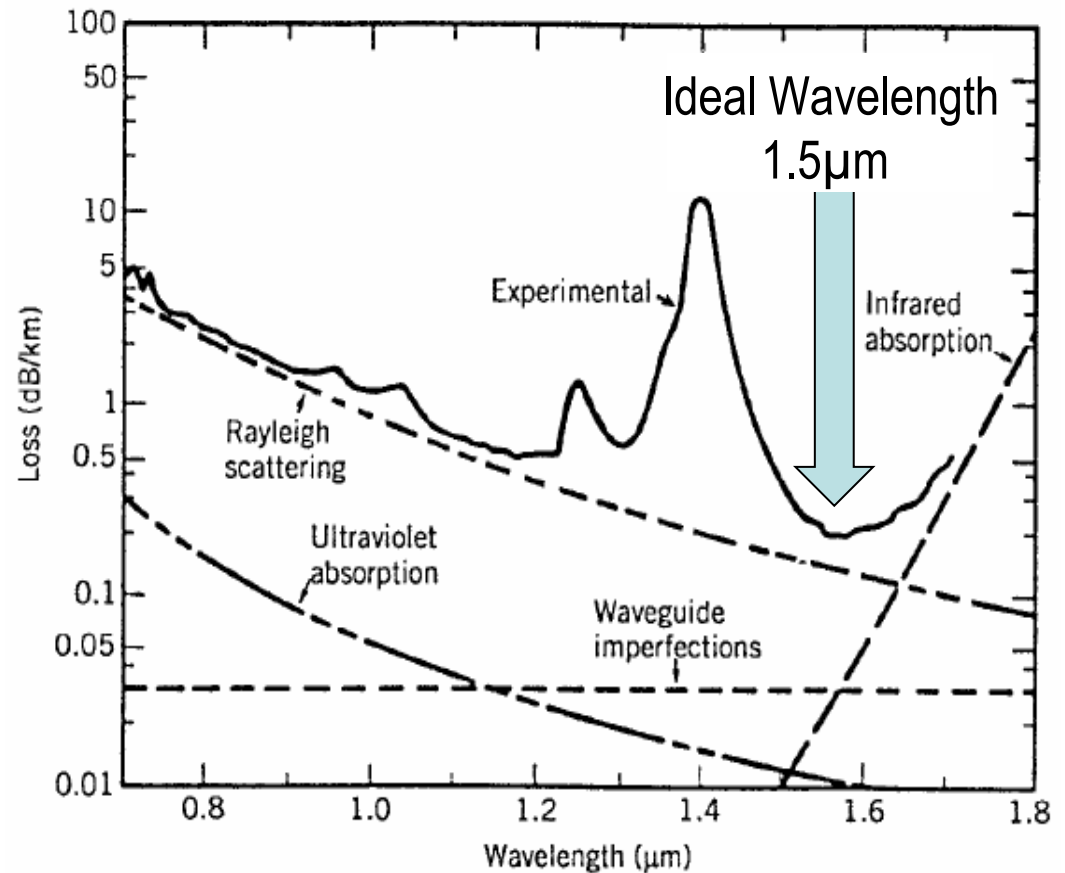
# Optische Fasertechnologie

- single-mode propagation
- 0.2dB/km attenuation



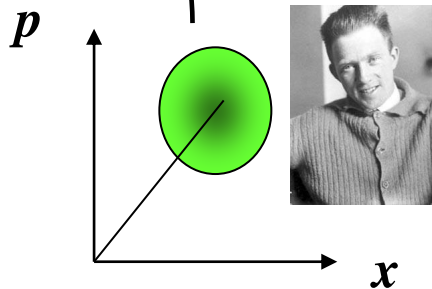
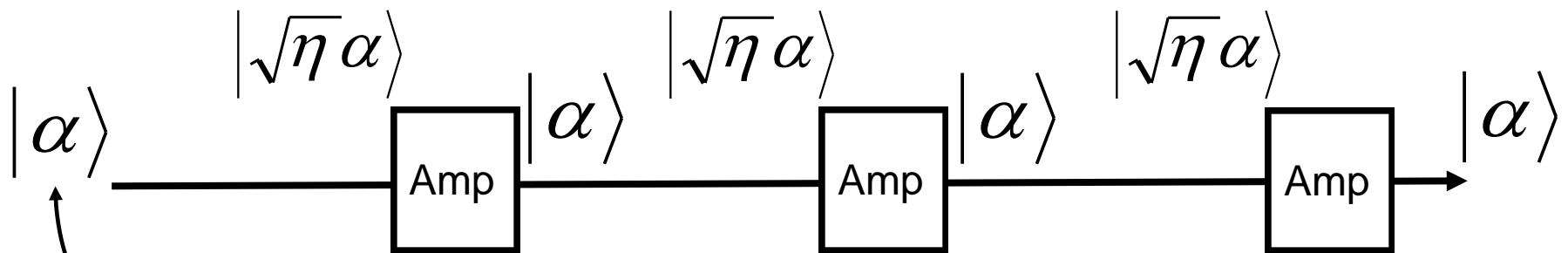
repeater stations for optical pulse recovery:

- light amplification
- compression of spreading wave packets



# Quantenrepeater durch Optische Verstärker

$$\eta = \exp(-L / L_{\text{att}})$$

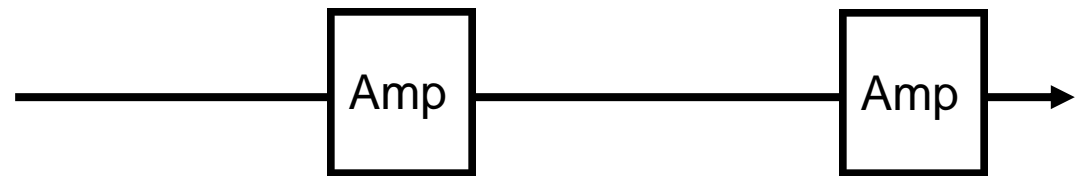


# Quantenrepeater durch Optische Verstärker

$$\eta = \exp(-L / L_{\text{att}})$$

$$\eta |\psi_{\text{in}}\rangle\langle\psi_{\text{in}}| + (1-\eta)|00\rangle\langle 00|$$

$$|\psi_{\text{in}}\rangle = \alpha |10\rangle + \beta |01\rangle$$



$$\alpha |10\rangle + \beta |01\rangle$$

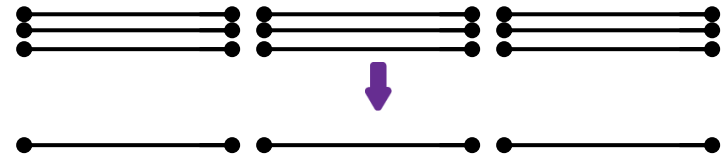


# Quantenrepeater mittels Verschränkung

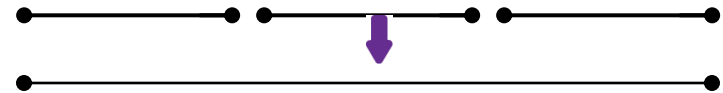
✓ Entanglement Distribution



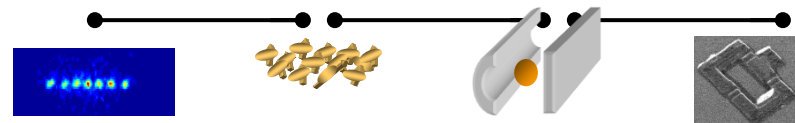
✓ Entanglement Purification



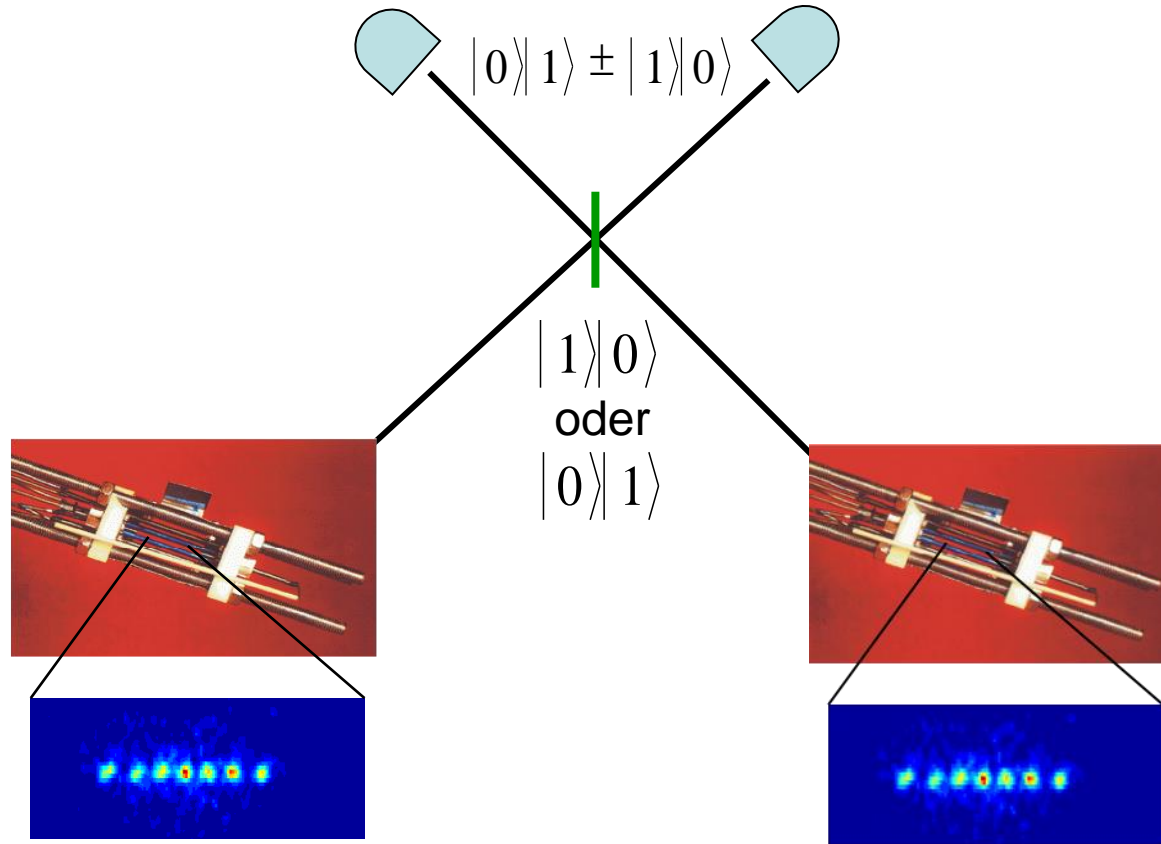
✓ Entanglement Swapping



✓ Quantum Memories



# Qubit-Verschränkung mit Ionen

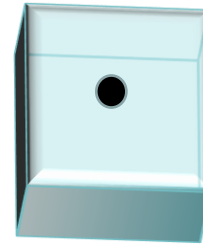
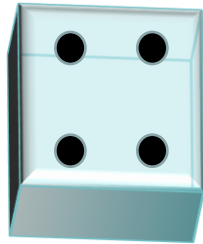


$$|\Psi^\pm\rangle = (|01\rangle \pm |10\rangle) / \sqrt{2}$$



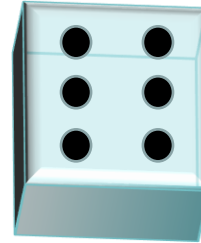
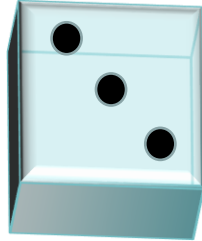
# Ohne Quantenspeicher

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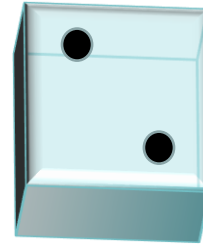
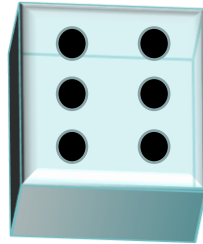
# Ohne Quantenspeicher

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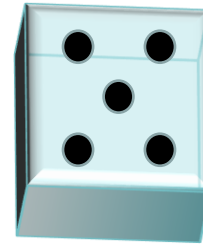
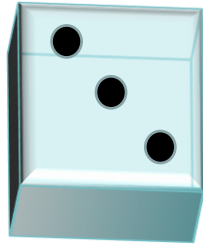
# Ohne Quantenspeicher

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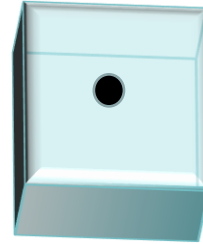
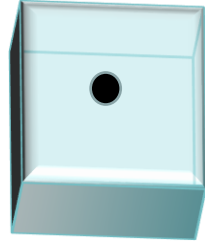
# Ohne Quantenspeicher

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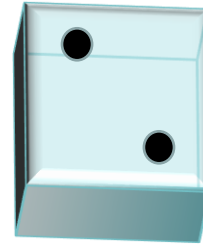
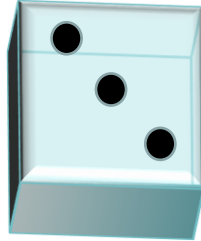
# Ohne Quantenspeicher

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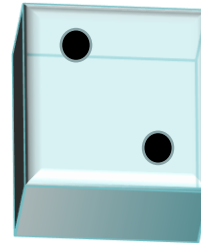
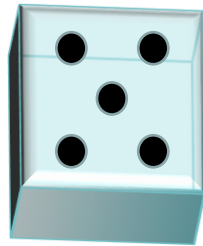
# Ohne Quantenspeicher

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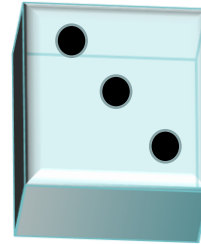
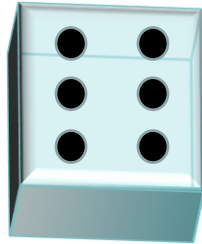
# Ohne Quantenspeicher

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# Ohne Quantenspeicher

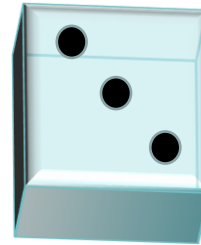
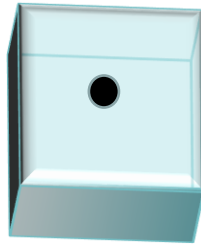
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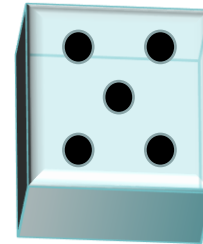
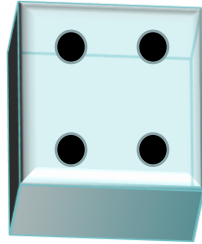
# Ohne Quantenspeicher

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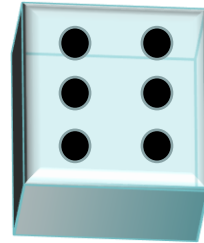
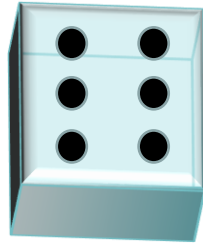
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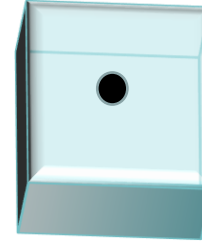
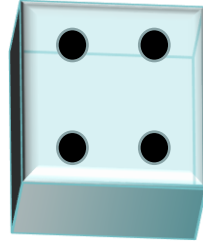
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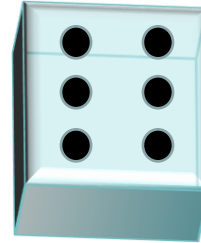
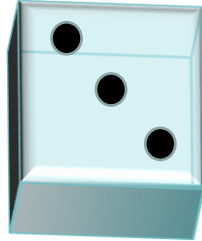
# Mit Quantenspeicher

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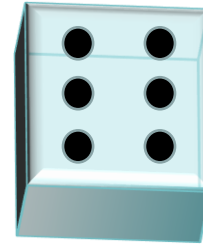
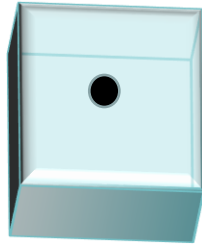
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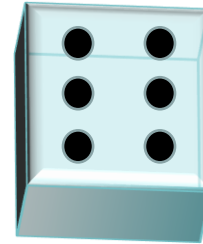
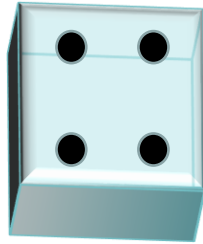
# Mit Quantenspeicher

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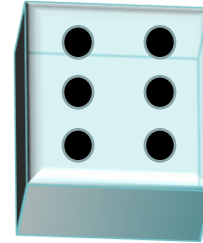
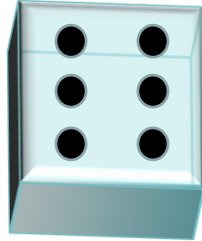
# Mit Quantenspeicher

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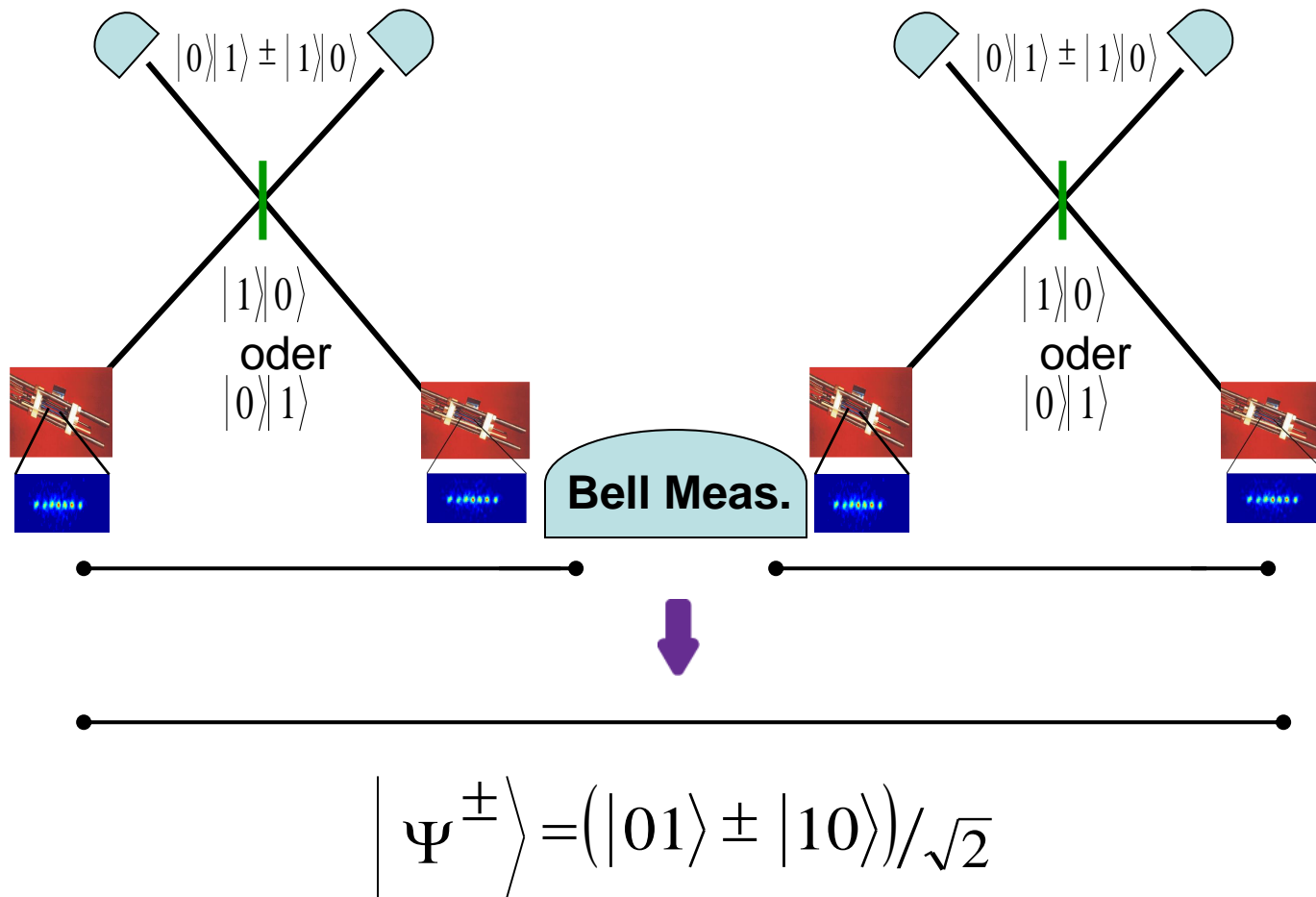
# Mit Quantenspeicher

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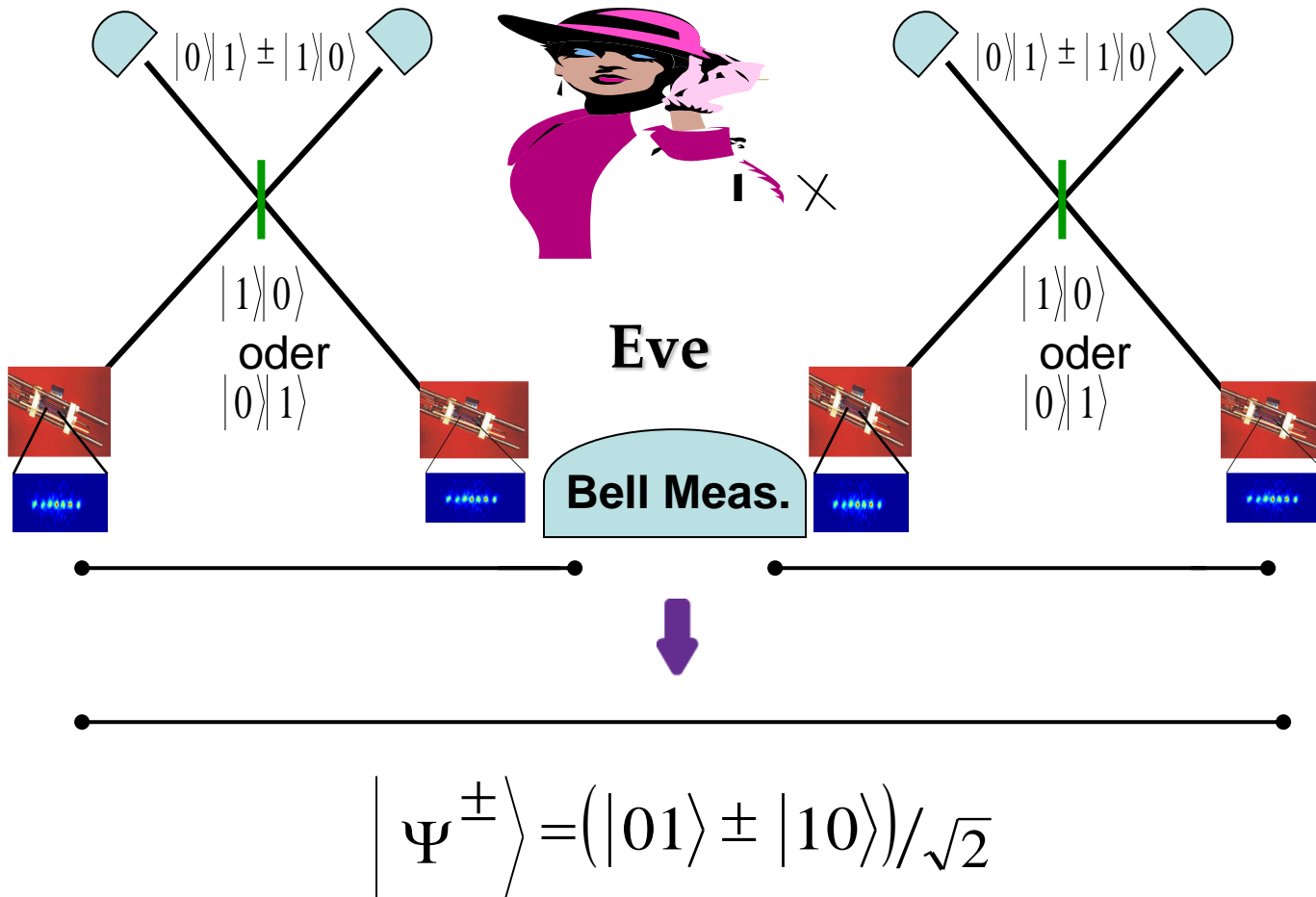




# “Verschränkung-Swapping”



# “Verschränkung-Swapping”

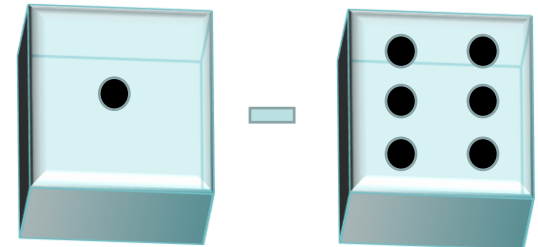
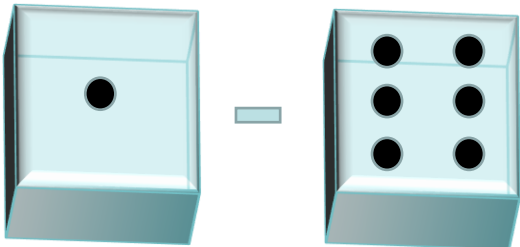
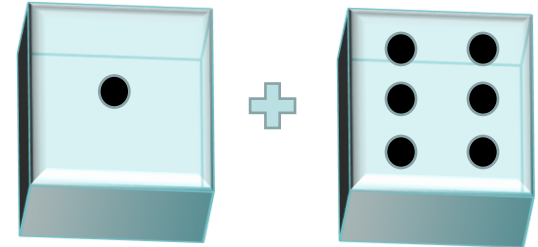
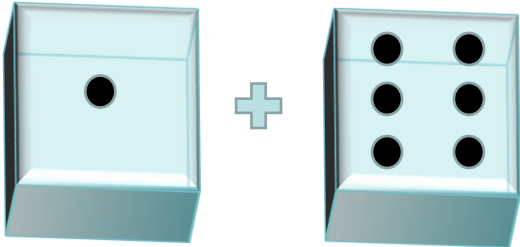
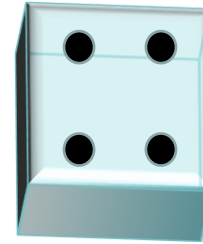
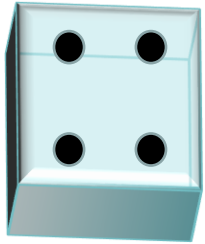


# Verschränkung: Klassischer Würfel

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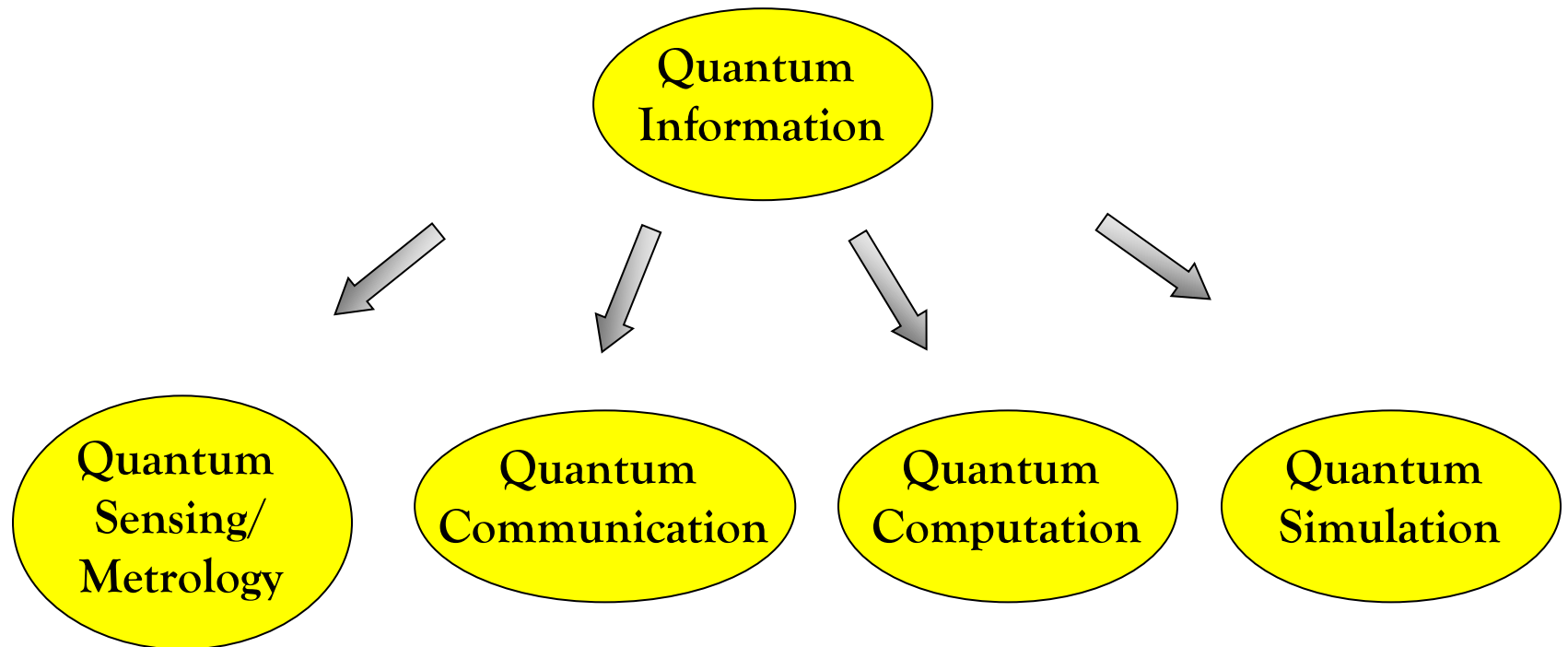


# Verschränkung: ``Quantenwürfel''



# Quanteninformation

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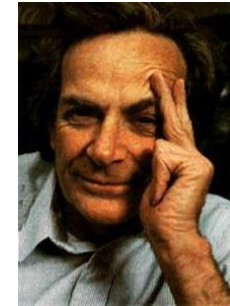


# Quantencomputer

Quantum  
Information

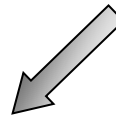


*Q. Turing Machine,  
Universal Q. Computer*  
Deutsch 1985



*There's Plenty of Room  
at the Bottom*  
Feynman 1959

Quantum  
Computation



Quantum Speedup, Quantum Parallelism,  
Quantum Algorithms,  
Universal Models, Scalability, Fault Tolerance,  
Quantum Error Correction  
...



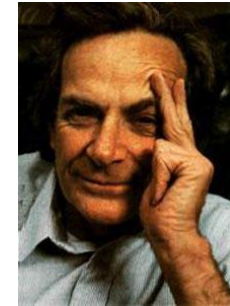
*Q. Algorithms and Codes*  
Shor 1994, 1995

# Quantencomputer

Quantum  
Information



*Q. Turing Machine,  
Universal Q. Computer*  
Deutsch 1985



*There's Plenty of Room  
at the Bottom*  
Feynman 1959

Quantum  
Computation



Quantum Speedup, Quantum Parallelism,  
Quantum Algorithms,  
Universal Models, Scalability, **Fault Tolerance,**  
**Quantum Error Correction**  
...



*Q. Algorithms and Codes*  
Shor 1994, 1995

# Quantenfehlerkorrektur: Shor Code

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THIRD SERIES, VOLUME 52, NUMBER 4

OCTOBER 1995

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## RAPID COMMUNICATIONS

*The Rapid Communications section is intended for the accelerated publication of important new results. Since manuscripts submitted to this section are given priority treatment both in the editorial office and in production, authors should explain in their submittal letter why the work justifies this special handling. A Rapid Communication should be no longer than 4 printed pages and must be accompanied by an abstract. Page proofs are sent to authors.*

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### **Scheme for reducing decoherence in quantum computer memory**

Peter W. Shor\*

*AT&T Bell Laboratories, Room 2D-149, 600 Mountain Avenue, Murray Hill, New Jersey 07974*

(Received 17 May 1995)

Recently, it was realized that use of the properties of quantum mechanics might speed up certain computations dramatically. Interest has since been growing in the area of quantum computation. One of the main difficulties of quantum computation is that decoherence destroys the information in a superposition of states contained in a quantum computer, thus making long computations impossible. It is shown how to reduce the effects of decoherence for information stored in quantum memory, assuming that the decoherence process acts independently on each of the bits stored in memory. This involves the use of a quantum analog of error correcting codes.

PACS number(s): 03.65.Bz, 89.70.+c



# Shor's Quantenfehlerkorrektur-Code

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$$\alpha |+++ \rangle + \beta |--- \rangle$$

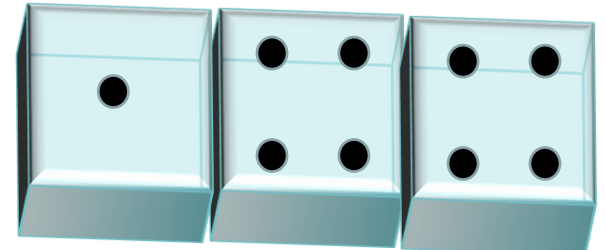
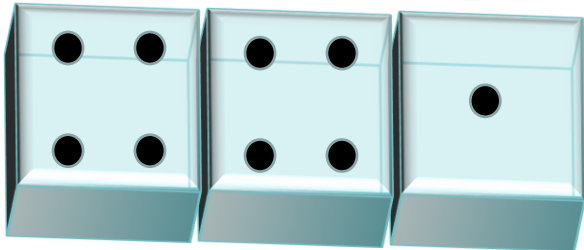
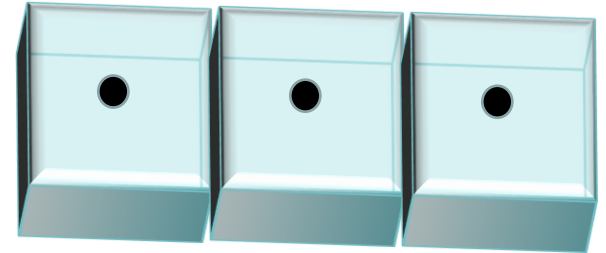
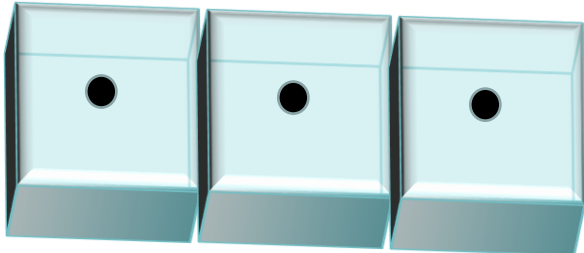
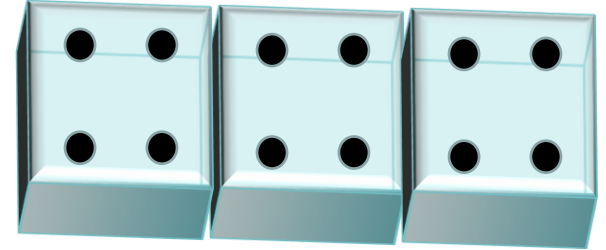
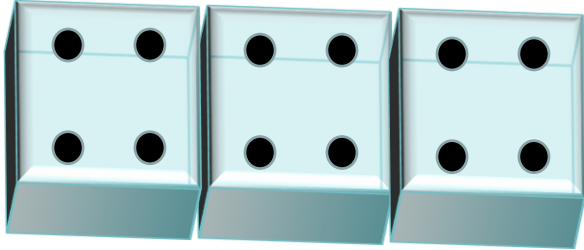
with

$$|\pm \rangle = ( |000 \rangle \pm |111 \rangle ) / \sqrt{2}$$

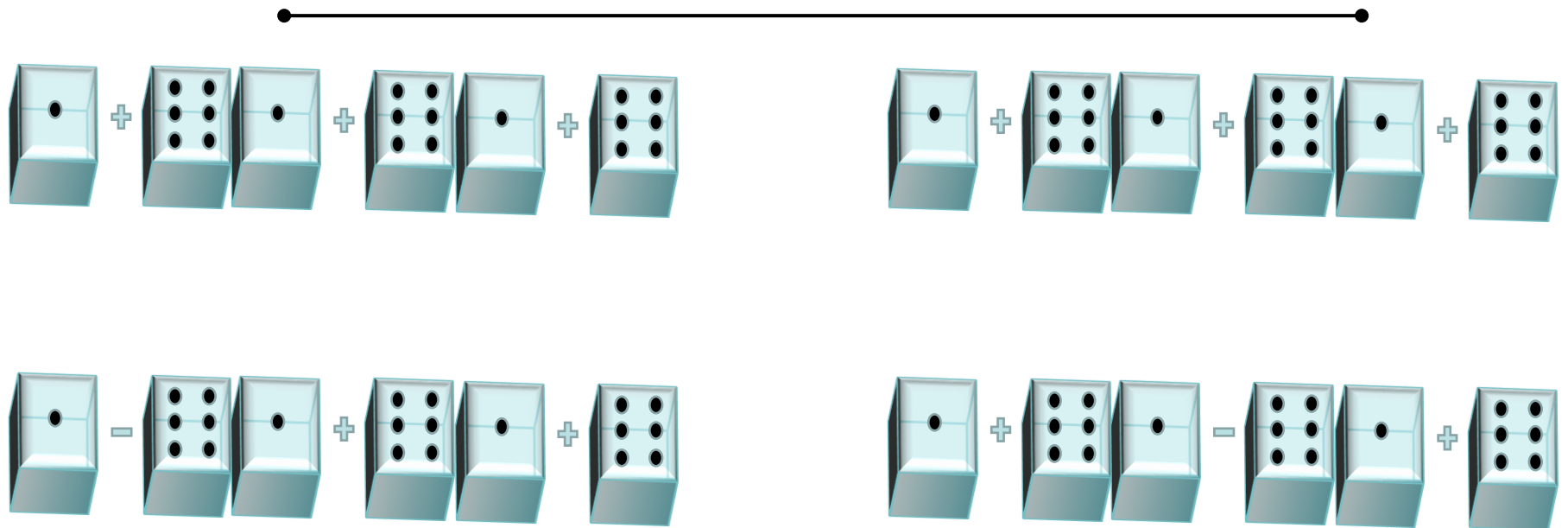


# Klassische Fehlerkorrektur

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# Quantenfehlerkorrektur



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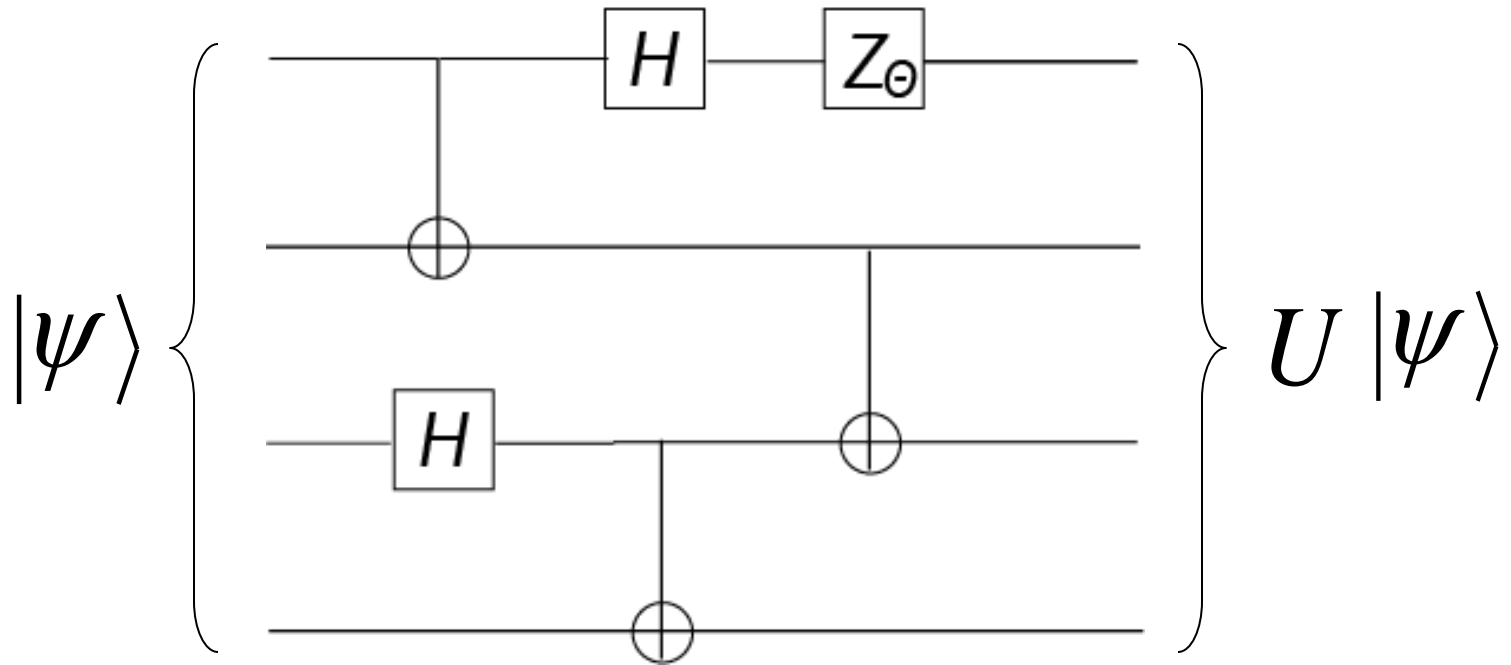
Quantum Computer:  
Software

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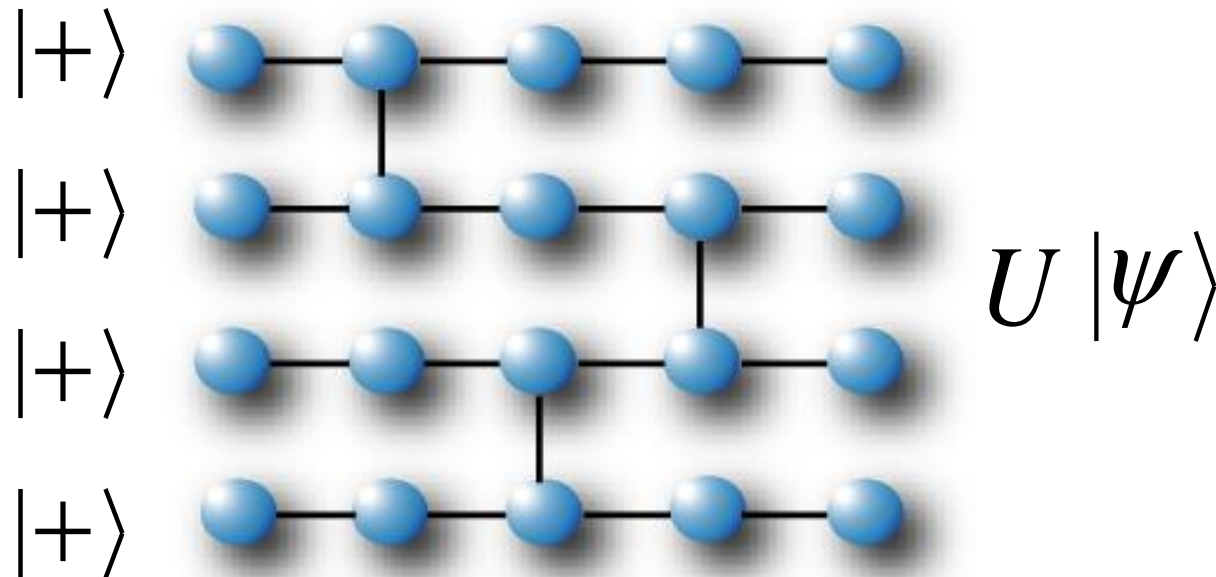
# ``Digitaler'' Quantencomputer mit Qubits

Circuit model of Quantum Computation:

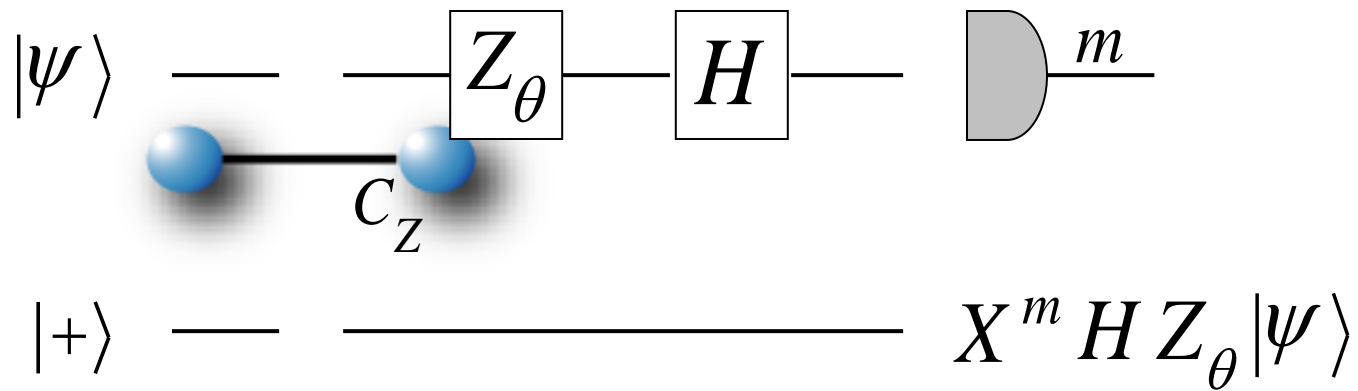


# ``Einwegquantencomputer`` mit Qubits

Cluster-state model of QC (``one-way QC``):



# Elementare Gatter-Teleportation



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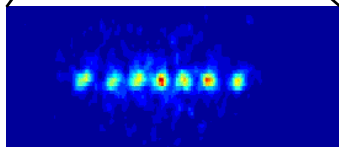
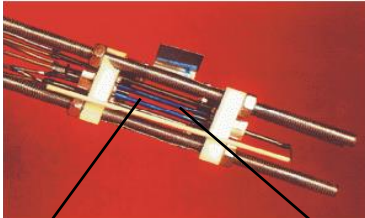
Quantum Computer:  
Hardware

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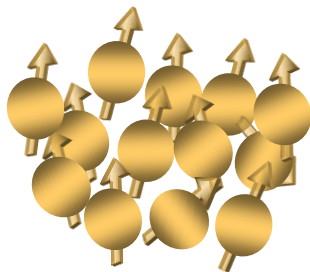
# Qubits: «Fliegend» vs. «Stationär»



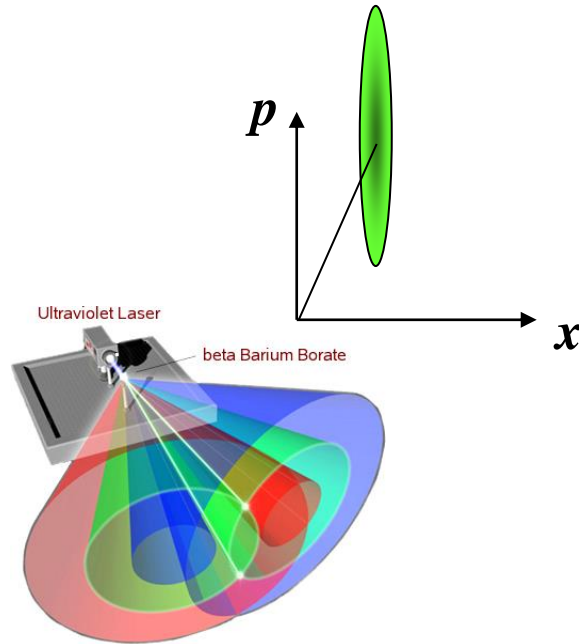
Ionenfallen



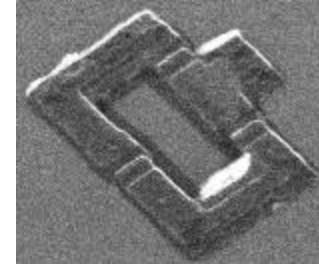
Resonator-QED



Frei-Raum-QED



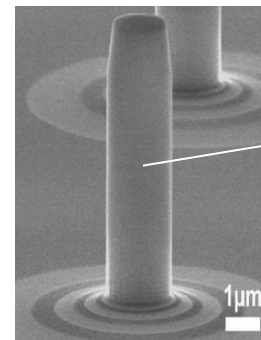
Photonen



Supraleiter



Farbzentren in Diamant



Halbleiter-Quantenpunkte

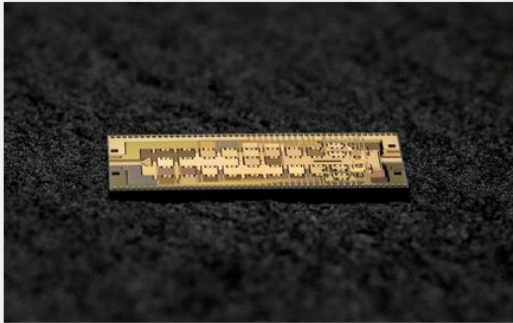
# Licht-Quantentechnologie



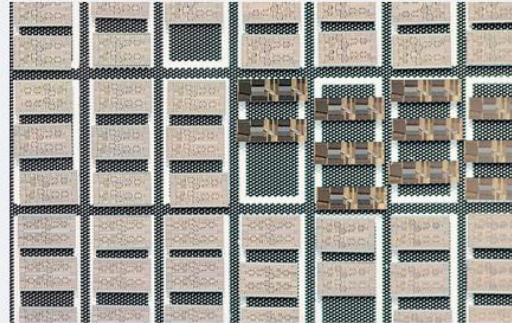
Products ▾ Pricing Photonics Community ▾ Company ▾

// Why Photonics

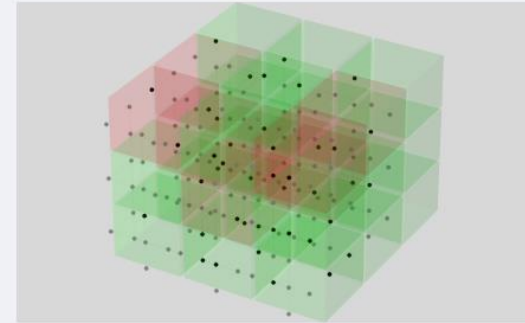
## The unique advantages of Photonics



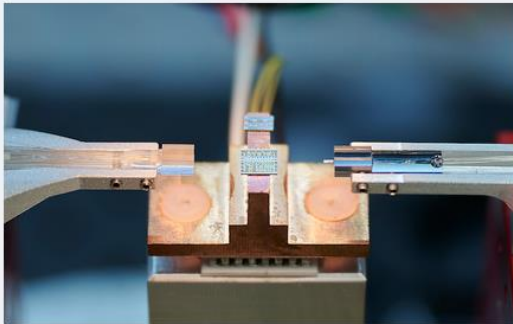
Room temperature computation



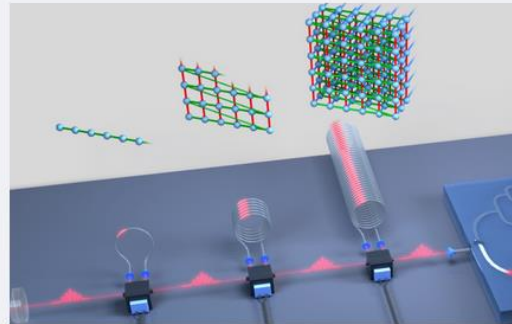
Manufacturability



Error correction flexibility



Modular and networkable



Fast clock speeds



Telecom compatibility

# Photonischer Quantencomputer

// FTQC

## Millions of qubits powered by light

Learn more about Xanadu's FTQC blueprint.

[Watch Video](#)



XANADU Products Pricing Photonics Community Company

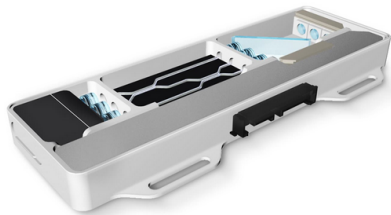
// Borealis

## Quantum computational advantage with 216 squeezed-state qubits

[Watch Video](#)

216 Squeezed-State Qubits

Modes Entangled



Technologische Anwendungen

Quantentechnologien sind der Innovationstreiber des 21. Jahrhunderts.

Und Licht ist eine wesentliche Ressource, um dieses Potential zu nutzen.

Licht ist weit bekanntlich ein idealer Zugang zu Quantentechnologien. Daher steht Licht und photonische Quantentechnologie im Zentrum unserer Q.ANTechnologie, um damit neue Produkte in den Bereichen Sensorik, Imaging und Computing zu realisieren.

Um die beste Qualität in unseren Produktentwicklungen zu gewährleisten, kümmern wir uns um die gesamte optische Prozesskette. Diese fängt bei der Umwandlung von Elektronen in Photonen an, gefolgt von der Erzeugung und Ausnutzung von optischen Quanteneffekten und schließlich der Rückwandlung der Quantensignale in elektrische Signale und Daten.

PsiQuantum Home About News Careers Resources

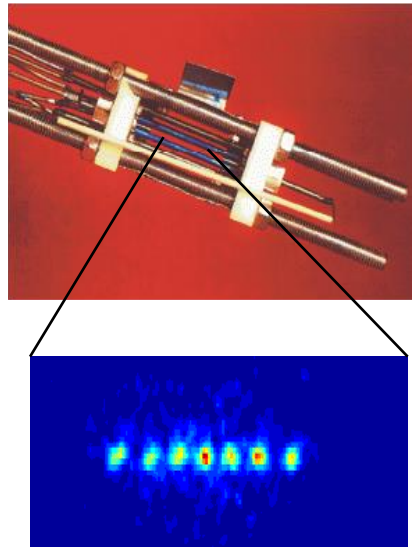
# Resources

Recorded Talks Detailed Technical Talks Technical Papers Google Scholars

## Silicon photonic quantum computing

# Ion-Qubits

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Ionenfallen

..... Ferdinand Schmidt-Kaler →