imagine the impossible

KIAS KOREA INSTITUTE FOR ADVANCED STUDY

Quantum technology:
What kind of resources do we need?

Colloquium @Seoul National University
2022. 05. 18.

Hyukjoon Kwon (권혁준)
Korea Institute for Advanced Study

What is quantum resource?

- **Resource: Something that a country, person, or organization has that they can use**

(Cambridge Dictionary)

자원 4 資源

발음

표준국어대사전 고려대한국어대사전 우리말샘

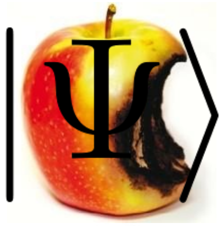
예문 열기

명사

1. 경제 인간 생활 및 경제 생산에 이용되는 원료로서의 광물, 산림, 수산물 따위를 통틀어 이르는 말.
   식량 자원.
2. 경제 인간 생활 및 경제 생산에 이용되는 노동력이나 기술 따위를 통틀어 이르는 말.
   청소년은 우리나라의 중요한 자원이다.

Ex) Gas/Oil, Materials, Water, Food, Human resources

- **Quantum resource: Something that we can use to do a "non-classical" task**
  - ✓ What are non-classical tasks using quantum principles? ➔ Quantum technology
  - ✓ What kind of quantum principle make this possible?
  - ✓ How can we quantify the non-classical resources?



Quantum state

Quantum technologies

Quantum communication

[Sending quantum bits]

- Quantum information transfer
- Quantum cryptography
  (quantum key distribution)

Quantum computing

[Faster computation]

- Quantum simulation
- Quantum algorithm
- Quantum error correction

Quantum metrology

[Precision measurement]

- Precise phase/force sensing
- Accurate measurement
  of physical constants

Quantum technologies

Quantum communication

[Sending quantum bits]

- Quantum information transfer
- Quantum cryptography (quantum key distribution)

Quantum computing

[Faster computation]

- Quantum simulation
- Quantum algorithm
- Quantum error correction

Quantum metrology

[Precision measurement]

- Precise phase/force sensing
- Accurate measurement of physical constants

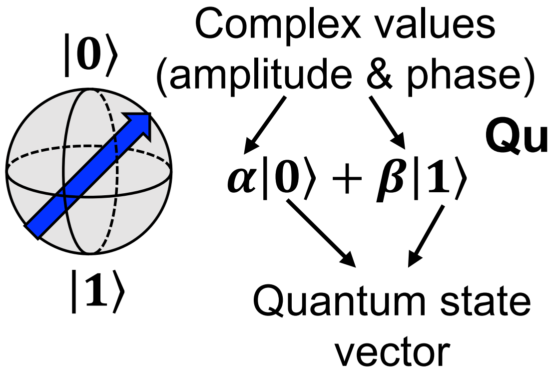
Bit and qubits

(Classical) Bit

Head (**0**) *or* Tail (**1**)

Quantum Bit

1 qubit



Complex values (amplitude & phase)

$\boldsymbol{\alpha}|\mathbf{0}\rangle + \boldsymbol{\beta}|\mathbf{1}\rangle$

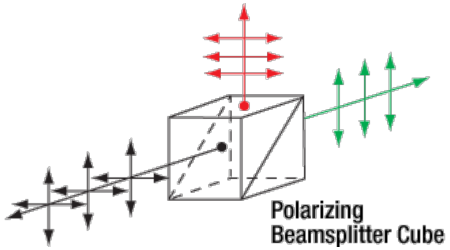
Quantum state vector

Quantum superposition
➔ Wave nature

Different from 0 or 1

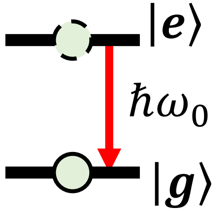
Any physical state can be in superposition

e.g., Polarization of light



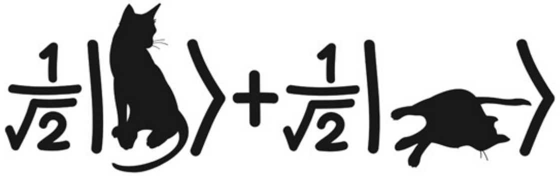
$|\boldsymbol{\psi}\rangle = \boldsymbol{\alpha}|\boldsymbol{H}\rangle + \boldsymbol{\beta}|\boldsymbol{V}\rangle$

Atomic energy level

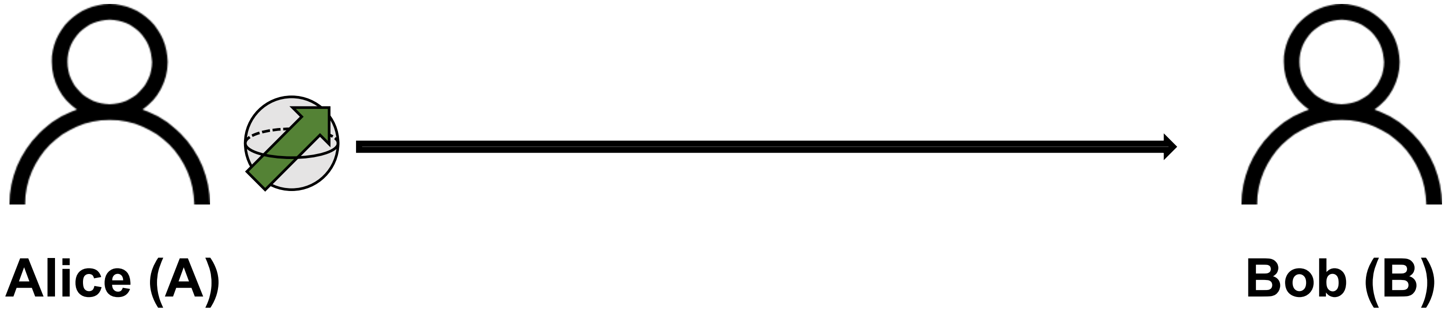


$|\boldsymbol{\psi}\rangle = \boldsymbol{\alpha}|\boldsymbol{e}\rangle + \boldsymbol{\beta}|\boldsymbol{g}\rangle$

or even a cat!



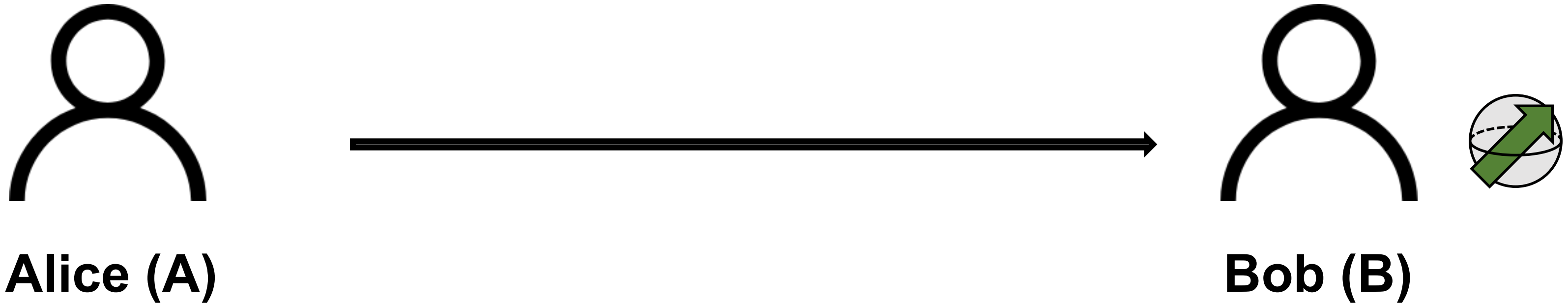
How to send a quantum state (qubit)?



Alice (A)

Bob (B)

How to send a quantum state (qubit)?

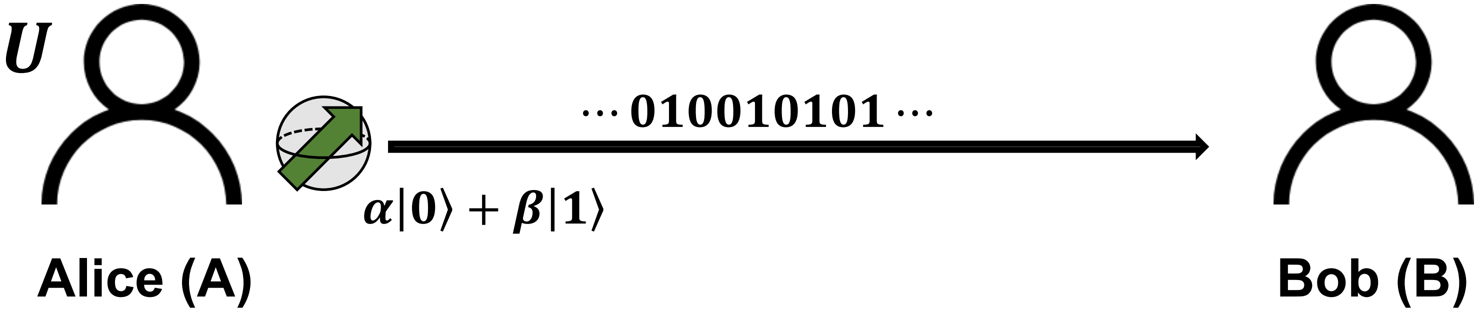


Alice (A)

Bob (B)

How to send a quantum state (qubit)?

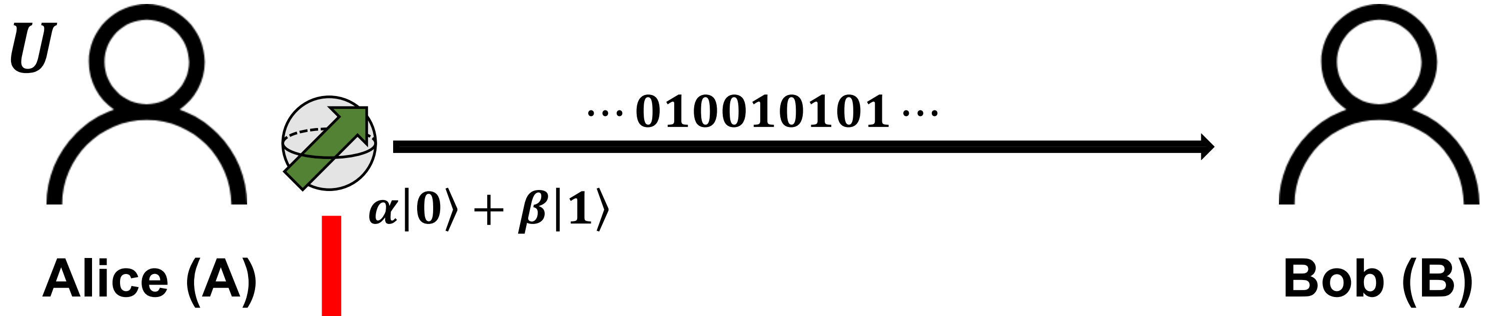
Let us suppose that only classical information (bit) can be transmitted
(but any quantum operation can be done locally)



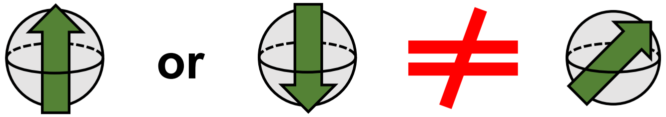
LOCC (local operation and classical communication)

How to send a quantum state (qubit)?

Let us suppose that only classical information (bit) can be transmitted
(but any quantum operation can be done locally)



Only gets the information 0 or 1



"Measurement" ➔ Wave function collapse

$|0\rangle$ is detected with probability $|\alpha|^2$
$|1\rangle$ is detected with probability $|\beta|^2$

c.f.) This is how quantum cryptography works (BB84, E91)

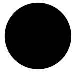
Alice may measure the state in different bases

➔ To get exact values of α and β, infinitely many bits should be sent to Bob

It is impossible to send a qubit using classical communication channels (LOCC)

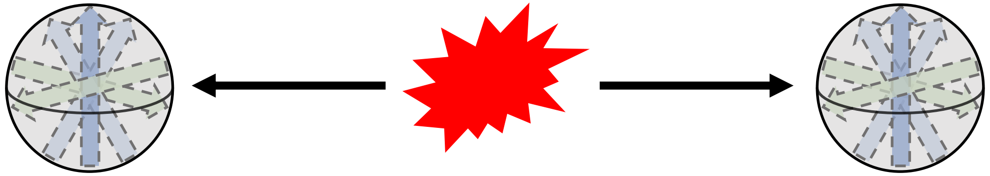
Quantum entanglement

Quantum entanglement

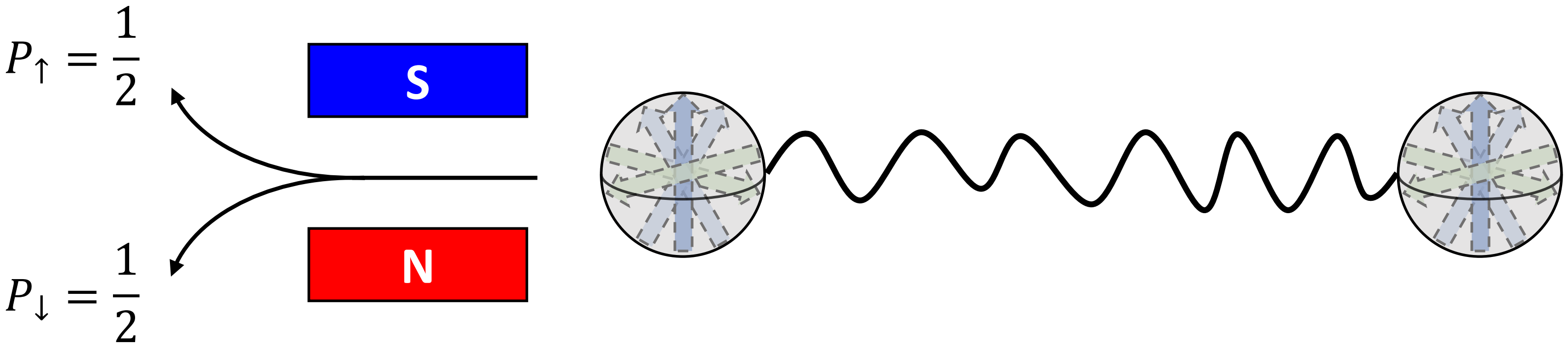


Spin=0

Quantum entanglement



Quantum entanglement

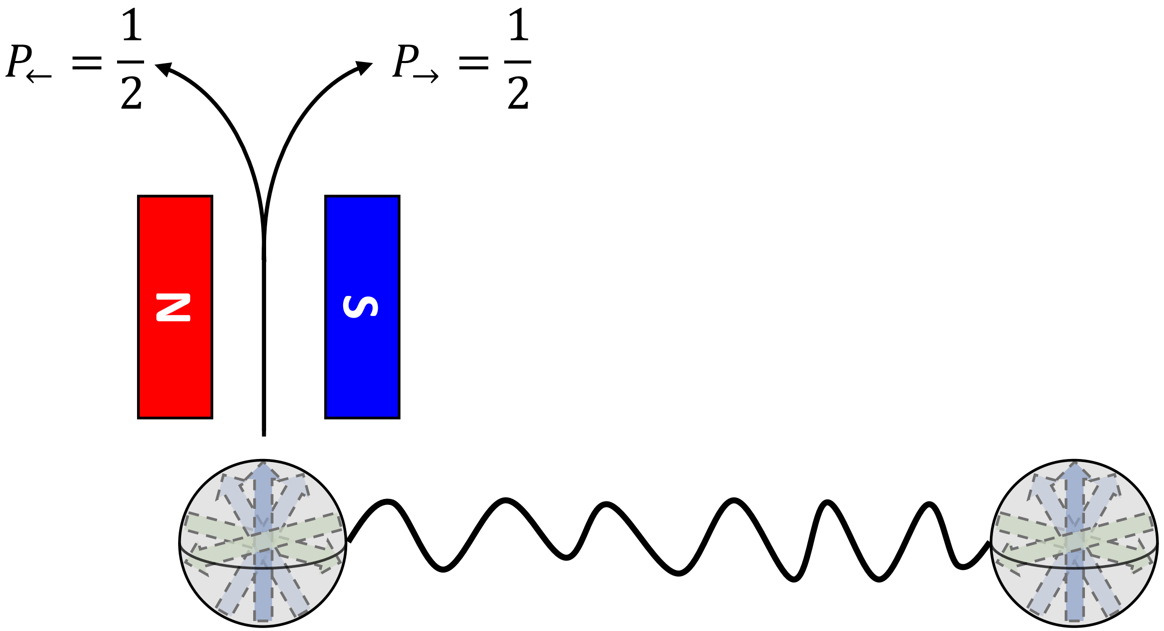


$P_{\uparrow} = \frac{1}{2}$

$P_{\downarrow} = \frac{1}{2}$

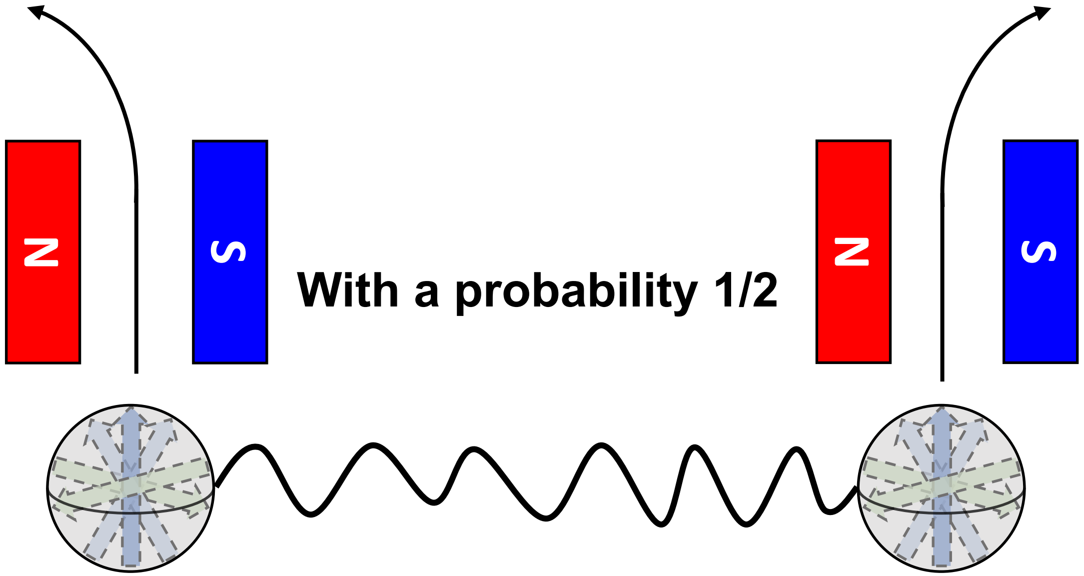
If we do only look at the local party, it is perfectly random (in any axis!)

Quantum entanglement



If we do only look at the local party, it is perfectly random (in any axis!)

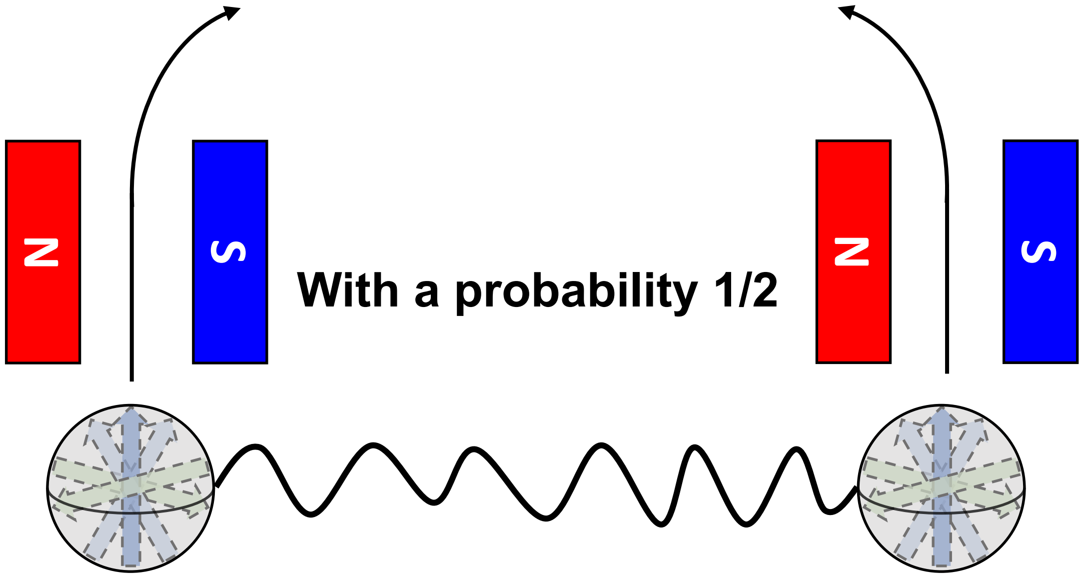
Quantum entanglement



With a probability 1/2

But if we at the overall system, it is perfectly (anti)-correlated (in any axis!)

Quantum entanglement

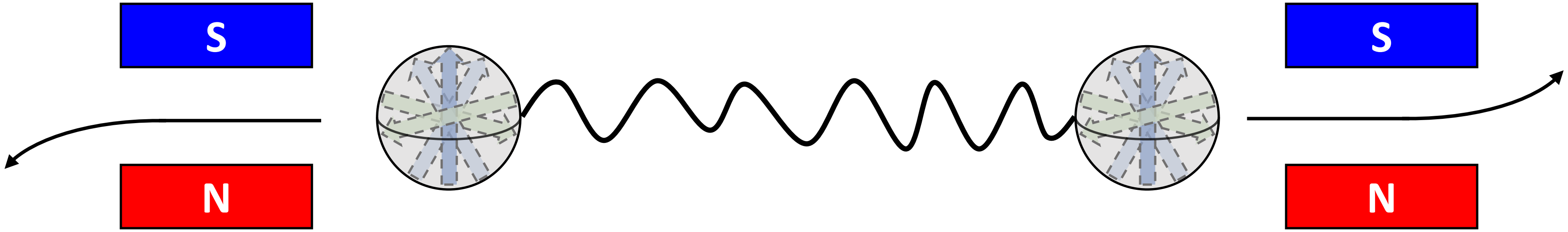


With a probability 1/2

But if we at the overall system, it is perfectly (anti)-correlated (in any axis!)

Quantum entanglement

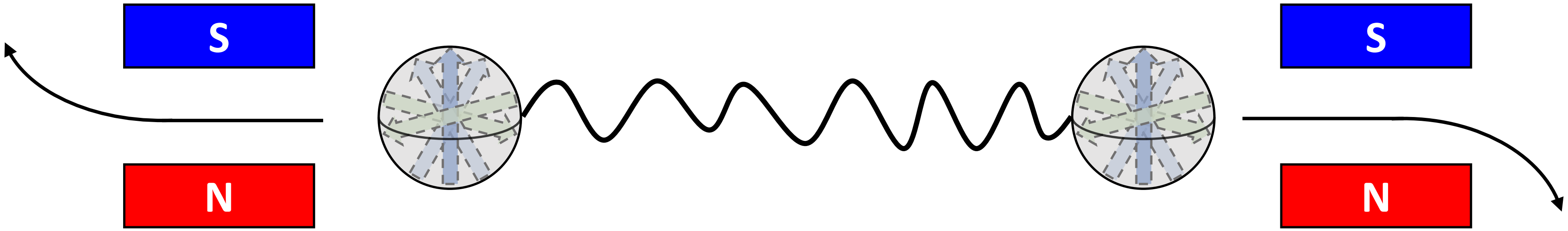
With a probability 1/2



But if we at the overall system, it is perfectly (anti)-correlated (in any axis!)

Quantum entanglement

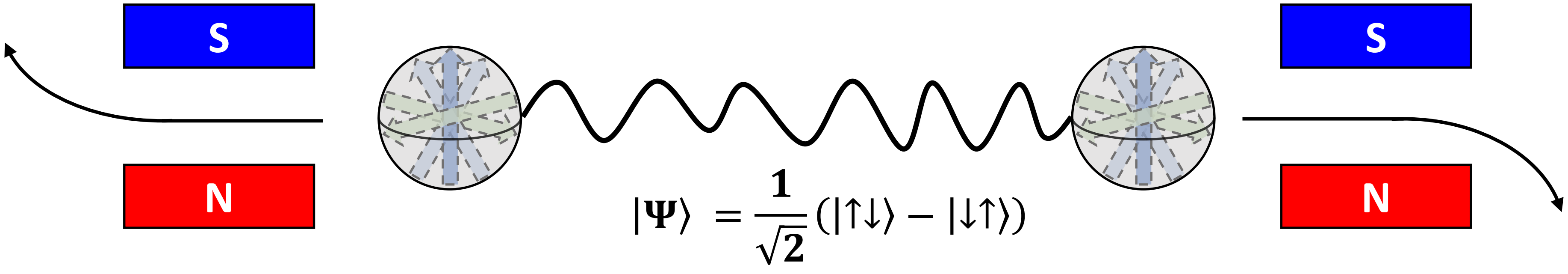
With a probability 1/2



But if we at the overall system, it is perfectly (anti)-correlated (in any axis!)

Quantum entanglement

With a probability 1/2



$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

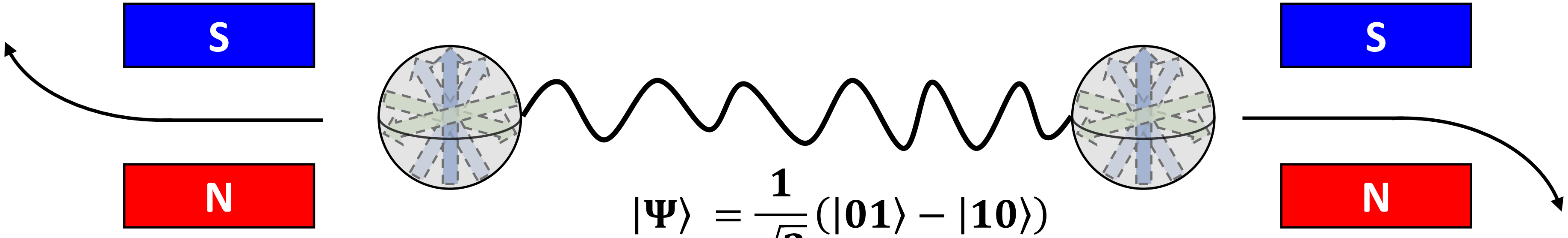
Entanglement!
(non-classical correlation)

If we do only look at the local party, it is perfectly random (in any axis!)

But if we at the overall system, it is perfectly (anti)-correlated (in any axis!)

Quantum entanglement

With a probability 1/2



$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

Entanglement!
(non-classical correlation)

If we do only look at the local party, it is perfectly random (in any axis!)

But if we at the overall system, it is perfectly (anti)-correlated (in any axis!)

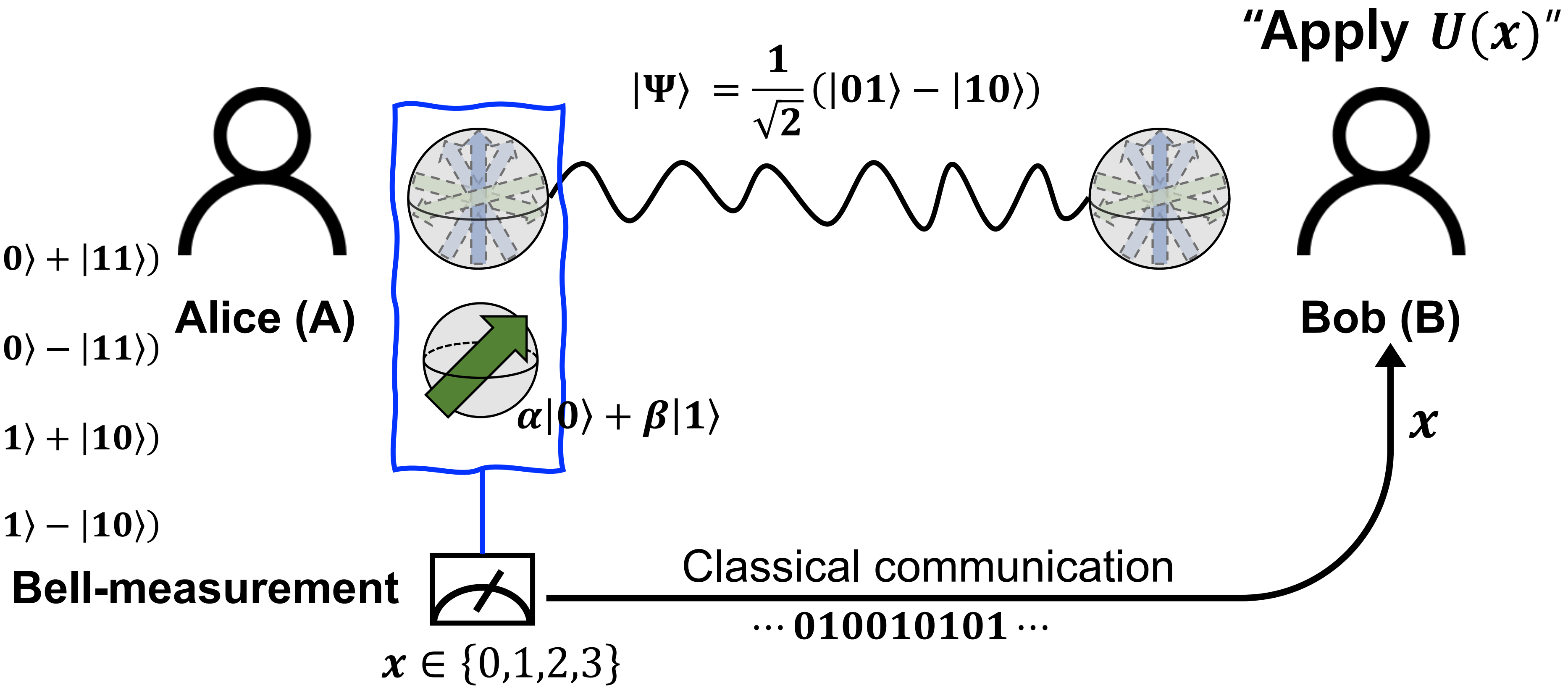
Quantum teleportation

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

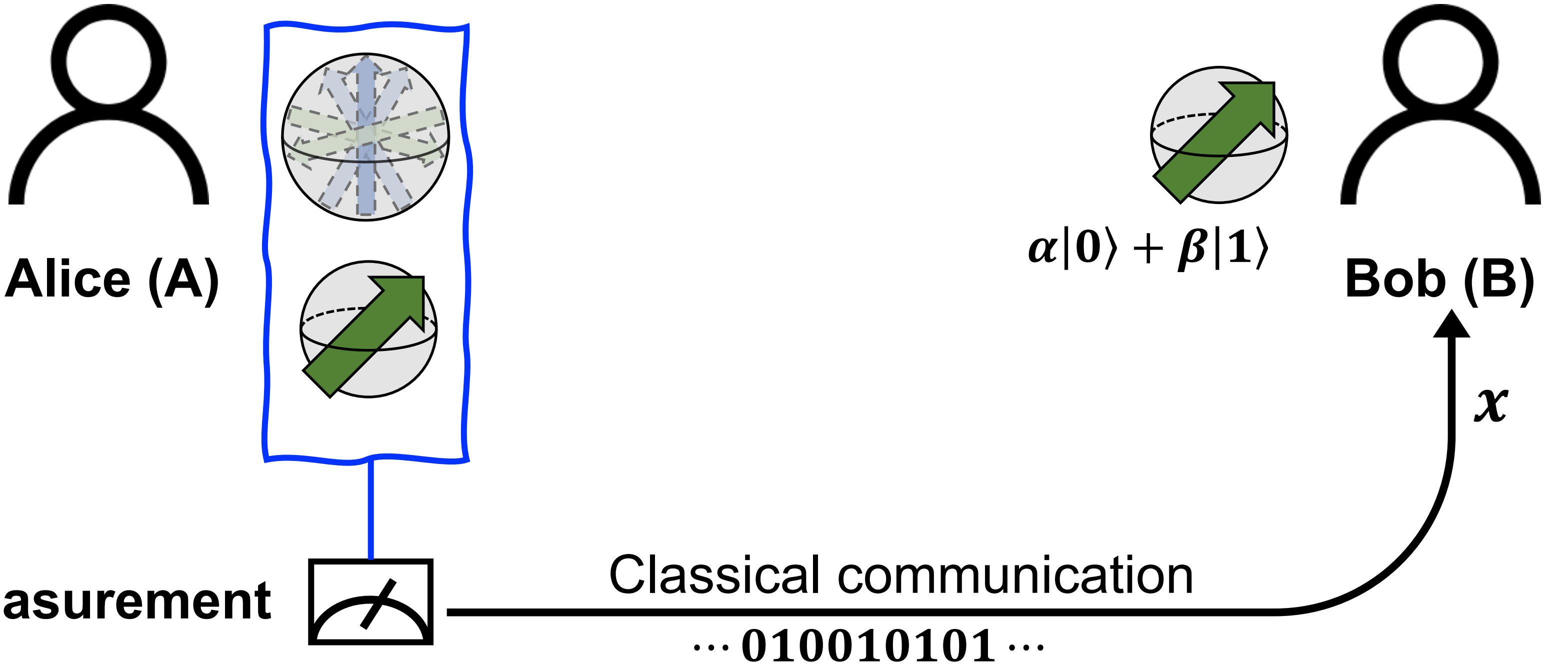
$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$



Quantum teleportation



Alice's state is teleported to Bob!

"Apply $U(x)$"

Alice (A)

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

Bob (B)

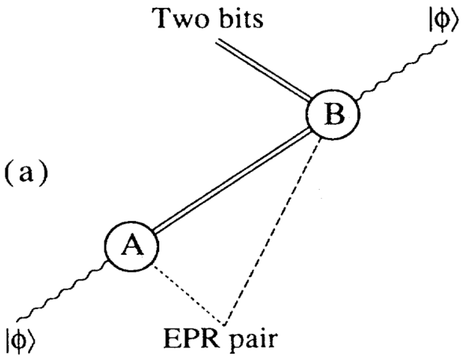
x

Bell-measurement

Classical communication

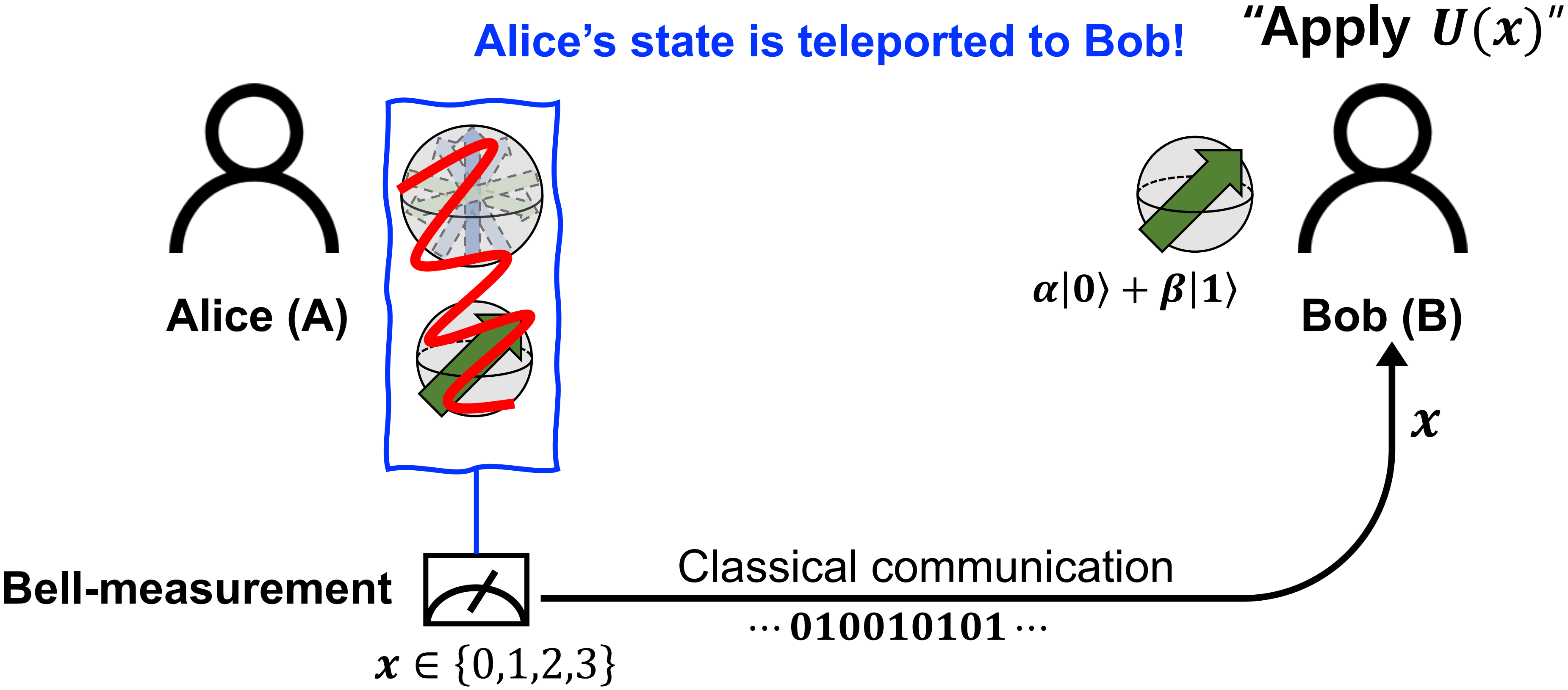
$\cdots 010010101 \cdots$

$x \in \{0,1,2,3\}$



"Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels"
C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. **70** 1895 (1993).

Quantum teleportation

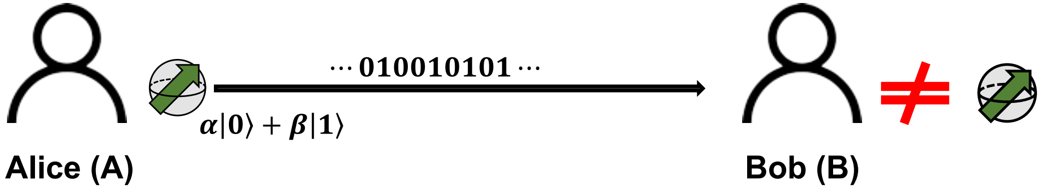


Note: 1. Quantum state is not copied (wave function collapse)
2. Not a superluminal signaling (classical communication)

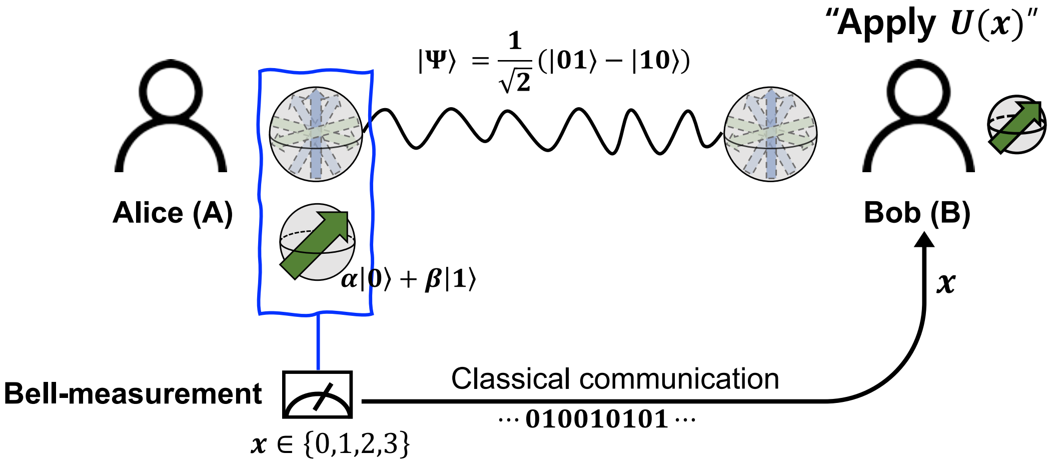
"Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels"
C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. **70** 1895 (1993).

Quantum communication

- **Qubit cannot be transmitted via LOCC (local operation and classical communication)**



- **Entanglement makes this possible (Quantum teleportation)**



➔ Entanglement is a (unit) resource for quantum communication
[1-ebit (assisted by 2-bit) can transmit 1-qubit]

Quantifying entanglement

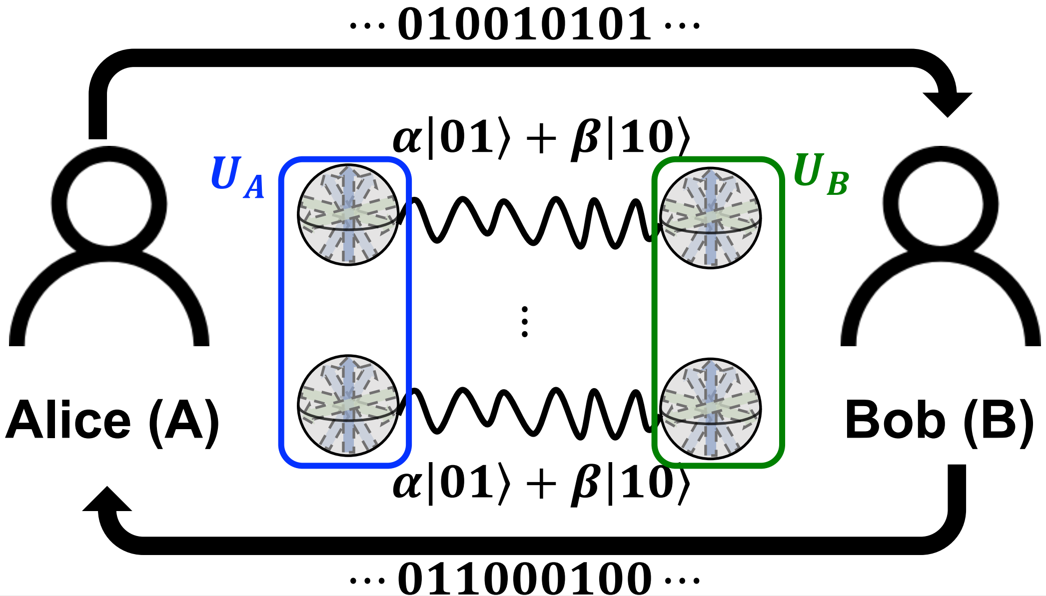
- **A pair of perfectly entangled state (Bell-state) can transmit 1 qubit**

- **What happens if we have a partially entangled state? (e.g.)** $|\boldsymbol{\Psi}\rangle = \boldsymbol{\alpha}|\mathbf{01}\rangle + \boldsymbol{\beta}|\mathbf{10}\rangle$

If we prepare many copies of imperfect entangled states, we can **distill** the Bell-states via LOCC!

$|\boldsymbol{\Psi}\rangle^{\otimes \boldsymbol{N}} \rightarrow |\boldsymbol{\Phi}^{+}\rangle^{\otimes \boldsymbol{RN}}$ **for** $\boldsymbol{N} \rightarrow \infty$ $\left(|\boldsymbol{\Phi}^{+}\rangle = \frac{|\mathbf{01}\rangle + |\mathbf{10}\rangle}{\sqrt{\mathbf{2}}}\right)$

$\boldsymbol{R} = -|\boldsymbol{\alpha}|^{2}\mathbf{ln}|\boldsymbol{\alpha}|^{2} - |\boldsymbol{\beta}|^{2}\mathbf{ln}|\boldsymbol{\beta}|^{2} \leq 1$: Distillation rate



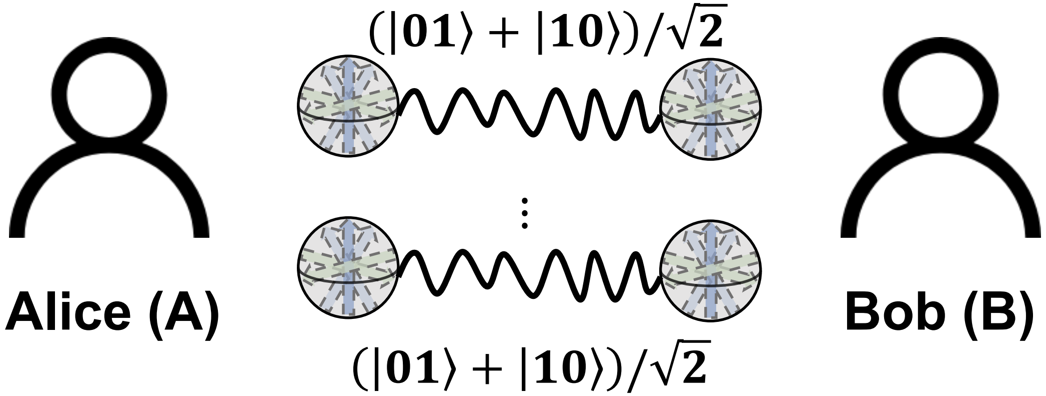
Quantifying entanglement

- **A pair of perfectly entangled state (Bell-state) can transmit 1 qubit**
- **What happens if we have a partially entangled state? (e.g.)** $|\Psi\rangle = \alpha|01\rangle + \beta|10\rangle$

If we prepare many copies of imperfect entangled states, we can **distill** the Bell-states via LOCC!

$$|\Psi\rangle^{\otimes N} \to |\Phi^+\rangle^{\otimes RN} \qquad \text{for } N \to \infty \qquad \left(|\Phi^+\rangle = \frac{|01\rangle+|10\rangle}{\sqrt{2}}\right)$$

$R = -|\alpha|^2 \ln|\alpha|^2 - |\beta|^2 \ln|\beta|^2 \leq 1$: Distillation rate



C. H. Bennett, H. J. Bernstein, S. Popescu, and B. Schumacher, Phys. Rev. A 53, 2046 (1996)

Quantifying entanglement

- **A pair of perfectly entangled state (Bell-state) can transmit 1 qubit**

- **What happens if we have a partially entangled state? (e.g.)** $|\Psi\rangle = \alpha|01\rangle + \beta|10\rangle$

If we prepare many copies of imperfect entangled states, we can **distill** the Bell-states via LOCC!

$|\Psi\rangle^{\otimes N} \to |\Phi^{+}\rangle^{\otimes RN}$ **for** $N \to \infty$ $\left(|\Phi^{+}\rangle = \frac{|01\rangle+|10\rangle}{\sqrt{2}}\right)$

$R = -|\alpha|^2 \ln|\alpha|^2 - |\beta|^2 \ln|\beta|^2 \leq 1$: Distillation rate

Fig. from Rev. Mod. Phys. 91, 025001 (2019)

Quantifying entanglement

- **What happens if we have a noisy entangled state?**

✓ Decoherence can wash out superposition, thus the state can be no more entangled

(e.g,) $|\Phi^+\rangle\langle\Phi^+| = \frac{1}{2}(|01\rangle\langle 01| + |01\rangle\langle 10| + |10\rangle\langle 01| + |10\rangle\langle 10|) \rightarrow \rho = \frac{1}{2}(|01\rangle\langle 01| + |10\rangle\langle 10|)$

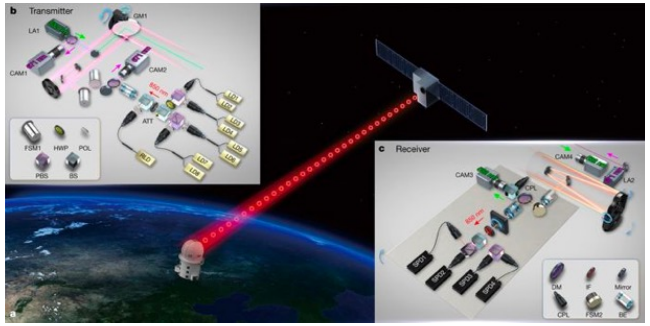
no entanglement (classically correlated state)

✓ Definition of (mixed-state) entanglement becomes more complicated ($\rho \neq \sum p_i \rho_A^{(i)} \otimes \rho_B^{(i)}$)

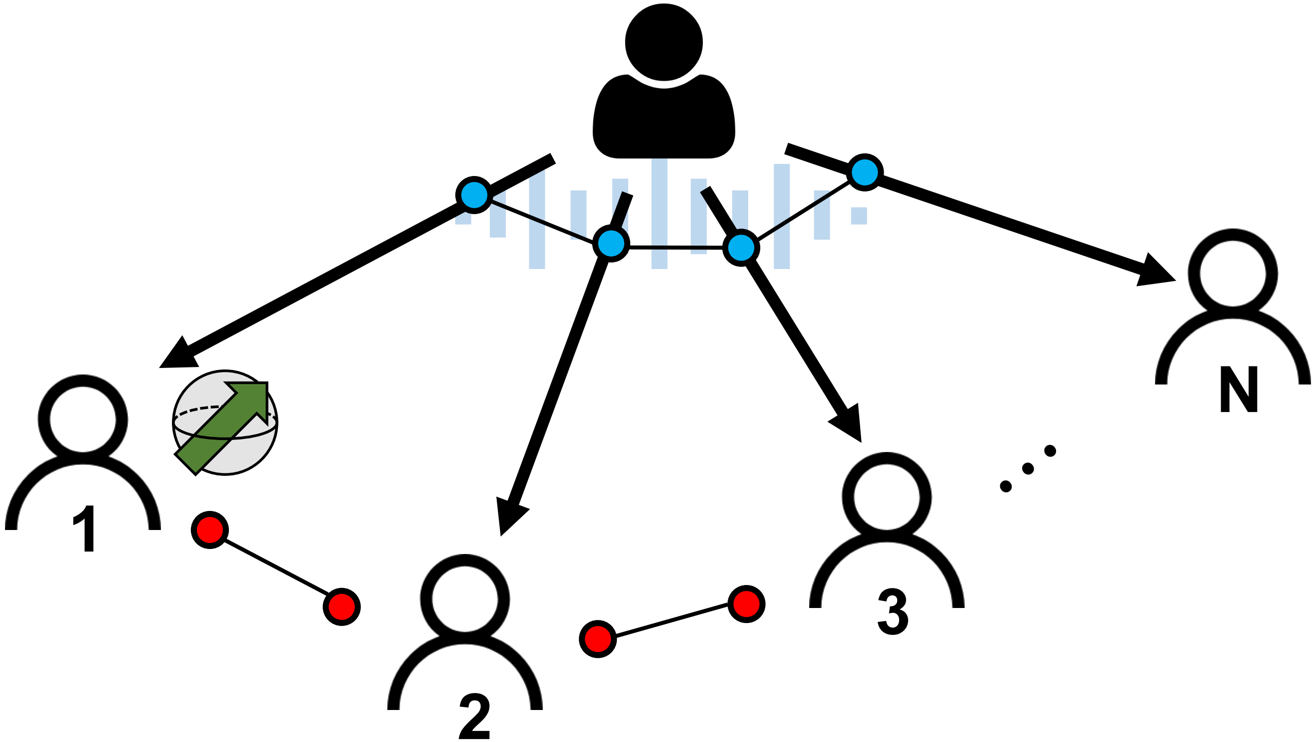
✓ We can always distill entanglement from noisy for entangled noisy qubit states

but it no more holds for a higher dimension **(bound entanglement problem)**

Quantum network



S.-K Liao *et al.*, Nature **549**, 43 (2017)



Quantum network: Distributing quantum entanglement over world!

Quantum technologies

Quantum communication

[Sending quantum bits]

- Quantum information transfer
- Quantum cryptography
  (quantum key distribution)

Quantum computing

[Faster computation]

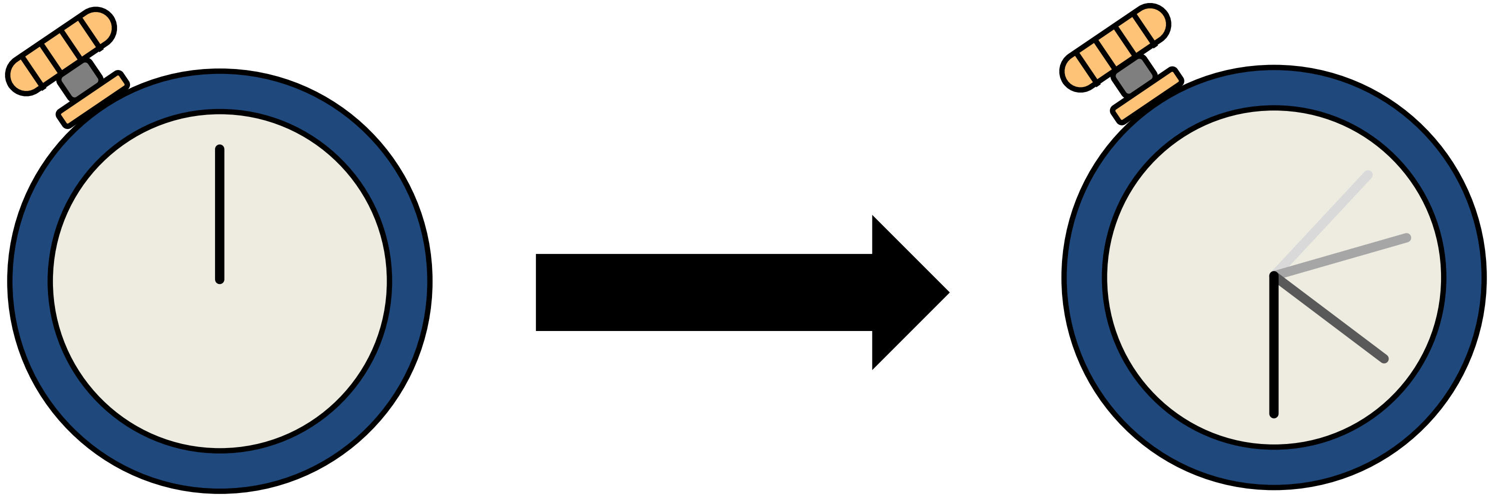
- Quantum simulation
- Quantum algorithm
- Quantum error correction

Quantum metrology

[Precision measurement]

- **Precise phase/force sensing**
- **Accurate measurement of physical constants**

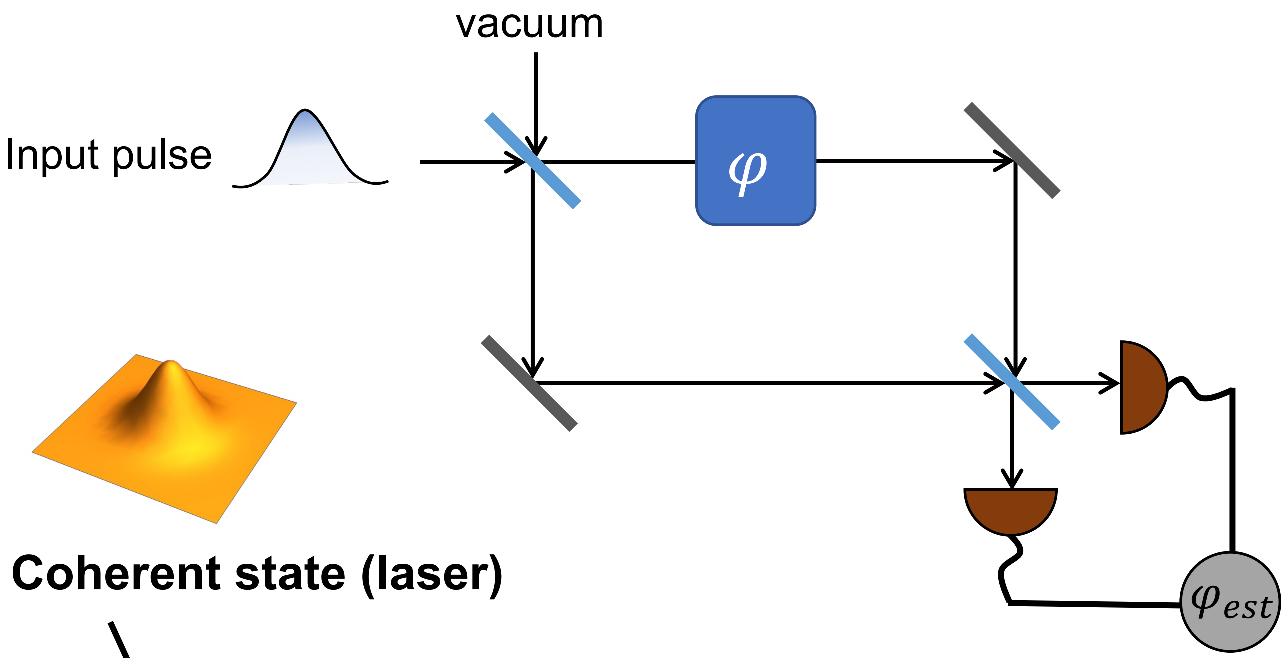
What is measurement?

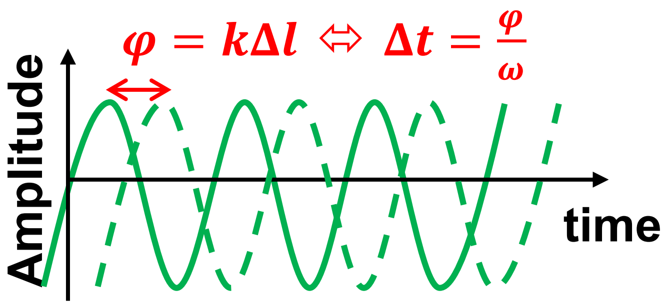


Measurement is detecting the difference

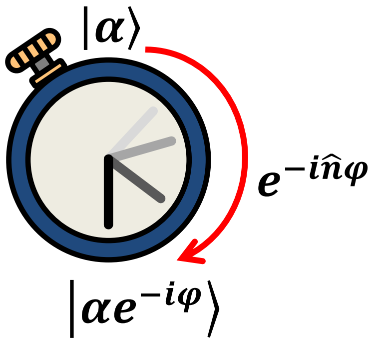
Precise measurement ➔ Detecting a small difference in physical quantities (time, distance)

Optical interferometer for phase sensing





e.g., Path/time difference induces phase difference φ



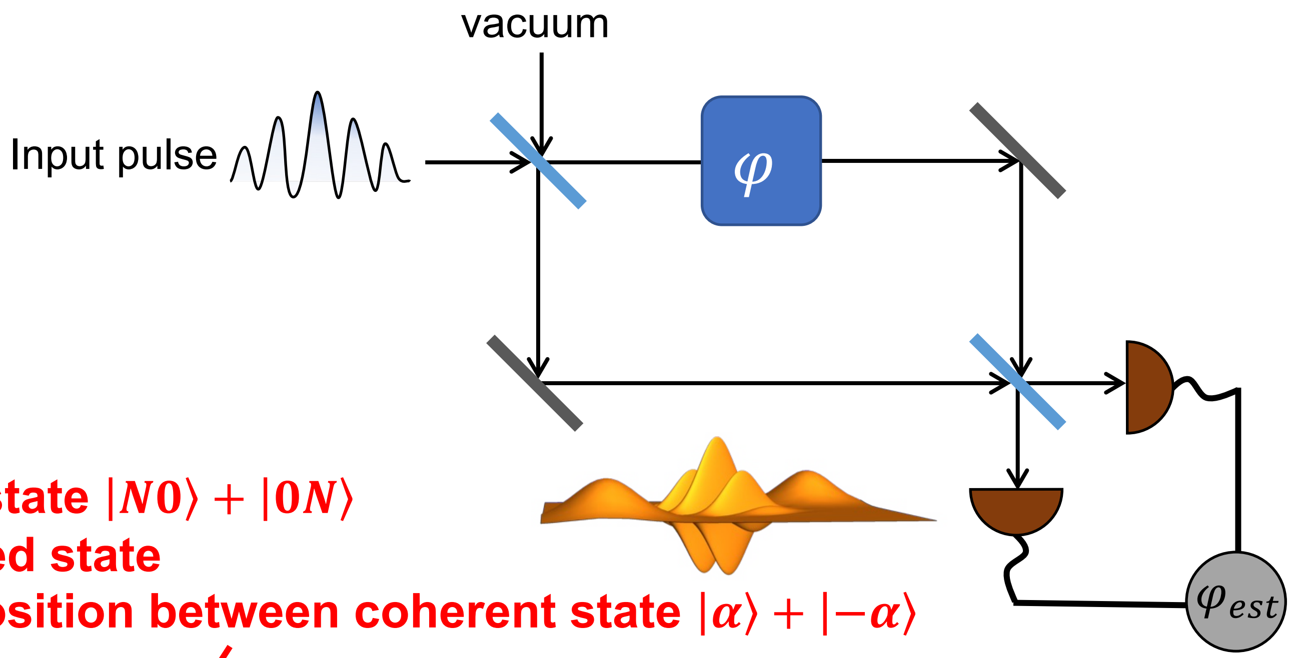
Input pulse: Coherent state (laser)

Classically, the sensitivity of phase estimation is bounded by

$$(\Delta\varphi)^2_{\mathrm{cl}} = \overline{|\varphi_{\mathrm{real}} - \varphi_{\mathrm{est}}|^2} \geq \frac{1}{\mathrm{Energy(photon\ number)}}$$

(standard quantum limit)

Quantum metrology



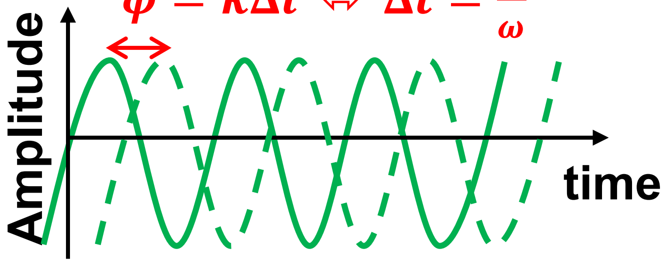
Input pulse:

e.g.) NOON-state $|N0\rangle + |0N\rangle$

Squeezed state

Superposition between coherent state $|\alpha\rangle + |-\alpha\rangle$

$\boldsymbol{\varphi = k\Delta l \Leftrightarrow \Delta t = \frac{\varphi}{\omega}}$



e.g., Path/time difference induces phase difference φ

If we use non-classical states, the sensitivity of phase estimation can be improved by

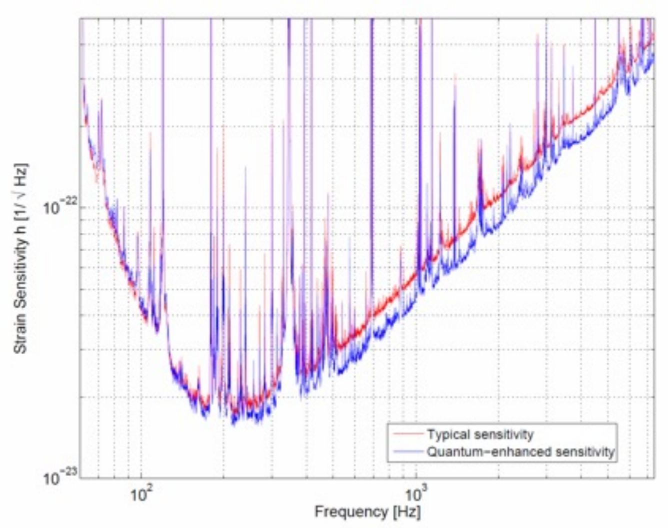
[Nature Photonics 5, 222–229 (2011)]

$$(\Delta\varphi)^2_{\text{qm}} = \overline{|\varphi_{\text{real}} - \varphi_{\text{est}}|^2} \geq \frac{1}{(\text{Energy})^2}$$

(Heisenberg limit)

Applications

- LIGO interferometer + quantum metrology



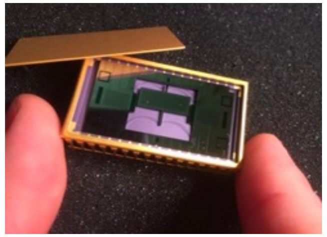
- Commercializing quantum sensing technique

BOSCH

SIEMENS

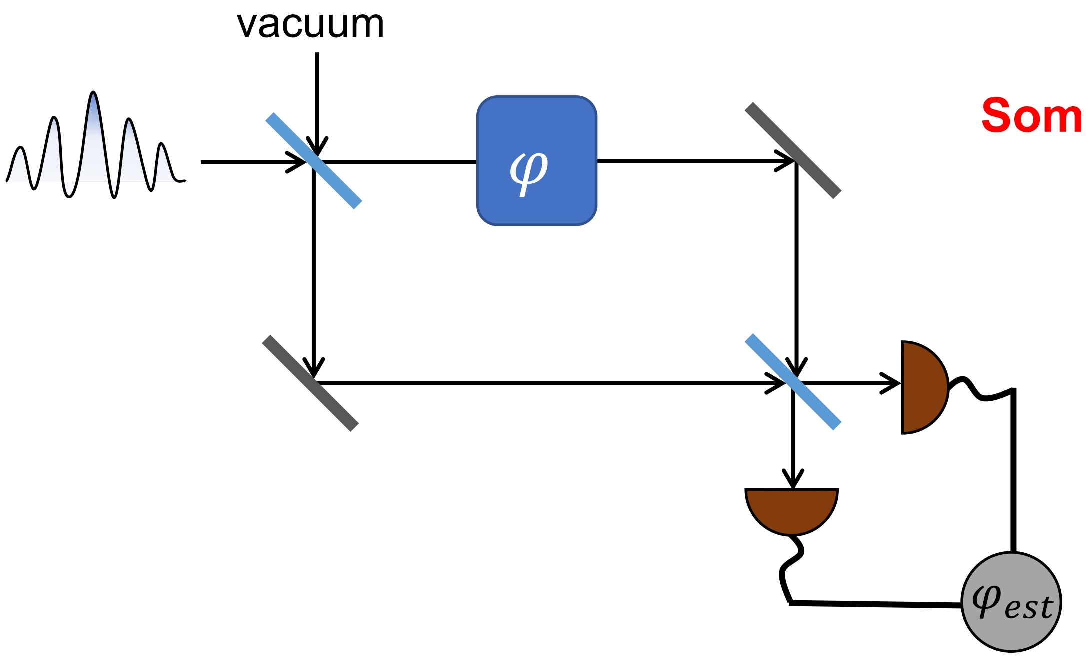
AIRBUS

Startups QUANTIC

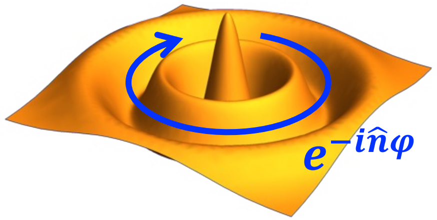


Resource for quantum metrology

Which kind of quantum states is resourceful?



Some entangled states, non-classical states
➔ No quantum advantage



Fock state $|n\rangle$: phase insensitive
$e^{-i\hat{n}\varphi}|n\rangle = |n\rangle$

What makes quantum advantage in sensing task (metrology)?

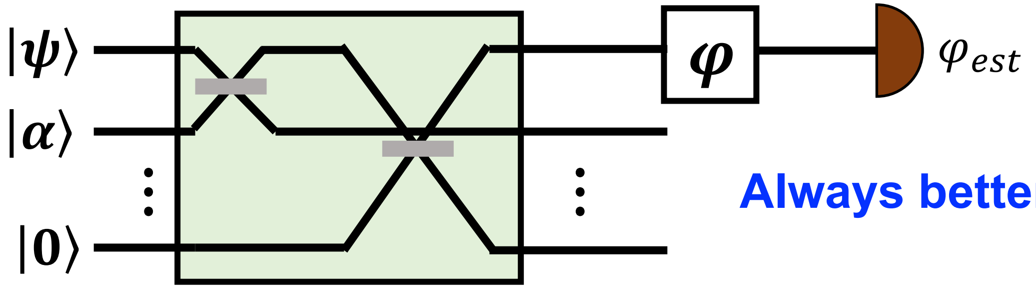
Can we quantify resource for quantum metrology?

Non-classicality and quantum metrology

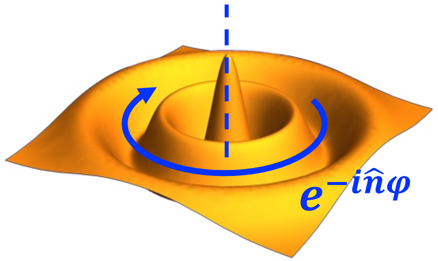
c.f.) Definition of non-classicality
= Negativity P-function in phase space

- **Non-classicality is indeed a resource!**

➔ **We can always convert any non-classical pure state to be useful in quantum metrology!**
(using linear interferometer + additional coherent state)



Always better than the classical limit!

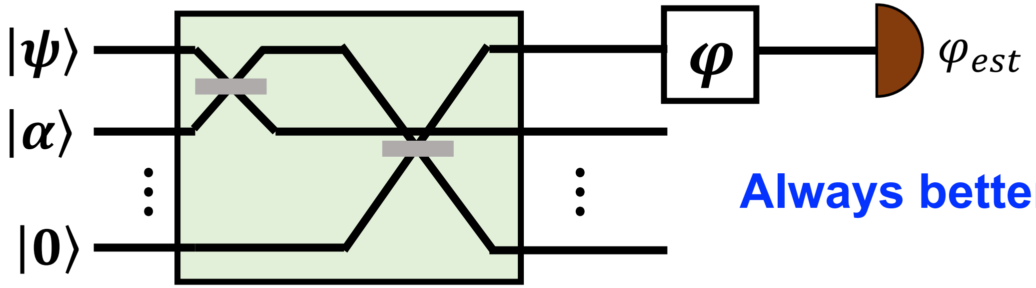


Non-classicality and quantum metrology

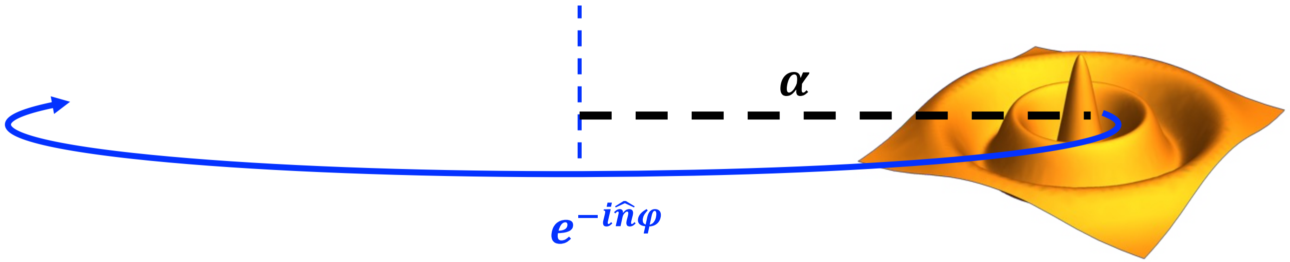
- **Non-classicality is indeed a resource!**

c.f.) Definition of non-classicality
= Negativity P-function in phase space

➔ **We can always convert any non-classical pure state to be useful in quantum metrology!**
(using linear interferometer + additional coherent state)



Always better than the classical limit!



Nonclassicality is necessary and sufficient condition for quantum metrology (for pure state)

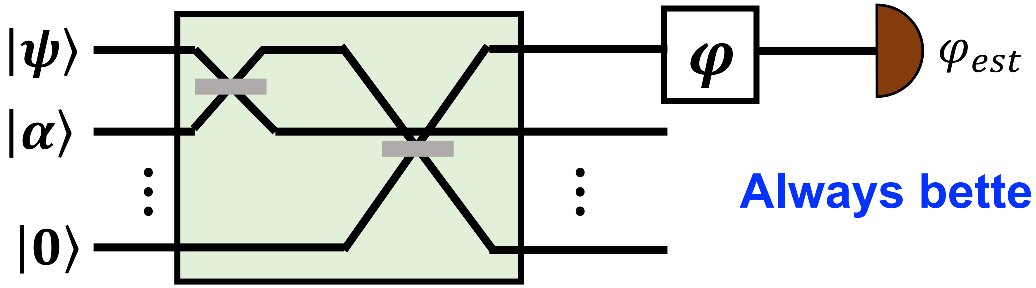
[HK, K. C. Tan, T. Volkoff, and H. Jeong, *Nonclassicality as a Quantifiable Resource for Quantum Metrology*, Phys. Rev. Lett. **122**, 040503 (2019)]

Non-classicality and quantum metrology

- **Non-classicality is indeed a resource!**

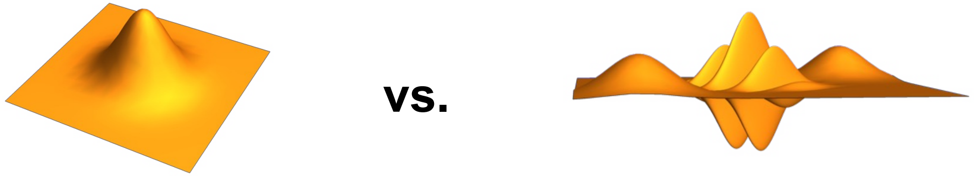
c.f.) Definition of non-classicality
= Negativity P-function in phase space

➔ We can always convert any non-classical pure state to be useful in quantum metrology!
(using linear interferometer + additional coherent state)



Always better than the classical limit!

- **Physical interpretation (why non-classicality?)**



Negativity probability ➔ Distribution can fluctuate (change) beyond classical limit ➔ Higher sensitivity

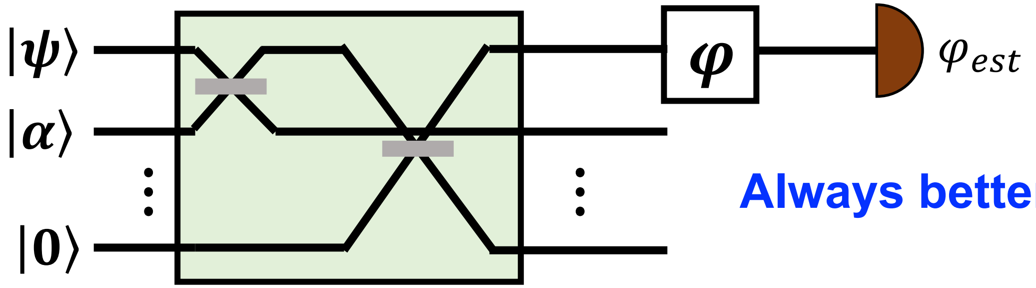
[HK, K. C. Tan, T. Volkoff, and H. Jeong, *Nonclassicality as a Quantifiable Resource for Quantum Metrology*, Phys. Rev. Lett. **122**, 040503 (2019)]

Non-classicality and quantum metrology

- **Non-classicality is indeed a resource!**

c.f.) Definition of non-classicality
= Negativity P-function in phase space

➔ We can always convert any non-classical pure state to be useful in quantum metrology!
(using linear interferometer + additional coherent state)

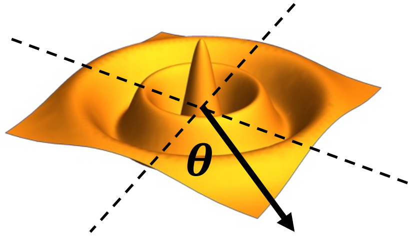


Always better than the classical limit!

- **How do we quantify negative probability?**

Simple way: Add all negative components ($N(\psi) = 1 - \int d^2\alpha \left|P_\psi(\alpha)\right|$)

Indirect way: Quantum Fisher information $M(\psi) = \frac{1}{2}\max_\theta[I_F(\psi)] - 1$

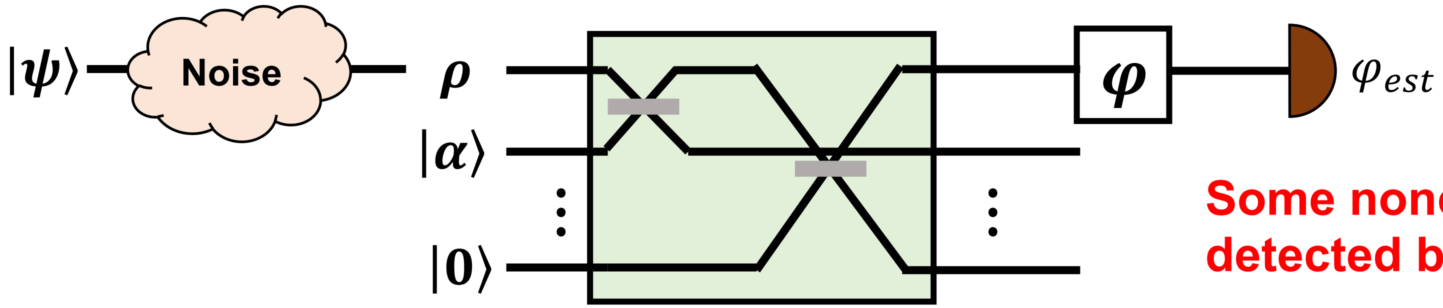


Indicator of displacement sensitivity

[HK, K. C. Tan, T. Volkoff, and H. Jeong, *Nonclassicality as a Quantifiable Resource for Quantum Metrology*, Phys. Rev. Lett. **122**, 040503 (2019)]

Non-classicality and quantum metrology

- **What happens when we have a noisy state (decoherence)?**

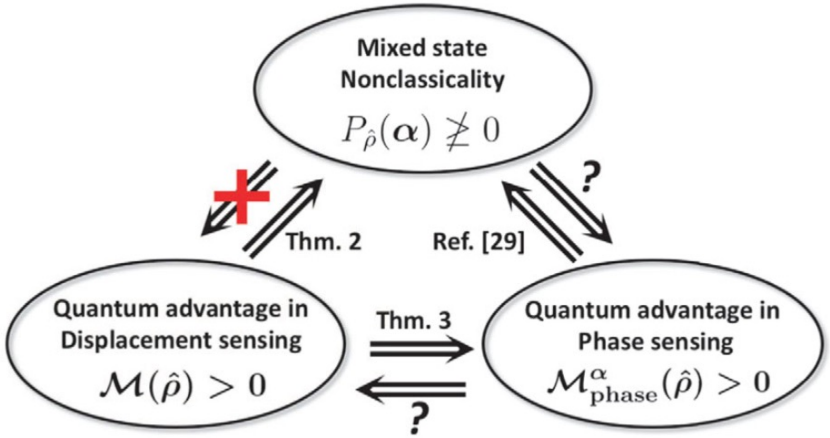


Some nonclassical states cannot be detected by quantum Fisher information $M(\rho)$

(recall: bound entanglement)

➔ **Non-classicality may not be sufficient to have a quantum advantage in metrology**

But it is still a necessary condition for mixed states



(c.f.) Detecting the non-classicality of mixed states is as complicated as detecting entanglement

[HK, K. C. Tan, T. Volkoff, and H. Jeong, *Nonclassicality as a Quantifiable Resource for Quantum Metrology*, Phys. Rev. Lett. **122**, 040503 (2019)]

Quantum technologies

Quantum communication

[Sending quantum bits]

- Quantum information transfer
- Quantum cryptography (quantum key distribution)

Quantum computing

[Faster computation]

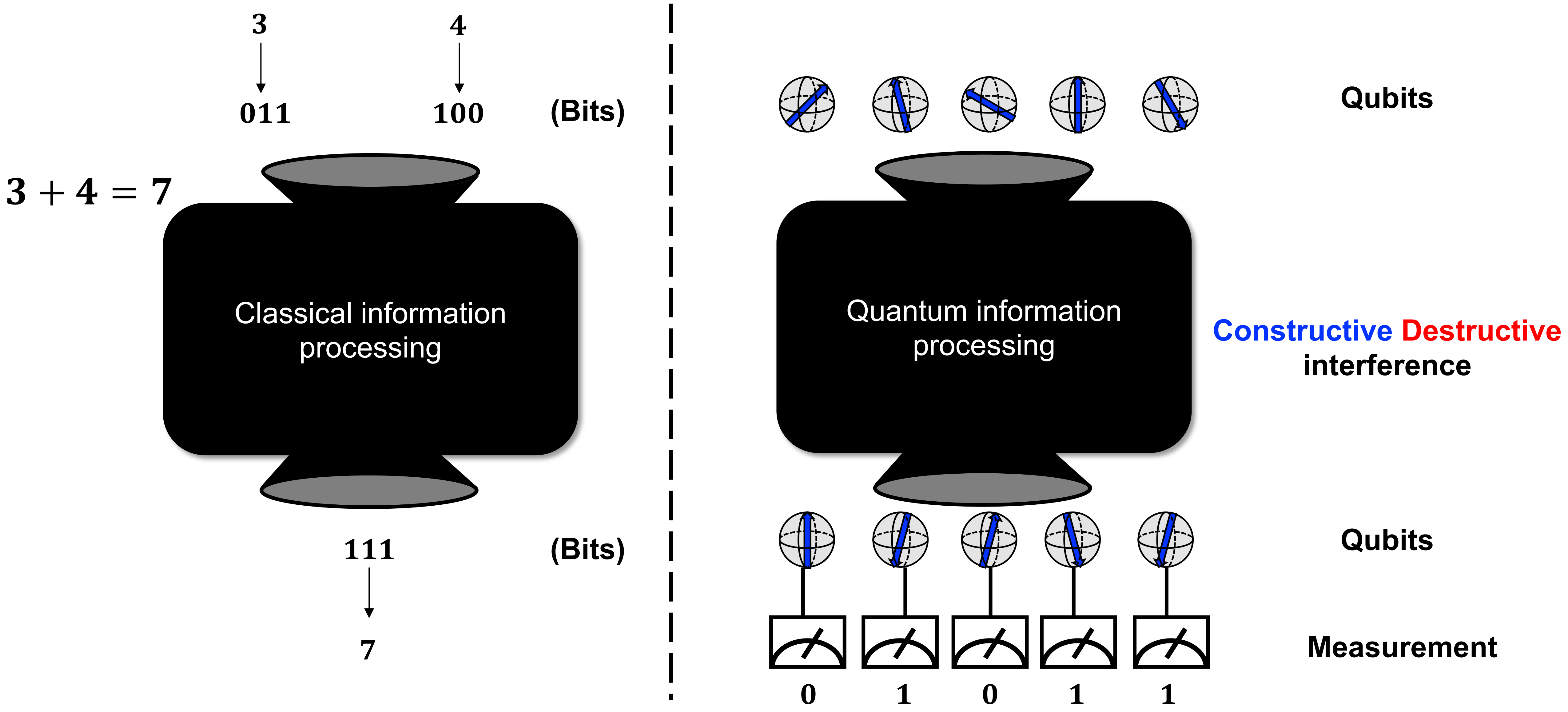
- **Quantum simulation**
- **Quantum algorithm**
- **Quantum error correction**

Quantum metrology

[Precision measurement]

- Precise phase/force sensing
- Accurate measurement of physical constants

Quantum computing in a nutshell



3

4

011

100

(Bits)

$3 + 4 = 7$

Classical information processing

111

(Bits)

7

Qubits

Quantum information processing

Constructive Destructive interference

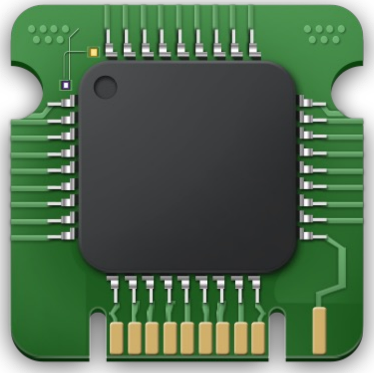
Qubits

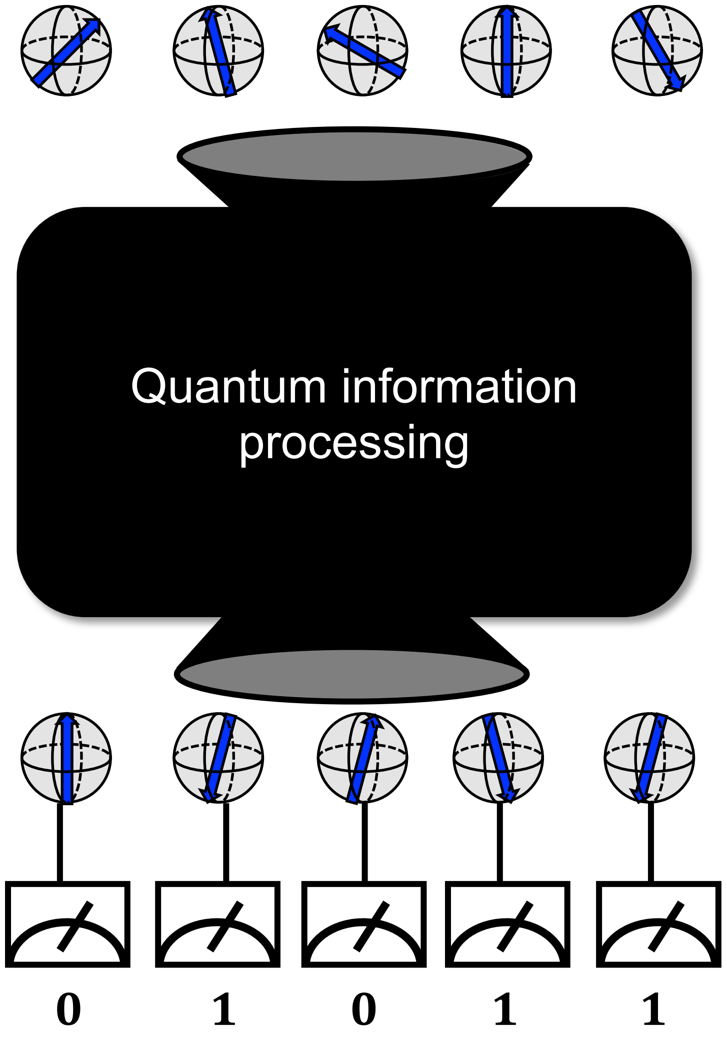
Measurement

0 1 0 1 1

Quantum computing in a nutshell

CPU





Qubits

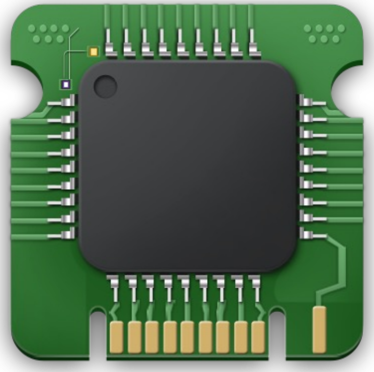
Constructive Destructive interference

Qubits

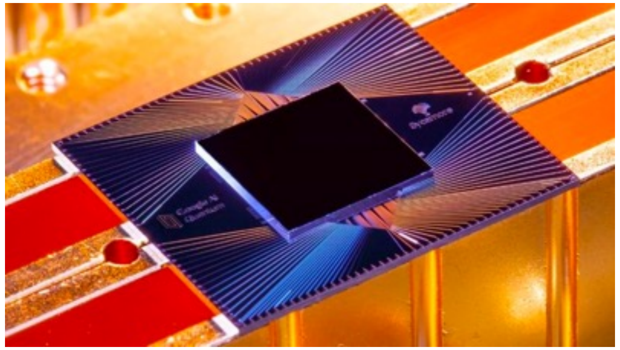
Measurement

Quantum computing in a nutshell

CPU



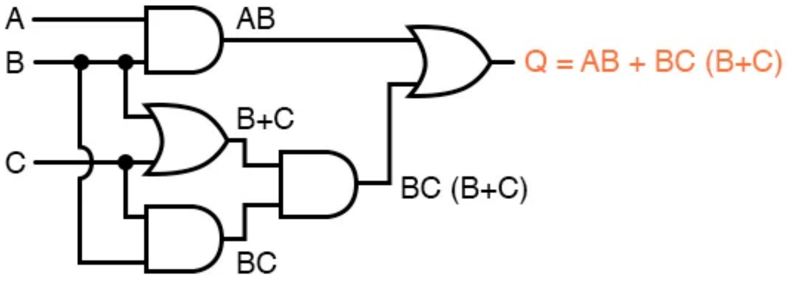
Quantum processor



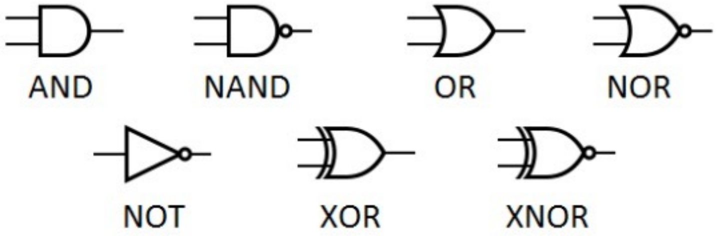
Sycamore processor (Google)

Quantum computing in a nutshell

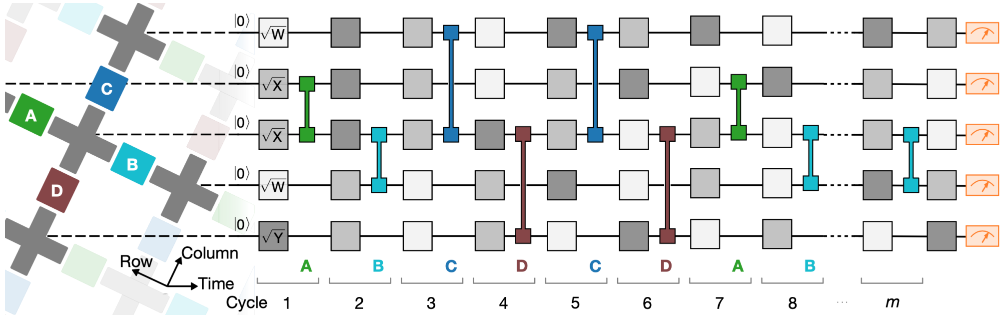
Classical circuit



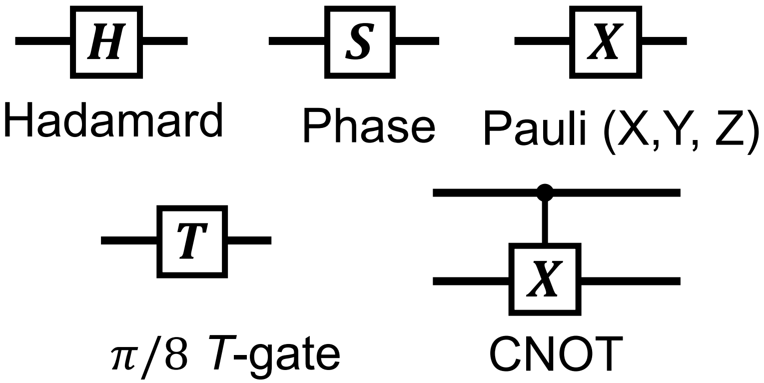
Classical (logic) gates



Quantum circuit

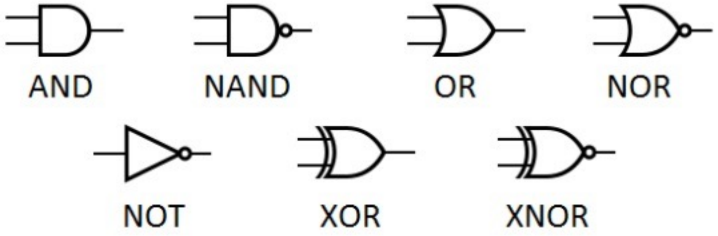


Quantum (logic) gates

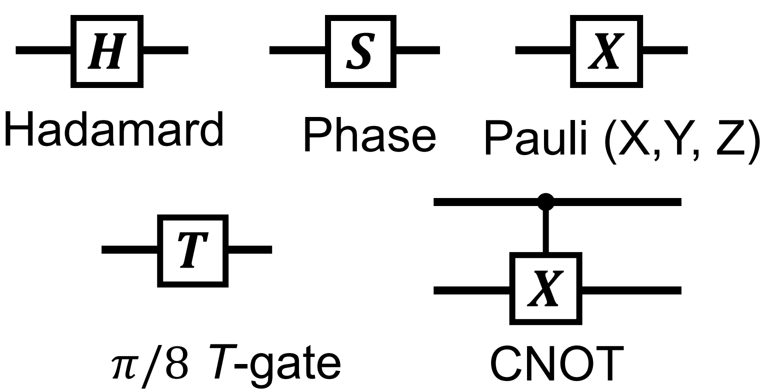


Quantum Logic Gates

Classical (logic) gates



Quantum (logic) gates



How to arrange quantum logic gates to solve a given problem

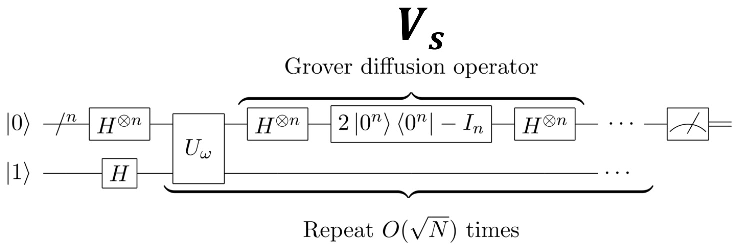
⬇

Quantum algorithm

Quantum algorithms

Grover's search algorithm

Database searching problem



Classical: $O(N)$

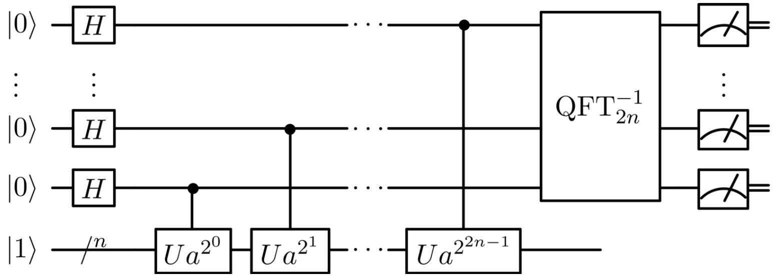
Quantum: $O(\sqrt{N})$

(polynomial speed up)

**1000000 classical operations vs.
1000 quantum operations**

Shor's factorization algorithm

Integer factoring problem ($15 = 3\times5$)
➔ Can break RSA cryptosystem



Fast computation of frequency
(quantum Fourier transformation)

$$|x\rangle \rightarrow \frac{|0\rangle + e^{\left(\frac{2\pi i}{N}\right)x}|1\rangle + \cdots + e^{\left(\frac{2\pi i}{N}\right)x\cdot(N-1)}|N-1\rangle}{\sqrt{N}}$$

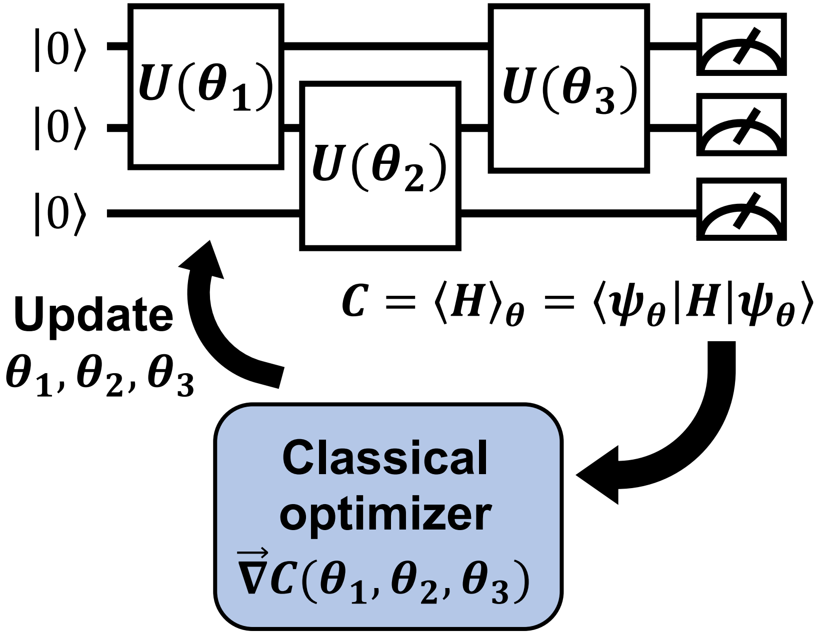
Classical: $O(\mathrm{poly}(N))$ or $O\left(e^{\sqrt[3]{\log N}}\right)$

Quantum: $O(\mathrm{poly}(\log N))$

(exponential speed up)

Variational quantum eigensolver

Calculate ground state energy $\langle H\rangle_{\min}$



Update $\theta_1, \theta_2, \theta_3$

$C = \langle H\rangle_\theta = \langle\psi_\theta|H|\psi_\theta\rangle$

Classical optimizer
$\vec{\nabla} C(\theta_1, \theta_2, \theta_3)$

Quantum-classical hybrid algorithm

Resource for quantum computing

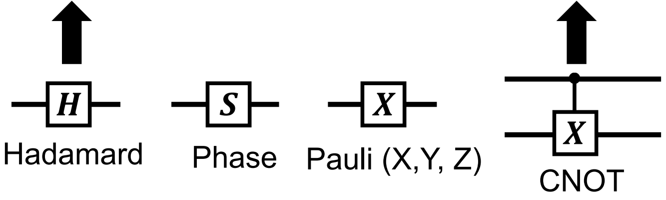
- **Can we obtain (exponential) quantum speed up only with entanglement?**

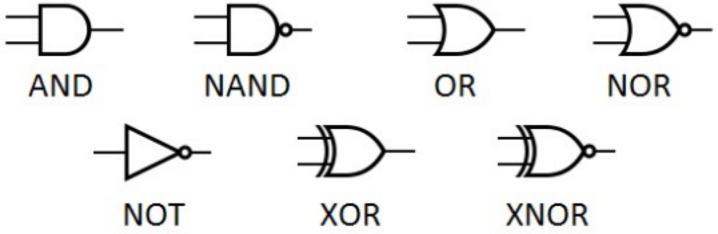
Superposition

$$H|0\rangle = \frac{(|0\rangle+|1\rangle)}{\sqrt{2}} = |+\rangle$$

Entanglement

$$\mathrm{CNOT}(|+\rangle \otimes |0\rangle) = \frac{(|00\rangle+|11\rangle)}{\sqrt{2}}$$



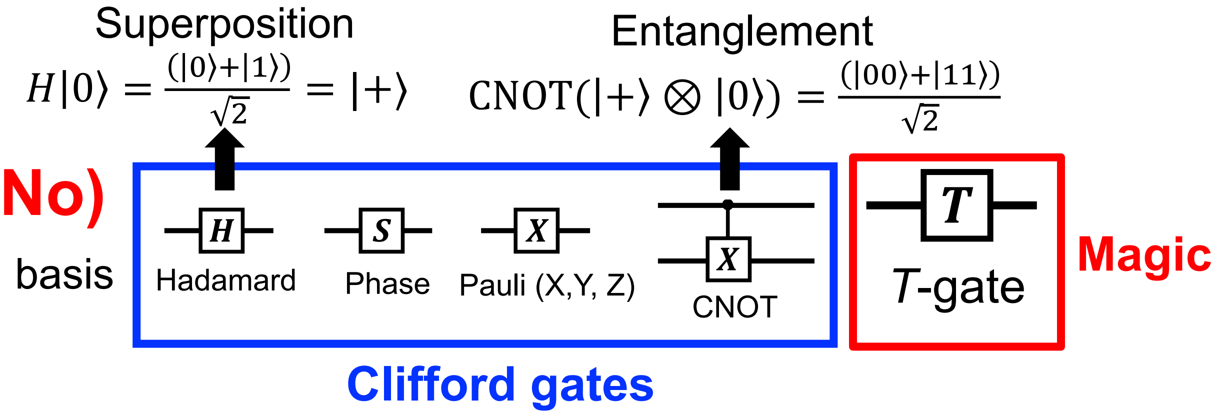


Resource for quantum computing

- **Can we obtain (exponential) quantum speed up only with entanglement?**

- **Gottesman-Knill theorem (the answer is No)**

“Quantum circuits that only involve the Clifford gates & computational basis can be **efficiently simulated on a classical computer**”



Superposition

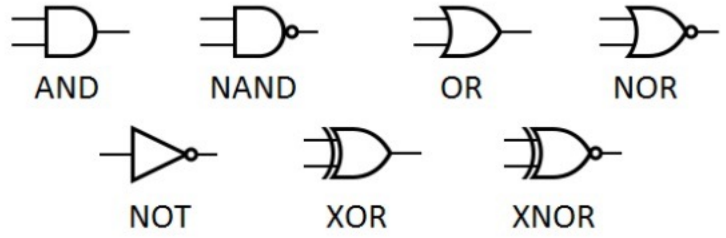
$H|0\rangle = \frac{(|0\rangle+|1\rangle)}{\sqrt{2}} = |+\rangle$

Entanglement

$\mathrm{CNOT}(|+\rangle \otimes |0\rangle) = \frac{(|00\rangle+|11\rangle)}{\sqrt{2}}$

Clifford gates

Magic



Resource for quantum computing

- **Can we obtain (exponential) quantum speed up only with entanglement?**

- **Gottesman-Knill theorem (the answer is No)**

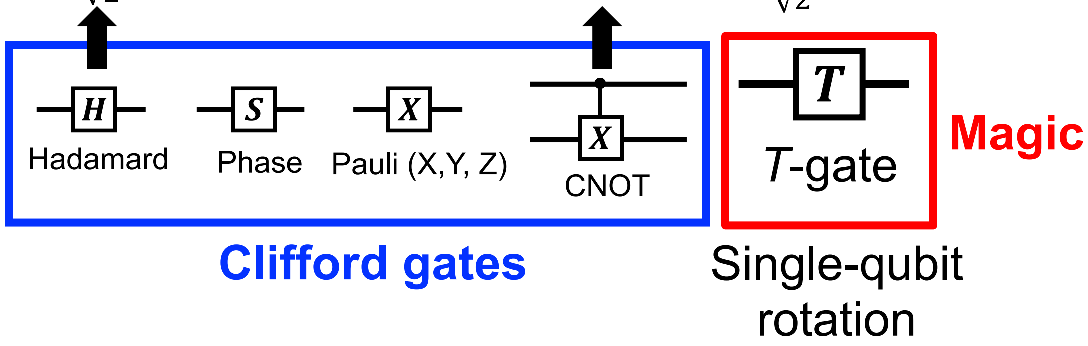
“Quantum circuits that only involve the Clifford gates & computational basis can be **efficiently simulated on a classical computer**”

Superposition

$H|0\rangle = \frac{(|0\rangle+|1\rangle)}{\sqrt{2}} = |+\rangle$

Entanglement

$\mathrm{CNOT}(|+\rangle \otimes |0\rangle) = \frac{(|00\rangle+|11\rangle)}{\sqrt{2}}$



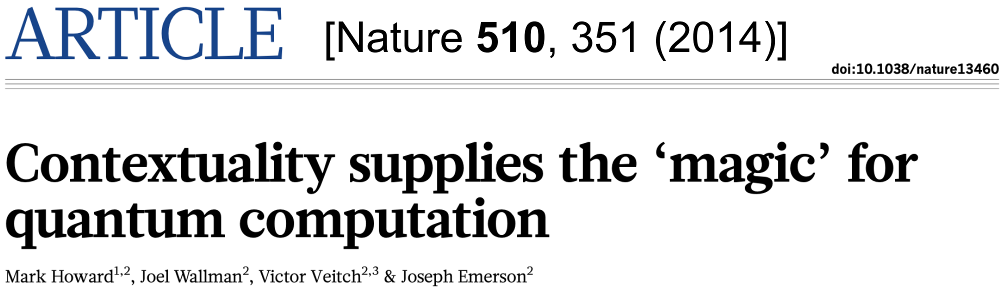
- **Then, where does the “quantum” computing power come from?**

Honest answer: We do not know yet

Resource for quantum computing

- **Then, where does the "quantum" computing power come from?**

Contextuality!?



ARTICLE [Nature **510**, 351 (2014)]

doi:10.1038/nature13460

Contextuality supplies the 'magic' for quantum computation

Mark Howard[1,2], Joel Wallman[2], Victor Veitch[2,3] & Joseph Emerson[2]

Bell–Kochen–Specker theorem (1966)

Measurement of quantum observables cannot simply reveal pre-existing values

(i.e., Realistic hidden variable models fail to describe our nature)

- **Example) Peres-Mermin Square**

$$\begin{bmatrix} A & B & C \\ a & b & c \\ \alpha & \beta & \gamma \end{bmatrix} \begin{matrix} \rightarrow +1 \\ \rightarrow +1 \\ \rightarrow +1 \end{matrix}$$

$$\begin{matrix} \downarrow & \downarrow & \downarrow \\ +1 & +1 & -1 \end{matrix}$$

Can we find a configuration such that $\langle ABC \rangle = \cdots = \langle \alpha\beta\gamma \rangle = +1 = -\langle Cc\gamma \rangle$?

Classically impossible!

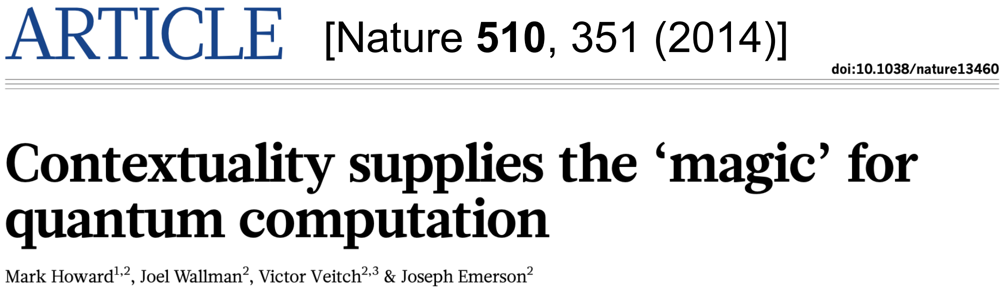
$$\begin{bmatrix} \sigma_z \otimes \mathbb{1} & \mathbb{1} \otimes \sigma_z & \sigma_z \otimes \sigma_z \\ \mathbb{1} \otimes \sigma_x & \sigma_x \otimes \mathbb{1} & \sigma_x \otimes \sigma_x \\ \sigma_z \otimes \sigma_x & \sigma_x \otimes \sigma_z & \sigma_y \otimes \sigma_y \end{bmatrix}$$

It is possible quantum-mechanically!

Resource for quantum computing

- **Then, where does the “quantum” computing power come from?**

Contextuality!?



ARTICLE [Nature **510**, 351 (2014)]

doi:10.1038/nature13460

Contextuality supplies the ‘magic’ for quantum computation

Mark Howard[1,2], Joel Wallman[2], Victor Veitch[2,3] & Joseph Emerson[2]

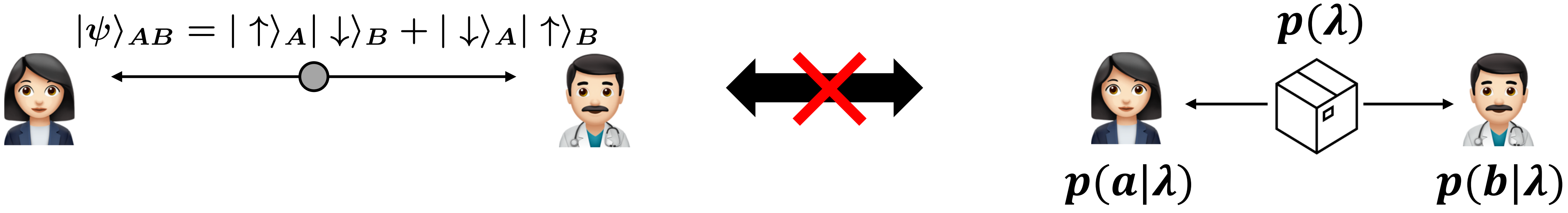
Bell–Kochen–Specker theorem (1966)

Measurement of quantum observables cannot simply reveal pre-existing values

(i.e., Realistic hidden variable models fail to describe our nature)

- **Entanglement (Bell non-locality)**

$$|\psi\rangle_{AB} = |\uparrow\rangle_A|\downarrow\rangle_B + |\downarrow\rangle_A|\uparrow\rangle_B$$



Resource for quantum computing

- **Then, where does the "quantum" computing power come from?**

ARTICLE [Nature **510**, 351 (2014)]

doi:10.1038/nature13460

Contextuality supplies the 'magic' for quantum computation

Mark Howard[1,2], Joel Wallman[2], Victor Veitch[2,3] & Joseph Emerson[2]

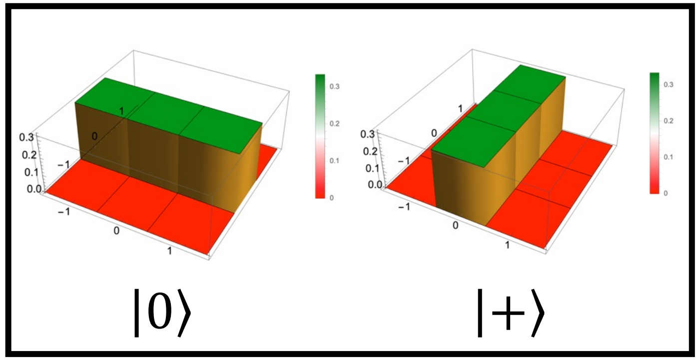
Contextuality!?

0) Non-contextual state ⇔ positive distribution in phase space ⇔ Classically simulable

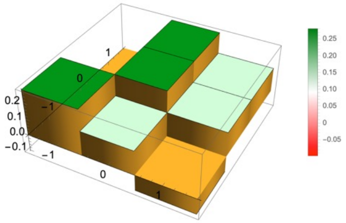
1) Magic gate can be converted to magic state + Clifford gates

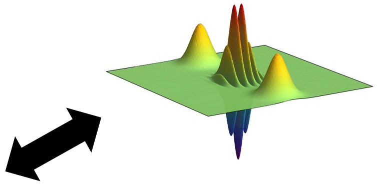
2) Magic state has negative distribution

Stabilizer state (classically simulable)



$|0\rangle$ $|+\rangle$





$|T\rangle$: Magic state
➔ Negativity!

But this is not a complete answer (this argument is true only for $d = 3, 5, 7, \cdots$)

Recent progress
[S. Bravyi, D. Gosset, R. Koenig, Science **362**, 308 (2018)]
[S. Bravyi *et al.*, Nat. Phys. **16**, 1040 (2020)]

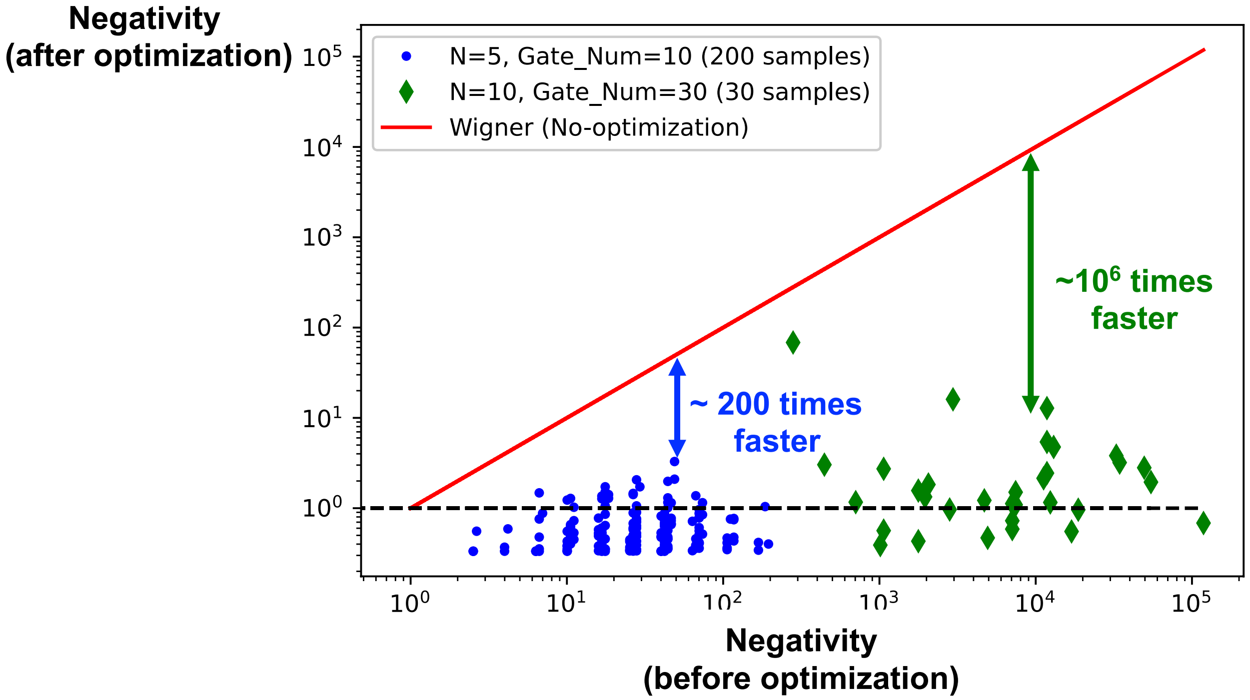
➔ Quantum algorithms with a shallow circuit which has a strict quantum advantage!

Can we go beyond the Clifford framework?

[H. Pashayan, J. J. Wallman, and S. D. Bartlett, Phys. Rev. Lett. 115, 070501 (2015)]

- **Negativity ➔ Overhead cost for classical simulation** **(not exactly quantifying a speed up)**
- **There are many different phase-space representations (Clifford is one of them)**
- **Can we reduce the negativity by taking different phase space structure?**

The answer is YES!



➔ Quantum circuits can be classically simulated faster after optimizing the negativity!

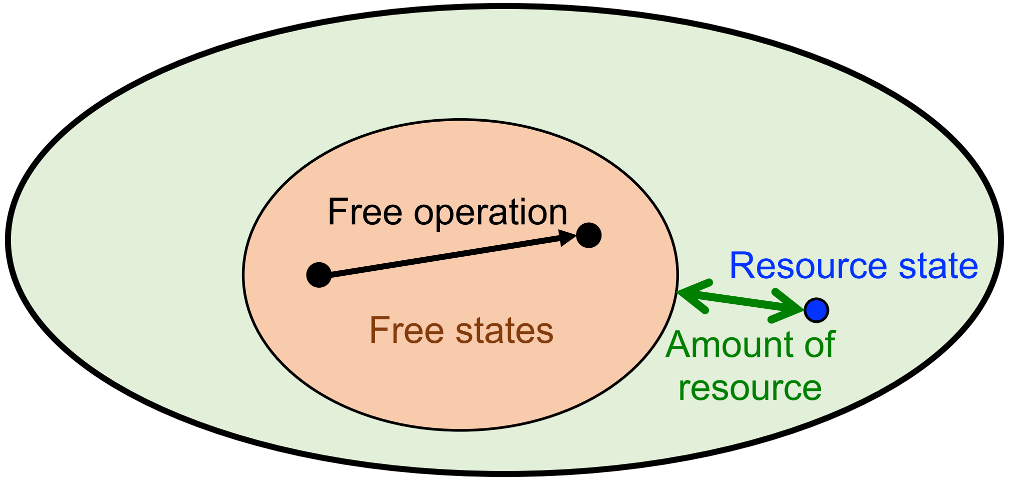
Born probability estimation via gate merging and dynamic frame optimisation

Nikolaos Koukoulekidis[1], Hyukjoon Kwon[1,2], Hyejung H. Jee[3], David Jennings[4,1], and M. S. Kim[1,2]

General framework of quantum resource theory

- **In order to quantify quantum resources, we need**
  1) Set of operations than can be done classically (Free operation)
  2) Set of quantum states that do not have a quantum advantage (Free state)

- **Then,**
  0) If a quantum state is a free state ➔ No quantum advantage
  1) If a quantum state is not a free state ➔ It contains non-classical resource
  2) How far it is from the free states quantifies the amount of resource



Task	Free operation	Free states	Quantum resources
Quantum communication	LOCC	Separable states $(\rho_{AB} = \sum_i p_i \rho_A^{(i)} \otimes \rho_B^{(i)})$	Entanglement
Quantum metrology	Linear interferometer	Classical states (positive distribution)	Non-classicality
Quantum computing	Clifford gates	Stabilizer state (positive distribution)	Contextuality

Coherence
Non-Gaussianity
⋮

For an overview: [Rev. Mod. Phys. 91, 025001 (2019)]

Summary

- **Quantum resource: Something that we can use to do a “non-classical” task**

- **For different quantum technologies, we need different types of quantum resources**

Quantum communication
[Sending quantum bits]
⇓
Entanglement

Quantum computing
[Faster computation]
⇓
Non-Clifford elements
Magic states/gates
Contextuality?
(Not fully understood)

Quantum metrology
[Precision measurement]
⇓
Negative quasi-probability
(non-classicality)

- **Open questions**
  - ✓ **How to efficiently distill/manipulate useful quantum resources (quantum thermodynamics)**
  - ✓ **How to protect quantum information efficiently against noise (quantum error-correction)**

Thank you