Recent breakthroughs in optical quantum computing with continuous variables

Prof Nicolas C Menicucci

RMIT UNIVERSITY

CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

QuRMIT

AIP Dec 2022

(Comic sans forever!)

ARC Centre of Excellence

CENTRE FOR
QUANTUM COMPUTATION &
COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

https://www.cqc2t.org/

UNSW SYDNEY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

UTS UNIVERSITY OF TECHNOLOGY SYDNEY

RMIT UNIVERSITY

THE UNIVERSITY OF MELBOURNE

Australian National University

Griffith UNIVERSITY Queensland, Australia

About CQC²T

CQC²T is an international team working to develop technology for universal quantum computing and secure quantum communication

- Over 200 researchers
- Across 7 Australian universities
- 25 formal international partners
- 22 co-ordinated research programs

UNSW SYDNEY

The University of Queensland AUSTRALIA

UTS UNIVERSITY OF TECHNOLOGY SYDNEY

RMIT UNIVERSITY

THE UNIVERSITY OF MELBOURNE

Australian National University

Griffith UNIVERSITY Queensland, Australia

My group

https://www.qurmit.org/

QuRMIT

What is quantum computing?

What is Computation?

What is Computation?

abstract:

What is Computation?

abstract:

input
(information)

What is Computation?

abstract:

input
(information)

output
(information)

What is Computation?

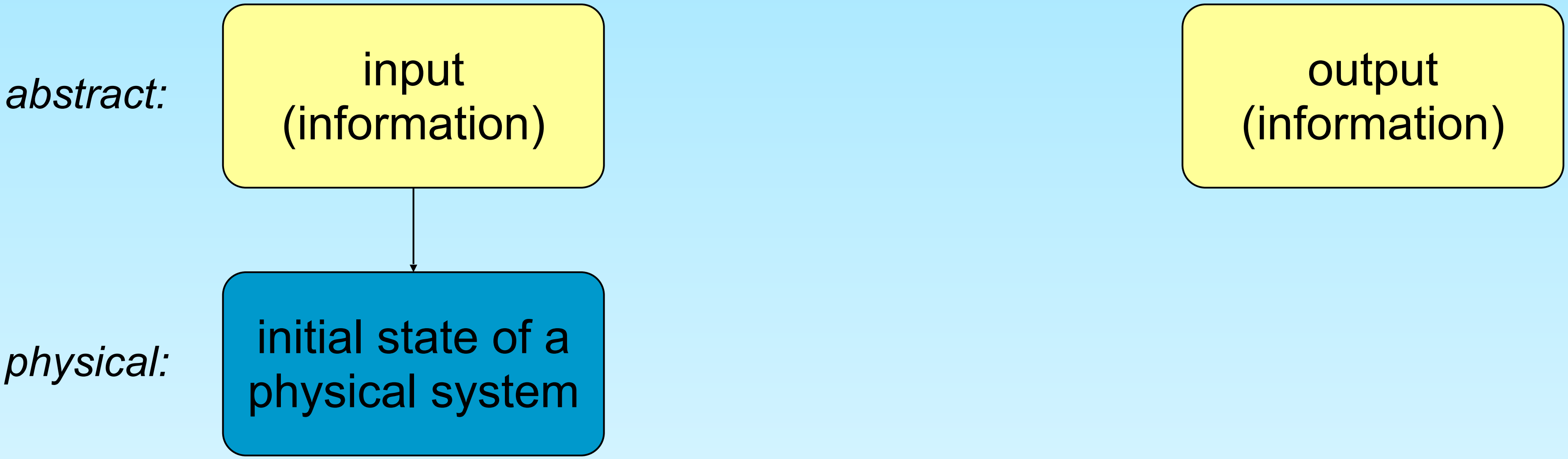
abstract:

input
(information)

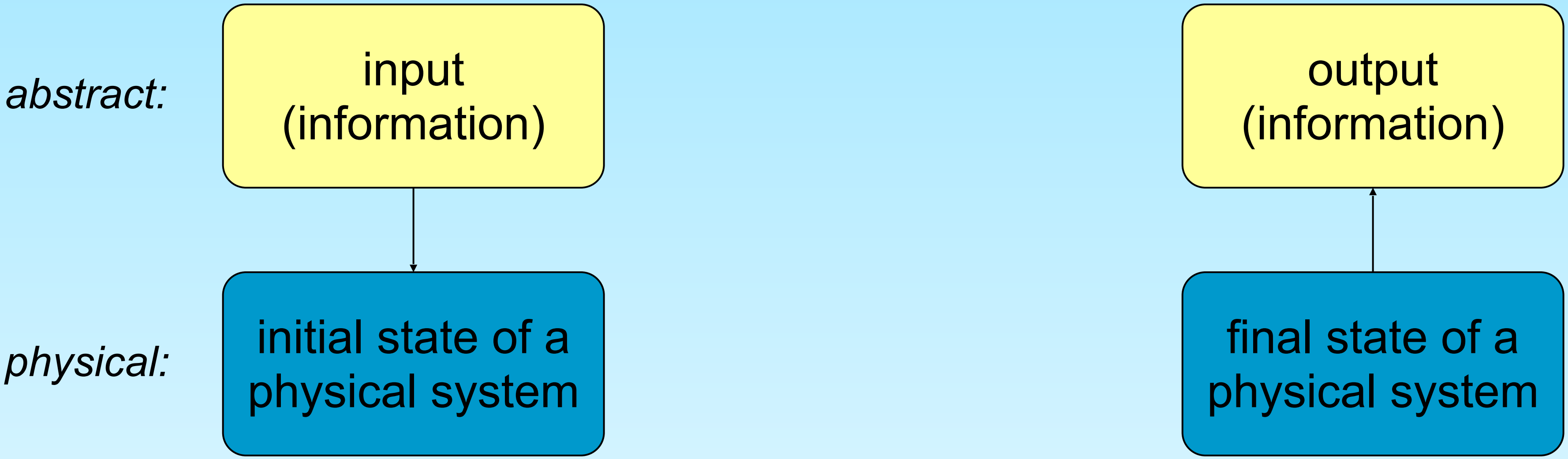
output
(information)

physical:

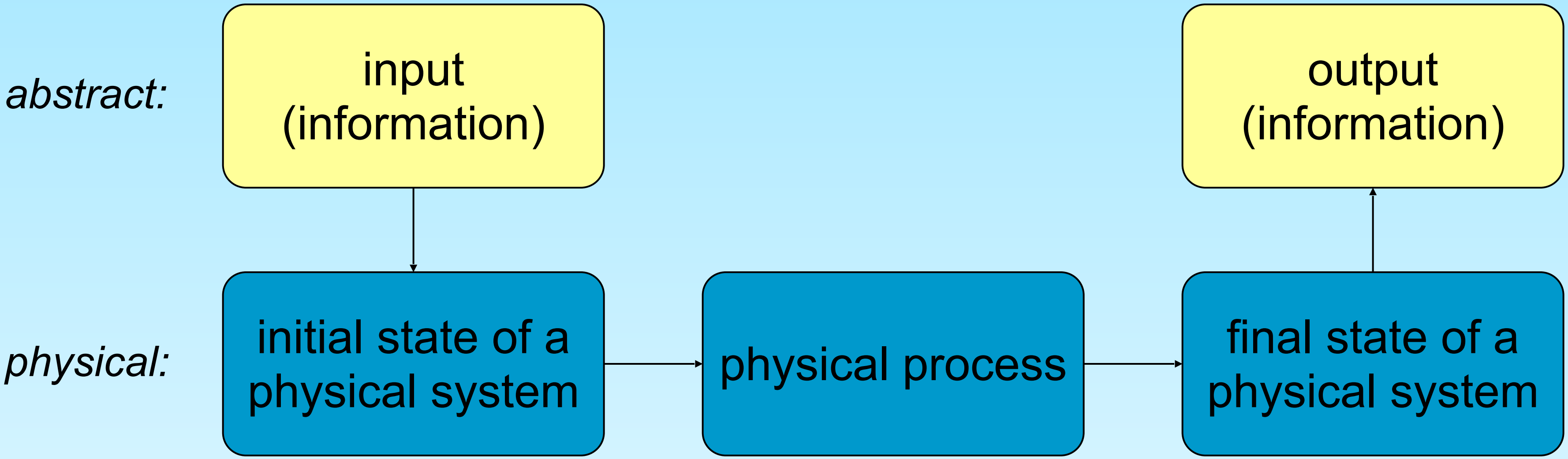
What is Computation?



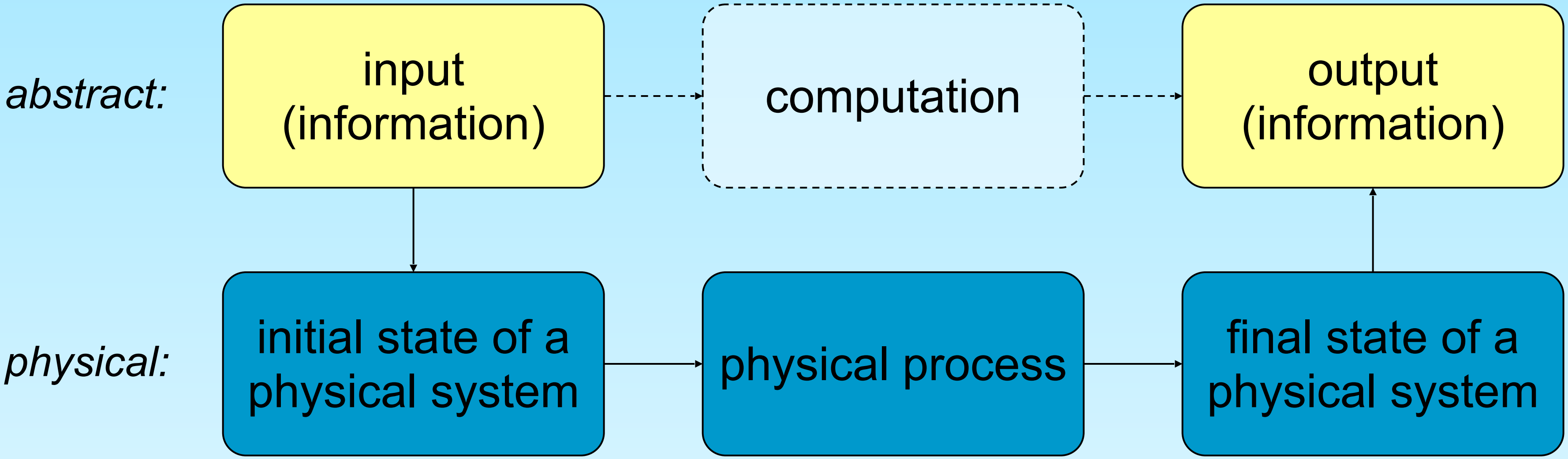
What is Computation?



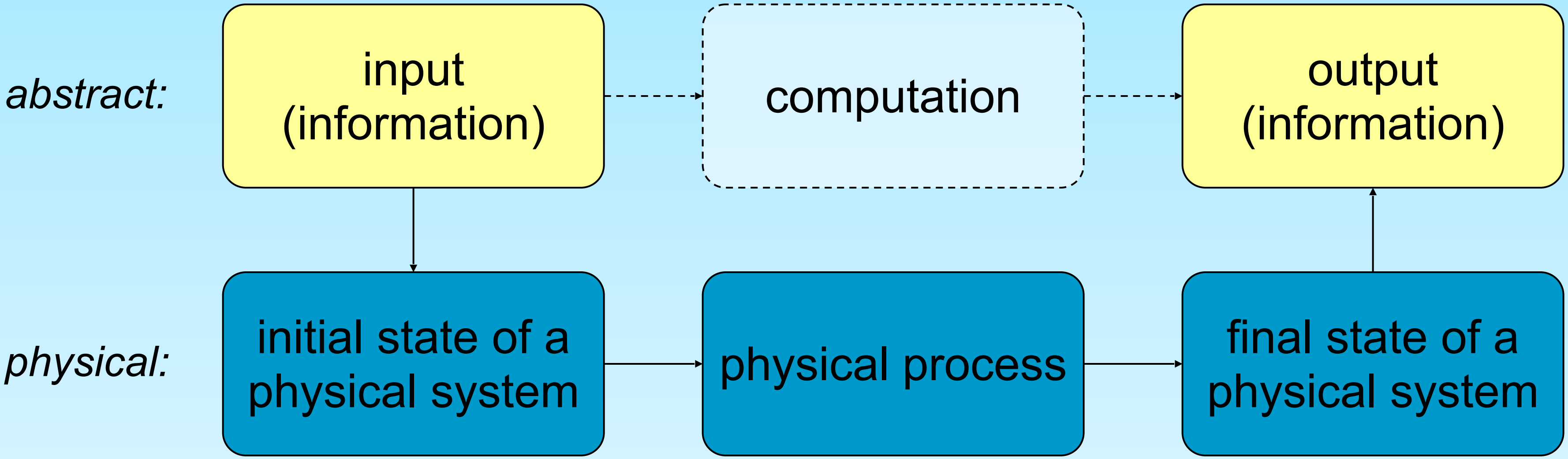
What is Computation?



What is Computation?

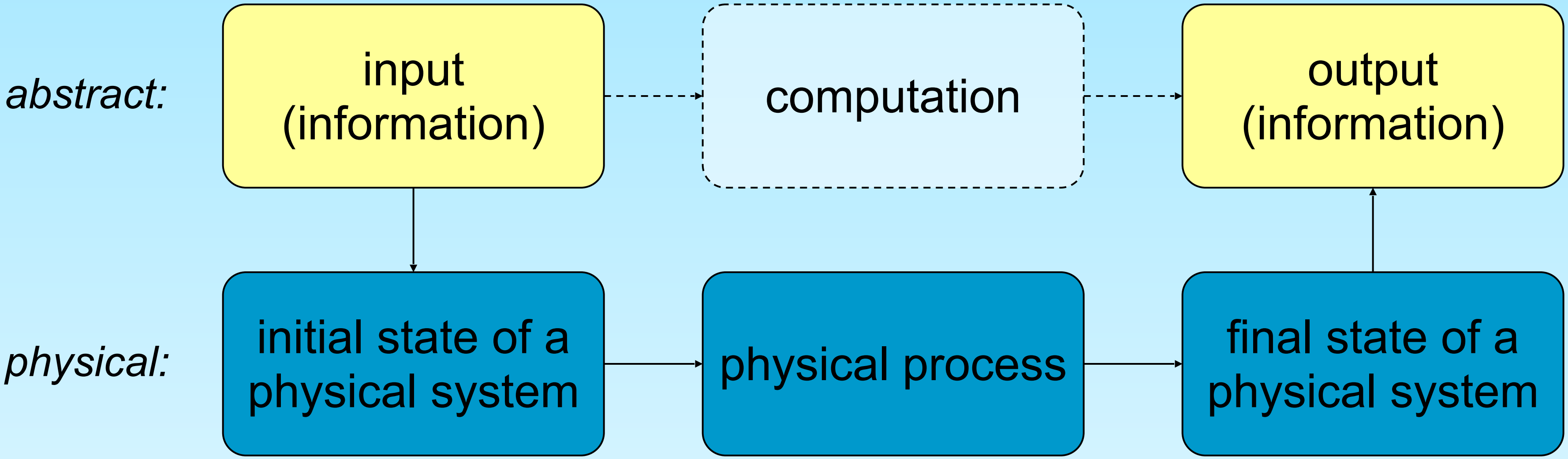


What is Computation?



- Laws of computation limited by knowledge of *physics*!

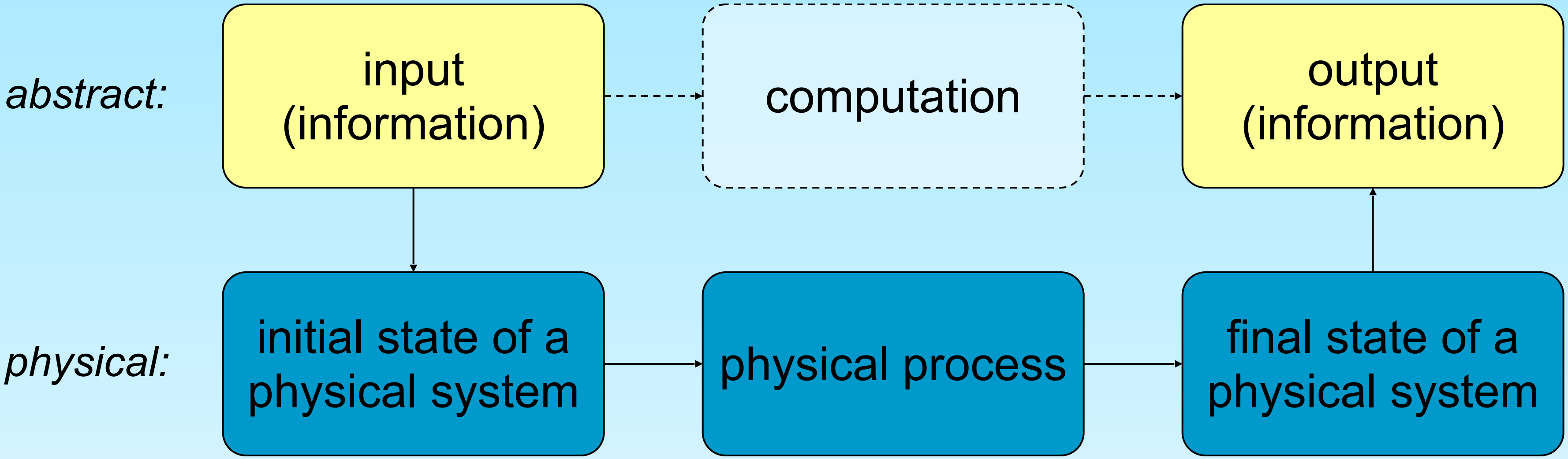
What is Computation?



- Laws of computation limited by knowledge of *physics*!
- Computations are *processes* within chosen model (classical / quantum / other)

RMIT UNIVERSITY

What is Computation?

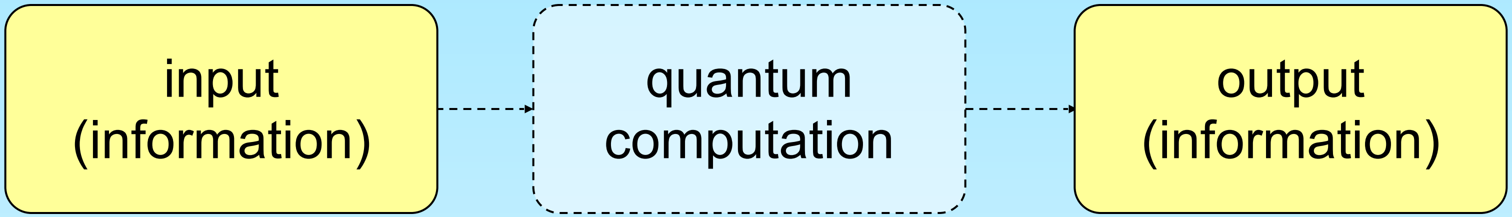


- Laws of computation limited by knowledge of *physics*!
- Computations are *processes* within chosen model (classical / quantum / other)
- Computations are constructed from a small, *universal* set of *gates* (elementary operations)

RMIT UNIVERSITY

Qubits and Continuous-Variable (CV) Systems

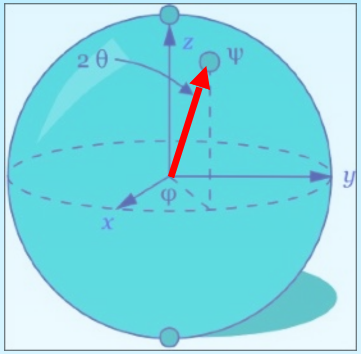
Qubits and Continuous-Variable (CV) Systems



Qubits and Continuous-Variable (CV) Systems

input (information) → quantum computation → output (information)

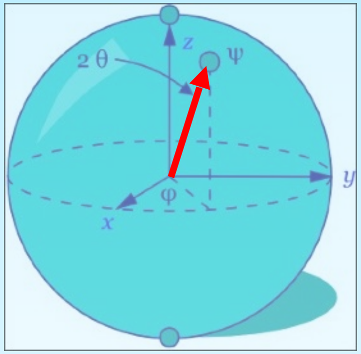
Qubits



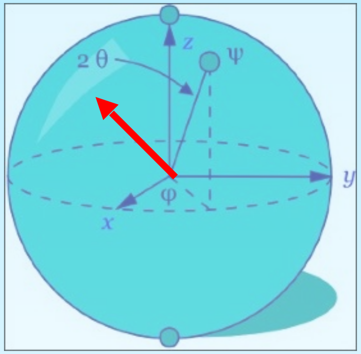
Qubits and Continuous-Variable (CV) Systems

input (information) → quantum computation → output (information)

Qubits



Unitary evolution

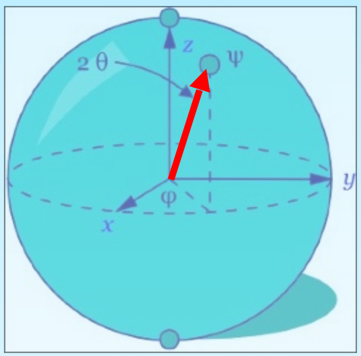


RMIT UNIVERSITY

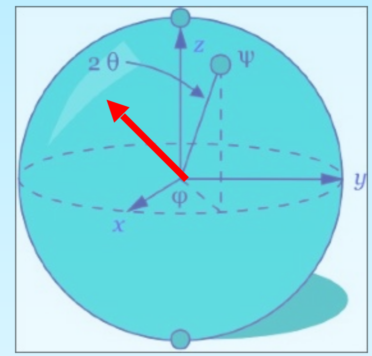
Qubits and Continuous-Variable (CV) Systems

input (information) → quantum computation → output (information)

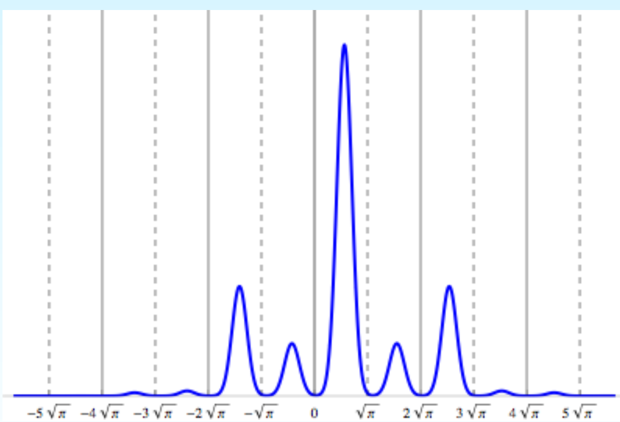
Qubits



Unitary evolution →



CVs

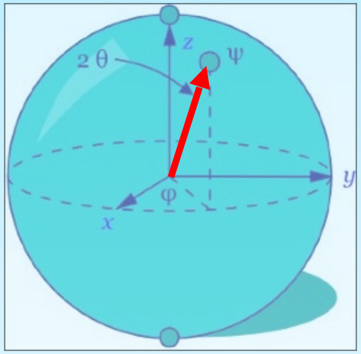


RMIT UNIVERSITY

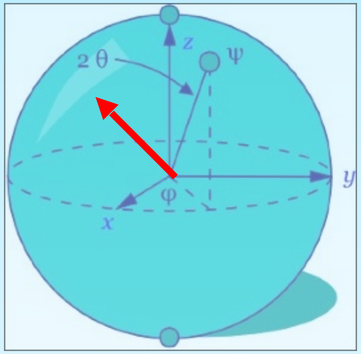
Qubits and Continuous-Variable (CV) Systems

input (information) → quantum computation → output (information)

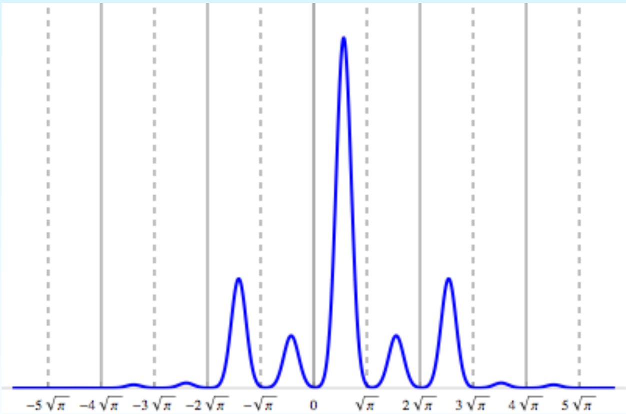
Qubits



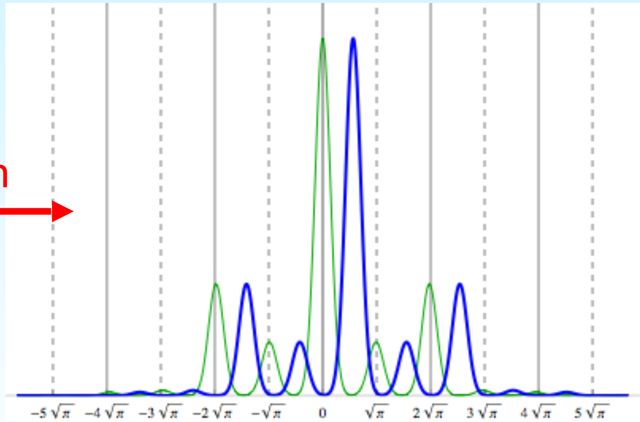
Unitary evolution →



CVs



Unitary evolution →



Why bother with CVs?

RMIT UNIVERSITY

CVs: Advantages

CVs: Advantages

- Practical
  - (optics) deterministic entanglement
  - (optics) immensely scalable
  - (optics) room-temperature operation
  - (circuit QED) microwave cavities are less noisy than transmons

RMIT UNIVERSITY

CVs: Advantages

- Practical
  - (optics) deterministic entanglement
  - (optics) immensely scalable
  - (optics) room-temperature operation
  - (circuit QED) microwave cavities are less noisy than transmons
- Fundamental
  - avoid premature optimisation
    (e.g,, in optics, why should we restrict to photonic qubits?)

RMIT UNIVERSITY

CVs: Advantages

- Practical
  - (optics) deterministic entanglement
  - (optics) immensely scalable
  - (optics) room-temperature operation
  - (circuit QED) microwave cavities are less noisy than transmons
- Fundamental
  - avoid premature optimisation
    (e.g,, in optics, why should we restrict to photonic qubits?)
- Both together
  - more options for practical tasks (e.g., quantum cryptography, cluster states)
  - "hybrid" schemes: CV technology helps to manipulate photonic quantum states

CVs: Disadvantages

RMIT UNIVERSITY

CVs: Disadvantages

- Practical
  - imperfections due to finite energy
  - eventually need to discretise for error correction

CVs: Disadvantages

- Practical
  - imperfections due to finite energy
  - eventually need to discretise for error correction
- Fundamental
  - more questions to answer (e.g., what discretisation?)
  - must incorporate effects of noise from day one (complicated, easy to end up writing a crap paper)

CVs: Disadvantages

- Practical
  - imperfections due to finite energy
  - eventually need to discretise for error correction
- Fundamental
  - more questions to answer (e.g., what discretisation?)
  - must incorporate effects of noise from day one (complicated, easy to end up writing a crap paper)
- Both together
  - must do extra work to employ existing algorithms
  - smaller literature, fewer optimised experimental platforms

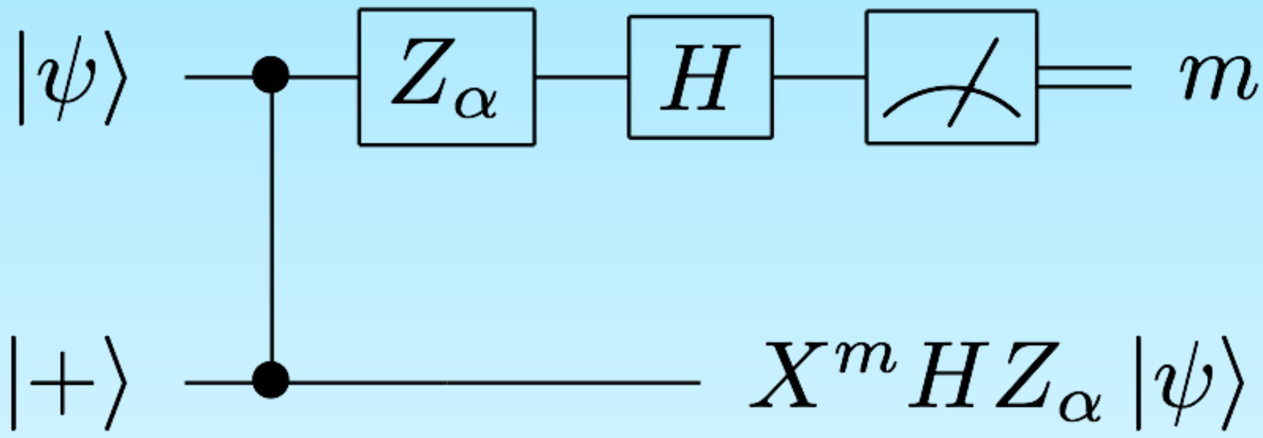
RMIT UNIVERSITY

Cluster states

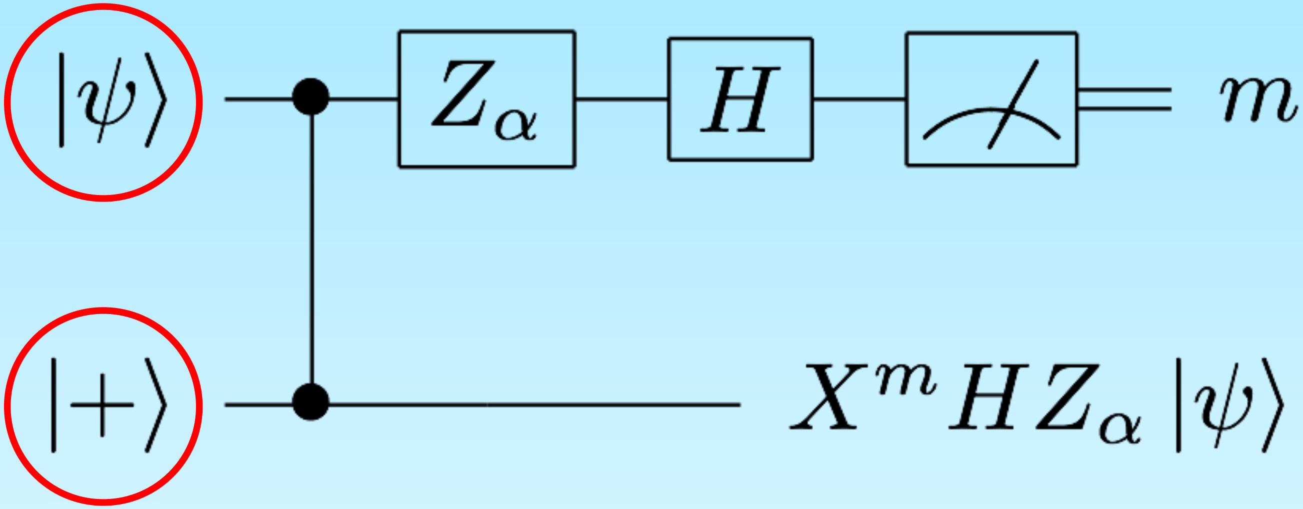
Teleportation "Lite"

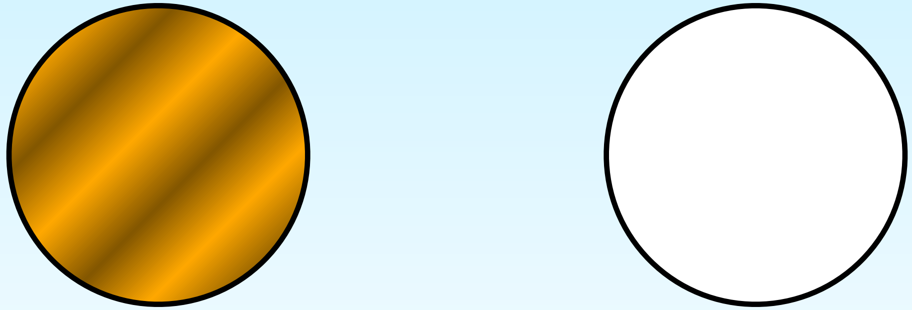
RMIT UNIVERSITY

Teleportation "Lite"

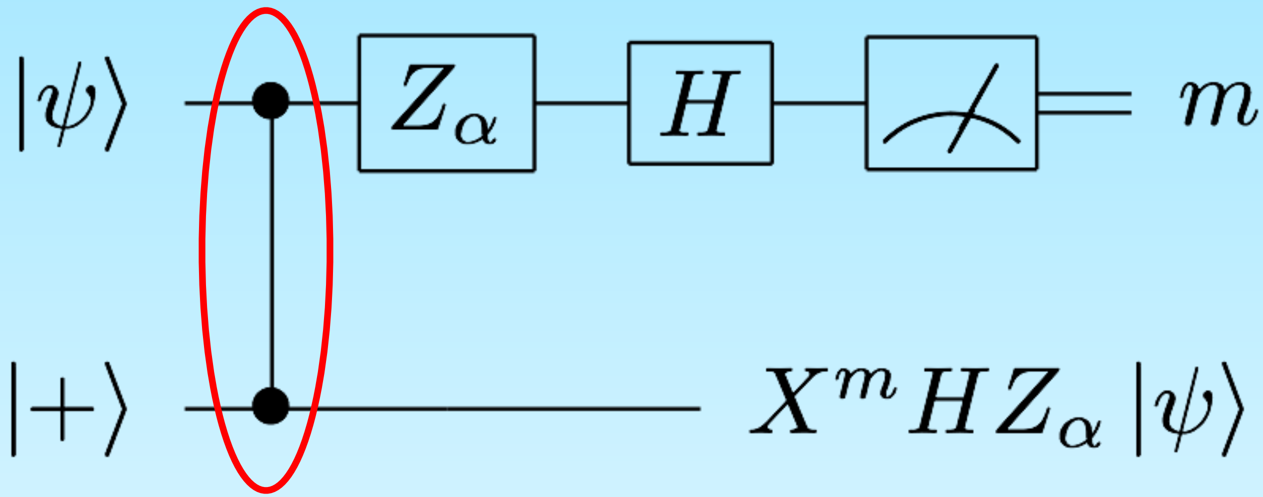


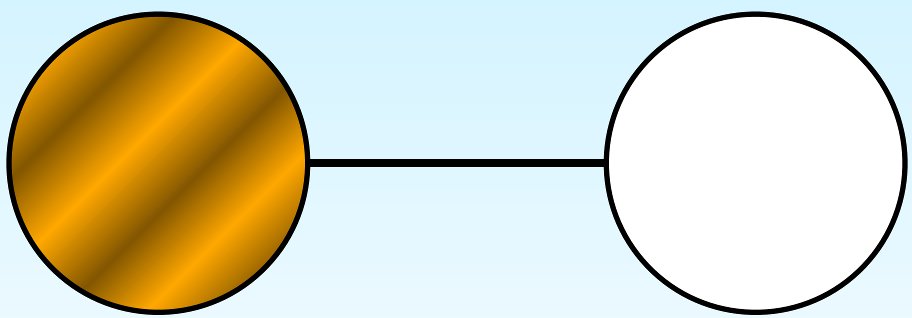
Teleportation "Lite"



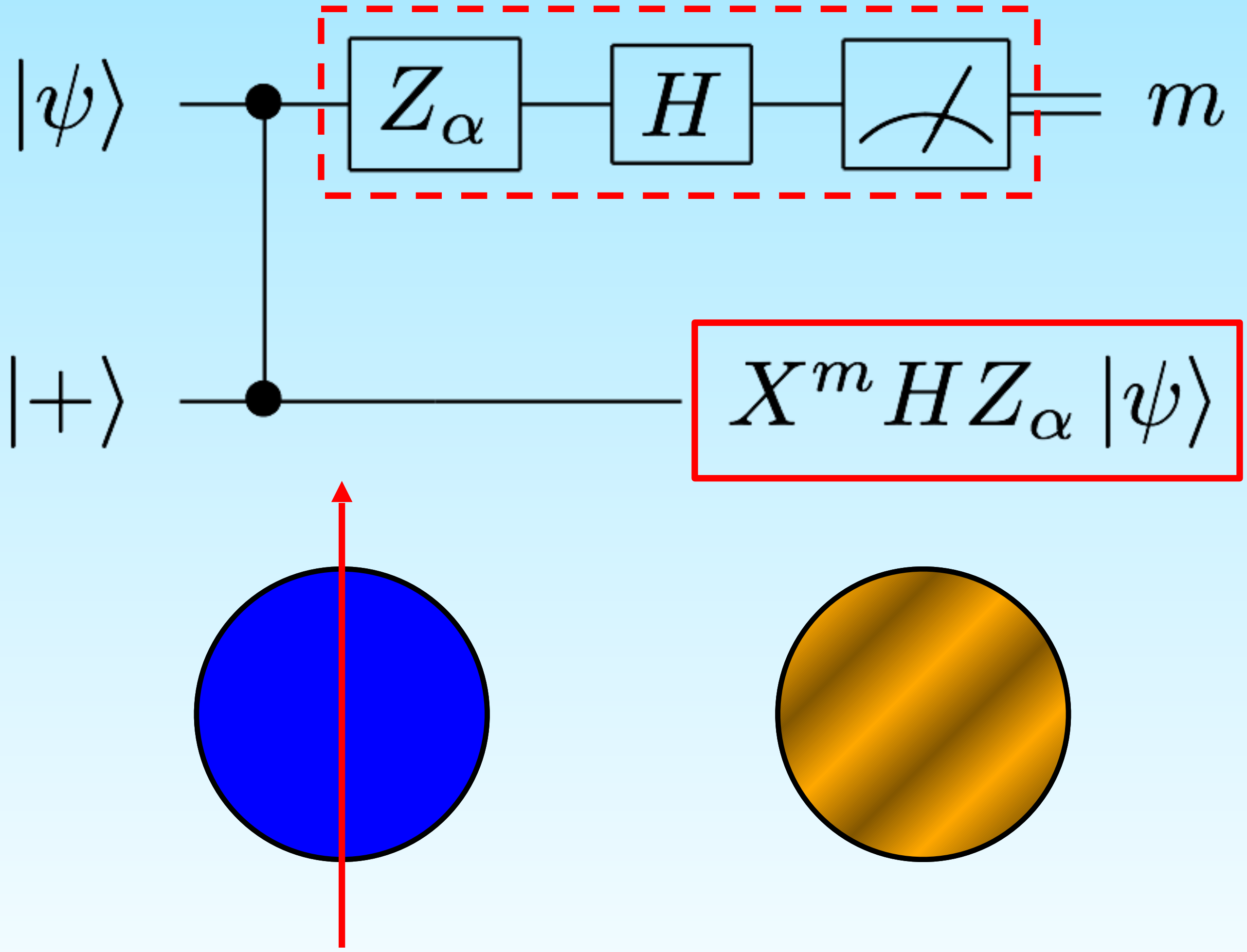


Teleportation "Lite"



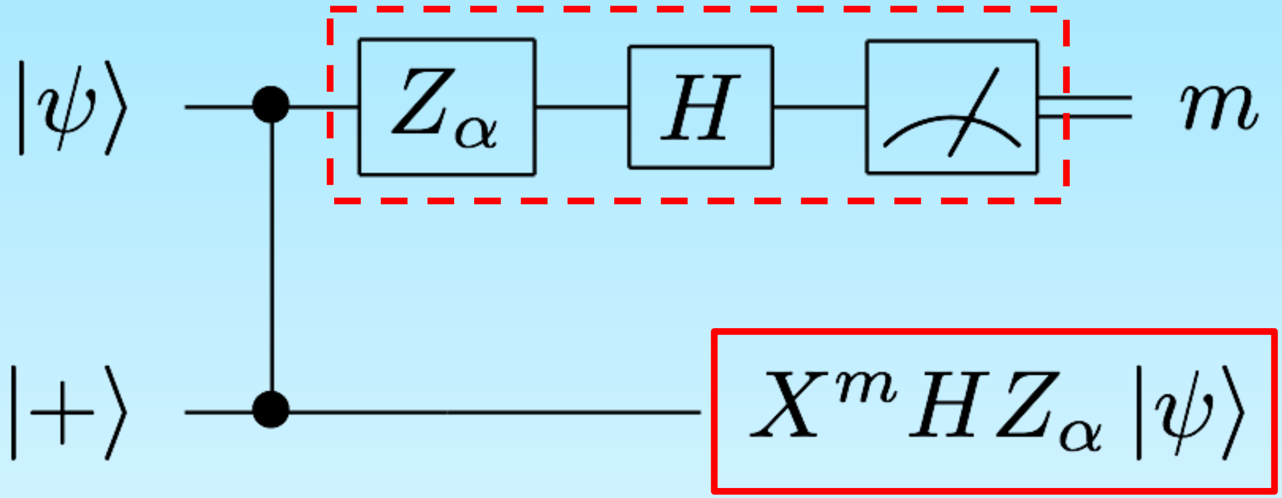


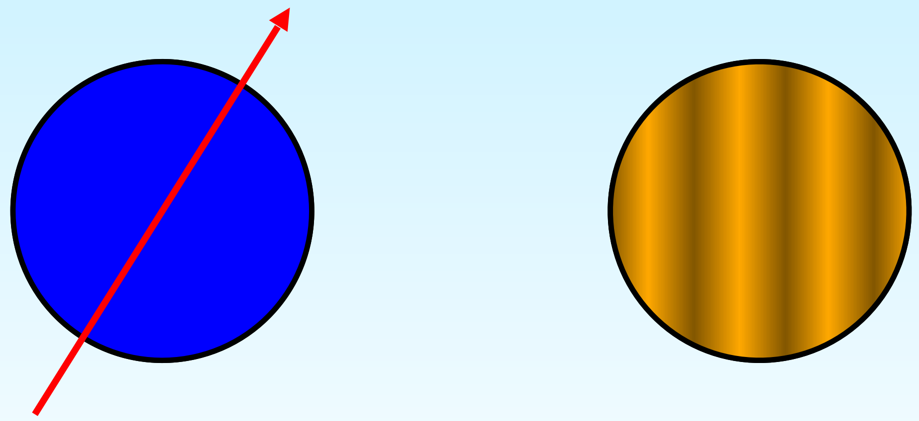
Teleportation "Lite"



RMIT UNIVERSITY

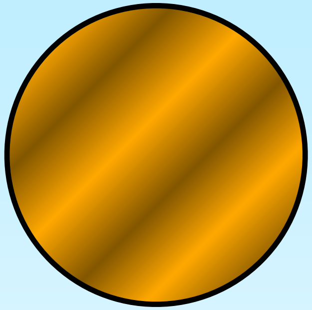
Teleportation "Lite"



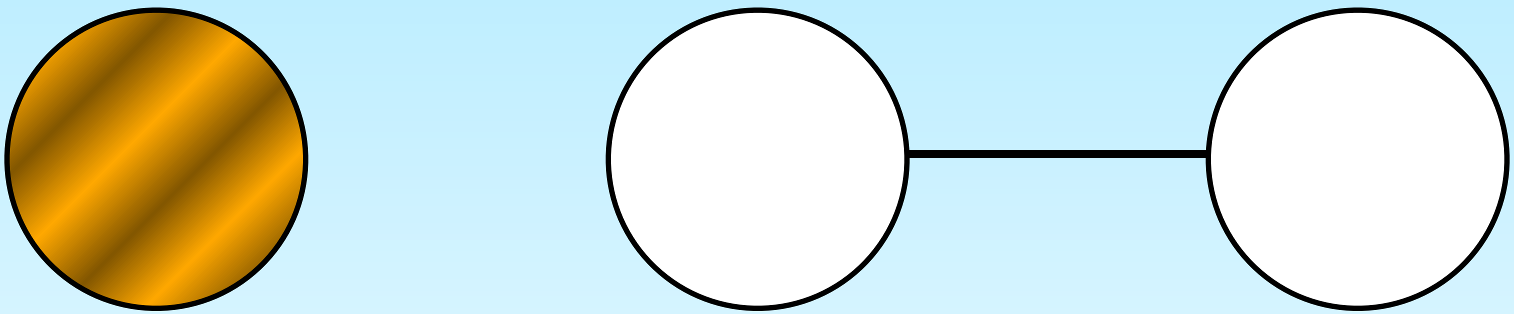


Teleportation

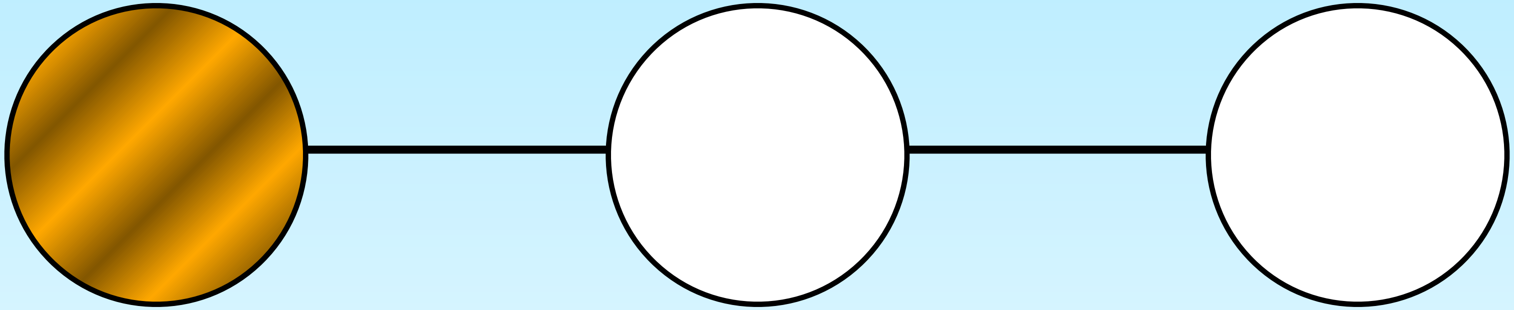
Teleportation



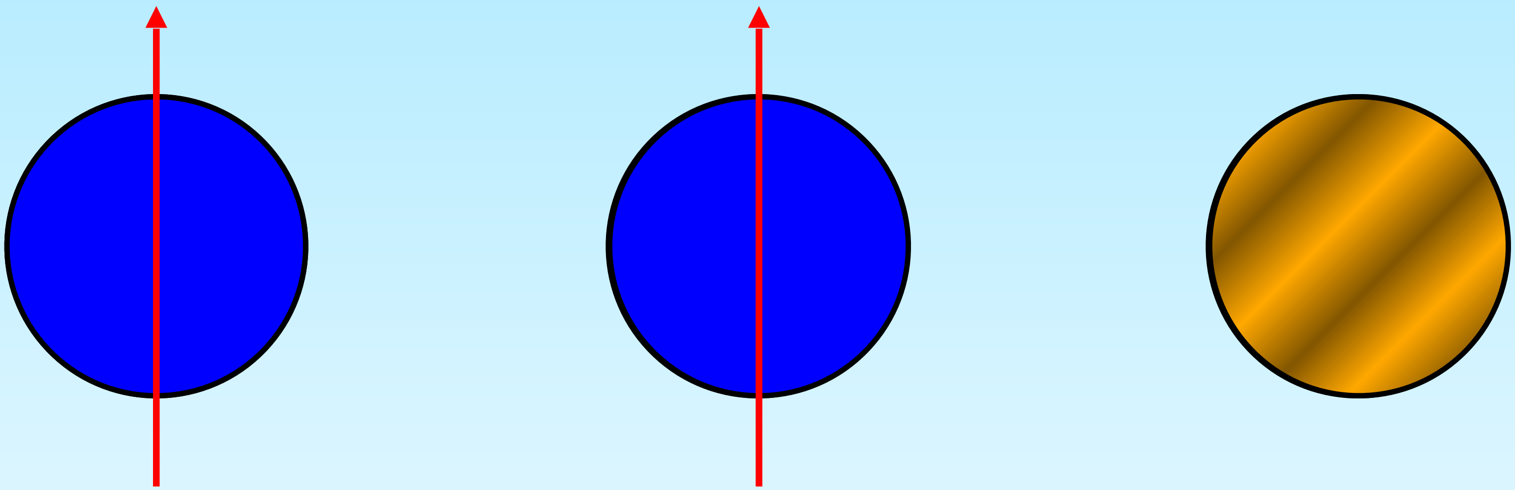
Teleportation



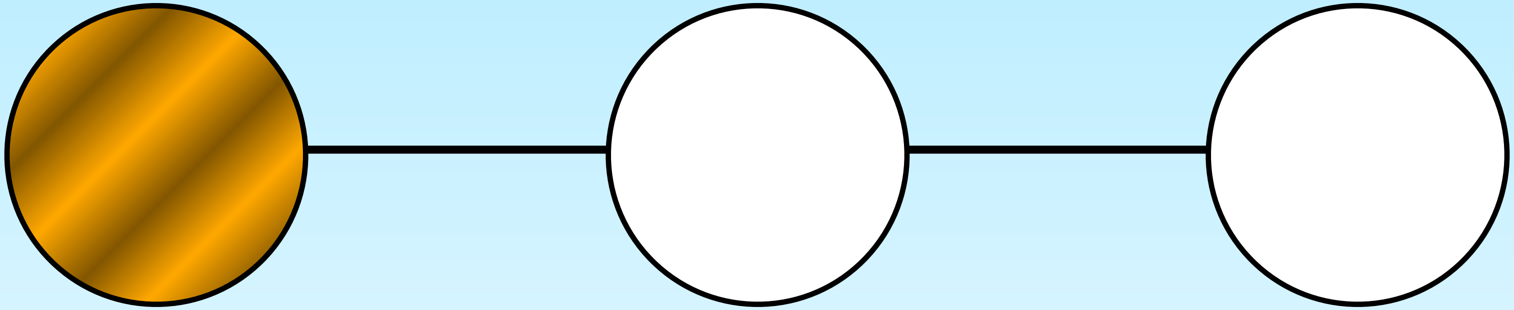
Teleportation



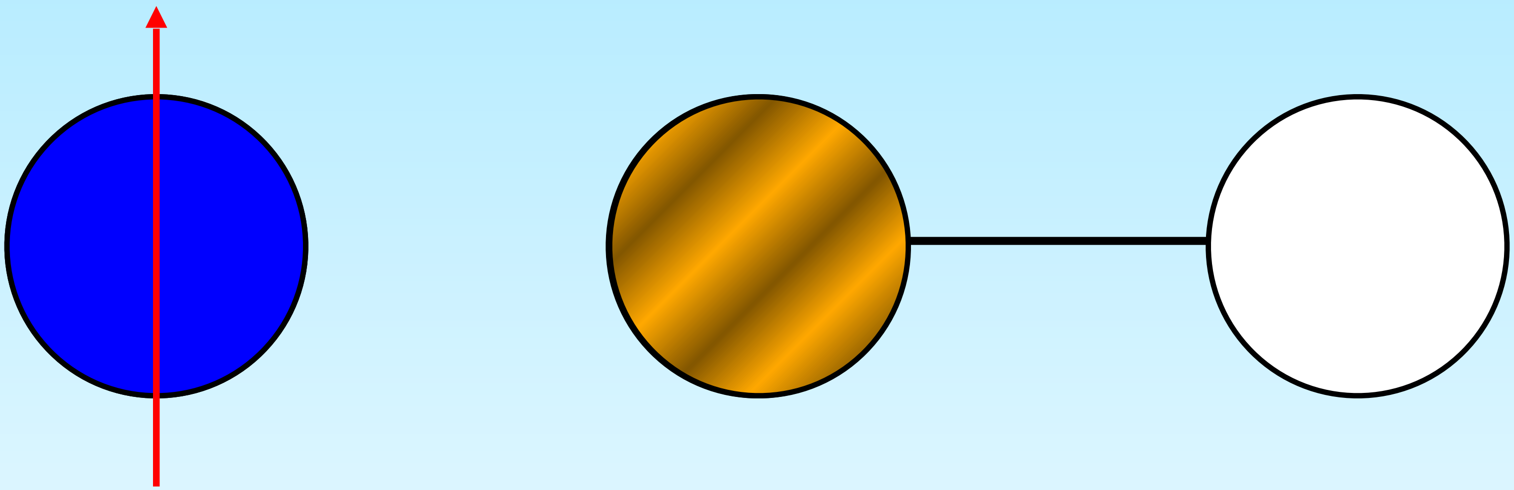
Teleportation



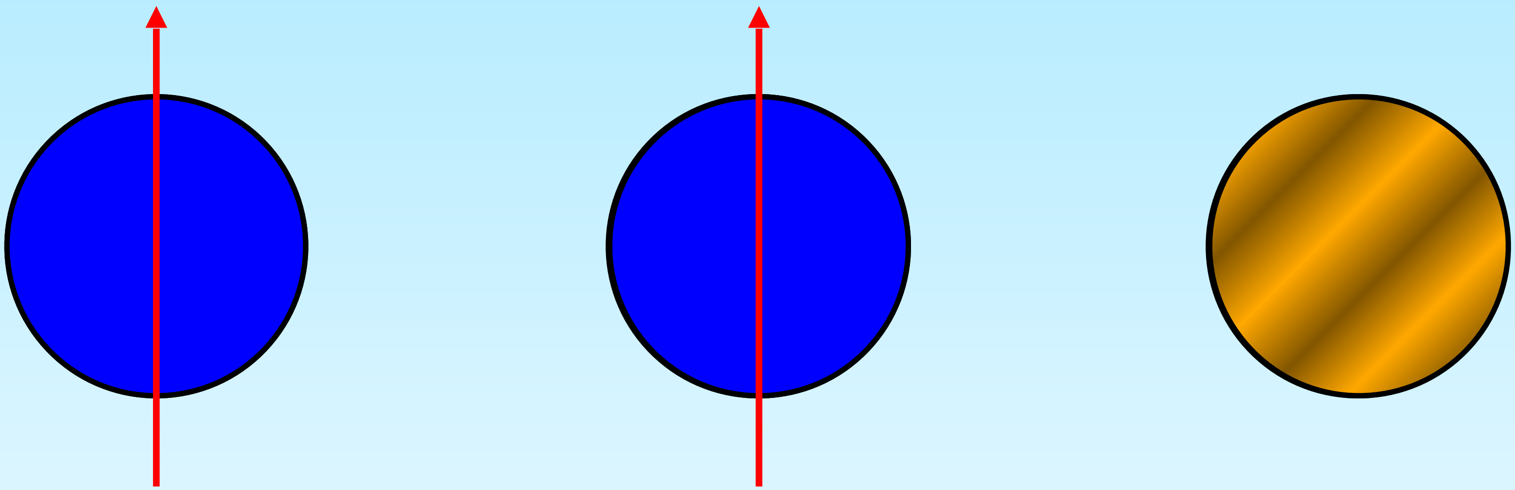
Teleportation



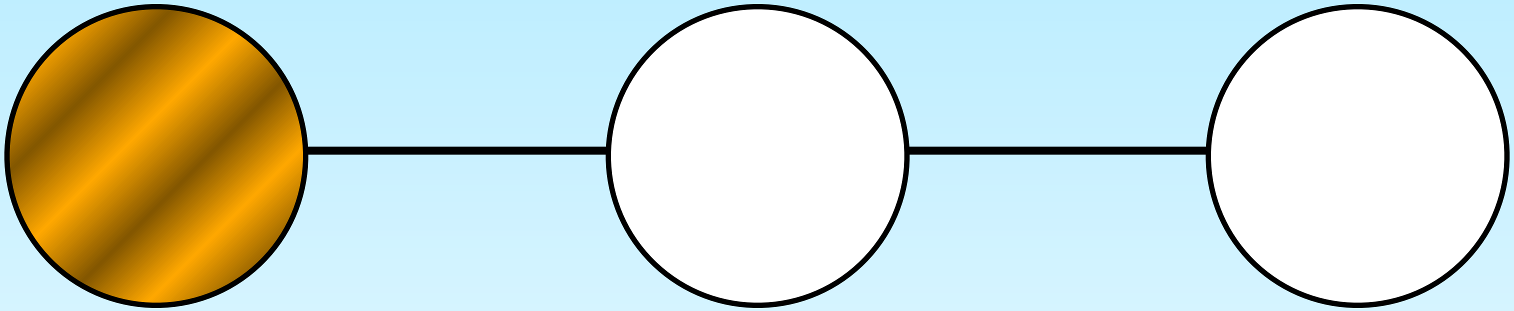
Teleportation



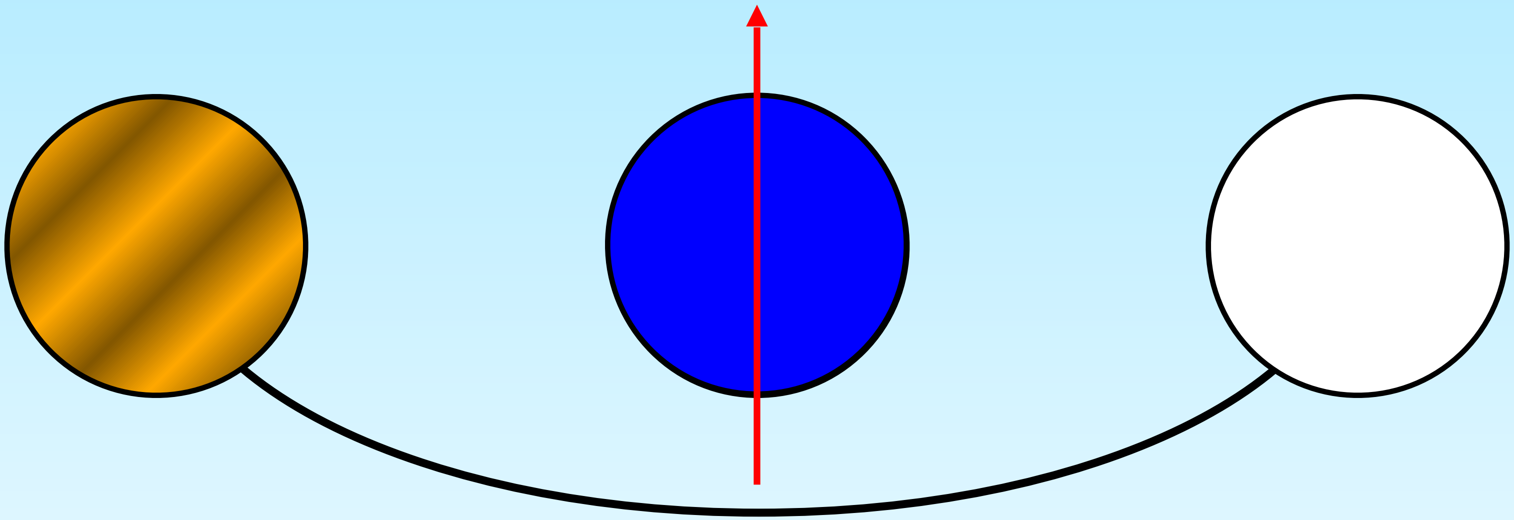
Teleportation



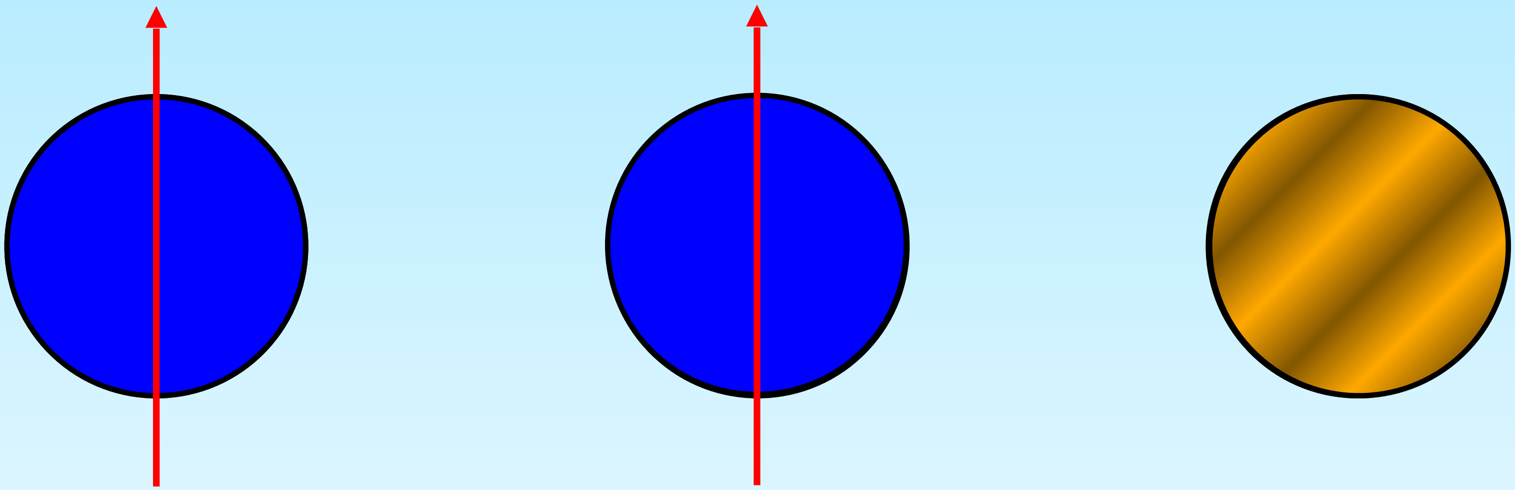
Teleportation



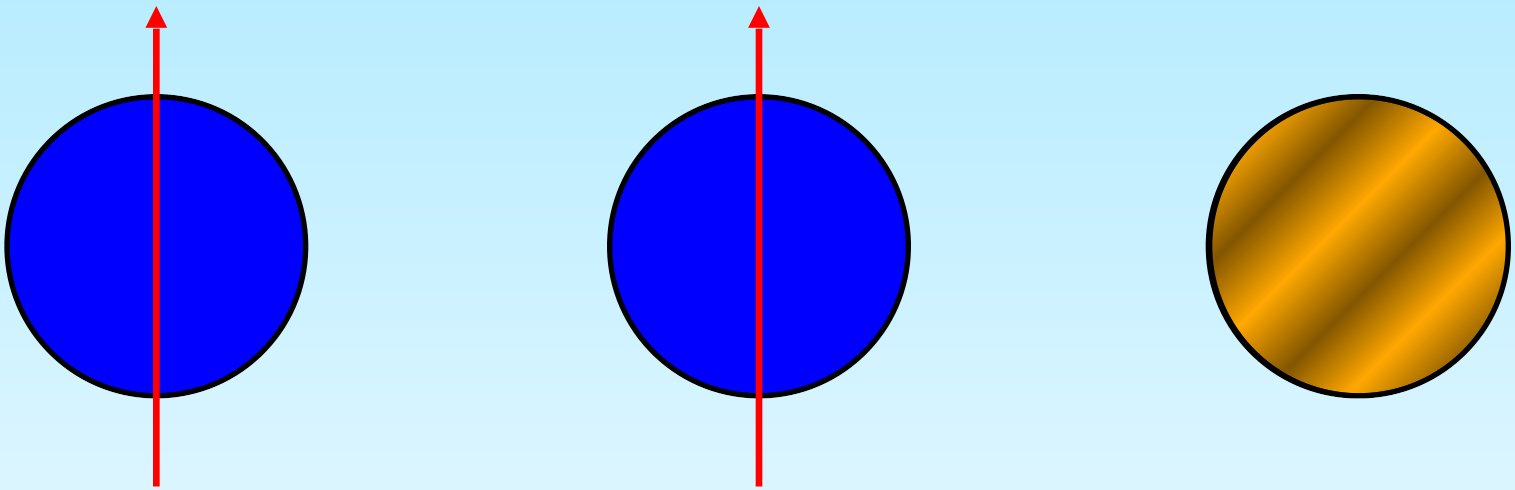
Teleportation



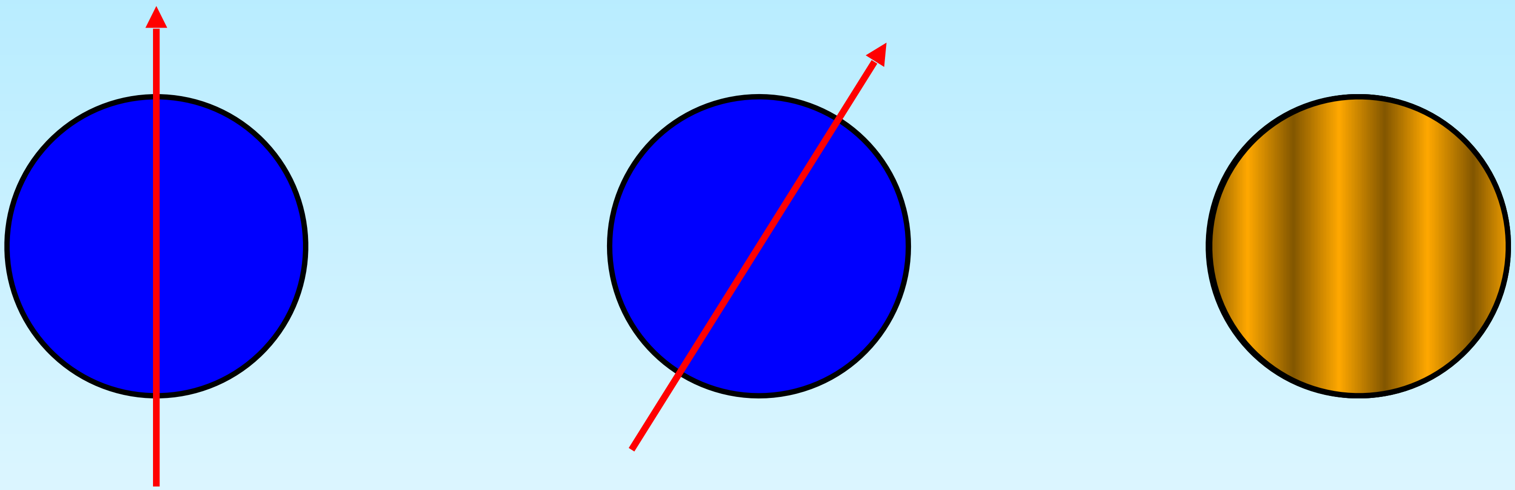
Teleportation



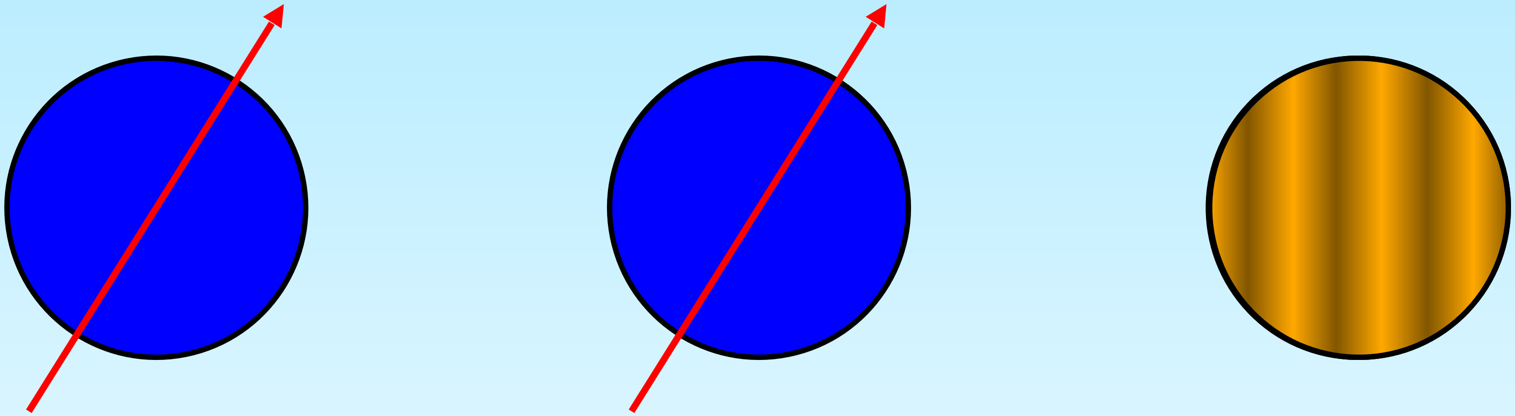
Teleportation



Teleportation

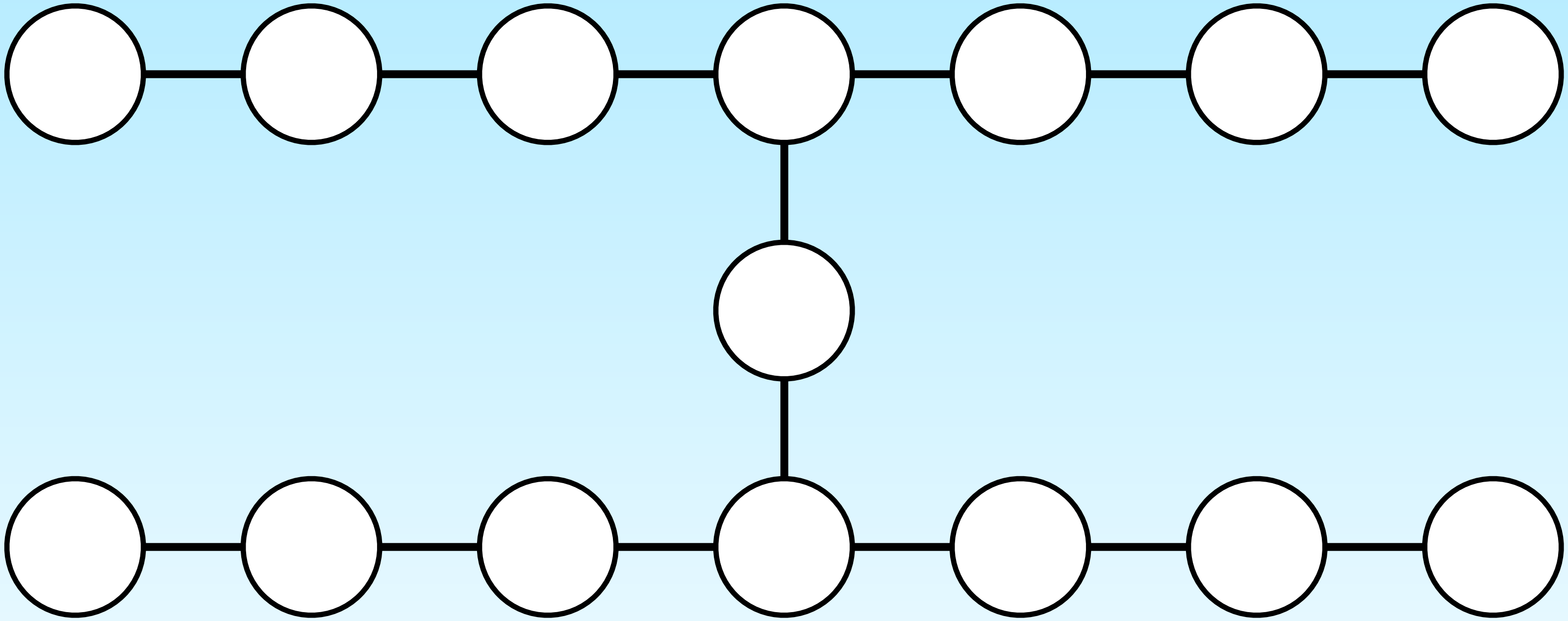


Teleportation

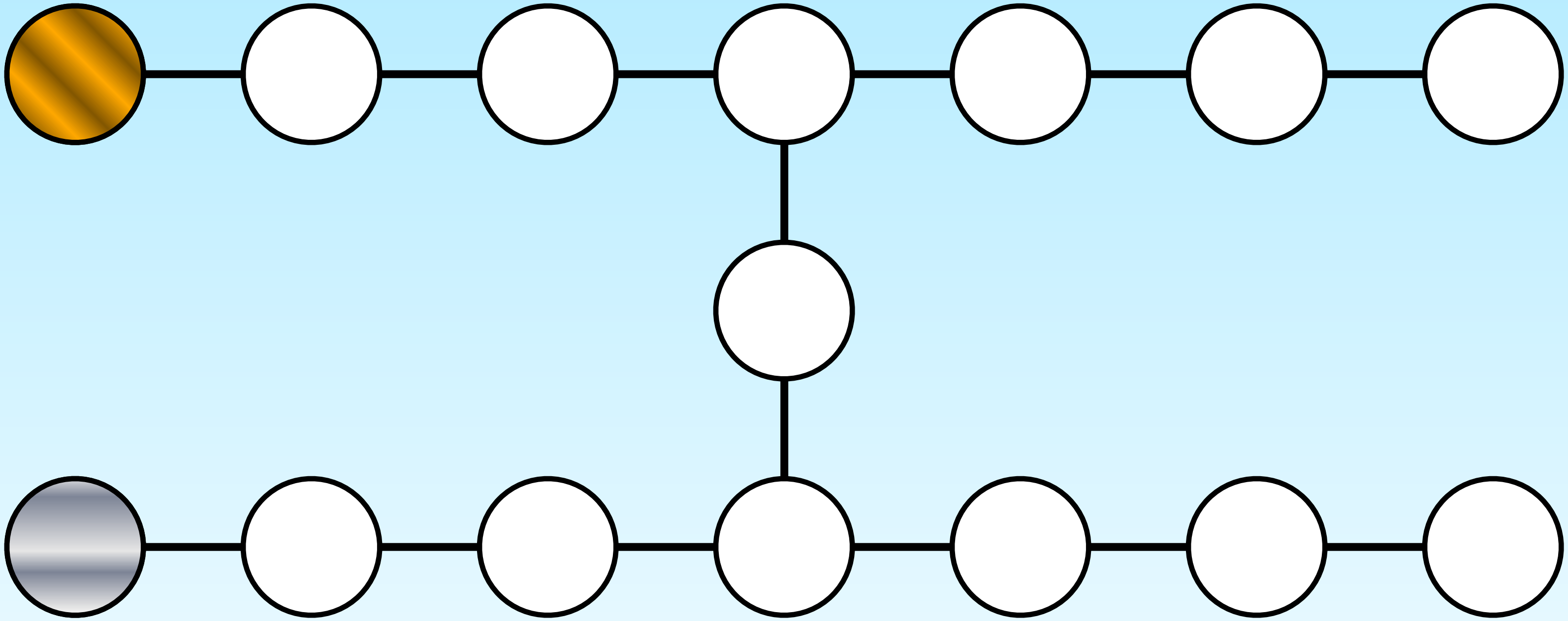


RMIT UNIVERSITY

Teleportation Network

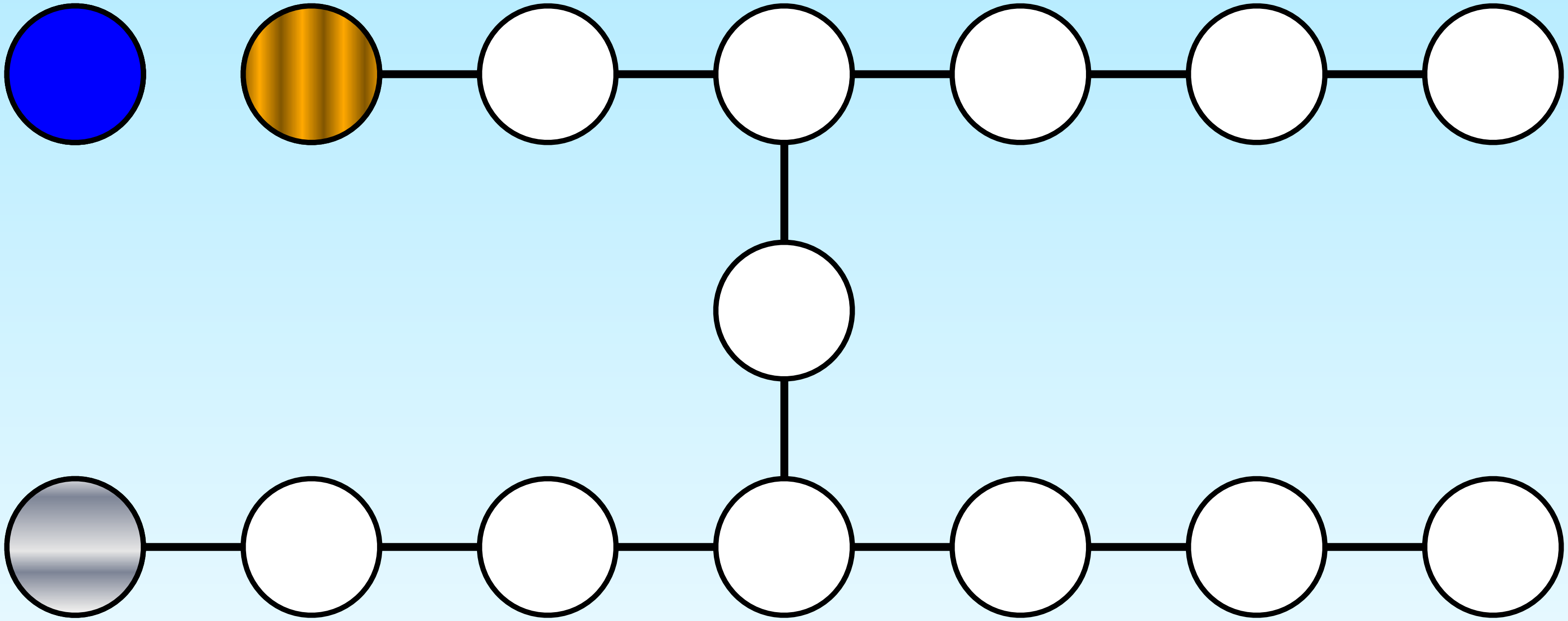


Teleportation Network

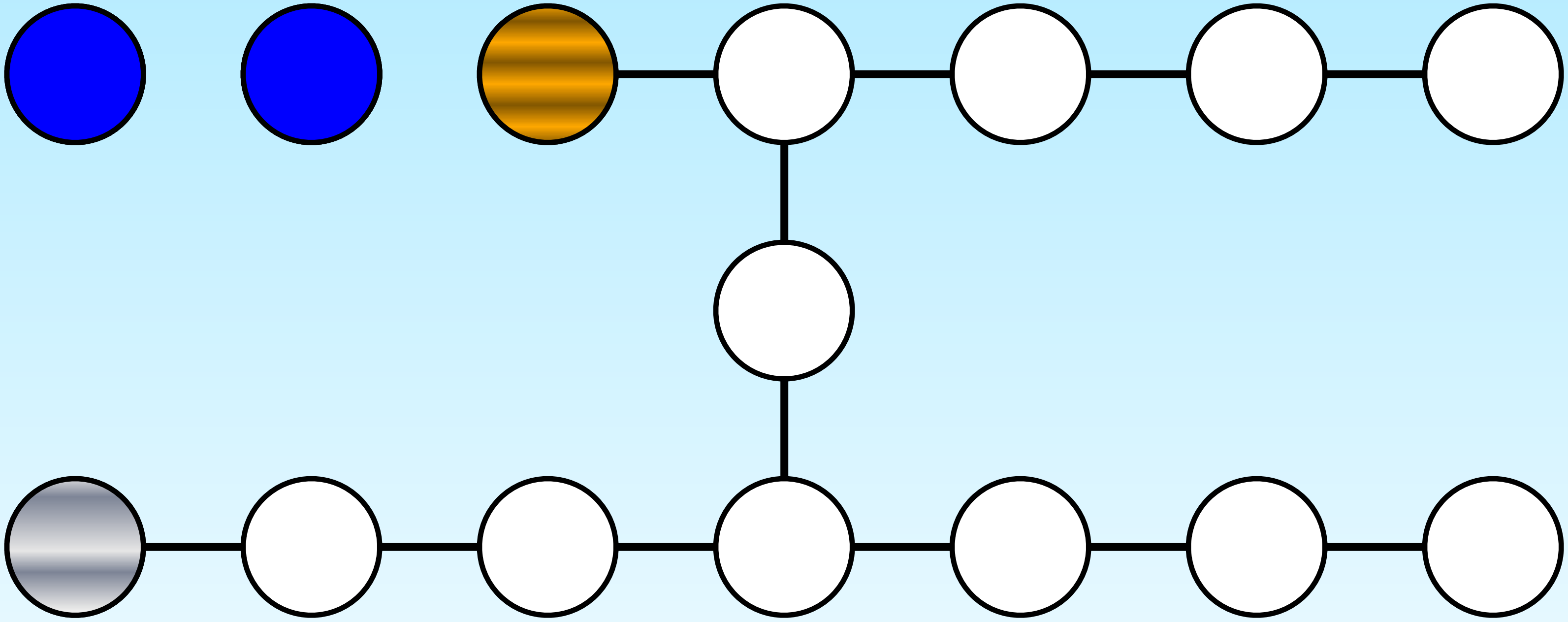


RMIT UNIVERSITY

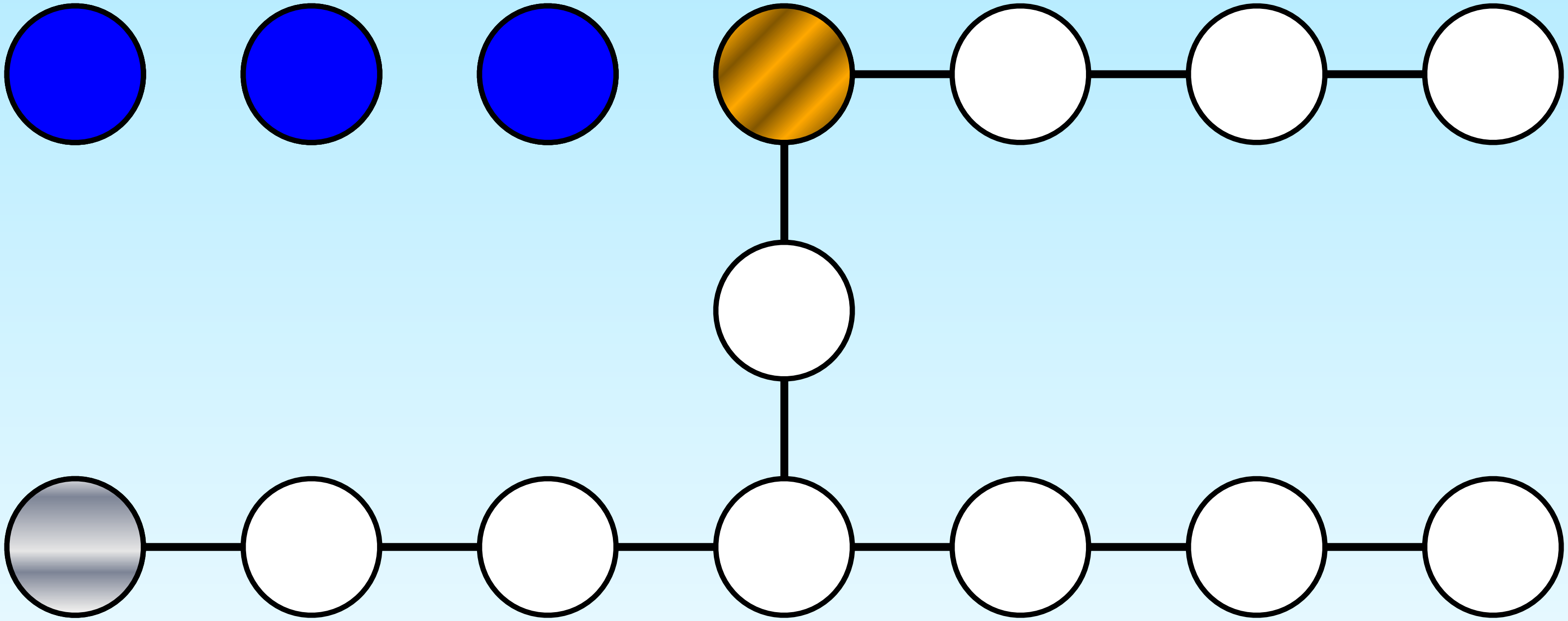
Teleportation Network



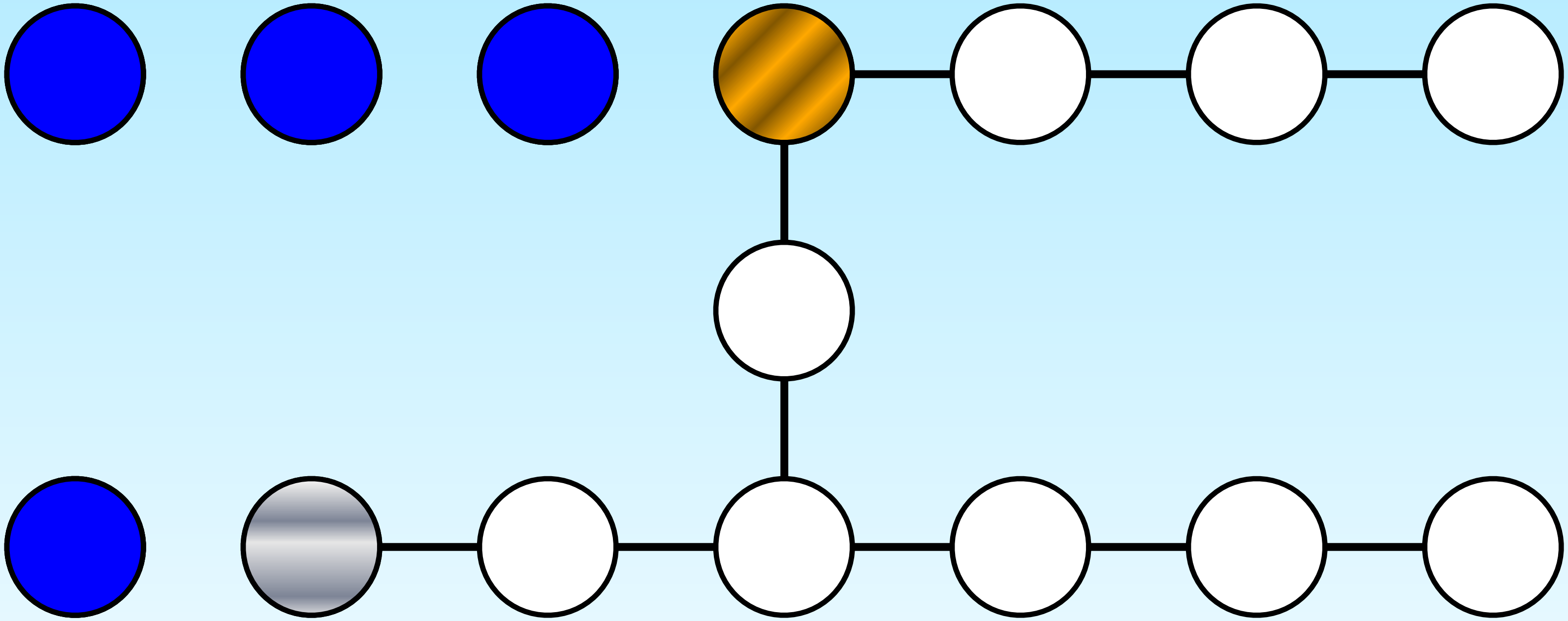
Teleportation Network



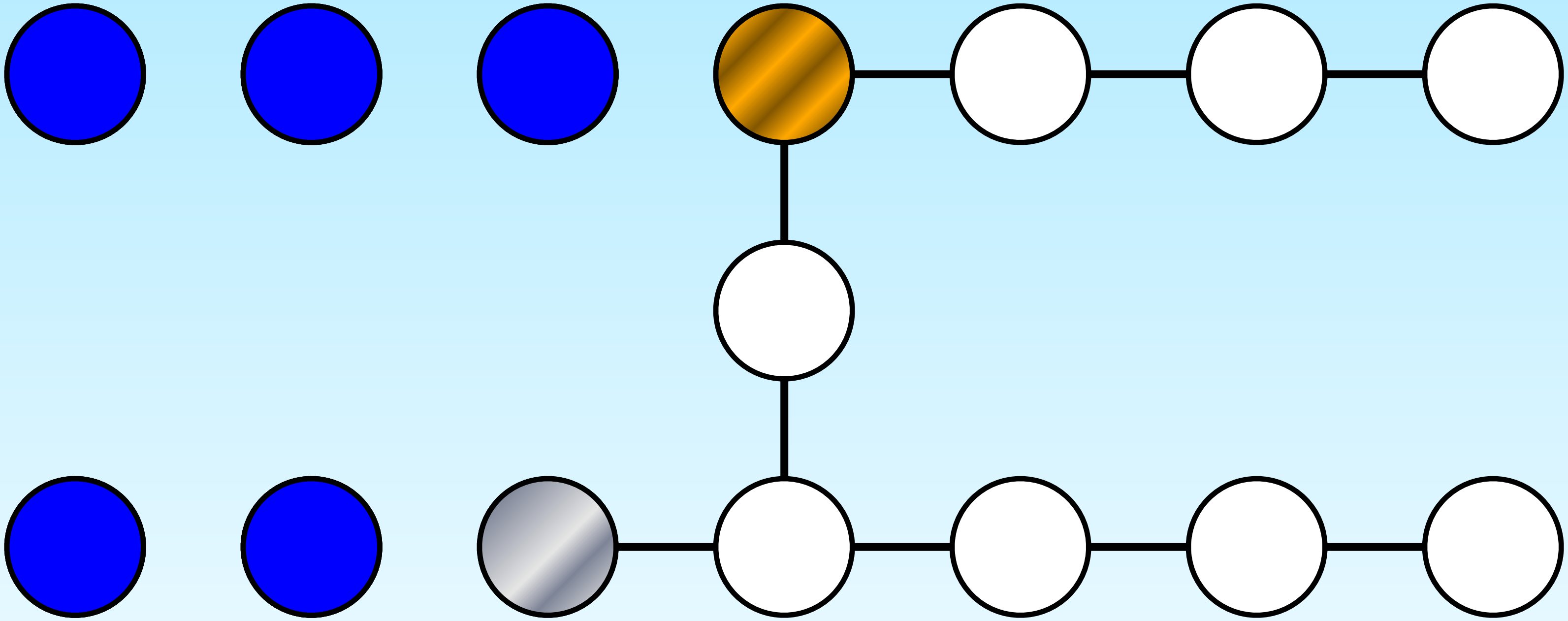
Teleportation Network



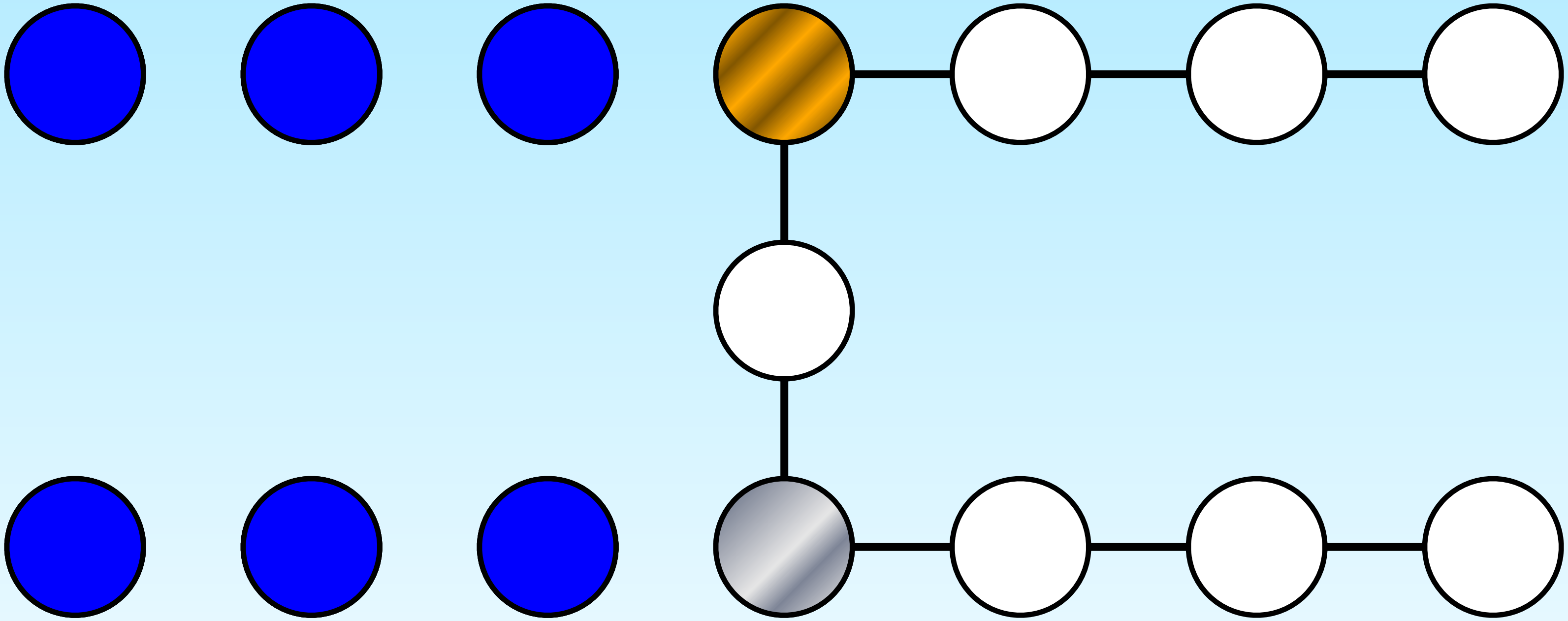
Teleportation Network



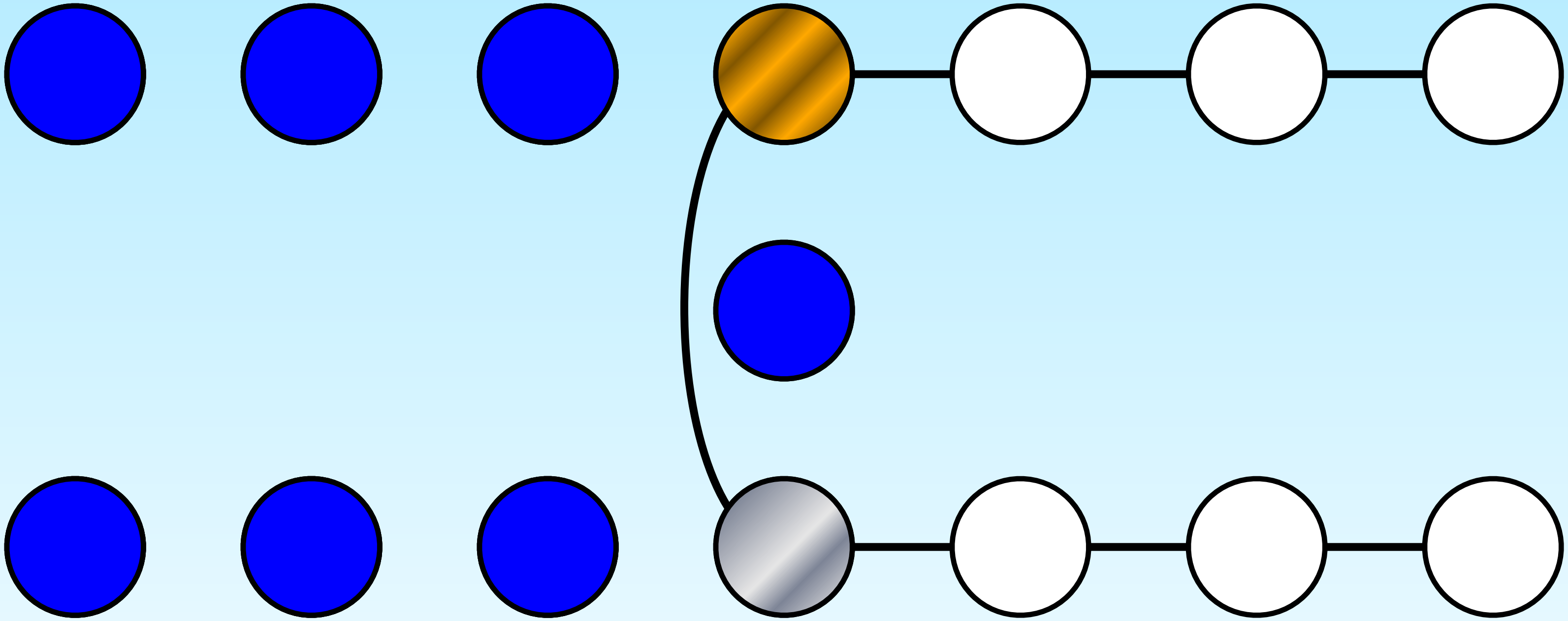
Teleportation Network



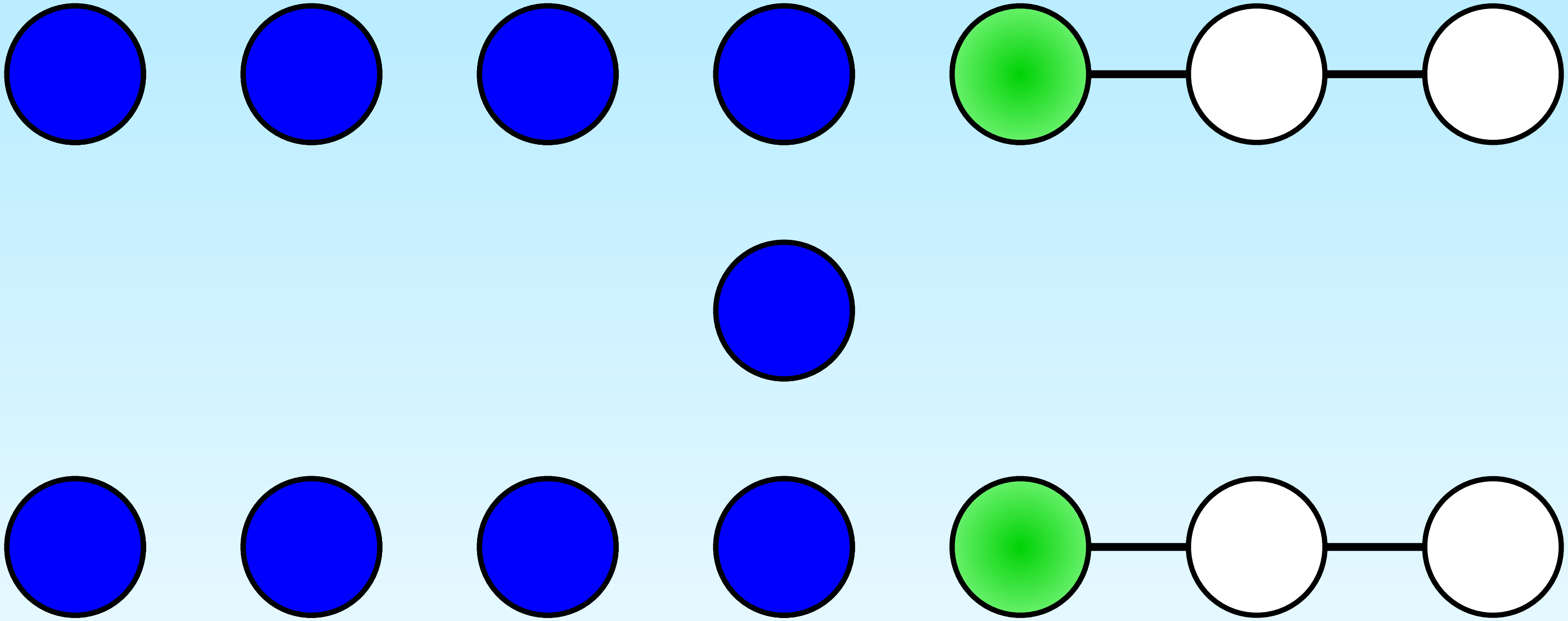
Teleportation Network



Teleportation Network

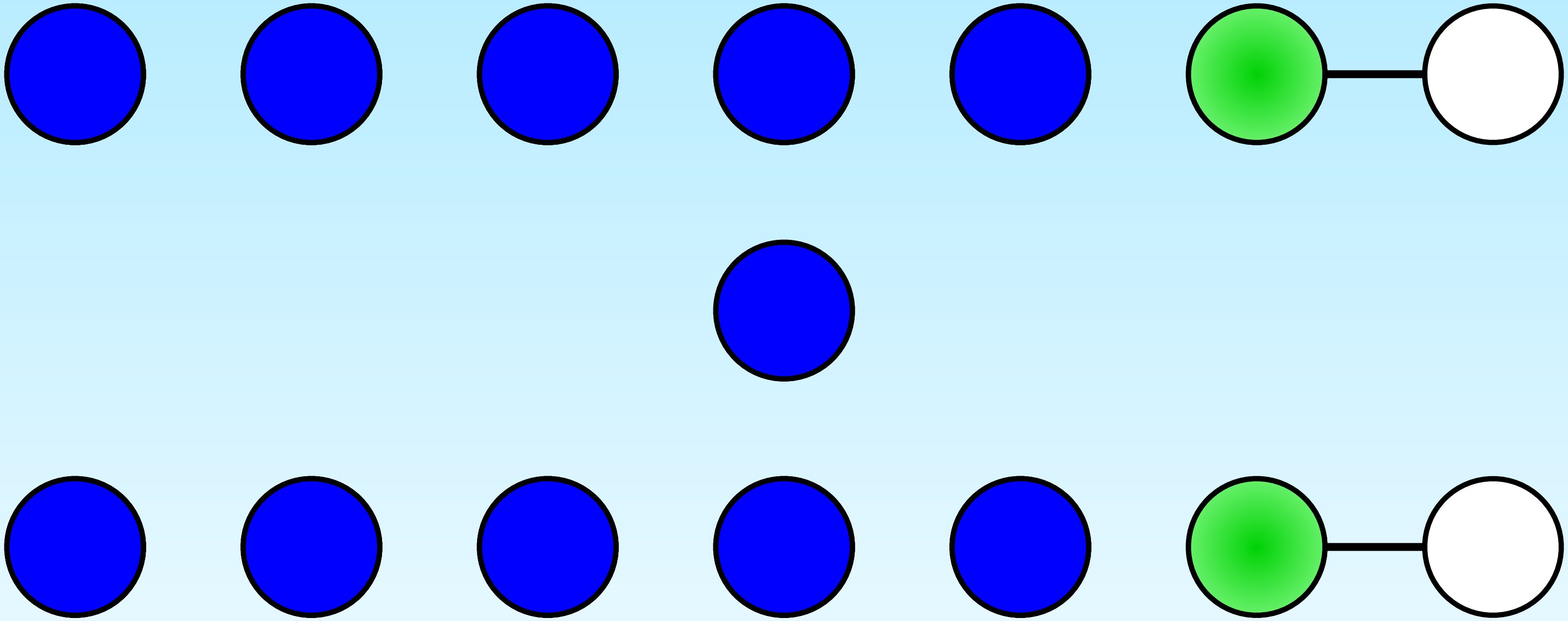


Teleportation Network

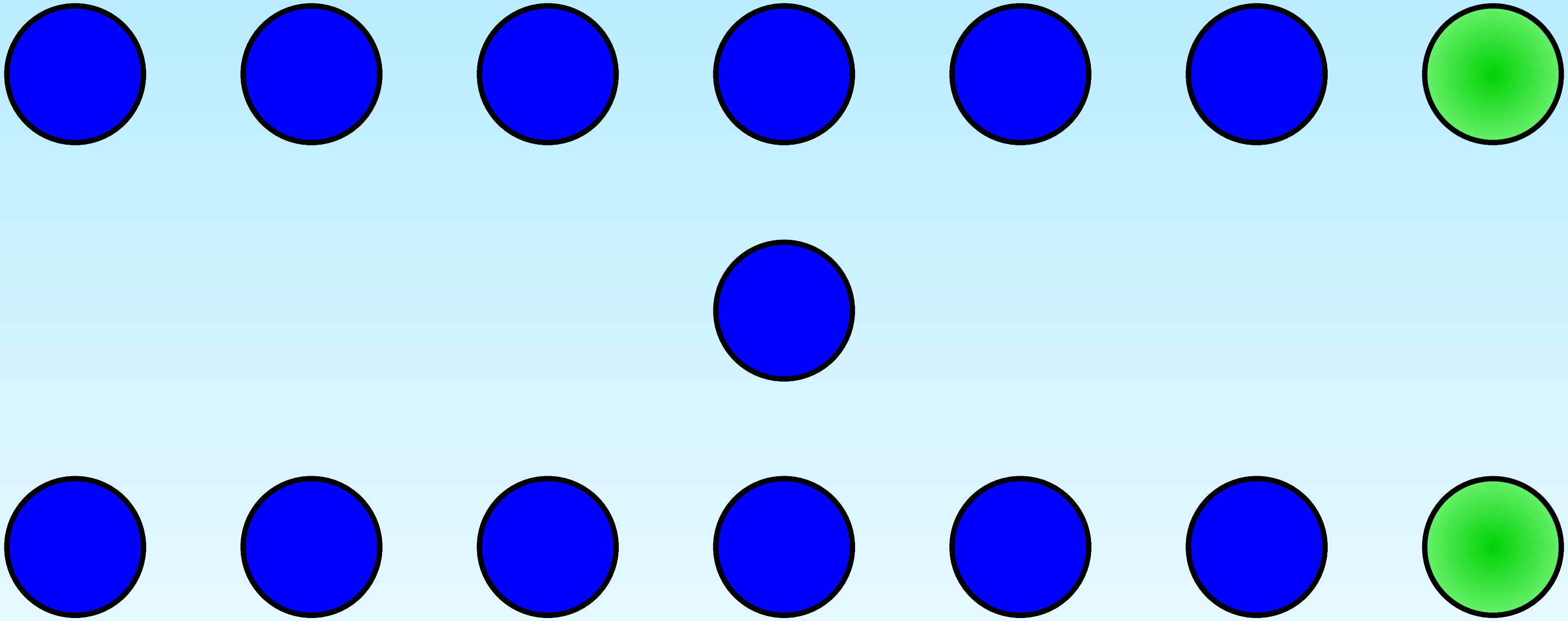


RMIT UNIVERSITY

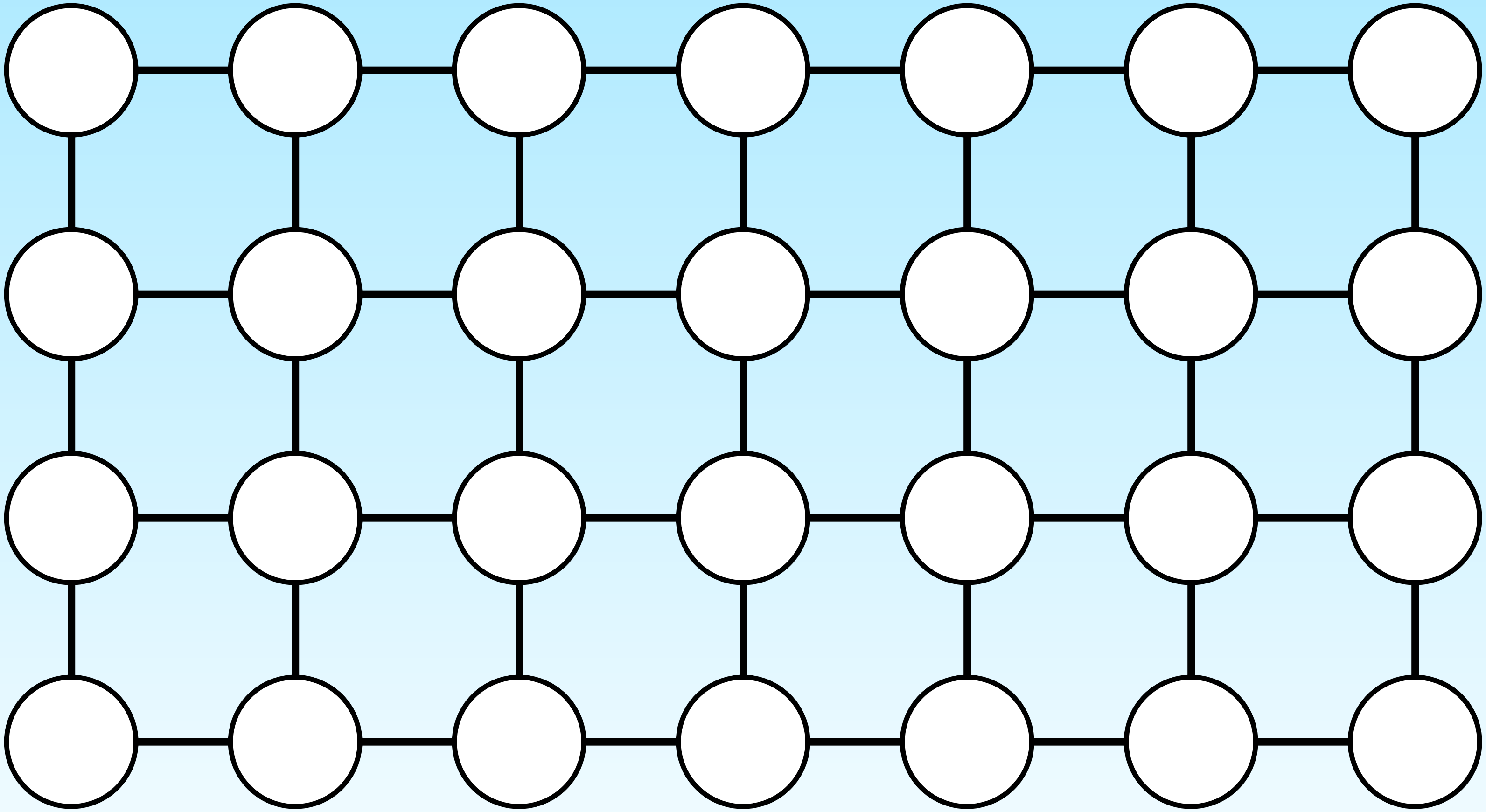
Teleportation Network



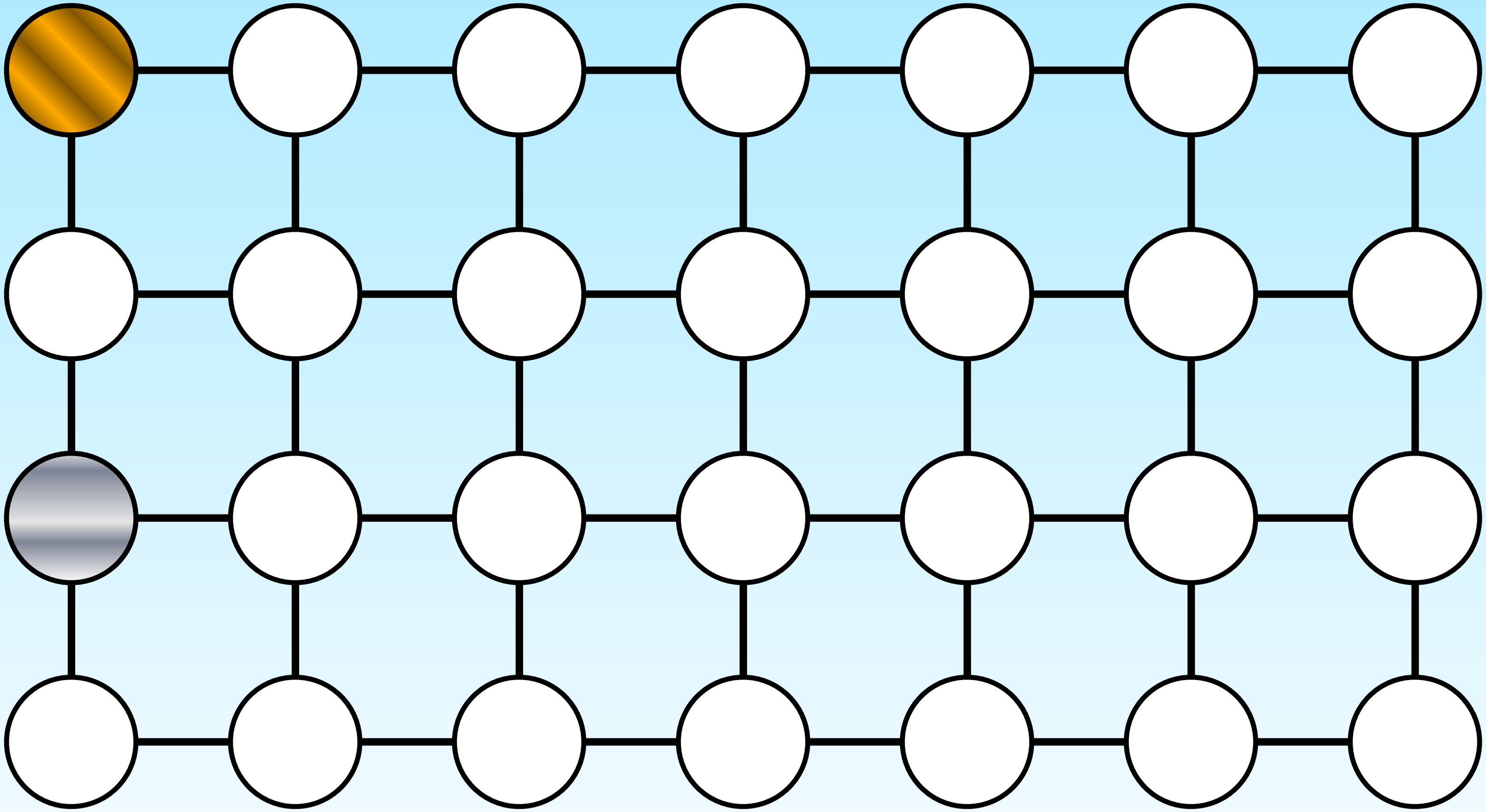
Teleportation Network



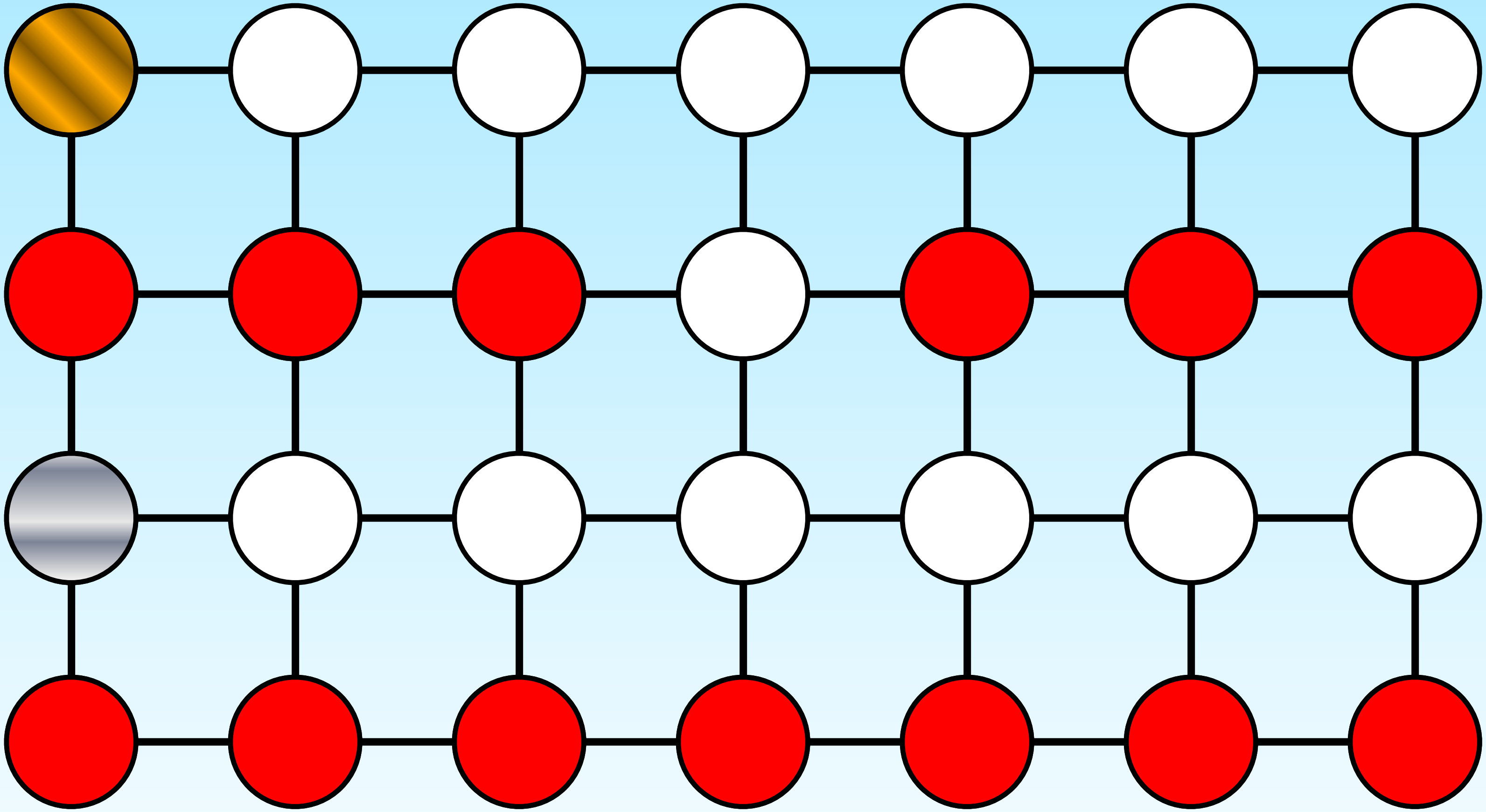
Cluster State



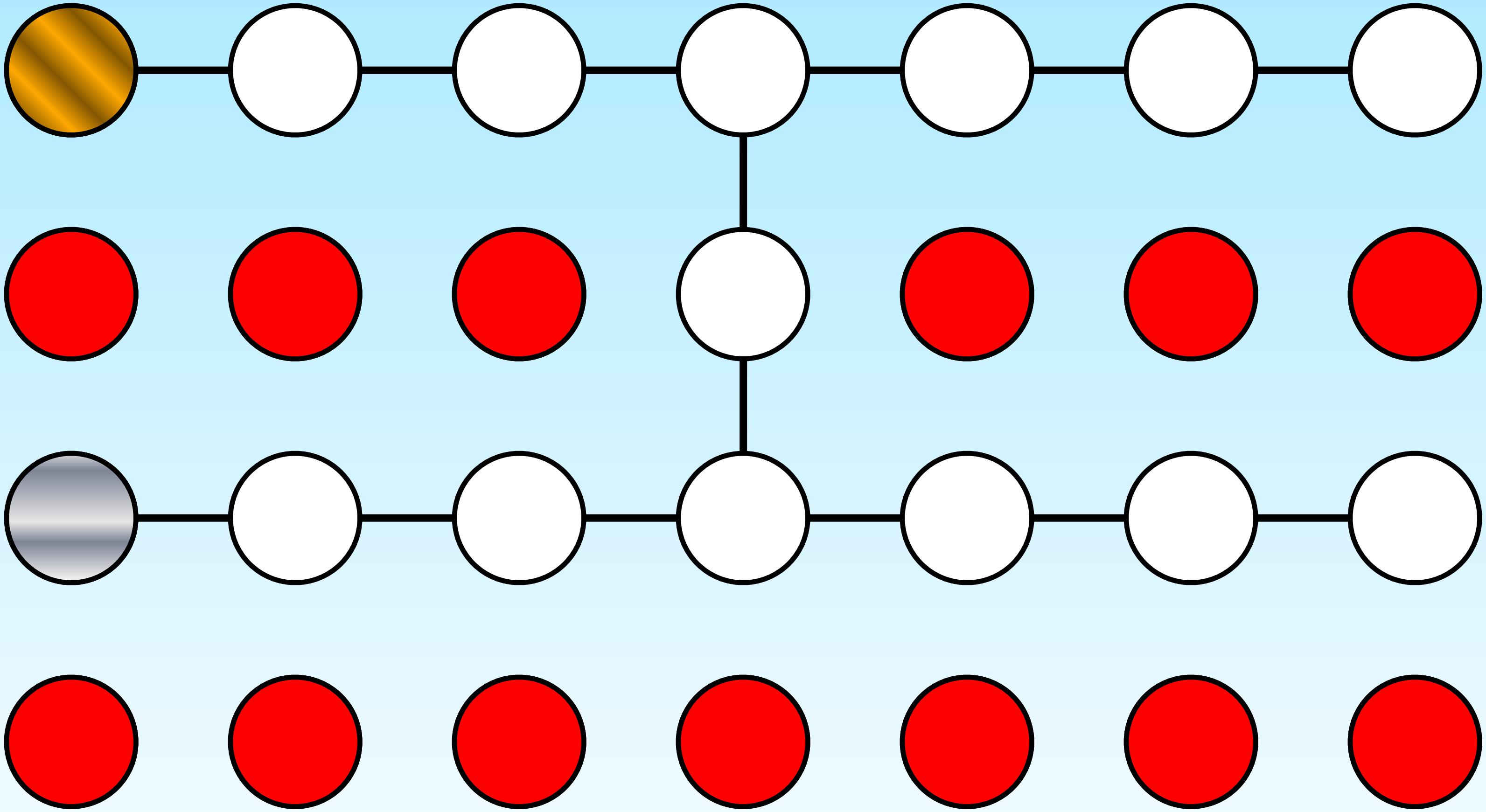
Cluster State



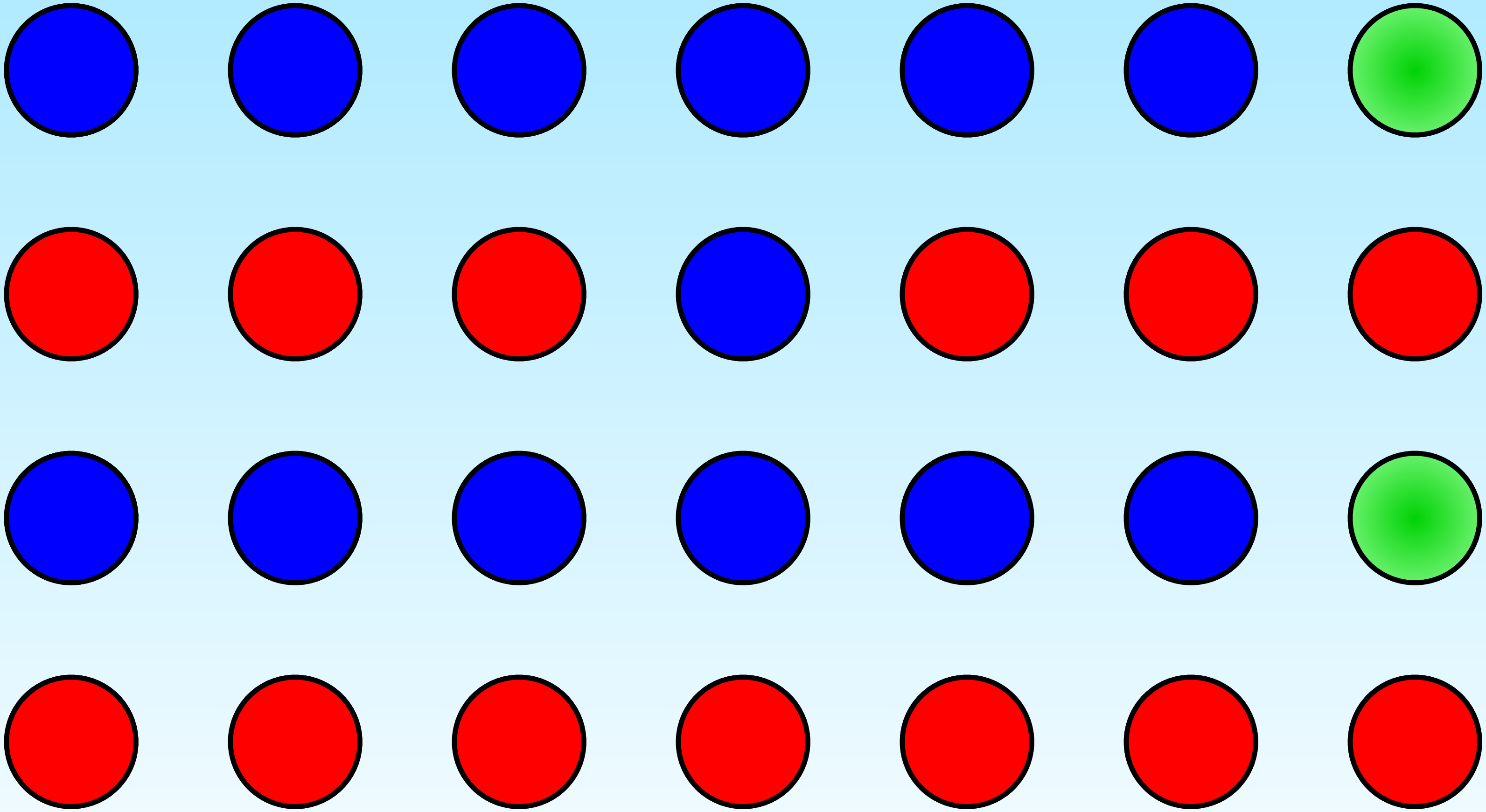
Cluster State



Cluster State



Cluster State



Cluster state

VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel

Theoretische Physik, Ludwig-Maximilians-Universität München, Germany

(Received 25 October 2000)

Cluster state

VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel
Theoretische Physik, Ludwig-Maximilians-Universität München, Germany
(Received 25 October 2000)

We present a scheme of quantum computation that consists entirely of one-qubit measurements on a particular class of entangled states, the cluster states. The measurements are used to imprint a quantum logic circuit on the state, thereby destroying its entanglement at the same time. Cluster states are thus one-way quantum computers and the measurements form the program.

Cluster state

VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel

Theoretische Physik, Ludwig-Maximilians-Universität München, Germany

(Received 25 October 2000)

We present a scheme of quantum computation that consists entirely of one-qubit measurements on a particular class of entangled states, the cluster states. The measurements are used to imprint a quantum logic circuit on the state, thereby destroying its entanglement at the same time. Cluster states are thus one-way quantum computers and the measurements form the program.

RMIT UNIVERSITY

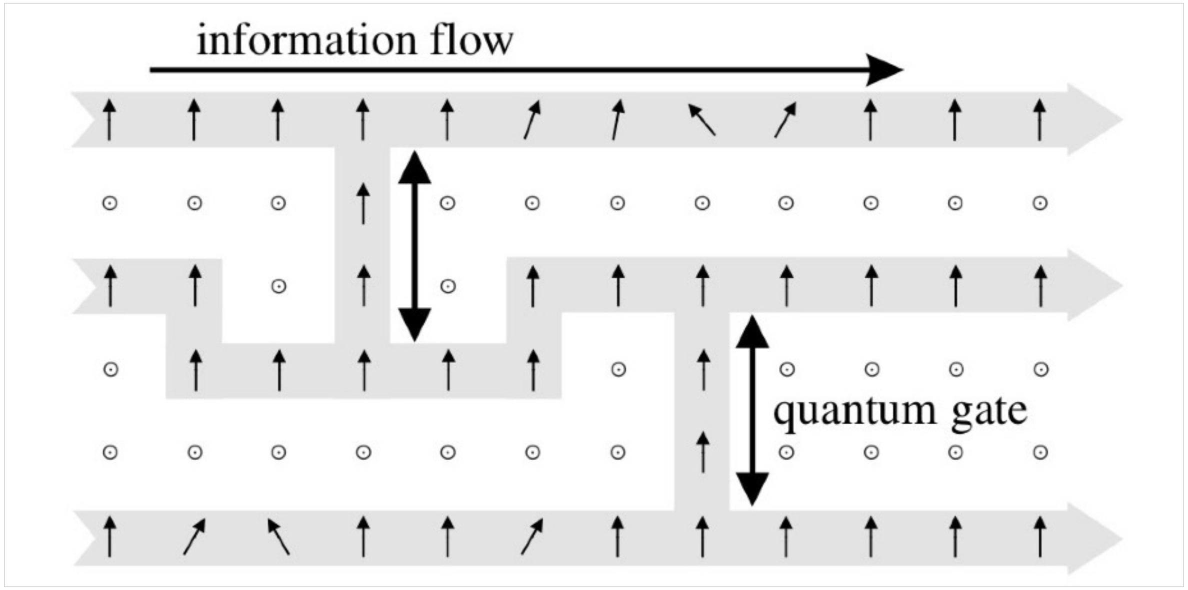
Cluster state

VOLUME 86, NUMBER 22 PHYSICAL REVIEW LETTERS 28 MAY 2001

A One-Way Quantum Computer

Robert Raussendorf and Hans J. Briegel
Theoretische Physik, Ludwig-Maximilians-Universität München, Germany
(Received 25 October 2000)

We present a scheme of quantum computation that consists entirely of one-qubit measurements on a particular class of entangled states, the cluster states. The measurements are used to imprint a quantum logic circuit on the state, thereby destroying its entanglement at the same time. Cluster states are thus one-way quantum computers and the measurements form the program.



RMIT UNIVERSITY

CV cluster states

CV cluster states

PHYSICAL REVIEW A **73**, 032318 (2006)

Continuous-variable Gaussian analog of cluster states

Jing Zhang[1,*] and Samuel L. Braunstein[2]
[1]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, People's Republic of China*
[2]*Computer Science, University of York, York YO10 5DD, United Kingdom*
(Received 21 October 2005; published 16 March 2006)

PRL **97,** 110501 (2006) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2006

Universal Quantum Computation with Continuous-Variable Cluster States

Nicolas C. Menicucci,[1,2,*] Peter van Loock,[3] Mile Gu,[1] Christian Weedbrook,[1] Timothy C. Ralph,[1] and Michael A. Nielsen[1]
[1]*Department of Physics, The University of Queensland, Brisbane, Queensland 4072, Australia*
[2]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[3]*National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan*
(Received 30 May 2006; published 13 September 2006)

RMIT UNIVERSITY

Optical implementation

Optical implementation

- Continuous quantum variables
  - Computational basis: eigenstates of $q = (a + a^\dagger)/\sqrt{2}$
  - Conjugate basis: eigenstates of $p = -i(a - a^\dagger)/\sqrt{2}$

Optical implementation

- Continuous quantum variables
  - Computational basis: eigenstates of $q = (a + a^\dagger)/\sqrt{2}$
  - Conjugate basis: eigenstates of $p = -i(a - a^\dagger)/\sqrt{2}$
- Advantages of CV (over qubit) cluster states
  - Deterministic generation
  - Scalable to huge sizes

RMIT UNIVERSITY

Optical implementation

- Continuous quantum variables
  - Computational basis: eigenstates of $q = (a + a^\dagger)/\sqrt{2}$
  - Conjugate basis: eigenstates of $p = -i(a - a^\dagger)/\sqrt{2}$
- Advantages of CV (over qubit) cluster states
  - Deterministic generation
  - Scalable to huge sizes
- Problem: ideal CV cluster states would require infinite energy!
  - Finite energy → errors ("noise") in computation
  - Fault tolerance still possible through quantum error correction

RMIT UNIVERSITY

Fault tolerance

Encoded qubits

PHYSICAL REVIEW A, VOLUME 64, 012310

Encoding a qubit in an oscillator

Daniel Gottesman,[1,2,*] Alexei Kitaev,[1,†] and John Preskill[3,‡]
[1]*Microsoft Corporation, One Microsoft Way, Redmond, Washington 98052*
[2]*Computer Science Division, EECS, University of California, Berkeley, California 94720*
[3]*Institute for Quantum Information, California Institute of Technology, Pasadena, California 91125*
(Received 9 August 2000; published 11 June 2001)

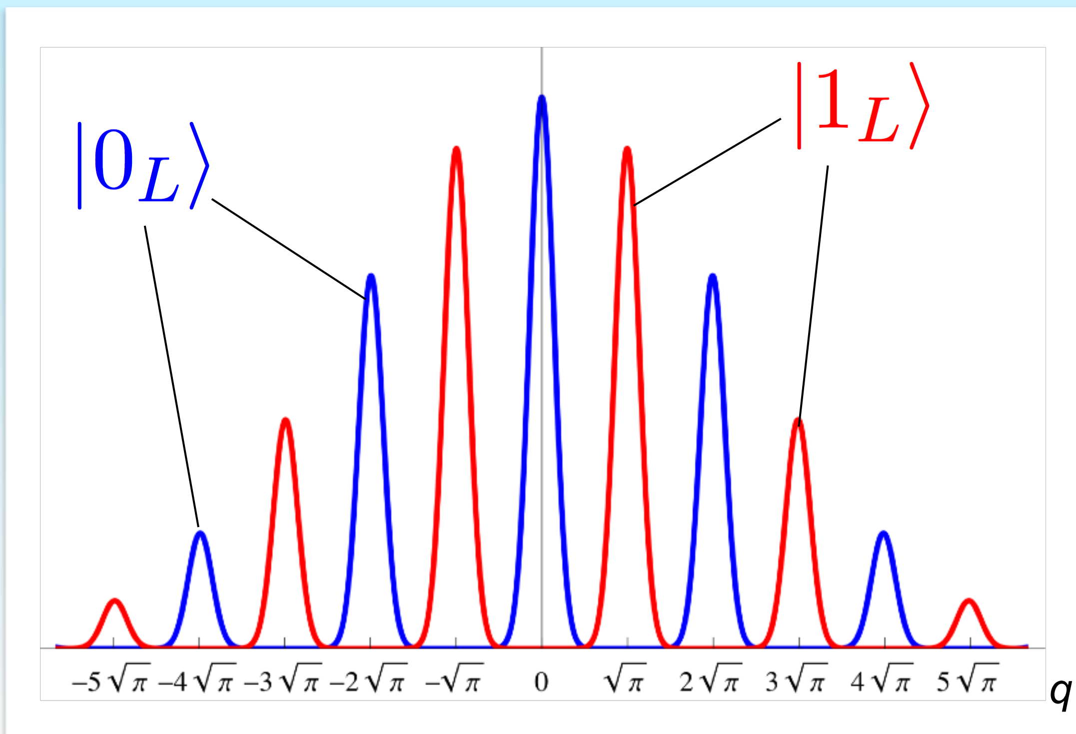
RMIT UNIVERSITY

Encoded qubits

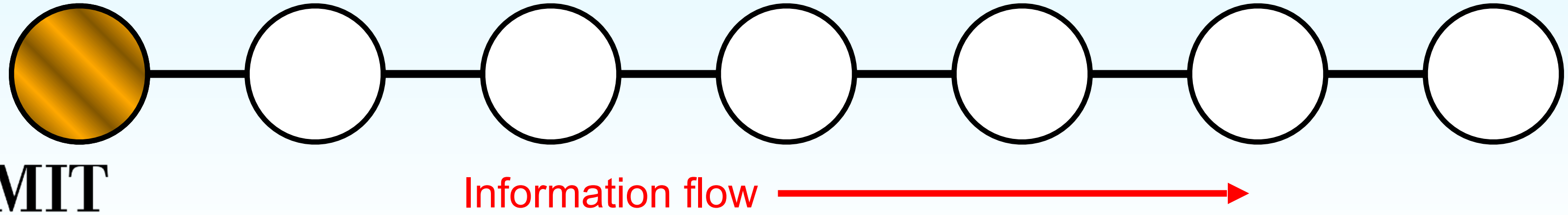
PHYSICAL REVIEW A, VOLUME 64, 012310

Encoding a qubit in an oscillator

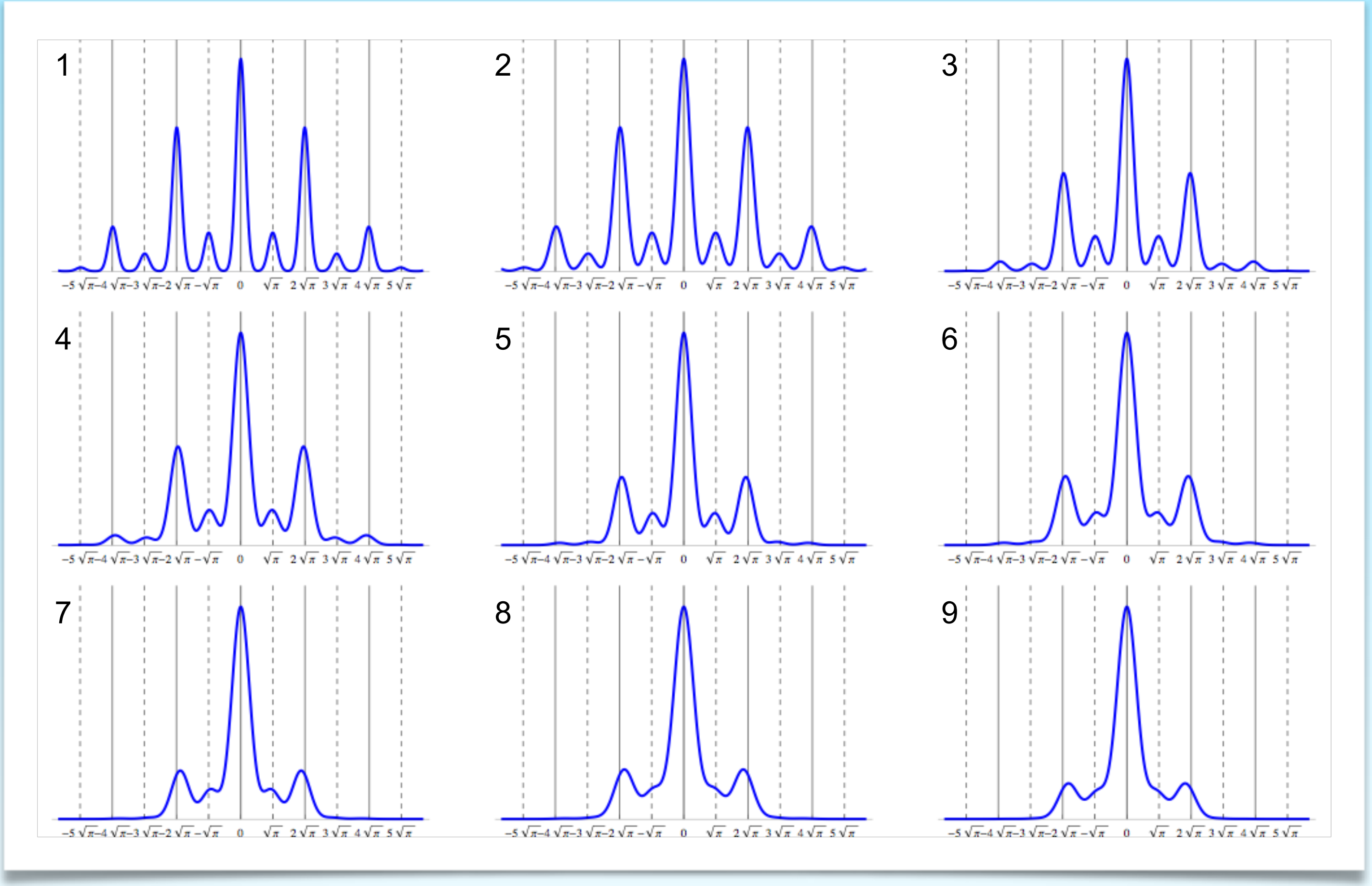
Daniel Gottesman,[1,2,*] Alexei Kitaev,[1,†] and John Preskill[3,‡]
[1]*Microsoft Corporation, One Microsoft Way, Redmond, Washington 98052*
[2]*Computer Science Division, EECS, University of California, Berkeley, California 94720*
[3]*Institute for Quantum Information, California Institute of Technology, Pasadena, California 91125*
(Received 9 August 2000; published 11 June 2001)

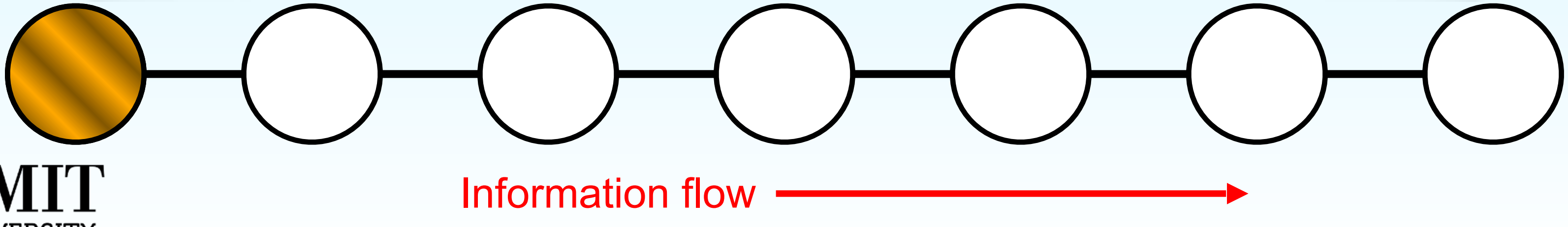


Noise process

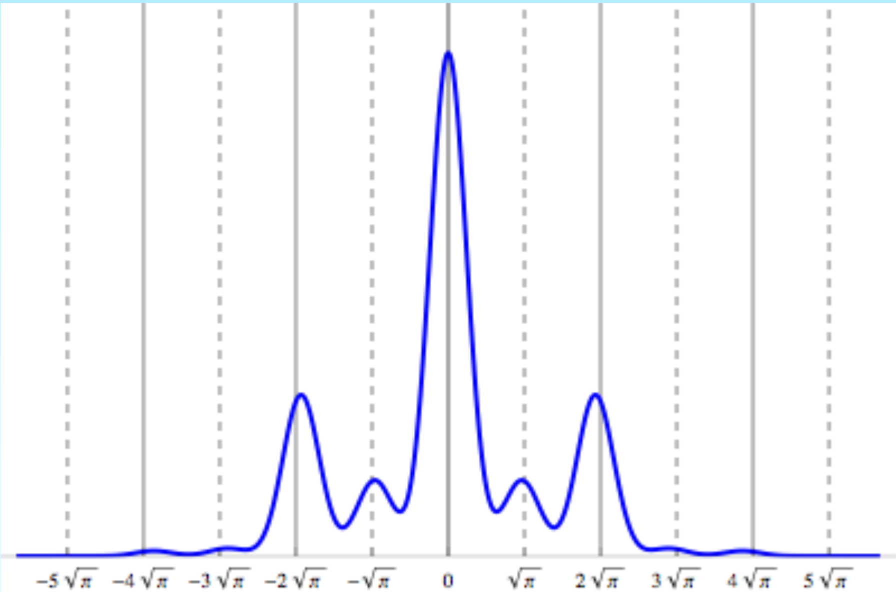


Noise process

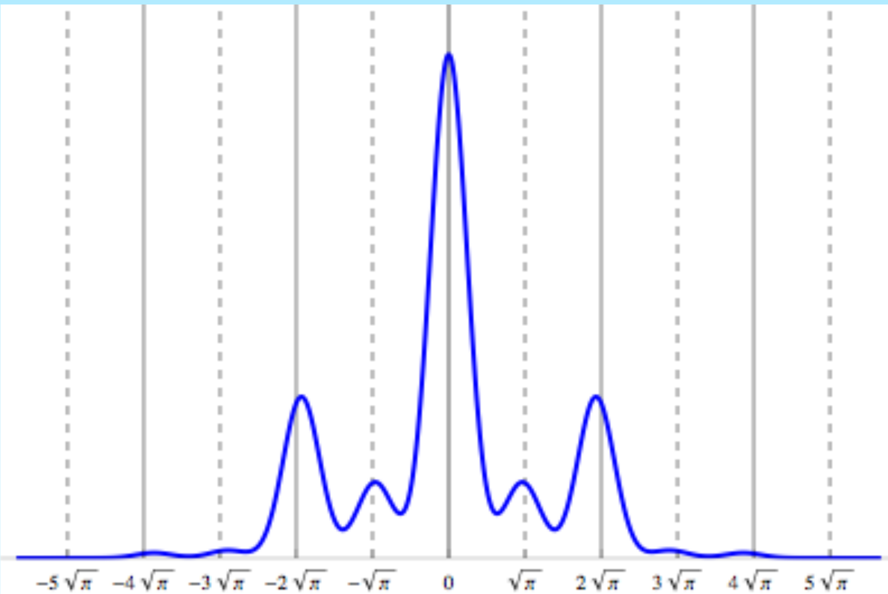


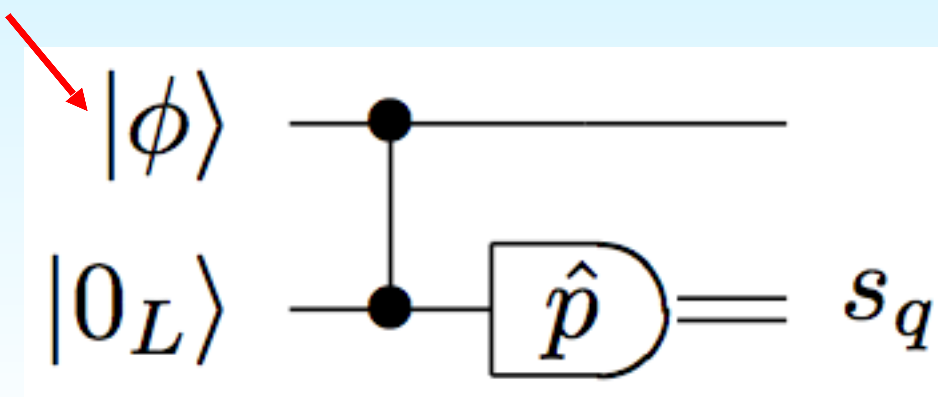


Projecting to qubit-level errors



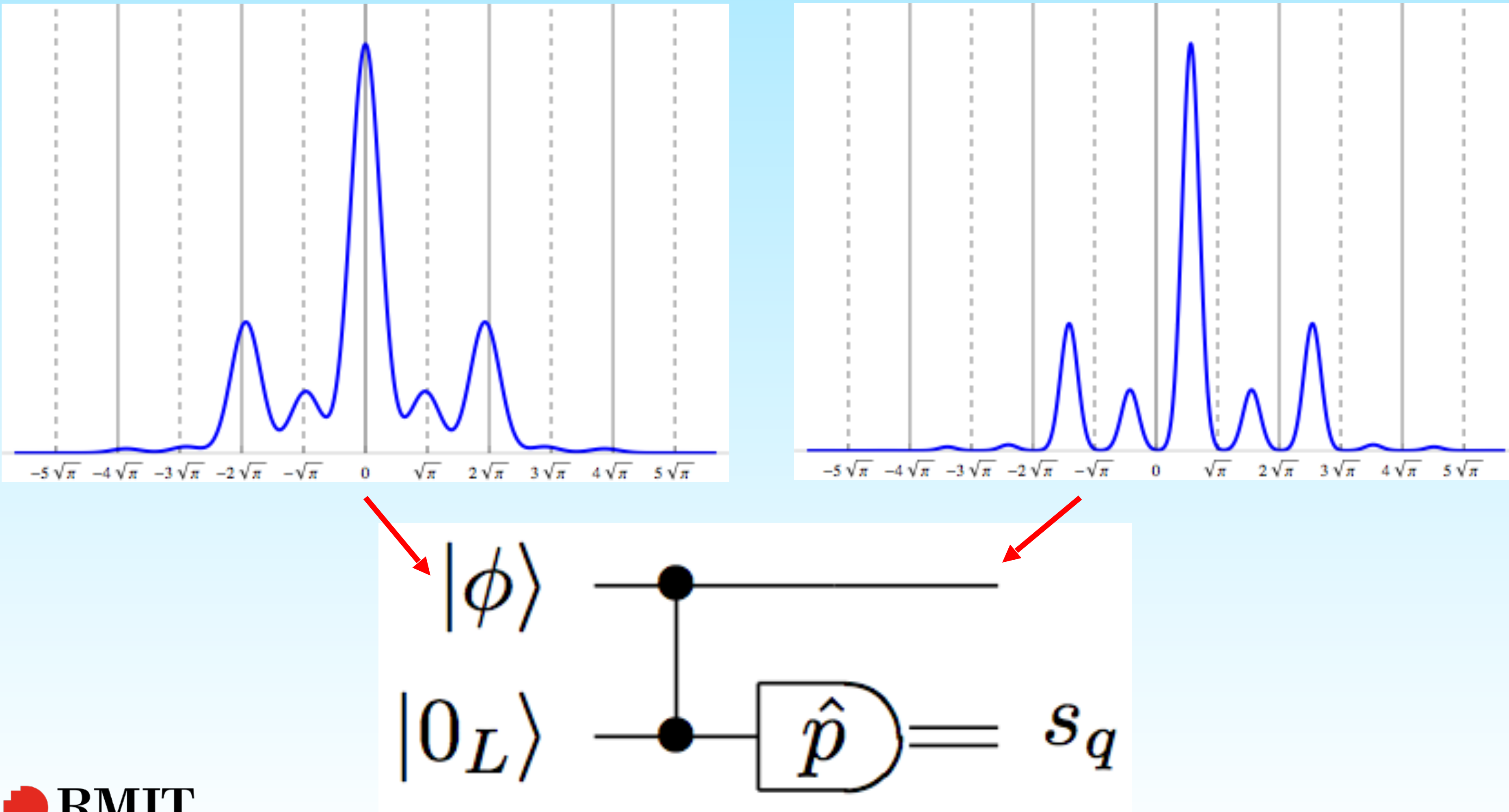
Projecting to qubit-level errors





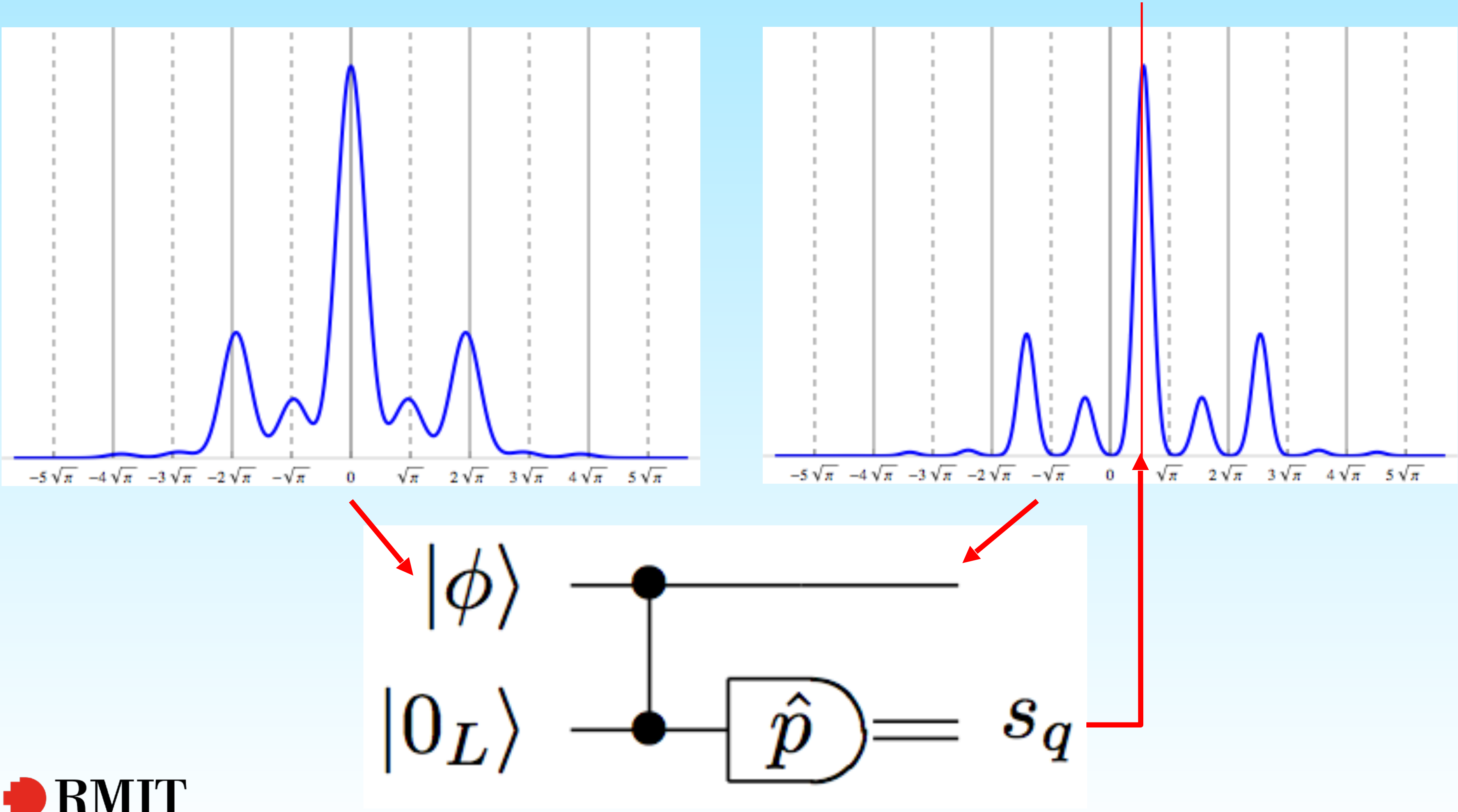
RMIT UNIVERSITY

Projecting to qubit-level errors

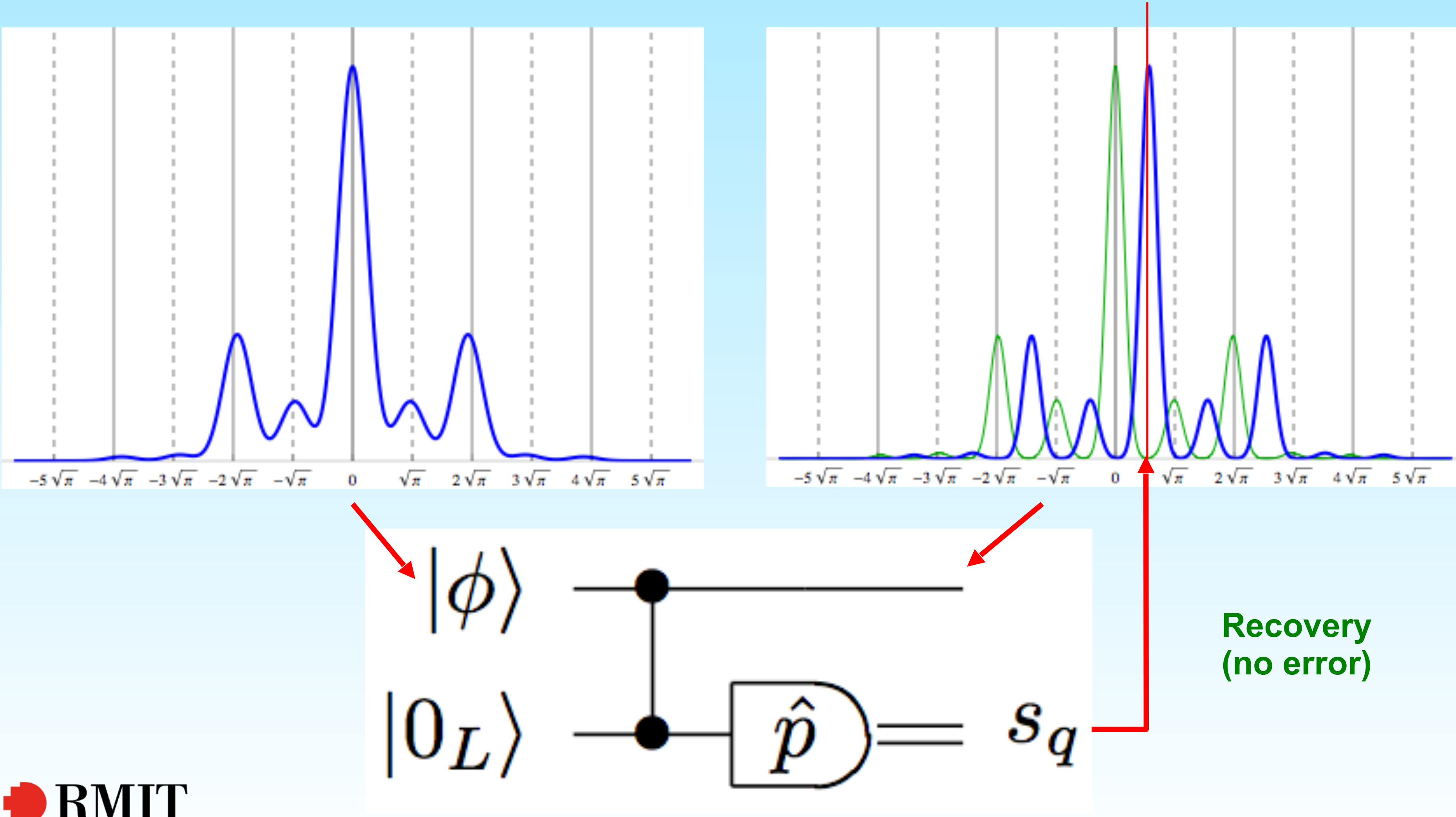


RMIT UNIVERSITY

Projecting to qubit-level errors

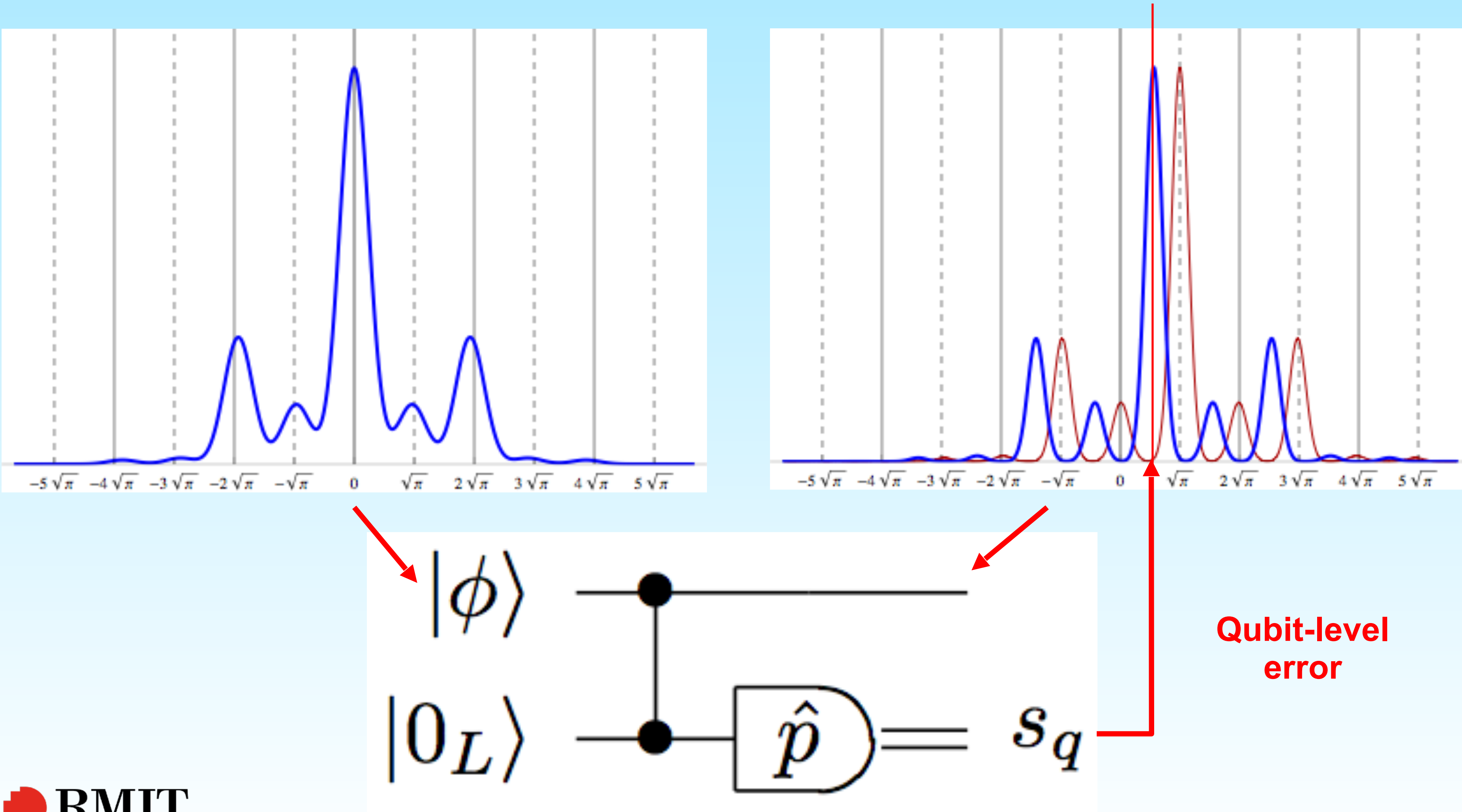


Projecting to qubit-level errors



Recovery (no error)

Projecting to qubit-level errors



Fault tolerance

- Measurements implement (slightly faulty) qubit gates
- Use qubit-level quantum error correction to reduce errors (well established)
- Fault tolerance
  (initial error < threshold amount) →
  (arbitrarily low error in final computation)

PRL **112,** 120504 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Fault-Tolerant Measurement-Based Quantum Computing with Continuous-Variable Cluster States

Nicolas C. Menicucci*
School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia
(Received 29 October 2013; published 26 March 2014)

RMIT UNIVERSITY

Fault tolerance – typical thresholds

PRL **112,** 120504 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Fault-Tolerant Measurement-Based Quantum Computing with Continuous-Variable Cluster States

Nicolas C. Menicucci*
School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia
(Received 29 October 2013; published 26 March 2014)

PRL **112**, 120504 (2014)

Fault tolerance – typical thresholds

PRL **112,** 120504 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Fault-Tolerant Measurement-Based Quantum Computing with Continuous-Variable Cluster States

Nicolas C. Menicucci*

School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia

(Received 29 October 2013; published 26 March 2014)

PRL **112**, 120504 (2014)

~15.6 – 20.5 dB

for qubit error rates 10^{-2} – 10^{-6}

(depends on qubit code employed)

RMIT UNIVERSITY

Fault tolerance – typical thresholds

PRL **112,** 120504 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Fault-Tolerant Measurement-Based Quantum Computing with Continuous-Variable Cluster States

Nicolas C. Menicucci*

School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia

(Received 29 October 2013; published 26 March 2014)

PRL **112**, 120504 (2014)

~15.6 – 20.5 dB

for qubit error rates 10^{-2} – 10^{-6}

(depends on qubit code employed)

PHYSICAL REVIEW X **8,** 021054 (2018)

High-Threshold Fault-Tolerant Quantum Computation with Analog Quantum Error Correction

Kosuke Fukui, Akihisa Tomita, and Atsushi Okamoto

Graduate School of Information Science and Technology, Hokkaido University, Kita14-Nishi9, Kita-ku, Sapporo 060-0814, Japan

Keisuke Fujii

Department of Physics, Graduate School of Science, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan

PRX **8**, 021054 (2018)

PRX QUANTUM **2,** 030325 (2021)

Fault-Tolerant Continuous-Variable Measurement-based Quantum Computation Architecture

Mikkel V. Larsen,[1,*] Christopher Chamberland,[2,3,‡] Kyungjoo Noh,[2,3,‡] Jonas S. Neergaard-Nielsen,[1] and Ulrik L. Andersen[1,†]

PRX Quantum **2**, 030325 (2021)

PHYSICAL REVIEW A **101**, 012316 (2020)

Editors' Suggestion

Fault-tolerant bosonic quantum error correction with the surface–Gottesman-Kitaev-Preskill code

Kyungjoo Noh[1,*] and Christopher Chamberland[2,†]

PRA **101**, 012316 (2020)

Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer

J. Eli Bourassa[1,2,*], Rafael N. Alexander[1,3,4,*], Michael Vasmer[5,6], Ashlesha Patil[1,7], Ilan Tzitrin[1,2], Takaya Matsuura[1,8], Daiqin Su[1], Ben Q. Baragiola[1,4], Saikat Guha[1,7], Guillaume Dauphinais[1], Krishna K. Sabapathy[1], Nicolas C. Menicucci[1,4], and Ish Dhand[1]

Quantum **5**, 392 (2021)

PRX QUANTUM **2,** 040353 (2021)

Fault-Tolerant Quantum Computation with Static Linear Optics

Ilan Tzitrin,[1,2,*,†] Takaya Matsuura,[1,3,†] Rafael N. Alexander,[1,4,5,†] Guillaume Dauphinais,[1] J. Eli Bourassa,[1,2] Krishna K. Sabapathy,[1] Nicolas C. Menicucci,[1,4] and Ish Dhand[1]

PRX Quantum **2**, 040353 (2021)

~10 – 18 dB

based on topological codes

RMIT UNIVERSITY

Why GKP?

GKP vs photonic qubits

	Photonic	GKP	General CV
1-system Clifford	passive	Gaussian	Gaussian
2-system Clifford	postselect (?)	Gaussian	Gaussian
1-system non-Clifford	passive	non-Gaussian	non-Gaussian
Preparation	SPDC, dots, rare-earth, etc	squeezed multi-cat state	?
Measurement	avalanche photodiode	homodyne	?

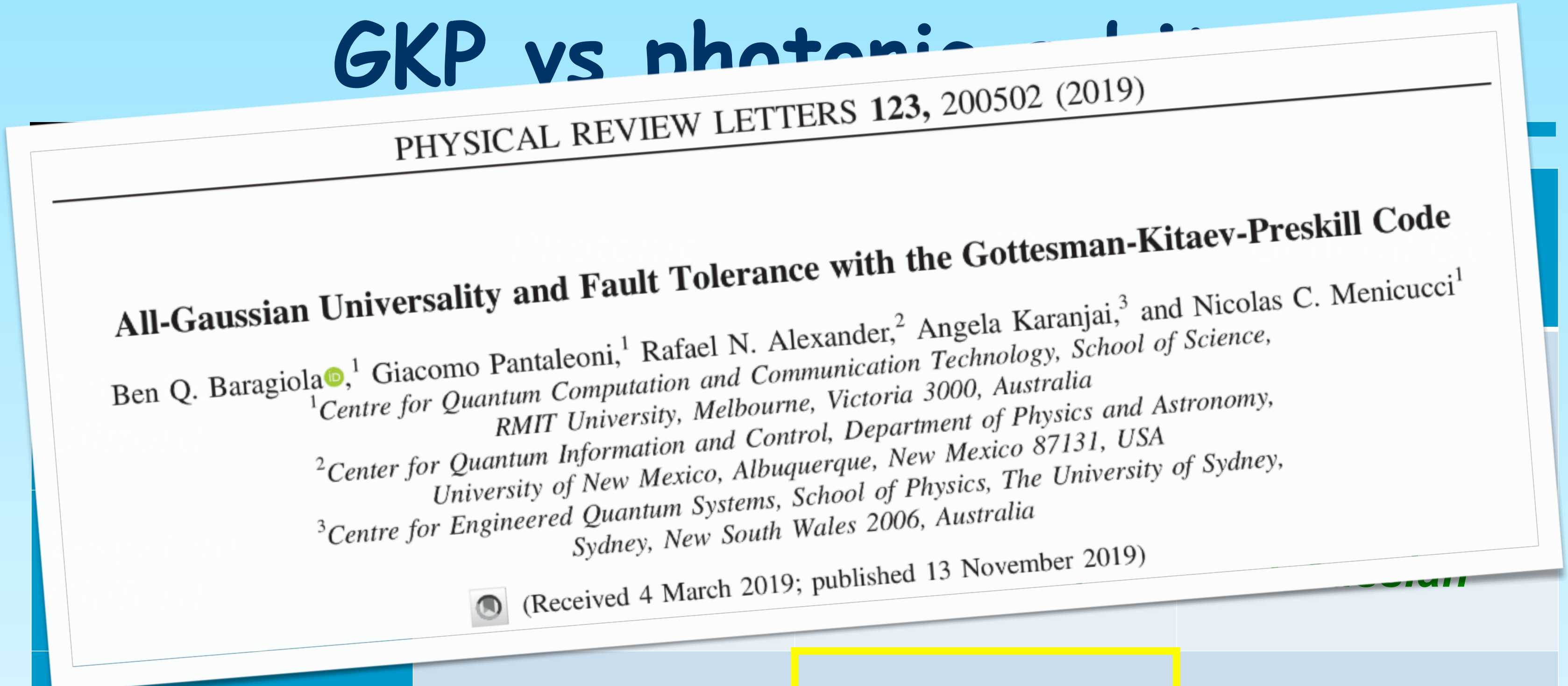
RMIT UNIVERSITY

GKP vs photonic qubits

	Photonic	GKP	General CV
1-system Clifford	passive	Gaussian	Gaussian
2-system Clifford	postselect (?)	Gaussian	Gaussian
1-system non-Clifford	passive	non-Gaussian	non-Gaussian
Preparation	SPDC, dots, rare-earth, etc	squeezed multi-cat state	?
Measurement	avalanche photodiode	homodyne	?

RMIT UNIVERSITY

GKP vs photonic



PHYSICAL REVIEW LETTERS **123**, 200502 (2019)

All-Gaussian Universality and Fault Tolerance with the Gottesman-Kitaev-Preskill Code

Ben Q. Baragiola,[1] Giacomo Pantaleoni,[1] Rafael N. Alexander,[2] Angela Karanjai,[3] and Nicolas C. Menicucci[1]
[1]*Centre for Quantum Computation and Communication Technology, School of Science, RMIT University, Melbourne, Victoria 3000, Australia*
[2]*Center for Quantum Information and Control, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA*
[3]*Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*

(Received 4 March 2019; published 13 November 2019)

1-system non-Clifford	passive	non-Gaussian	non-Gaussian
Preparation	SPDC, dots, rare-earth, etc	squeezed multi-cat state	?
Measurement	avalanche photodiode	homodyne	?

RMIT UNIVERSITY

GKP vs photonic

PHYSICAL REVIEW LETTERS **123,** 200502 (2019)

All-Gaussian Universality and Fault Tolerance with the Gottesman-Kitaev-Preskill Code

Ben Q. Baragiola,[1] Giacomo Pantaleoni,[1] Rafael N. Alexander,[2] Angela Karanjai,[3] and Nicolas C. Menicucci[1]

[1]*Centre for Quantum Computation and Communication Technology, School of Science, RMIT University, Melbourne, Victoria 3000, Australia*

[2]*Center for Quantum Information and Control, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA*

[3]*Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*

(Received 4 March 2019; published 13 November 2019)

1-system non-Clifford	passive	Gaussian (new!)	non-Gaussian
Preparation	SPDC, dots, rare-earth, etc	squeezed multi-cat state	?
Measurement	avalanche photodiode	homodyne	?

RMIT UNIVERSITY

GKP vs photoni

PHYSICAL REVIEW LETTERS **123**, 200502 (2019)

All-Gaussian Universality and Fault Tolerance with the Gottesman-Kitaev-Preskill Code

Ben Q. Baragiola,[1] Giacomo Pantaleoni,[1] Rafael N. Alexander,[2] Angela Karanjai,[3] and Nicolas C. Menicucci[1]

[1]*Centre for Quantum Computation and Communication Technology, School of Science, RMIT University, Melbourne, Victoria 3000, Australia*

[2]*Center for Quantum Information and Control, Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico 87131, USA*

[3]*Centre for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*

(Received 4 March 2019; published 13 November 2019)

PHYSICAL REVIEW RESEARCH **2**, 023270 (2020)

Cost-reduced all-Gaussian universality with the Gottesman-Kitaev-Preskill code: Resource-theoretic approach to cost analysis

Hayata Yamasaki,[1,*] Takaya Matsuura,[2,†] and Masato Koashi[2,1,‡]

[1]*Photon Science Center, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

[2]*Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

(Received 12 December 2019; revised manuscript received 8 March 2020; accepted 30 April 2020; published 2 June 2020)

GKP vs photonic qubits

	Photonic	GKP	General CV
1-system Clifford	passive	Gaussian	Gaussian
2-system Clifford	postselect (?)	Gaussian	Gaussian
1-system non-Clifford	passive	Gaussian (new!)	non-Gaussian
Preparation	SPDC, dots, rare-earth, etc	squeezed multi-cat state	?
Measurement	avalanche photodiode	homodyne	?

RMIT UNIVERSITY

Experimental GKP states

Encoding a qubit in a trapped-ion mechanical oscillator

C. Flühmann[1]*, T. L. Nguyen[1], M. Marinelli[1], V. Negnevitsky[1], K. Mehta[1] & J. P. Home[1]*

Nature **566**, 513–517(2019)

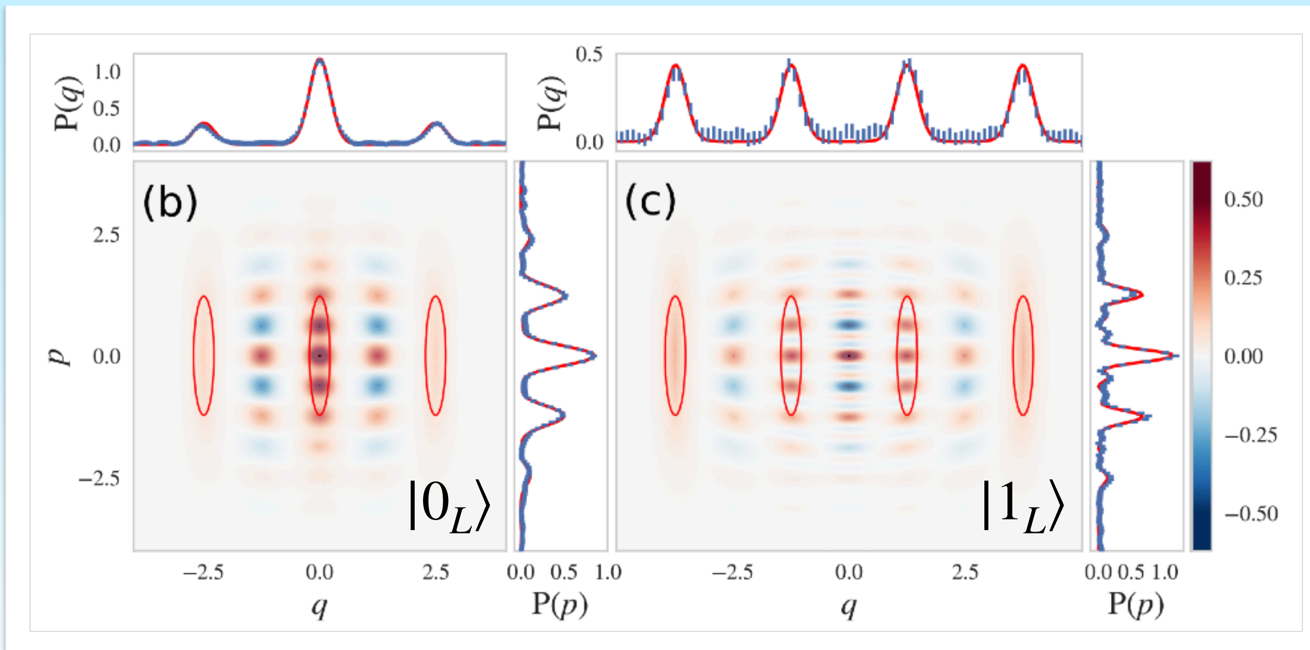
RMIT UNIVERSITY

Experimental GKP states

Encoding a qubit in a trapped-ion mechanical oscillator

C. Flühmann[1]*, T. L. Nguyen[1], M. Marinelli[1], V. Negnevitsky[1], K. Mehta[1] & J. P. Home[1]*

Nature **566**, 513–517(2019)



Experimental GKP states

Article | Published: 19 August 2020

Quantum error correction of a qubit encoded in grid states of an oscillator

P. Campagne-Ibarcq, A. Eickbusch, S. Touzard, E. Zalys-Geller, N. E. Frattini, V. V. Sivak, P. Reinhold, S. Puri, S. Shankar, R. J. Schoelkopf, L. Frunzio, M. Mirrahimi & M. H. Devoret

Nature **584**, 368–372(2020) | Cite this article

RMIT UNIVERSITY

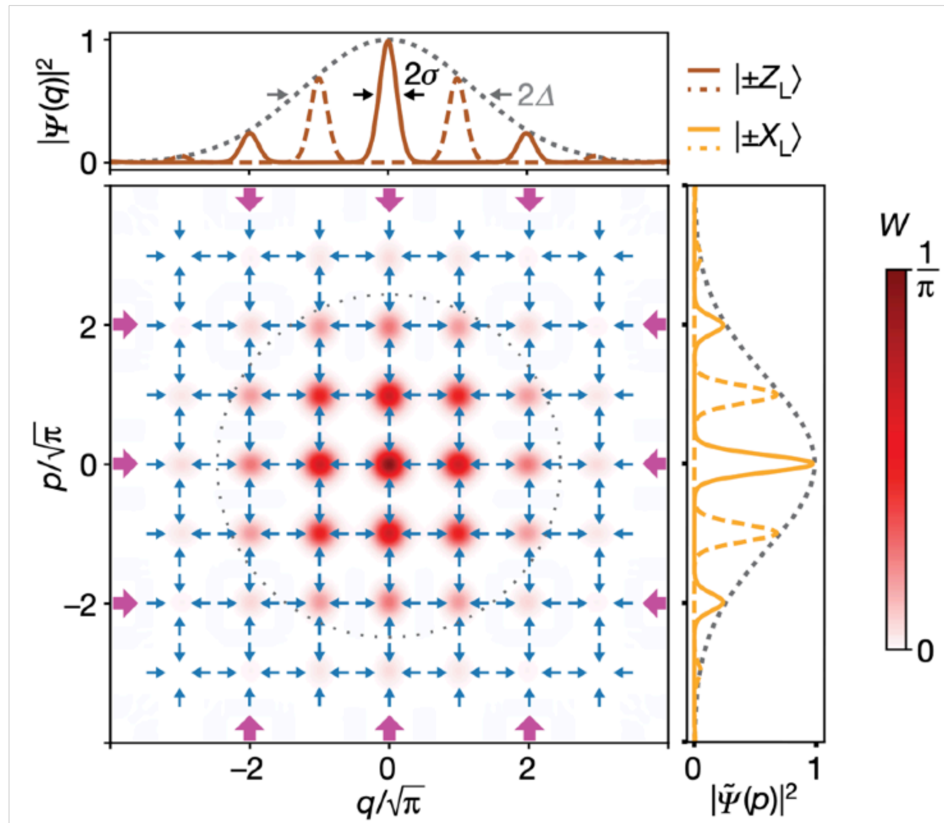
Experimental GKP states

Article | Published: 19 August 2020

Quantum error correction of a qubit encoded in grid states of an oscillator

P. Campagne-Ibarcq, A. Eickbusch, S. Touzard, E. Zalys-Geller, N. E. Frattini, V. V. Sivak, P. Reinhold, S. Puri, S. Shankar, R. J. Schoelkopf, L. Frunzio, M. Mirrahimi & M. H. Devoret

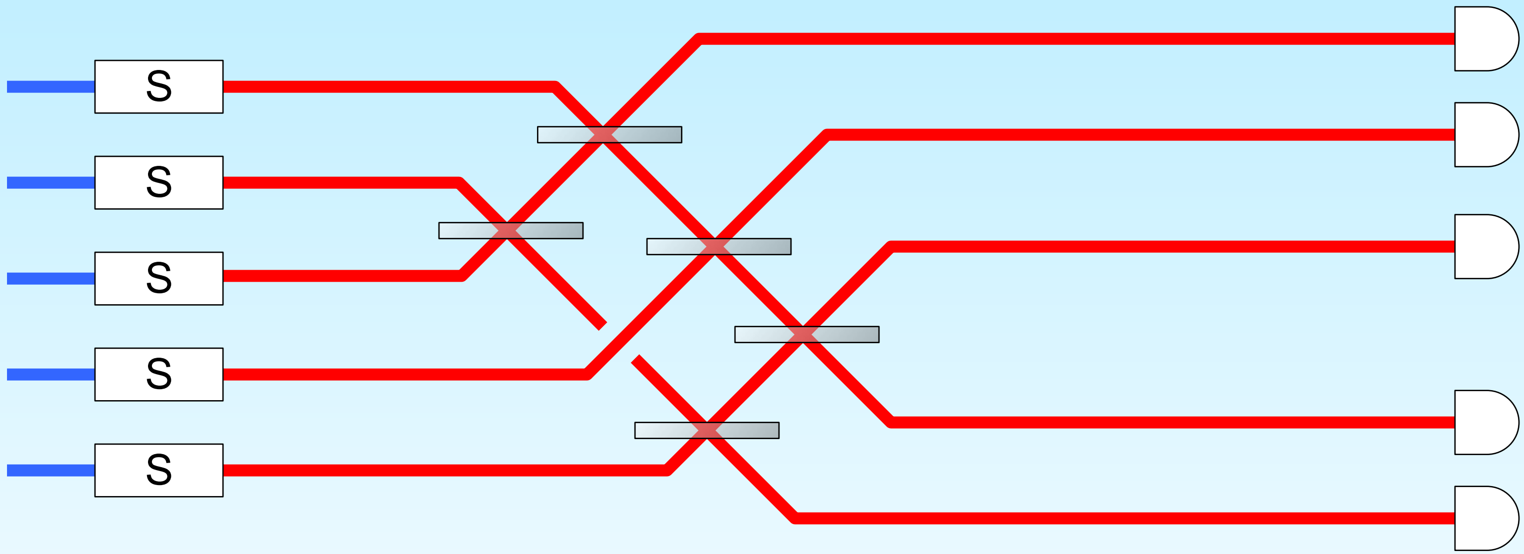
Nature **584**, 368–372(2020) | Cite this article



Making CV cluster states

Linear optics

- Squeezed light (laser on a nonlinear crystal) + beamsplitter network



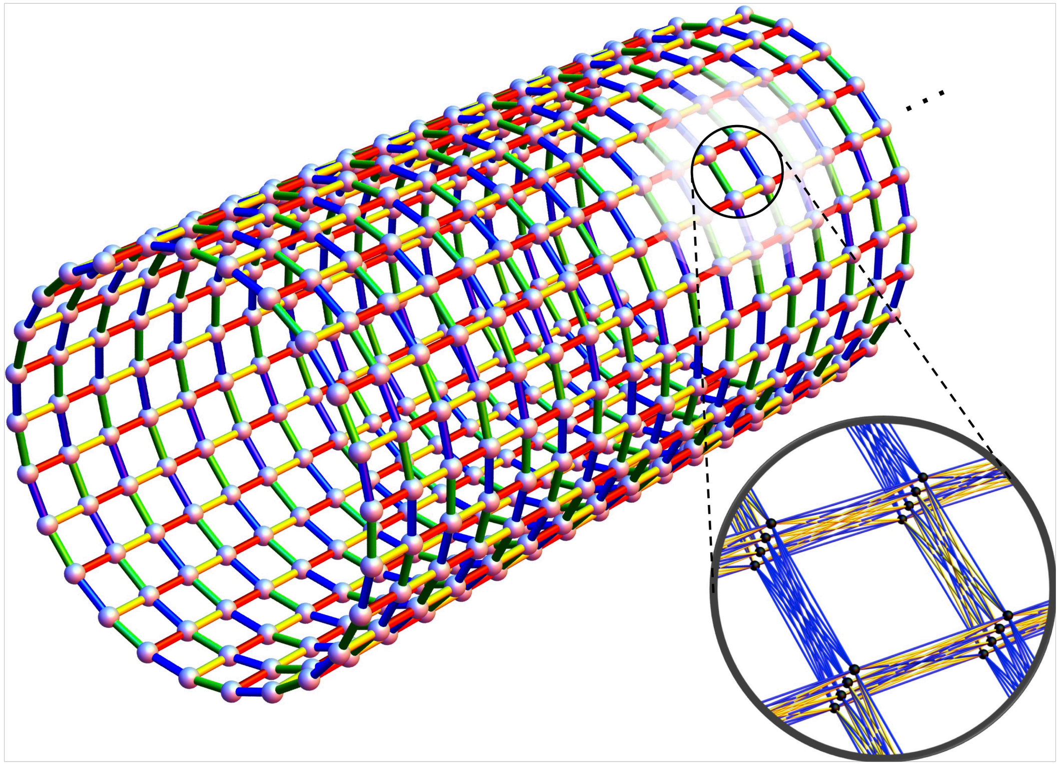
RMIT UNIVERSITY

* P. van Loock, C. Weedbrook, M. Gu, PRA **76**, 032321 (2007)

How can we make scalable resource states?

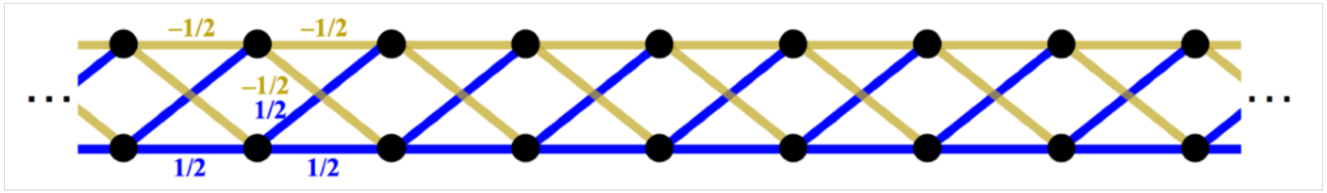
RMIT UNIVERSITY

Macronode-based cluster states



Each black dot (node) represents either
(1) a specific colour or
(2) a pulse of light

Edges represent entanglement



RMIT UNIVERSITY

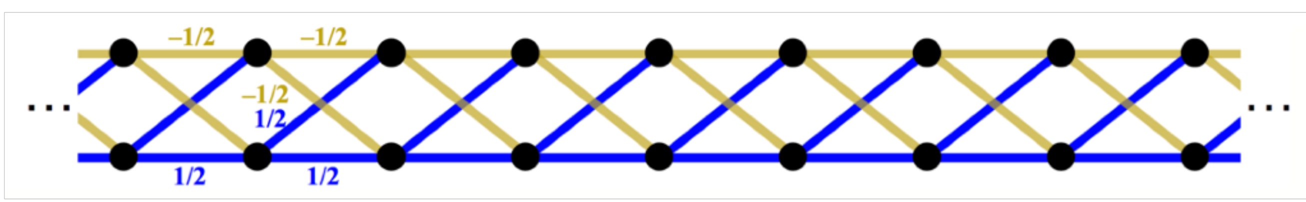
Frequency-mode (colour-based) cluster states

Frequency-mode cluster states

PRL **112,** 120505 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Experimental Realization of Multipartite Entanglement of 60 Modes of a Quantum Optical Frequency Comb

Moran Chen,[1] Nicolas C. Menicucci,[2,*] and Olivier Pfister[1,†]
[1]*Department of Physics, University of Virginia, Charlottesville, Virginia 22903, USA*
[2]*School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*
(Received 11 November 2013; revised manuscript received 31 January 2014; published 26 March 2014)



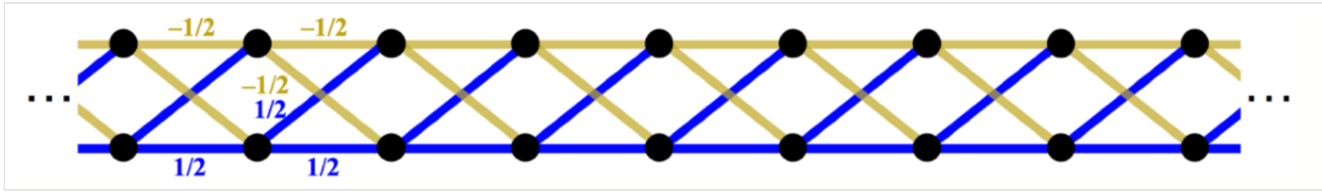
Frequency-mode cluster states

PRL **112,** 120505 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

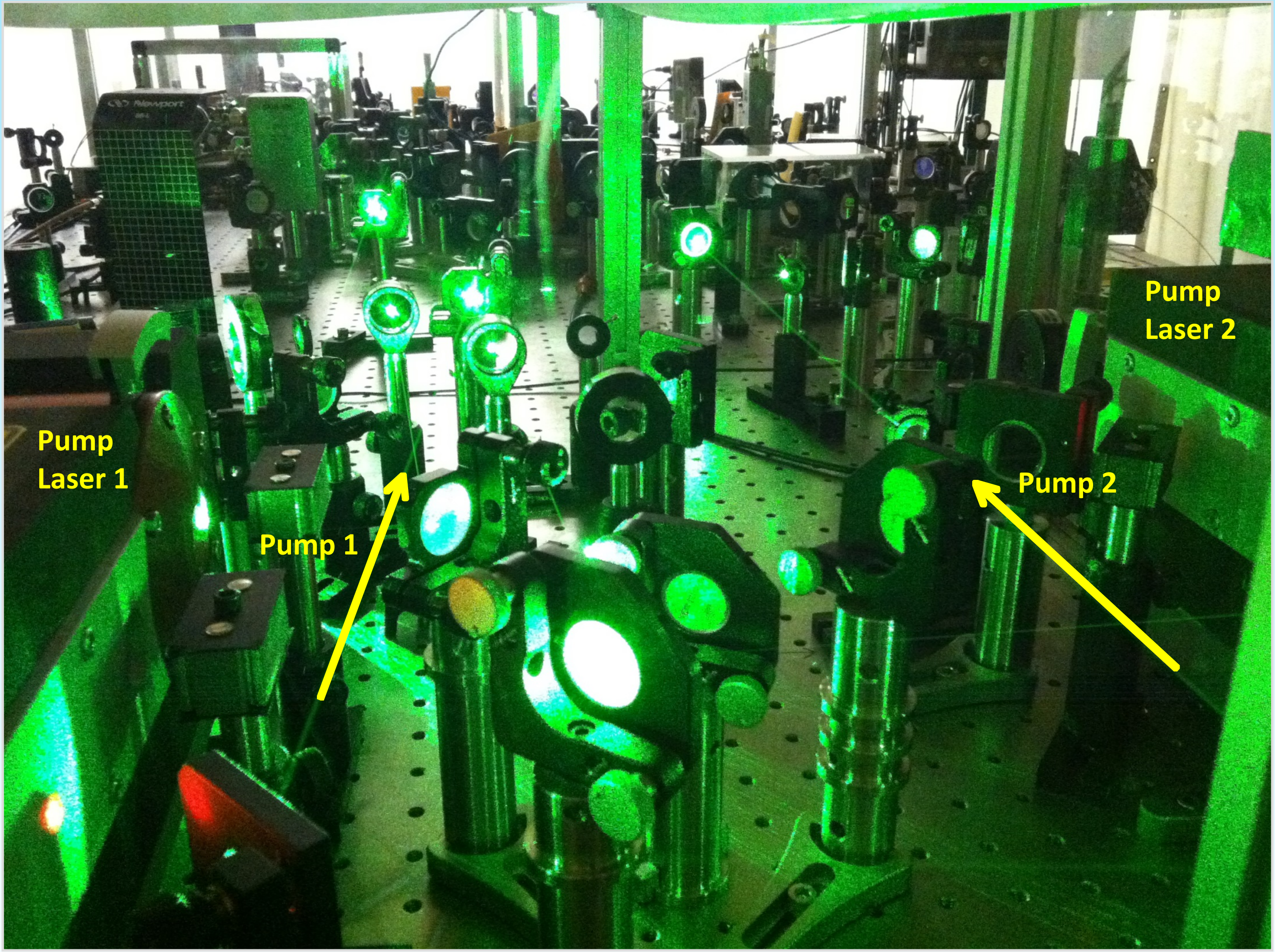
Experimental Realization of Multipartite Entanglement of 60 Modes of a Quantum Optical Frequency Comb

Moran Chen,[1] Nicolas C. Menicucci,[2,*] and Olivier Pfister[1,†]
[1]*Department of Physics, University of Virginia, Charlottesville, Virginia 22903, USA*
[2]*School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*
(Received 11 November 2013; revised manuscript received 31 January 2014; published 26 March 2014)

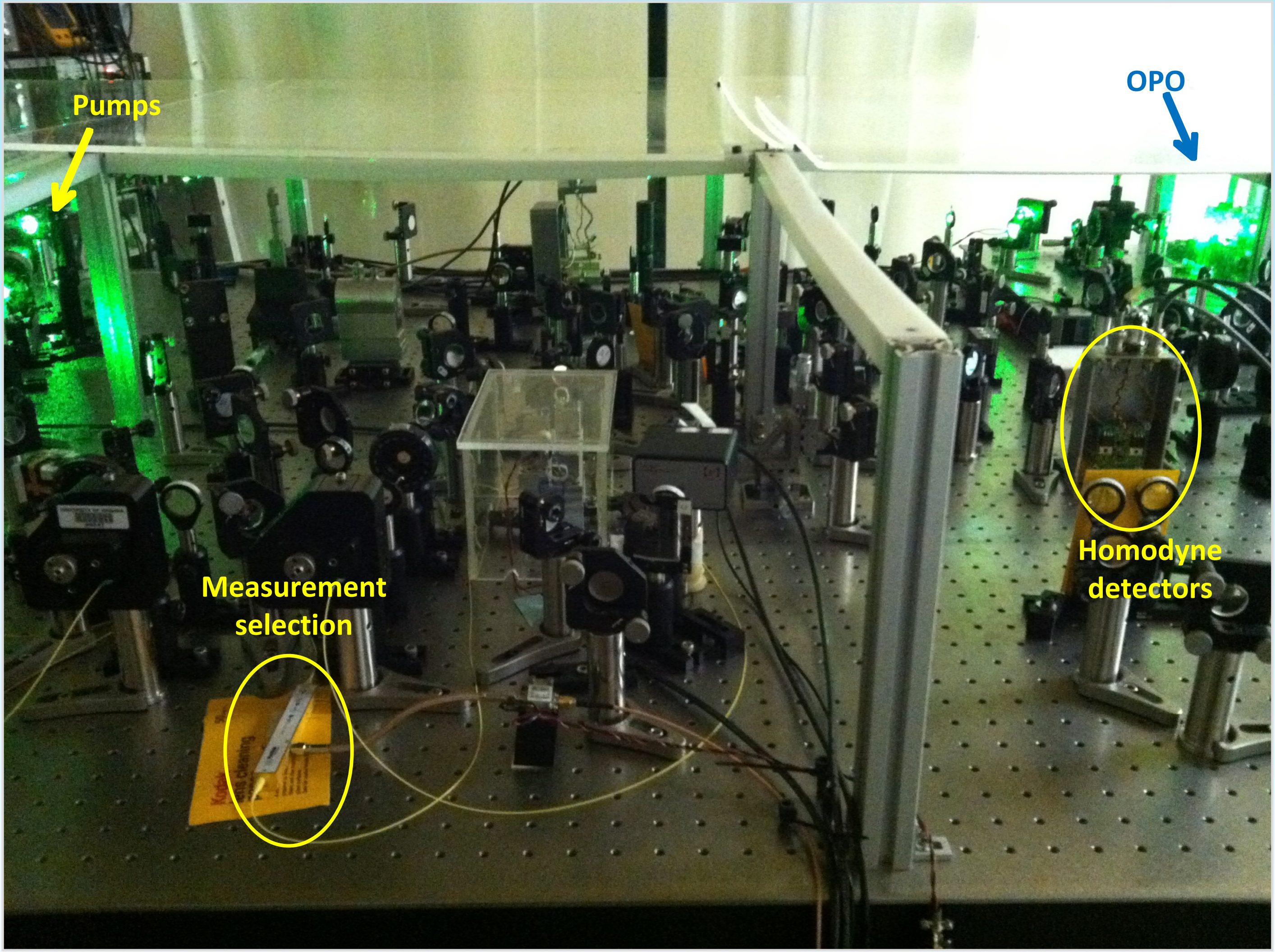
60-mode linear cluster state



Frequency-mode cluster state (wire)



Frequency-mode cluster state (wire)



RMIT UNIVERSITY

Temporal-mode (pulse-based) cluster states

RMIT UNIVERSITY

Temporal-mode cluster states

RMIT UNIVERSITY

Temporal-mode cluster states

nature photonics
LETTERS
PUBLISHED ONLINE: 17 NOVEMBER 2013 | DOI: 10.1038/NPHOTON.2013.287

Ultra-large-scale continuous-variable cluster states multiplexed in the time domain

Shota Yokoyama[1], Ryuji Ukai[1], Seiji C. Armstrong[1,2], Chanond Sornphiphatphong[1], Toshiyuki Kaji[1], Shigenari Suzuki[1], Jun-ichi Yoshikawa[1], Hidehiro Yonezawa[1], Nicolas C. Menicucci[3] and Akira Furusawa[1]*

Temporal-mode cluster states

nature photonics

LETTERS

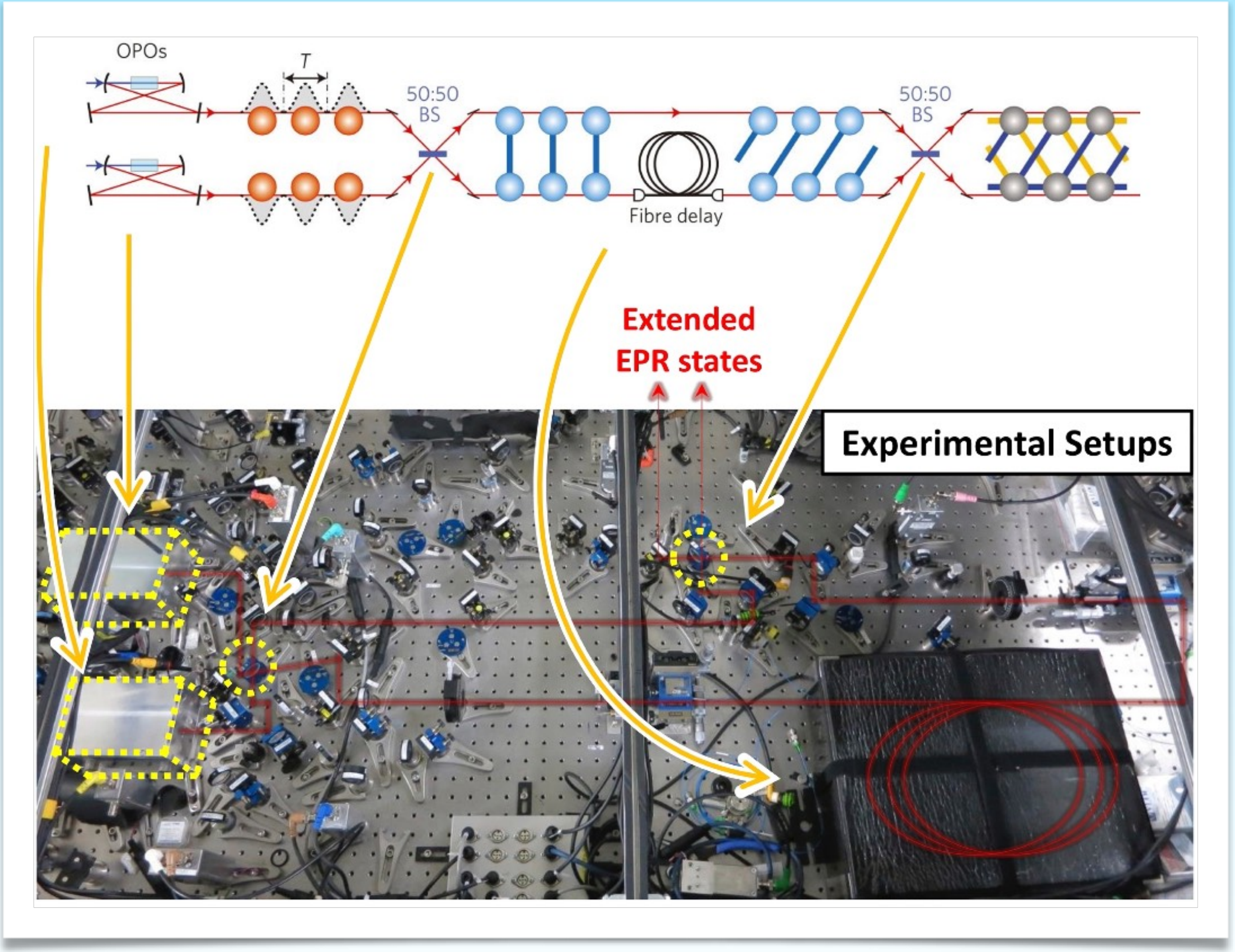
PUBLISHED ONLINE: 17 NOVEMBER 2013 | DOI: 10.1038/NPHOTON.2013.287

Ultra-large-scale continuous-variable cluster states multiplexed in the time domain

Shota Yokoyama[1], Ryuji Ukai[1], Seiji C. Armstrong[1,2], Chanond Sornphiphatphong[1], Toshiyuki Kaji[1], Shigenari Suzuki[1], Jun-ichi Yoshikawa[1], Hidehiro Yonezawa[1], Nicolas C. Menicucci[3] and Akira Furusawa[1]*

10,000-mode linear cluster state

Temporal-mode cluster states



RMIT UNIVERSITY

Temporal-mode cluster states

APL PHOTONICS **1**, 060801 (2016)

Invited Article: Generation of one-million-mode continuous-variable cluster state by unlimited time-domain multiplexing

Jun-ichi Yoshikawa,[1] Shota Yokoyama,[1,2] Toshiyuki Kaji,[1]
Chanond Sornphiphatphong,[1] Yu Shiozawa,[1] Kenzo Makino,[1]
and Akira Furusawa[1,a]

Temporal-mode cluster states

APL PHOTONICS **1**, 060801 (2016)

Invited Article: Generation of one-million-mode continuous-variable cluster state by unlimited time-domain multiplexing

Jun-ichi Yoshikawa,[1] Shota Yokoyama,[1,2] Toshiyuki Kaji,[1] Chanond Sornphiphatphong,[1] Yu Shiozawa,[1] Kenzo Makino,[1] and Akira Furusawa[1,a]

1-million-mode linear cluster state!

Temporal-mode cluster states

QUANTUM COMPUTING

Generation of time-domain-multiplexed two-dimensional cluster state

Warit Asavanant[1], Yu Shiozawa[1], Shota Yokoyama[2], Baramee Charoensombutamon[1], Hiroki Emura[1], Rafael N. Alexander[3], Shuntaro Takeda[1,4], Jun-ichi Yoshikawa[1], Nicolas C. Menicucci[5], Hidehiro Yonezawa[2], Akira Furusawa[1*]

Asavanant *et al.*, *Science* **366**, 373–376 (2019)

QUANTUM COMPUTING

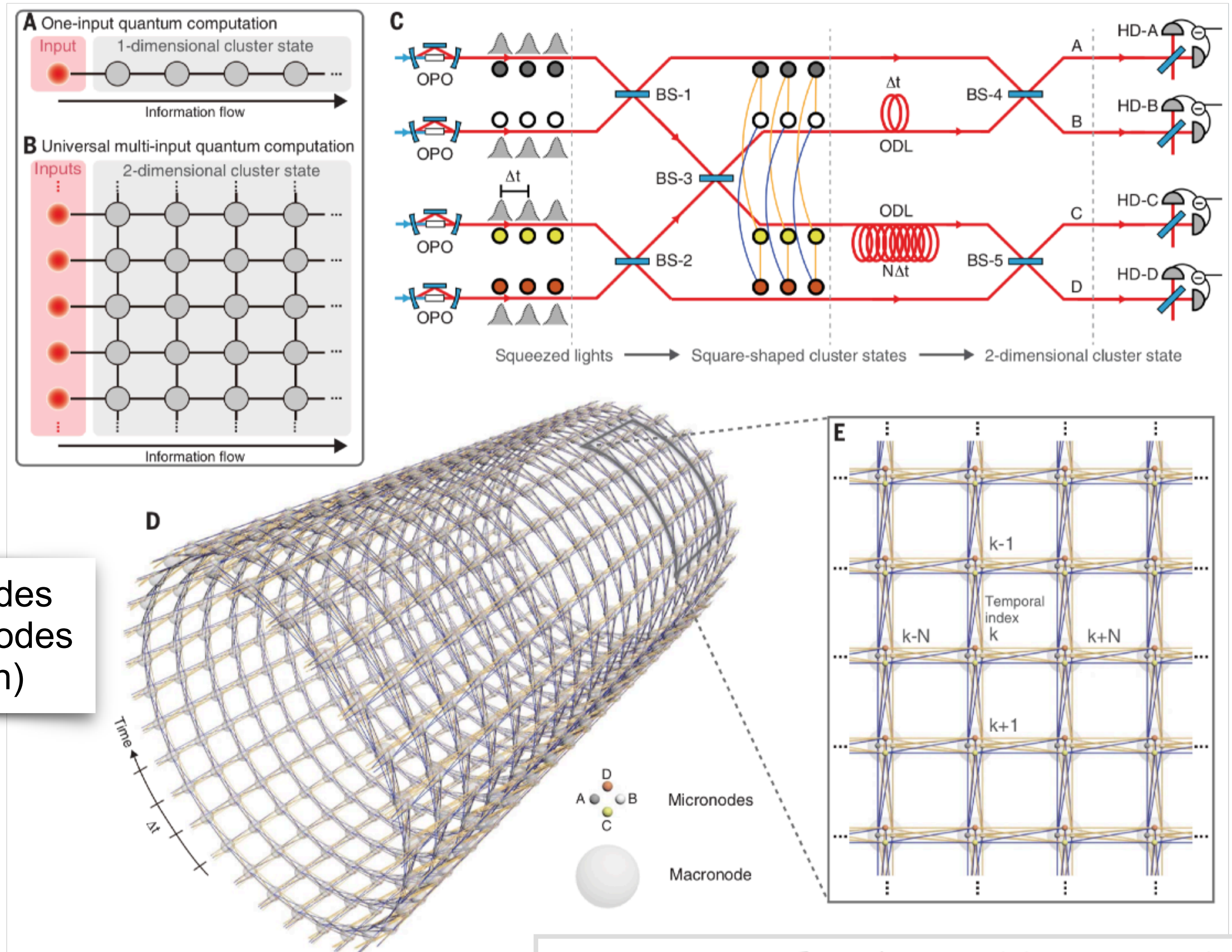
Deterministic generation of a two-dimensional cluster state

Mikkel V. Larsen*, Xueshi Guo, Casper R. Breum, Jonas S. Neergaard-Nielsen, Ulrik L. Andersen*

Larsen *et al.*, *Science* **366**, 369–372 (2019)

RMIT UNIVERSITY

Temporal-mode cluster states



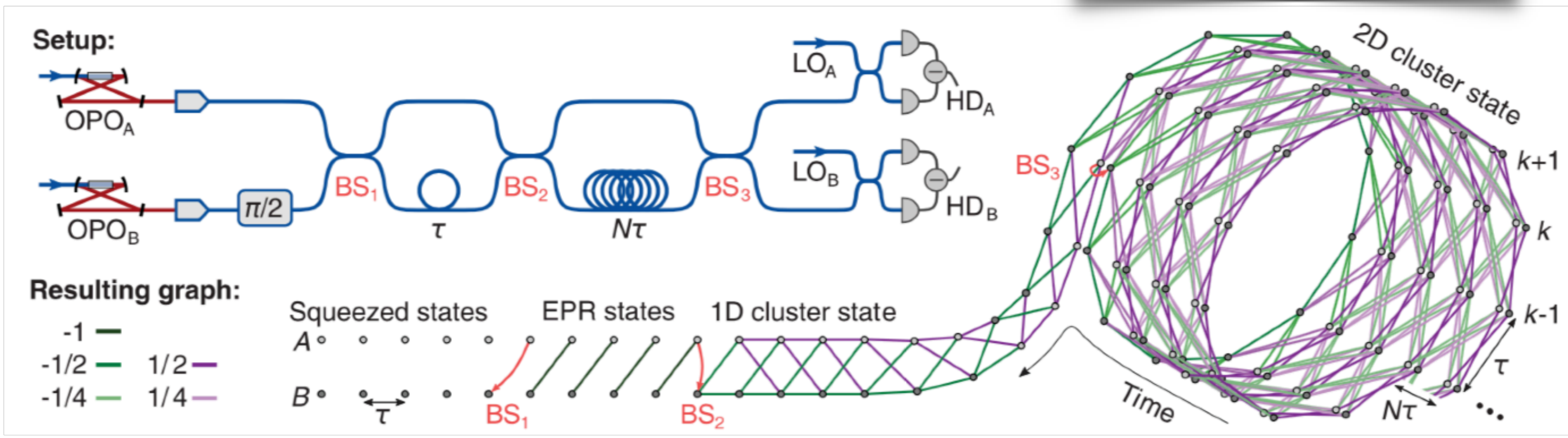
24,800 total modes
5 x 1240 macronodes
(4 modes each)

Asavanant *et al.*, *Science* **366**, 373–376 (2019)

RMIT UNIVERSITY

Temporal-mode cluster states

30,000 total modes
12 x 1250 macronodes
(2 modes each)



Larsen *et al.*, *Science* **366**, 369–372 (2019)

Temporal-mode cluster states

ARTICLES
https://doi.org/10.1038/s41567-021-01296-y
nature physics
Check for updates

Deterministic multi-mode gates on a scalable photonic quantum computing platform

Mikkel V. Larsen ✉, Xueshi Guo, Casper R. Breum, Jonas S. Neergaard-Nielsen and Ulrik L. Andersen ✉

Larsen et al., *Nature Phys.* **17**, 1018 (2021)

PHYSICAL REVIEW APPLIED **16,** 034005 (2021)

Time-Domain-Multiplexed Measurement-Based Quantum Operations with 25-MHz Clock Frequency

Warit Asavanant,[1,*] Baramee Charoensombutamon,[1] Shota Yokoyama,[2] Takeru Ebihara,[1] Tomohiro Nakamura,[1] Rafael N. Alexander,[3,4] Mamoru Endo,[1] Jun-ichi Yoshikawa,[1] Nicolas C. Menicucci,[4] Hidehiro Yonezawa,[2] and Akira Furusawa[1,5,†]

Asavanant et al., *Phys. Rev. Applied* **16**, 034005 (2021)

Prototypes of CV measurement-based quantum computing

RMIT UNIVERSITY

Gaussian boson sampling

Gaussian boson sampling

QUANTUM COMPUTING

Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†

Zhong *et al.*, *Science* **370**, 1460–1463 (2020)

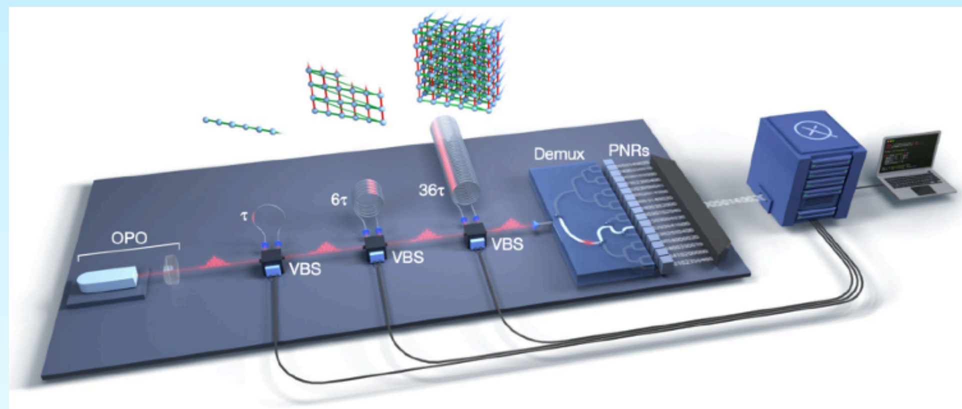
Article | Open Access | Published: 01 June 2022

Quantum computational advantage with a programmable photonic processor

Lars S. Madsen, Fabian Laudenbach, Mohsen Falamarzi. Askarani, Fabien Rortais, Trevor Vincent, Jacob F. F. Bulmer, Filippo M. Miatto, Leonhard Neuhaus, Lukas G. Helt, Matthew J. Collins, Adriana E. Lita, Thomas Gerrits, Sae Woo Nam, Varun D. Vaidya, Matteo Menotti, Ish Dhand, Zachary Vernon, Nicolás Quesada & Jonathan Lavoie

Nature **606**, 75–81 (2022)

50 squeezed states, 100 modes



216 squeezed states, 216 modes, programmable

Photon-sampled multimode Gaussian state

RMIT UNIVERSITY

https://thequantuminsider.com/2020/12/03/china-joins-the-quantum-supremacy-club-chinese-research-team-claims-to-demonstrate-quantum-supremacy-with-gaussian-boson-sampling/

Commercial architecture

Commercial Architecture by Xanadu

Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer

J. Eli Bourassa[1,2,*], Rafael N. Alexander[1,3,4,*], Michael Vasmer[5,6], Ashlesha Patil[1,7], Ilan Tzitrin[1,2], Takaya Matsuura[1,8], Daiqin Su[1], Ben Q. Baragiola[1,4], Saikat Guha[1,7], Guillaume Dauphinais[1], Krishna K. Sabapathy[1], Nicolas C. Menicucci[1,4], and Ish Dhand[1]

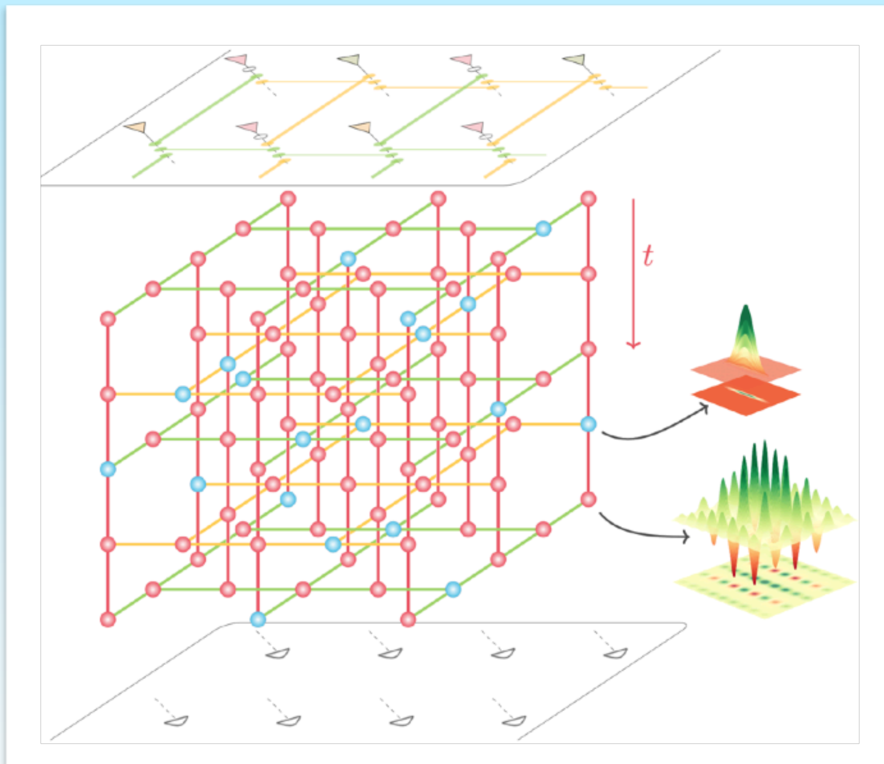
Bourassa et al., *Quantum* **5**, 392 (2021)

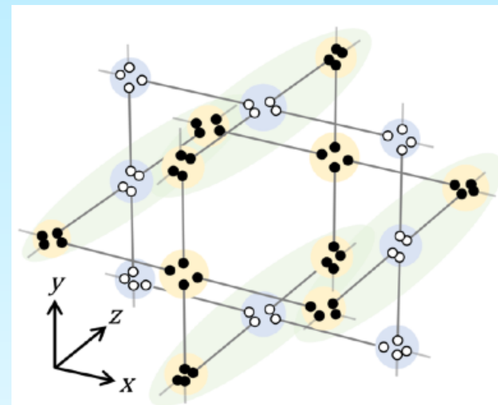
PRX QUANTUM **2**, 040353 (2021)

Fault-Tolerant Quantum Computation with Static Linear Optics

Ilan Tzitrin[1,2,*,†] Takaya Matsuura,[1,3,†] Rafael N. Alexander,[1,4,5,†] Guillaume Dauphinais,[1] J. Eli Bourassa,[1,2] Krishna K. Sabapathy,[1] Nicolas C. Menicucci,[1,4] and Ish Dhand[1]

Tzitrin et al., *PRX Quantum* **2**, 040353 (2021)





Proposal for 3D hybrid GKP-CV cluster state for topological, fault-tolerant, optical quantum computing

(~10-13 dB threshold)

RMIT UNIVERSITY

What's left to do?

What's left to do?

- Quality of states produced is too low (measured in amount of squeezing)

What's left to do?

- Quality of states produced is too low (measured in amount of squeezing)
- Table-top experiments; need to be miniaturised (optical chip)

RMIT UNIVERSITY

What's left to do?

- Quality of states produced is too low (measured in amount of squeezing)
- Table-top experiments; need to be miniaturised (optical chip)
- GKP states are hard to make—they've been made in trapped ions and microwave cavities, not in optics yet, but proposals exist:

RMIT UNIVERSITY

What's left to do?

- Quality of states produced is too low (measured in amount of squeezing)
- Table-top experiments; need to be miniaturised (optical chip)
- GKP states are hard to make—they've been made in trapped ions and microwave cavities, not in optics yet, but proposals exist:
  - Gaussian boson sampling

RMIT UNIVERSITY

What's left to do?

- Quality of states produced is too low (measured in amount of squeezing)
- Table-top experiments; need to be miniaturised (optical chip)
- GKP states are hard to make—they've been made in trapped ions and microwave cavities, not in optics yet, but proposals exist:
  - Gaussian boson sampling
  - Breeding squeezed cat states

RMIT UNIVERSITY

Conclusion

Conclusion

- CV cluster states
  - Enable quantum computation using measurements of quantum continuous variables
  - Fault tolerance is possible with quantum error correction
  - GKP code is promising bosonic code for this purpose
  - Proposal for fault-tolerant quantum computer: hybrid CV-GKP cluster states

- Experimental methods shown to be scalable
  - 1D and 2D CV cluster states
  - Millions of modes achieved
  - Measurement-based quantum-computing prototype demoed
  - Need to improve squeezing
  - Need to make GKP states
  - Gaussian boson sampling demonstrated

RMIT UNIVERSITY