Information flow in MBQC and Adiabatic quantum computation

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Joint work with

Bobby Antonio and Janet Anders arxiv:1309.1443

and

Elham Kashefi arxiv:1311.3610

CNRS, LTCI– ENST (Telecom ParisTech), Paris

① Background

- MBQC
- gFlow (causal order and corrections)

② Information light cone

- Causal cone from gFlow is also an information light cone!

③ Classical simulatability and universality

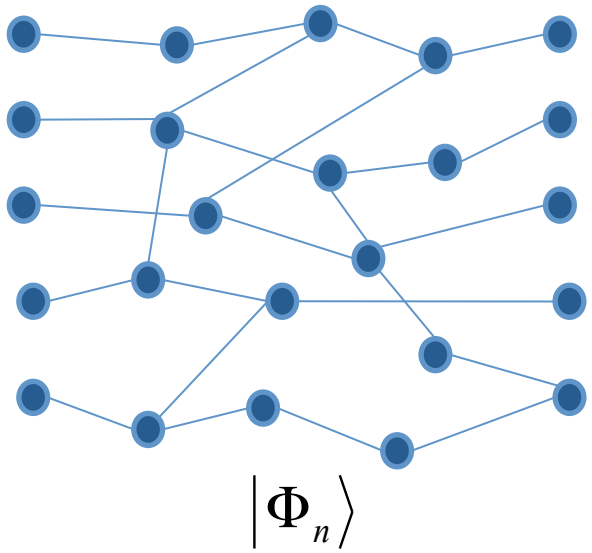
- Size of light cone bounds simulatability
- Points to tradeoff:
  'spread' of information Vs 'use' of spread

④ gFlow for translating MBAC to Adiabatic QC

- gFlow provides translation, hence ideas and intuitions follow

Measurement Based Quantum Computation (MBQC)

- Initial entangled resource state $|\Phi_n\rangle$
- Single qubit measurements
- Local corrections



R. Raussendorf and H. J. Briegel, PRL **85** 5188 (2001)
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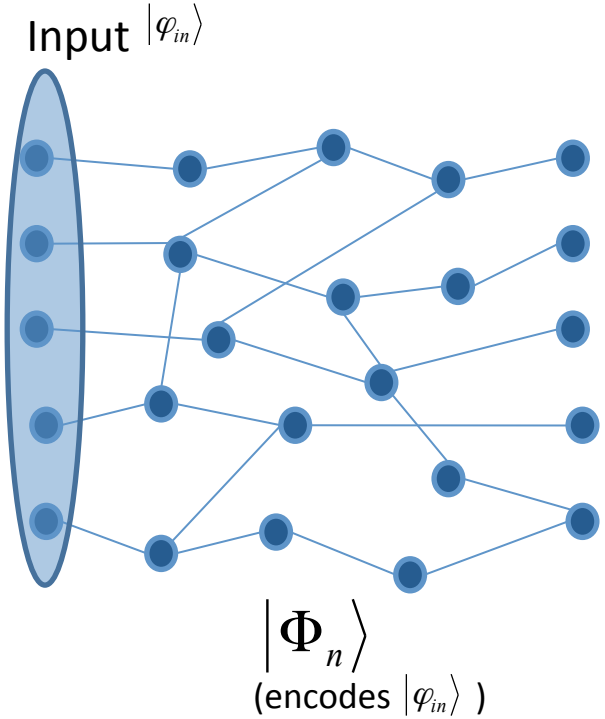

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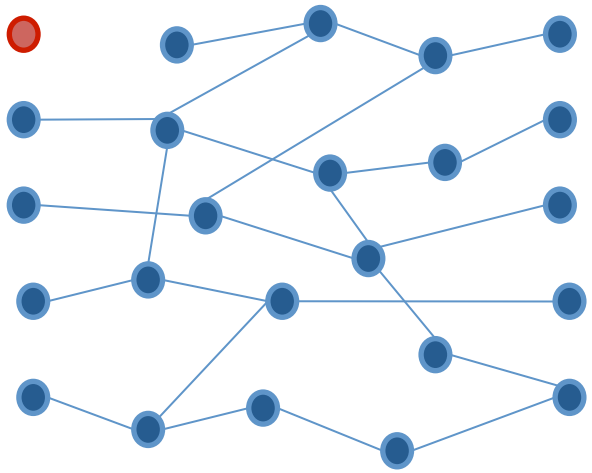

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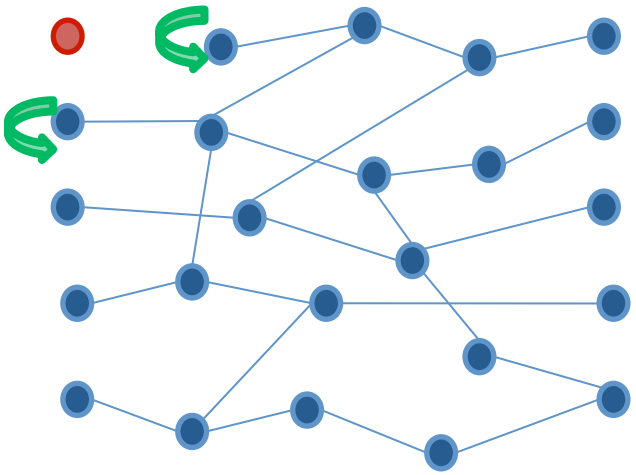

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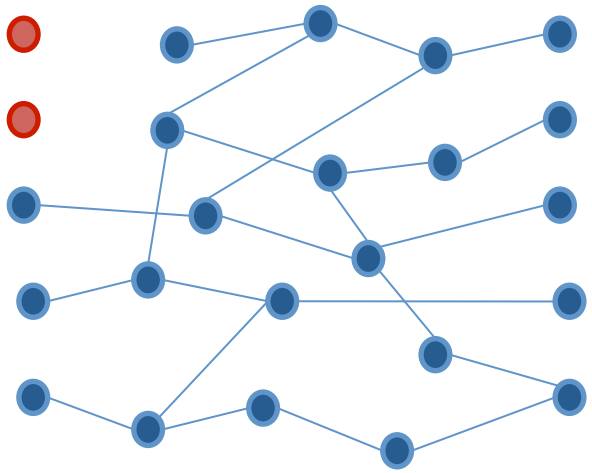

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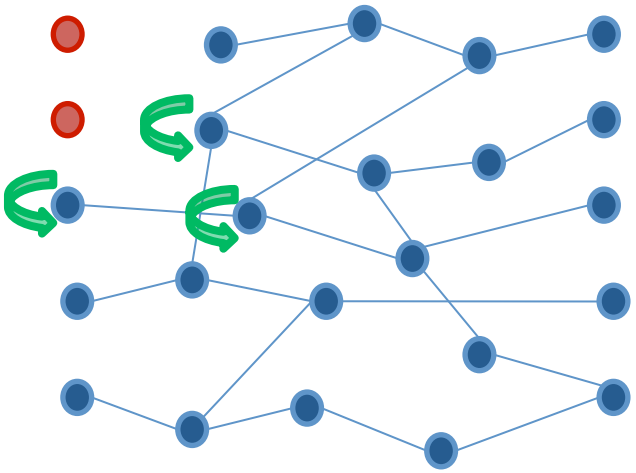

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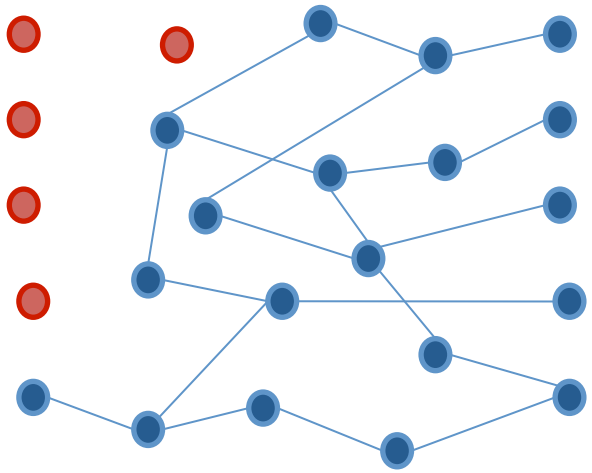

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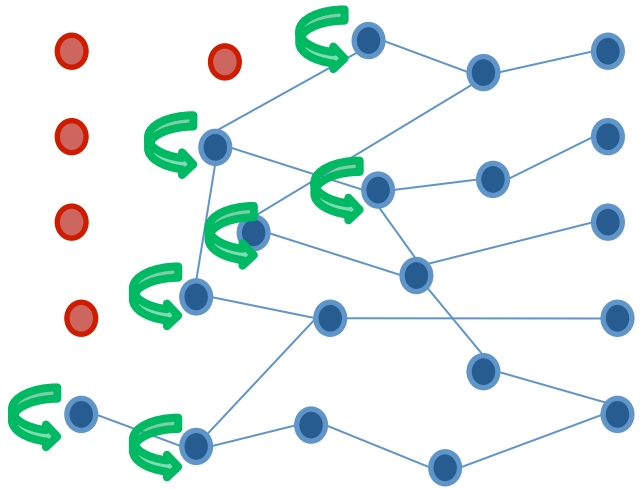

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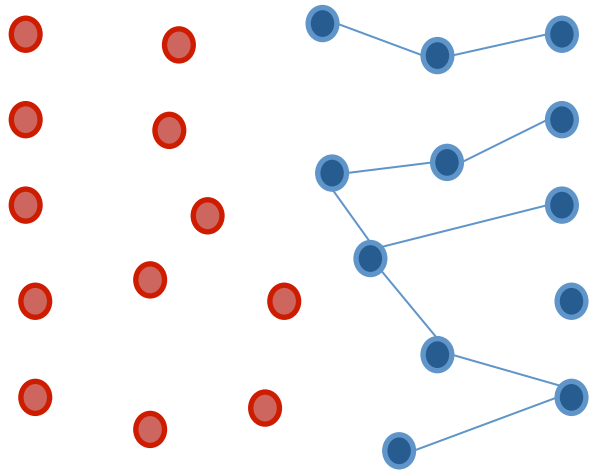

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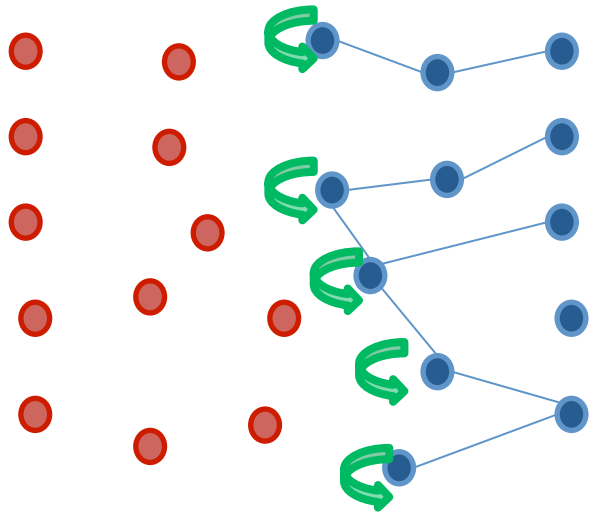

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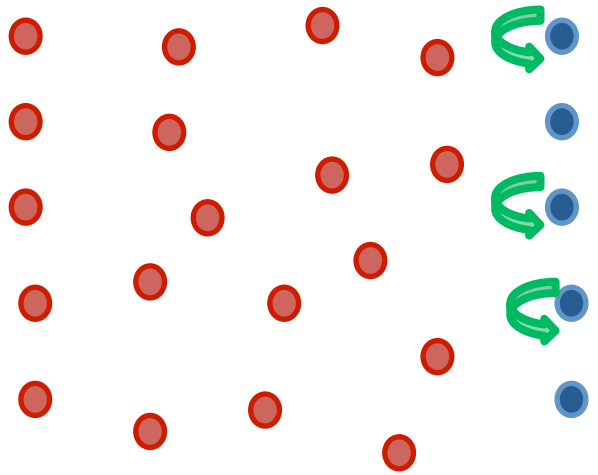

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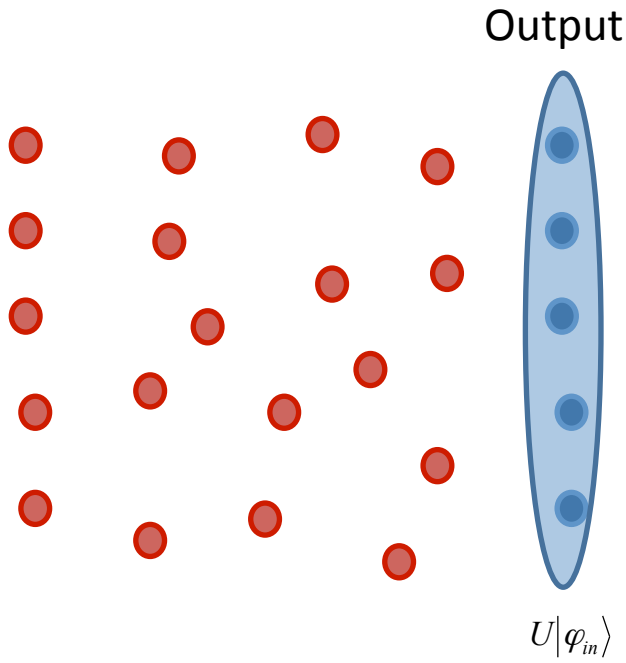

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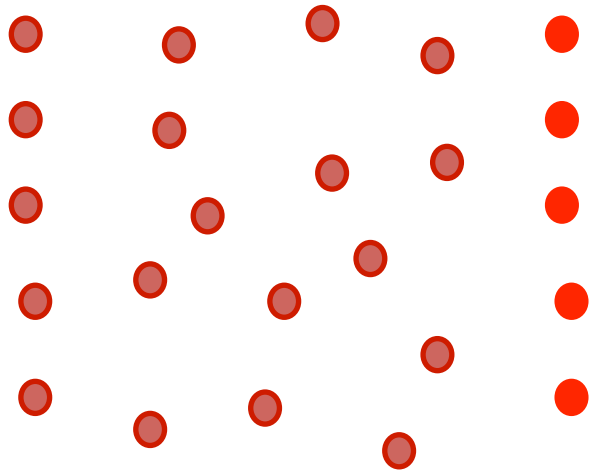

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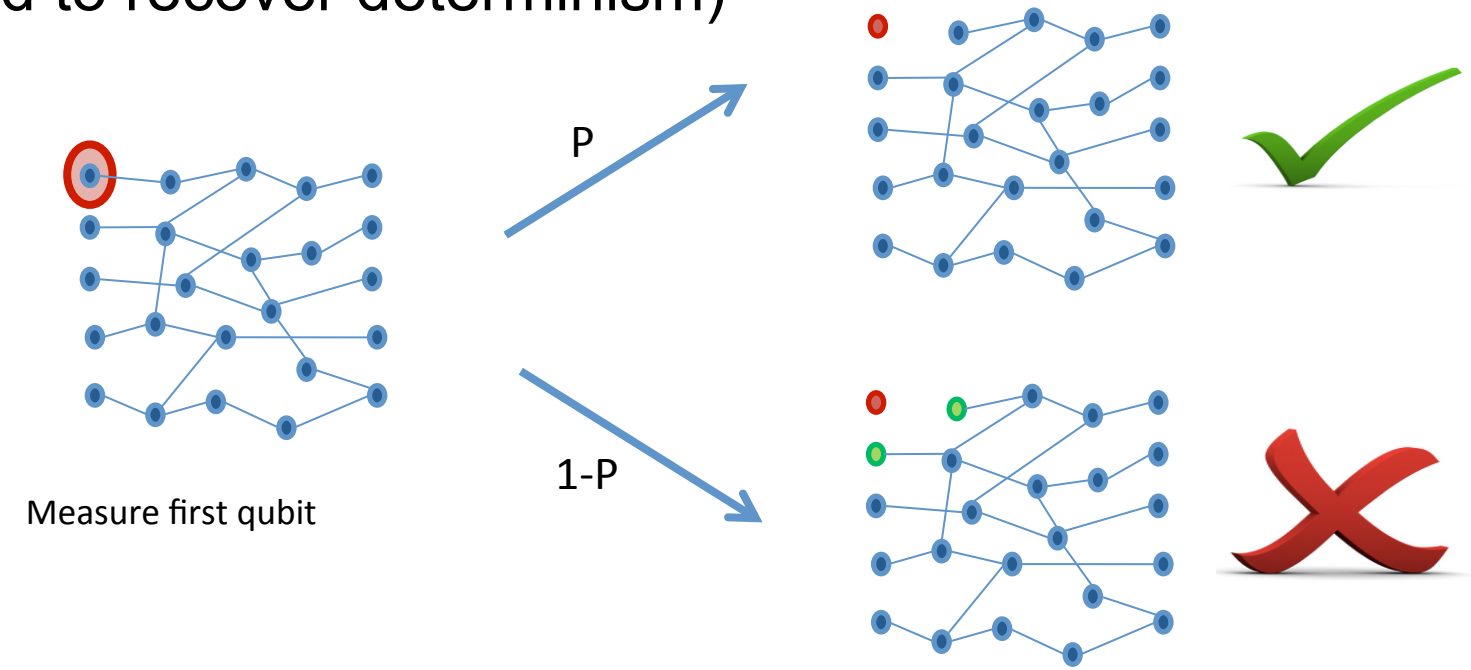

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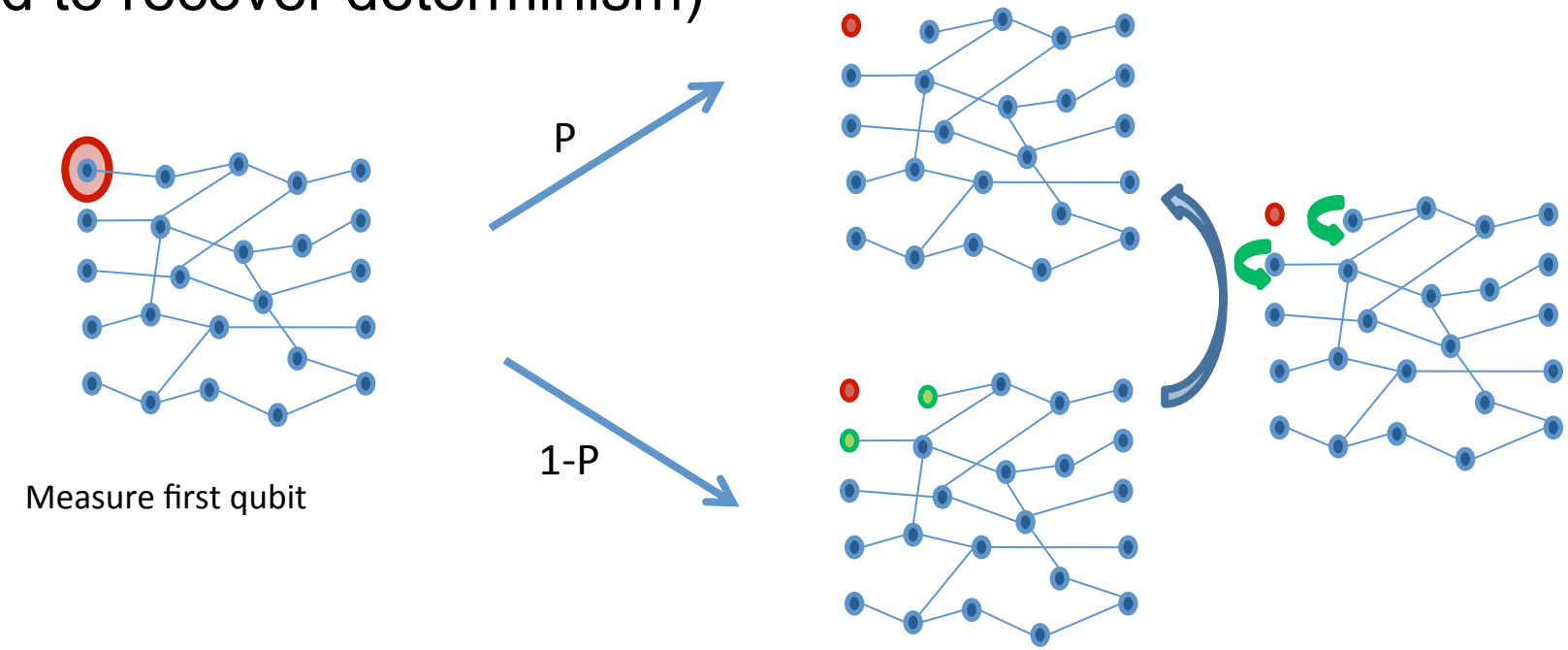

Measurement Based Quantum Computation (MBQC)

- What are the correction operations, and **why do we need them**?

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Measure first qubit

Measurement Based Quantum Computation (MBQC)

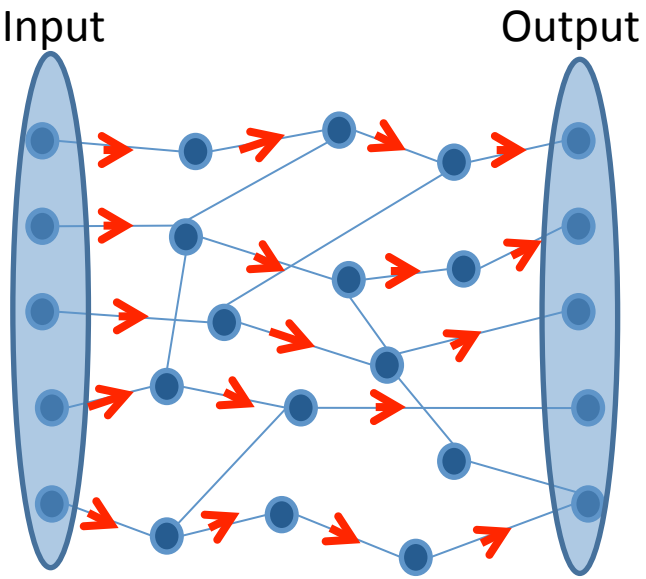
- **What are the correction operations**, and why do we need them?

  gFlow tells us when it can be done, and which operations to make

- Imposes a CAUSAL ORDER (measurement sequence)
- Describes information spread
- Concequences for simulatability / universality
- Translation to other models of computation (AQC)

gFlow

- Condition for a graph state to allow deterministic computation (tells you if corrections exist and what they are)



gFlow: - 'correcting sets': who corrects for what measurements
- time order (so corrections can be consistent)

V. Danos and E. Kashefi, Phys. Rev. A., 74, (2006)
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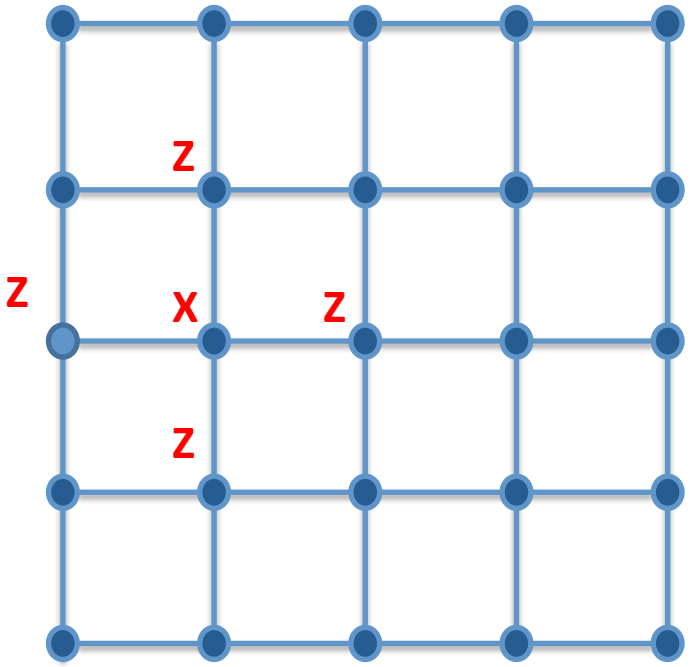
gFlow as acronychal corrections

- Tools: Graph states and stabilisers

$$K_i := X_i \otimes \prod_{(i,j)\in Ed} Z_j$$

$$K_i \left| G \right\rangle = \left| G \right\rangle$$



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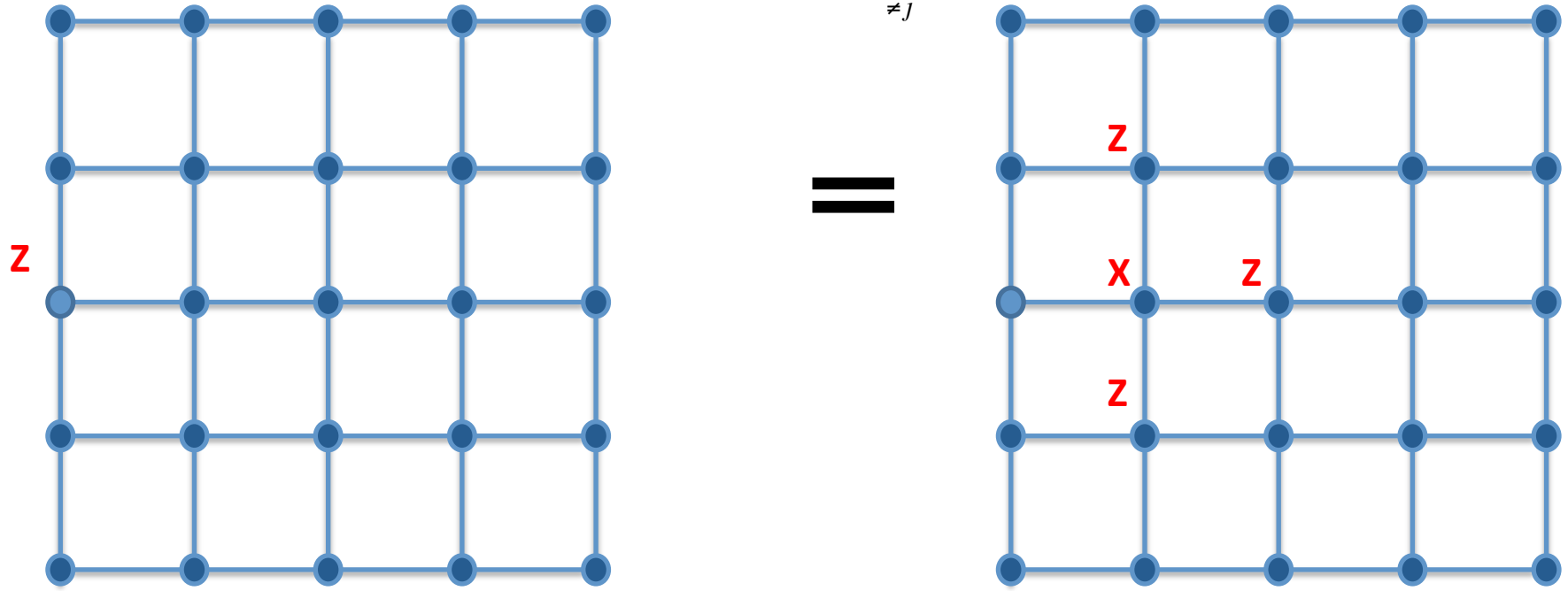
$$K_i \left|G\right\rangle = \left|G\right\rangle$$

$$Z_j \left|G\right\rangle = X_{i\in N(j)} \otimes \prod_{\substack{k\in N(i) \\ \neq j}} Z_k \left|G\right\rangle$$



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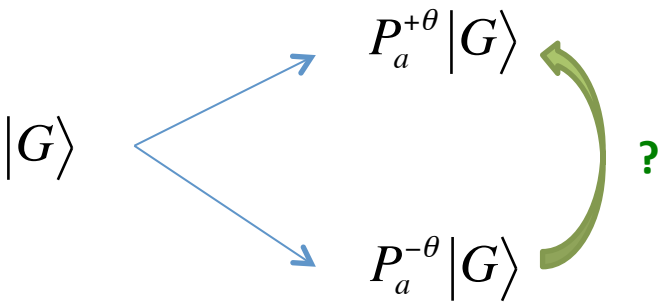
- Measure qubit a

$$M_a^{\theta} = P_a^{+\theta} - P_a^{-\theta} \qquad P_a^{\pm\theta} := \left|\pm\theta\right\rangle\left\langle\pm\theta\right| \qquad \left|\pm\theta\right\rangle = \frac{\left|0\right\rangle \pm e^{-i\theta}\left|1\right\rangle}{\sqrt{2}}$$



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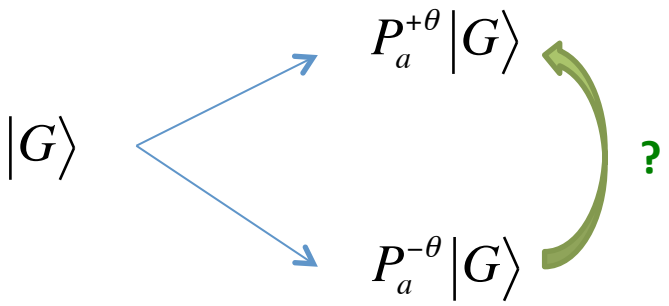

- …. use $ZP_a^{-\theta}Z = P_a^{+\theta}$

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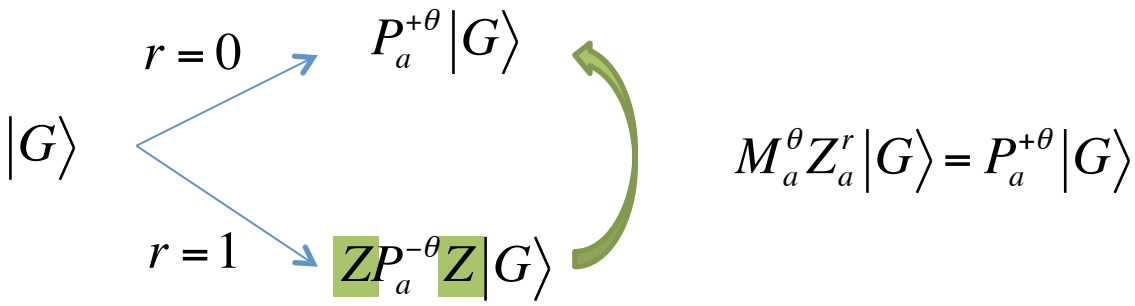

$$M_a^{\theta} Z_a^{r} \left|G\right\rangle = P_a^{+\theta} \left|G\right\rangle$$

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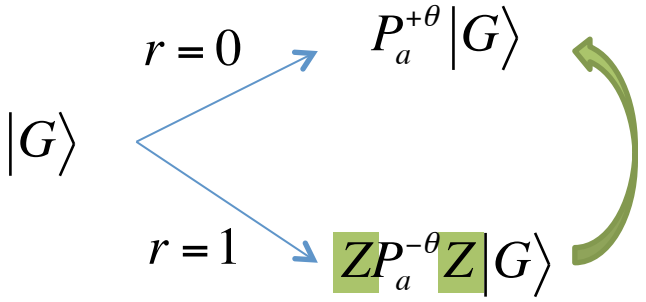

$$M_a^{\theta} Z_a^r \left|G\right\rangle = P_a^{+\theta}\left|G\right\rangle$$

- Problem: have to know r before we do the measurement!

(acronycal)

- Solution: Use the graph stabilisers to simulate…

Correct on different systems - commutes with measurement!

$$M_a Z_a^{r_a}\left|G\right\rangle = X_i^{r_a} \bigotimes_{\substack{j\in N(i)\\ \neq a}} Z_j^{r_a} M_a \left|G\right\rangle$$

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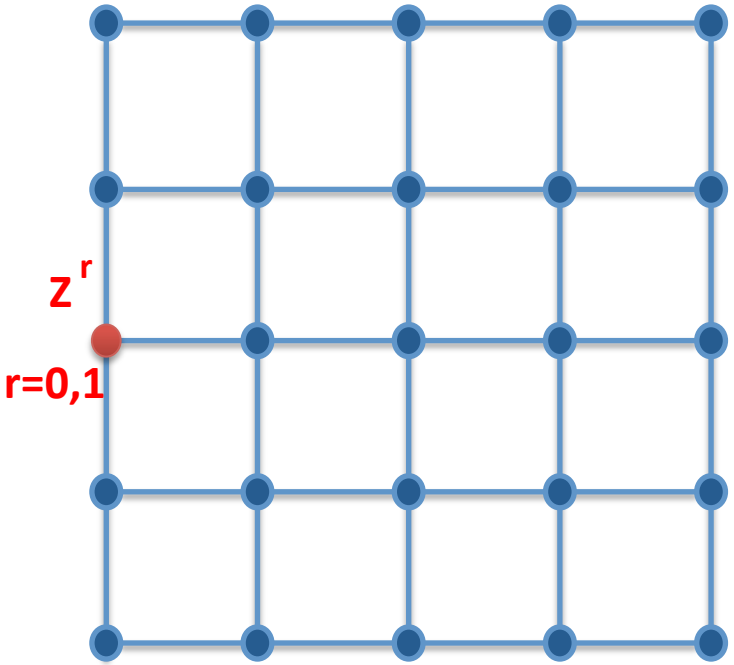

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- then measure (impossible)

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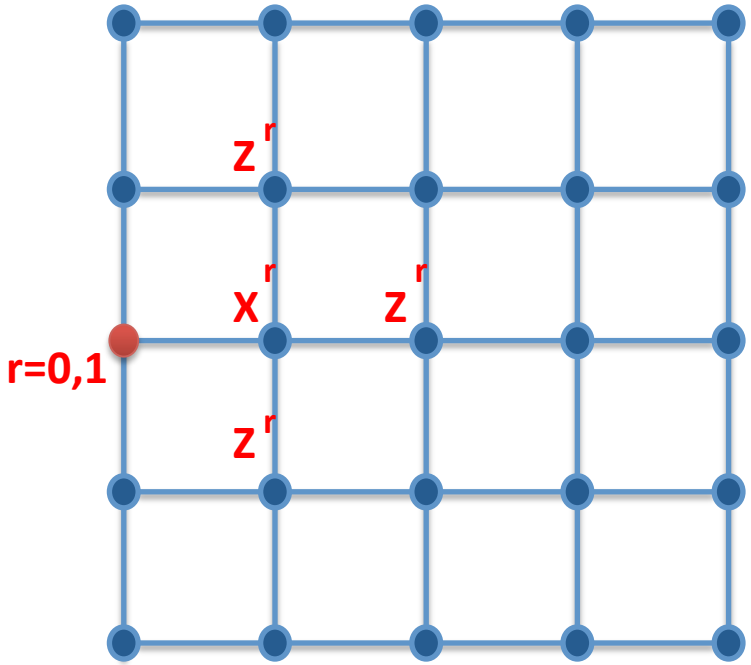

- measure
- then correct (great!)

- Can measure first, then correct
  - how to choose correction set?
  - consistent time order?

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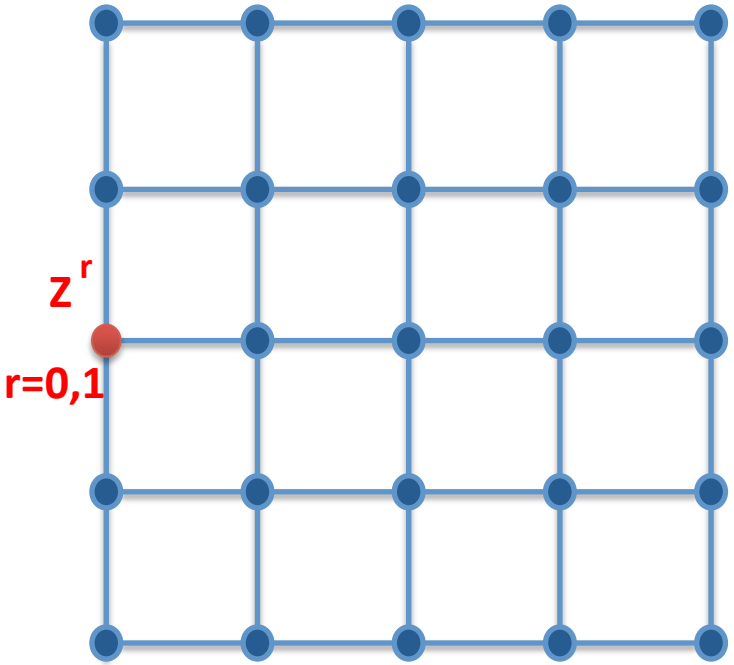

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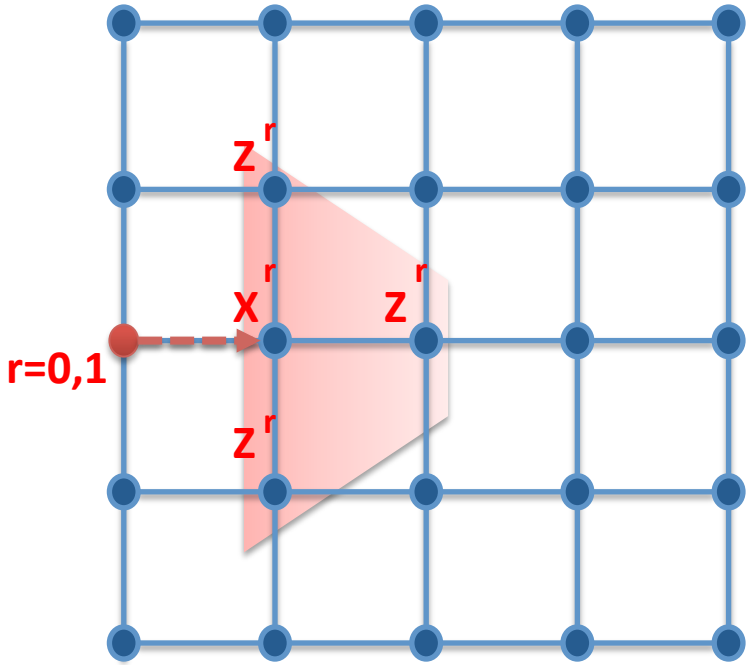

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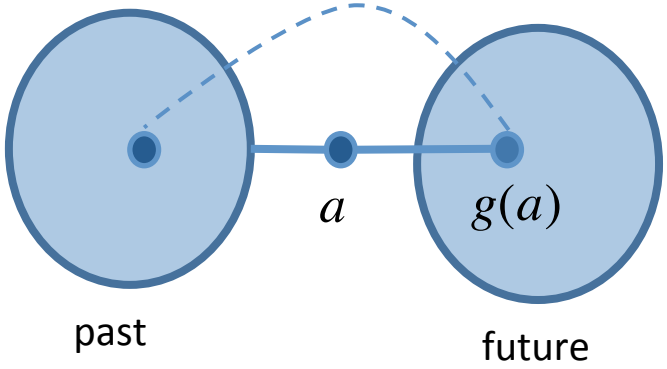
} gFlow

gFlow

- Find a good set of neighbours to to corrections in a *consistent* way



1) $g(a)$ is in 'future' of a (time order)
2) It corrects! (neighbour / odd edges)
3) It does not interfere with previous corrections (not neighbour / even to past)

- $\prod_{i \in g(a)} K_i$ gives you a Z_a , and nothing on past
  - Achronycal correction $\left(Z_a \prod_{i \in g(a)} K_i \right)^{r_a}$
  - Anticorrolation with X_a (Logical operator update) (translation to AQC)

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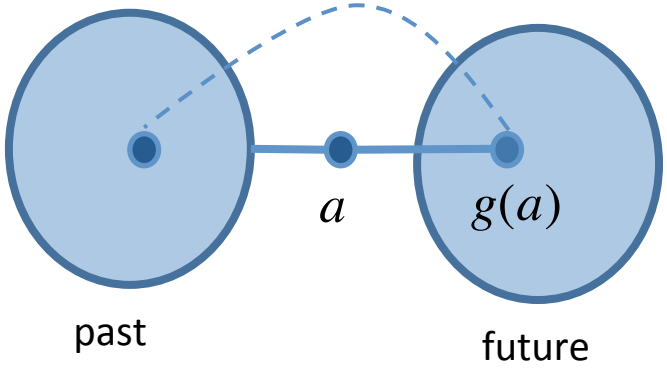

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$$\left(Z_a \prod_{i \in g(a)} K_i \right)^{r_a}$$

- Optimisation of time/depth
- Optimisation of number of qubits
- Information light cone
- Simulatability / universality
- Translation to AQC

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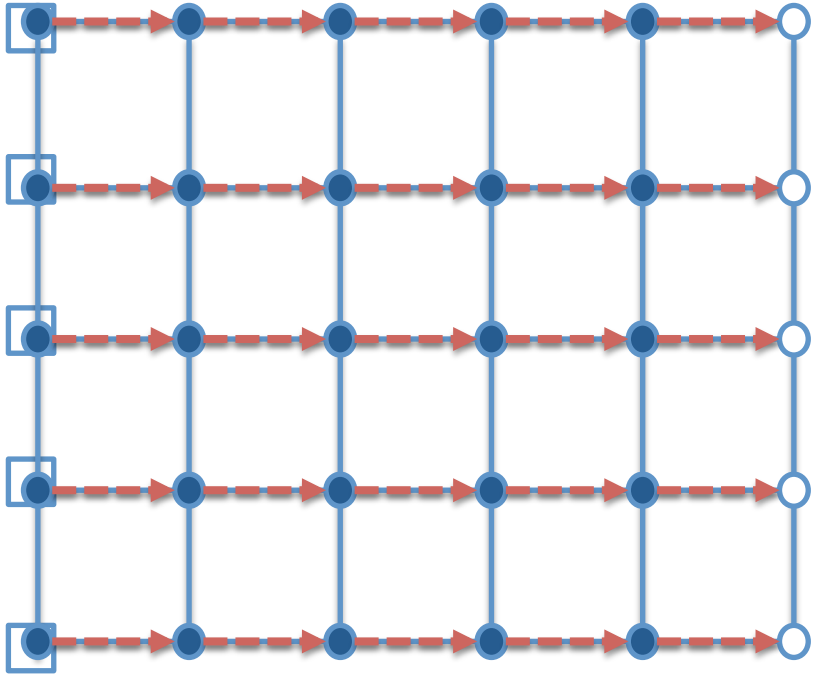
D. Browne, E. Kashefi and S. Perdrix TQC 2010
R. da Silva, E. Galvao, E. Kasehfi PRA 2011

Light Cones

- E.g. Cluster state



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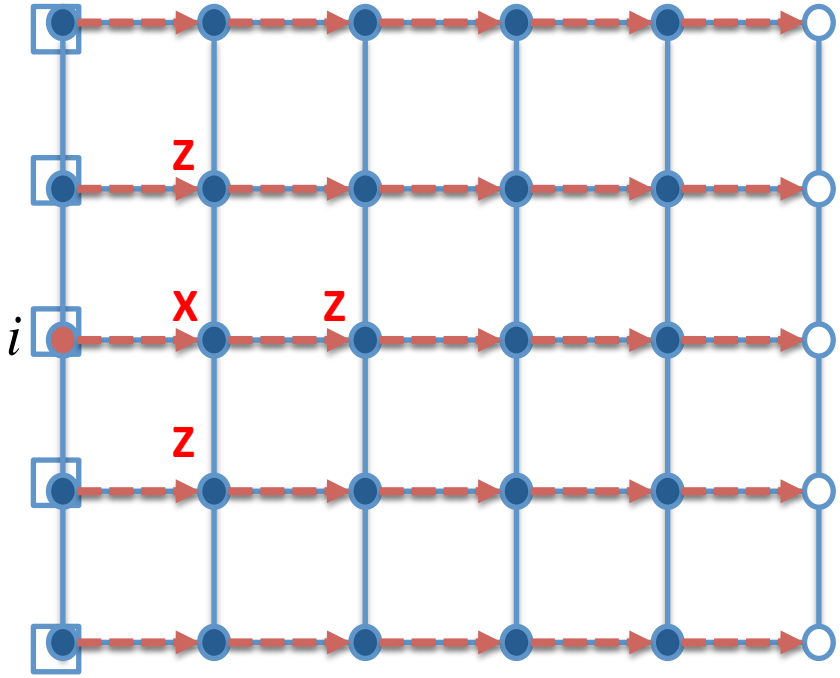

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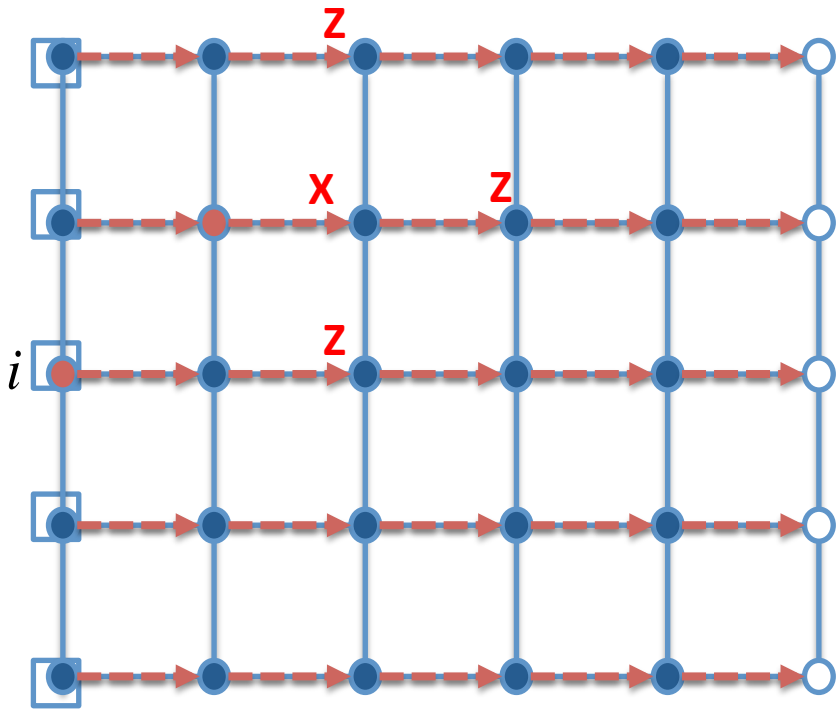
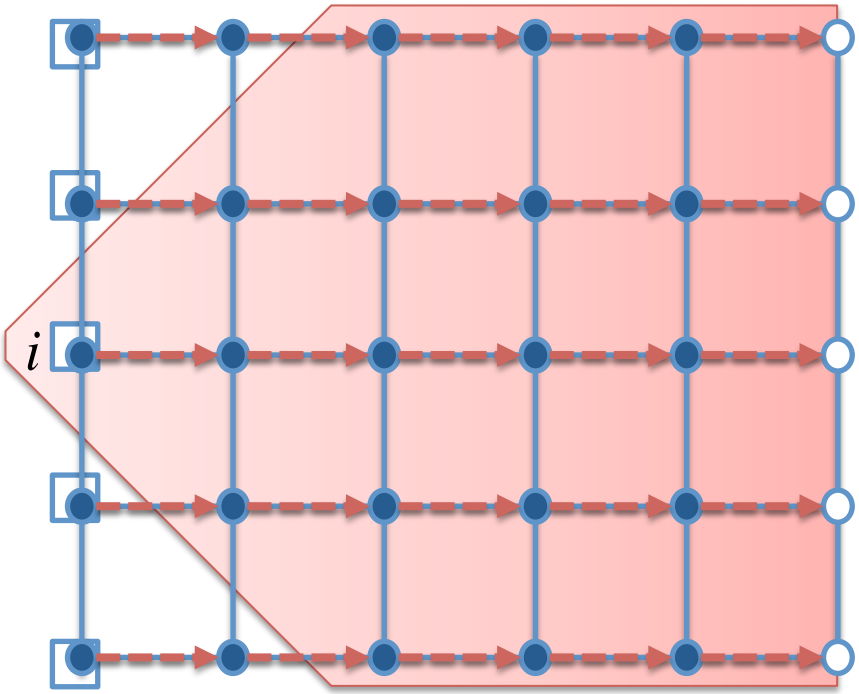


Light Cones

- E.g. Cluster state: causal light cone



R. da Silva, E. Galvao, E. Kasehfi PRA 2011
R. Raussendorf, P. Sarvepalli, T.C. Wei, P. Haghnegahdar, arxiv:1108.5774, EPTCS 2012, arxiv:1210.0620

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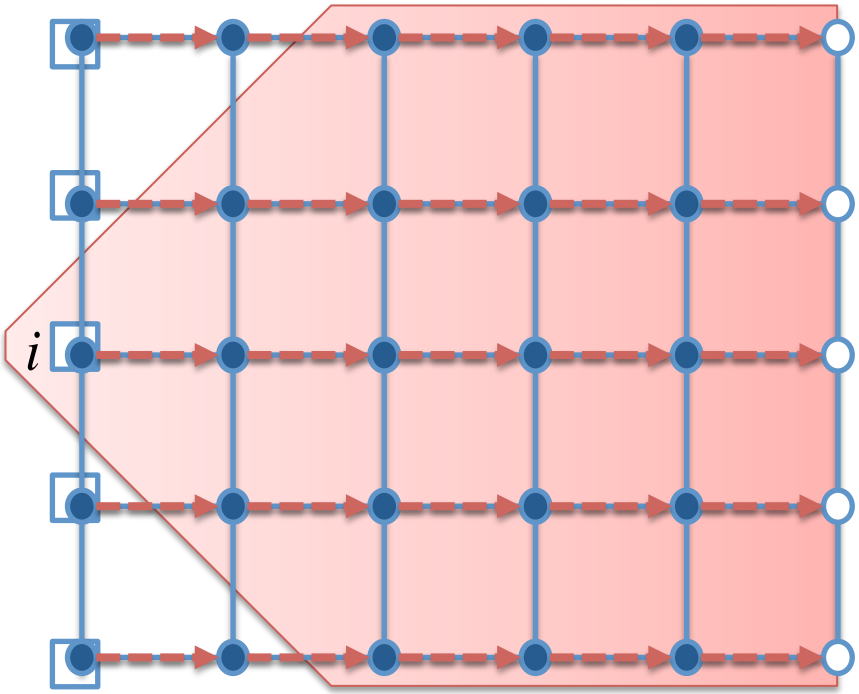
Information?

X_i, Z_i i



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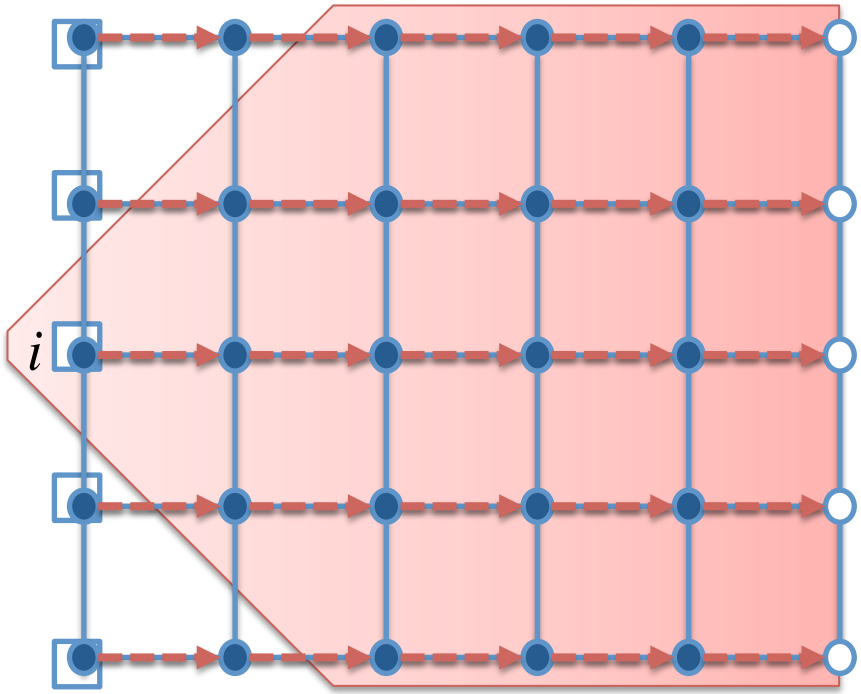


- Logical operators X_i, Z_i spread across the same cone!

-> information light cone

Information spread and simulation

- Logical Heisenberg picture

$$\rho = \frac{1}{2}\left(I + \eta_x X + \eta_Y Y + \eta_Z Z\right) \quad \Rightarrow \quad \tilde{\rho} = \frac{1}{2}\left(I + \eta_x \tilde{X} + \eta_Y \tilde{Y} + \eta_Z \tilde{Z}\right)$$

- Trace complete set of logical operators

$$L_{X_i} \quad \Rightarrow \quad \tilde{L}_{X_i}$$

$$\langle\varphi|L_{X_i}|\varphi\rangle = \langle\tilde{\varphi}|\tilde{L}_{X_i}|\tilde{\varphi}\rangle$$

E.g. Unitary

$$L_{X_i} \quad \Rightarrow \quad \tilde{L}_\alpha = U L_\alpha U^+$$

$$\langle\varphi|L_{X_i}|\varphi\rangle = \langle\varphi|U^+\tilde{L}_{X_i}U|\varphi\rangle$$

- All information can be read from $\tilde{L}_{X_i}$

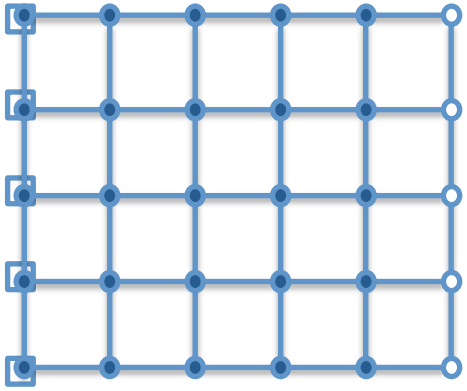
-> location of info ~ extent of $\tilde{L}_{X_i}$

D. Deutsch, P. Hayden, PRSL 2000
D. Gottesman PhD Thesis 1997

D. Browne, H. Briegel, arxiv: 0603226

Information spread and simulation

- Graph state MBQC



$$K_i := X_i \otimes \prod_{(i,j)\in Ed} Z_j$$

$$K_i \left|G(\varphi)\right\rangle = \left|G(\varphi)\right\rangle \qquad \forall i \notin I$$

Space of dim. $2^{|I|}$

- Stabilisers are logical identities

$$L_\alpha \approx L_\alpha K_i$$

$$\left\langle G(\varphi)\right| L_\alpha \left|G(\varphi)\right\rangle = \left\langle G(\varphi)\right| L_\alpha K_i \left|G(\varphi)\right\rangle$$

- Measurements?
  - If $[L_\alpha, M] = 0$ -> L_α do not change!
  - Use stablisers (logical identities)… choice? -> gFlow

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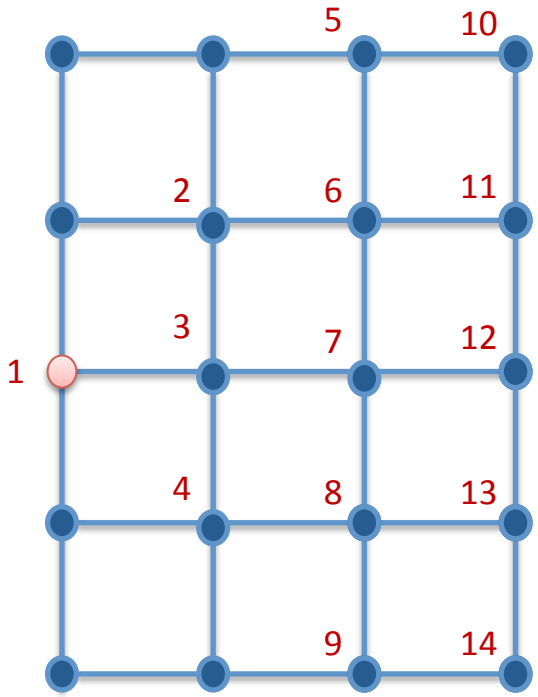
Information spread and simulation

- E.g. Cluster state



$$L_{X_1} = X_1 \otimes Z_3$$
$$L_{Z_1} = Z_1$$

Information spread and simulation

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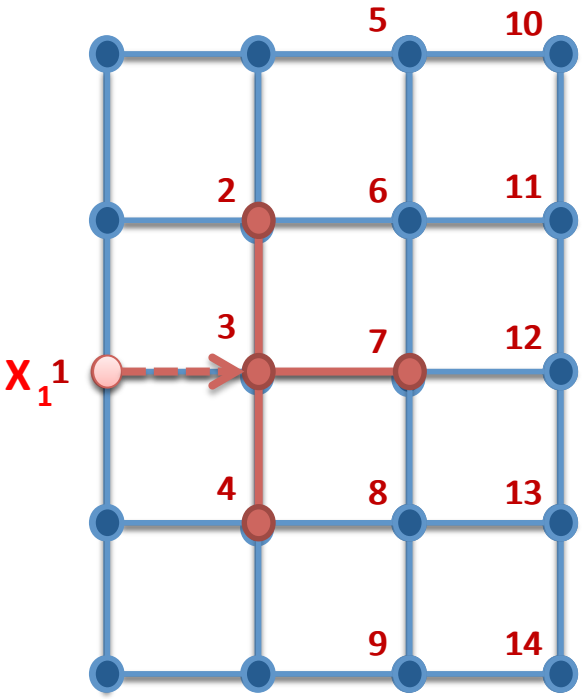

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Information spread and simulation

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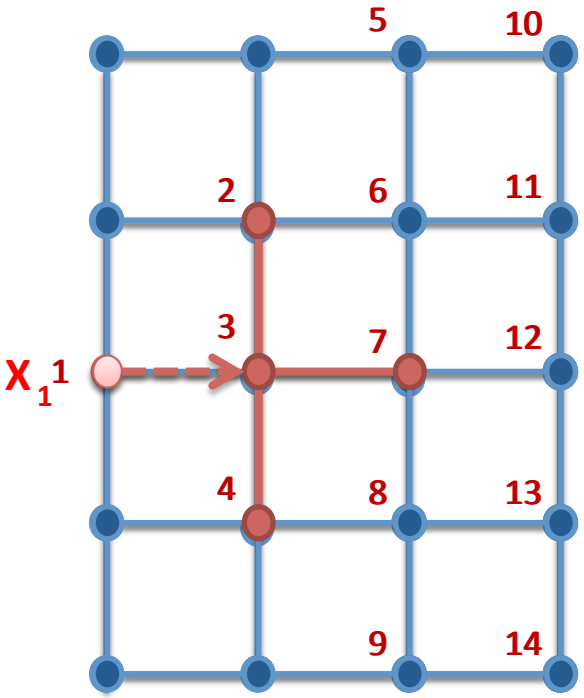

$$L_{X_1} = X_1 \otimes Z_3$$
$$L_{Z_1} = I_1 \otimes Z_2 \otimes X_3 \otimes Z_4 \otimes Z_7$$

Information spread and simulation

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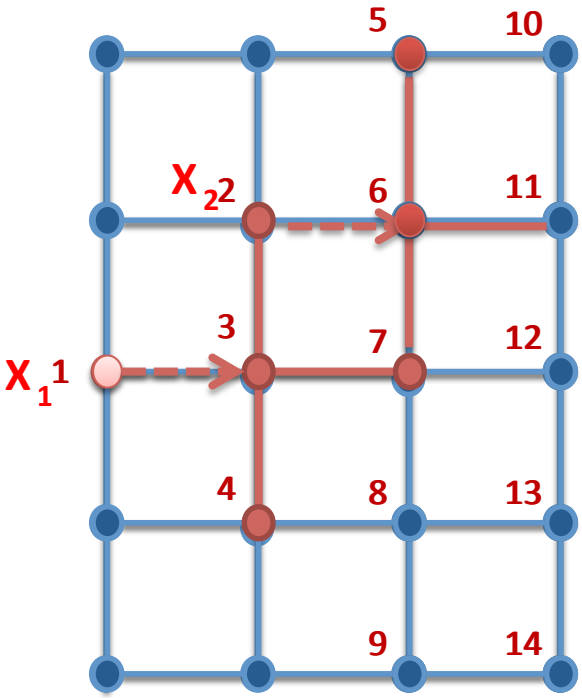

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Information spread and simulation

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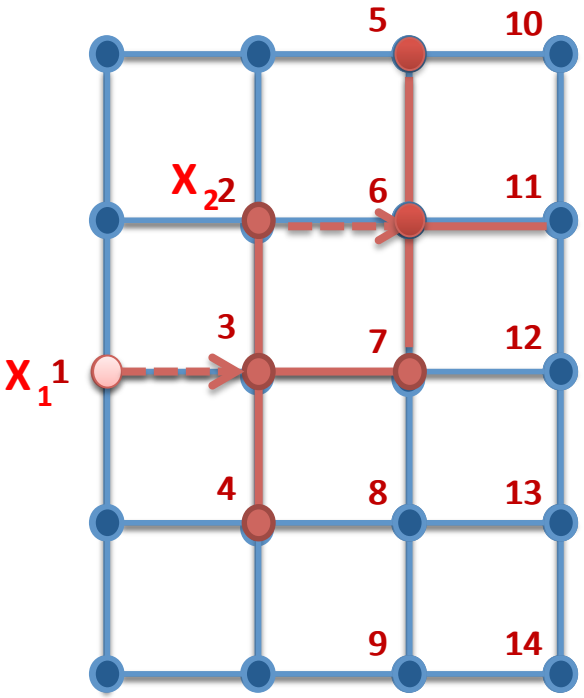
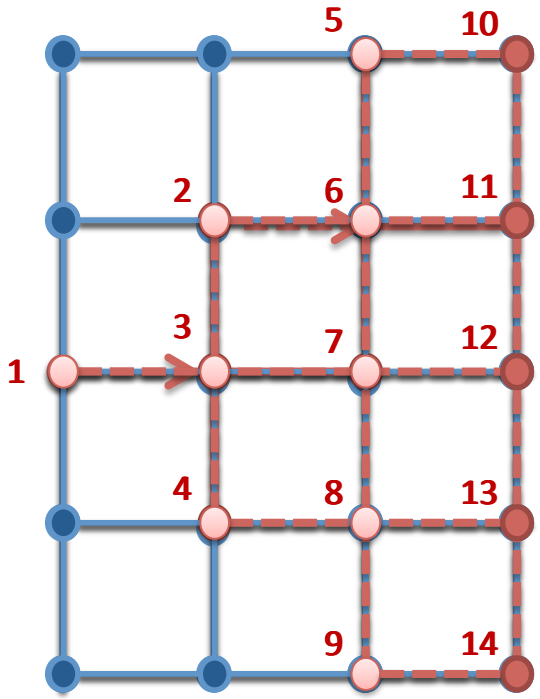


$$L_{X_1} = X_1 \otimes Z_3$$

$$L_{Z_1} = I_1 \otimes I_2 \otimes X_3 \otimes Z_4 \otimes Z_5 \otimes X_6 \otimes I_7 \otimes Z_{11}$$

Information spread and simulation

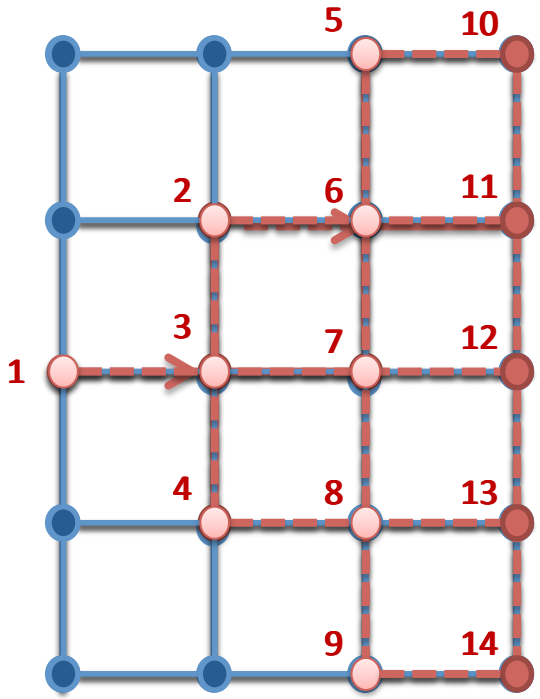
- E.g. Cluster state



$$L_{X_1} = Z_{10} \otimes X_{11} \otimes Z_{12}$$
$$L_{Z_1} = X_{10} \otimes Z_{11} \otimes X_{12} \otimes Z_{13} \otimes X_{14}$$

Information spread and simulation

- E.g. Cluster state



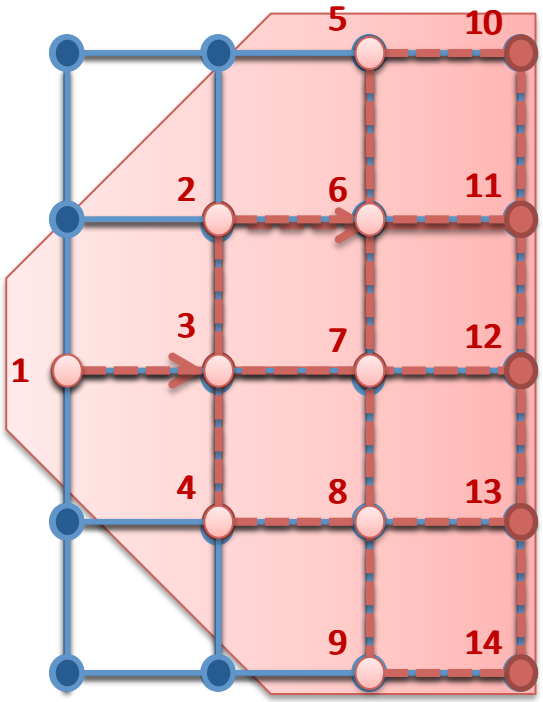
- General case: round by round

- if $\{X_i, L_\alpha\} = 0$

$$L_\alpha \longrightarrow L_\alpha \prod_{j \in g(i)} K_j$$

Information spread and simulation

- E.g. Cluster state



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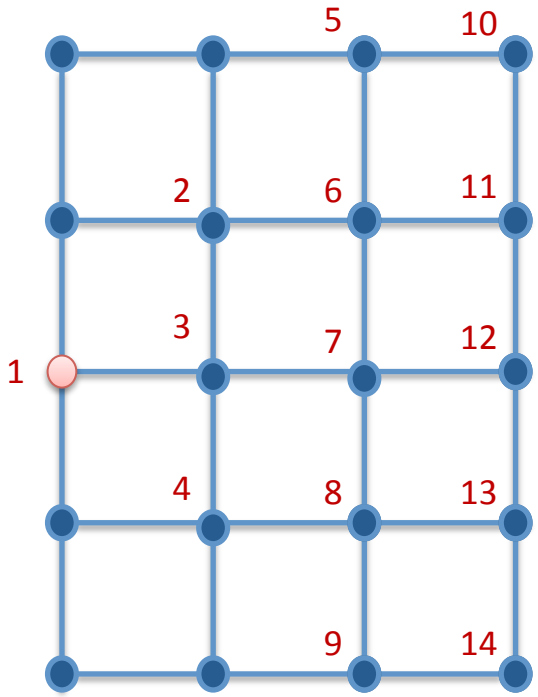
- Information forward cone: spread across F_C

Information spread and simulation

- E.g. Cluster state: general angles
  - $M_a^{\theta} = P_a^{+\theta} - P_a^{-\theta}$ rotate by $Z(\theta)$ and measure X



$$K_i^{\theta_i} := \cos(\theta_i) X_i \otimes \prod_{(i,j)\in Ed} Z_j + i \sin(\theta_i) Z_i X_i \otimes \prod_{(i,j)\in Ed} Z_j$$

$$L_{X_1} = \cos(\theta_1) X_1 \otimes Z_3 + i \sin(\theta_1) Z_1 X_1 \otimes Z_3$$

$$L_{Z_1} = Z_1$$

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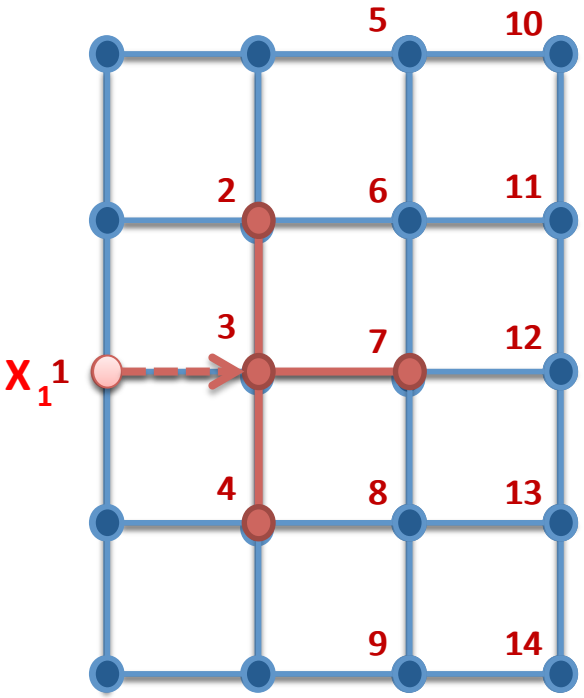

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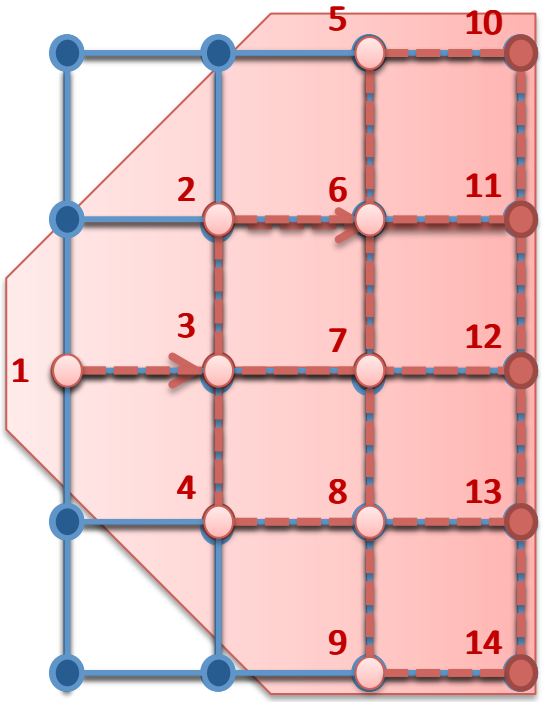
$$L_{Z_1} = Z_1$$

- Every time we use a stabiliser, double terms (or more)

Information spread and simulation

- E.g. Cluster state



- Information forward cone: spread across F_C
- Cost of simulation $O(\exp(F_C))$

Information spread and simulation

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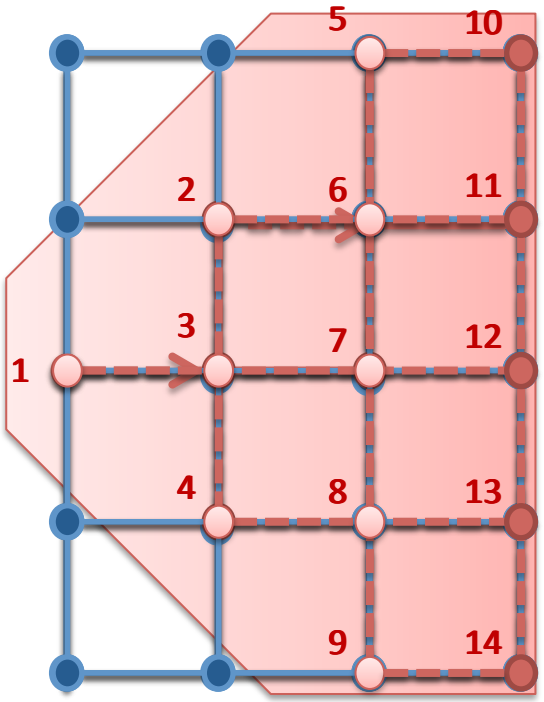

- Information forward cone: spread across F_C
- Cost of simulation $O(\exp(F_C))$

worst case angles!
- efficient for Pauli (Clifford) $\theta = 0, \pi$

Universality?

- Balance:

Spread (via ent)	Vs	Use of spread (# ways of using ent)

Universality?

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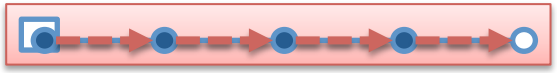
Spread (via ent) Vs Use of spread (# ways of using ent)

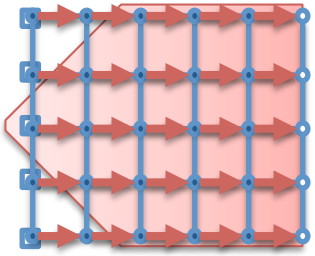
- e.g.

1D)



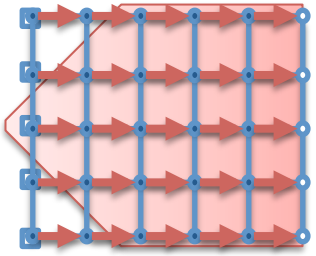
Limited spread

2D)



Spread balanced with use (arbitrary θ)

2D) Pauli



Spread, but not 'used' ($\theta = 0, \pi$)

DM, J. Anders, M. Hadusek and V. Vedral, EPTCS 26 (2010)
J. Anders, DM, V. Vedral and M. Hadusek, Found. Phys. 38, 506 (2008).

Universality?

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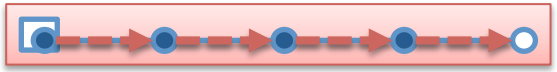
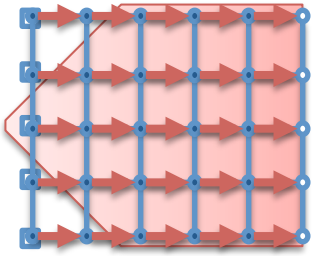


Limited spread

2D)



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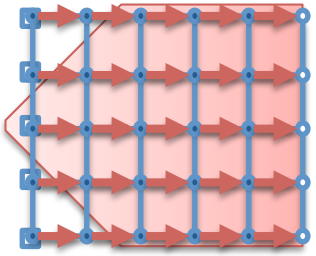

Spread, but not 'used' ($\theta = 0, \pi$)

- Analogy to 2nd law / phase transition?

Energy Vs Entropy?

DM, J. Anders, M. Hadusek and V. Vedral, EPTCS 26 (2010)
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MBQC and gFlow

- Structure for feed forward: corrections and time order

- Natural spread of information

  - Simulation $O(\exp(F_C))$

  - Information light cone F_C

- True difficulty in simulation / universality balance

Spread Vs Use

MBQC and gFlow

- Structure for feed forward: corrections and time order

- Natural spread of information

  - Simulation $O(\exp(F_C))$

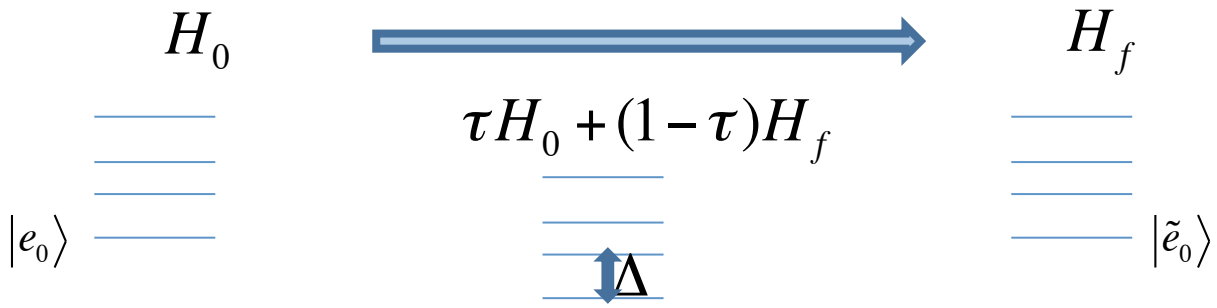
  - Information light cone F_C

- True difficulty in simulation / universality balance

Spread vs Use

Not simple! (clifford + $\pi/8$)
-> maybe gFlow helps (same language)

AQC and gFlow?



- Adiabatic theorem: slow enough, stay in ground state

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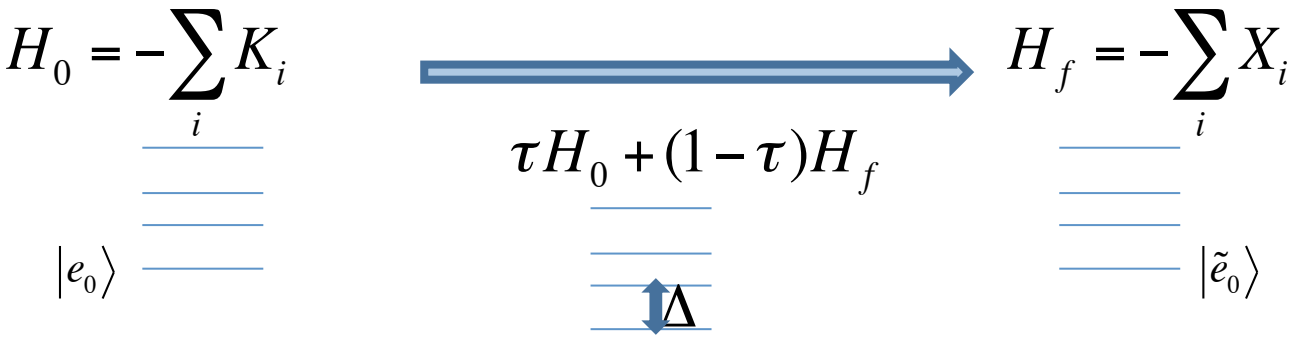

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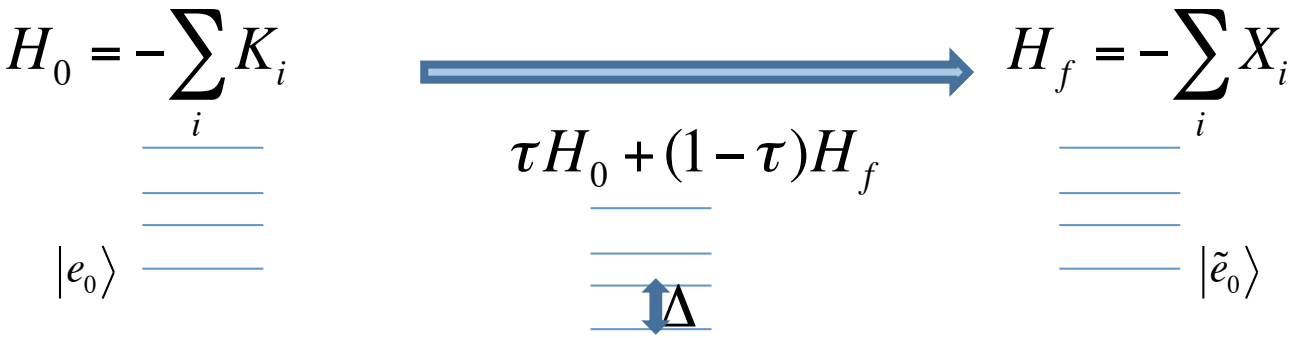
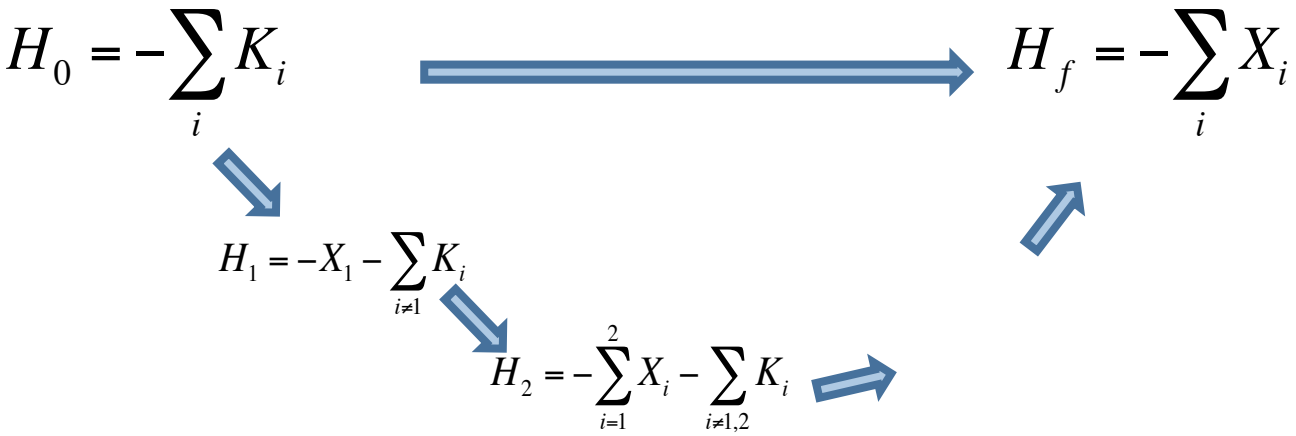
AQC and gFlow?



- Adiabatic theorem: slow enough, stay in ground state
- Bacon Flammia, cluster state -> AQC
- Use gFlow to generalise AGSQC

B. Antonio, DM, J. Anders arxiv:1309.1443

AGSQC and gFlow



- gFlow gives natural H_i
- Easy to solve
- Tradeoff?

Classical computation ⟷ degree of H_0

- Spread of information bounds t

gFlow AGSQC 1:

Step by step

$$H_0 = -\sum_i K_i \Rightarrow H_1 = -X_1 - \sum_{i\neq 1} K_i \Rightarrow H_2 = -\sum_{i=1}^{2} X_i - \sum_{i\neq 1,2} K_i \Rightarrow \cdots \Rightarrow H_f = -\sum_i X_i$$

- gFlow implies gives natural H_i

$$\forall i, \quad \exists \quad \alpha(i) \in g(i) \quad \text{s.t.}$$

$$\{X_i, K_{\alpha(i)}\} = 0 \qquad [X_i, K_{j>i}] = 0$$

$$H(\tau) = \tau\left(-\sum_i K_i\right) + (1-\tau)\left(-X_1 - \sum_{\substack{j\neq\alpha(i)\\ j\geq i}} K_j\right)$$

$$= \tau K_{\alpha(1)} + (1-\tau)\left(-X_1 - \sum_{\substack{j\neq\alpha(i)\\ j\approx i}} K_j\right) + \sum_{\substack{j\neq\alpha(i)\\ j>i}} K_j$$

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- time

$$t = O(poly(n))$$

gFlow AGSQC 2:

Round by round

$$\tilde{H}_0 = -\sum_i T_i \Rightarrow \tilde{H}_1 = -\sum_{i\in R_1} X_i - \sum_{i\notin R_1} T_i \Rightarrow \tilde{H}_2 = -\sum_{i\in R_1 R_2} X_i - \sum_{i\notin R_1 R_2} T_i \Rightarrow \cdots \Rightarrow H_f = -\sum_i X_i$$

- Play with degree using gFlow

$$\tilde{H}_0 = -\sum_i T_i \qquad T_i = \prod_{j\in g(i)} K_j$$

-> same ground state space, same spectrum

$$\{X_i, T_i\} = 0 \qquad [X_i, T_{j\geq i}] = 0$$

- Round by round, as gFlow

-> not quite $t = depth(MBQC)$ as is [work in progress!]

- Trade-off

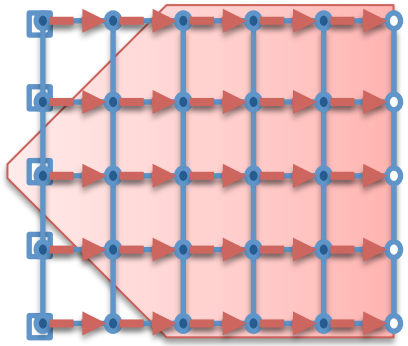
-> speed against degree

gFlow AGSQC 2:

Direct

$$H_0 = -\sum_i K_i \longrightarrow H_f = -\sum_i X_i$$

- Speed t depends on spread (finite speed of spread)



- Trade-off: countered by high degree

$$\tilde{H}_0 = -\sum_i T_i \longrightarrow H_f = -\sum_i X_i$$

Conclusions

- gFlow shows information spread

Information light cone = causal light cone
Playground for causal order?

$\mathcal{G}1$ $\mathcal{G}2$

- Spread bounds simulation

Cost $O(\exp(F_C))$

- `Good' resource

Balance: Spread Vs 'Use'

- General translation to AGSQC

Translation of trade-offs?
Notions of spread

Thank you!

http://iq.enst.fr/

LOOKING FOR POST DOCS

cnrs

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HIPERCOM

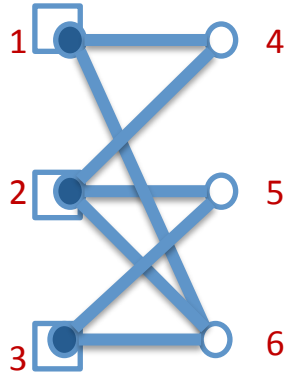
MAIRIE DE PARIS
CIQWII

AGENCE NATIONALE DE LA RECHERCHE
ANR
FREQUENCY

TELECOM ParisTech

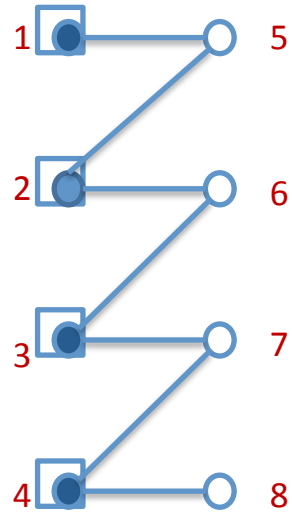
Examples

- Sometimes need more than one in correcting set



$$g(1) = 4$$
$$g(2) = 5$$
$$g(3) = 4, 6$$
$$1 < 2 < 3$$

- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10



$$g(i) = i + 4$$

$$1 < 2 < 3 < 4$$
$$\#\,rounds = n$$

$$g(i) = 5, \ldots, i + 4$$
$$g(1) = 5$$
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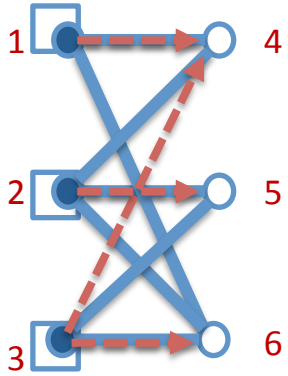
$$\ldots$$
$$1 \approx 2 \approx 3 \approx 4$$
$$\#\,rounds = 1$$

Examples

- Sometimes need more than one in correcting set



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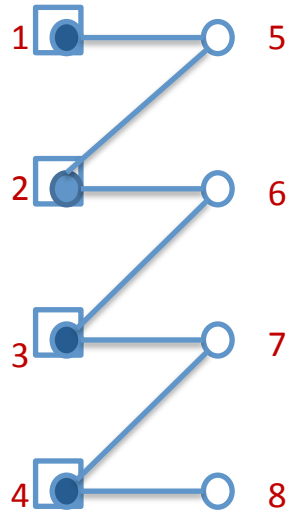

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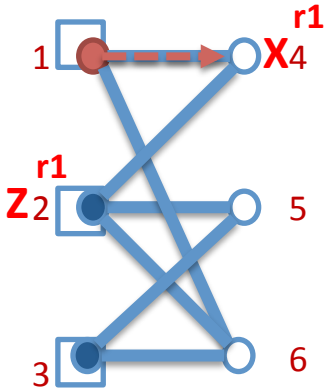

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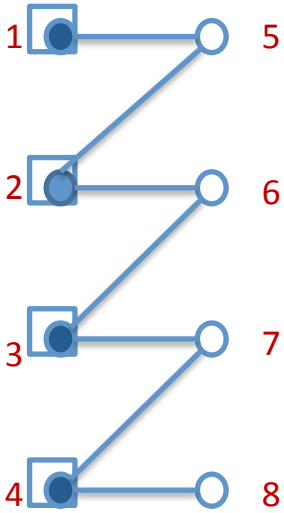
$$K_4 = Z_1 \otimes Z_2 \otimes X_4$$

- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10



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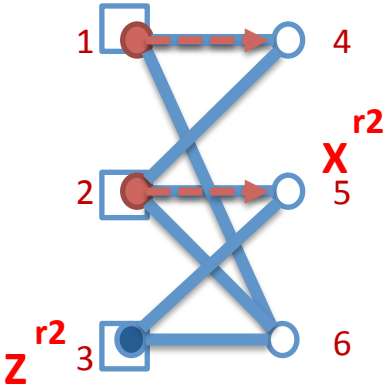
Examples

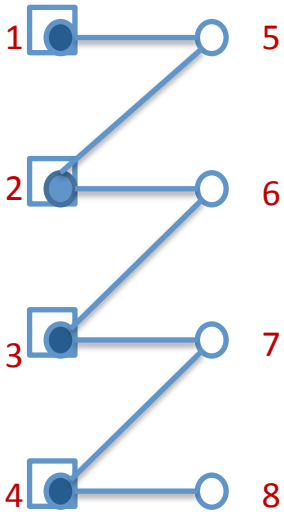
- Sometimes need more than one in correcting set



$$g(1) = 4$$
$$g(2) = 5$$
$$g(3) = 4,6$$
$$1 < 2 < 3$$

$$K_5 = Z_2 \otimes Z_3 \otimes X_5$$

- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10



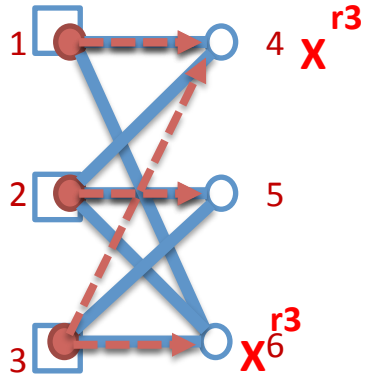
$$g(i) = i + 4$$

$$1 < 2 < 3 < 4$$
$$\#\,rounds = n$$

$$g(i) = 5,\ldots,i+4$$
$$g(1) = 5$$
$$g(2) = 5,6$$
$$\ldots$$
$$1 \approx 2 \approx 3 \approx 4$$
$$\#\,rounds = 1$$

Examples

- Sometimes need more than one in correcting set

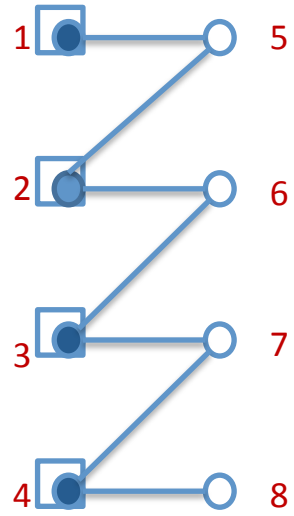


$$g(1) = 4$$
$$g(2) = 5$$
$$g(3) = 4,6$$
$$1 < 2 < 3$$

$$K_4 K_6 = X_4 \otimes X_6$$

Other Zs cancel

- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10



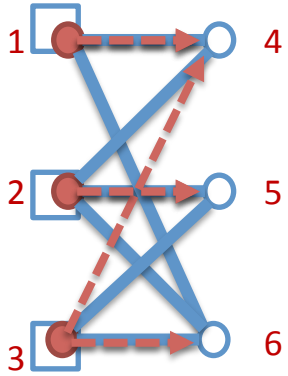
$$g(i) = i + 4$$

$$1 < 2 < 3 < 4$$
$$\#\,rounds = n$$

$$g(i) = 5,\ldots,i+4$$
$$g(1) = 5$$
$$g(2) = 5,6$$
$$\ldots$$
$$1 \approx 2 \approx 3 \approx 4$$
$$\#\,rounds = 1$$

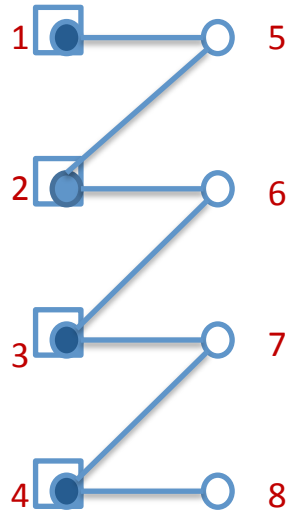
Examples

- Sometimes need more than one in correcting set



$$g(1) = 4$$
$$g(2) = 5$$
$$g(3) = 4, 6$$
$$1 < 2 < 3$$

- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10



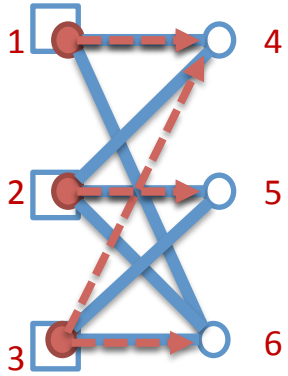
$$g(i) = i + 4$$

$$1 < 2 < 3 < 4$$
$$\#\,rounds = n$$

$$g(i) = 5, \ldots, i + 4$$
$$g(1) = 5$$
$$g(2) = 5, 6$$
$$\ldots$$
$$1 \approx 2 \approx 3 \approx 4$$
$$\#\,rounds = 1$$

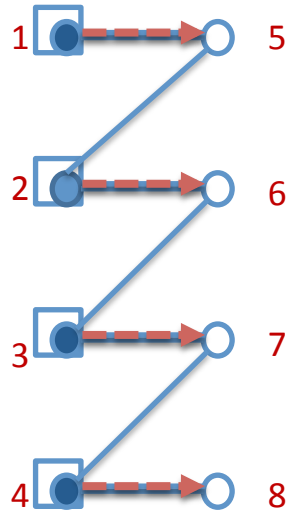
Examples

- Sometimes need more than one in correcting set



$$g(1) = 4$$
$$g(2) = 5$$
$$g(3) = 4, 6$$
$$1 < 2 < 3$$

- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10

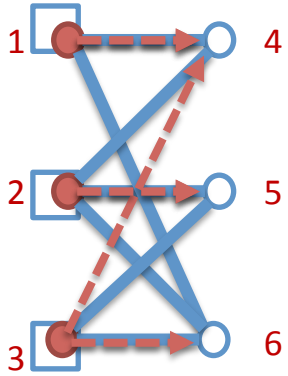


$$g(i) = i + 4$$

$$1 < 2 < 3 < 4$$
$$\#\,rounds = n$$

Examples

- Sometimes need more than one in correcting set



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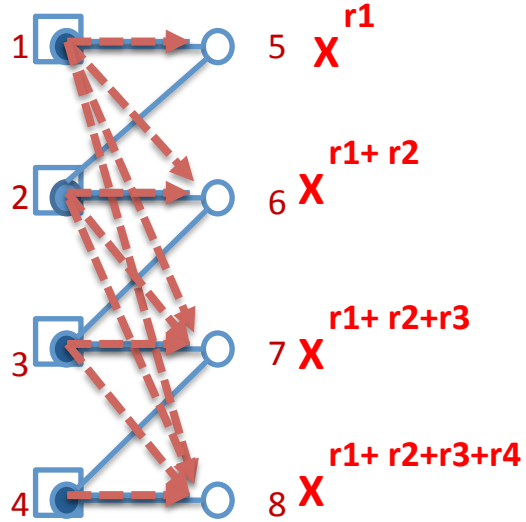
- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10

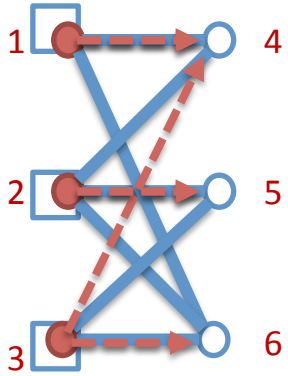


$$g(i) = i + 4$$
$$1 < 2 < 3 < 4$$
$$\#\,rounds = n$$

$$g(i) = i + 4, \ldots, 8$$
$$g(1) = 5, 6, 7, 8$$
$$g(2) = 6, 7, 8$$
$$\ldots$$
$$1 \approx 2 \approx 3 \approx 4$$
$$\#\,rounds = 1$$

Examples

- Sometimes need more than one in correcting set



$$g(1) = 4$$
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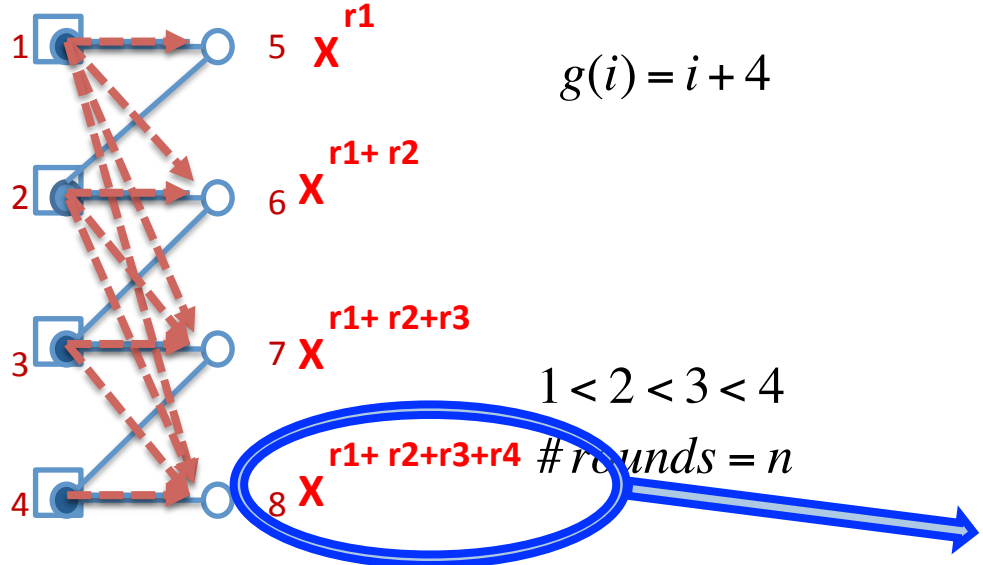
- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10



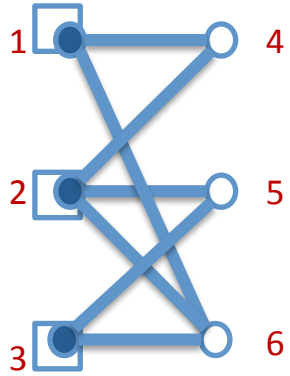
$$g(i) = i + 4$$
$$1 < 2 < 3 < 4$$
$$\#\,rounds = n$$

$$g(i) = i + 4,\ldots,8$$
$$g(1) = 5,6,7,8$$
$$g(2) = 6,7,8$$
$$\ldots$$
$$1 \approx 2 \approx 3 \approx 4$$
$$\#\,rounds = 1$$

Classical comp $\log(n)$

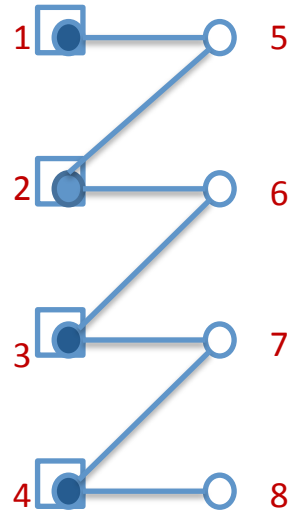
Examples

- Sometimes need more than one in correcting set



$$g(1) = 4$$
$$g(2) = 5$$
$$g(3) = 4, 6$$
$$1 < 2 < 3$$

- Not unique (allows for tradeoff) A. Broadbent, E. Kashefi TCS '07, D. Browne, E. Kashefi and S. Perdrix TQC '10



$$g(i) = i + 4$$

$$1 < 2 < 3 < 4$$

$$\#\,rounds = n$$

Classical comp $const.$

$$g(i) = i + 4, \ldots, 8$$
$$g(1) = 5, 6, 7, 8$$
$$g(2) = 6, 7, 8$$
$$\ldots$$

$$1 \approx 2 \approx 3 \approx 4$$

$$\#\,rounds = 1$$

Classical comp $\log(n)$