Scalable repeater architectures for multi-party states

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ÖAW IQI universität innsbruck

Quantum states

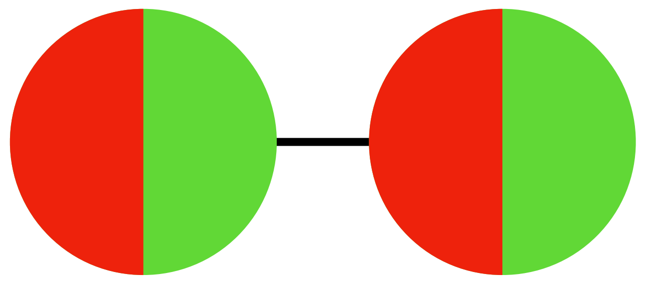
Classical bit

$|0\rangle$ $|1\rangle$

Quantum bit (Qbit)

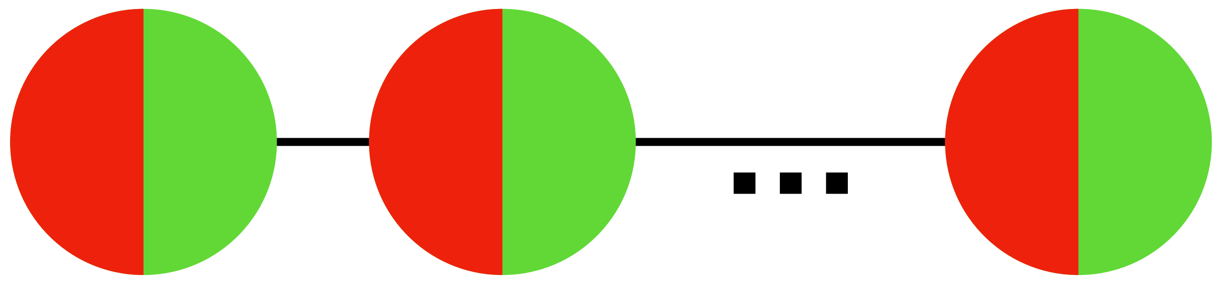
$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

Quantum states

2 qubits: 

Bell state

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

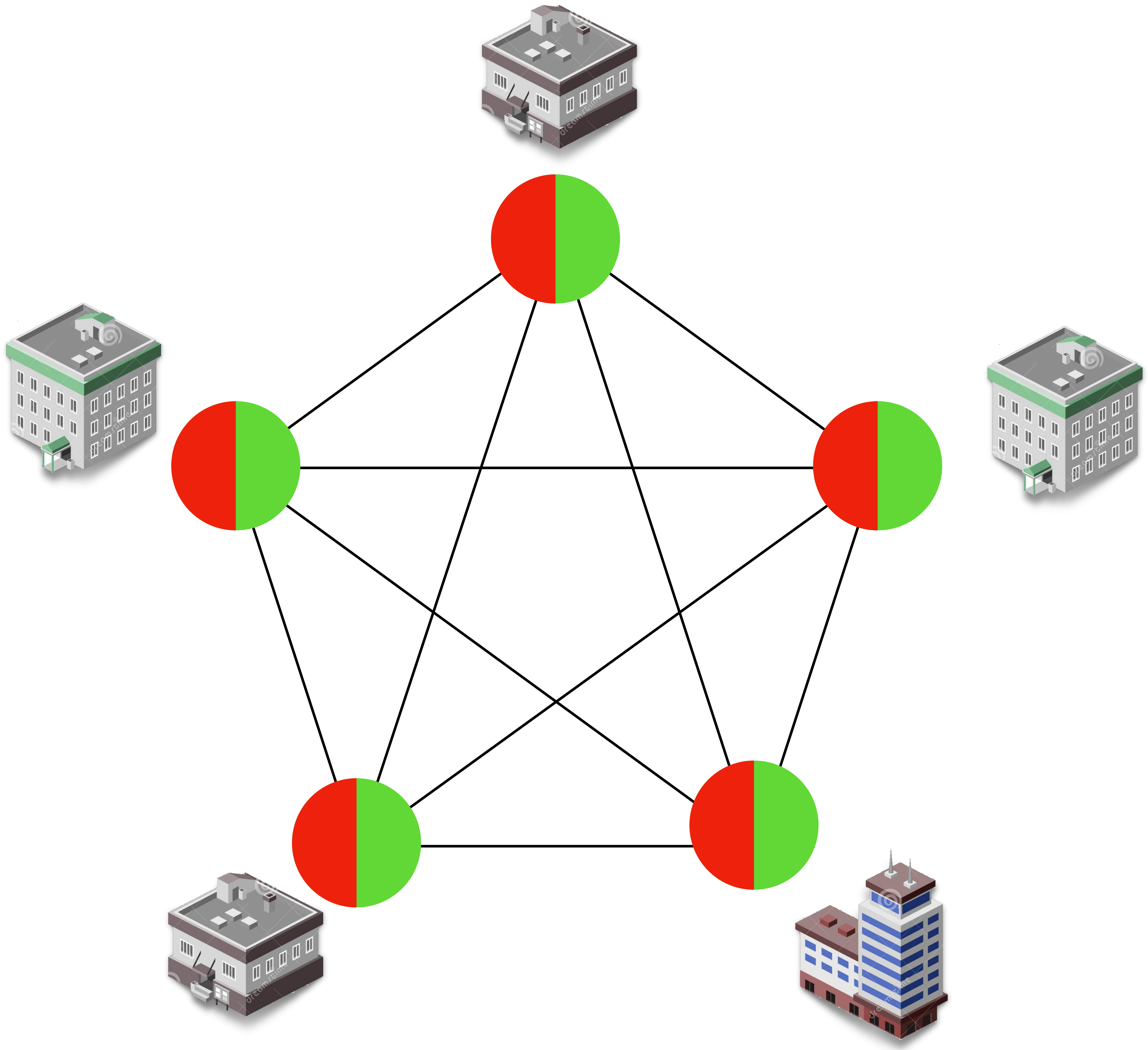
n qubits: 

n-party GHZ states

$$\frac{1}{\sqrt{2}}(|00..0\rangle + |11..1\rangle)$$

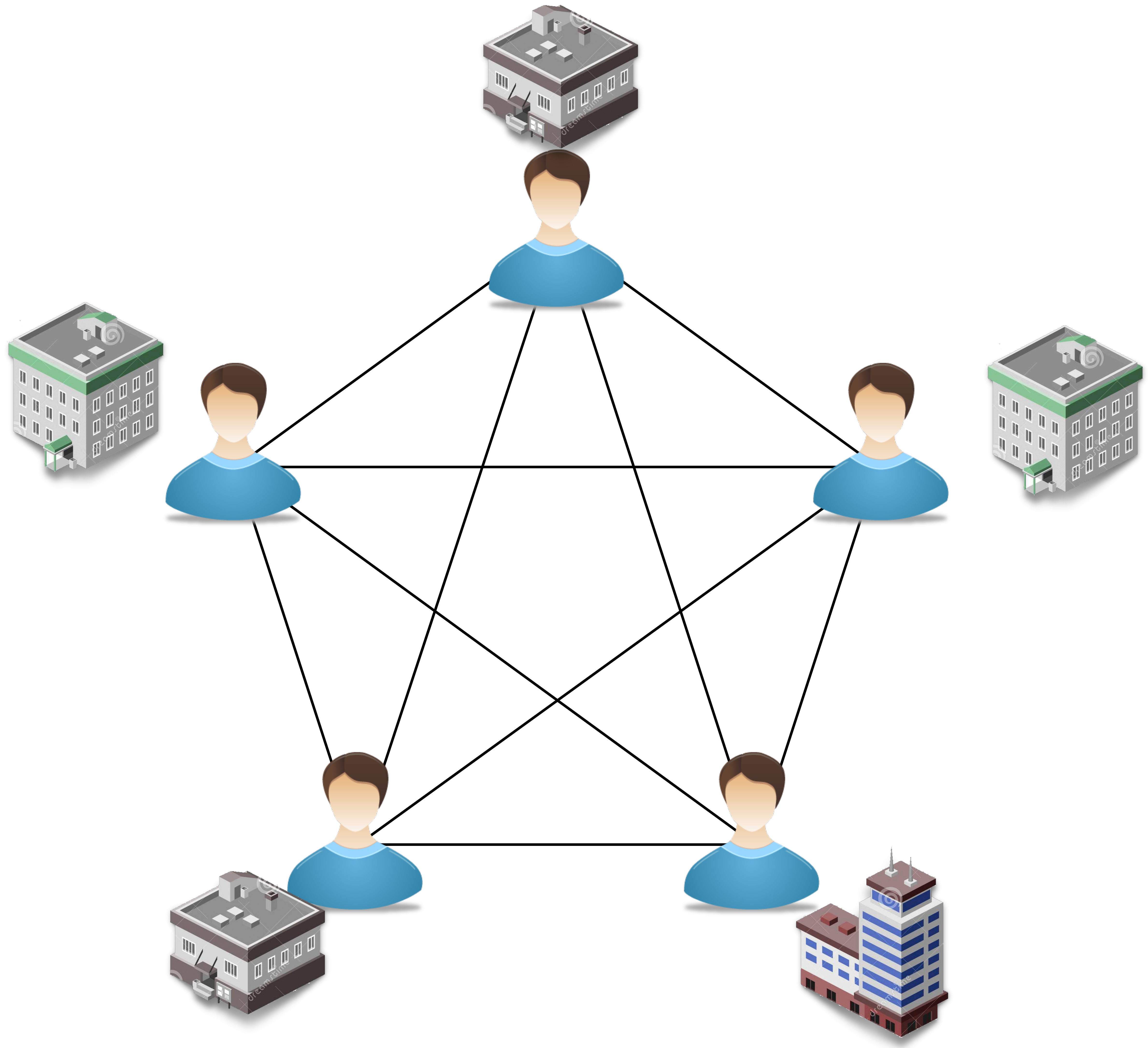
Applications

- Secure communication
- Secret voting
- Distributed quantum computing



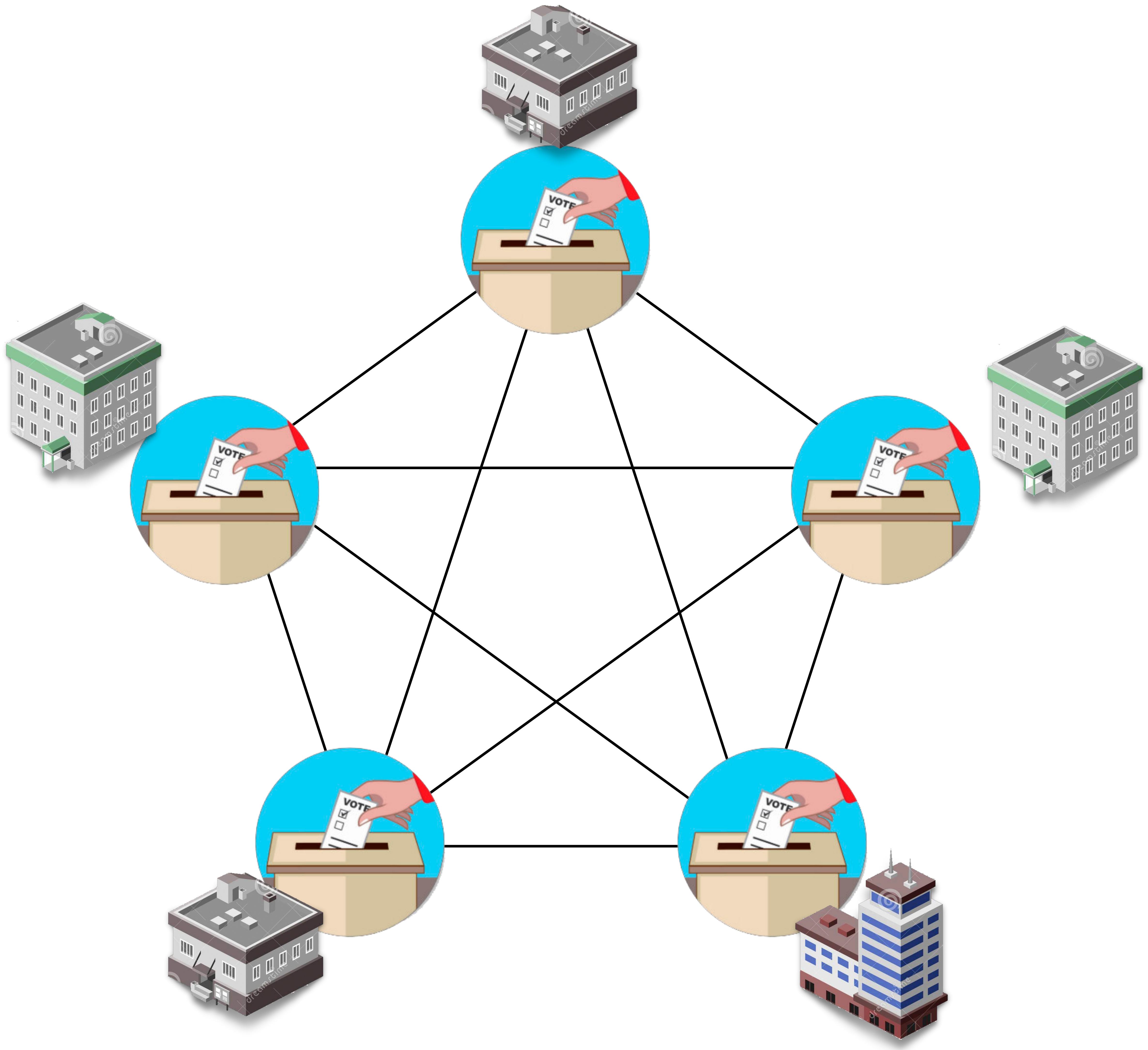
Applications

- **Secure communication**
- Secret voting
- Distributed quantum computing



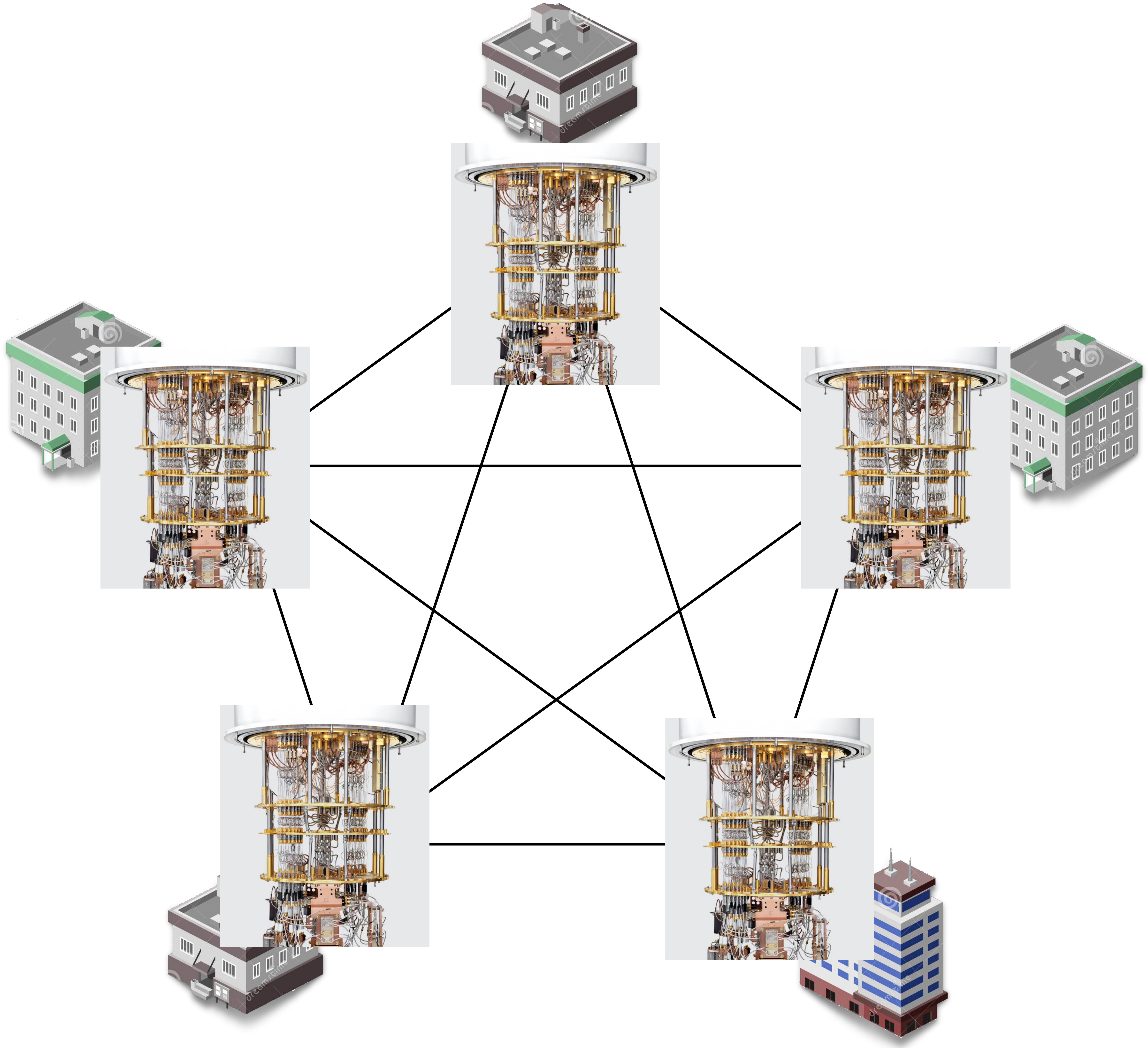
Applications

- Secure communication
- **Secret voting**
- Distributed quantum computing



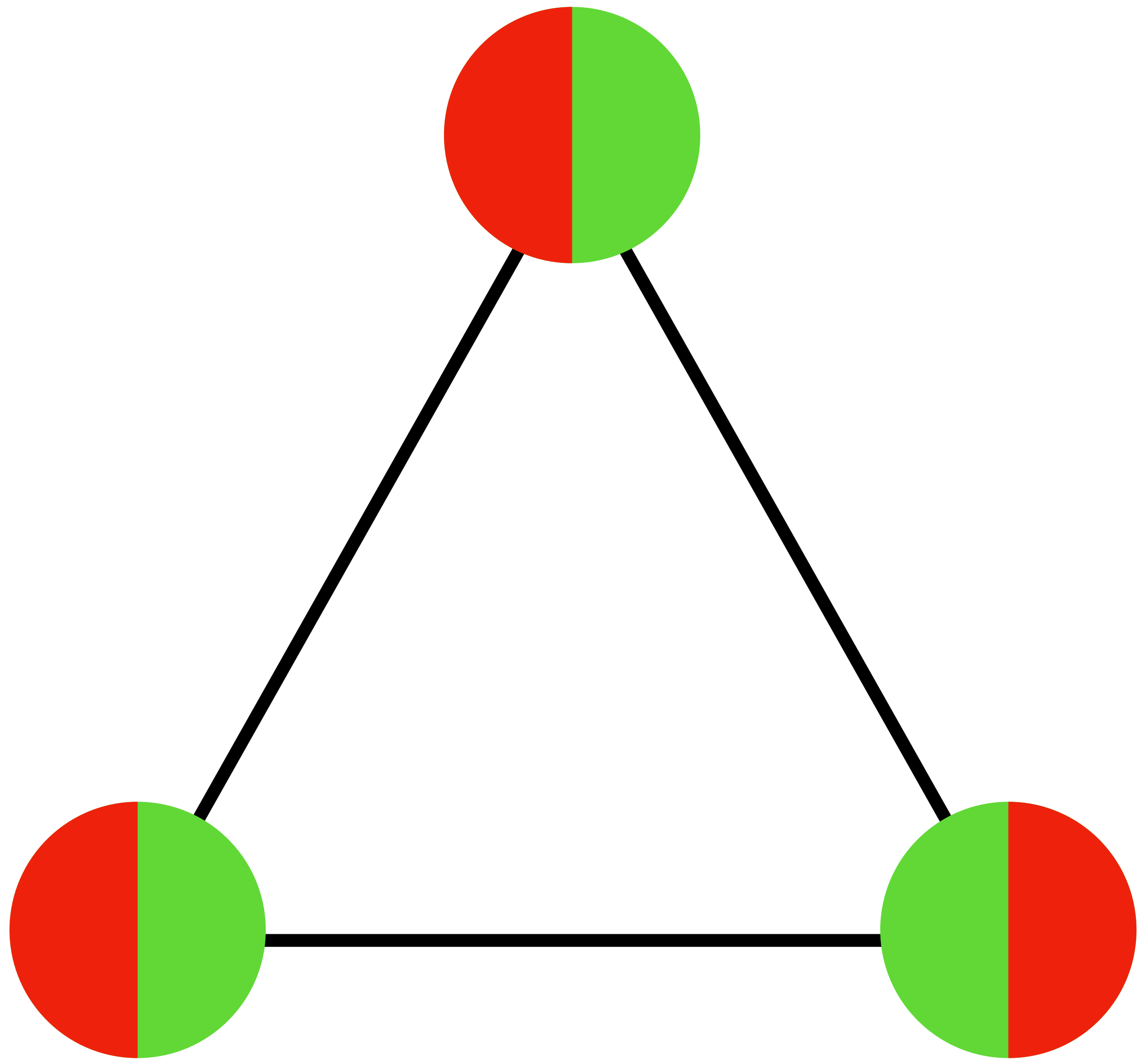
Applications

- Secure communication
- Secret voting
- **Distributed quantum computing**



Target tripartite state

$$\frac{1}{\sqrt{2}}(|001\rangle + |110\rangle)$$



Plan

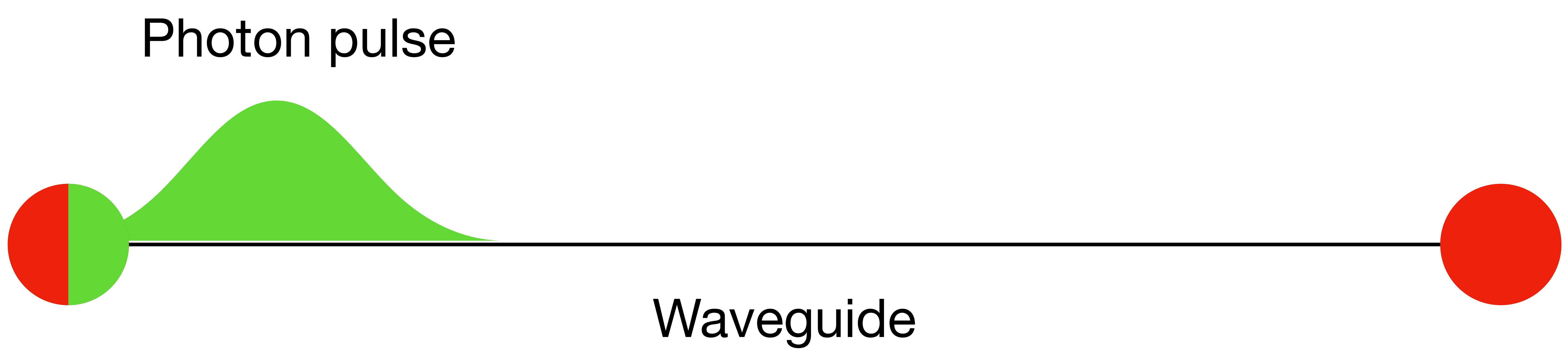
1. 1D and 2D quantum repeaters for distribution of entangled states

2. Protocol for the 2D quantum repeater

3. Comparison of quantum networks build with the 1D and 2D quantum repeaters

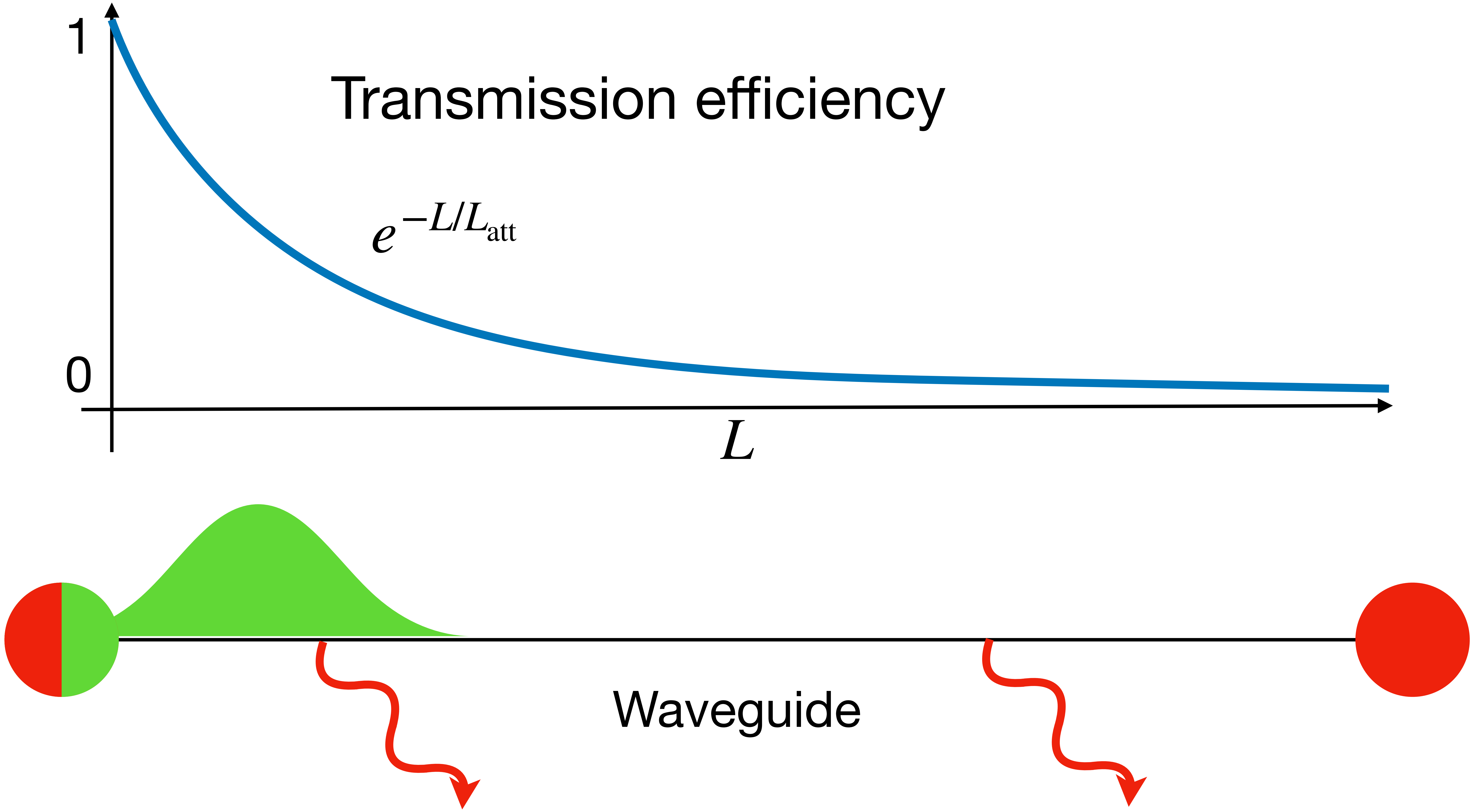
Direct transmission

Direct transmission

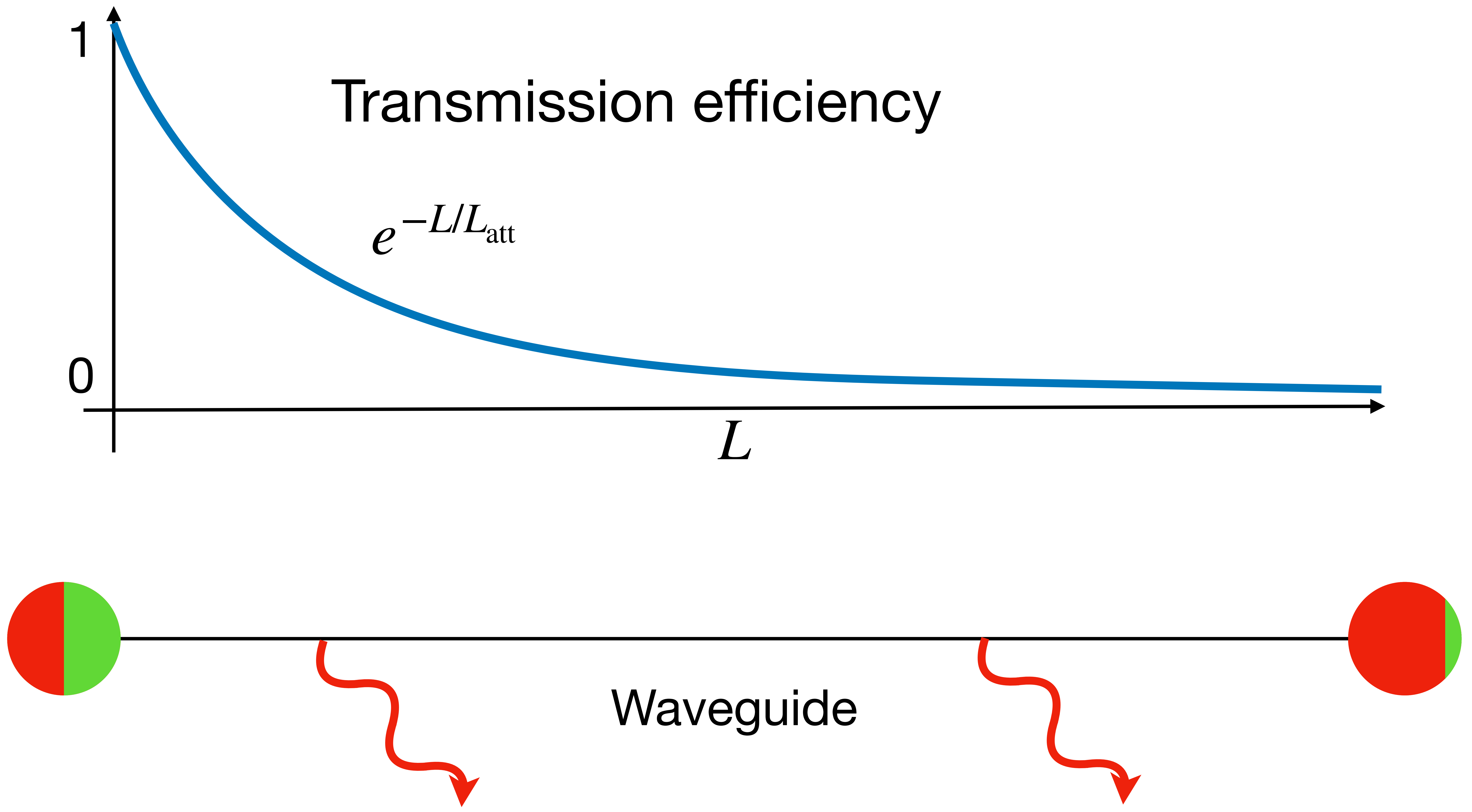


Direct transmission

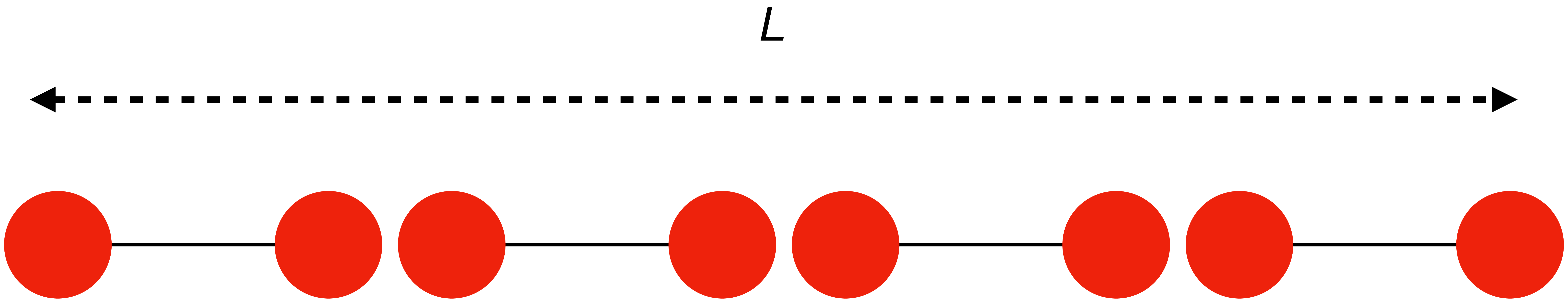
Direct transmission



Direct transmission

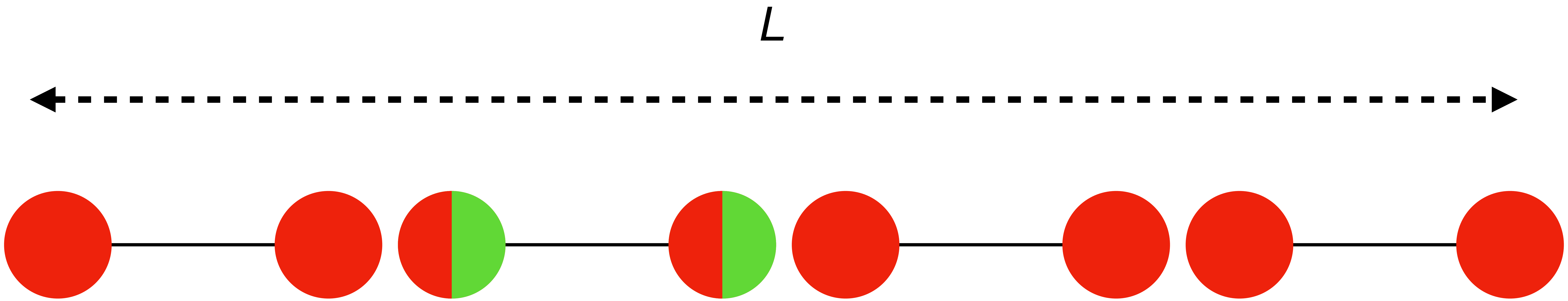


Quantum repeater*



*Briegel, H.-J., Dür, W., Cirac, J. I., & Zoller, P. (1998). PRL, *81*(26), 5932–5935

Quantum repeater*



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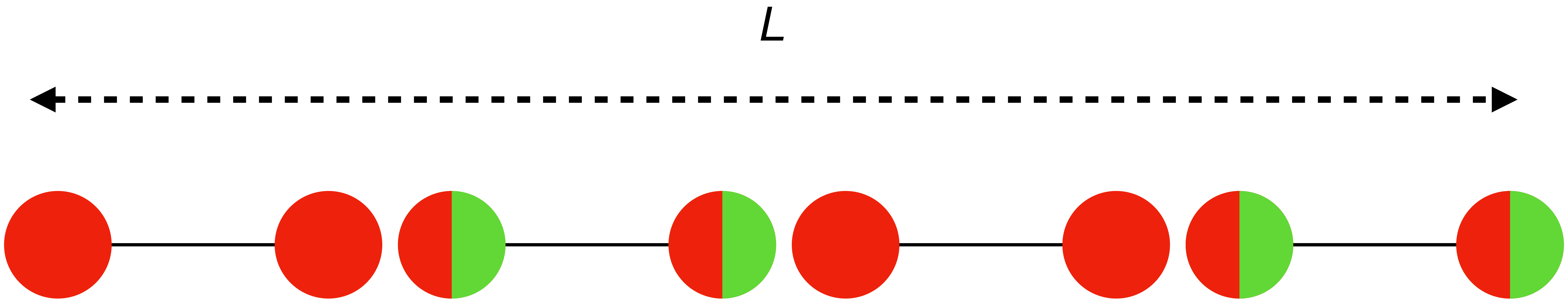

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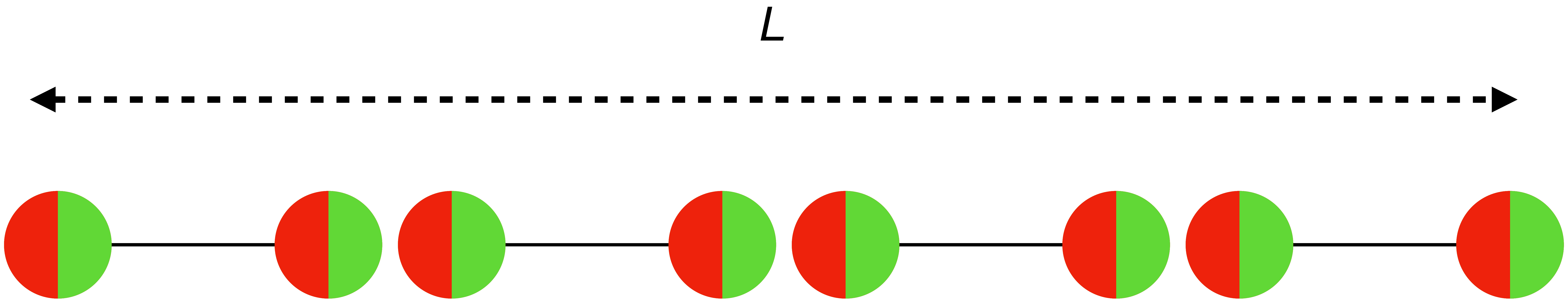

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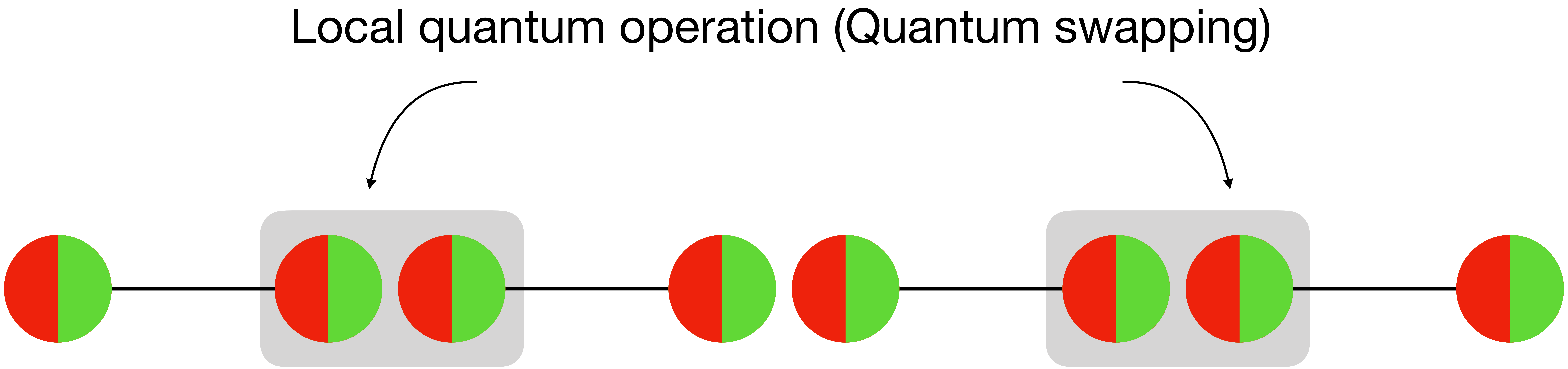

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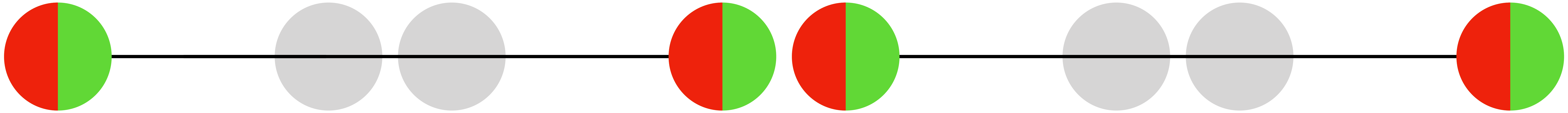

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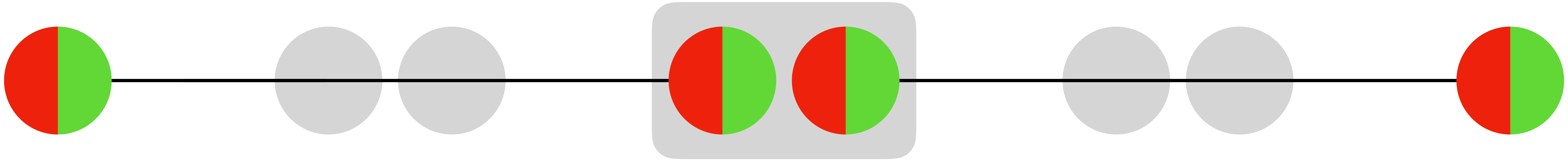

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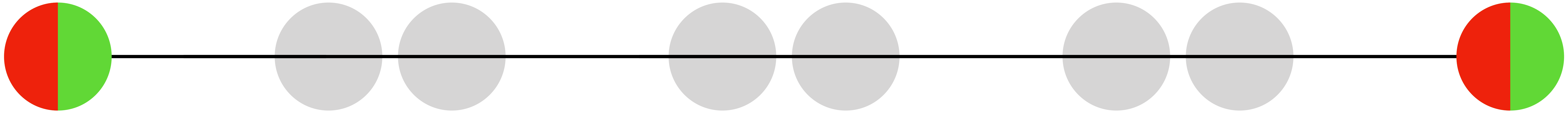

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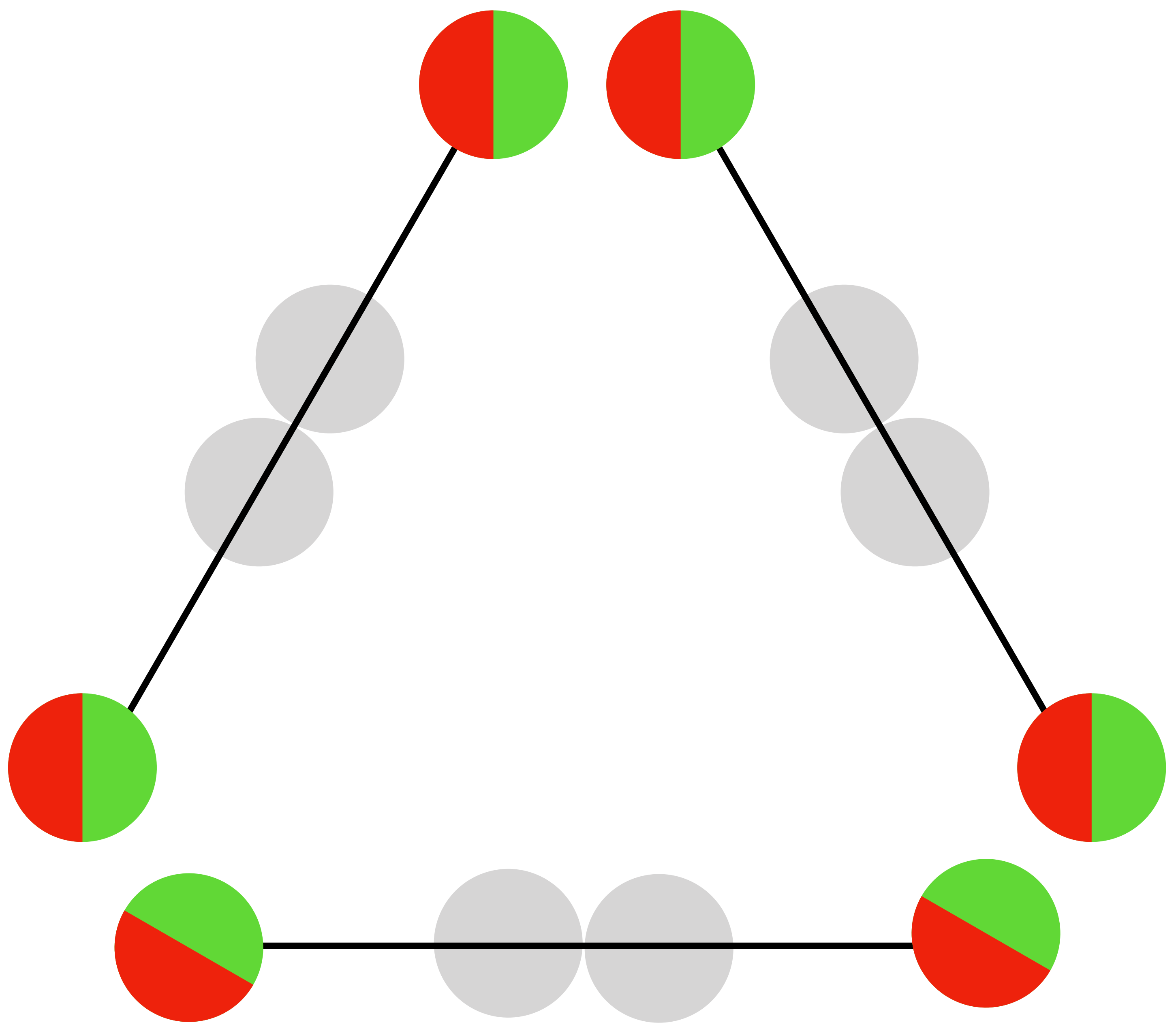
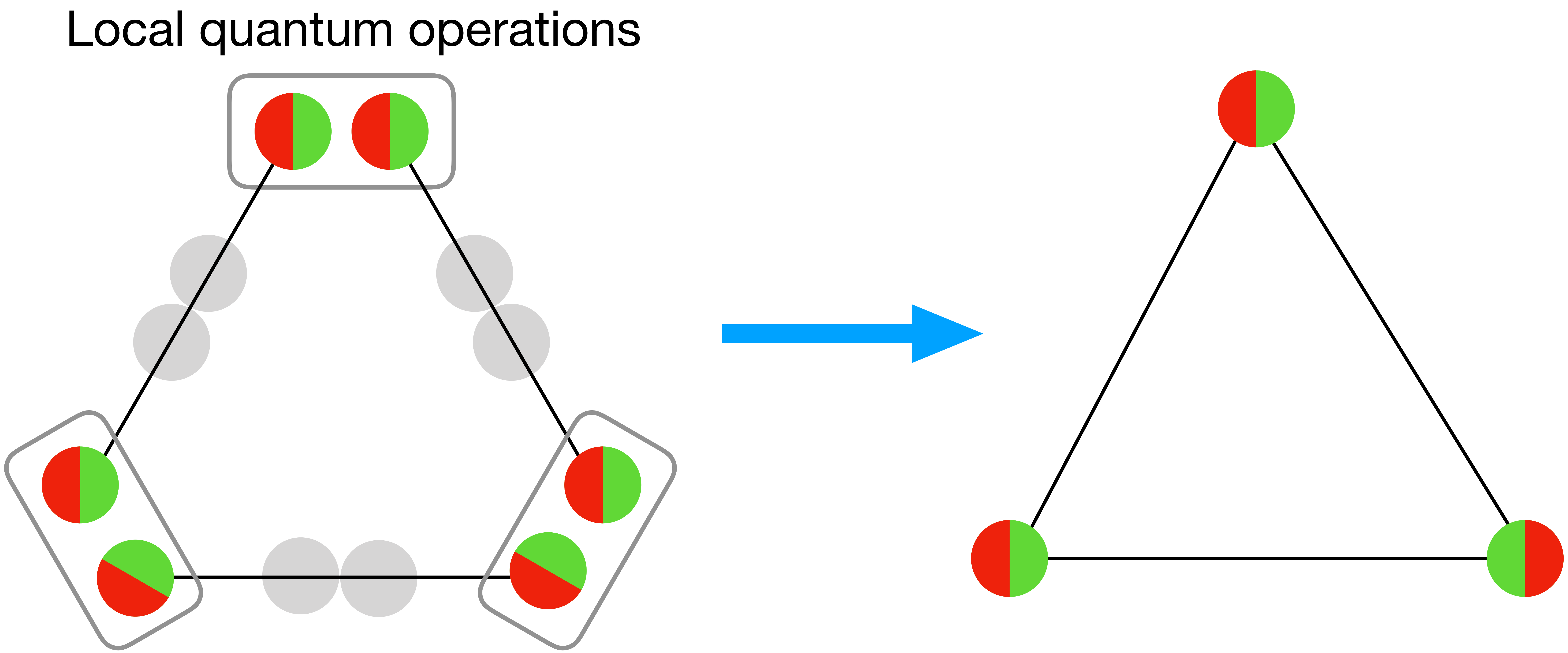
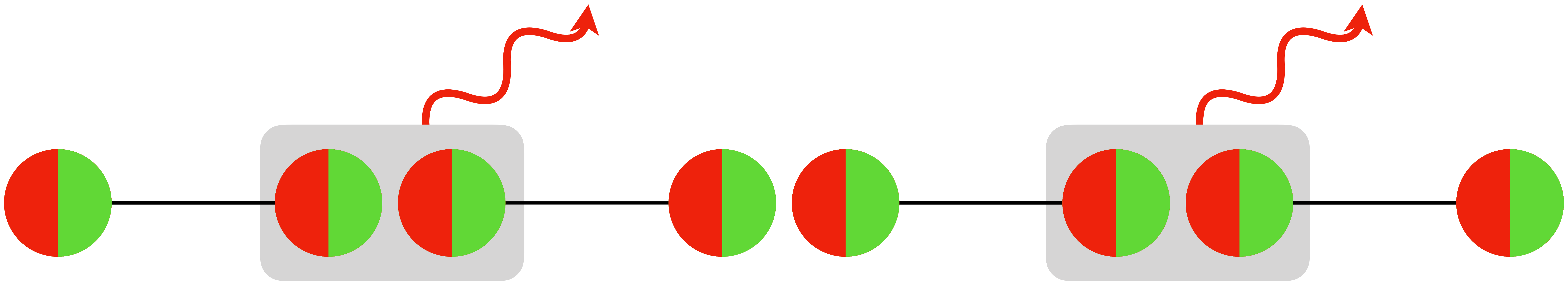
1D repeater network



1D repeater network



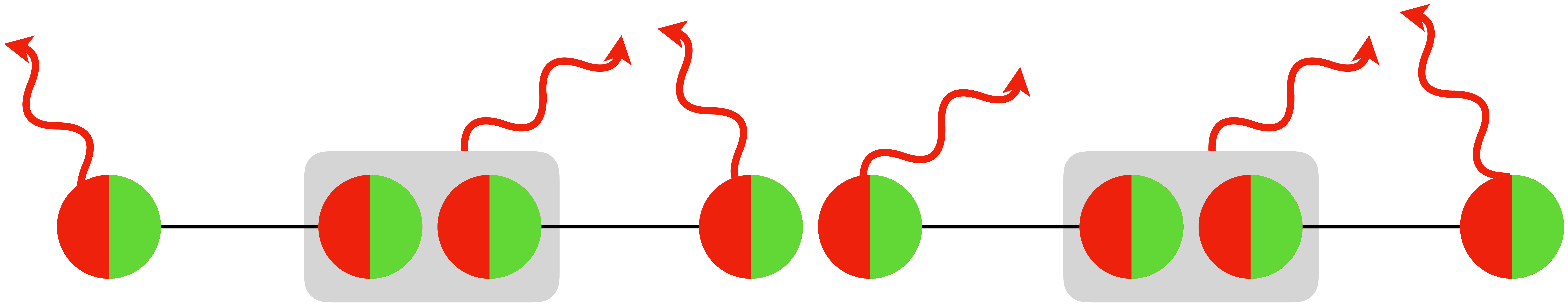
Quantum repeater



Imperfections:

- Errors in quantum local operations

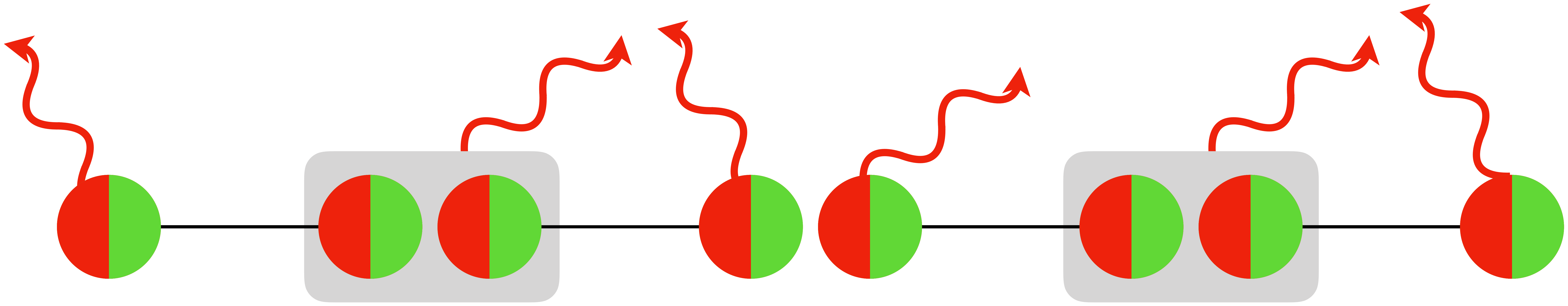
Quantum repeater



Imperfections:

- Errors in quantum local operations
- Finite memory time ~10ms

Quantum repeater



Imperfections:

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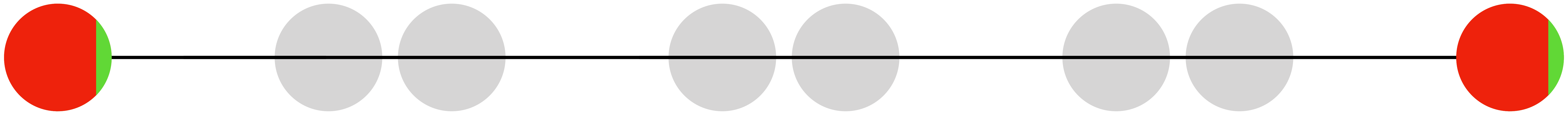
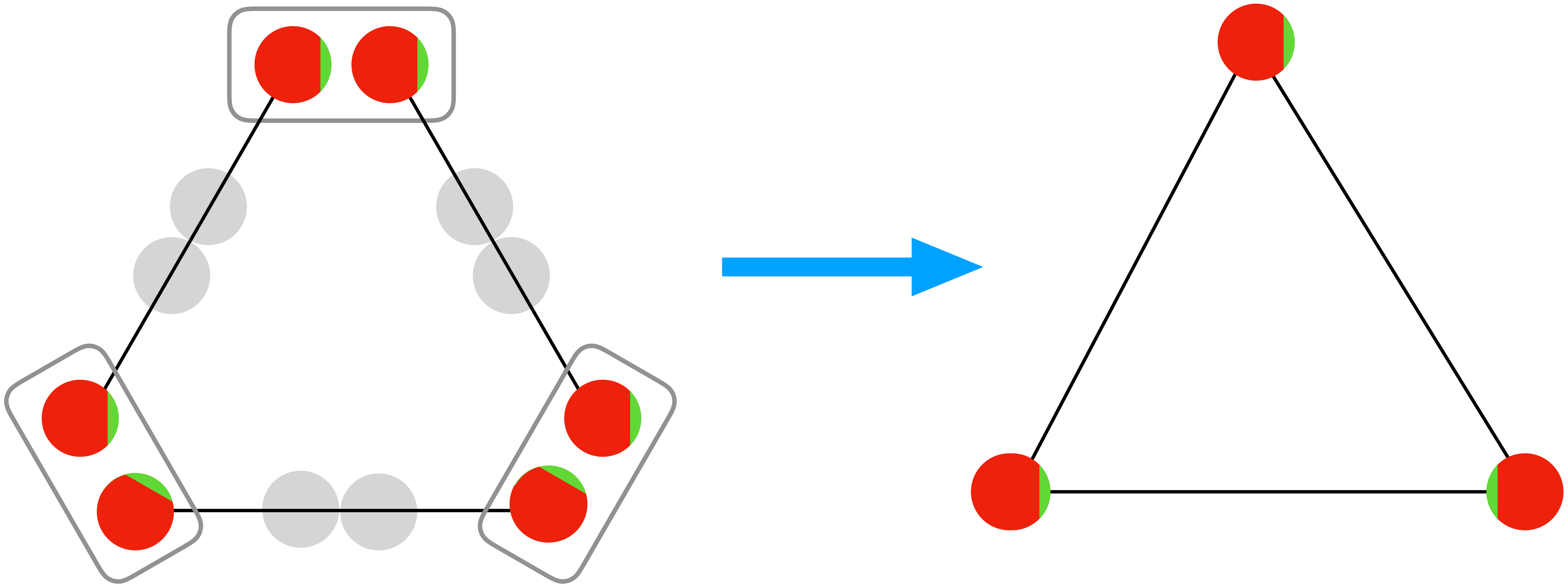
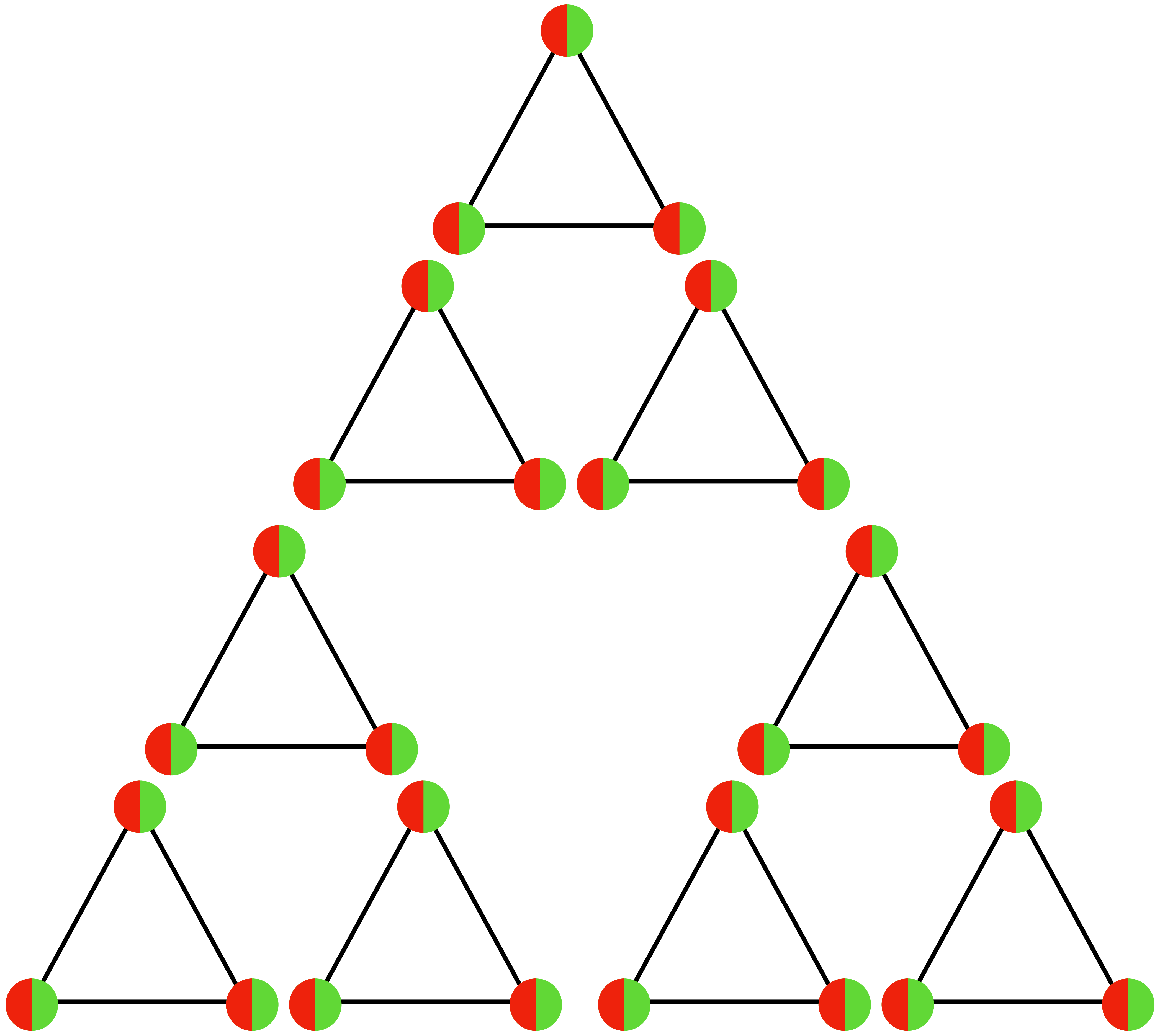


1D repeater network

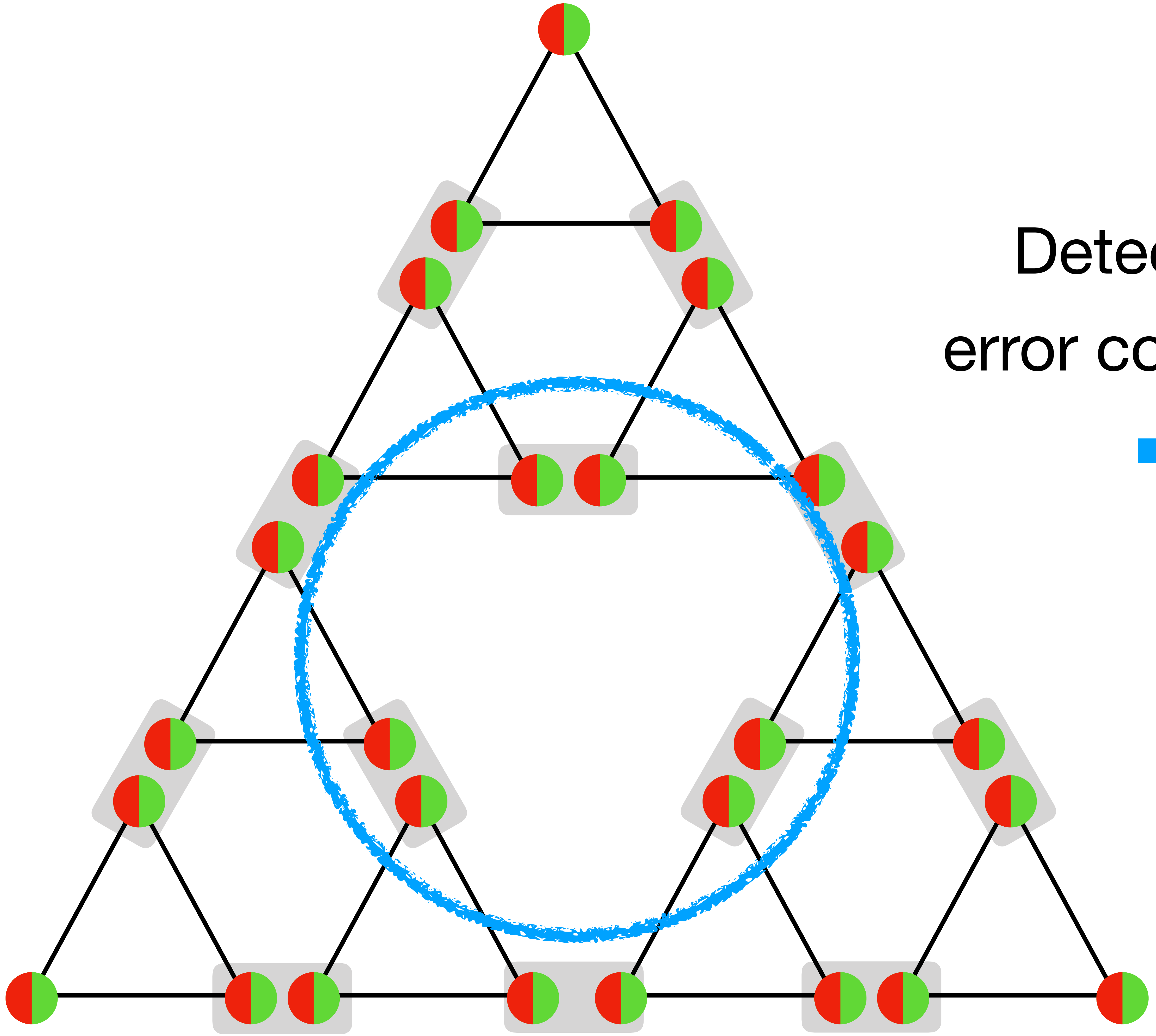


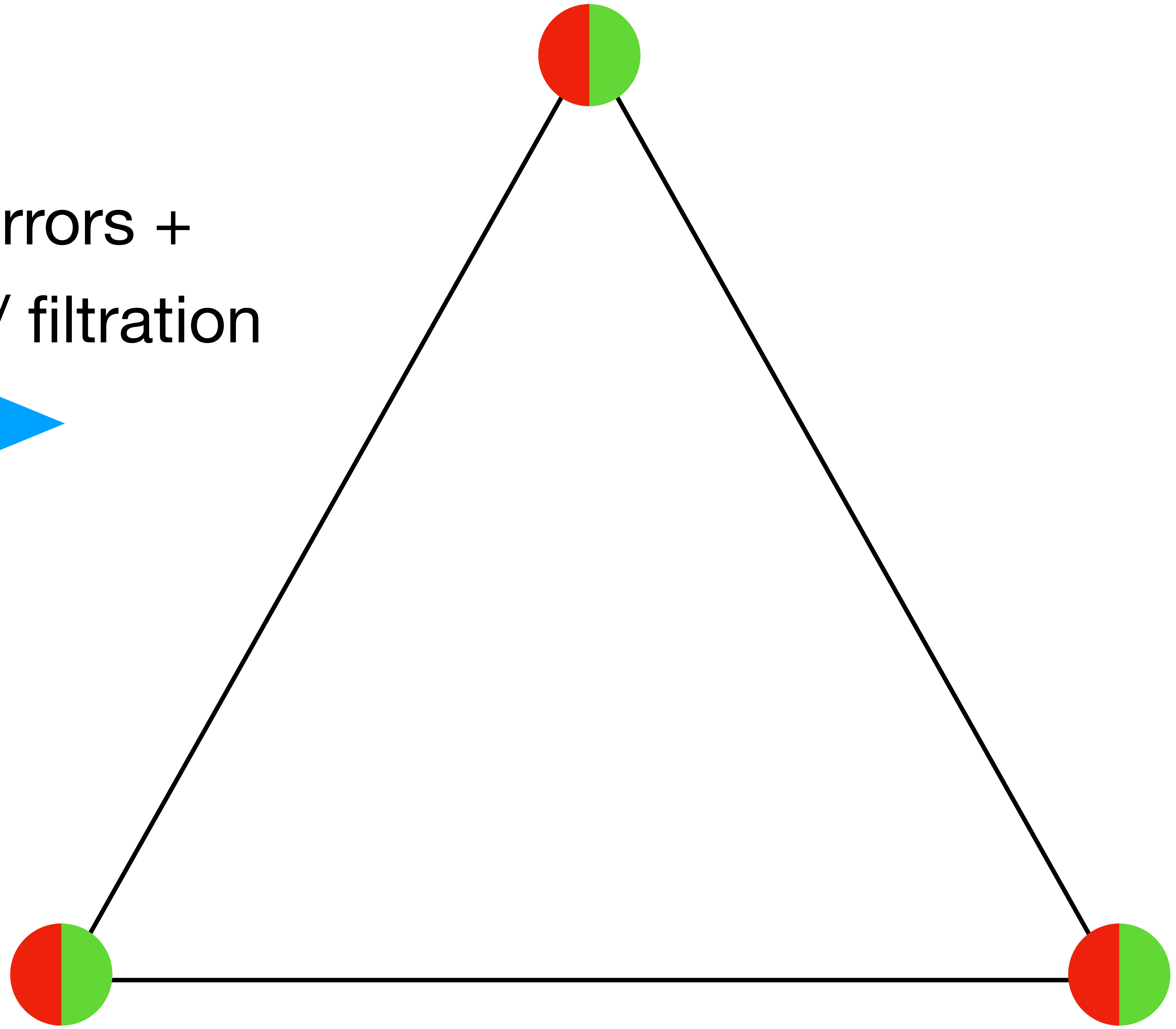
2D repeater network*



*Wallnöfer, J., Zwerger, M., Muschik, C., Sangouard, N., & Dür, W. (2016). *PRA*, *94*(5)

2D repeater network*





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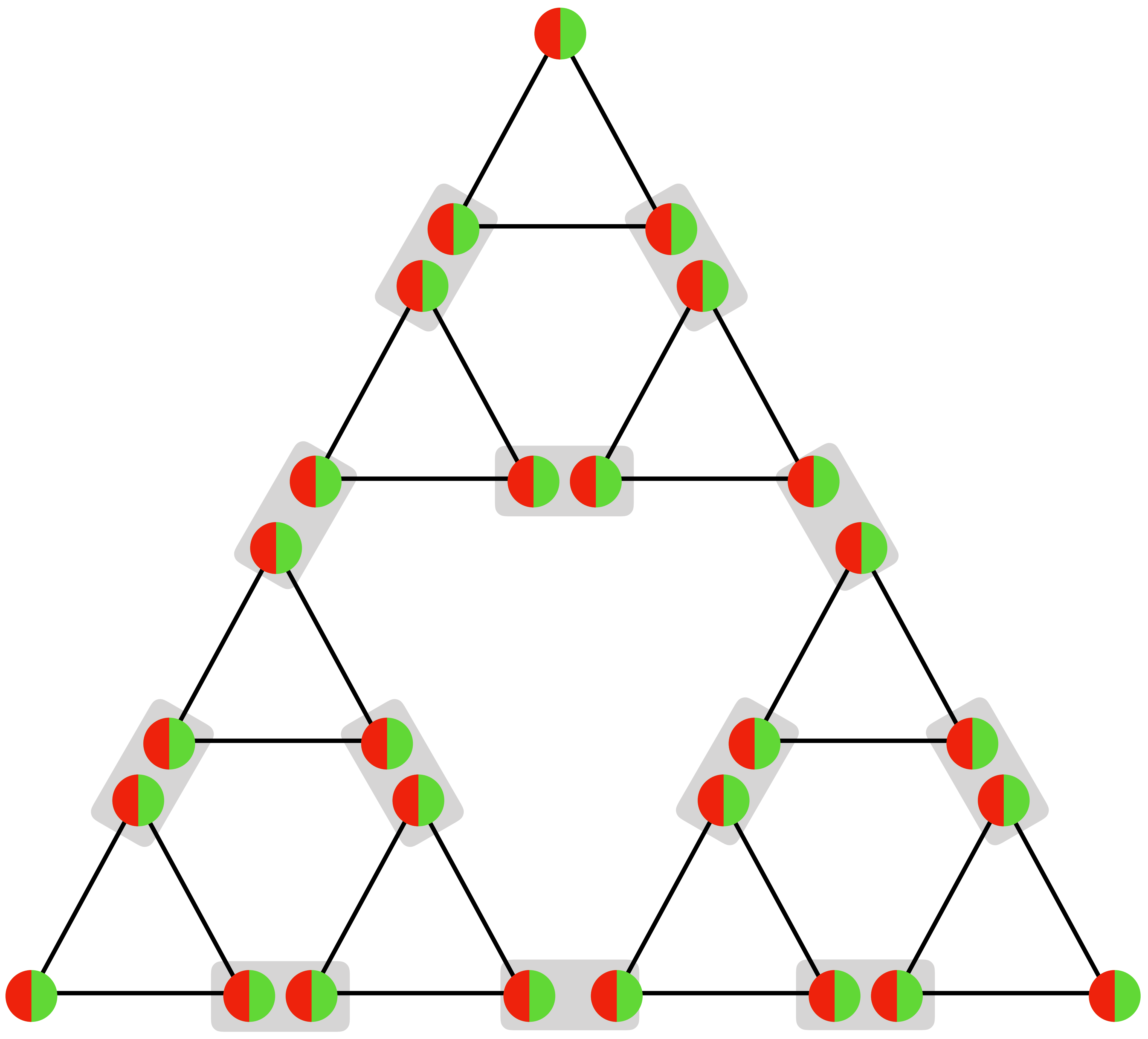
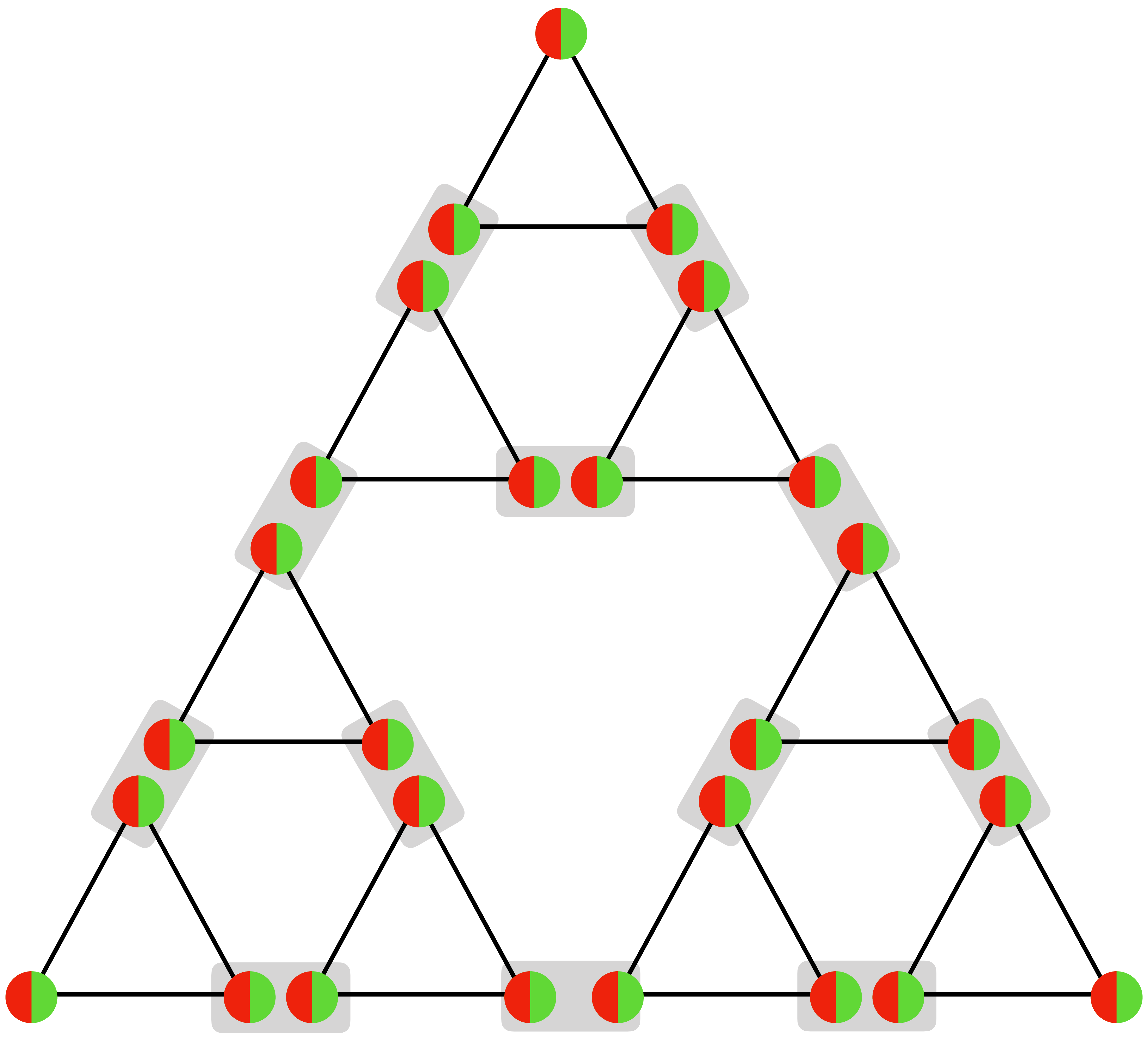
Our goal



Develop protocol for **2D quantum repeater** using **scalable resources** and compare it with the 1D repeater in presence of **realistic imperfections**

Our goal

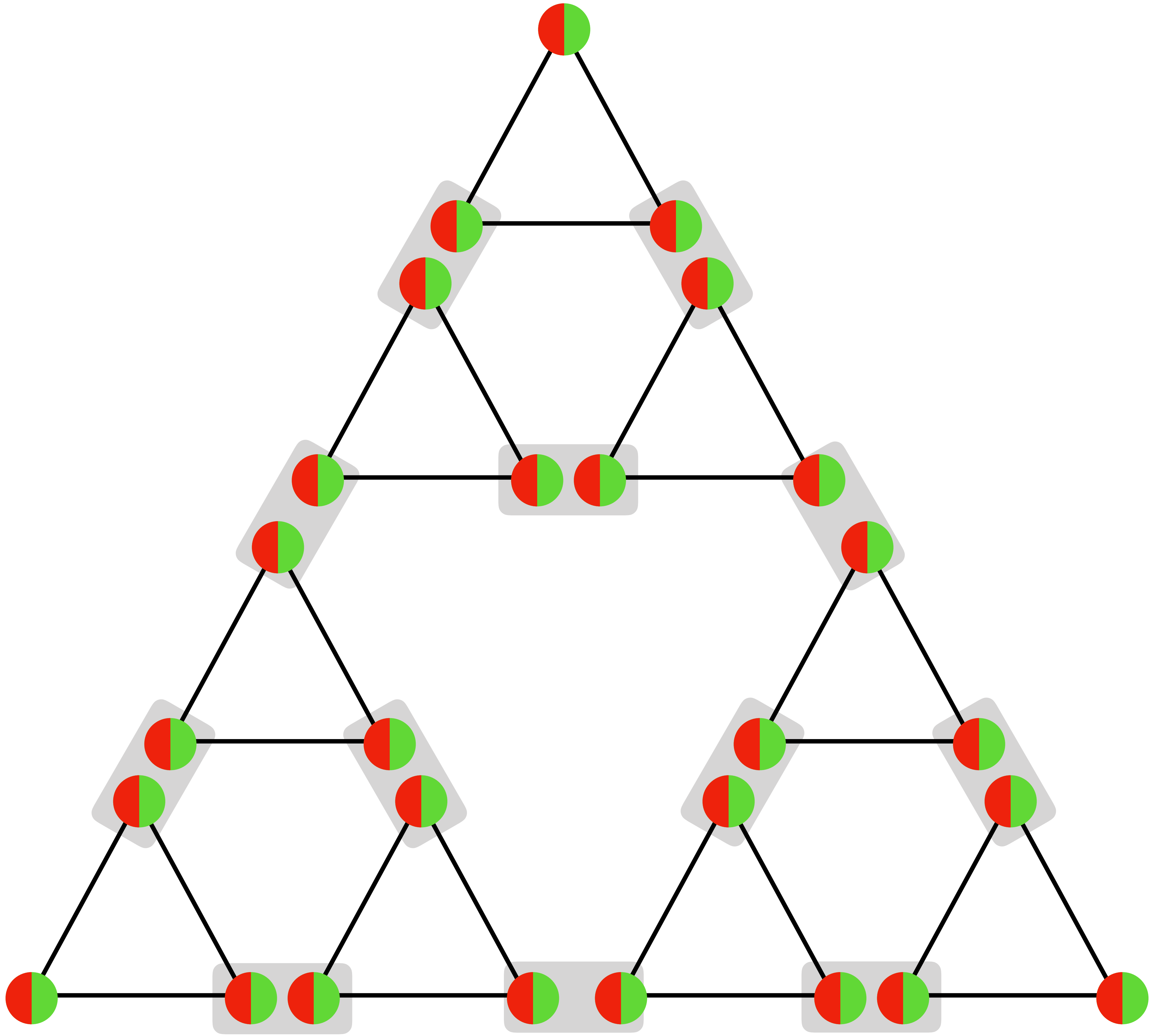


Scalable resources:

- Room temperature atomic ensembles in glass cells*
- Beamsplitters
- Photon detectors

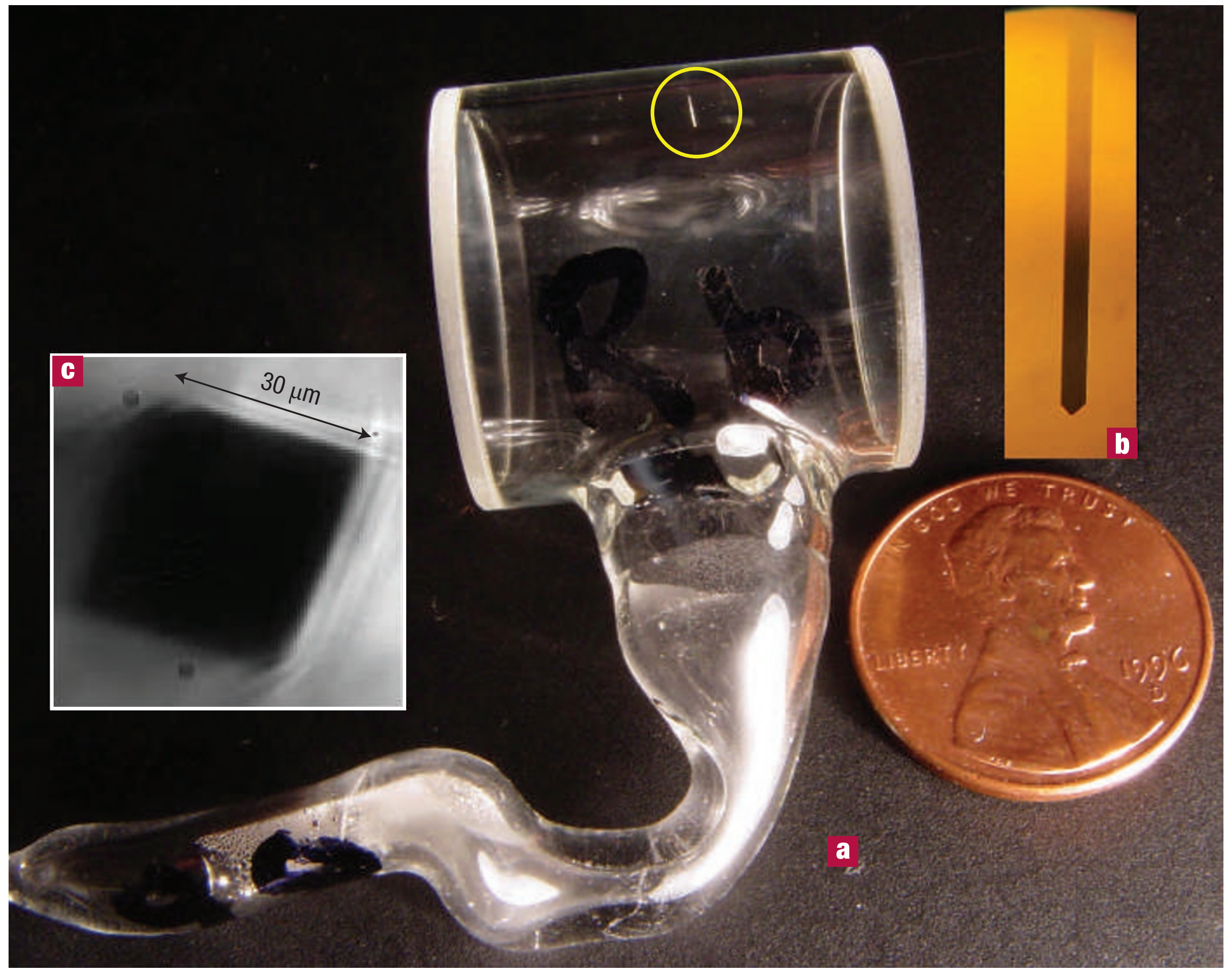
*Balabas, M., Sushkov, A. & Budker, D. *Nature Phys* **3,** 2 (2007)

Our goal



Scalable resources:

- **Room temperature atomic ensembles in glass cells***
- Beamsplitters
- Photon detectors



*Balabas, M., Sushkov, A. & Budker, D. *Nature Phys* **3,** 2 (2007)

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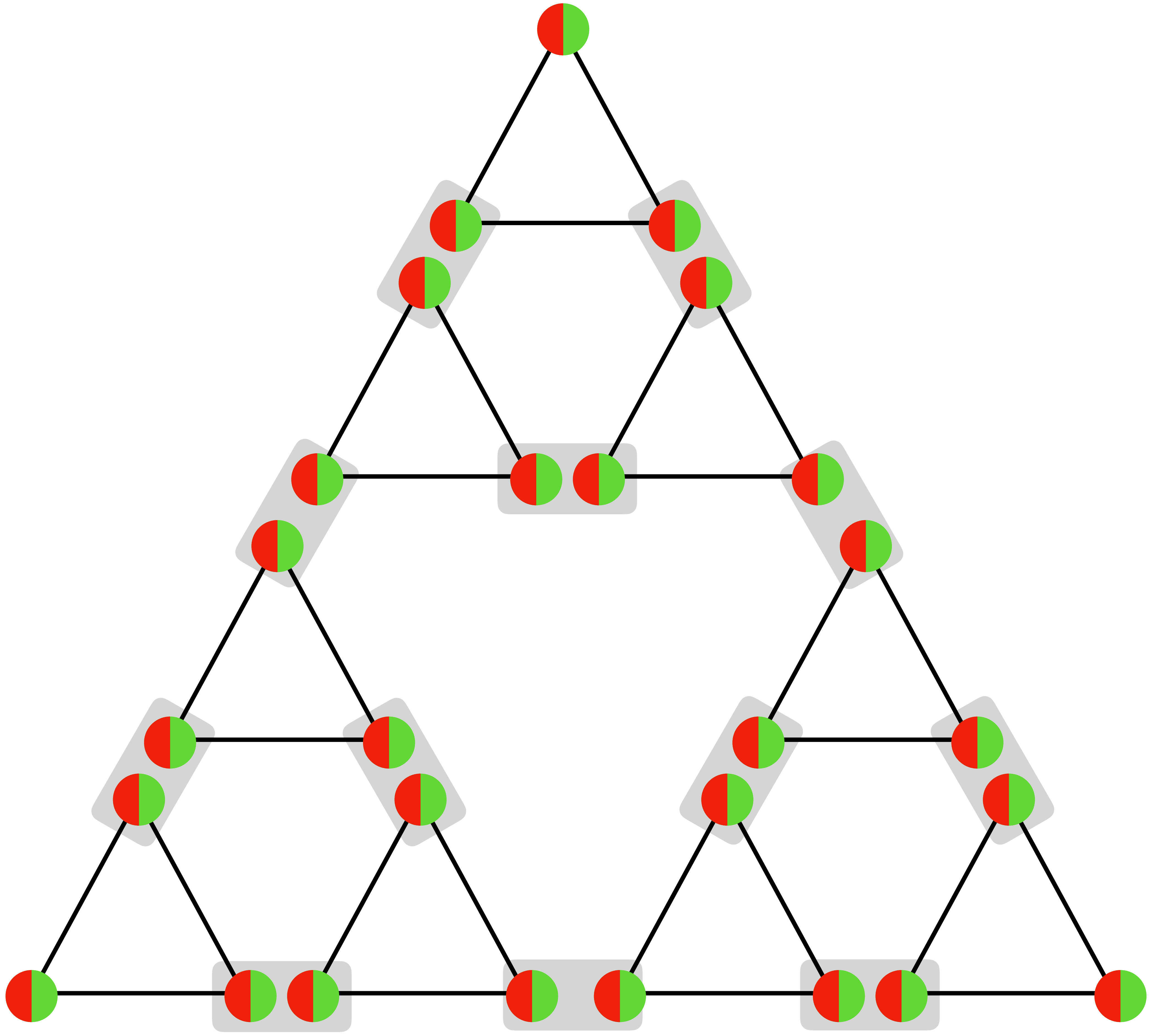
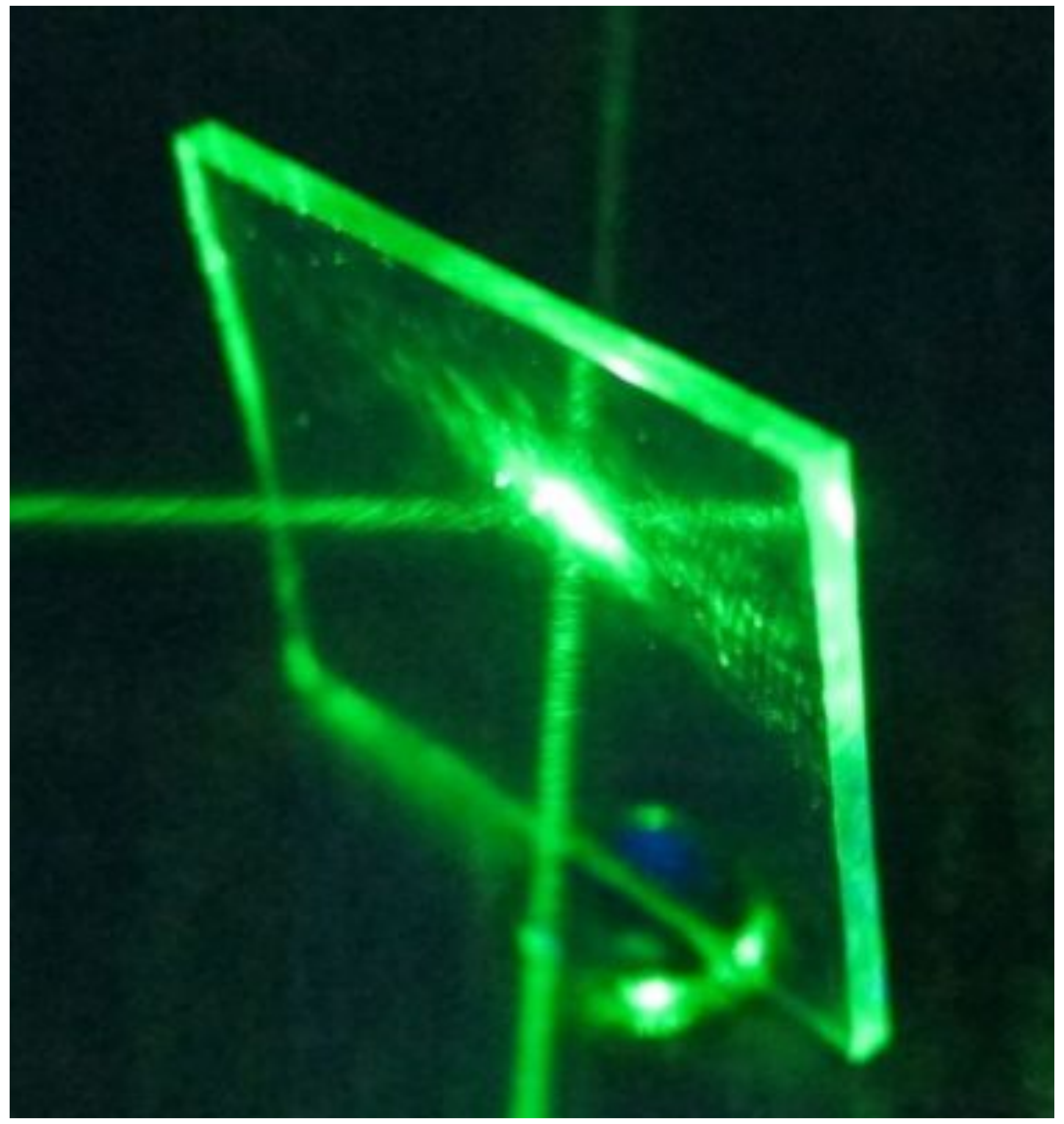


Scalable resources:

- Room temperature atomic ensembles in glass cells*
- **Beamsplitters**
- Photon detectors



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Plan

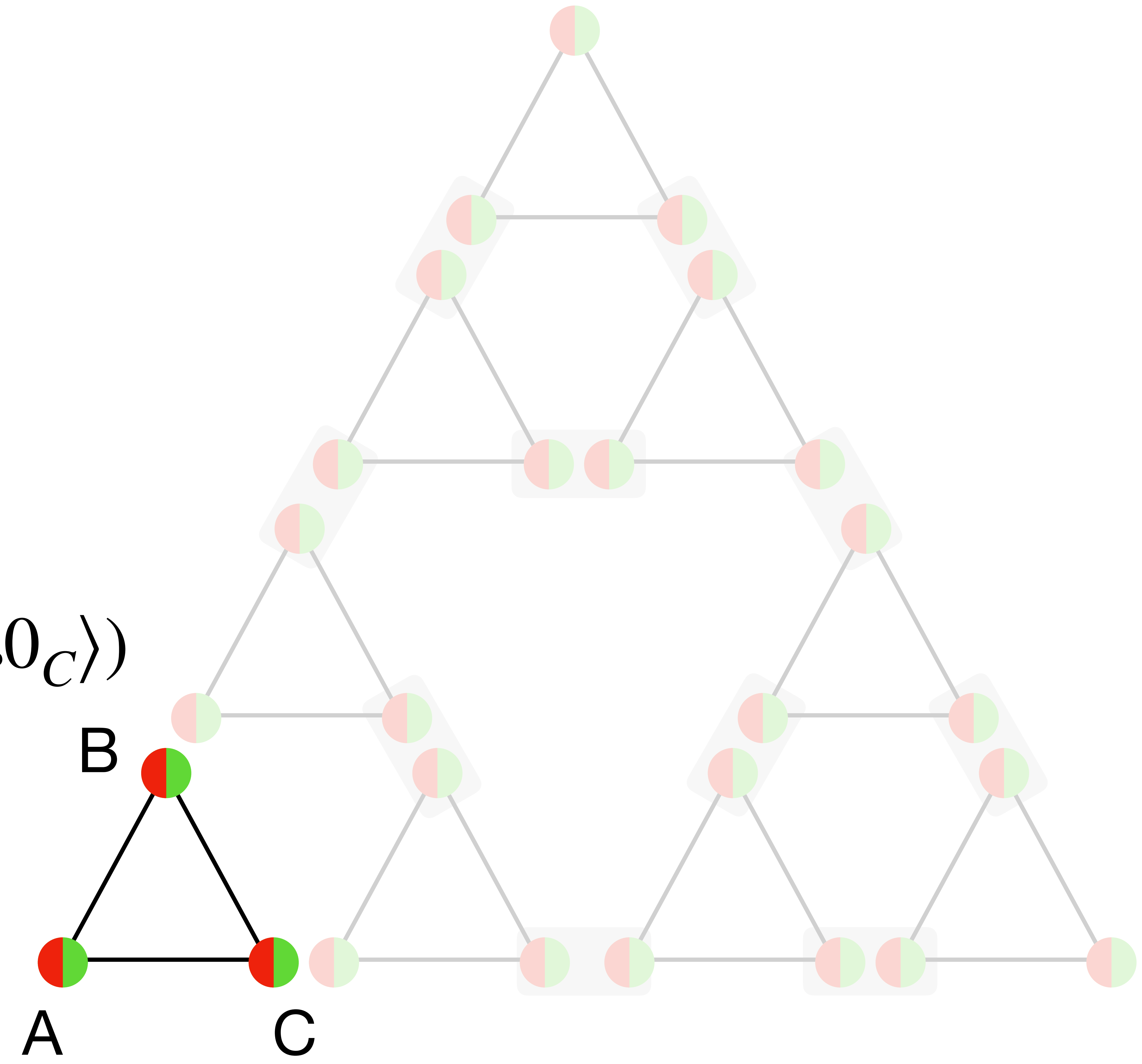
1. 1D and 2D quantum repeaters for distribution of entangled states

2. Protocol for the 2D quantum repeater

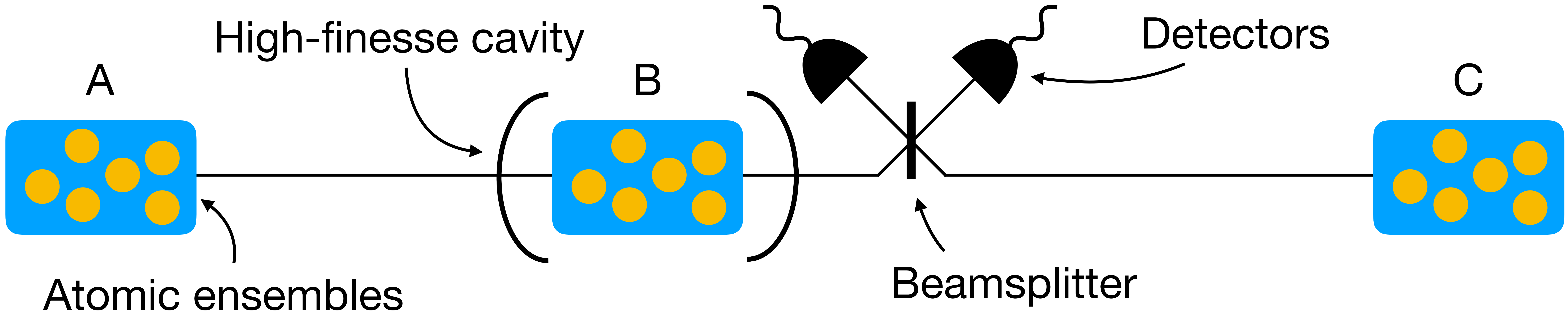
3. Comparison of quantum networks build with the 1D and 2D quantum repeaters

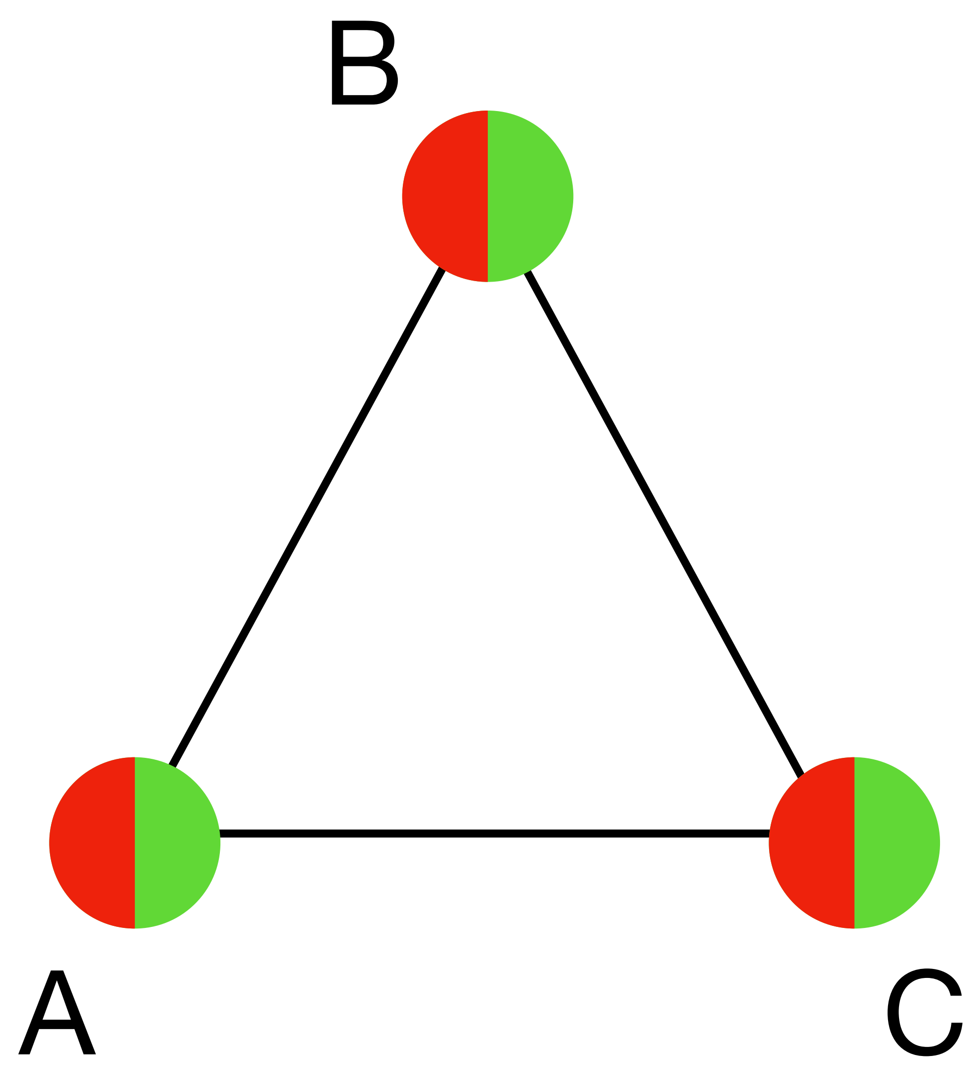
Elementary segment

$$\frac{1}{\sqrt{2}}(|0_A0_B1_C\rangle + |1_A1_B0_C\rangle)$$

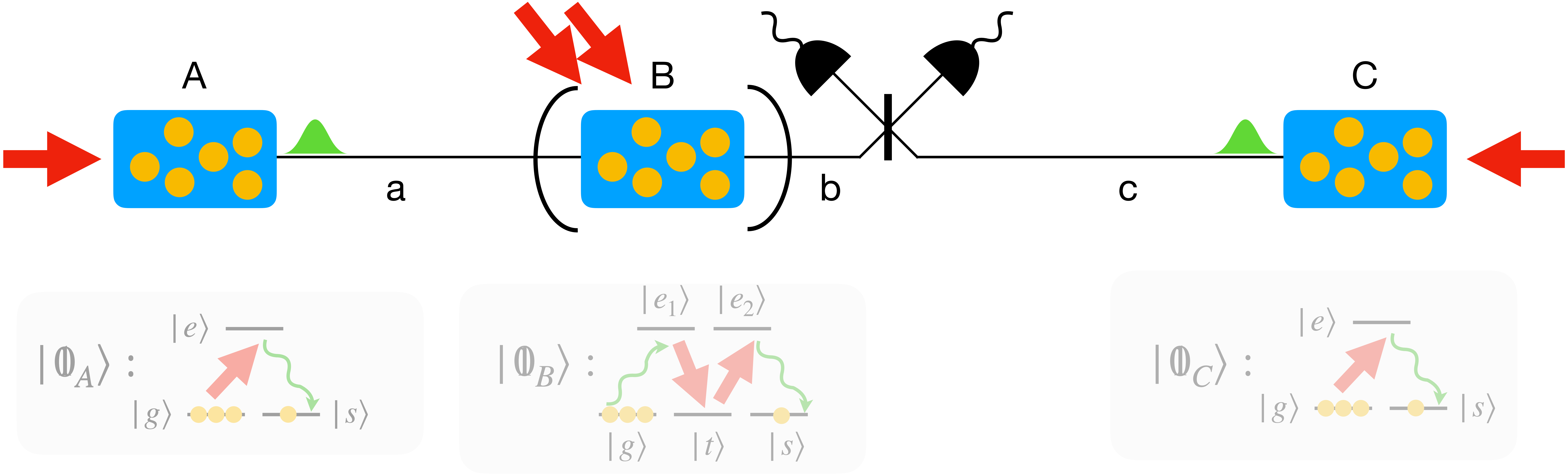


Elementary segment





Elementary segment



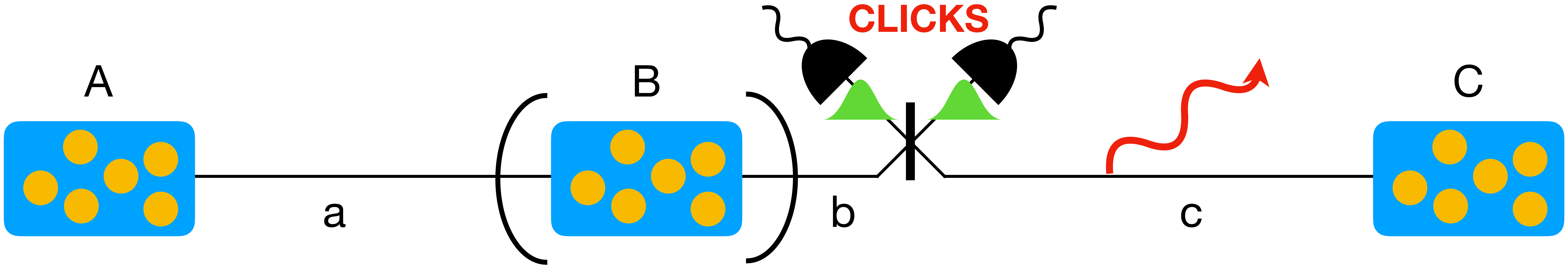
$$|0_A 0_a\rangle + \sqrt{\varepsilon}\,|1_A 1_a\rangle + O(\varepsilon),\ \varepsilon \ll 1$$

$$\downarrow$$

$$|0_A 0_B 0_b\rangle + \sqrt{\varepsilon}\,|1_A 1_B 1_b\rangle + O(\varepsilon)$$

$$|0_C 0_c\rangle + \sqrt{\varepsilon}\,|1_C 1_c\rangle + O(\varepsilon)$$

Elementary segment

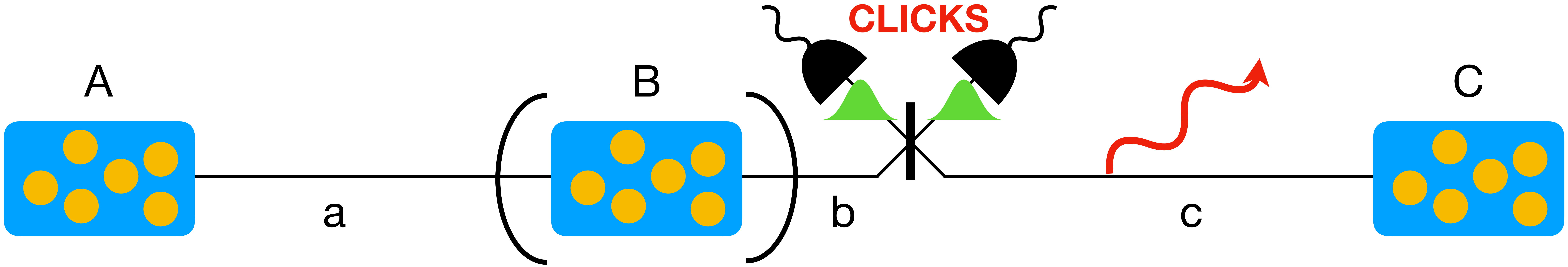


$|0_A 0_B 0_b\rangle + \sqrt{\varepsilon}\,|1_A 1_B 1_b\rangle + O(\varepsilon)$

$|0_C 0_c\rangle + \sqrt{\varepsilon}\,|1_C 1_c\rangle + O(\varepsilon)$

Probability	**Event**	**State**	**Response**
~ 1	**0** clicks	$\|0_A 0_B 0_C\rangle$	↻
$\sim \varepsilon$	**0** clicks + 1 loss	i.e. $\|0_A 0_B 1_C\rangle$	↻
$\sim \varepsilon$	**1** click	$\sim \|0_A 0_B 1_C\rangle + \|1_A 1_B 0_C\rangle$	✓
$\sim \varepsilon^2$	**2** click	$\|1_A 1_B 1_C\rangle$	↻
$\sim \varepsilon^2$	**1** clicks + 1 loss	$\|1_A 1_B 1_C\rangle$	✓ !

Elementary segment

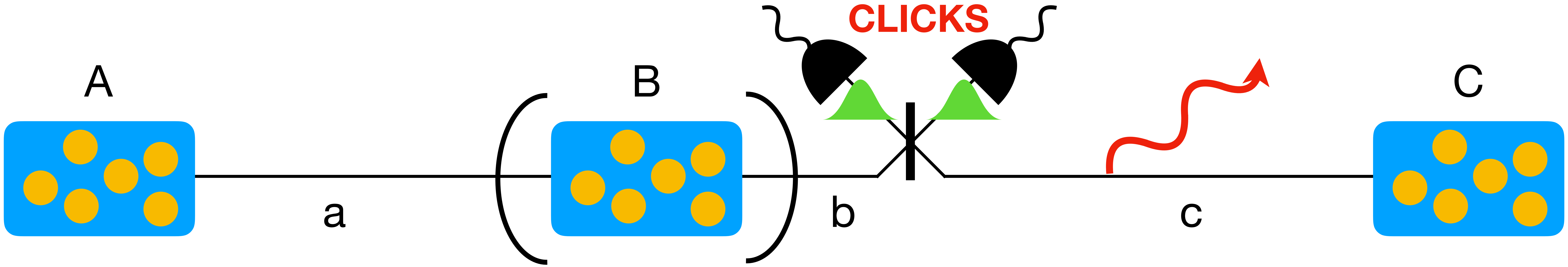


$|0_A 0_B 0_b\rangle + \sqrt{\varepsilon}\,|1_A 1_B 1_b\rangle + O(\varepsilon)$

$|0_C 0_c\rangle + \sqrt{\varepsilon}\,|1_C 1_c\rangle + O(\varepsilon)$

Probability	Event	State	Response
~ 1	**0** clicks	$|0_A 0_B 0_C\rangle$	
$\sim \varepsilon$	**0** clicks + 1 loss	i.e. $|0_A 0_B 1_C\rangle$	
$\sim \varepsilon$	**1** click	$\sim |0_A 0_B 1_C\rangle + |1_A 1_B 0_C\rangle$	
$\sim \varepsilon^2$	**2** click	$|1_A 1_B 1_C\rangle$	
$\sim \varepsilon^2$	**1** clicks + 1 loss	$|1_A 1_B 1_C\rangle$	!

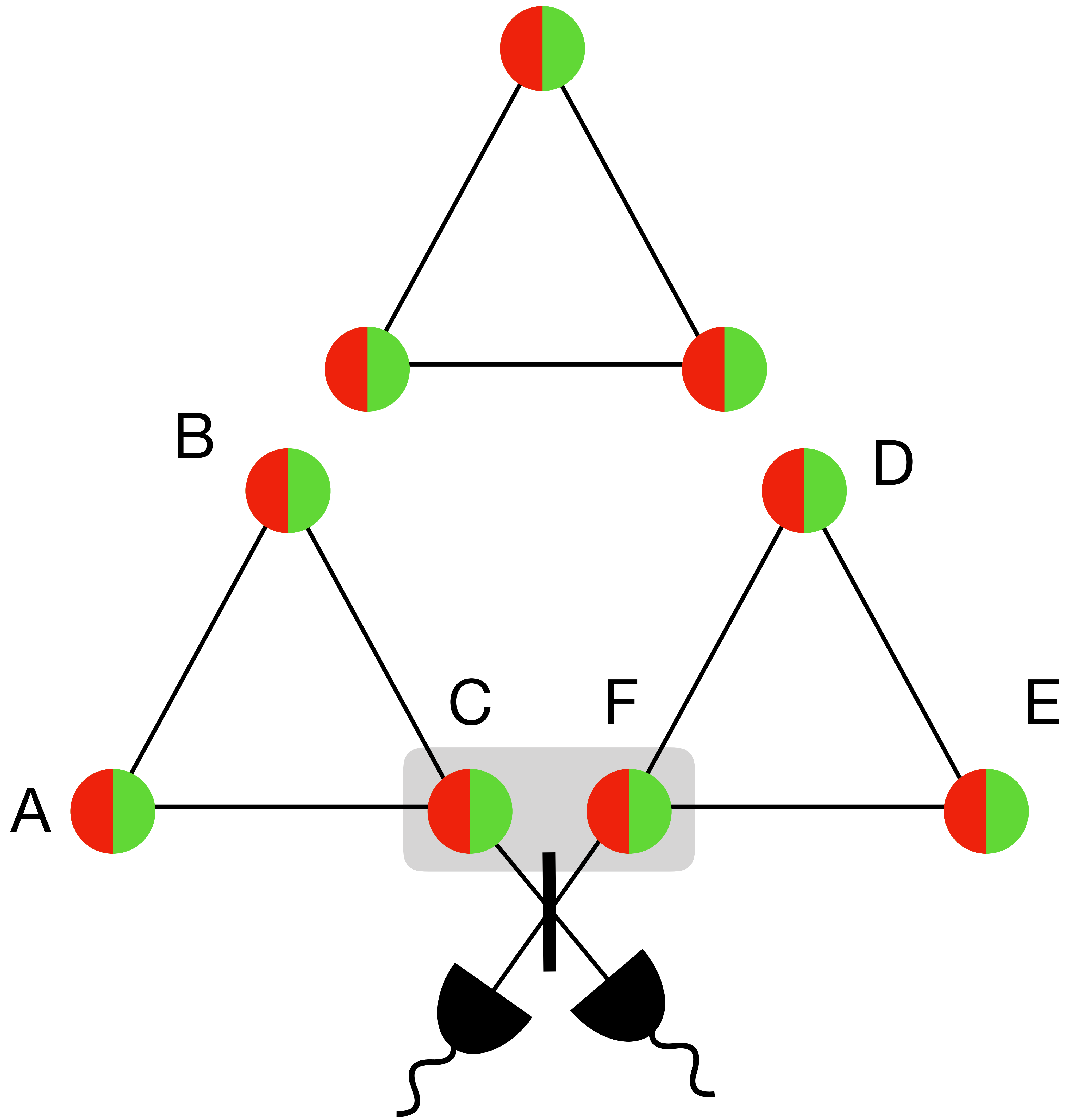
Elementary segment



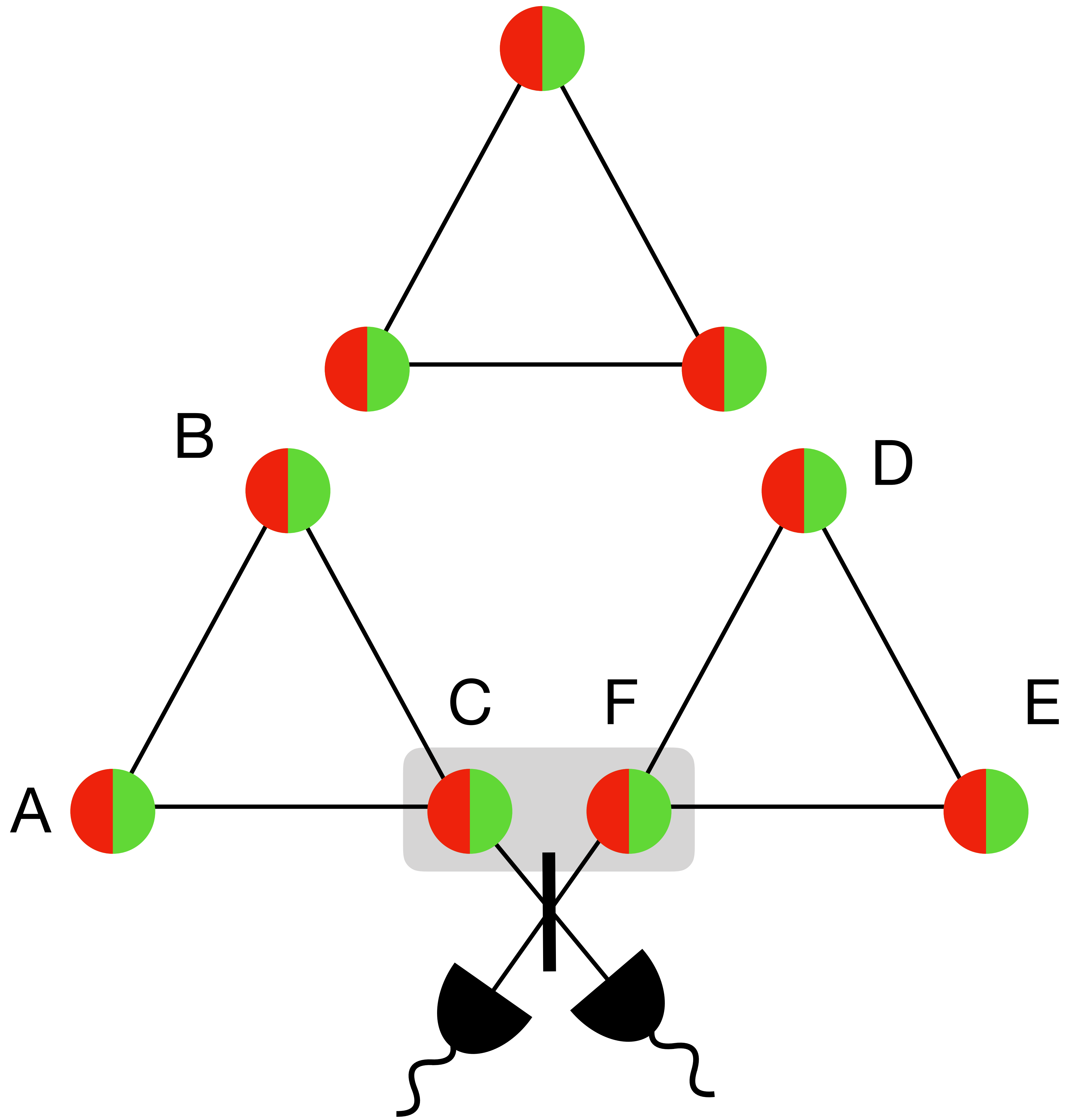
$$|0_A 0_B 0_b\rangle + \sqrt{\varepsilon}\,|1_A 1_B 1_b\rangle + O(\varepsilon) \qquad\qquad |0_C 0_c\rangle + \sqrt{\varepsilon}\,|1_C 1_c\rangle + O(\varepsilon)$$

Probability	Event	State	Response
~ 1	0 clicks	$\vert 0_A 0_B 0_C\rangle$	
$\sim \varepsilon$	0 clicks + 1 loss	i.e. $\vert 0_A 0_B 1_C\rangle$	
$\sim \varepsilon$	**1** click	$\sim \vert 0_A 0_B 1_C\rangle + \vert 1_A 1_B 0_C\rangle$	✓
$\sim \varepsilon^2$	2 click	$\vert 1_A 1_B 1_C\rangle$	
$\sim \varepsilon^2$	**1** clicks + 1 loss	$\vert 1_A 1_B 1_C\rangle$	✓ !

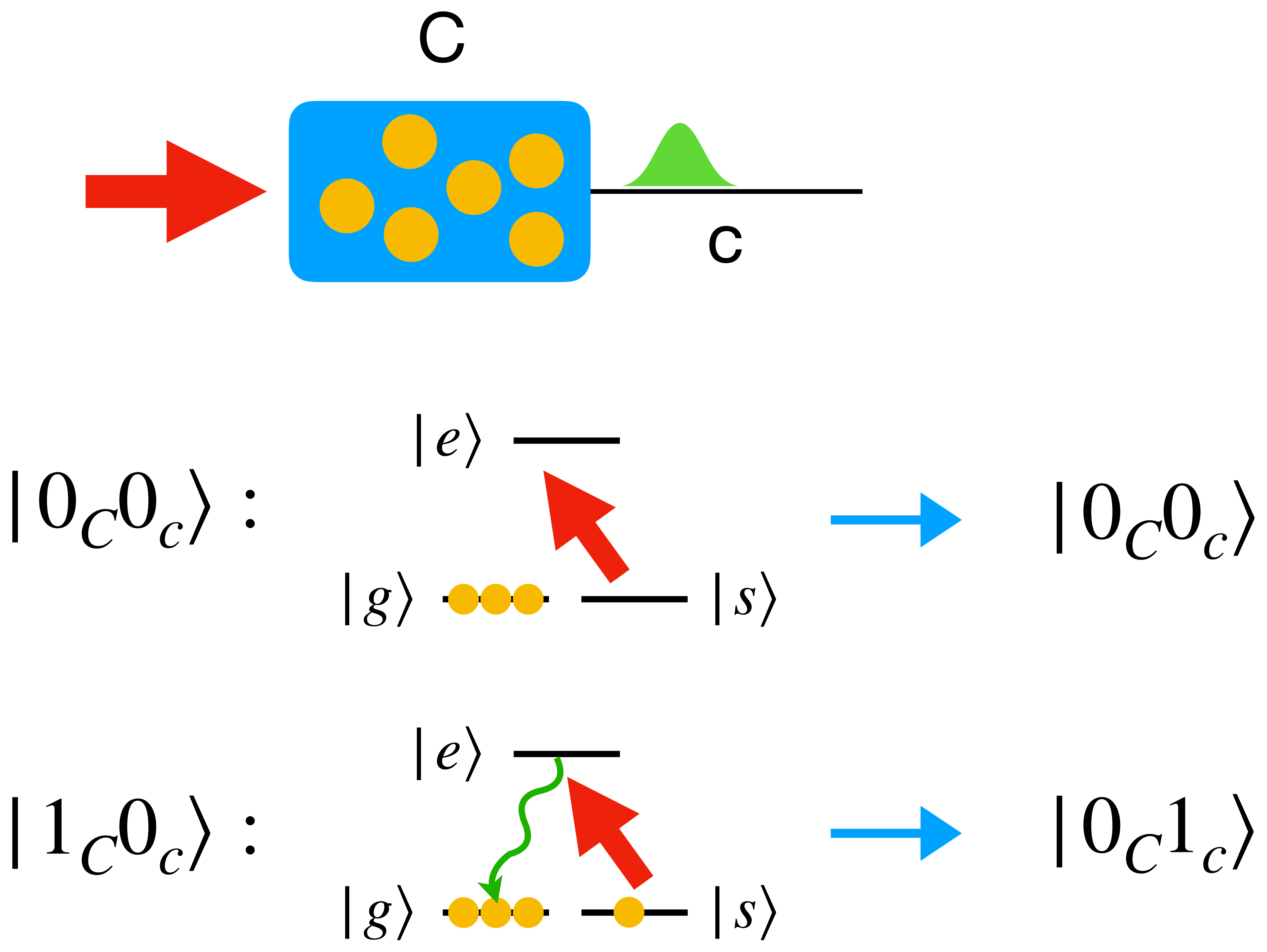
Swapping operations



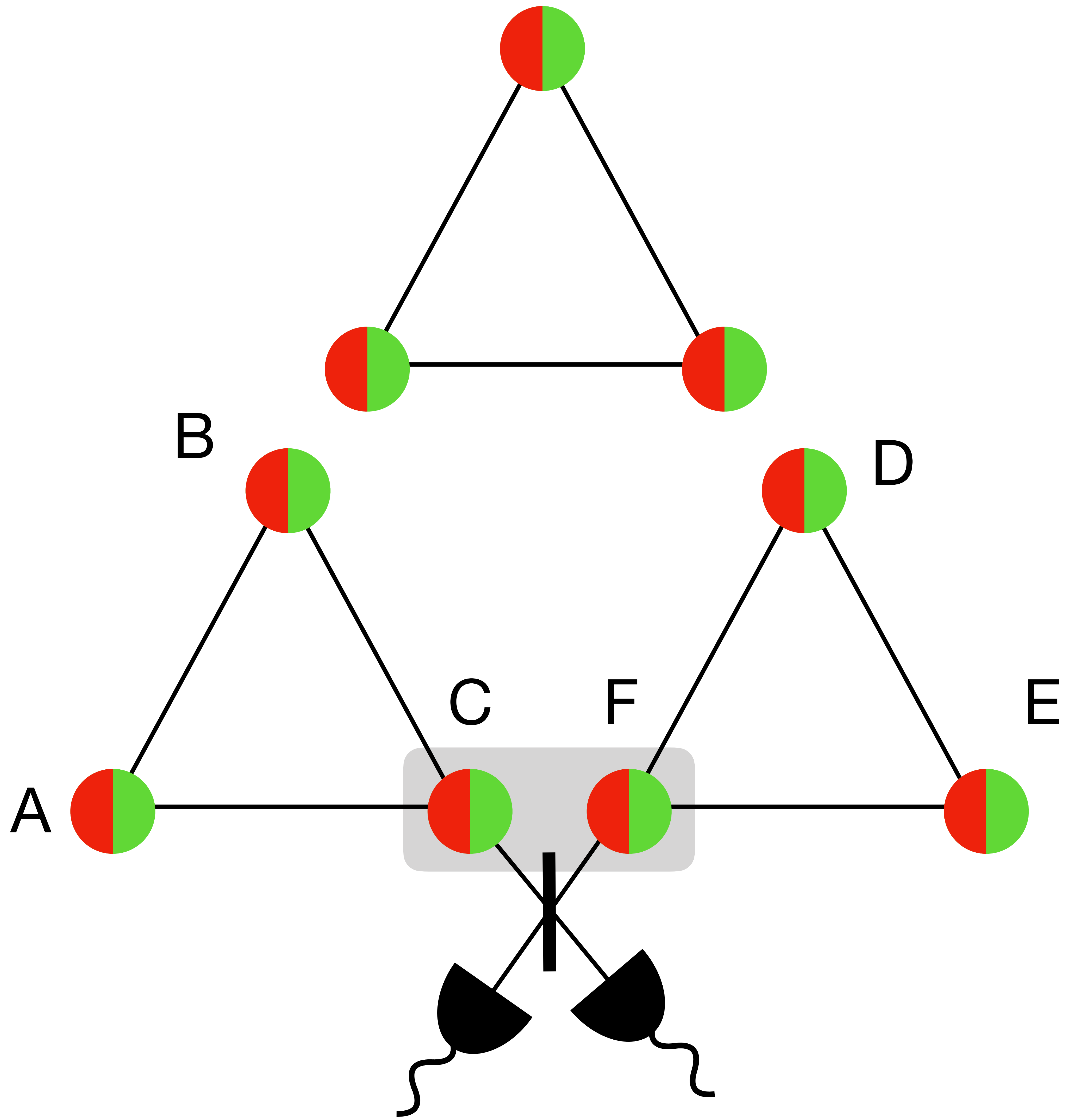
Swapping operations



Read-out of quantum information:



Swapping operations



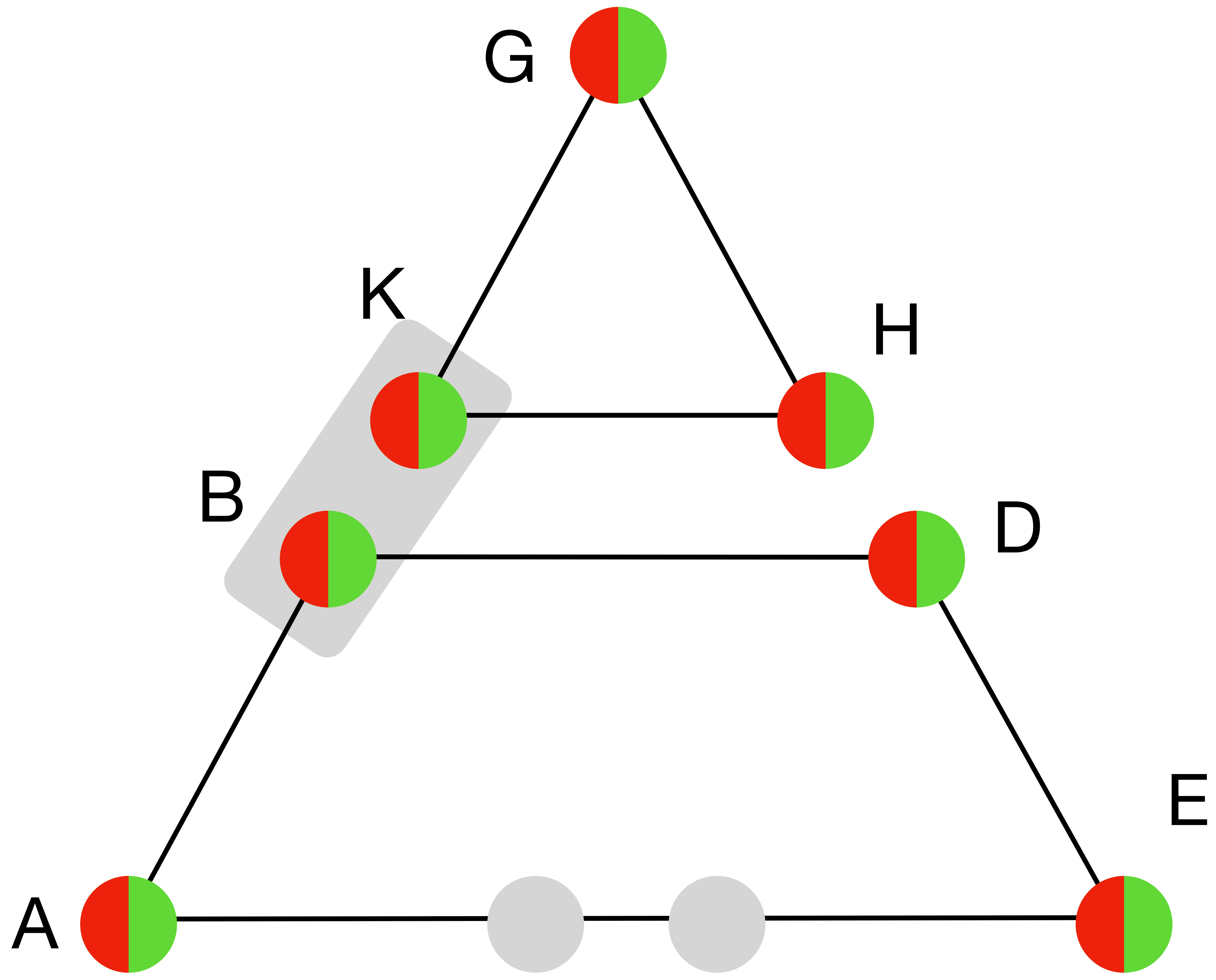
Initial state:

$|0_A 0_B 1_C\rangle + |1_A 1_B 0_C\rangle$

$|1_D 1_E 0_F\rangle + |0_D 0_E 1_F\rangle$

Probability	Event	State	Response
~25 %	0 click	$|1_A 1_B 1_D 1_E\rangle$	↻
~25 %	2 click	$|0_A 0_B 0_D 0_E\rangle$	↻
~50 %	1 click	$|0_A 0_B 1_D 1_E\rangle + |1_A 1_B 0_D 0_E\rangle$	✓

Swapping operations



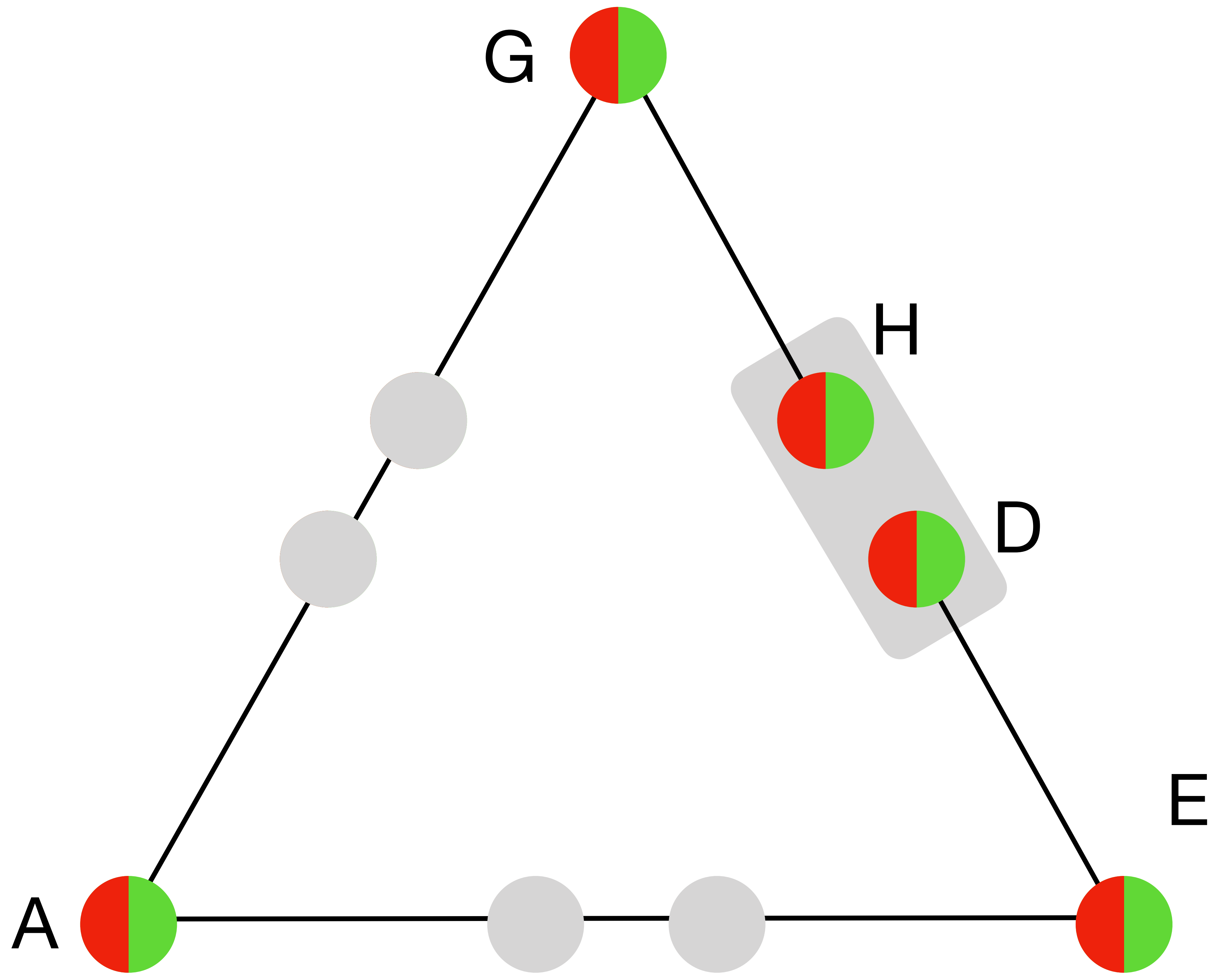
Initial state:

$|0_A\, 0_B\, 1_D 1_E\rangle + |1_A\, 1_B\, 0_D 0_E\rangle$

$|0_G 0_H 1_K\rangle + |1_G 1_H 0_K\rangle$

Probability	Event	State	Response
~25 %	0 click	…	↻
~25 %	2 click	…	↻
~50 %	1 click	$|0_A 1_D 1_E 0_G 0_H\rangle + |1_A 0_D 0_E 1_G 1_H\rangle$	✓

Swapping operations

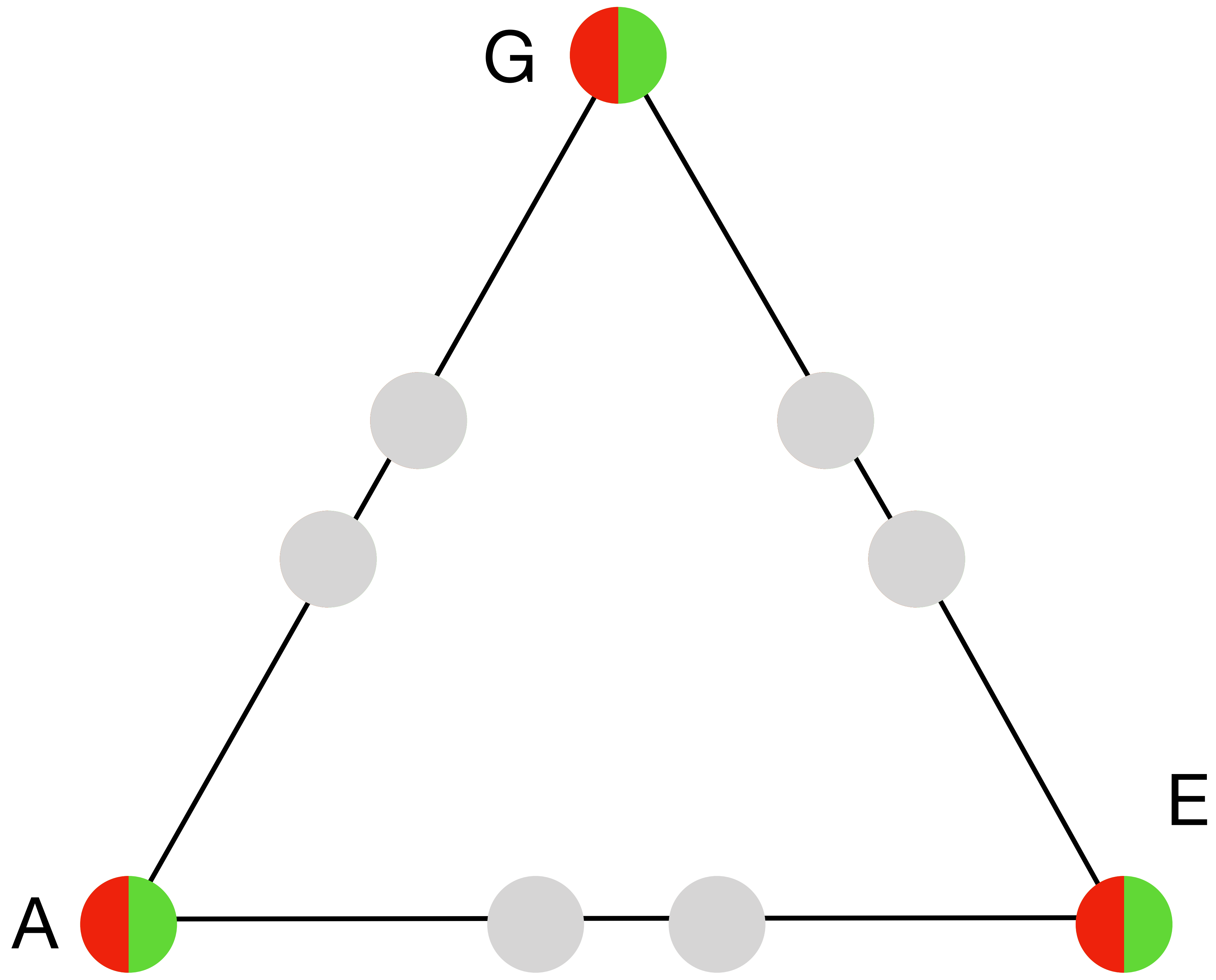


Initial state:

$|0_A\, 1_D\, 1_E 0_G 0_H\rangle + |1_A\, 0_D\, 0_E 1_G 1_H\rangle$

Probability	Event	State	Response
100 %	1 click	$\|0_A 1_E 0_G\rangle + \|1_A 0_E 1_G\rangle$	✓

Swapping operations

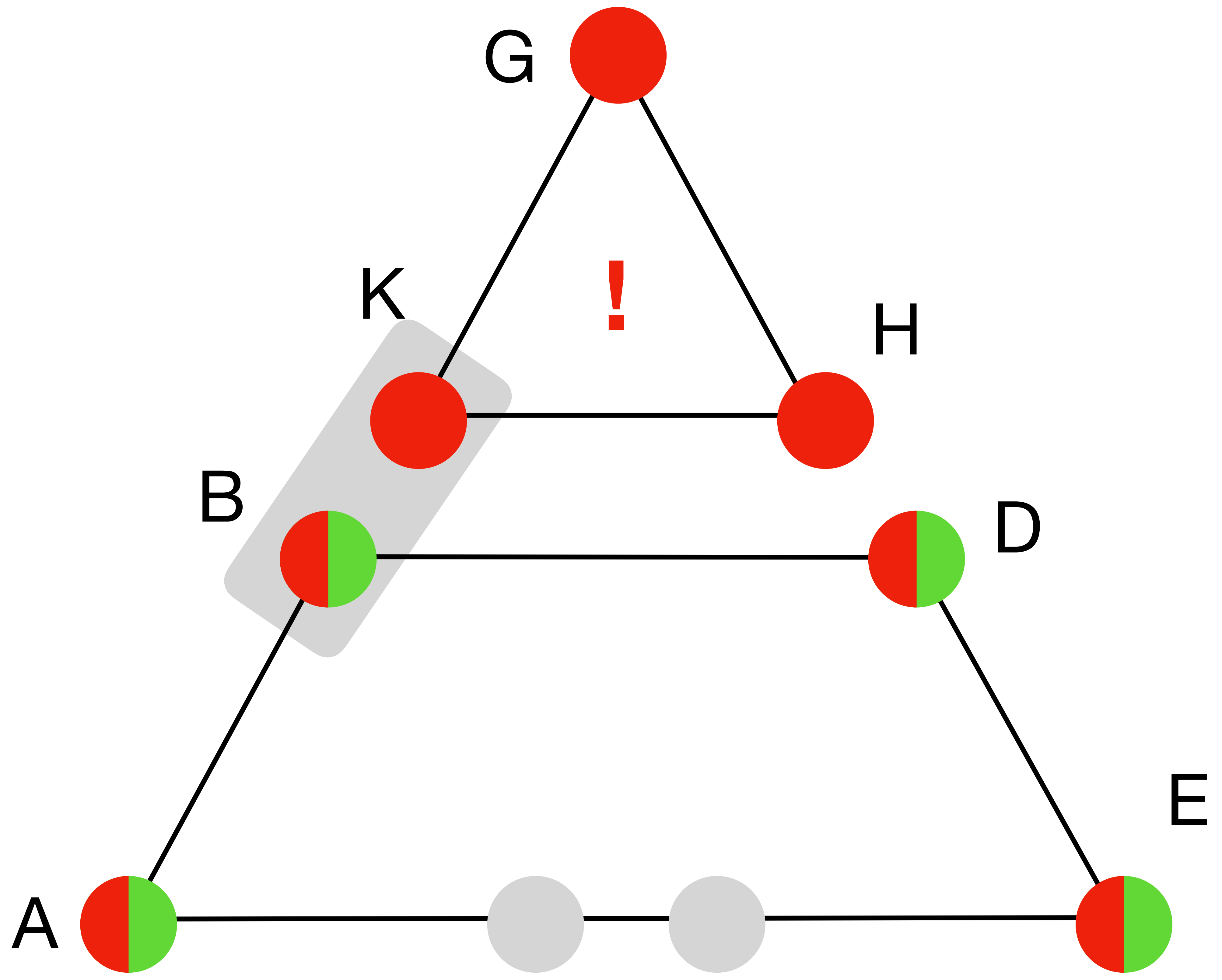


Initial state:

$|0_A\,1_D\,1_E 0_G 0_H\rangle + |1_A\,0_D\,0_E 1_G 1_H\rangle$

Probability	Event	State	Response
100 %	1 click	$\|0_A 1_E 0_G\rangle + \|1_A 0_E 1_G\rangle$	✓

Swapping operations



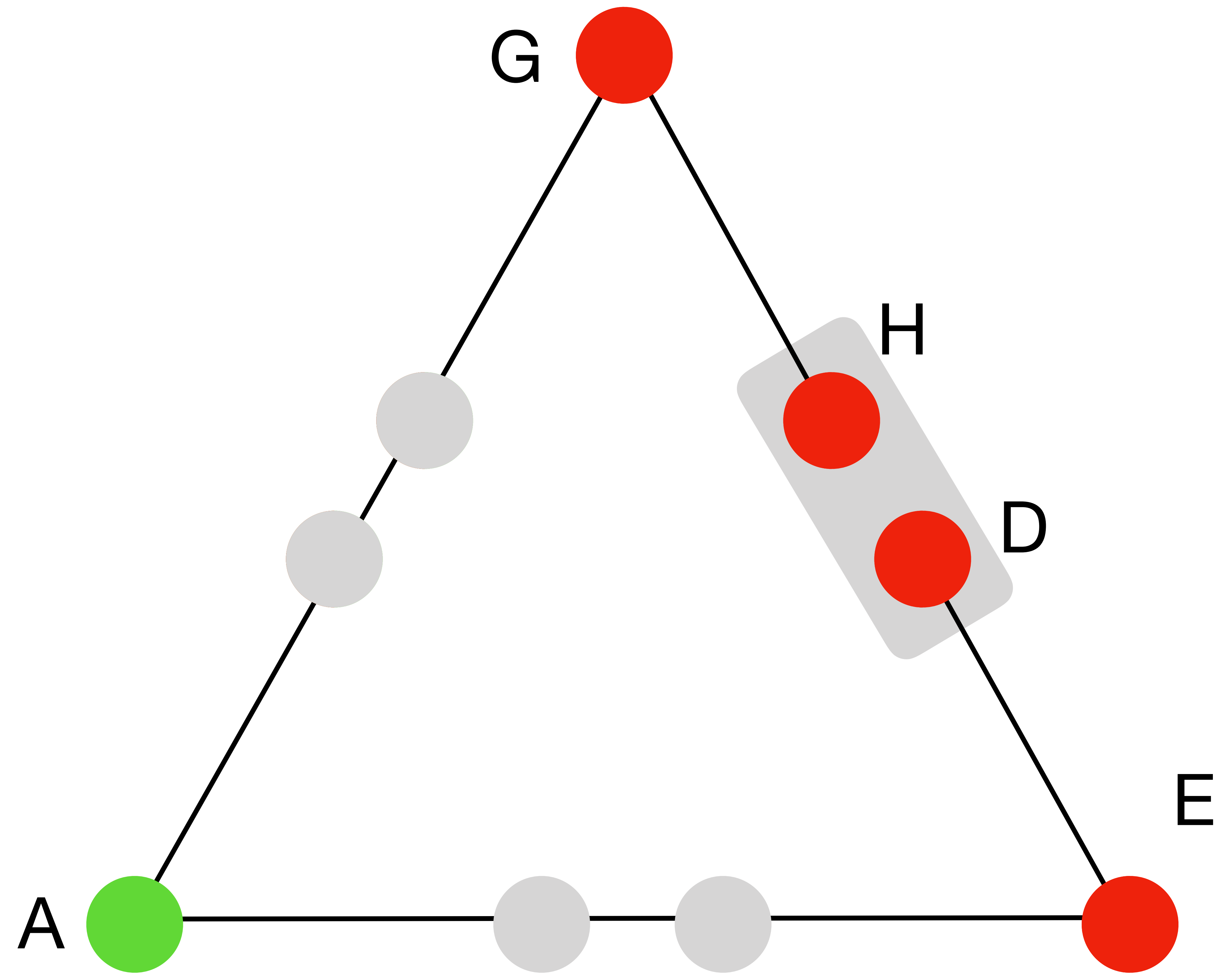
Initial state:

$|0_A\, 0_B\, 1_D 1_E\rangle + |1_A\, 1_B\, 0_D 0_E\rangle$

! $|0_G 0_H 0_K\rangle$

Probability	Event	State	Response
~50 %	0 click	…	
~50 %	1 click	$|1_A 0_D 0_E 0_G 0_H\rangle$	✓ !

Swapping operations

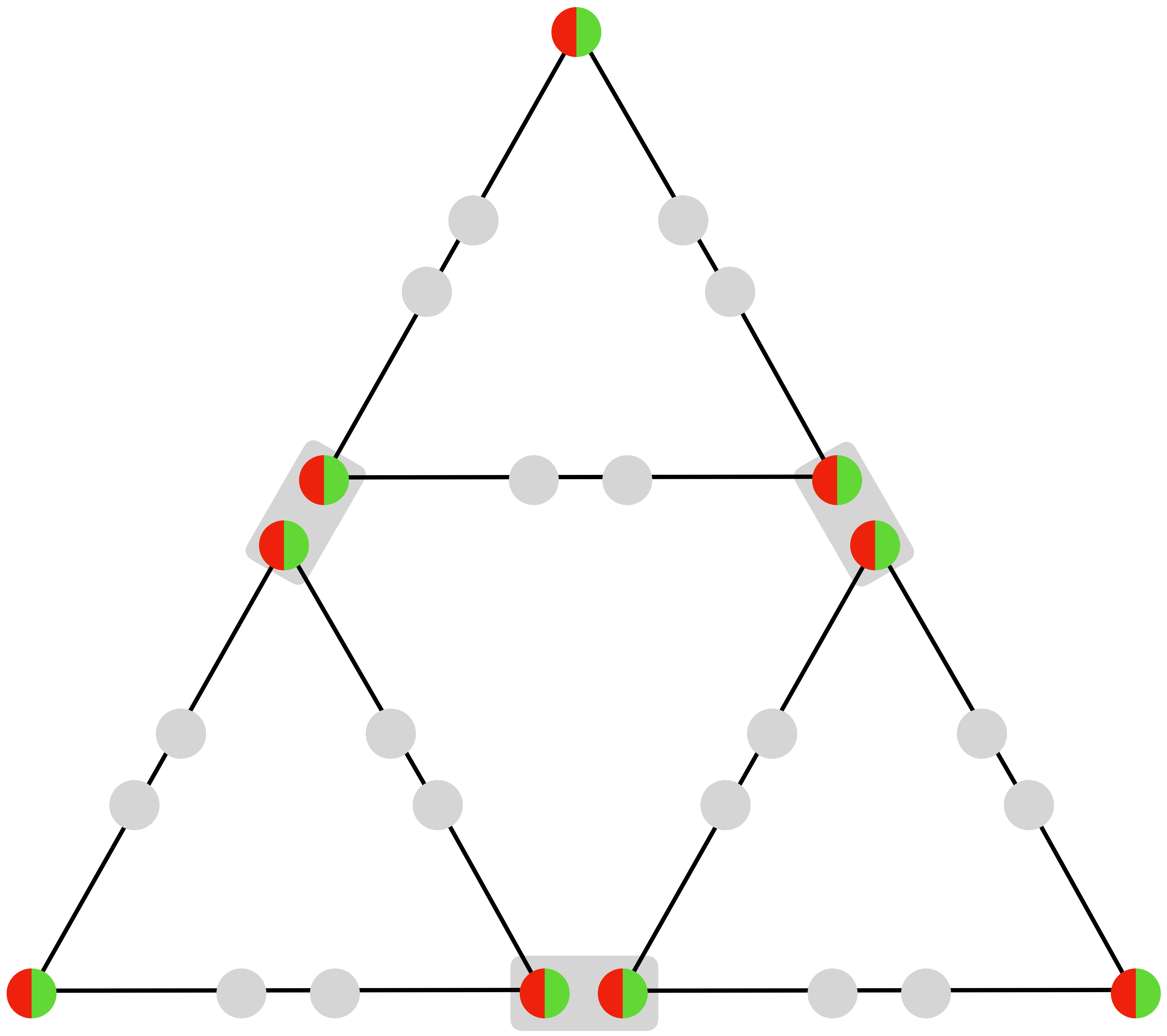


Initial state:

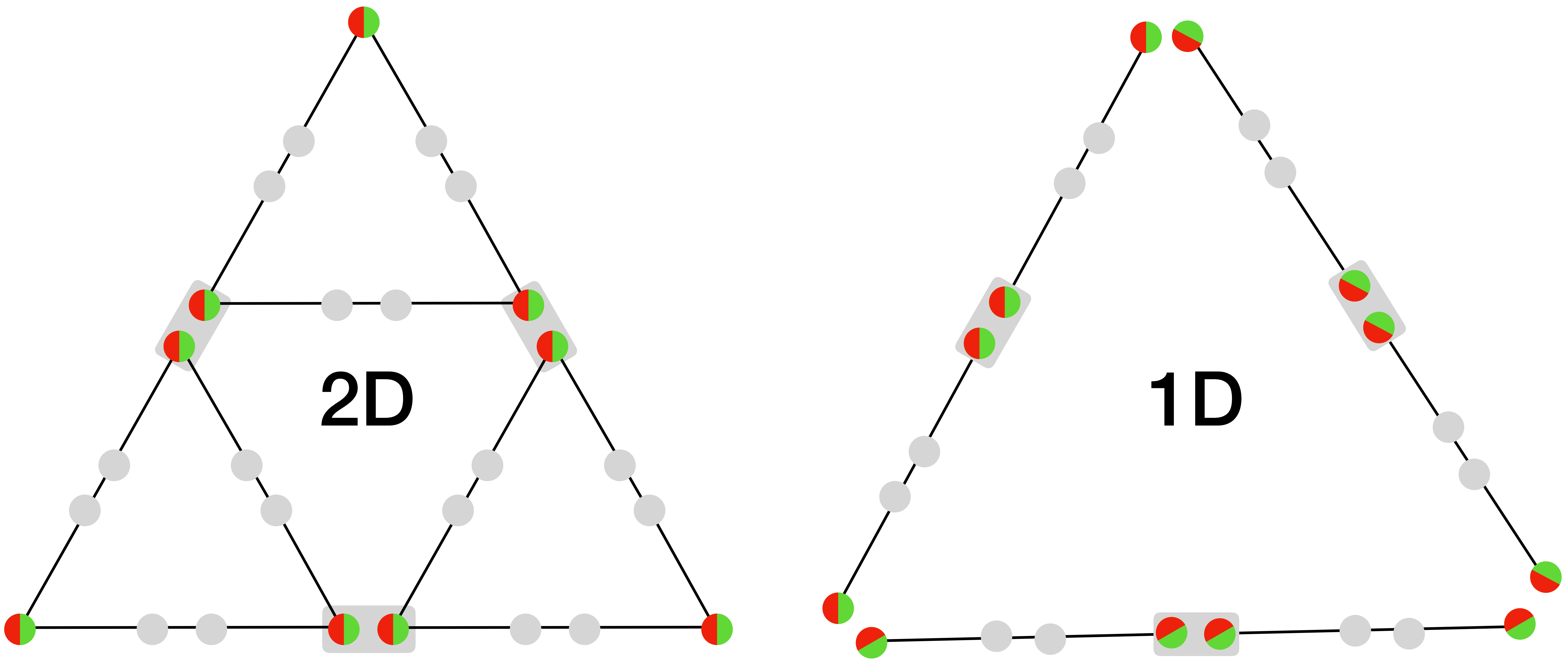
$|1_A\,0_D\,0_E0_G0_H\rangle$

Probability	Event	State	Response
100 %	0 click	$|1_A0_E0_G\rangle$	

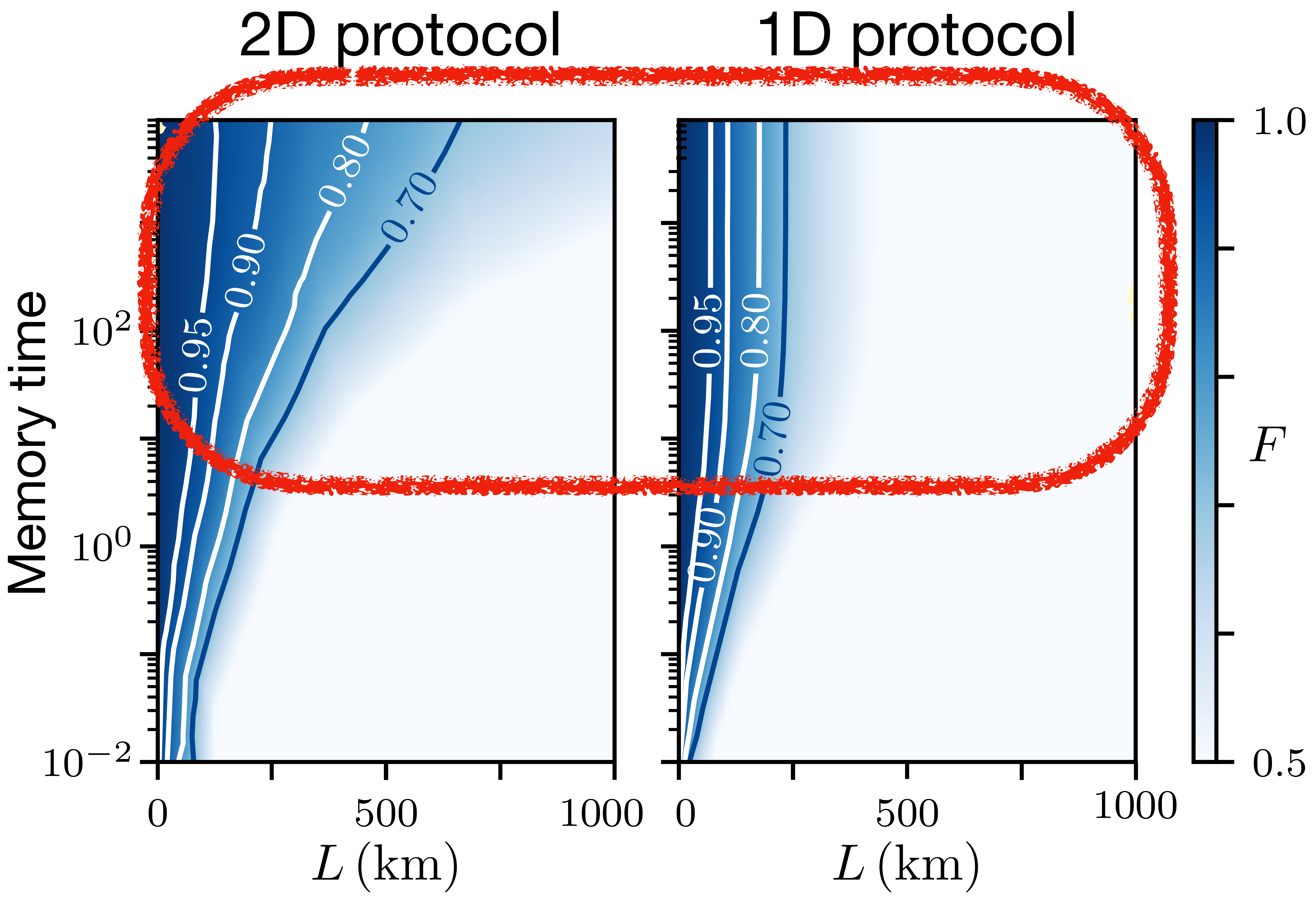
Next nesting level



Comparison



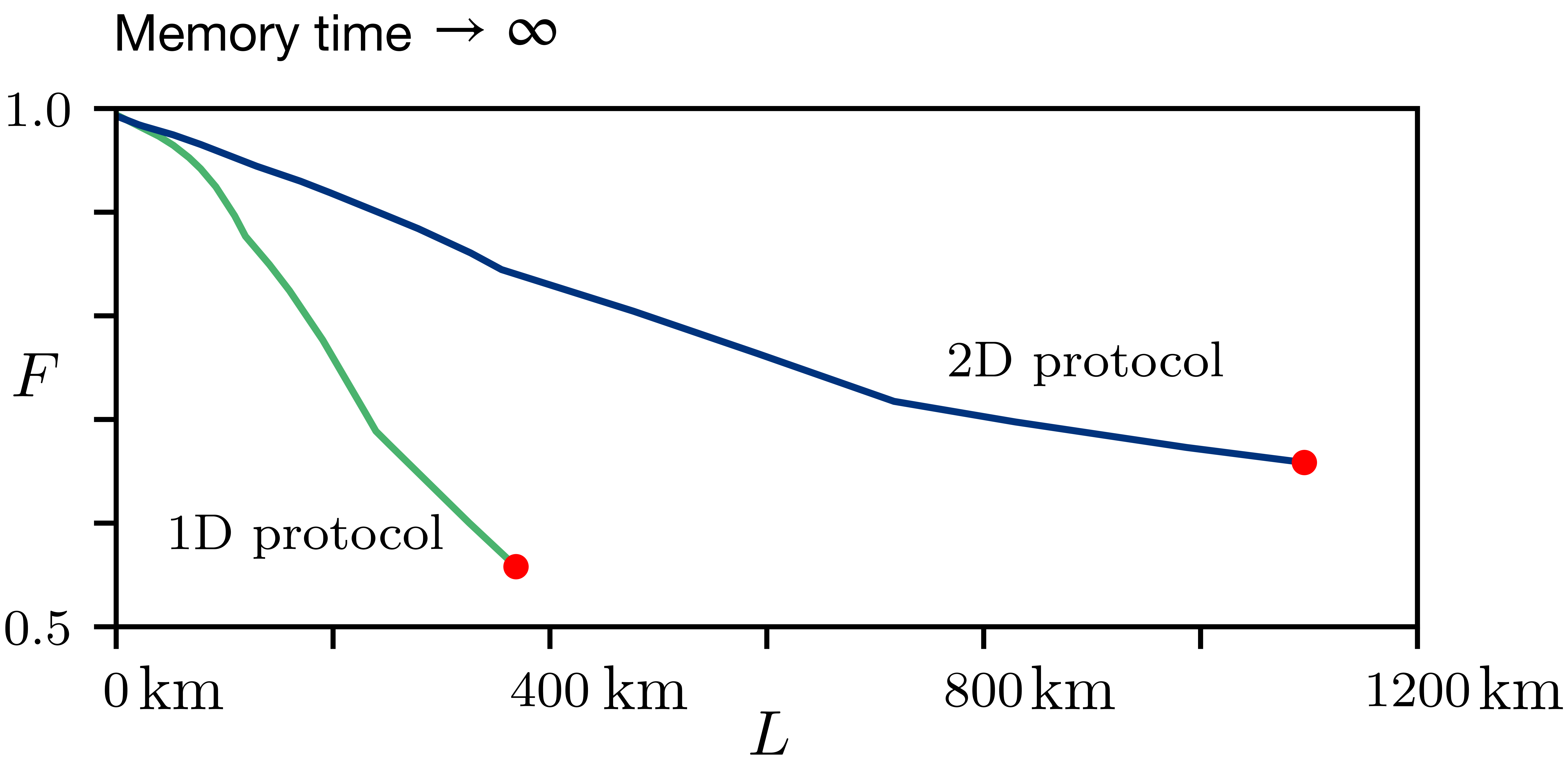
Comparison



Imperfections:

- Dark counts 10Hz
- Detector efficiency 95%
- Read-out efficiency 95%
- Fiber attenuation length 22km
- Cavity losses 40%

Comparison



Memory time → ∞
1.0
0.5
F
2D protocol
1D protocol
0 km
400 km
800 km
1200 km
L

Results

1. Scalable protocol for 2D repeaters

2. 2D repeater protocol outperforms 1D repeater