Entanglement Distribution on Complex Networks

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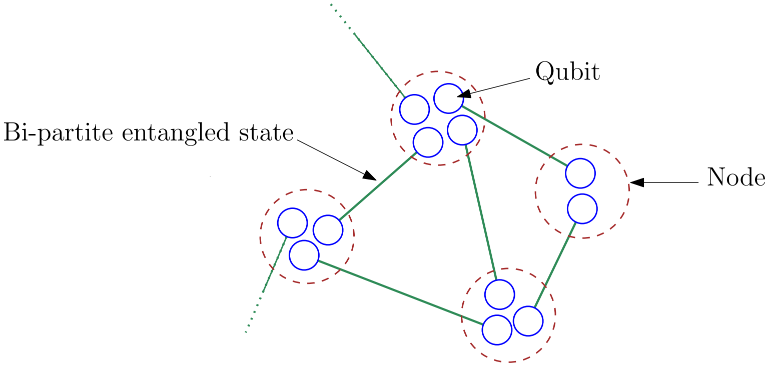


- *qubits* (two-level quantum systems)
- Multiple qubits and classical resources at each *node* (vertex)
- *links* (edges): bi-partite entangled (pure/mixed) two-qubit states.
- Goal: entangle pairs of qubits between distant nodes
- Quantum operations local: within nodes. Classical can be global. Local Operations and Classical Communication LOCC

Generalization of one-dimensional networks

- Quantum Information: Entanglement is a resource for tasks:teleportation, key distribution, fault tolerant computation
  - Creating entanglement requires local interaction. Noise increases with distance. Depolarization. Absorption. Can't distribute entanglement over long distance in a single stage!
- Long range entanglement via Network of stations or nodes that store and purify a state.
  - Generalization of quantum repeater schemes. Dür, Briegel, Cirac, Zoller, PRA 1999
  - Nodes share partially entangled states of qubits
  - Nodes(stations)/channels, Vertices/edges, Sites/bonds
  - Quantum operations probabilistic
  - Large number of random components $\Rightarrow$ Complex Networks, Percolation, Phase transition

Entanglement: Two entangled qubits

Two entangled qubits: four-dimensional Hilbert space.

Bi-partite pure state

All such states LOCC equivalent to unique state in Schmidt basis.

$$|\alpha\rangle = \sqrt{\alpha_0}\,|00\rangle + \sqrt{\alpha_1}\,|11\rangle$$

$$\alpha_0 > \alpha_1 \qquad \alpha_0 + \alpha_1 = 1 \qquad \alpha_1 \in [0, 1/2]$$

Pure, partially entangled, bipartite state

$\alpha_1 = 0$: no entanglement, $\alpha_1 = 1/2$: max. entanglement

Bell State: Singlet Conversion

Partially Entangled: $|\alpha\rangle = \sqrt{\alpha_0}\,|00\rangle + \sqrt{\alpha_1}\,|11\rangle$

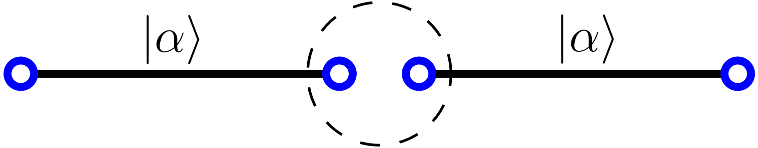
Local operations (and classical communication): qubits not allowed to interact

Maximally Entangled: $|\Psi\rangle = \frac{1}{\sqrt{2}}\,|00\rangle + \frac{1}{\sqrt{2}}\,|11\rangle$

Singlet, Bell State, Maximally Entangled State Singlet Conversion Probability $p = 2\alpha_1$, for $\alpha_0 > \alpha_1$

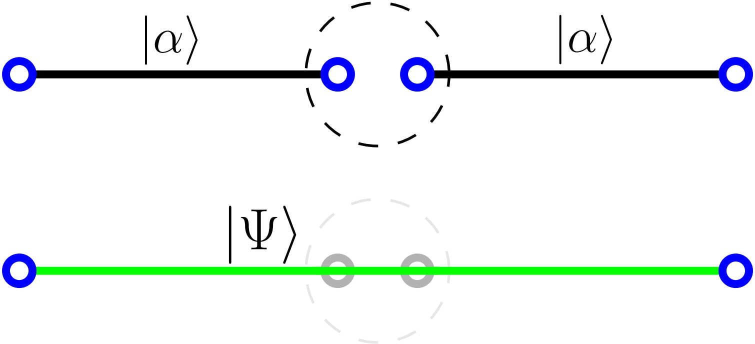
Otherwise: product state (failure)

Entanglement Swapping



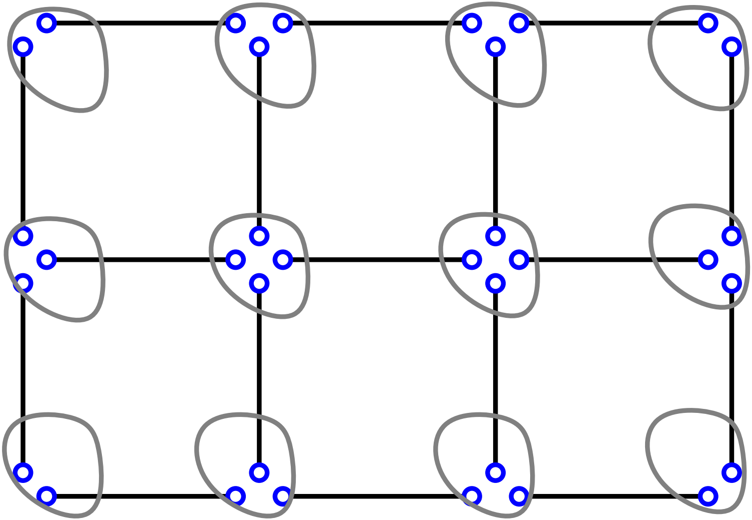
We can entangle the two outermost qubits, using only local operations and classical communication: *i.e.* without interacting outermost qubits. Using entanglement swapping.

Entanglement Swapping



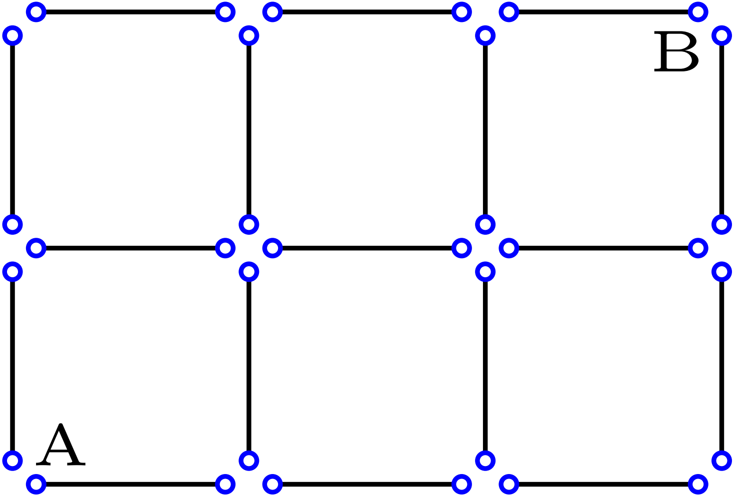
Entanglement Swapping. Get Bell state with same probability as in singlet conversion $p = 2\alpha_1$! (product state otherwise) Note: if $\alpha_1 = 1/2$, then $p = 1$.

Quantum Network



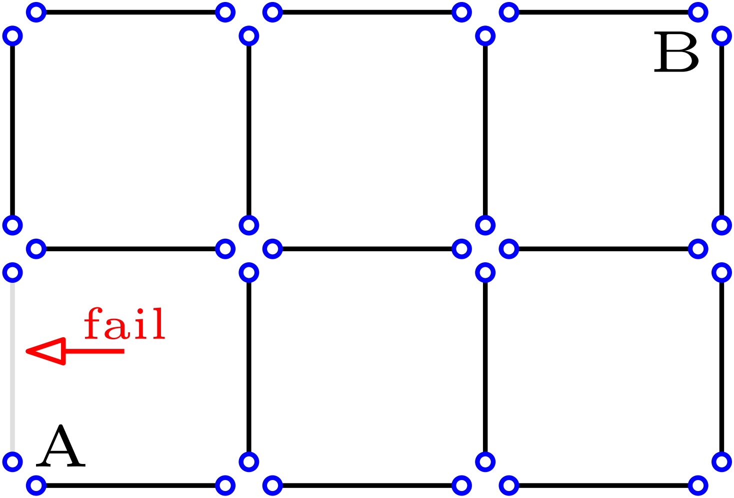
Concrete: Square lattice. Each bond is an entangled pair with amount of entanglement α_1.

"Classical" Entanglement Percolation



Entangle nodes A and B

“Classical” Entanglement Percolation



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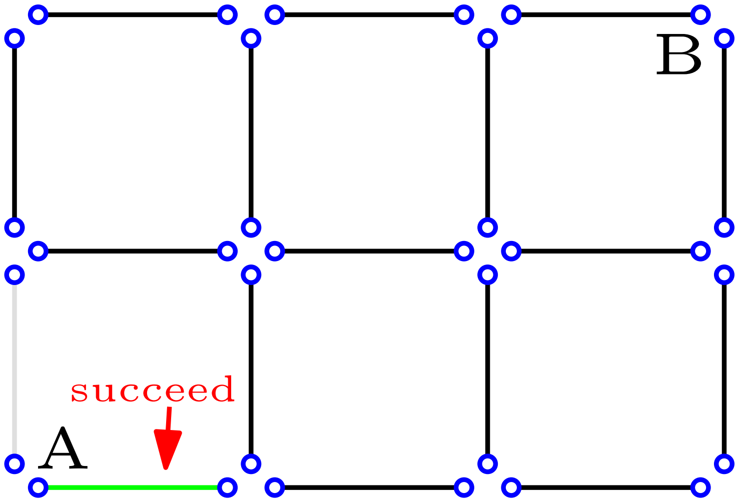

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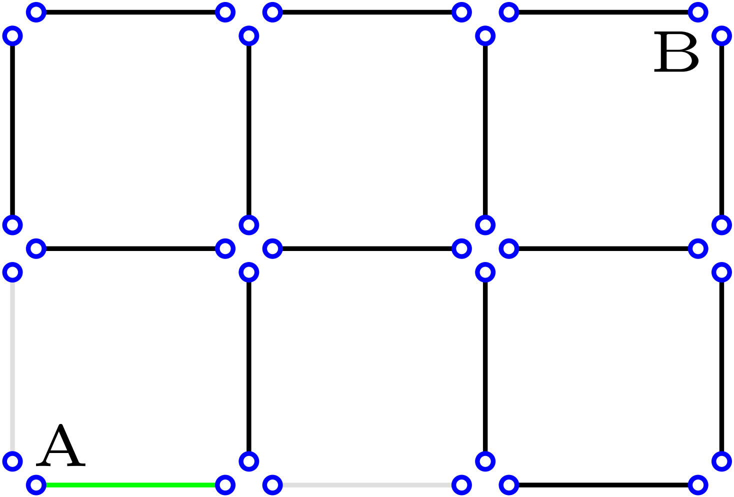

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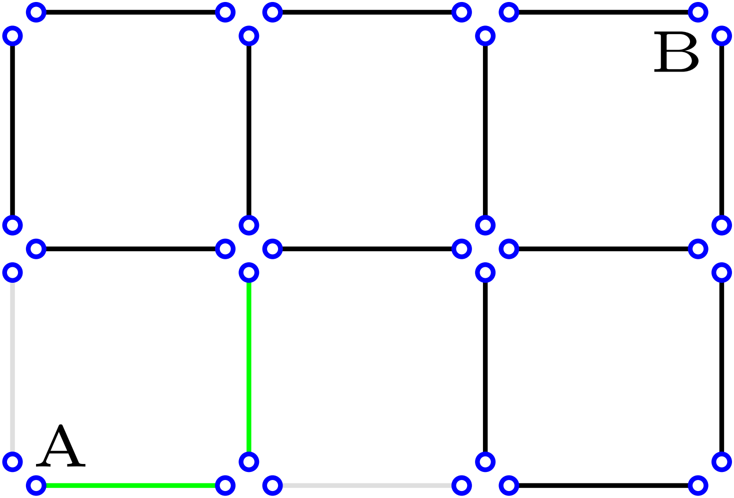

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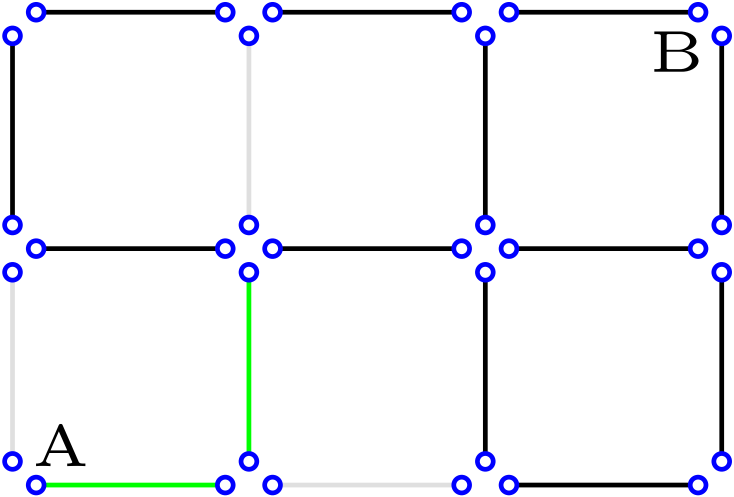

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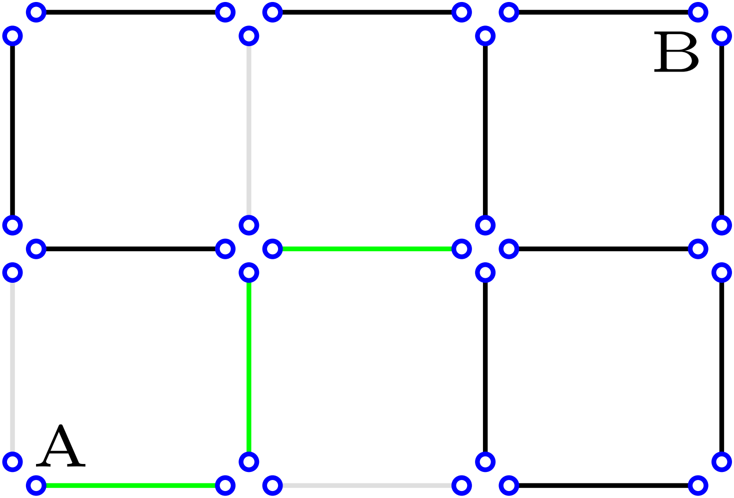

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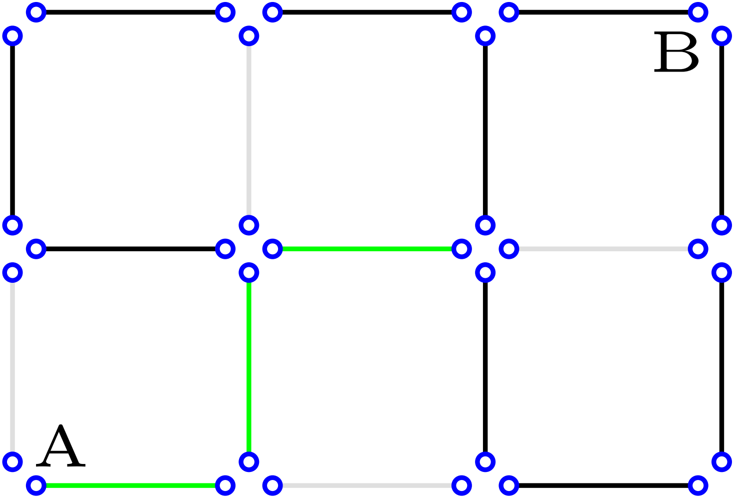

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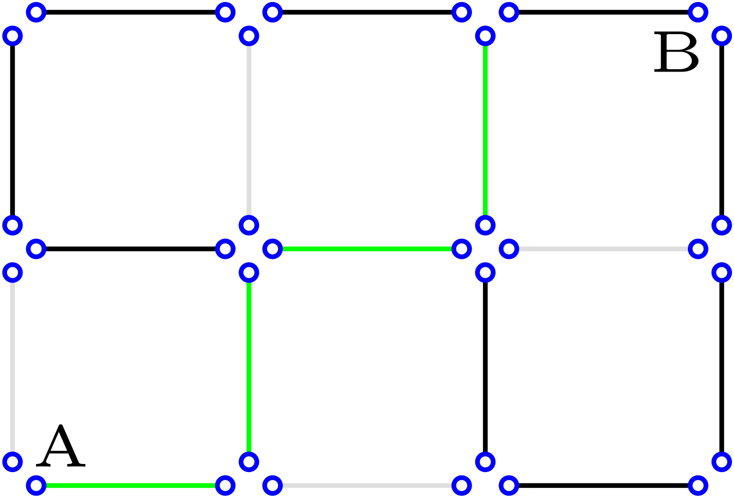

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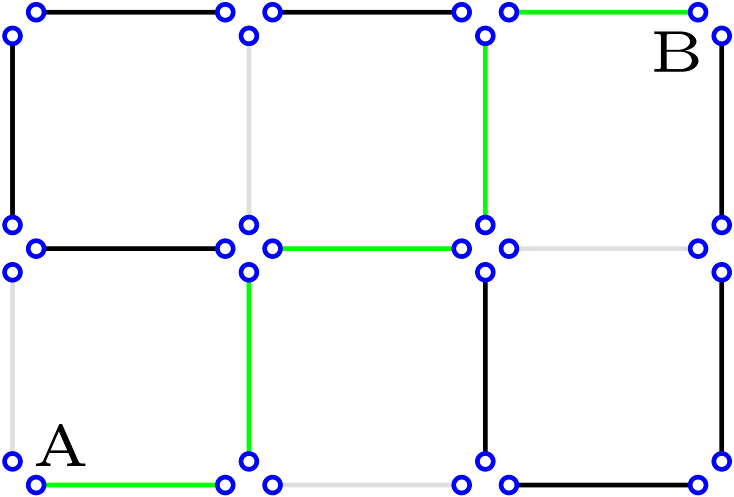

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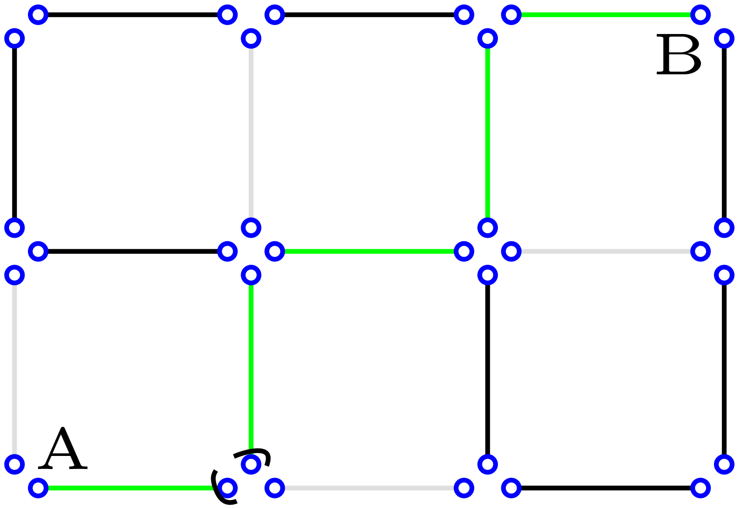

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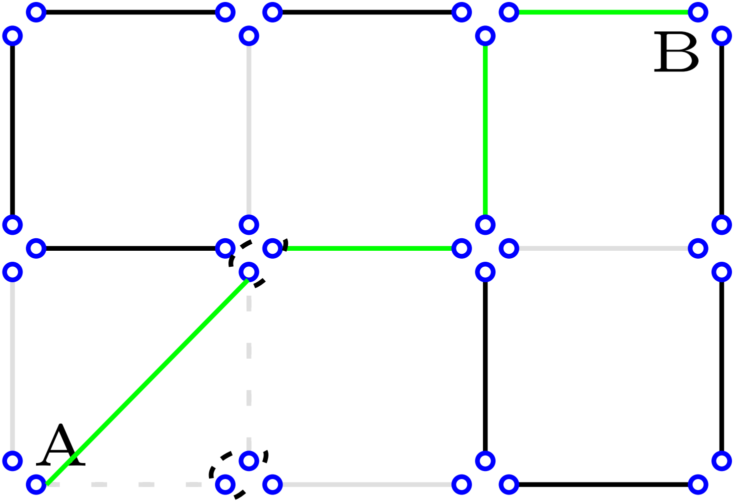

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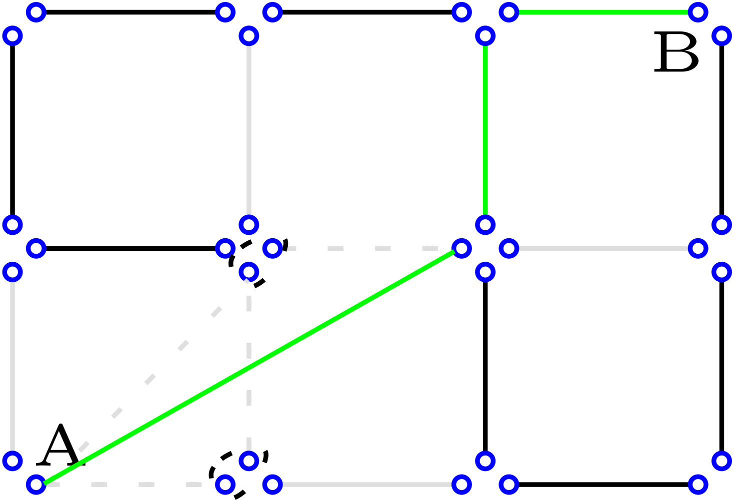

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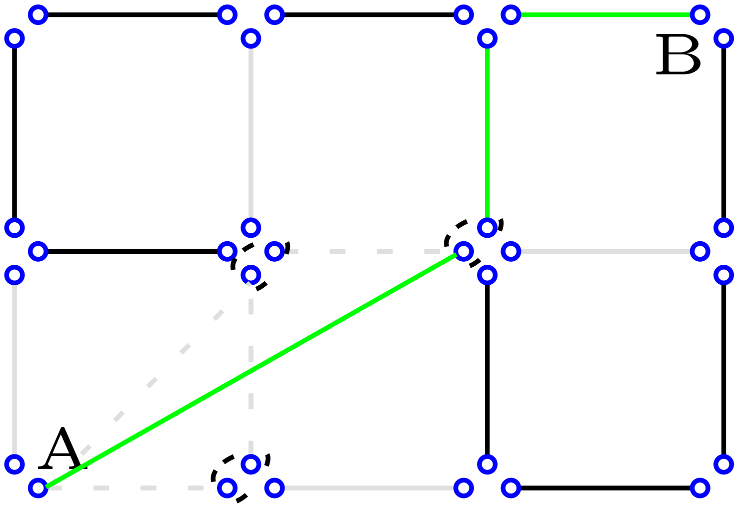

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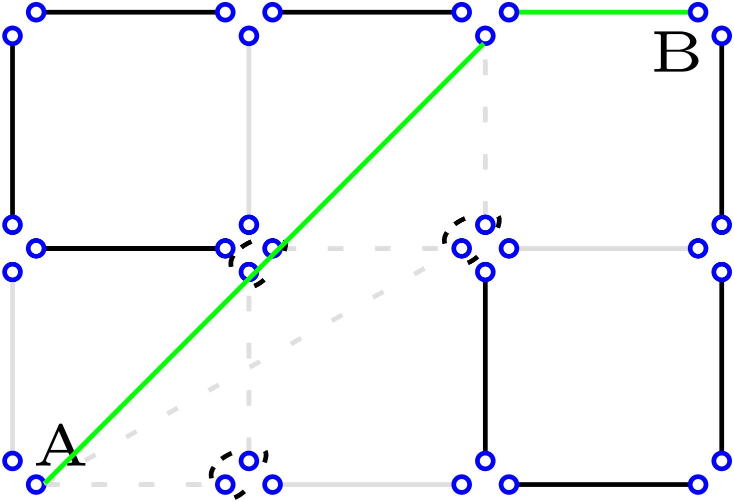

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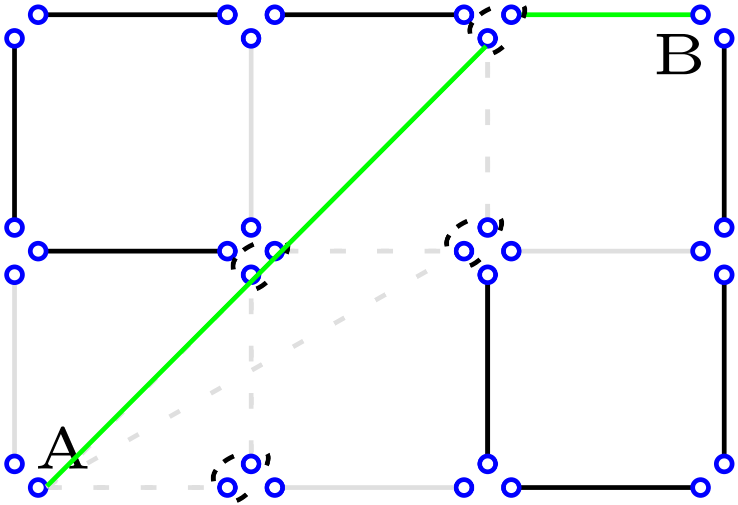

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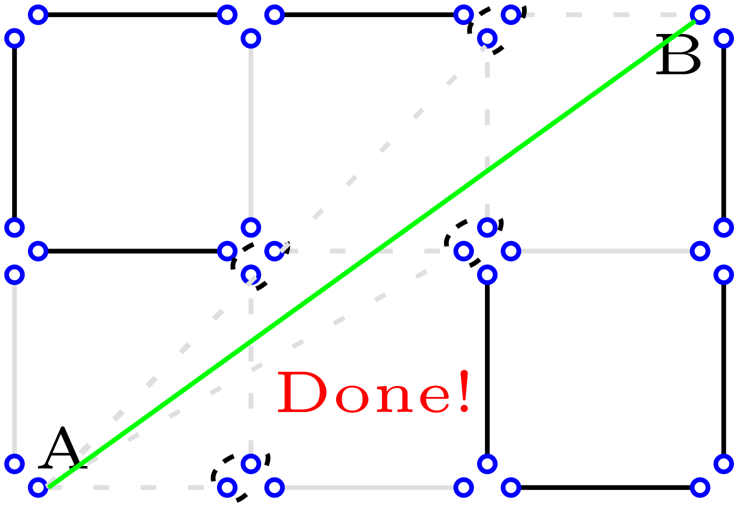
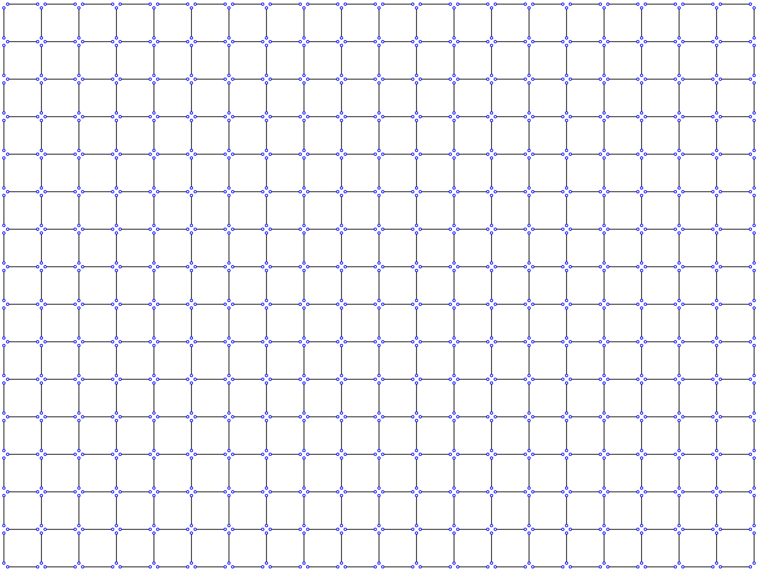


Big Network: $\alpha_1 = 0.175 \;\; p = 0.35$



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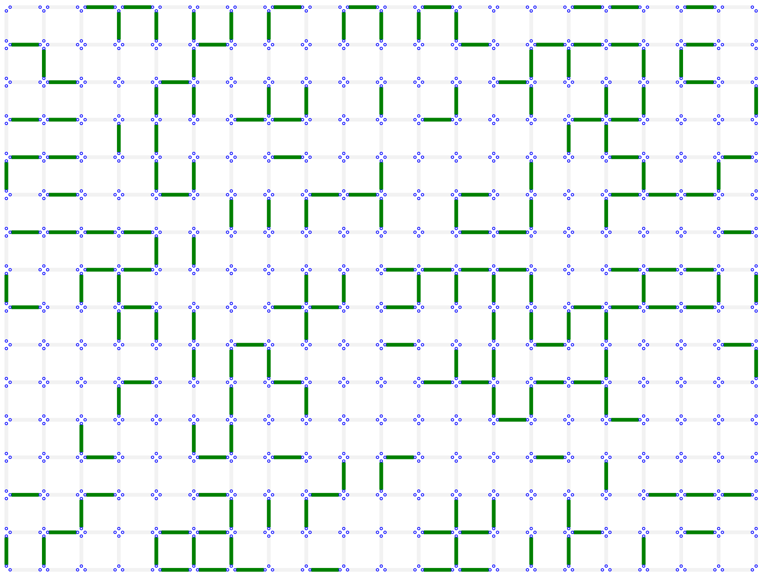

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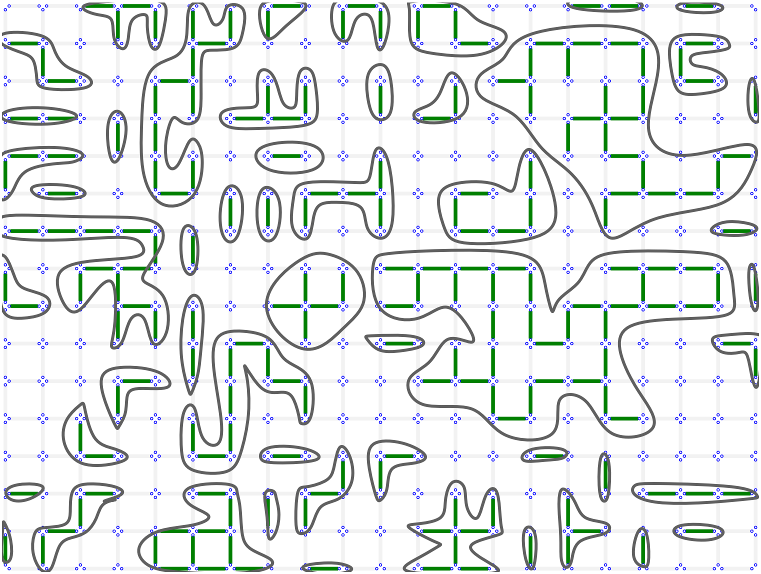
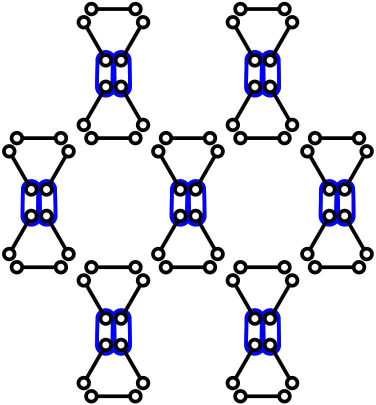
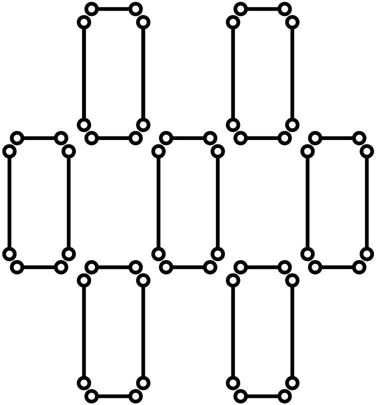


Percolation structure. Infinite cluster iff $p > p_c = 0.5$ on square lattice.

Kagome lattice to Square lattice



$p_c \approx 0.52$ Kagome

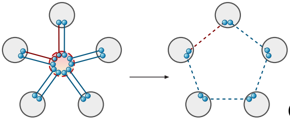


$p_c = 0.5$ Square lattice

Acín, Cirac, Lewenstein, Nature Phys 2007
Perseguers, Cirac, Acín, Lewenstein, Wehr, PRA 2008

Lapeyre, Wehr, Lewenstein, PRA 2009

More entanglement percolation with pure states:

- Multipartite (GHZ) initial states $\Rightarrow$ percolation on Archimedean and non-planar graphs. Perseguers, Cavalcanti, Lapeyre, Lewenstein, and Acín
- Improved swapping. Project onto larger subspace
- Conditionally complete swapping.
- Mixed states of rank ≤ 3 Broadfoot, Dorner, Jaksch, PRA 2010, EPL 2009
- Q-star transformation applied to various complex networks. E.g. for scale-free network, q-star usually advantageous when applied where degree is near mean degree.  Cuquet, Calsamiglia, PRL 2009, PRA 2011

Let's leave these and move to full-rank mixed states and complex networks.

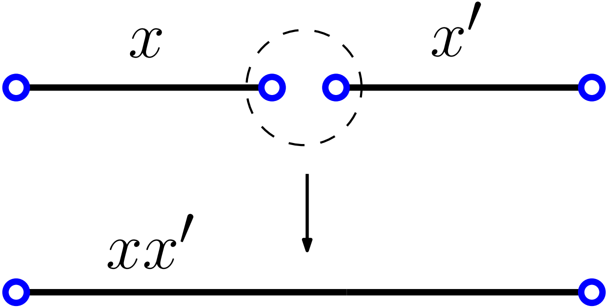
Two-qubit Mixed States

- Full-rank mixed state. All four eigenvalues positive.
- Realisic noise. But, Cannot purify finite number of states to Bell pair (Jané QIC 2002)
- Two-qubit Werner (actually *isotropic*) state parameterized by x

$$\rho_{\mathsf{W}}(x) = x\,|\Phi_{00}\rangle\langle\Phi_{00}| + \frac{1-x}{4}\mathbb{1}_4, \qquad 0 \leq x \leq 1$$

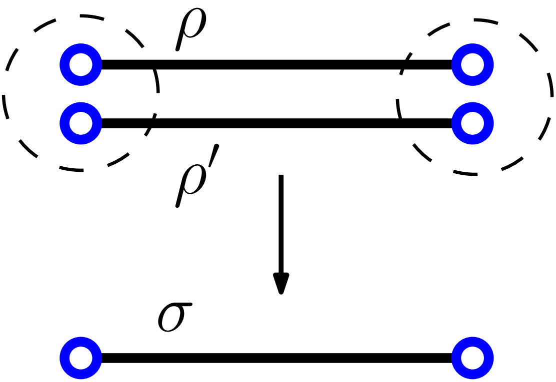
  - Werner state is a full-rank state (for $x < 1$).
  - Separable for $x \leq 1/3$.
  - Concurrence: $C(x) = \max\{0, (3x-1)/2\}$. Linear in x, $C(\text{separable}) = 0$, $C(\text{Bell pair}) = 1$
  - Convert any state to $\rho_{\mathsf{W}}(x)$ via twirling. Can be done in lab. $\rho_{\mathsf{W}}(x)$ invariant under twirl.

Swap Werner states. Get another Werner state.



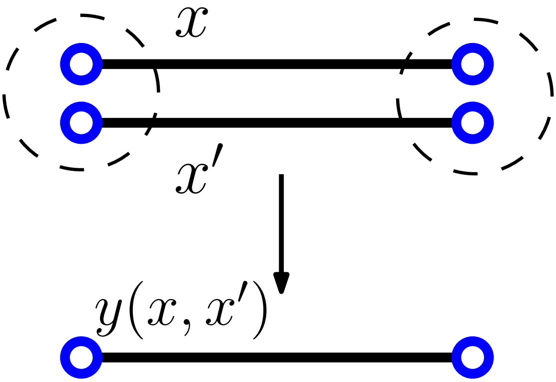
Entanglement increases with x; Exponential decay of entanglement with length of chain. Swapping: lose entanglement, Purification: gain entanglement.

Mixed states: Entanglement Purification



Obtain σ with entanglement greater than ρ, ρ' using LOCC
(local operations and classical communication)

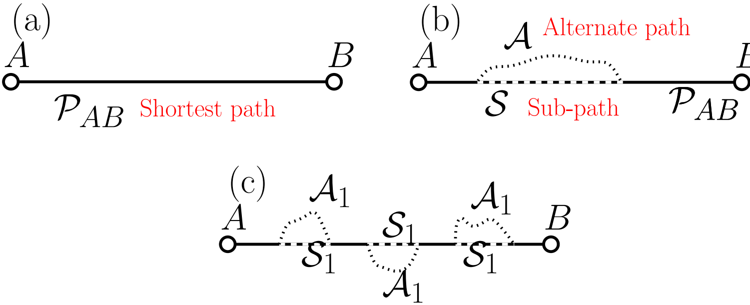
Purify Werner states. Get another Werner state.



$$y(x, x') = \frac{x + x' + 4xx'}{3 + 3xx'}, \text{ with probability } \frac{1 + xx'}{2}$$

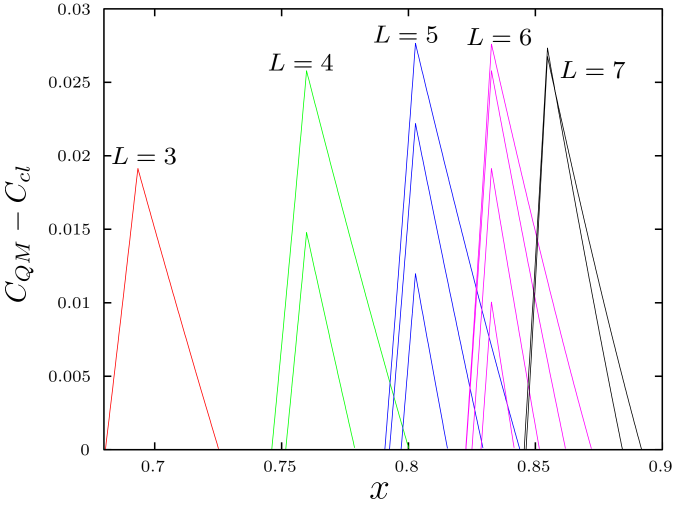
Bennett, Brassard, Popescu, Schumacher, PRL 1996 Dür, Briegel, Rep. Prog. Phys. 2007

More generic network. Combine swapping and purification.



Swap first, or purify first? We call single-path purification SPP: 1) swap along sub-path; 2) swap along alternate path; 3) purify resulting states.

What is average concurrence? (over quantum outcomes)



Advantage of purify-swap depends on shortest path length L, sub-path length n, alternate path length m, Werner parameter x. Optimizing formula for gain in average concurrence is messy.

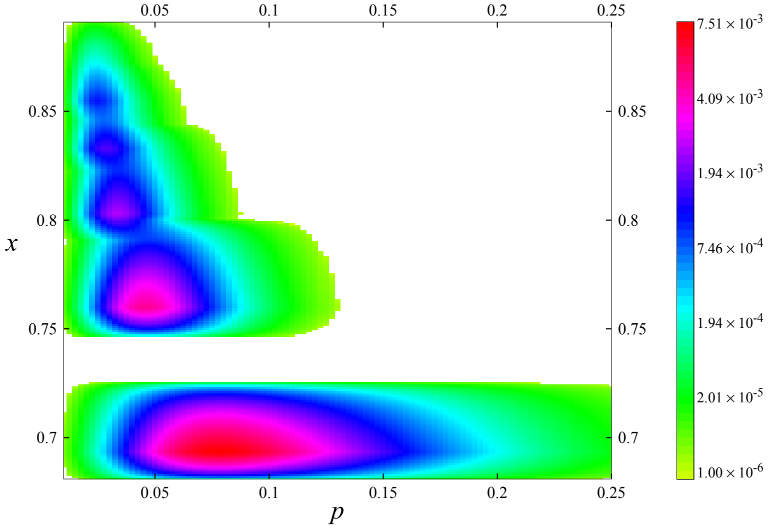
Poisson Random Graph (or Erdös–Rényi Graph)

Apply SPP between random pairs of nodes.

- Graph with N vertices. Zero or one edge between each pair. Each of the $N(N-1)/2$ edges is present with probability p.
- Density of shortest paths of length L, σ_L

$$
\begin{aligned}
\sigma_1 =& p, \\
\sigma_2 =& (1-p)[1-(1-p^2)^{N-2}] \approx (1-p)\left(1-e^{-p^2 N}\right), \\
\sigma_3 \approx& \left(1-e^{-p^3(1-p)^5(N-2)(N-3)}\right)(1-p^2)^{N-2}(1-p), \quad \text{large } p \\
\approx& \left(1-e^{-p^3(1-p)^5 N^2}\right) e^{-p^2 N}(1-p) \\
\sigma_L =& p^L \frac{(N-2)!}{(N-L-1)!} + \mathcal{O}(p^{L+1}), \quad \text{small } p \\
\sigma_L \approx& \frac{1}{N} \quad \text{for } pN = 1, \; L < \text{ radius}
\end{aligned}
$$

Solomonoff, Rapoport, Bull. Math. Biophys. 1948 (Who has these ?), 1951   Erdös Rényi 1959,1960,1961



Advantage of purify-swap depends on Werner parameter x and bond density of random graph p.

Monte Carlo $N = 200$, $L < 8$

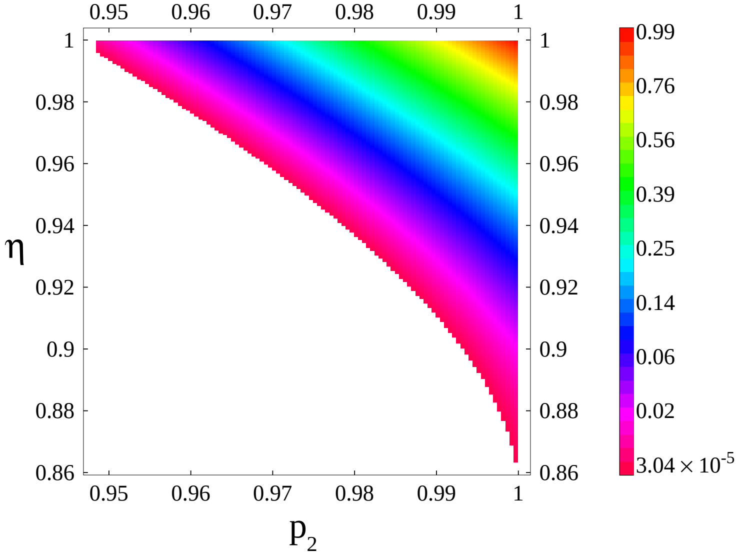
Poisson Random Graph at critical point $pN = 1$

Choose random pair of vertices. Entangle pair via purify-swap, or direct swap. What is average gain in final entanglement ?

- Giant cluster of mass $N^{2/3}$
- Density of shortest paths independent of L. So, as Werner param. $x \to 1$ long paths dominate.
- "Good" ranges of x overlap more for large L: $\Rightarrow$ integrate
- Each path-subpath occurs with probability $\approx 1/N^2$
- At fixed x, contributions are from $L \approx 1/(1-x)$. Four factors
  - $\approx L$ paths contribute near x
  - $\approx L$ sub-path lengths per path
  - $\approx L$ alternate paths per sub-path
  - $\approx L$ positions along path for sub,alt-path pair.
- Advantage of purify-swap over swap, averaged over network is

$$\Delta\overline{C} \sim \frac{K}{N^2(1-x)^4} \text{ for large } N \text{ small } 1-x, \quad \left(K \approx 6.5 \times 10^{-5}\right)$$

Lapeyre, Perseguers, Lewenstein, Acín, QIC 2012

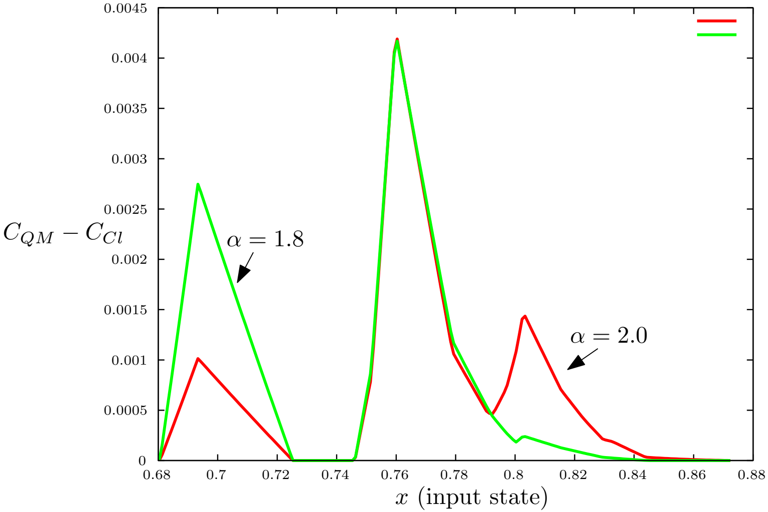


Noisy operations: $y = y_{\mathsf{max}}$, $a = a_{\mathsf{max}}(y_{\mathsf{max}})$, gives $\Delta C = 1/36$. η: reliability of measurement. p_2: reliability of two-qubit operator.

Poisson Random Graph at critical point $pN = 1$

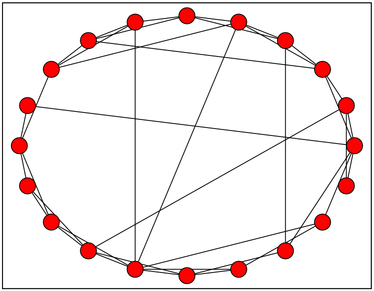
But wait,... there's more. Return to perfect operations.

- For $Np = 1$, Radius grows like $N^{1/3}$ Nachmias, Peres, Ann. Prob. 2008
- Our MC shows radius of largest cluster $\approx 3N^{1/3}$.
- Since $L \approx 1/(1-x) \Rightarrow \Delta\overline{C} < 81AN^{-2/3}$
- Purification protocols always give modest results. They must be used iteratively.
- *But*, Choose bond density to favor $L = 2, 3$: $p^2N = c$. Then $\sigma_2 \to (1 - e^{-c})$ and $\sigma_3 \to e^{-c}$. Now for Werner parameter around 0.7, we have many subgraphs for purify-swap.



Advantage of purify-swap for Werner states on scale-free network with $p(k) \propto k^{-\alpha}$. Monte Carlo with $N = 200$.

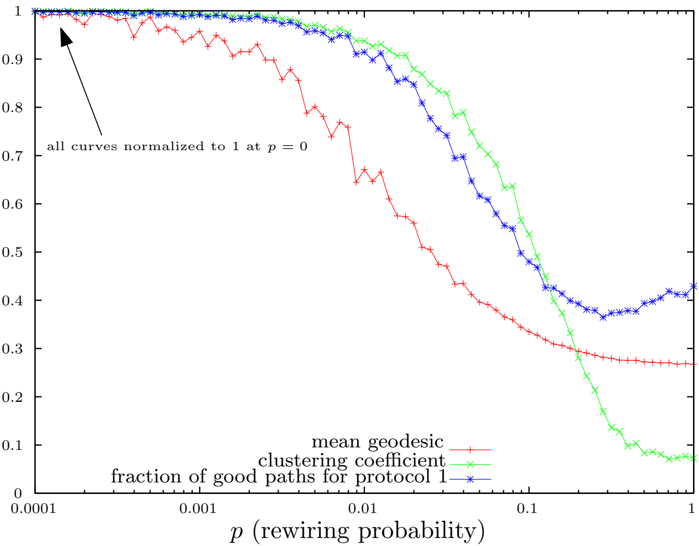
Watts-Strogatz model has parameter p that tunes between lattice-like model with regular local connections, and an Erdös–Rényi–like model. We compute distribution of shortest paths on Watts-Strogatz model for $p = 0$. One link to each neighbor at $\pm 1, \pm 2,\ (K = 4)$.



- $N(N-1)/2$ shortest paths (SPs)
- Number of SPs of each length L from 1 through $N/4 - 1$ is $2N$ (and $3N/2$ for boundary case $L = N/4$.
- Density of SPs of length L is then $\sigma_L = 4/(N-1)$. Flat.(except for boundary case.)

Number of shortest paths admitting SPP (single purify-swap)

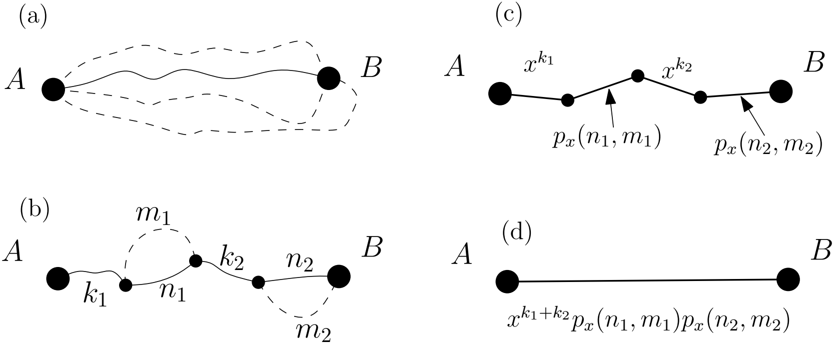
$$\frac{N^2 - N}{2} - 4N - \frac{1}{2} 2N(5) = \frac{N(N-19)}{2}.$$



Watts-Strogatz small world (2×2 neighbors). Fraction of paths admitting purify-swap. ($N = 100$). The separation of the red and green lines is the main point of the model.

Mixed states on complex network

Werner state on each link. What is average concurrence?
(over quantum outcomes)



$p_x(n, m)$ is average Werner parameter after SPP with subpath length n, alternate path length m.