# How (Not) to Shoot in Your Foot with SDN Local Fast Failover

A Load-Connectivity Tradeoff

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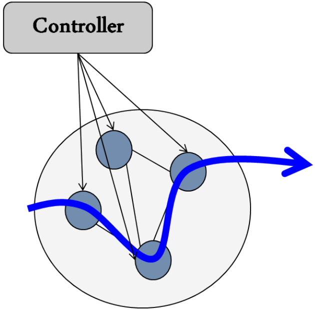
# Motivation: SDN Local Fast Failover



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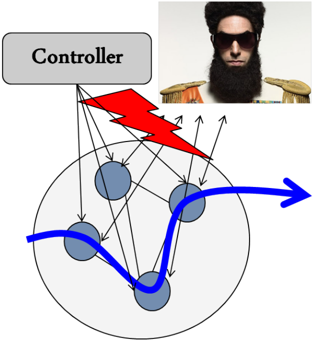

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  - **(header, failed links)** $\longrightarrow$ **(backup port)**
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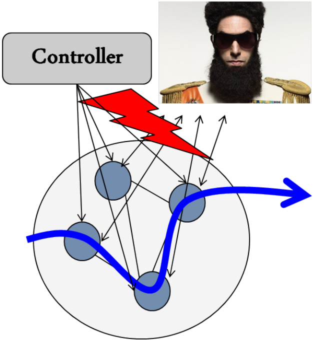

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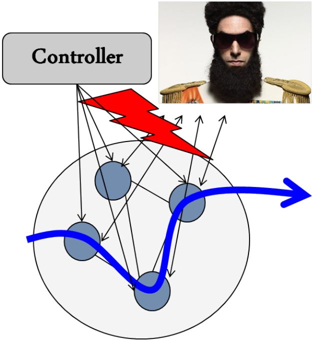

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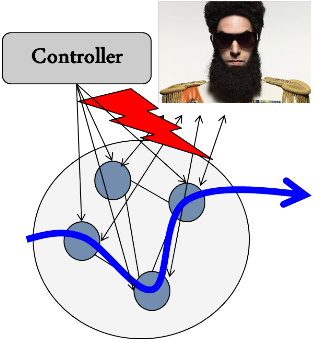

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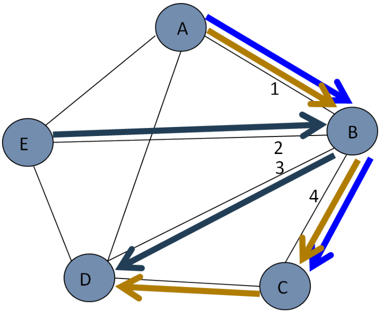

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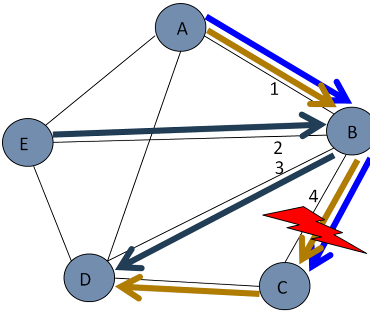


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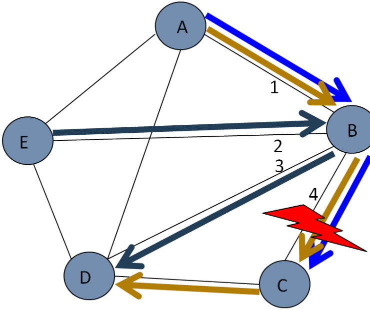
# Model: General Failover Rules

Flows can be treated individually!

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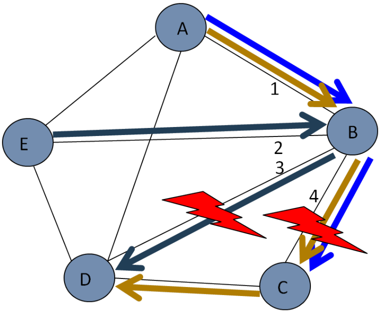


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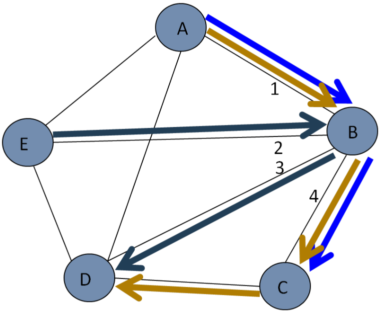
Depending on failure set,
(A,C) is forwarded differently!

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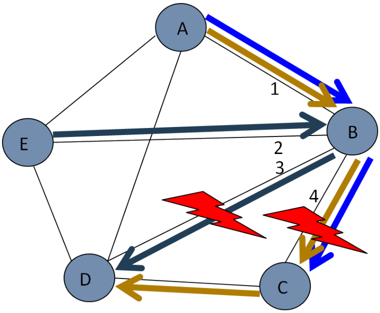


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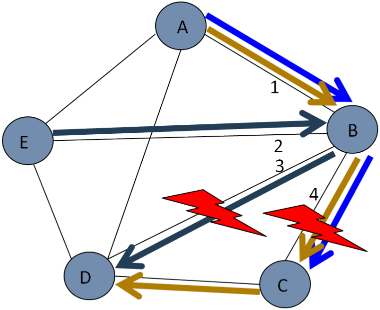
Same destination requires same forwarding port.

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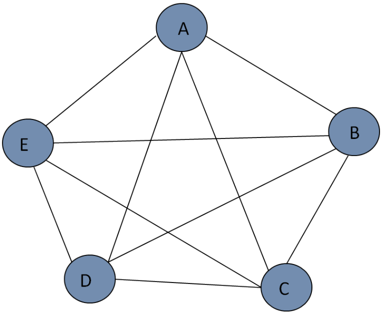
A simple example: full mesh (clique) & all-to-one communication



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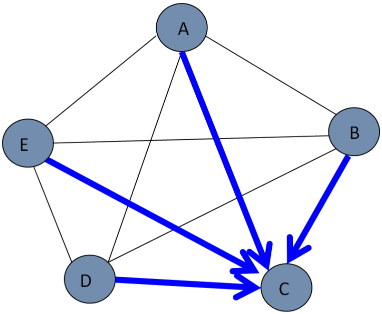

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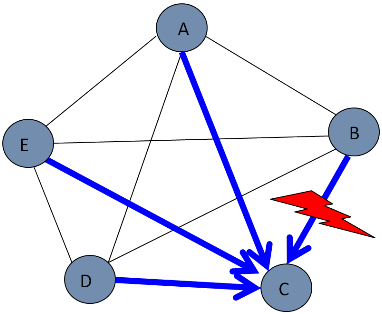


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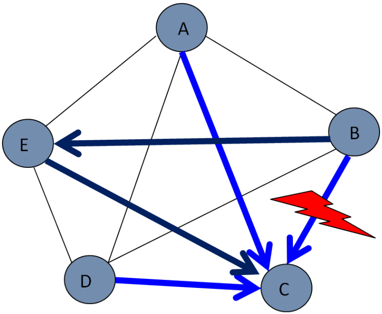


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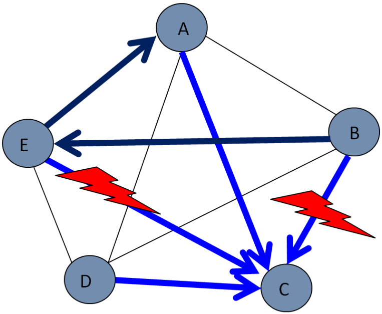

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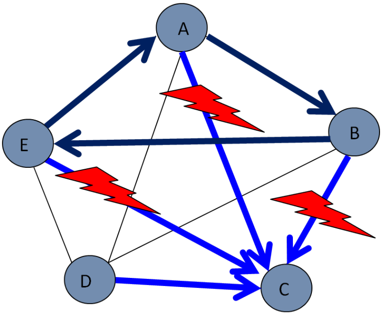


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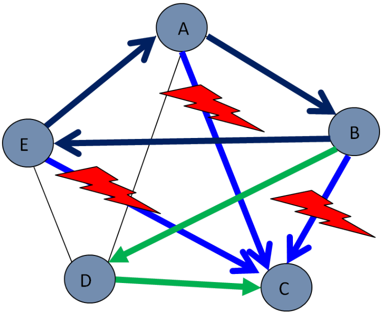


**Loop!**

Unnecessary: Many paths left!
But do not know remote state...

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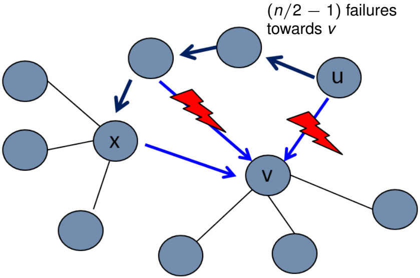
- Fail any link which would directly lead to destination node $v$ until $(n/2-1)$ links failed



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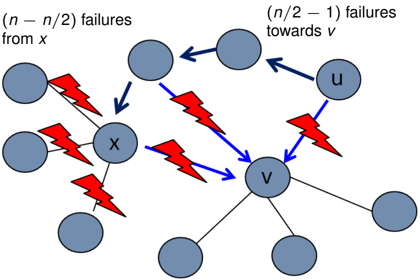

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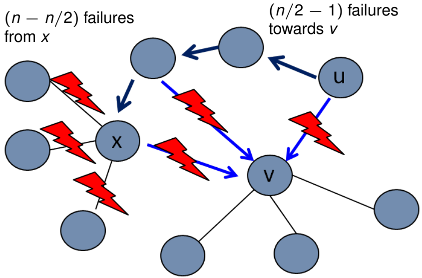
- Fail links from $x$ to $(n - n/2)$ other nodes
- $x$ only has links to already visited nodes: **loop unavoidable!**
- But all nodes still have degree at least $n/2 - 1$ ($x$ and $v$ have the lowest)



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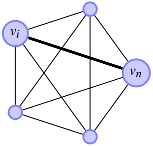


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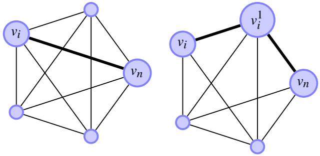


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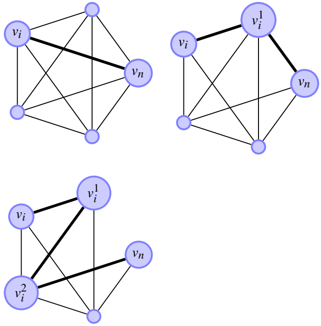

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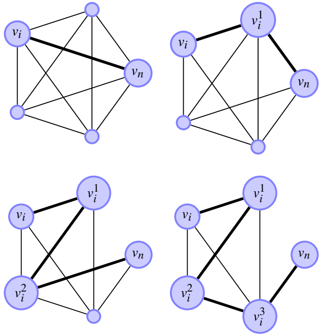

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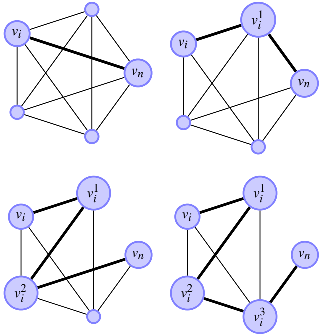


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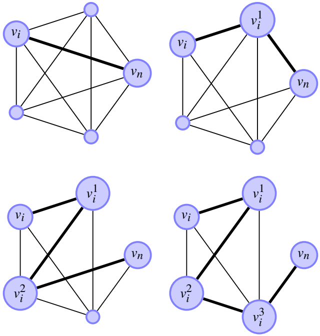


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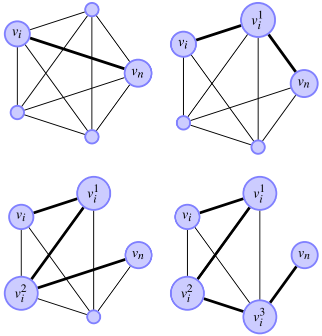


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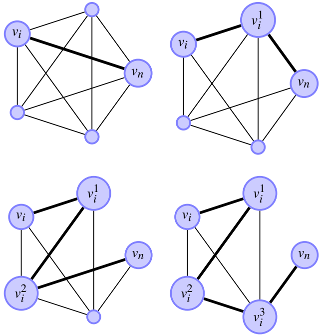


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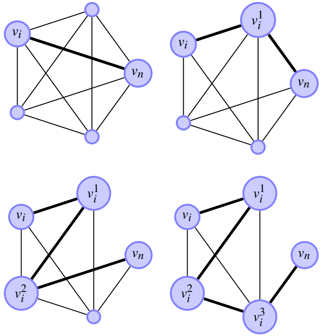


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- By a counting argument, there exists a node $x \in \bigcup_i A_i$ which appears in at least $\sqrt{\varphi}$ sets $A_i$.
- For each such $A_i$, the adversary can route $v_i \to v_n$ via $x$ by failing links to $v_n$.

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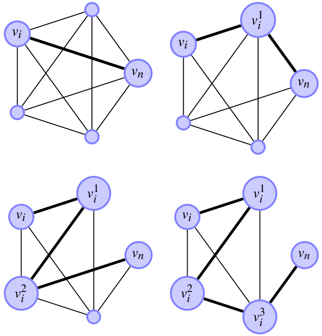


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$(v_i \to \cdots \to v_i^1 \to \cdots \to v_i^2 \to \cdots \to v_i^{\varphi} \to v_n)$.

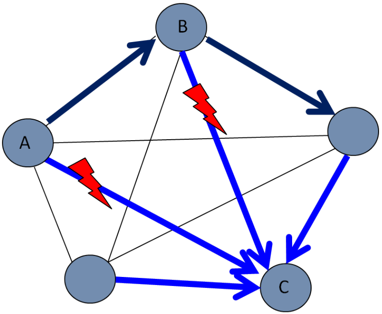
- The last hop $v_i^j$ ($j \in [1, \ldots, \varphi]$) is unique for every path.
- Consider the set $A_i = \{v_i, v_i^1, \ldots, v_i^{\sqrt{\varphi}}\}$ (set of possible last hops on the path to $v_n$).
- Consider a multiset of $\left|\bigcup_i A_i\right| = (n-1)(\sqrt{\varphi}+1)$ nodes.
- By a counting argument, there exists a node $x \in \bigcup_i A_i$ which appears in at least $\sqrt{\varphi}$ sets $A_i$.
- For each such $A_i$, the adversary can route $v_i \to v_n$ via $x$ by failing links to $v_n$.
- The adversary will fail $\sqrt{\varphi} \times \sqrt{\varphi} = \varphi$ links incident to $v_n$; load of link $(x, v_n)$ becomes $\sqrt{\varphi}$.

# Negative Result: You must shoot in your foot!

**Theorem**

*For any local **destination-based** failover scheme, there exists a failure scenario which yields max link load of at least $\varphi$.*

Why worse for destination-based? Intuition:




At B, flow (A,C) gets combined with flow (B,C) and never splits again. Etc.!

# Positive Result: Make the best out of the situation!

A general failover scheme:

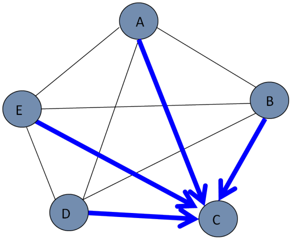
$\delta_{1,1}, \delta_{1,2}, \ldots, \delta_{1,n-2}$

$\ldots$

$\delta_{i,1}, \delta_{i,2}, \ldots, \delta_{i,n-2}$

$\ldots$

$\delta_{n-1,1}, \delta_{n-1,2}, \ldots, \delta_{n-1,n-2}$



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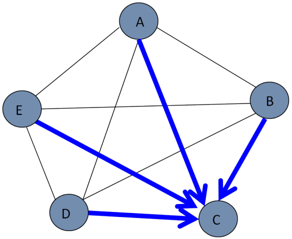


- Matrix $\delta_{i,j}$: if node $v_i$ cannot reach destination directly, try node $\delta_{i,1}$; if not reachable either, try node $\delta_{i,2}$, ...

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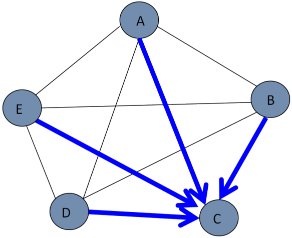


- Matrix $\delta_{i,j}$: if node $v_i$ cannot reach destination directly, try node $\delta_{i,1}$; if not reachable either, try node $\delta_{i,2}$, ...
- Choosing random permutations:

**Theorem**

***Random*** *Failover Scheme (RFS) can tolerate $\varphi$ failures ($0 < \varphi < n$) with load no more than $\sqrt{\varphi} \log n$.*

# Positive Result: Make the best out of the situation!

Can also be achieved **deterministically**, as long as number of failures bounded by log $n$:

$$\delta_{1,1}, \delta_{1,2}, \ldots, \delta_{1,n-2}$$

$$\ldots$$

$$\delta_{i,1}, \delta_{i,2}, \ldots, \delta_{i,n-2}$$

$$\ldots$$

$$\delta_{n-1,1}, \delta_{n-1,2}, \ldots, \delta_{n-1,n-2}$$

$$\xrightarrow[\delta_{i,j} = (i-1) + 2^{j-1}]{}$$

$$1, 2, 4, 8, \ldots, \left(0 + 2^{\lfloor \log n \rfloor}\right) \mod n$$

$$2, 3, 5, 9, \ldots, \left(1 + 2^{\lfloor \log n \rfloor}\right) \mod n$$

$$3, 4, 6, 10 \ldots, \left(2 + 2^{\lfloor \log n \rfloor}\right) \mod n$$

$$\ldots$$

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**Theorem**

***Deterministic*** *Failover Scheme (DFS) can tolerate $\varphi$ failures ($0 < \varphi < \log n$) with load no more than $\sqrt{\varphi}$.*

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Can also be achieved **deterministically**, as long as number of failures bounded by $\log n$:

$$\begin{array}{l} \delta_{1,1}, \delta_{1,2}, \ldots, \delta_{1,n-2} \\ \ldots \\ \delta_{i,1}, \delta_{i,2}, \ldots, \delta_{i,n-2} \\ \ldots \\ \delta_{n-1,1}, \delta_{n-1,2}, \ldots, \delta_{n-1,n-2} \end{array} \quad \xrightarrow[\delta_{i,j} = (i-1) + 2^{j-1}]{} \quad \begin{array}{l} 1, 2, 4, 8, \ldots, \left(0 + 2^{\lfloor \log n \rfloor}\right) \mod n \\ 2, 3, 5, 9, \ldots, \left(1 + 2^{\lfloor \log n \rfloor}\right) \mod n \\ 3, 4, 6, 10 \ldots, \left(2 + 2^{\lfloor \log n \rfloor}\right) \mod n \\ \ldots \end{array}$$

**Theorem**

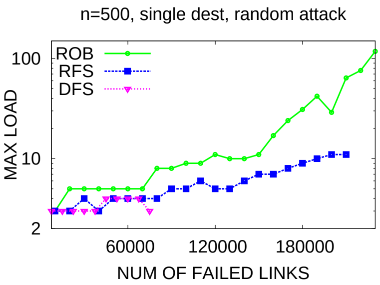
***Deterministic** Failover Scheme (DFS) can tolerate $\varphi$ failures ($0 < \varphi < \log n$) with load no more than $\sqrt{\varphi}$.*

Proof idea:

- There are no repetitions in the matrix columns. Thus any node appears exactly once at the first position, exactly once at the second, and so on...
- For any node index $\ell$, all $\ell$-prefixes (sets of indices preceding $\ell$ in the sequences) are disjoint.

**Better in reality (i.e., under random failures):**

- ROB is a simple destination-based scheme.
- In ROB, when a link fails, use next available link.



# Simulations: Beyond Worst-Case Failures

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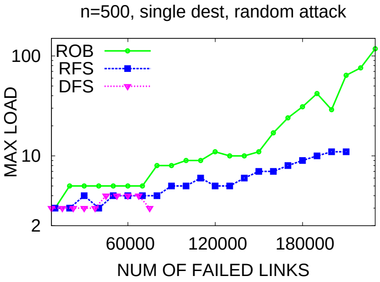
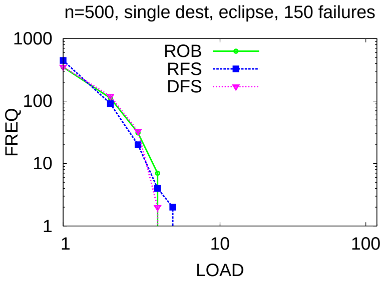
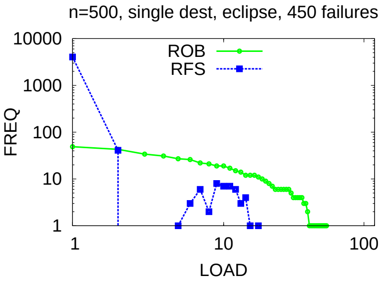



**Only small fraction of links highly loaded:**



# Summary

- How to shoot in your foot:
  - No local failover scheme can tolerate more than $n - 1$ failures.
  - Any local failover scheme can yield a max load of $\sqrt{\varphi}$, where $\varphi < n$.
  - Any **destination-based** local failover scheme can yield a max load of $\varphi$, where $\varphi < n$.

# Summary

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- How **not** to shoot in your foot:
  - **Random** local failover scheme (RFS) yields a max load of at most $\sqrt{\varphi} \log n$, where $\varphi \leq n$.
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  - A **simple destination-based** local failover scheme (ROB) performs well under random failures.

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- Extensions and future work:
  - For **random** failures, RFS yields a max load of at most $\sqrt{\varphi}$.
  - All-to-all communication.

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THANK YOU!