ECE 8823 A / CS 8803 - ICN

**Interconnection Networks**

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http://tusharkrishna.ece.gatech.edu/teaching/icn_s17/

# Lecture 4: Routing


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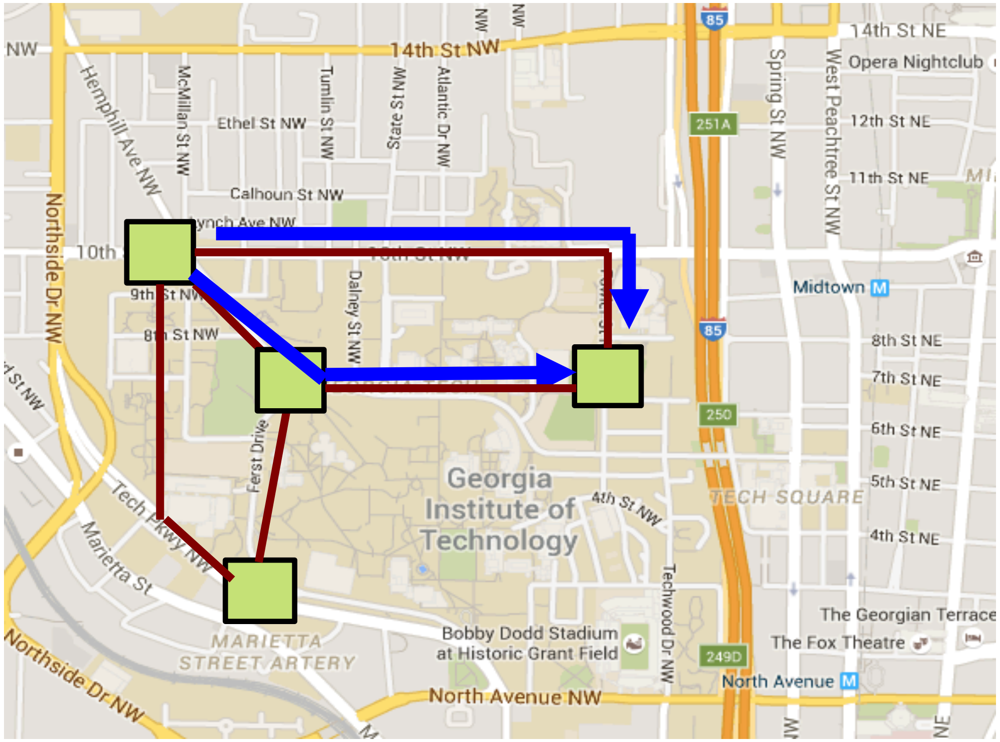
*Acknowledgment: Some slides adapted from Univ of Toronto ECE 1749 H (N Jerger) and MIT 6.883 (L-S Peh)*

# Network Architecture

- **Topology**
  - How to connect the nodes
  - ~Road Network
- **Routing**
  - Which path should a message take
  - ~Series of road segments from source to destination
- **Flow Control**
  - When does the message have to stop/proceed
  - ~Traffic signals at end of each road segment
- **Router Microarchitecture**
  - How to build the routers
  - ~Design of traffic intersection (number of lanes, algorithm for turning red/green)

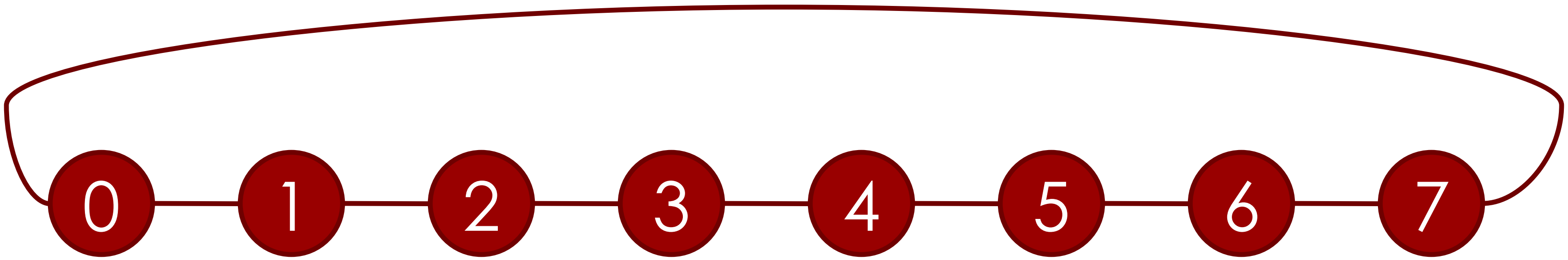
# Routing

- Once topology is fixed, routing determines exact path from source to destination
- Analogous to the series of road segments from source to destination



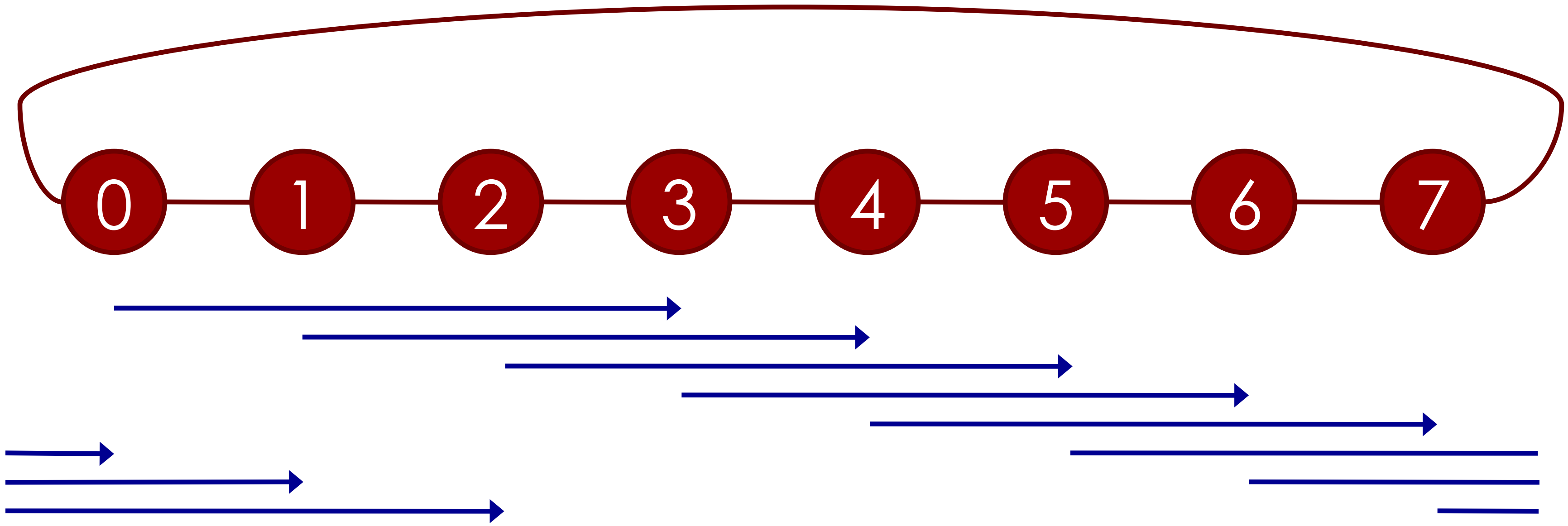

  

# Why does Routing matter?



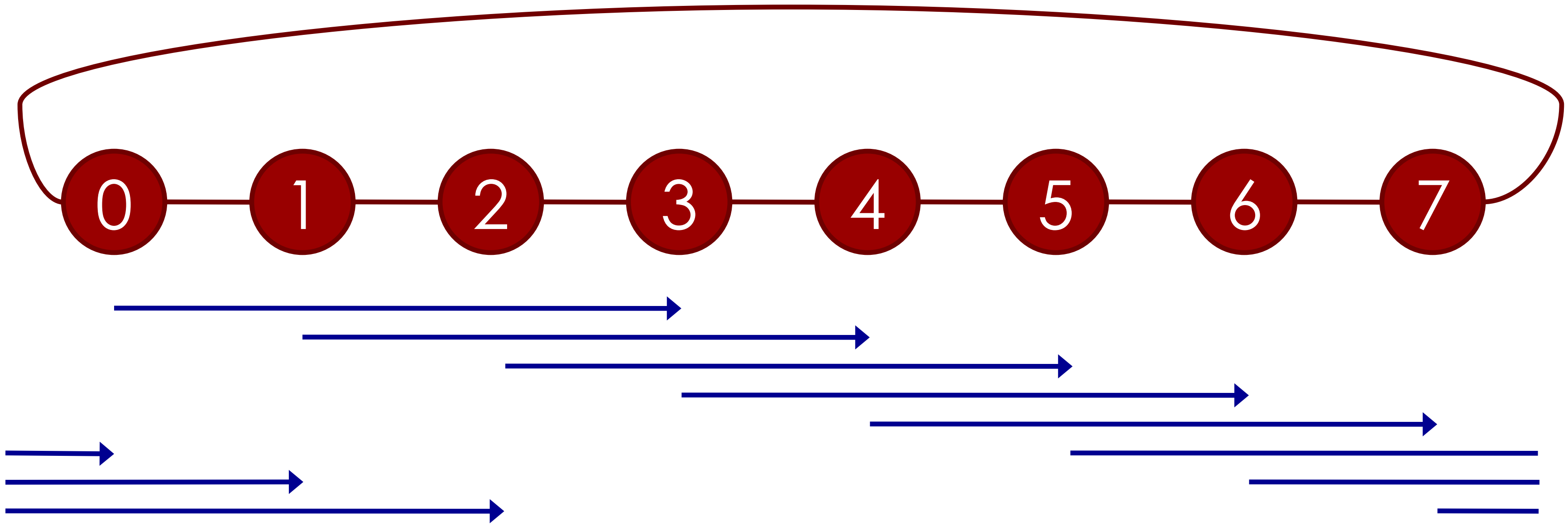

- Suppose three routing options
  - **Greedy:** shortest path
  - **Random:** randomly pick direction
  - **Adaptive:** monitor load in each direction and send
- Which routing algorithm is the best?
  - Depends …what is the traffic pattern?
  - What metric (latency/throughput/energy) do we care about?

# Suppose Traffic = Tornado




- k-ary n-cube, $node_i \rightarrow node_{(i + (k/2) - 1) \bmod k}$
  - Here k = 8, $node_i \rightarrow node_{i+3 \bmod 8}$

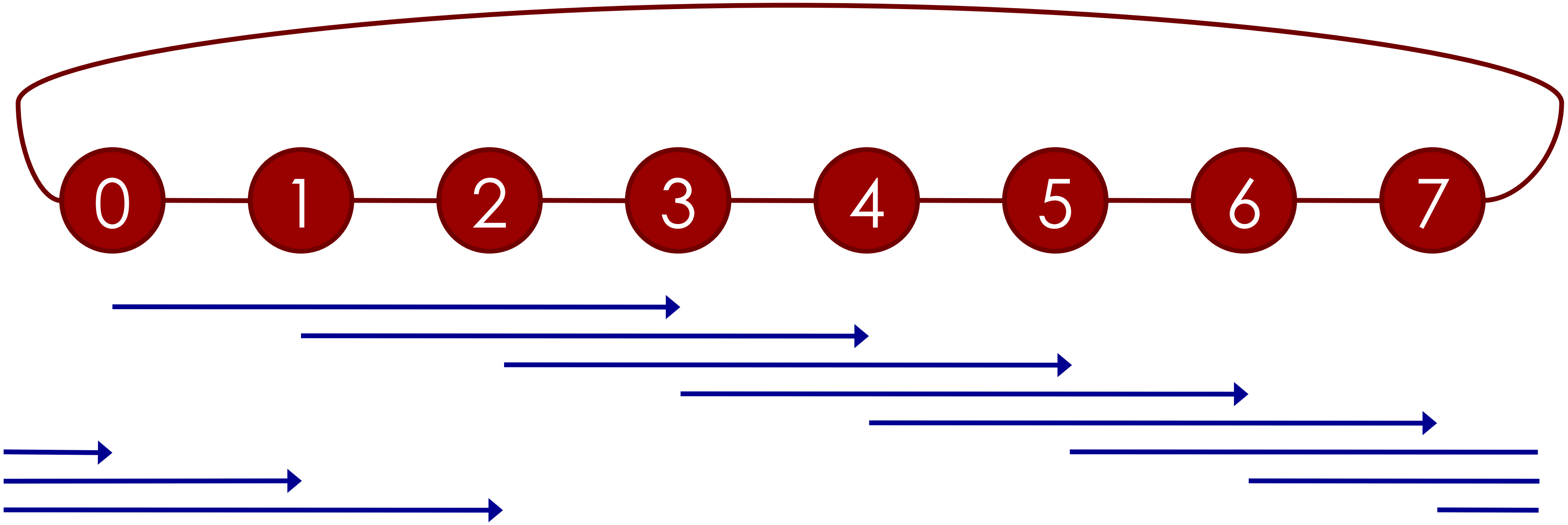
# Metric = Zero-load Latency




- Best routing algorithm?

| | Greedy | Random | Adaptive |
|---|---|---|---|
| **Hops** | 3 | (3+5)/2 = 4 | 3 at low-loads |

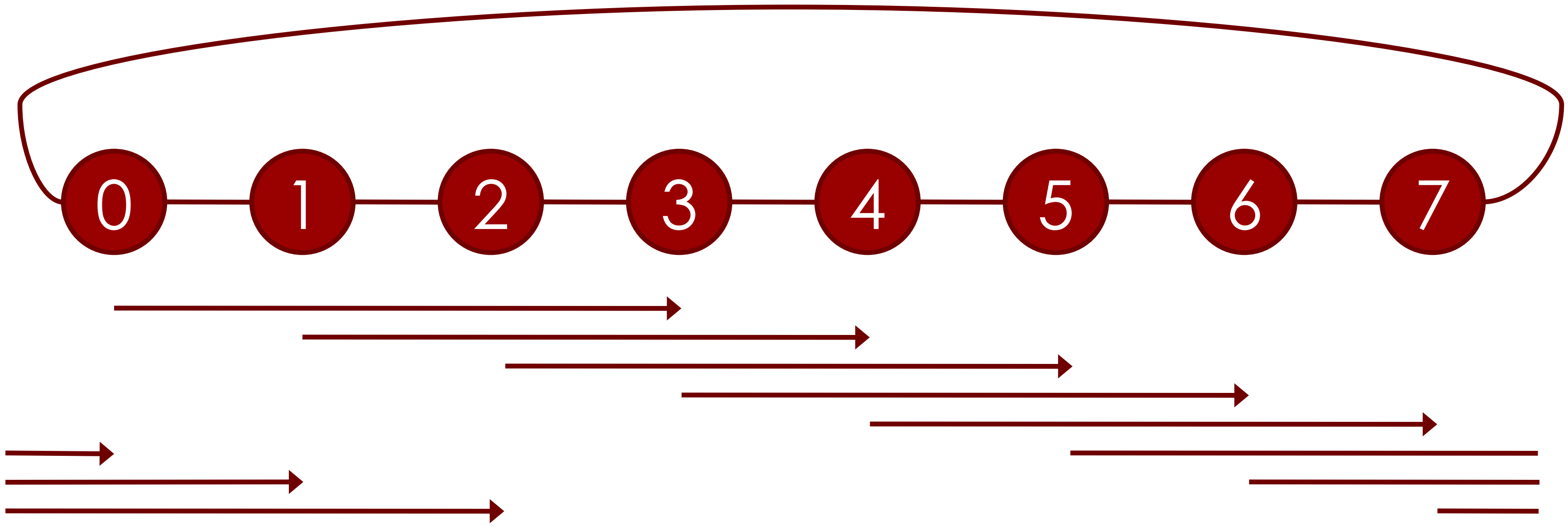
# Metric = Energy




- Best routing algorithm?

| | Greedy | Random | Adaptive |
|---|---|---|---|
| **Hops** | 3 | (3+5)/2 = 4 | 3 at low-loads |

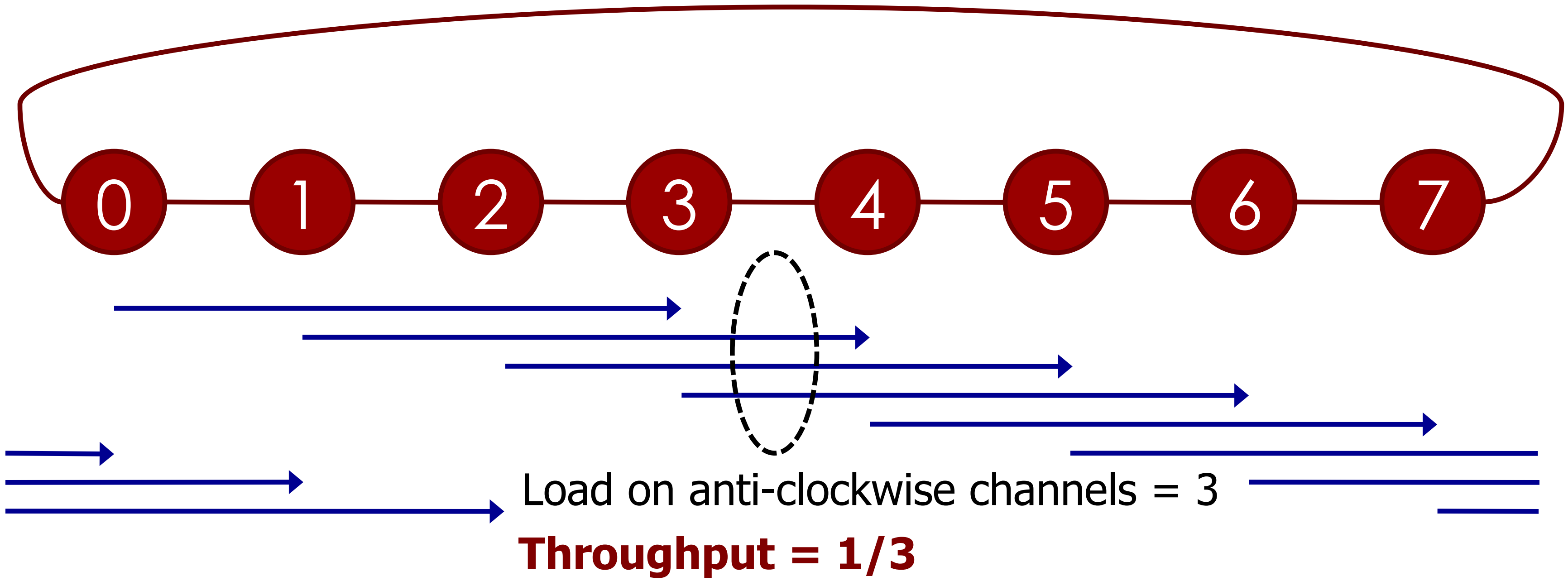
# Metric = Throughput




- Best routing algorithm?

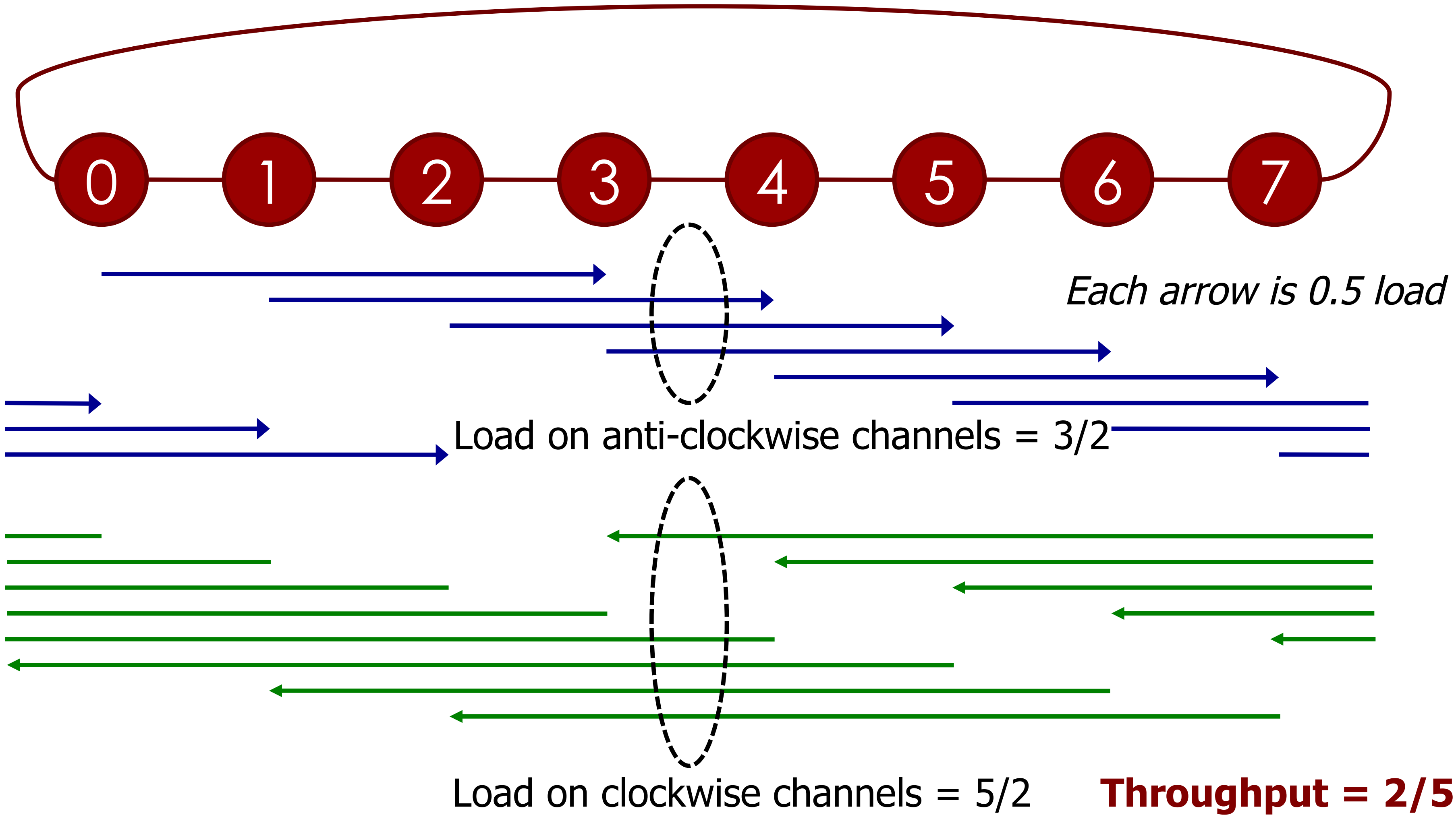
| | Greedy | Random | Adaptive |
|---|---|---|---|
| **Max Channel Load** | | | |
| **Throughput** | | | |

# Channel Load for Greedy Traffic



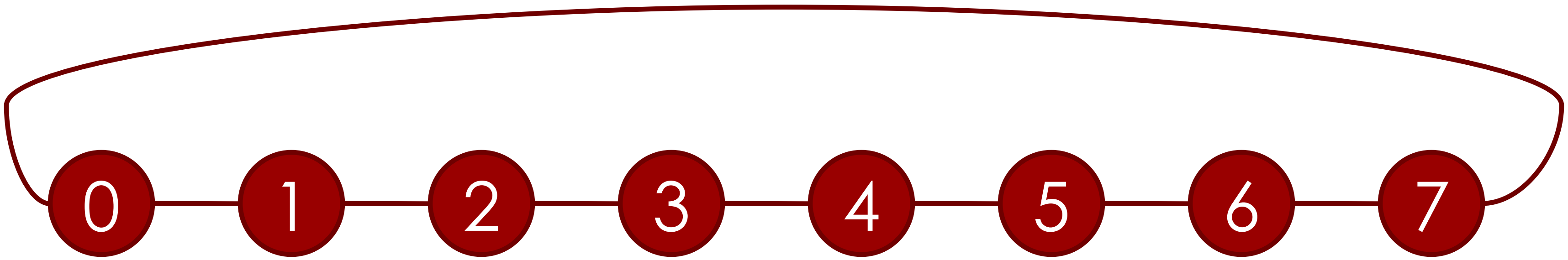

- All traffic moves anti-clockwise
  - Clockwise channels are idle

# Channel Load for Random Traffic




**Throughput = 2/5**

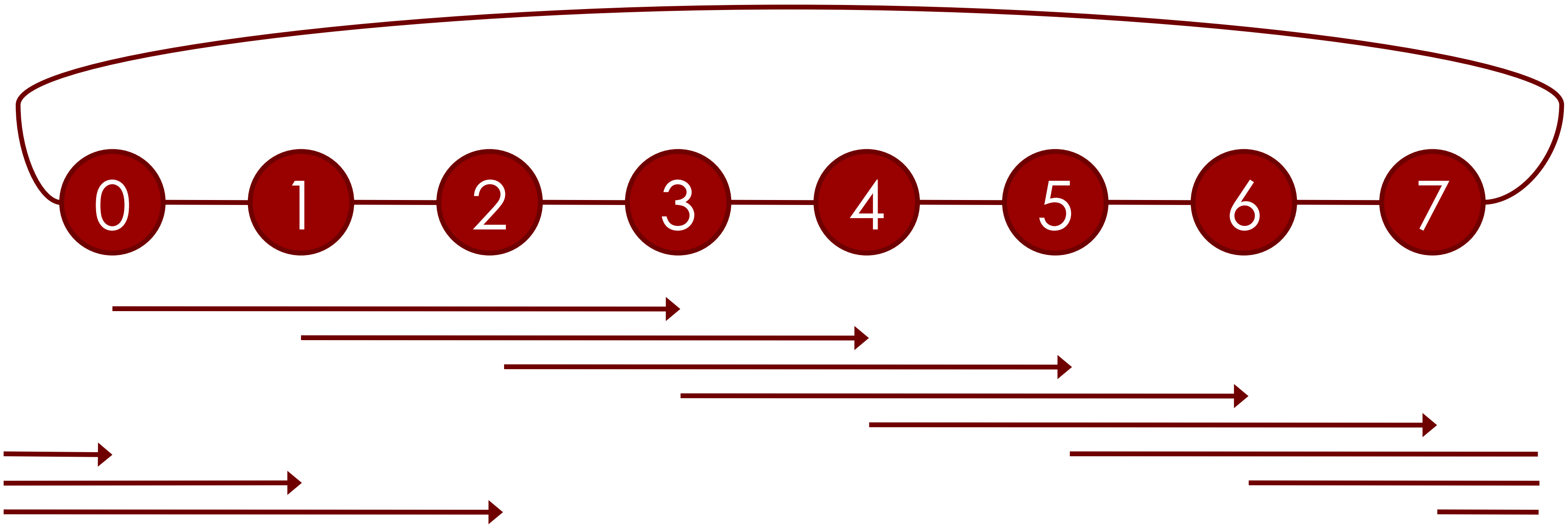
# Channel Load for Adaptive Traffic




- Assume ideal implementation
- For equal load on both anti-clockwise and clockwise links, suppose each node sends a fraction f anticlockwise, and (1-f) clockwise
  - Channel Load = 3f = 5(1-f)
    - f = 5/8
    - Send 5/8th traffic anticlockwise, 3/8th traffic clockwise
  - Channel Load = 15/8, Throughput = 8/15

# Metric = Throughput




- Best routing algorithm?

| | Greedy | Random | Adaptive |
|---|---|---|---|
| **Max Channel Load** | 3 | 5/2 = 2.5 | 15/8= 1.875 |
| **Throughput** | 1/3 = 0.33 | 2/5 = 0.4 | 8/15 = 0.53 |

# Taxonomy of Routing Algorithms

- **Classification I: path length**
  - **Minimal**: shortest paths
    - Example: Greedy over Ring
  - **Non-minimal**: non-shortest paths
    - Example: Random and Adaptive over Ring

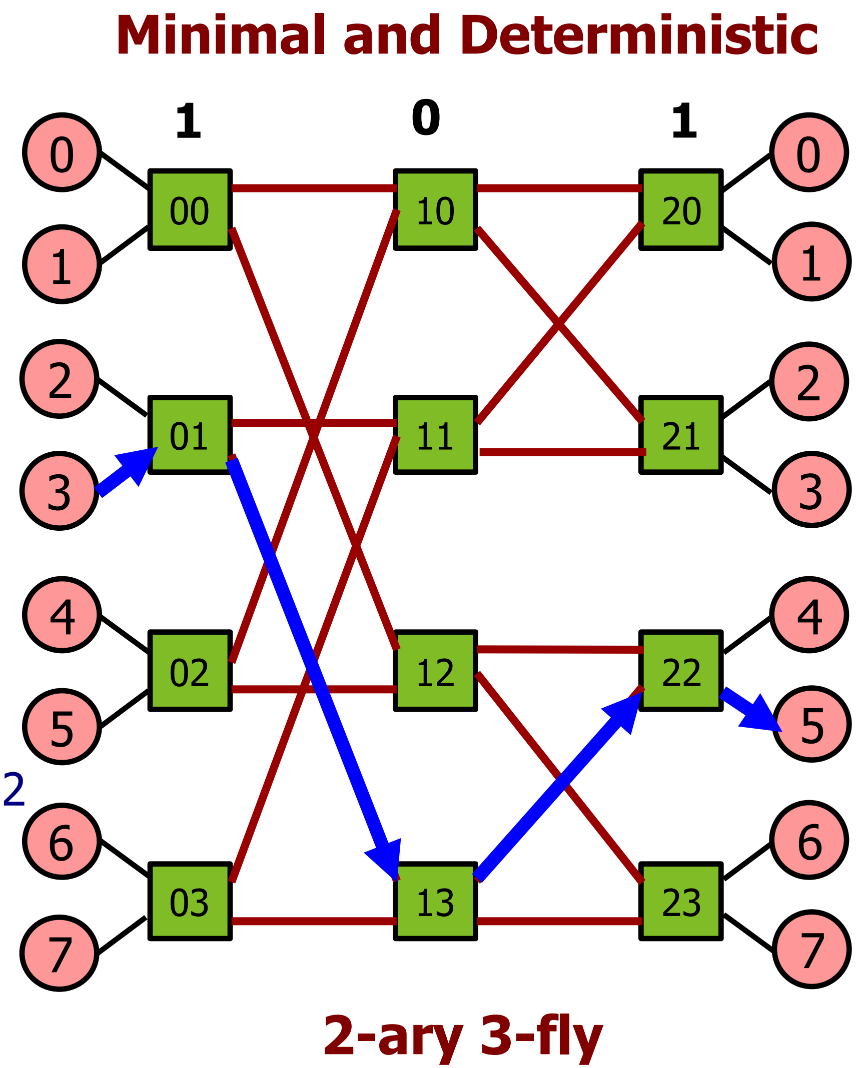
# Taxonomy of Routing Algorithms

- **Classification II: path diversity** (how to select between the set of all possible paths $R_{xy}$ from the source x to the dest y)
  - **Deterministic:** always choose the same route between x and y, even if $|R_{xy}| > 1$
    - **Example:** Greedy over Ring
    - Most restrictive but **most popular** due to ease of implementation and analysis
  - **Oblivious:** choose any of the routes in $R_{xy}$ without considering any information about current network state (i.e., congestion)
    - **Example:** Random over Ring
    - Deterministic are a subset of oblivious
  - **Adaptive:** choose one of the routes in $R_{xy}$ depending on the current network state (i.e., congestion)
    - **Example:** Adaptive over Ring
    - Congestion Metrics: link availability, buffer occupancy, history of channel load

# Destination-Tag Routing in Butterfly Networks (1)



- Destination address directly routes packet
  - Interpreted as an n-digit radix-k number
  - Each digit selects output port at each step
- Example
  - k = 2 (ports per switch)
  - Destination node 5 = $101_2$
  - All switches route out of top if 1, bottom if 0

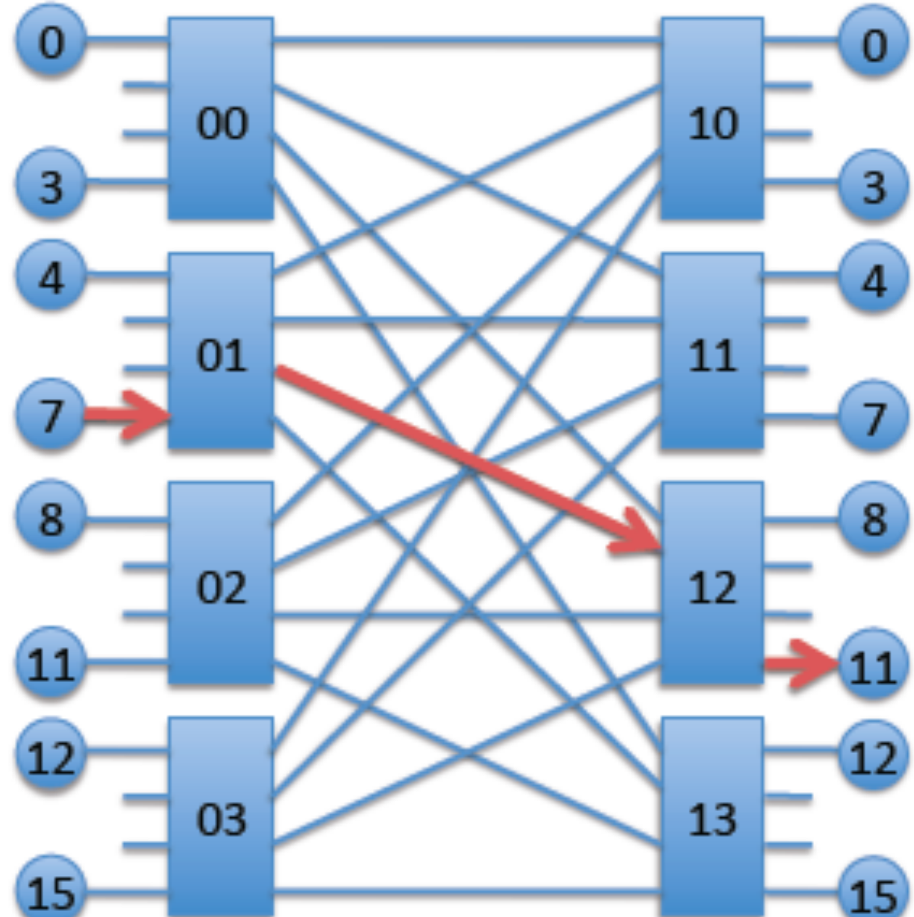


# Destination-Tag Routing in Butterfly Networks (2)



- Routing from 7 to 11
  - k = 4 (ports per switch)
  - Destination node 11 $= 1011_2 = 23_4$
  - To route to Node 11 use port 2 then 3
- Source does not play any role in routing

Minimal and Deterministic



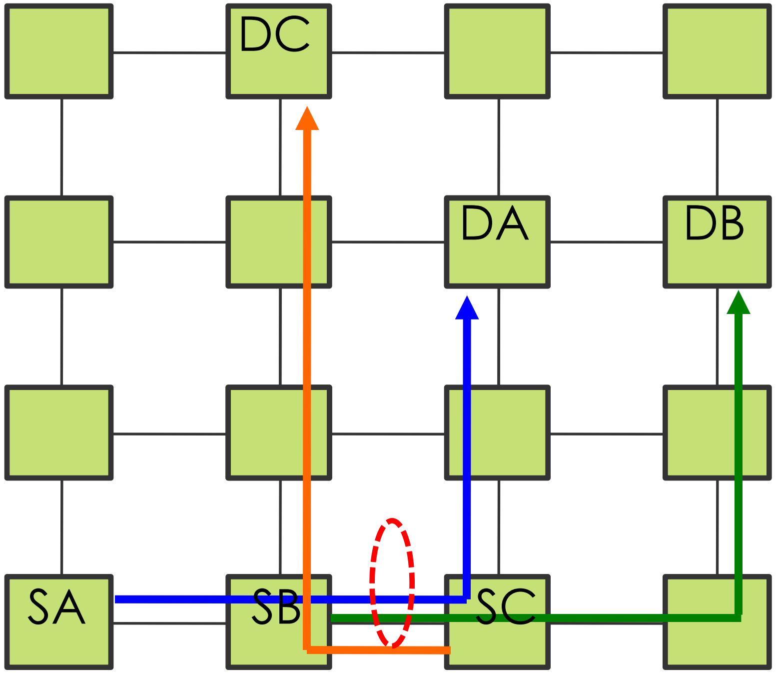

4-ary 2-fly

# Dimension-Ordered Routing (DOR) in a Mesh/Torus



## XY Routing: Always go X first, then Y




**Minimal and Deterministic**

**Cons of this approach?**

- Eliminates any path diversity provided by topology
- Poor load balancing

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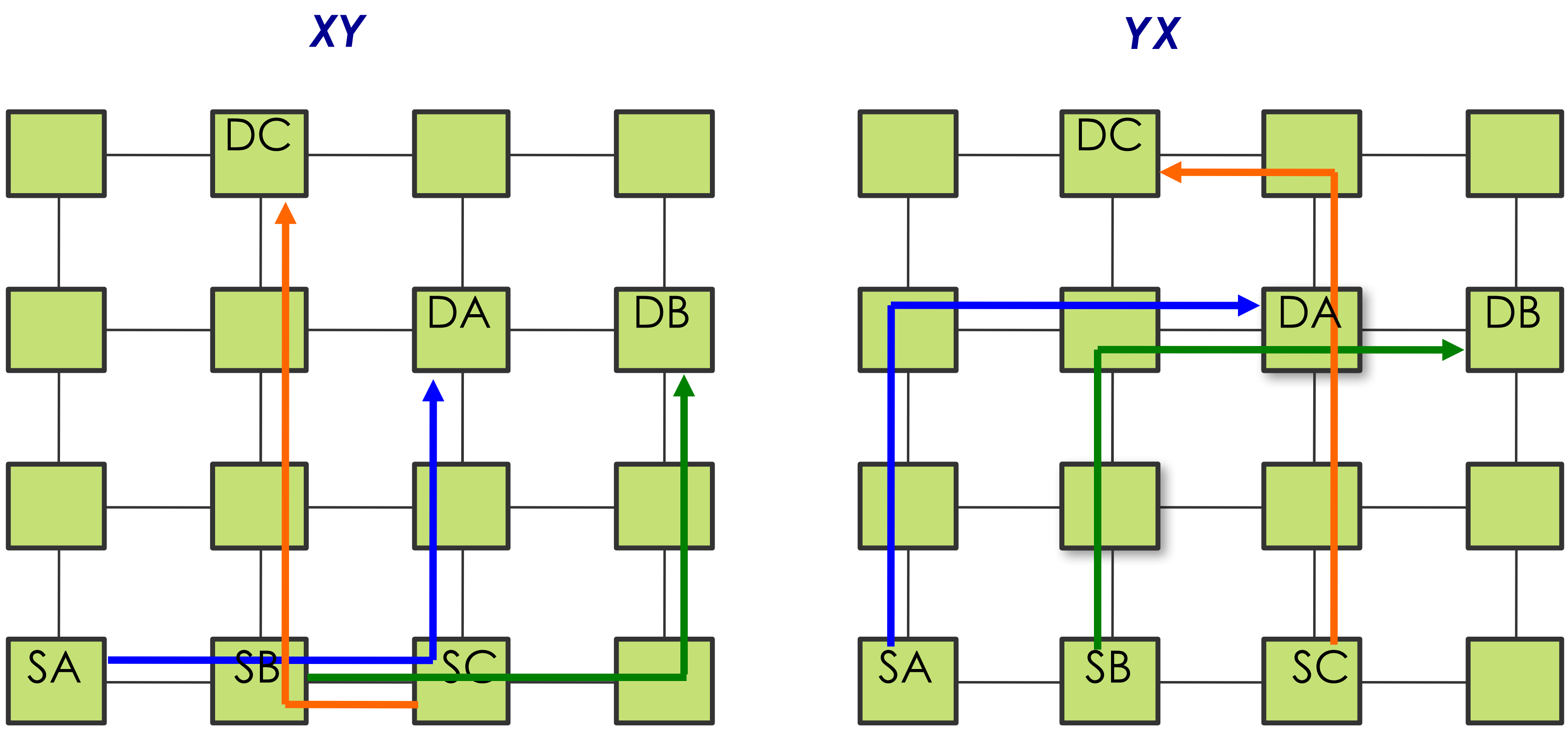
# O1TURN (Seo *et al.*, ISCA 2005)

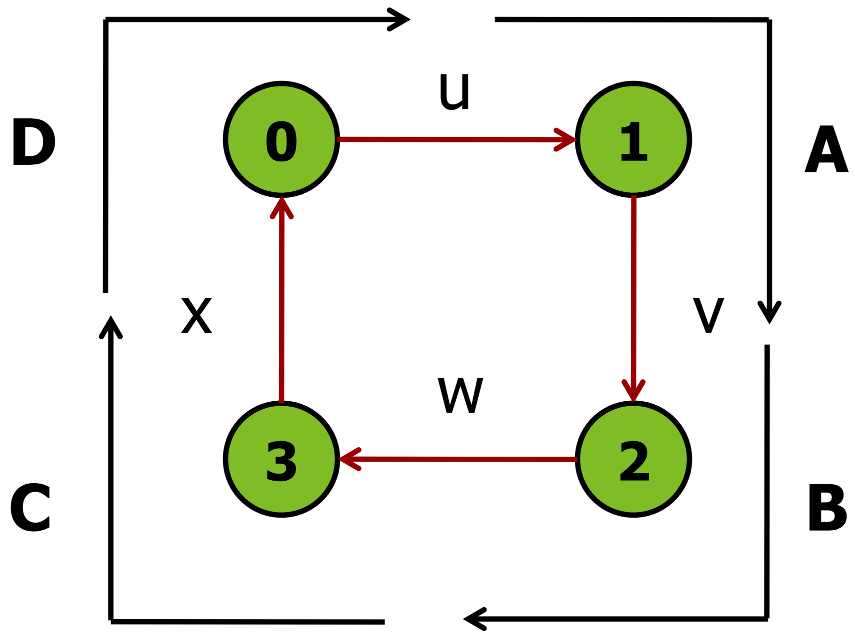



Randomly send over XY or YX

**Minimal and Oblivious**

**Any problem?**

# Network Deadlock

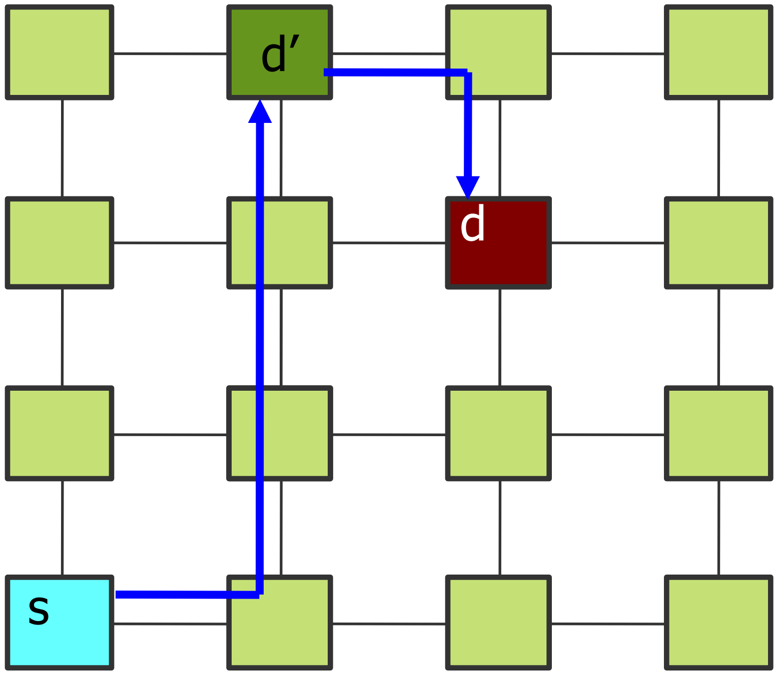



- Flow A holds u and wants v
- Flow B holds v and wants w
- Flow C holds w and wants x
- Flow D holds x and wants u

**Next lecture!**

# Valiant's Routing Algorithm

- To route from s to d
  - Randomly choose intermediate node d'
  - Route* from s to d' (Phase I), and d' to d (Phase II)
- Pros
  - Randomizes any traffic pattern
    - All patterns appear uniform random
  - Balances network-load
    - Higher throughput
- Cons
  - Non-minimal
    - Higher latency and energy
  - Destroys locality



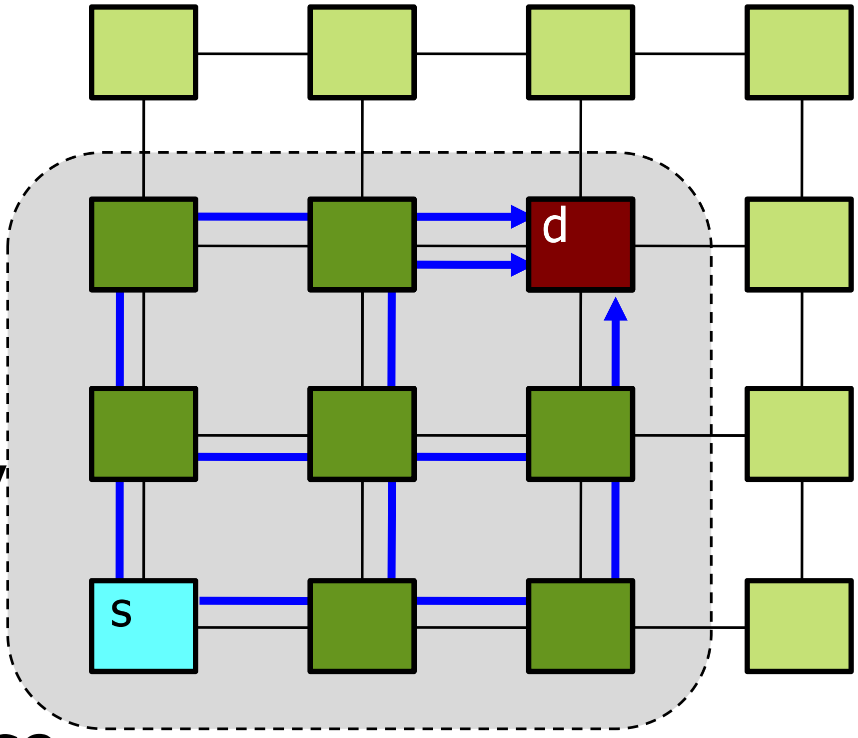

**Non-Minimal and *Oblivious**

***can also be Adaptive***

# ROMM: Randomized, Oblivious Multi-phase Minimal Routing

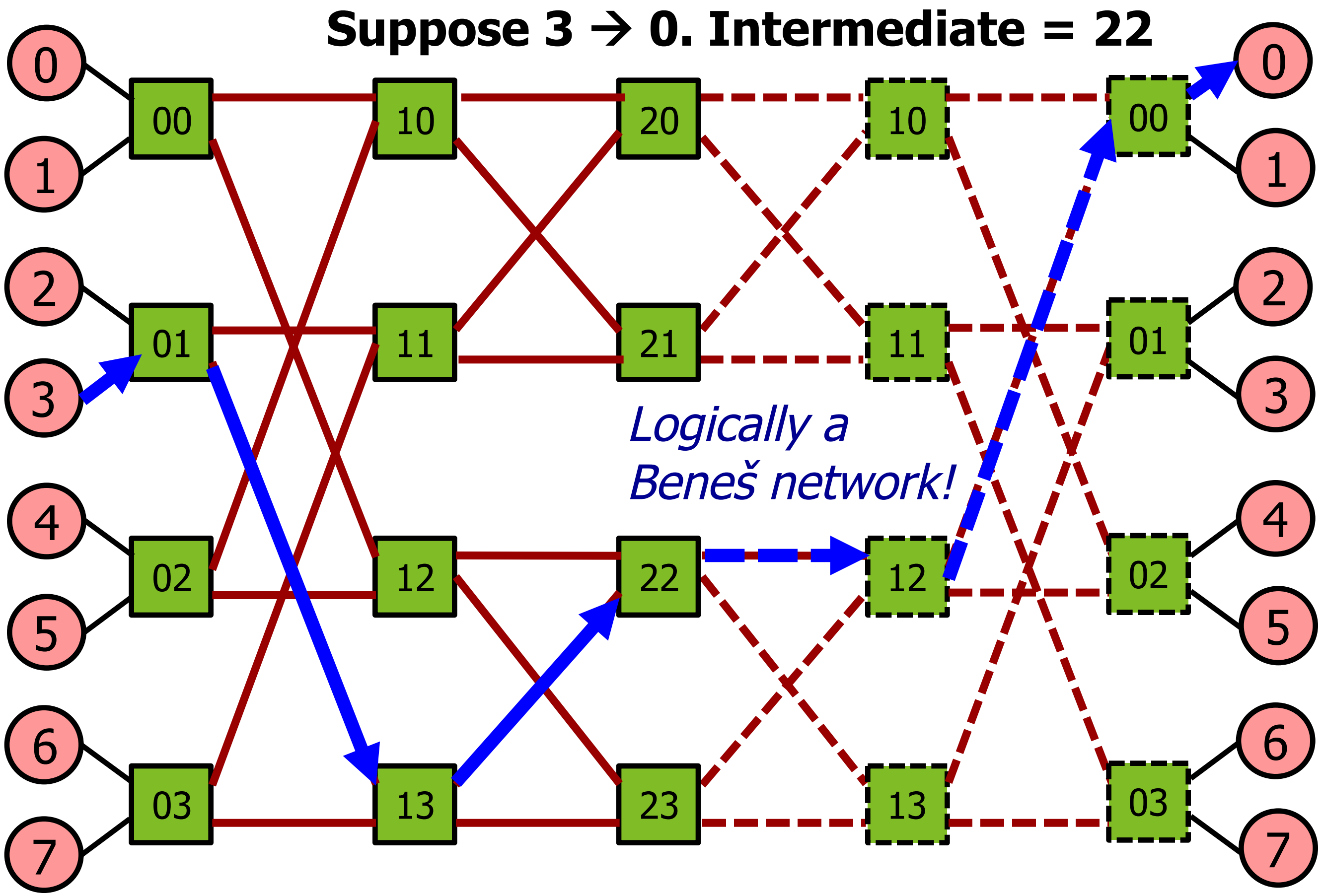


- Confine intermediate node to be within minimal quadrant
- Retain locality + some load-balancing
- This approach essentially translates to randomly selecting between all minimal paths from source to destination




**Minimal and Oblivious**

# Valiant's Algorithm on Indirect Networks



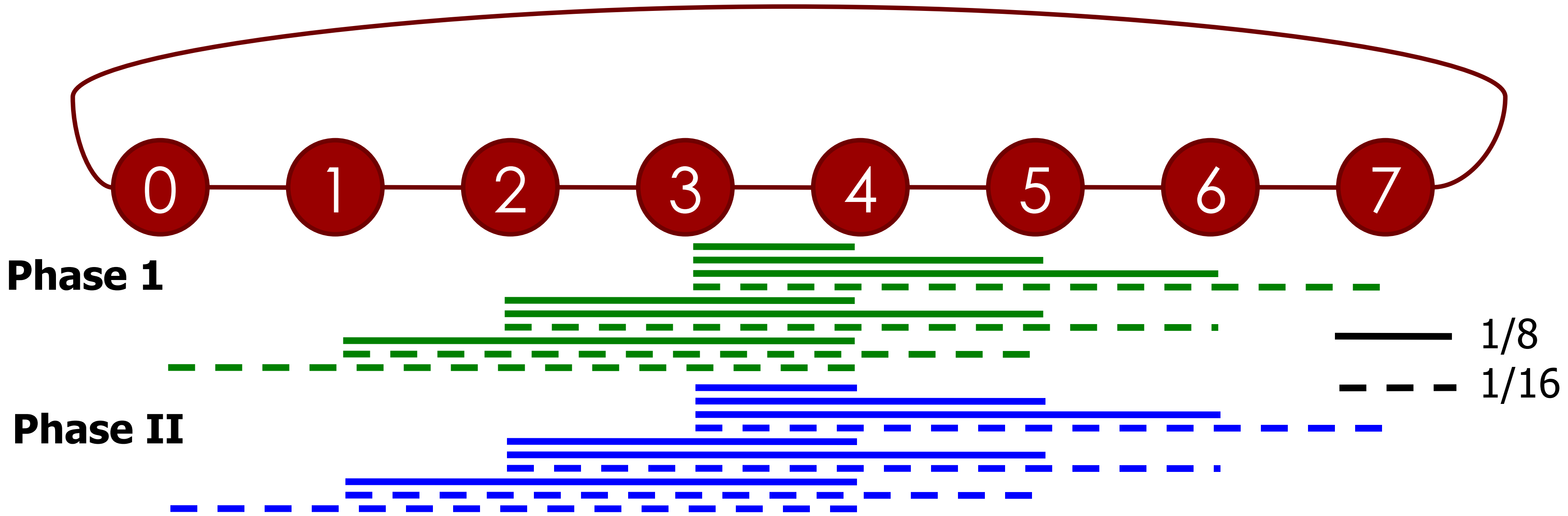

Two-phase Valiant routing equivalent to logically duplicating butterfly network

Can eliminate bottlenecks causes by certain traffic patterns. e.g., Traffic = {0,1,2,3}→ {0,1,2,3} leads to a channel load of 2 on top half of the links

**Non-Minimal and Oblivious**

| | Max Channel Load | Throughput |
|---|---|---|
| **Dest = (0, 1, 2, 3)** | 2 | 0.5 |
| **Valiant (Uniform Random)** | 1 | 1 |

# Valiant's on our Ring for Tornado?




| | Greedy | Random | Adaptive | Valiant's |
|---|---|---|---|---|
| **Max Channel Load** | 3 | 5/2 = 2.5 | 15/8= 1.875 | 2 (two phases) |
| **Throughput** | 1/3 = 0.33 | 2/5 = 0.4 | 8/15 = 0.53 | ½ = 0.5 |

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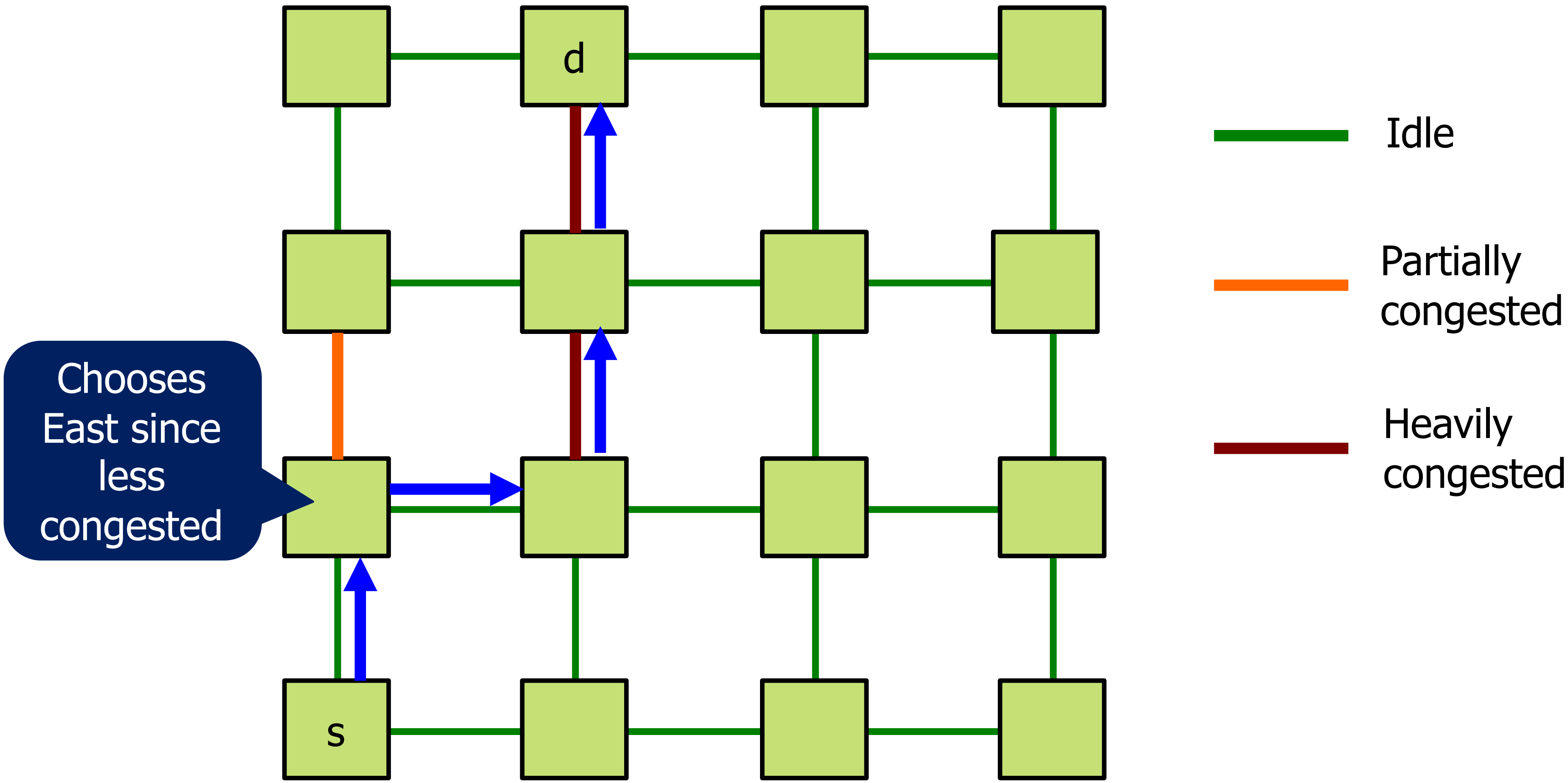
    - **Example:** Adaptive over Ring
    - Congestion Metrics: link availability, buffer occupancy, history of channel load

# Adaptive Routing Algorithms

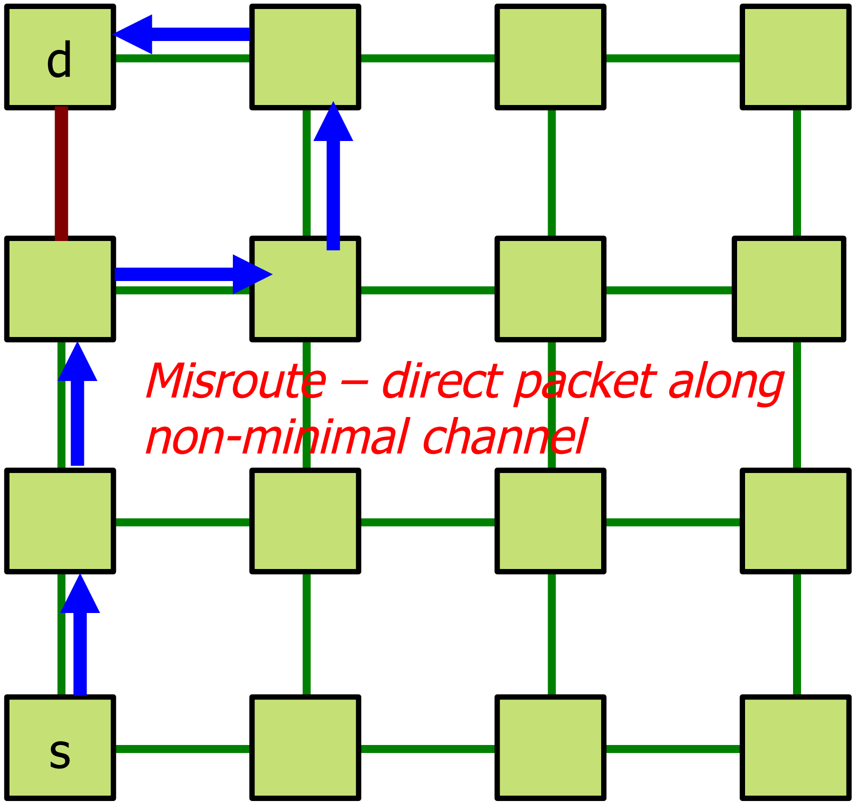
- Exploits path diversity
- Can be minimal or non-minimal
- Uses network state to make routing decisions
  - Buffer occupancies often used
  - Coupled with flow control mechanism
- Local information readily available
  - Global information more costly to obtain
  - Problems
    - Network state can change rapidly
    - Use of local information can lead to non-optimal choices

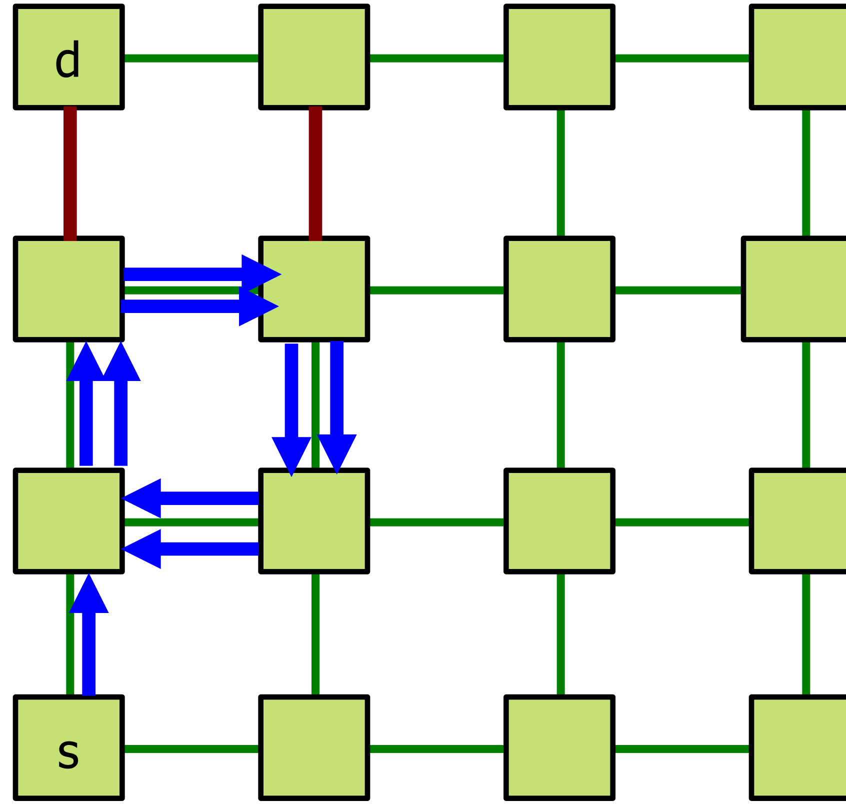
# Example 1: Minimal Adaptive Routing




**Local info can result in sub-optimal choices**

# Example 2: Non-Minimal Adaptive Routing



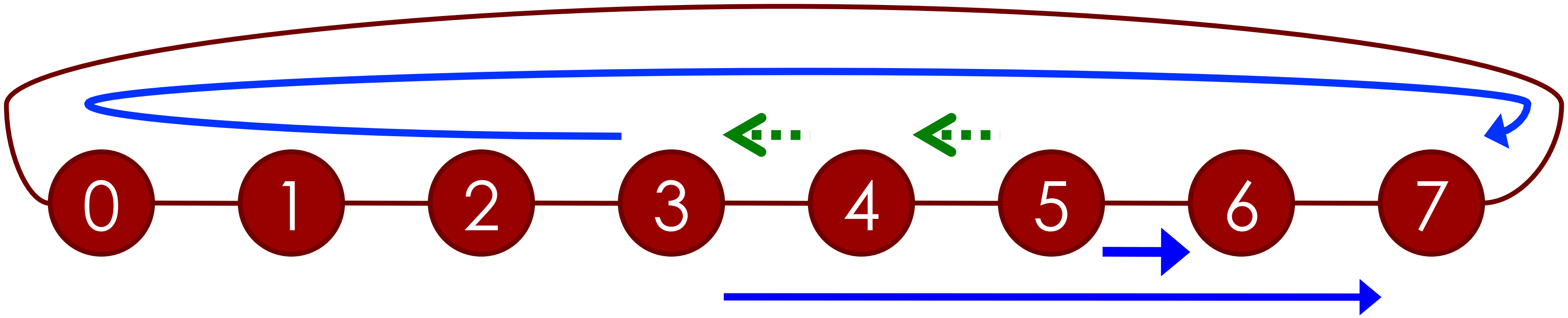

**Livelock! – continue routing in cycle**

**Longer path with potentially lower latency**

*To guarantee forward progress, limit number of misroutings*

# How to sense congestion?

**5→6 and 3→7**

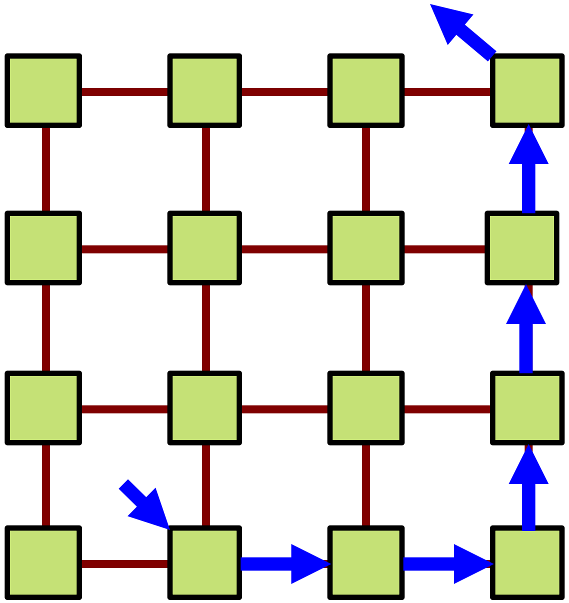



- **5 → 6:** Route counterclockwise (1-hop)
- **3 → 7:** Both clockwise and counterclockwise are 4 hops!
  - Which one should 3 choose?
    - Clockwise, since 5 is using all the capacity of link 5→6
  - **Problem?**
    - Queue at node 5 will sense contention. But node 3 will not, and may continue to send counterclockwise
- **Backpressure** – allows nodes to indirectly sense congestion
  - Queue in node 5 will fill up and stop receiving flits
  - Previous queues will start filling up
    - If each queue holds 4 packets, node 3 will send 8 packets before sensing congestion
  - More on backpressure later in Flow Control lectures!

# Taxonomy of Routing Algorithms

- **Classification III – implementation**
  - **Source Routing:** embed entire route (i.e., list of output ports) in the packet
    - Example: (E, E, N, N, N, N, Eject)
    - Each router reads left most entry, and then strips it away for next hop
    - Pros
      - Save latency at each hop
      - Save routing-hardware at each hop
      - Can reconfigure routes based on faults
      - Supports irregular topologies
    - Cons
      - Overhead to store all routes at NIC
      - Overhead to carry routing bits in every packet (3-bits port x max hops)
      - Cannot adapt based on congestion



# Taxonomy of Routing Algorithms

- **Classification III – implementation**
  - **Source Routing:** embed entire route (i.e., list of output ports) in the packet
  - **Node-Table Routing:** every node has a routing table which stores the output link that a packet from each source should take
  - **Combinational Circuits:** packet carries only destination coordinates, and each router computes output port based on packet state and router state
    - e.g., **deterministic:** use remaining hops and direction
    - e.g., **oblivious:** use remaining hops and direction and some randomness factor
    - e.g., **adaptive:** use congestion metrics (such as buffer occupancy), history, etc.

# That's all for today!

- What will be the combinational circuit / pseudo-code for generating the `output_port` for the XY routing algorithm in a Mesh at every hop?
  - Use the following signals:
    - **From Flit:** `x_hops_remaining, x_direction, y_hops_remaining, y_direction`