Interconnection Networks:

Routing

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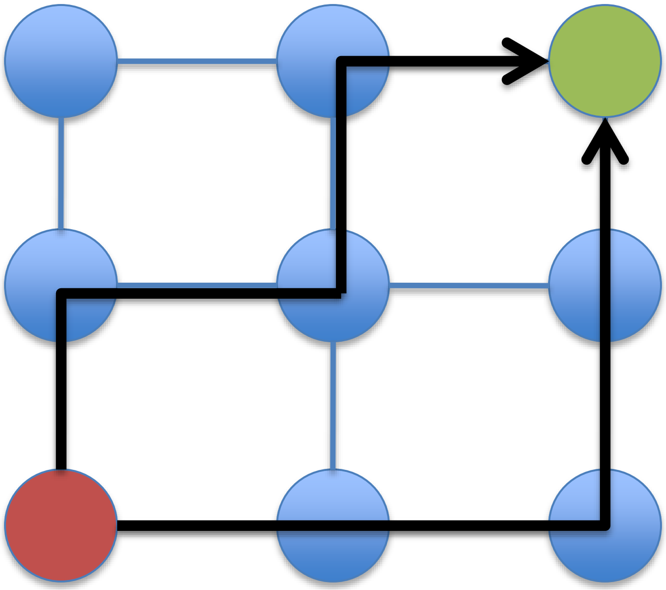
Routing Overview

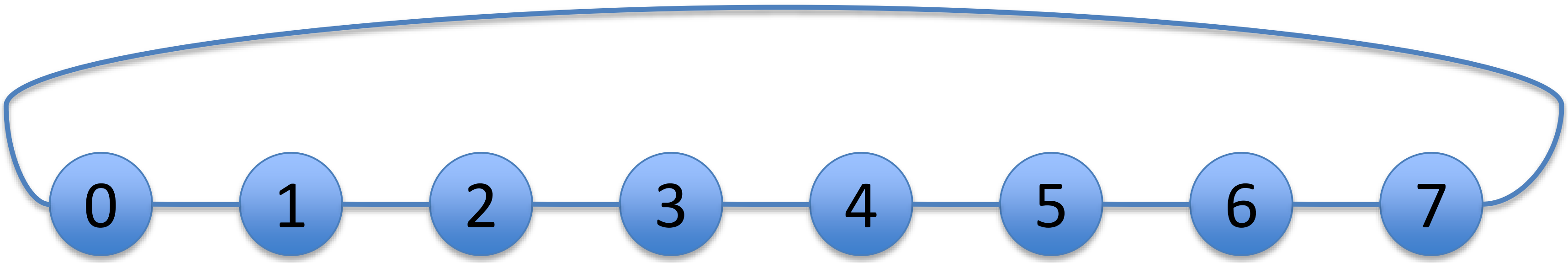
- Discussion of topologies assumed ideal routing
- In practice…
  - Routing algorithms are not ideal
- Goal: distribute traffic **evenly** among paths
  - Avoid hot spots, contention
  - More balanced → closer throughput is to ideal
- Keep complexity in mind

Routing Basics

- Once topology is fixed
- Routing algorithm determines path(s) from source to destination



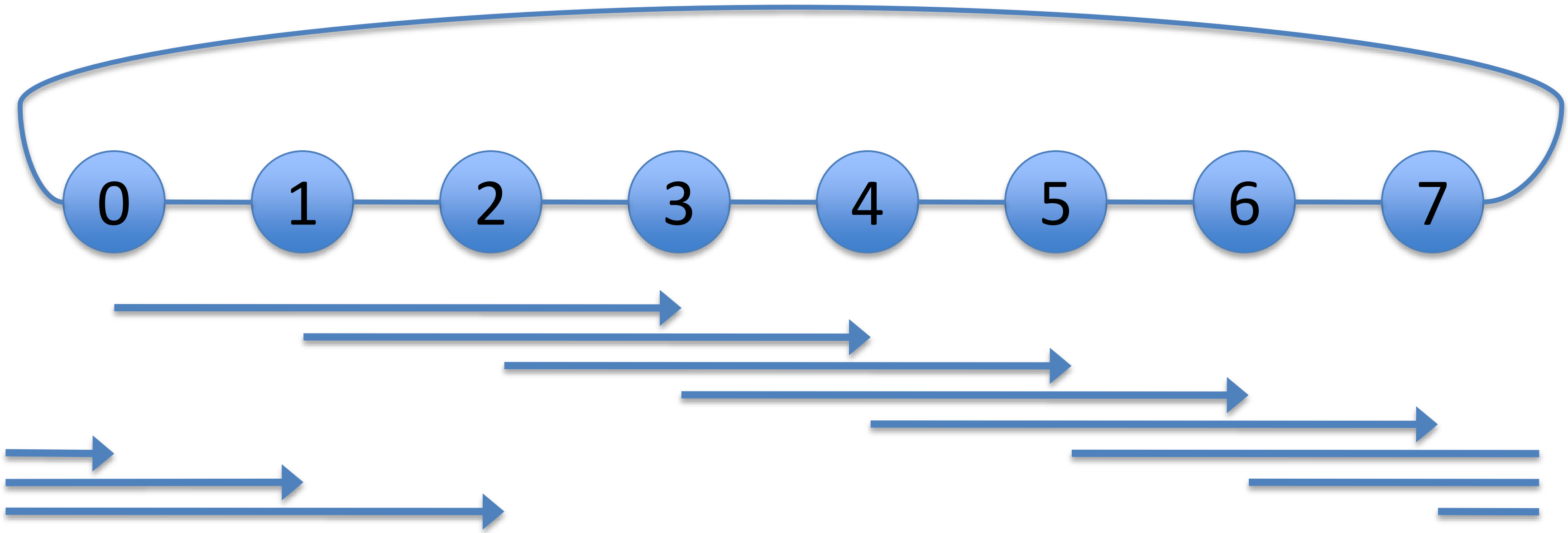
Routing Example



- Some routing options:
  - Greedy: shortest path
  - Uniform random: randomly pick direction
  - Adaptive: send packet in direction with lowest local channel load

- Which gives best worst-case throughput?

Routing Example (2)



- Consider tornado traffic
  - node *i* sends to *i+3 mod 8*

Routing Example (3)

- Greedy:
  - All traffic moves counterclockwise
    - Loads counterclockwise with 3 units of traffic
      - Each node gets 1/3 throughput
    - Clockwise channels are idle

- Random:
  - Clockwise channels become bottleneck
    - Load of 5/2
      - Half of traffic traverses 5 links in clockwise direction
      - Gives throughput of 2/5

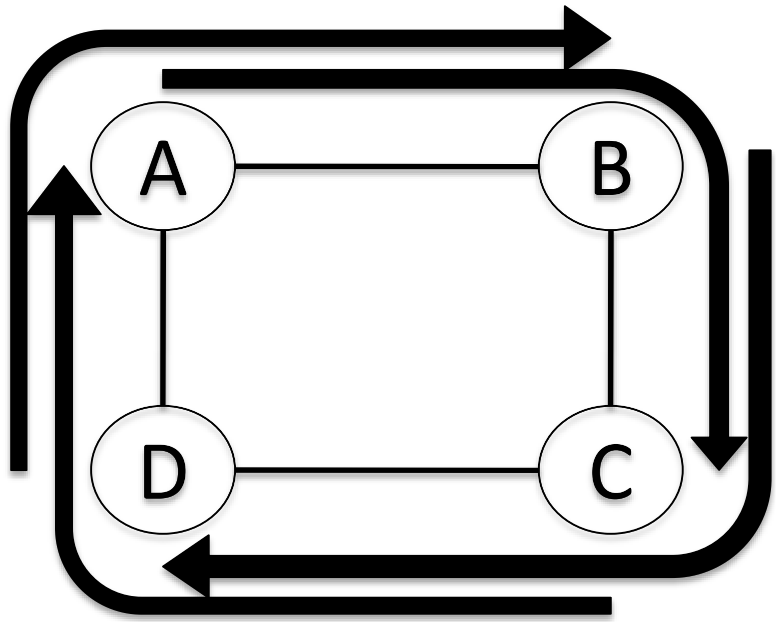
Routing Example (4)

- Adaptive:
  - Perfect load balancing (some assumptions about implementation)
  - Sends 5/8 of traffic over 3 links, sends 3/8 over 5 links
    - Channel load is 15/8, throughput of 8/15
- Note: worst case throughput just 1 metric designer might optimize

Routing Algorithm Attributes

- Types
  - Deterministic, Oblivious, Adaptive
- Number of destinations
  - Unicast, Multicast, Broadcast?
- Adaptivity
  - Oblivious or Adaptive? Local or Global knowledge?
  - Minimal or non-minimal?
- Implementation
  - Source or node routing?
  - Table or circuit?

Routing Deadlock

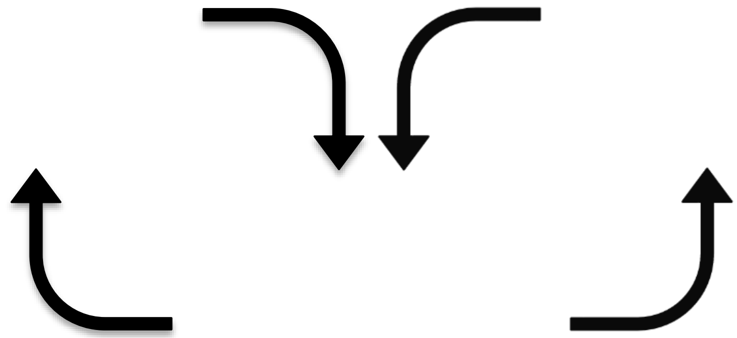


- Each packet is occupying a link and waiting for a link
- Without routing restrictions, a **resource cycle** can occur
  - Leads to deadlock

Deterministic

- All messages from *Source* to *Destination* traverse the same path
- Common example: Dimension Order Routing (DOR)
  - Message traverses network dimension by dimension
  - Aka XY routing
- Cons:
  - Eliminates any path diversity provided by topology
  - **Poor load balancing**
- Pros:
  - **Simple** and inexpensive to implement
  - **Deadlock-free**

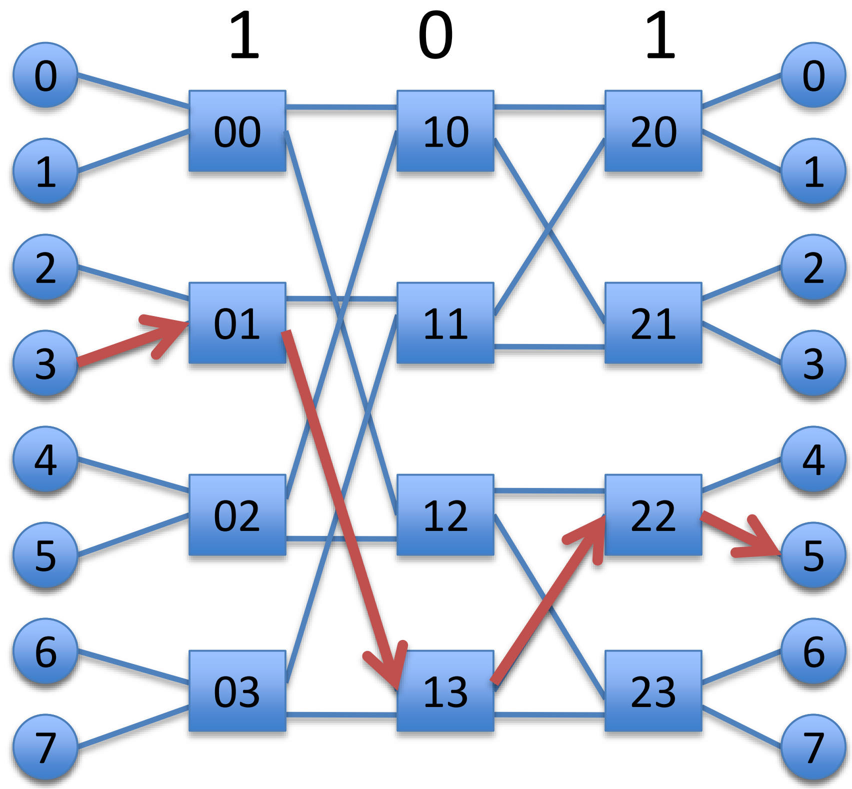
Dimension Order Routing: Cube networks



- a.k.a X-Y Routing
  - Traverse network dimension by dimension
  - Can only turn to Y dimension after finished X

Destination-Tag Routing: Butterfly Networks

- Destination address
  - Interpreted as an n-digit radix-k number
  - Directly routes packet
- Each digit selects the output port at each step



2-ary 3-fly

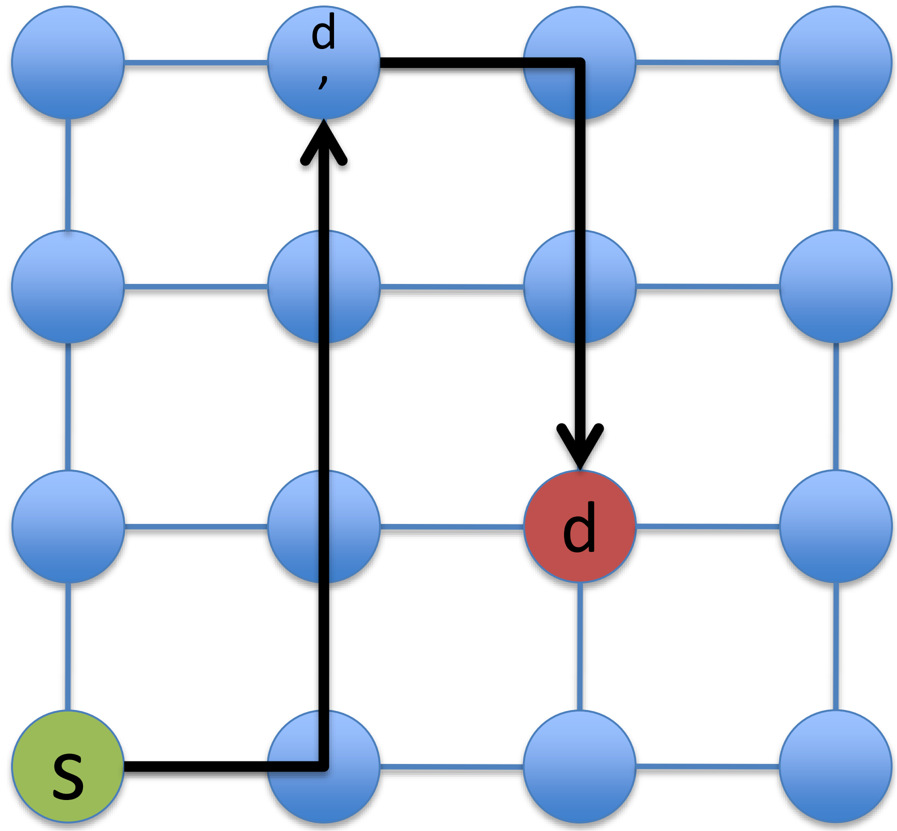
Oblivious

- Routing decisions are made without regard to network state
  - Keeps algorithms simple
  - Unable to adapt

- Deterministic algorithms are a subset of oblivious

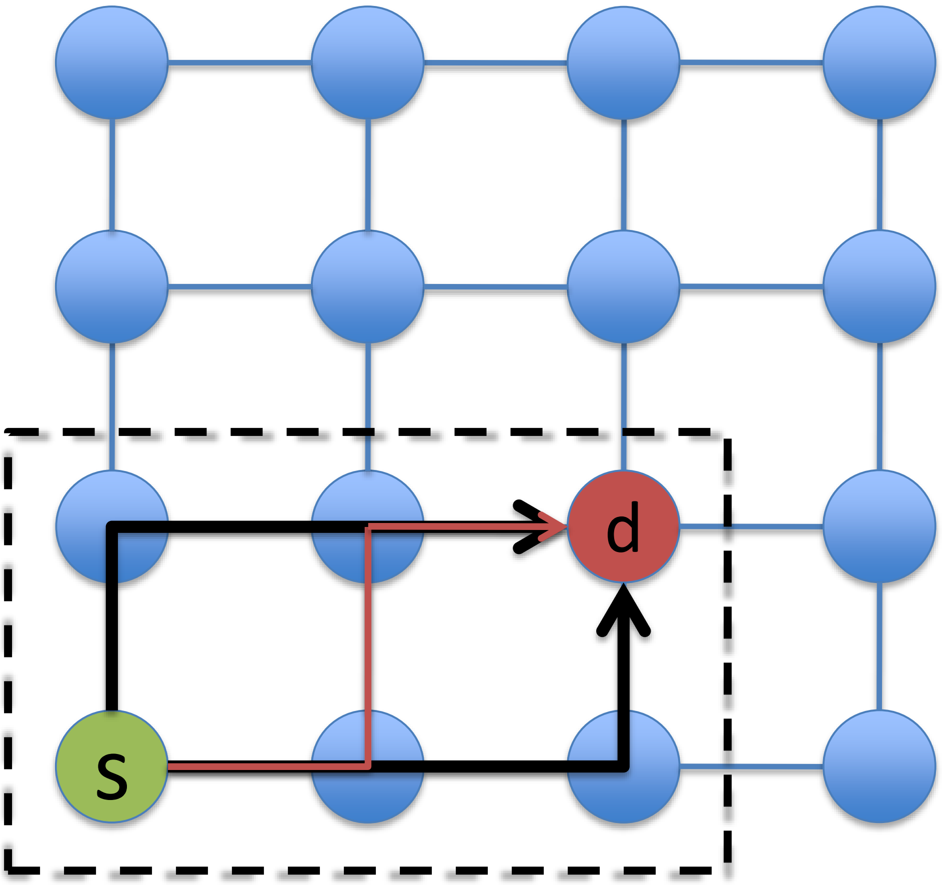
Valiant's Routing Algorithm

- To route from s to d
  - Randomly choose intermediate node d'
  - Route from s to d' and from d' to d.
- Randomizes any traffic pattern
  - All patterns appear uniform random
  - Balances network load
- Non-minimal
- Destroys locality



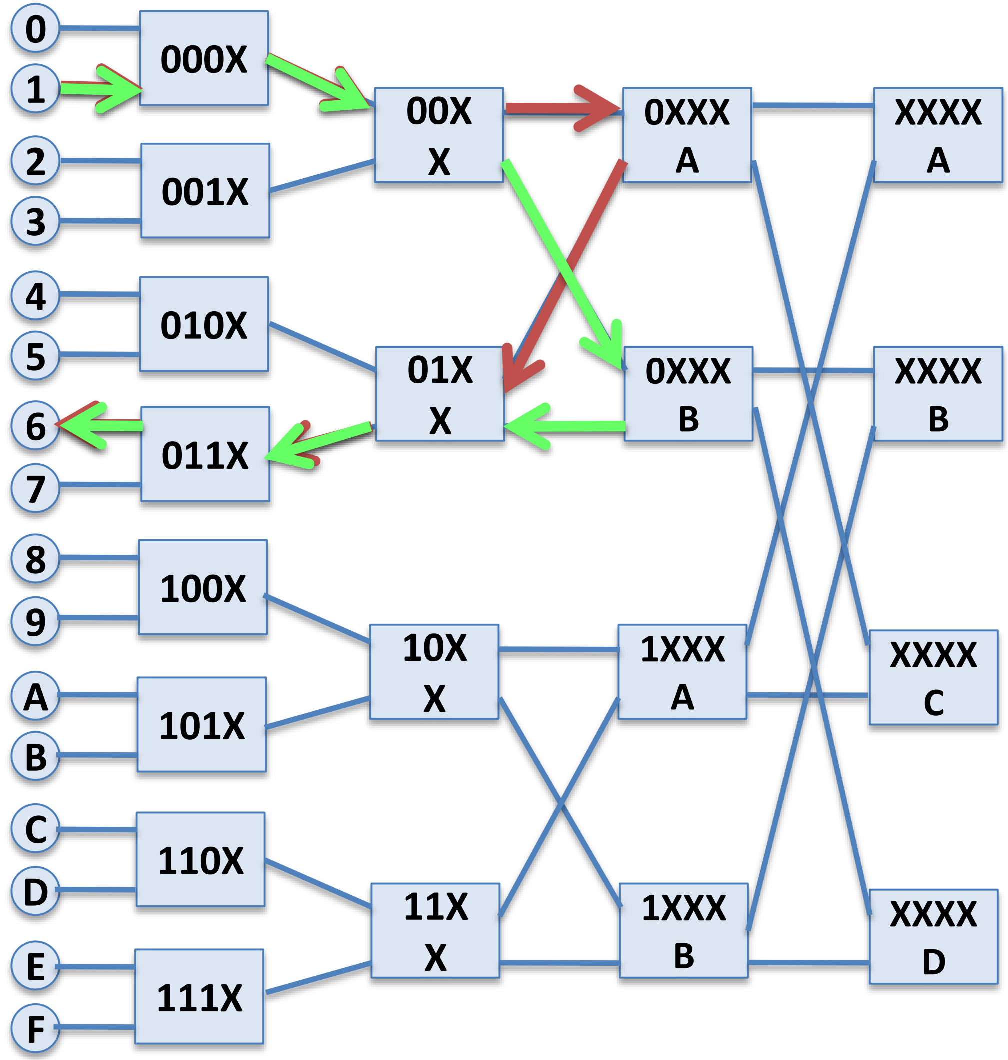
Minimal Oblivious

- Valiant's: Load balancing but significant increase in hop count
- Minimal Oblivious: some load balancing, but use shortest paths
  - d' must lie within min quadrant
  - 6 options for d'
  - Only 3 different paths



Minimal Oblivious Routing on Fat Tree

- Node labels (addr template)
  - All nodes reachable from left terminals
- Route from s to d
  - Randomly selected, nearest common ancestor x of s and d
- Route s to x then x to d
- Example s = 1, d = 6
- Construct route incrementally
  - Randomly select output port
  - Until addr template matches d



Oblivious Routing

- Valiant's and Minimal Oblivious
  - Deadlock free
    - When used in conjunction with X-Y routing
- Randomly choose between X-Y and Y-X routes
  - Oblivious but not deadlock free!

Adaptive

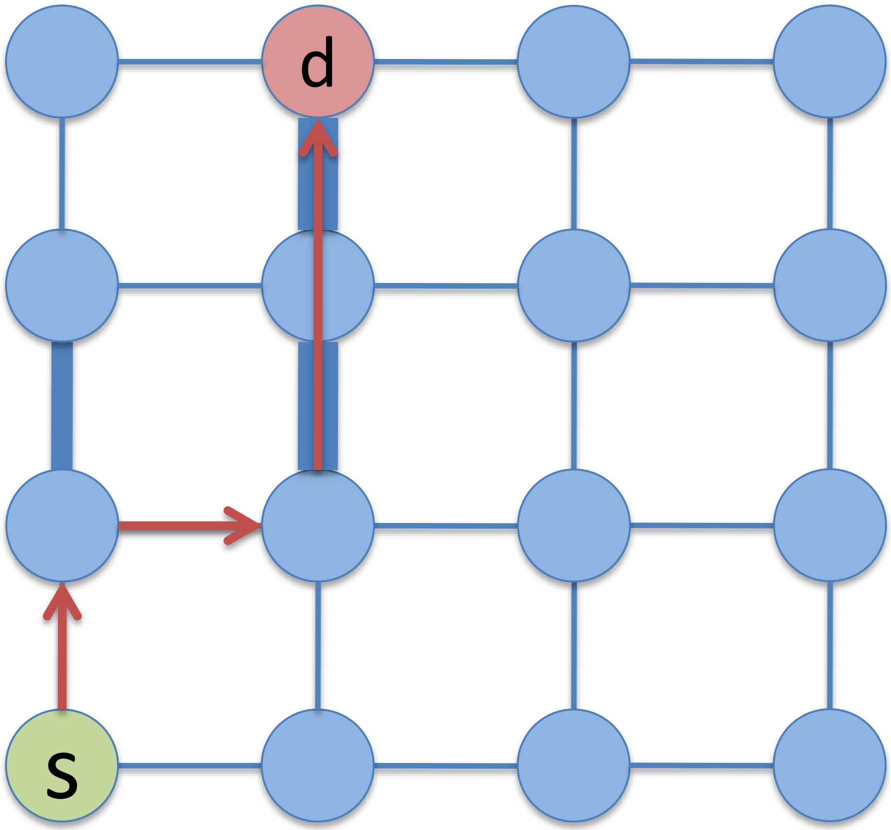
- Exploits path diversity

- 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
  - Network state can change rapidly
  - Use of local information can lead to non-optimal choices

- Can be minimal or non-minimal

Minimal Adaptive Routing

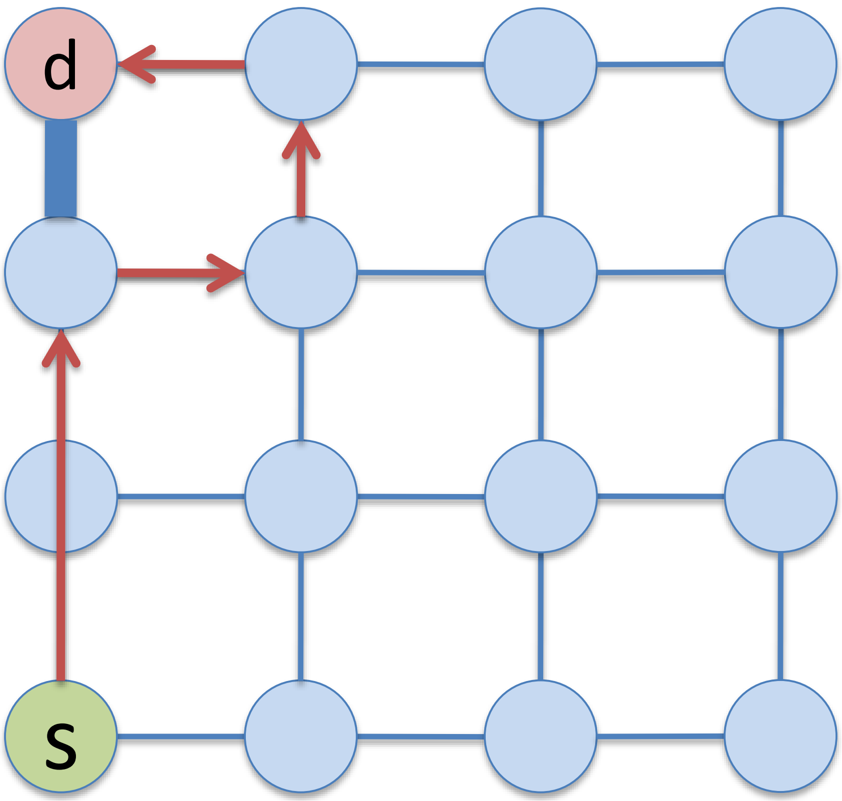


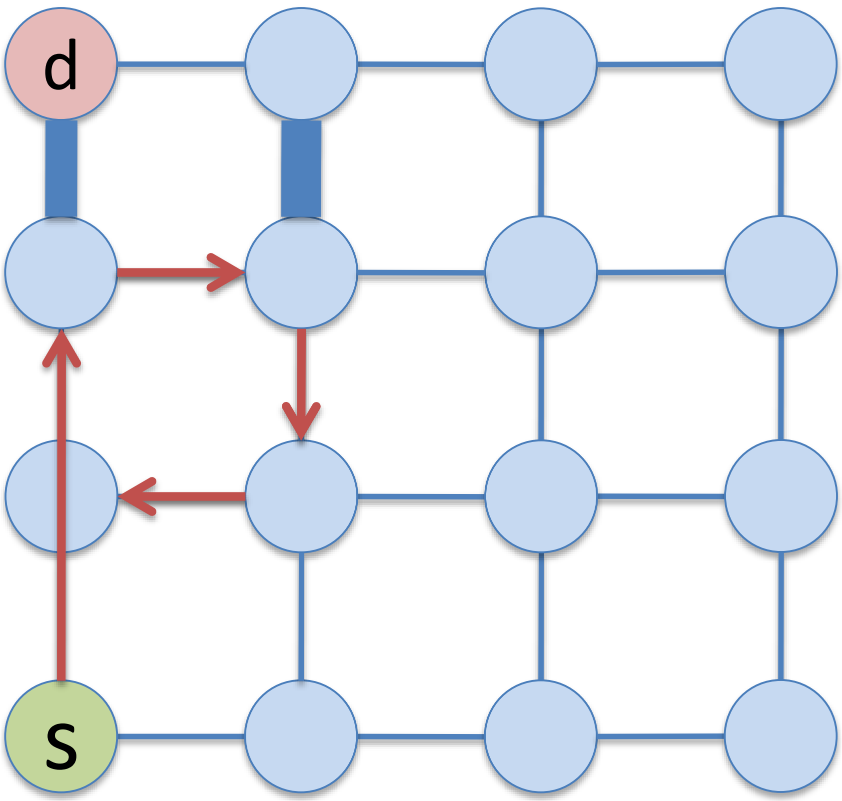
- Local info can result in sub-optimal choices

Non-minimal adaptive

- Fully adaptive
- Not restricted to take shortest path
- Misrouting: directing packet along non-productive channel
  - Priority given to productive output
  - Some algorithms forbid U-turns
- Livelock potential: traversing network without ever reaching destination
  - Mechanism to guarantee forward progress
    - Limit number of misroutings

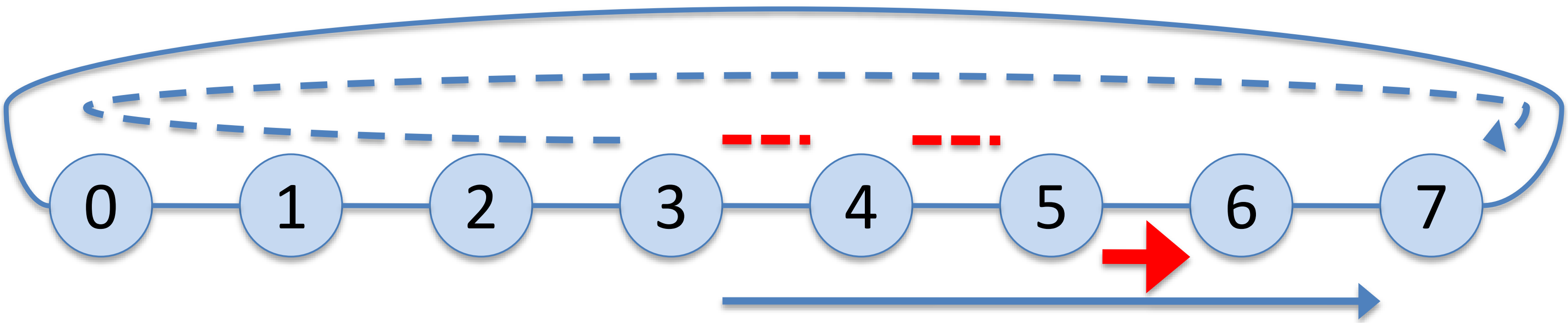
Non-minimal routing example





- Longer path with potentially lower latency
- Livelock: continue routing in cycle

Adaptive Routing Example



- Should 3 route clockwise or counterclockwise to 7?
  - 5 is using all the capacity of link 5 → 6
- Queue at node 5 will sense contention but not at node 3
- Backpressure: allows nodes to indirectly sense congestion
  - Queue in one node fills up, it will stop receiving flits
  - Previous queue will fill up
- If each queue holds 4 packets
  - 3 will send 8 packets before sensing congestion

Congestion Information

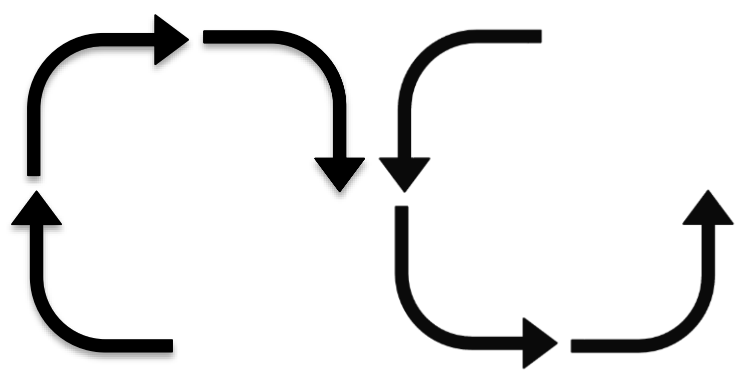
- Local
  - Information about my neighbors only
  - Implicitly available – I know how many downstream buffers are available (from flow control)
- Global
  - Information about all nodes
  - Explicitly send status information
  - Usually based on VC utilization or buffer occupancy
- Timeliness

Sending Congestion Information

- Piggybacking
  - Send congestion information along with packets
- Extra side network
  - More affordable in on-chip networks
  - Broadcast
  - Packetize
- Aggregate or individual node

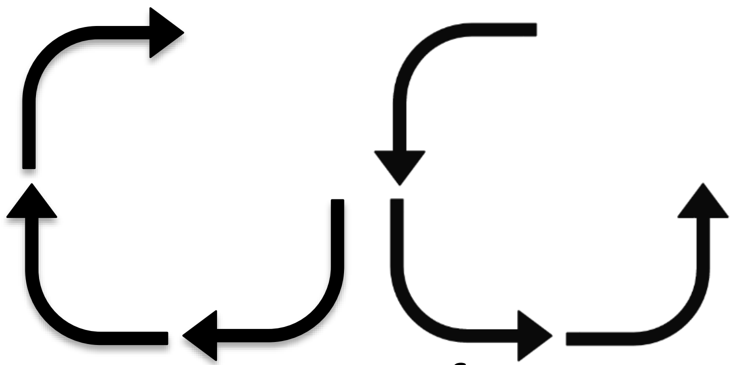
Partially Adaptive Routing: Turn Model

- DOR eliminates 4 turns
  – N to E, N to W, S to E, S to W
  – No adaptivity
- Some adaptivity by removing 2 of 8 turns
  – Remains deadlock free (like DOR)
- West first
  – Eliminates S to W and N to W

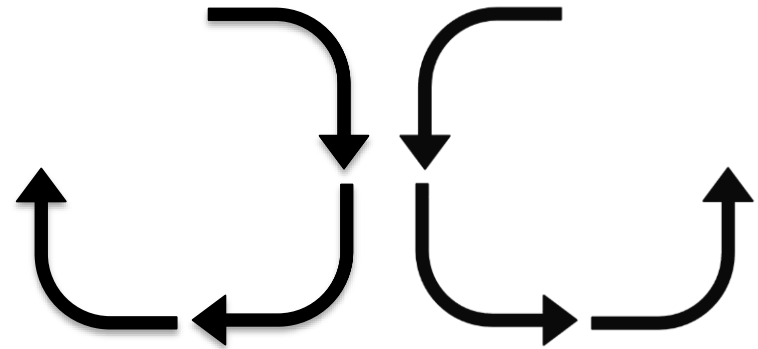


West first

Turn Model Routing



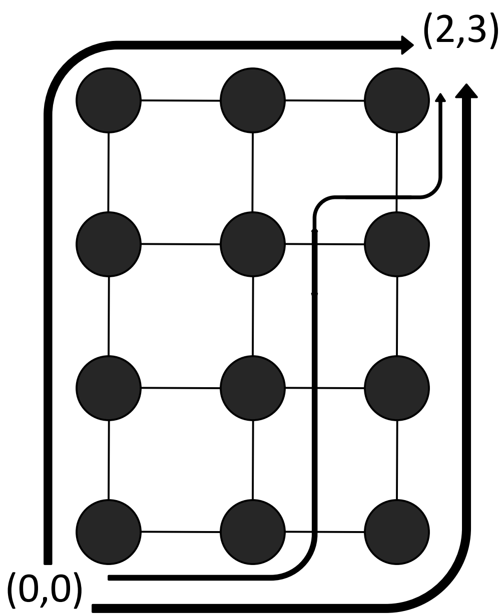
Negative first

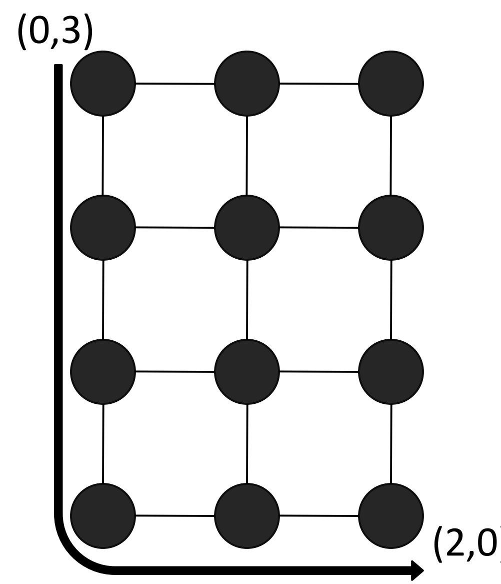


North last

- Negative first
  - Eliminates E to S and N to W
- North last
  - Eliminates N to E and N to W
- Odd-Even
  - Eliminates 2 turns depending on if current node is in odd of even column
    - Even column: E to N and N to W
    - Odd column: E to S and S to W
  - Deadlock free (disallow 180 turns)
  - Better adaptivity

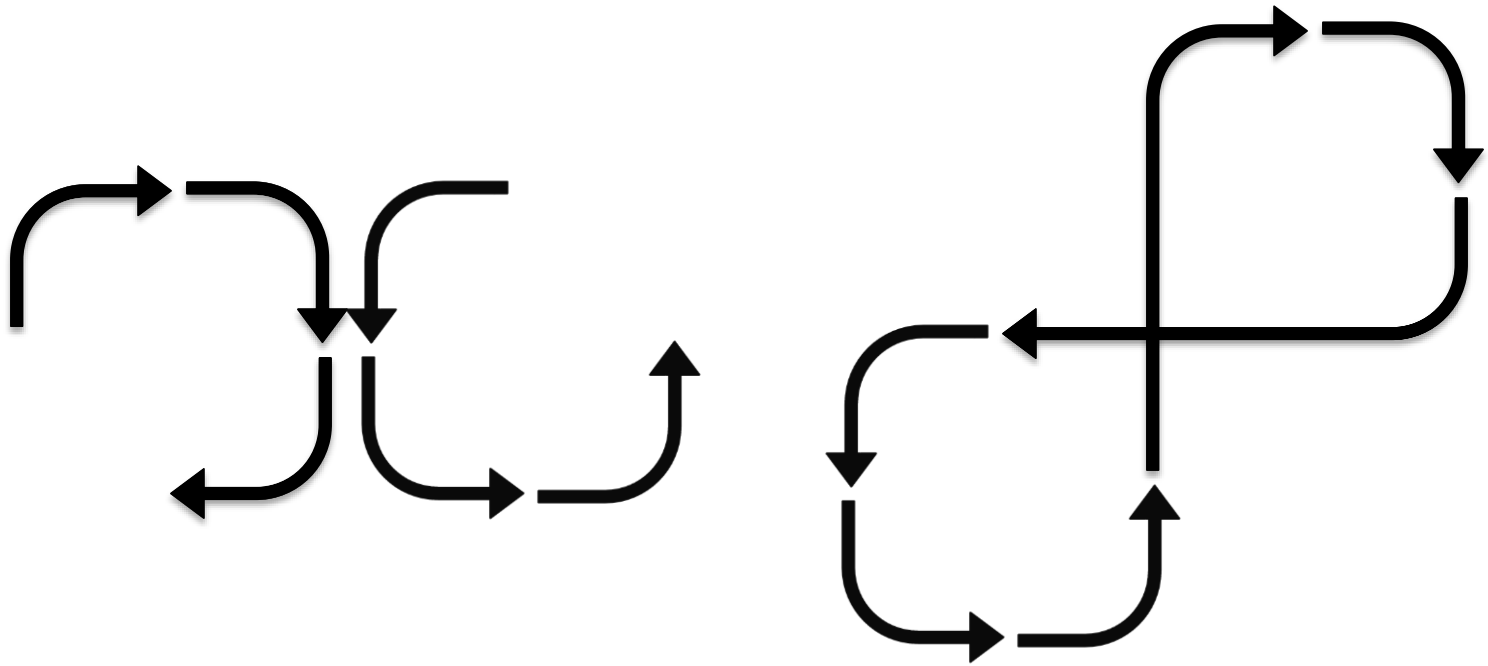
Negative-First Routing Example





- Limited or no adaptivity for certain source-destination pairs

Turn Model Routing Deadlock



- What about eliminating turns NW and WN?
- Not a valid turn elimination
  - Resource cycle results

Adaptive Routing and Deadlock

- Option 1: Eliminate turns that lead to deadlock
  - Limits flexibility

- Option 2: Allow all turns
  - Give more flexibility
  - Must use other mechanism to prevent deadlock
  - Rely on flow control (later)
    - Escape virtual channels

Adaptive Routing: Other Topologies

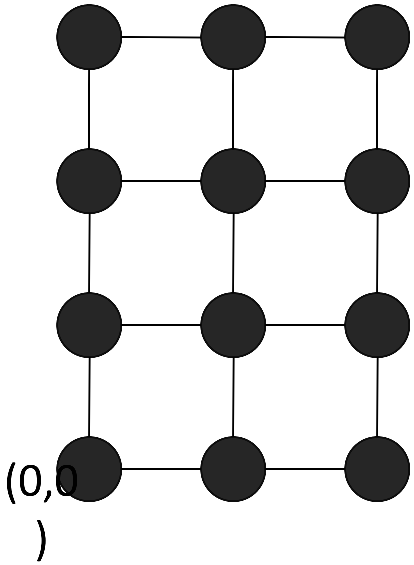
- Butterfly: no path diversity
  - Can add extra stages for path diversity, adaptive routing
- Fat tree (folded Clos)
  - Similar to minimal oblivious
    - But instead of randomly selecting path to least common ancestor
      - Select adaptively (upstream)
      - Message routed deterministically (downstream)

Routing Implementation

- Source tables
  - Entire route specified at source
  - Avoids per-hop routing latency
  - Unable to adapt dynamically to network conditions
  - Can specify multiple routes per destination
    - Give fault tolerance and load balance
  - Support reconfiguration (not specific to topology)

Source Table Routing

Destination	Route 1	Route 2
00	X	X
10	EX	EX
20	EEX	EEX
01	NX	NX
11	NEX	ENX
21	NEEX	ENEX
02	NNX	NNX
12	ENNX	NNEX
22	EENNX	NNEEX
03	NNNX	NNNX
13	NENNX	ENNNX
23	EENNNX	NNNEEX



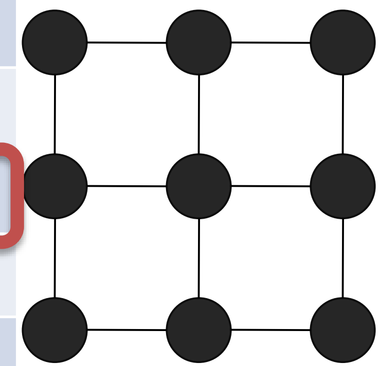
- Arbitrary length paths: storage overhead and packet overhead

Node Tables

- Store only next direction at each node
- Smaller tables than source routing
- Adds per-hop routing latency
- Can adapt to network conditions
  - Specify multiple possible outputs per destination
  - Select randomly to improve load balancing

Node Table Routing

	To								
From	00	01	02	10	11	12	20	21	22
00	X |-	N | -	N | -	E | -	E | N	E | N	E | -	E | N	E | N
01	S | -	X | -	N | -	E | S	E | -	E | N	E | S	E | -	E | N
02	S | -	S| -	X | -	E | S	E | S	E | -	E | S	E | S	E | -
10	W|-	W|-	W|-	X | -	N | -	N | -	E | -	E | N	E | N
11	W|-	W|-	W|-	S | -	X | -	N | -	E | S	E | -	E | N
12	W|-	W|-	W|-	S | -	S | -	X | -	E | S	E | S	E | -
20	W|-	W|-	W|-	W|-	W|-	W|-	X | -	N | -	N | -
21	W|-	W|-	W|-	W|-	W|-	W|-	S | -	X | -	N | -
22	W|-	W|-	W|-	W|-	W|-	W|-	S | -	S | -	X | -



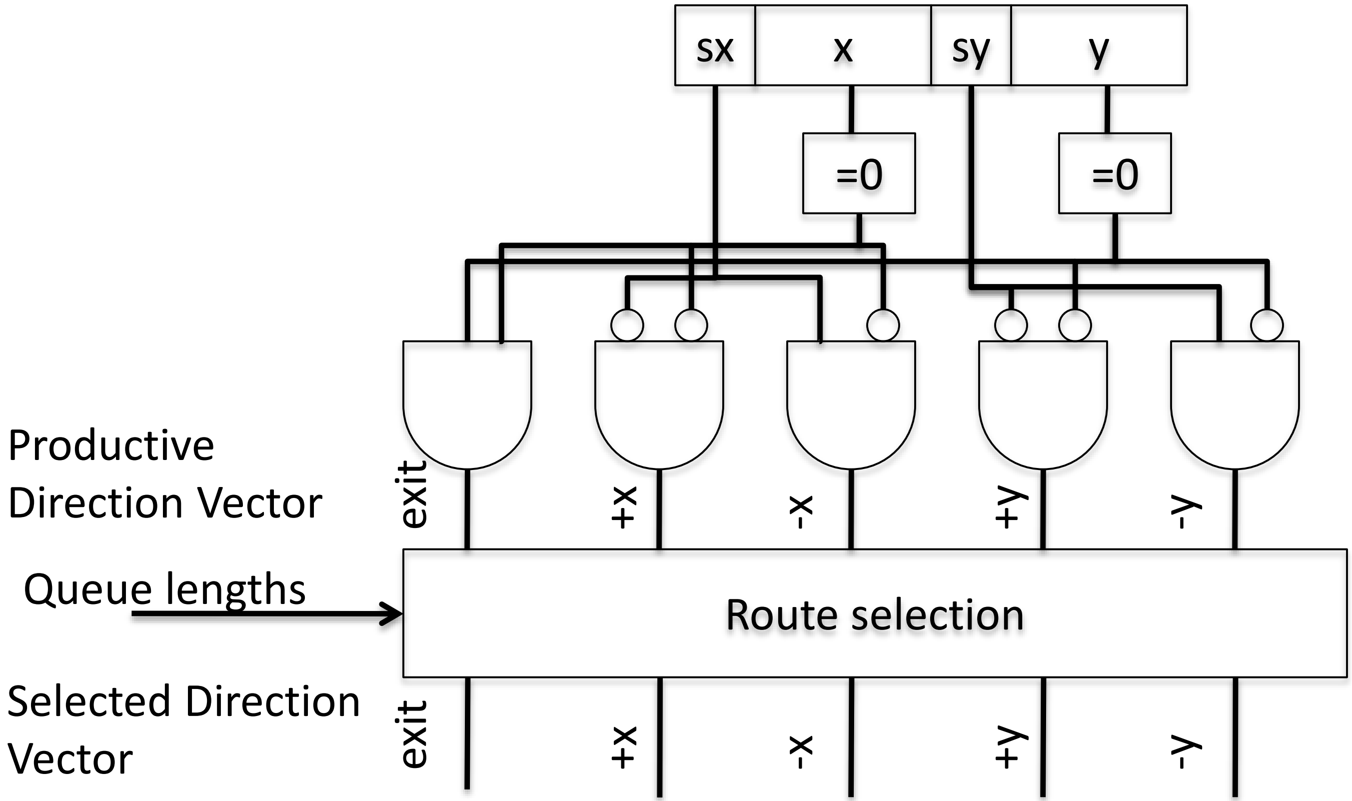
- Implements West-First Routing
- Each node would have 1 row of table
  - Max two possible output ports

Implementation

- Combinational circuits can be used
  - Simple (e.g. DOR): low router overhead
  - Specific to one topology and one routing algorithm
    - Limits fault tolerance

- Tables can be updated to reflect new configuration, network faults, etc

Circuit Based



- Next hop based on buffer occupancies
- Or could implement simple DOR
- Fixed w.r.t. topology

Routing Algorithms: Implementation

Routing Algorithm	Source Routing	Combinational	Node Table
Deterministic			
DOR	Yes	Yes	Yes
Oblivious			
Valiant’s	Yes	Yes	Yes
Minimal	Yes	Yes	Yes
Adaptive	No	Yes	Yes

Routing Summary

- Latency paramount concern
  - Minimal routing most common for NoC
  - Non-minimal can avoid congestion and deliver low latency
- To date: NoC research favors DOR for simplicity and deadlock freedom
  - On-chip networks often lightly loaded
- Only covered unicast routing
  - Recent work on extending on-chip routing to support multicast