Lecture 25: Interconnection Networks

- Topics: communication latency, centralized and decentralized switches, routing, deadlocks (Appendix E)

- Review session, Wednesday Dec 1st, 10-12, LCR (MEB 3147)

- Final exam reminders
  - Come early, 10:35 – 12:15
  - Same rules as first midterm, open books/notes/…,
  - Can use calculators and laptops (no search or internet)
  - 20% from first midterm material; remaining 80% from caches, multiprocs, TM
  - 20% new problems
  - Attempt every question

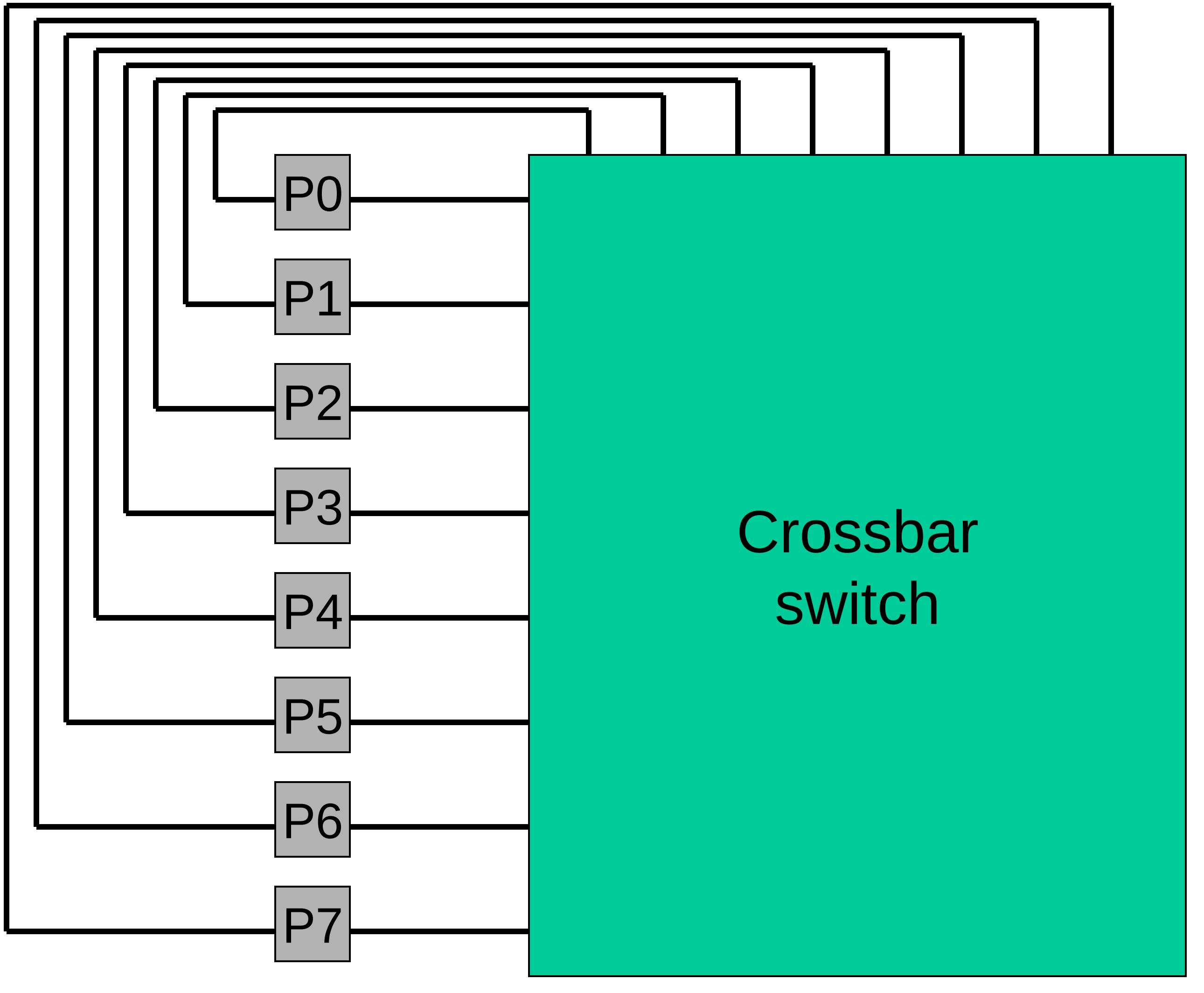
Topologies

- Internet topologies are not very regular – they grew incrementally

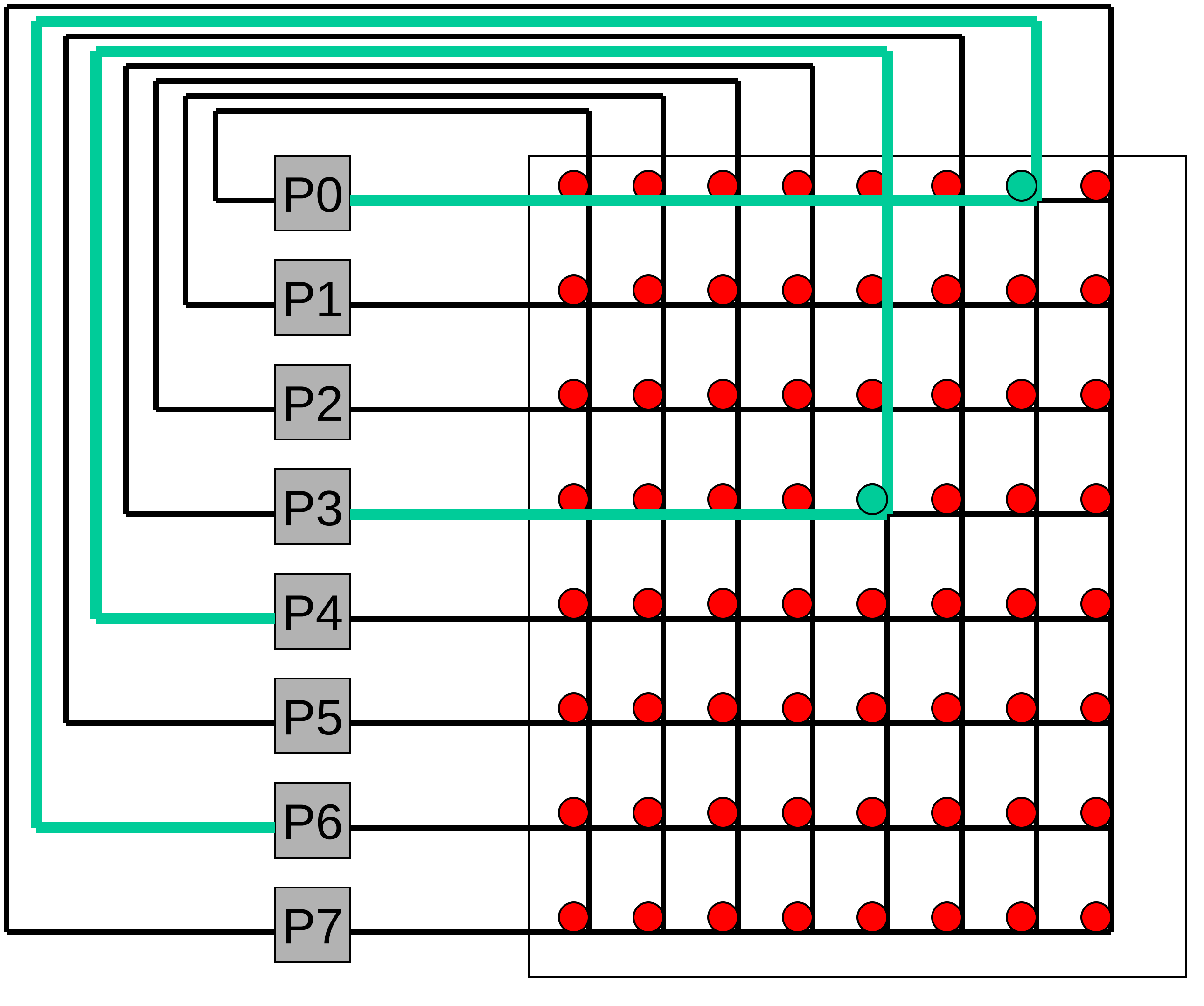
- Supercomputers have regular interconnect topologies and trade off cost for high bandwidth

- Nodes can be connected with
  - centralized switch: all nodes have input and output wires going to a centralized chip that internally handles all routing
  - decentralized switch: each node is connected to a switch that routes data to one of a few neighbors

Centralized Crossbar Switch



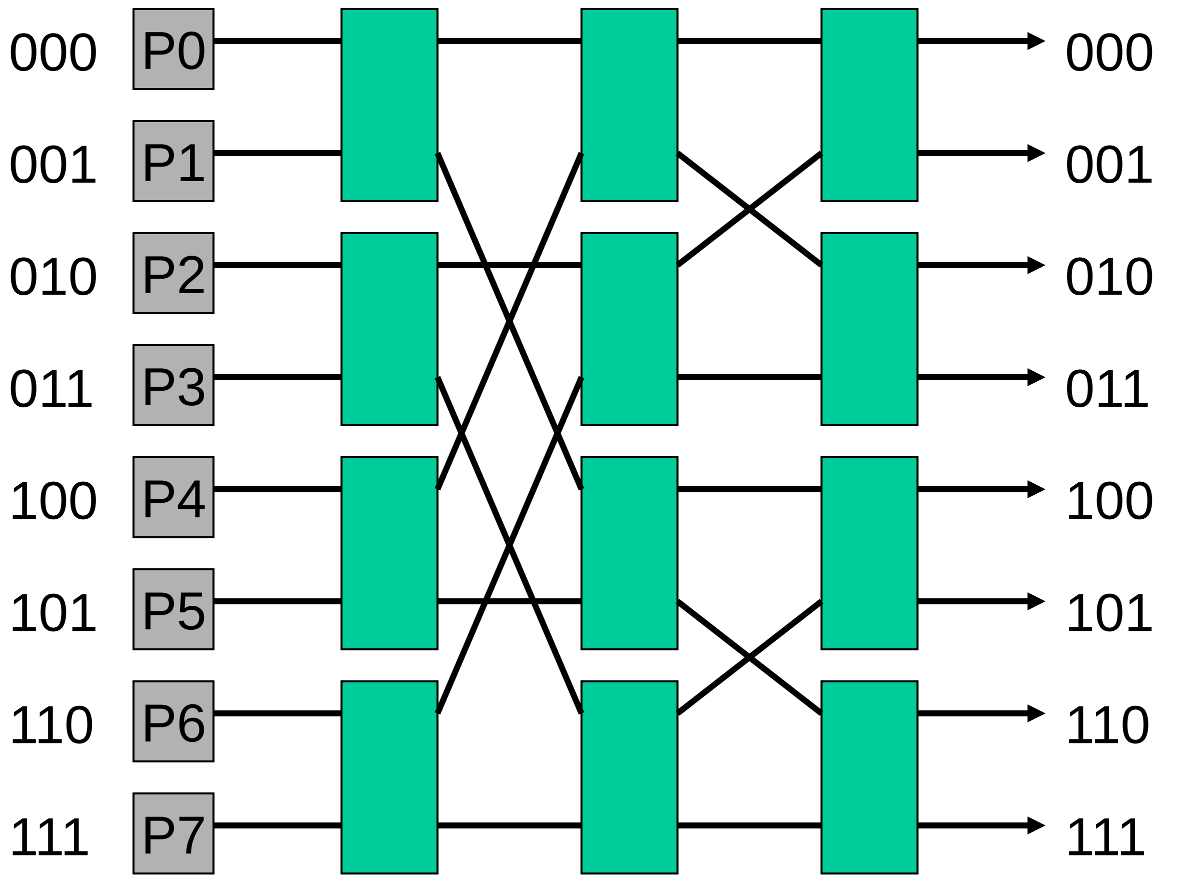
Centralized Crossbar Switch



Crossbar Properties

- Assuming each node has one input and one output, a crossbar can provide maximum bandwidth: N messages can be sent as long as there are N unique sources and N unique destinations
- Maximum overhead: WN^2 internal switches, where W is data width and N is number of nodes
- To reduce overhead, use smaller switches as building blocks – trade off overhead for lower effective bandwidth

Switch with Omega Network

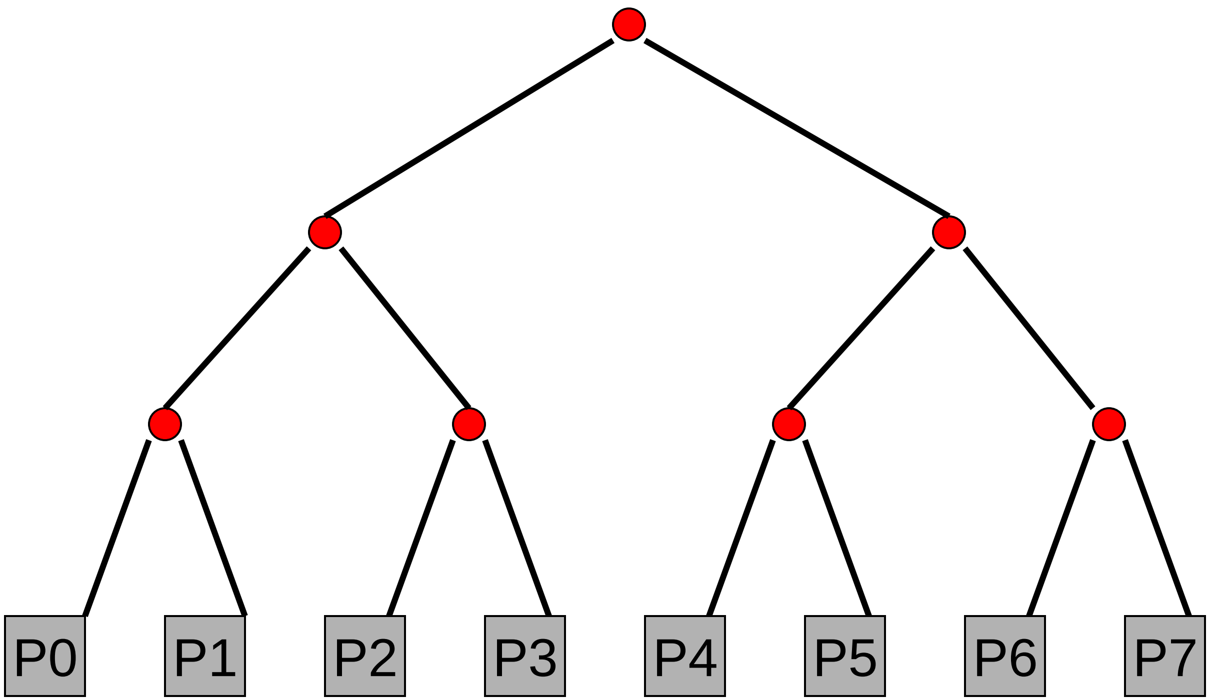


Omega Network Properties

- The switch complexity is now O(N log N)
- Contention increases: P0 → P5 and P1 → P7 cannot happen concurrently (this was possible in a crossbar)
- To deal with contention, can increase the number of levels (redundant paths) – by mirroring the network, we can route from P0 to P5 via N intermediate nodes, while increasing complexity by a factor of 2

Tree Network

- Complexity is O(N)
- Can yield low latencies when communicating with neighbors
- Can build a fat tree by having multiple incoming and outgoing links



Bisection Bandwidth

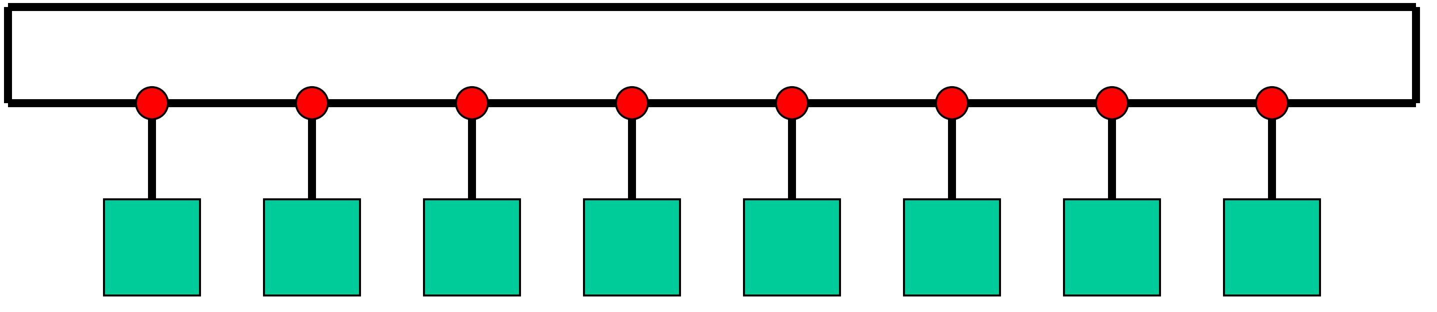
- Split N nodes into two groups of N/2 nodes such that the bandwidth between these two groups is minimum: that is the bisection bandwidth

- Why is it relevant: if traffic is completely random, the probability of a message going across the two halves is ½ – if all nodes send a message, the bisection bandwidth will have to be N/2

- The concept of bisection bandwidth confirms that the tree network is not suited for random traffic patterns, but for localized traffic patterns

Distributed Switches: Ring

- Each node is connected to a 3x3 switch that routes messages between the node and its two neighbors
- Effectively a repeated bus: multiple messages in transit
- Disadvantage: bisection bandwidth of 2 and N/2 hops on average

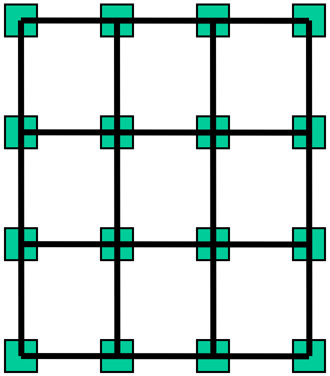


Distributed Switch Options

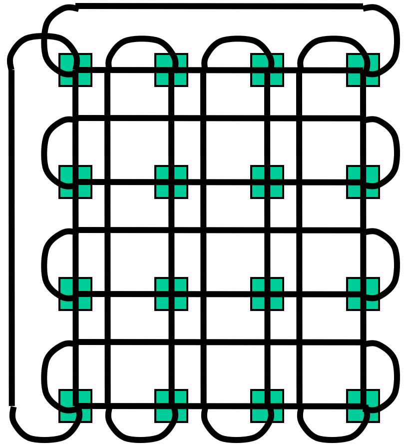
- Performance can be increased by throwing more hardware at the problem: fully-connected switches: every switch is connected to every other switch: N^2 wiring complexity, $N^2/4$ bisection bandwidth

- Most commercial designs adopt a point between the two extremes (ring and fully-connected):
  - Grid: each node connects with its N, E, W, S neighbors
  - Torus: connections wrap around
  - Hypercube: links between nodes whose binary names differ in a single bit

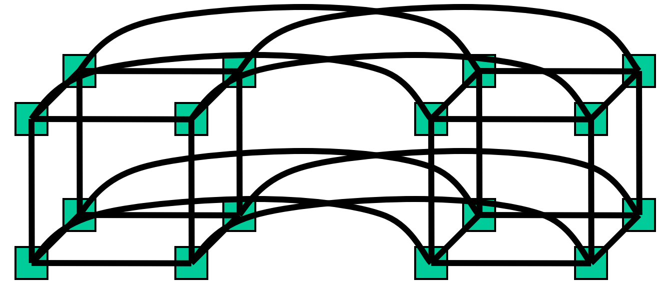
Topology Examples



Grid



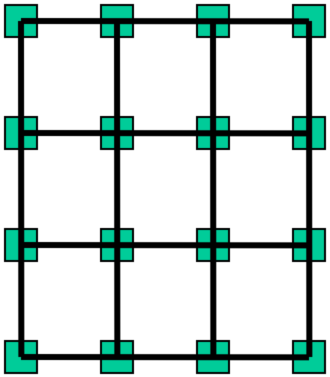
Torus



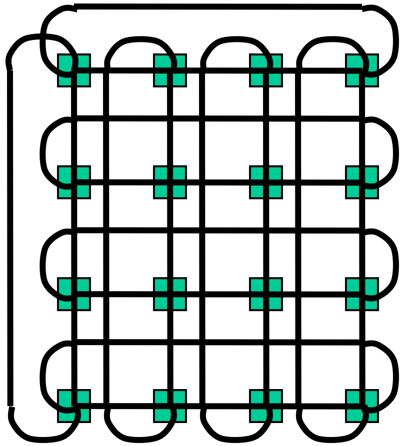
Hypercube

Criteria	Bus	Ring	2Dtorus	6-cube	Fully connected
Performance Bisection bandwidth					
Cost Ports/switch Total links					

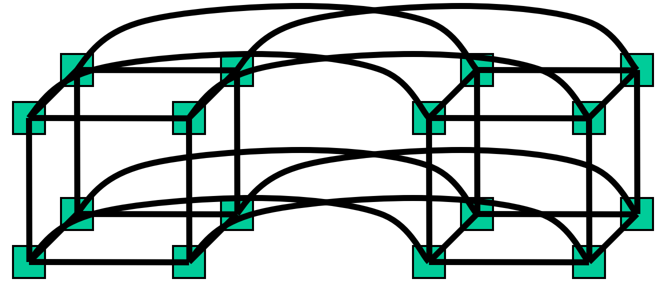
Topology Examples



Grid



Torus



Hypercube

Criteria	Bus	Ring	2Dtorus	6-cube	Fully connected
Performance Bisection bandwidth	1	2	16	32	1024
Cost Ports/switch Total links	 1	 3 128	 5 192	 7 256	 64 2080

k-ary d-cube

- Consider a k-ary d-cube: a d-dimension array with k elements in each dimension, there are links between elements that differ in one dimension by 1 (mod k)
- Number of nodes $N = k^d$

Number of switches :
Switch degree :
Number of links :
Pins per node :

Avg. routing distance:
Diameter :
Bisection bandwidth :
Switch complexity :

Should we minimize or maximize dimension?

k-ary d-Cube

- Consider a k-ary d-cube: a d-dimension array with k elements in each dimension, there are links between elements that differ in one dimension by 1 (mod k)

- Number of nodes $N = k^d$

(with no wraparound)

Number of switches	N	Avg. routing distance	$d(k-1)/2$
Switch degree	$2d + 1$	Diameter	$d(k-1)$
Number of links	Nd	Bisection bandwidth	$2wk^{d-1}$
Pins per node	2wd	Switch complexity	$(2d + 1)^2$

Should we minimize or maximize dimension?

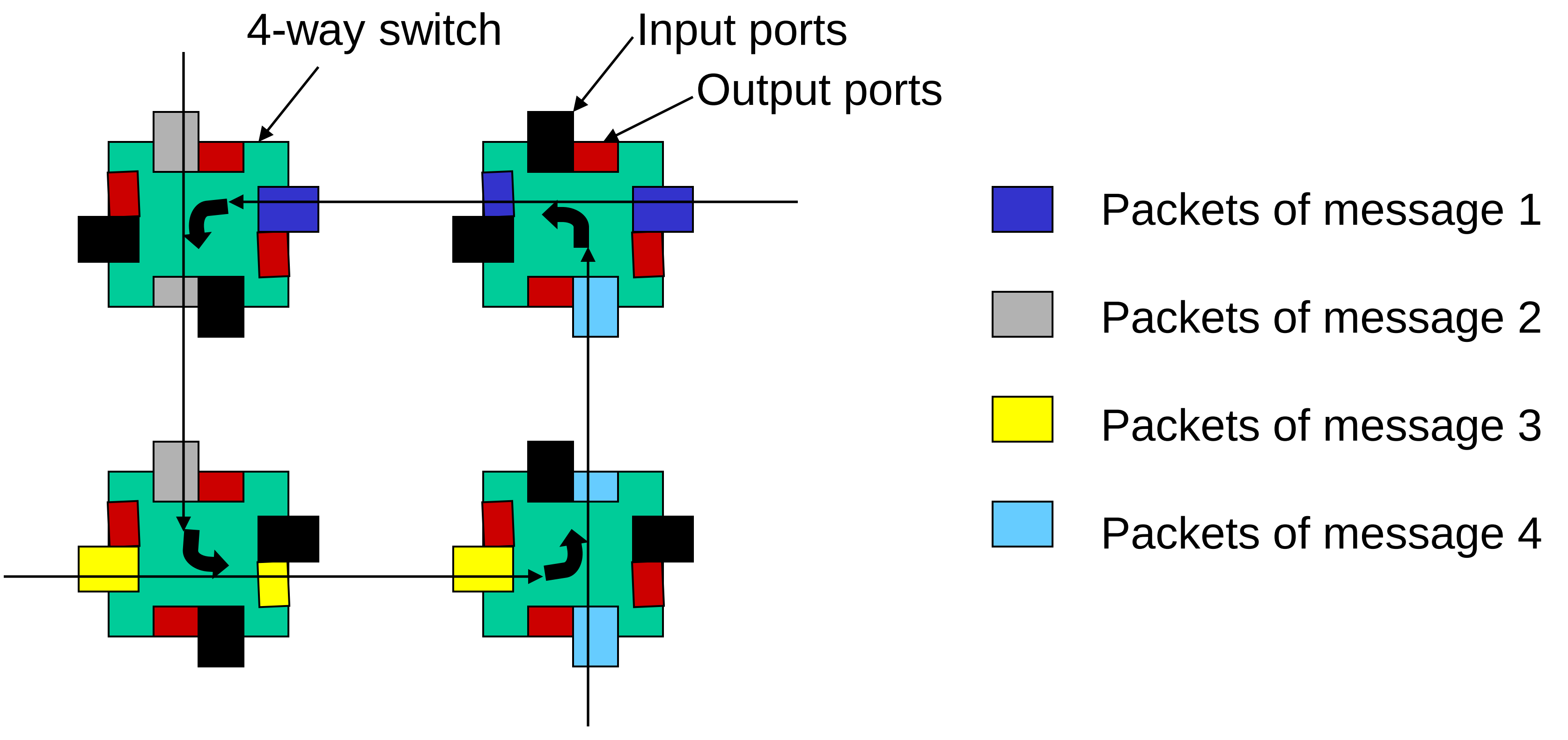
Routing

- Deterministic routing: given the source and destination, there exists a unique route
- Adaptive routing: a switch may alter the route in order to deal with unexpected events (faults, congestion) – more complexity in the router vs. potentially better performance
- Example of deterministic routing: dimension order routing: send packet along first dimension until destination co-ord (in that dimension) is reached, then next dimension, etc.

Deadlock

- Deadlock happens when there is a cycle of resource dependencies – a process holds on to a resource (A) and attempts to acquire another resource (B) – A is not relinquished until B is acquired

Deadlock Example

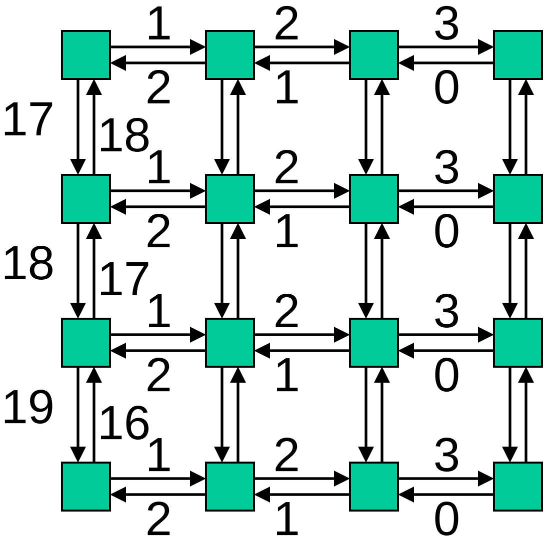


Each message is attempting to make a left turn – it must acquire an output port, while still holding on to a series of input and output ports

Deadlock-Free Proofs

- Number edges and show that all routes will traverse edges in increasing (or decreasing) order – therefore, it will be impossible to have cyclic dependencies

- Example: k-ary 2-d array with dimension routing: first route along x-dimension, then along y

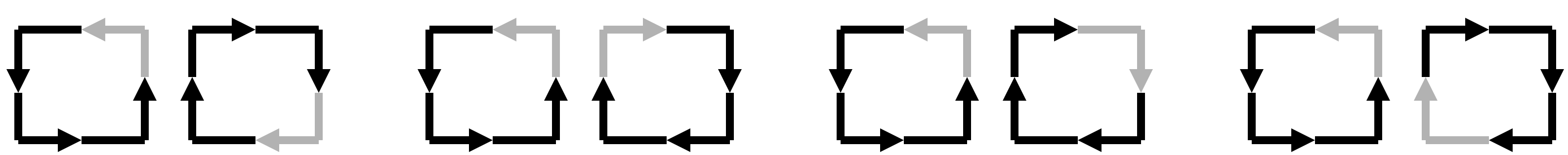


Breaking Deadlock I

- The earlier proof does not apply to tori because of wraparound edges
- Partition resources across multiple virtual channels
- If a wraparound edge must be used in a torus, travel on virtual channel 1, else travel on virtual channel 0

Breaking Deadlock II

- Consider the eight possible turns in a 2-d array (note that turns lead to cycles)
- By preventing just two turns, cycles can be eliminated
- Dimension-order routing disallows four turns
- Helps avoid deadlock even in adaptive routing



West-First | North-Last | Negative-First | Can allow deadlocks

Title

- Bullet