

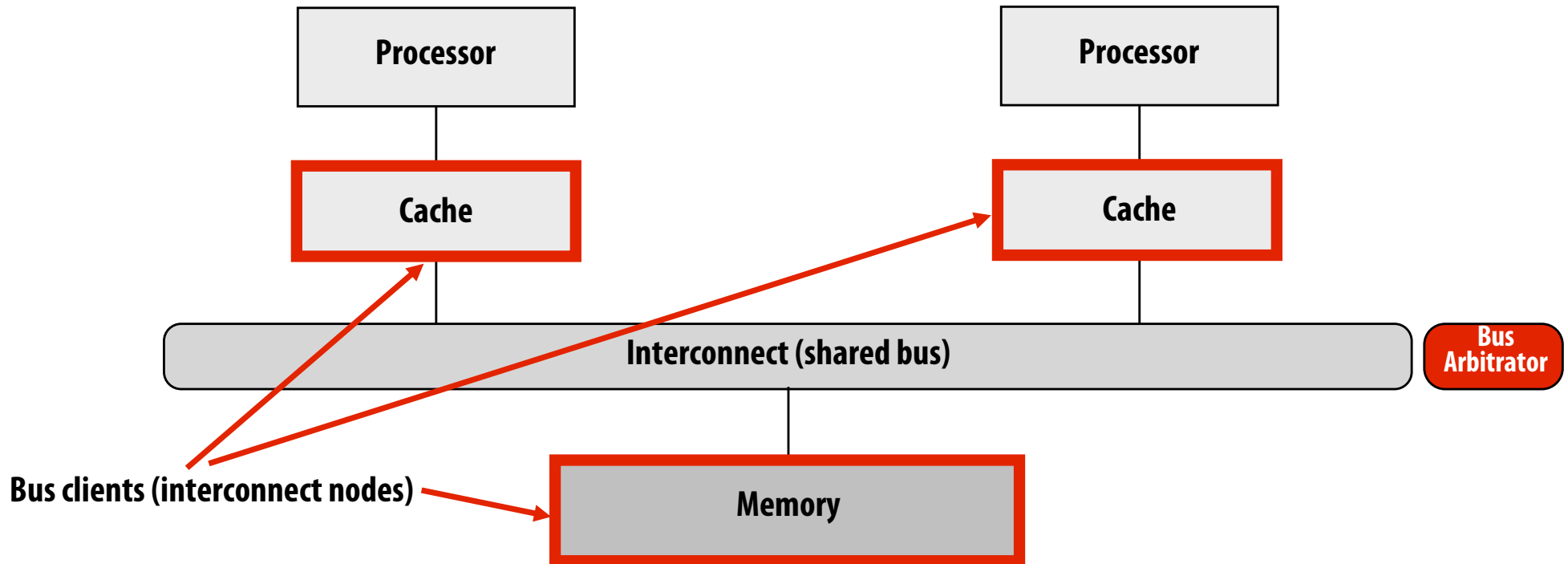
Lecture 15:

Interconnection Networks

**Parallel Computer Architecture and Programming
CMU 15-418/15-618, Spring 2020**

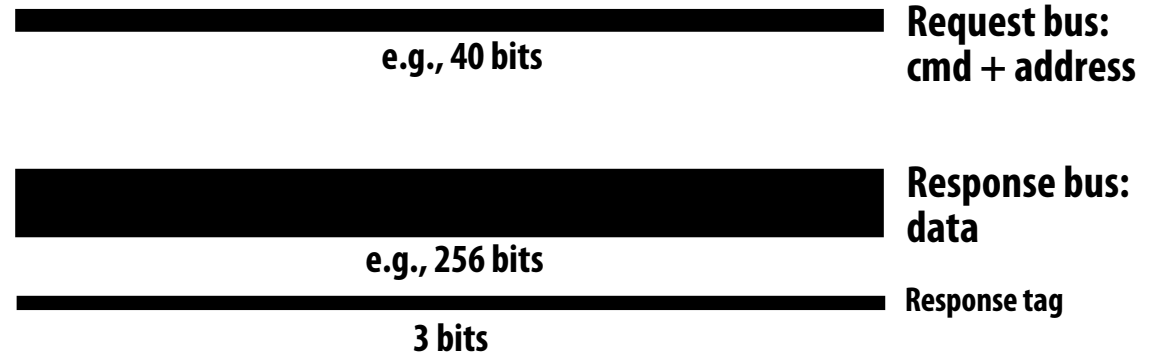
Credit: some slides created by Michael Papamichael, others based on slides from Onur Mutlu's 18-742

Basic system design from previous lectures

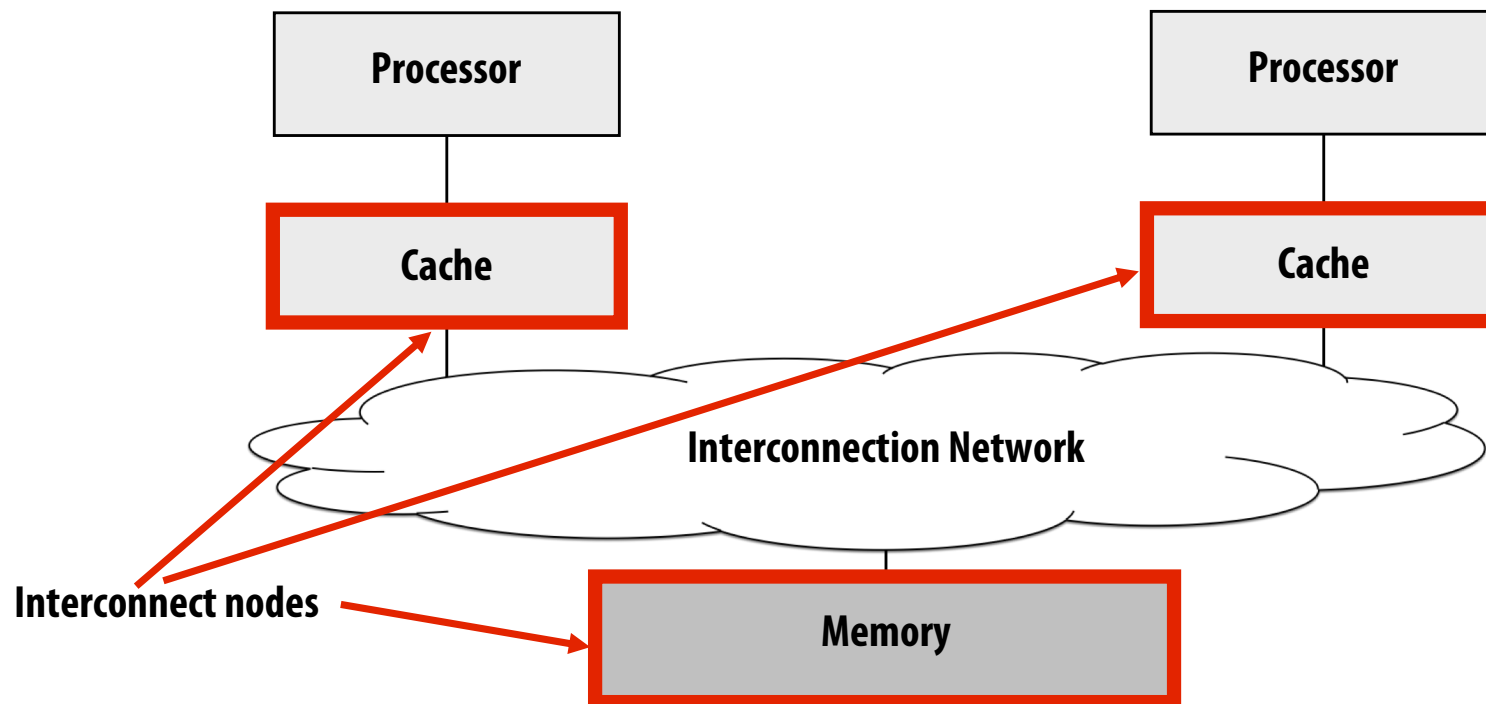


Bus interconnect:

All nodes connected by a shared set of wires



Today: modern interconnect designs



**Today's topics: the basic ideas of building a high-performance interconnection network in a parallel processor.
(think: "a network-on-a-chip")**

What are interconnection networks used for?

- **To connect:**
 - **Processor cores with other cores**
 - **Processors and memories**
 - **Processor cores and caches**
 - **Caches and caches**
 - **I/O devices**

Why is the design of the interconnection network important?

■ System scalability

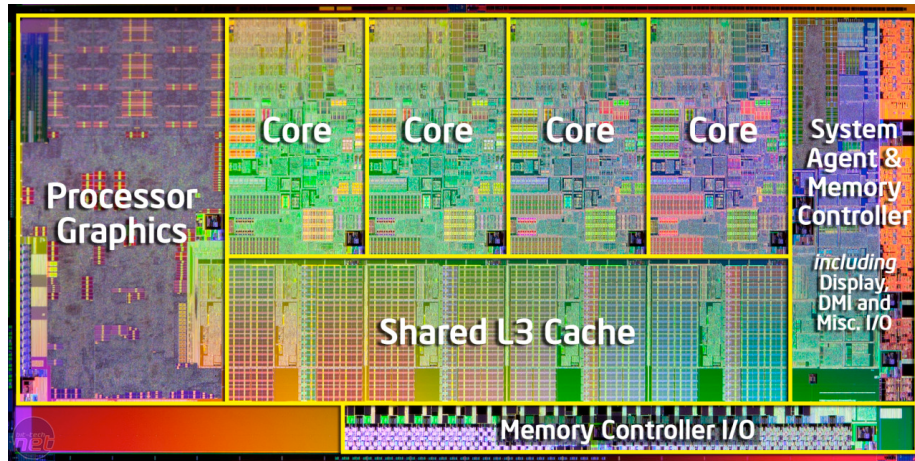
- How large of a system can be built?
- How easy is it to add more nodes (e.g., cores)

■ System performance and energy efficiency

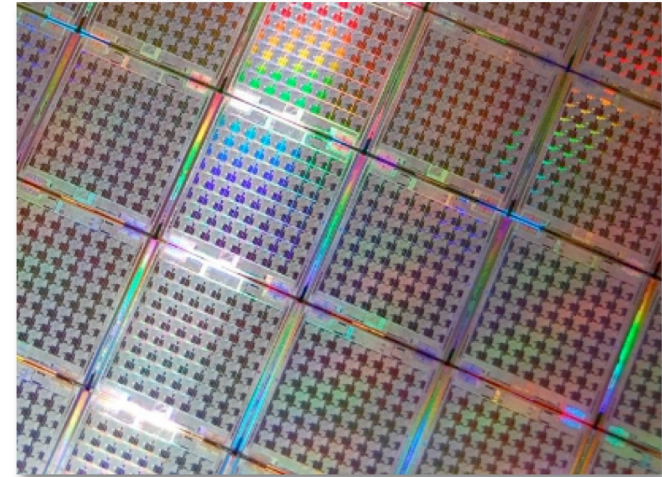
- How fast can cores, caches, memory communicate
- How long is latency to memory?
- How much energy is spent on communication?

With increasing core counts...

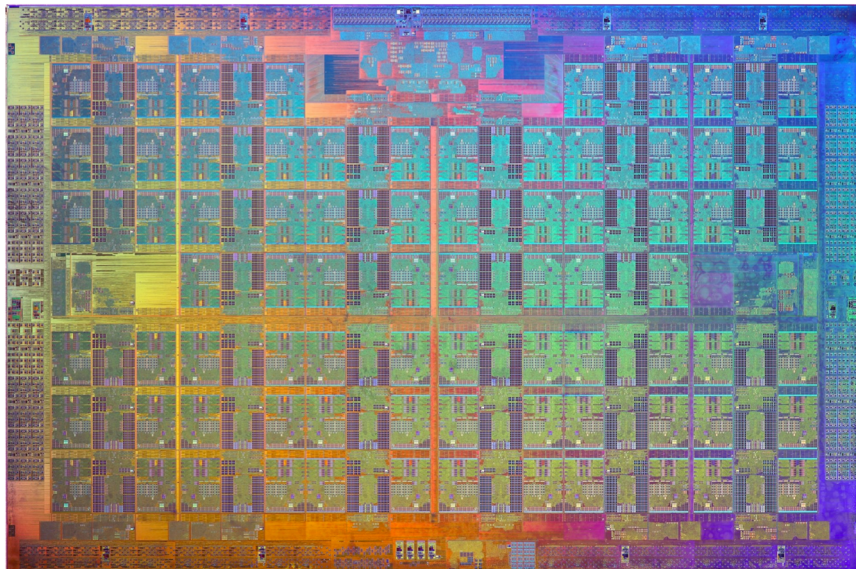
Scalability of on-chip interconnection network becomes increasingly important



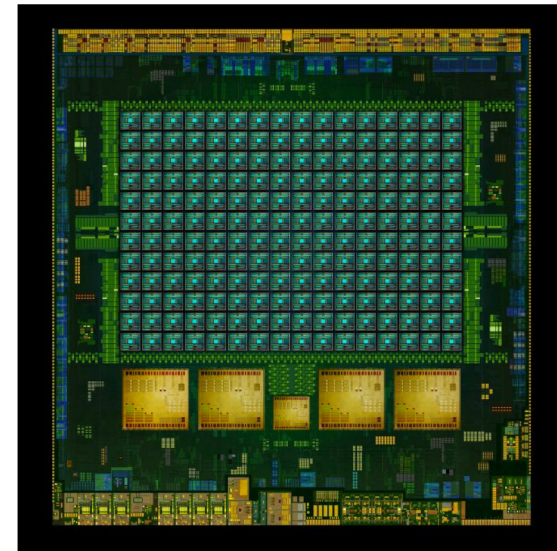
Intel core i7 (4-CPU cores, + GPU)



Tiler GX 64-core chip



Intel Xeon Phi (72-core x86)

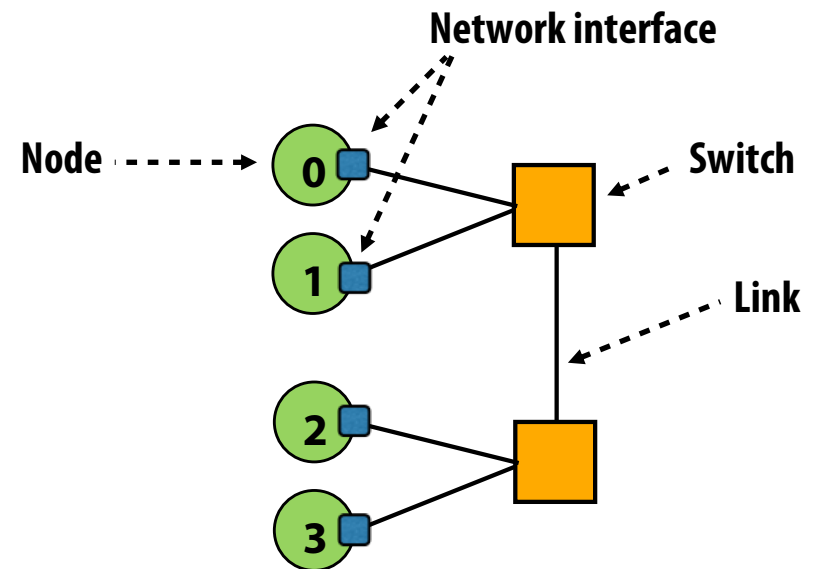


Tegra K1: 4 + 1 ARM cores + GPU cores

Interconnect terminology

Terminology

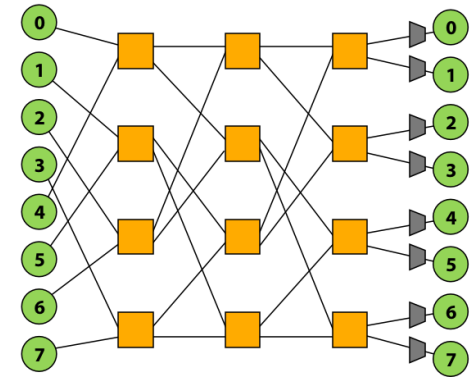
- **Network node: a network endpoint connected to a router/switch**
 - Examples: processor caches, the memory controller
- **Network interface:**
 - Connects nodes to the network
- **Switch/router:**
 - Connects a fixed number of input links to a fixed number of output links
- **Link:**
 - A bundle of wires carrying a signal



Design issues

- **Topology: how switches are connected via links**

- Affects routing, throughput, latency, complexity/cost of implementation



- **Routing: how a message gets from its source to its destination in the network**

- Can be static (messages take a predetermined path) or adaptive based on load

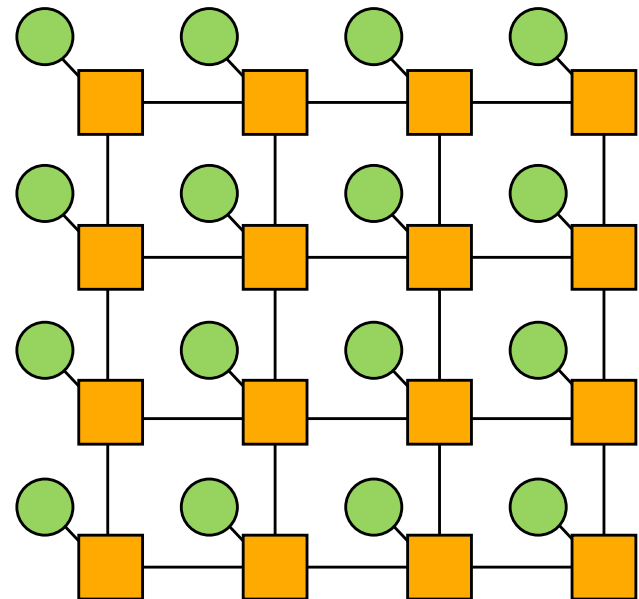
- **Buffering and flow control**

- What data are stored in the network? packets, partial packets? etc.
- How does the network manage buffer space?

Properties of interconnect topology

- **Routing distance**
 - Number of links (“hops”) along a route between two nodes
- **Diameter: the maximum routing distance**
- **Average distance: average routing distance over all valid routes**

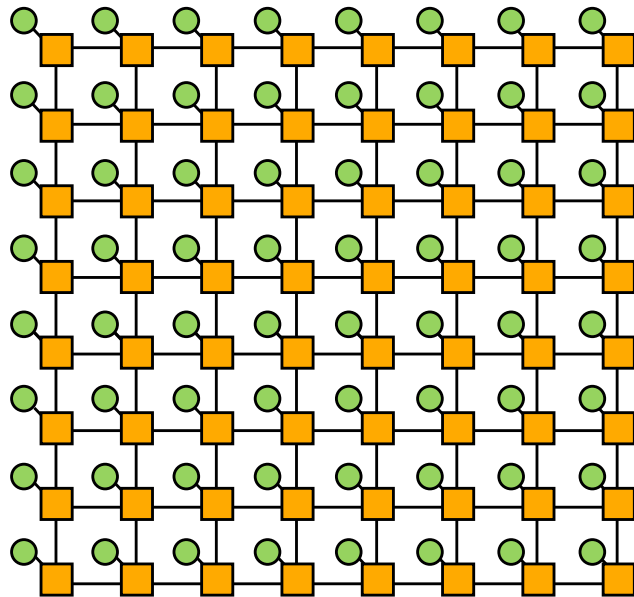
**Example:
diameter = 6**



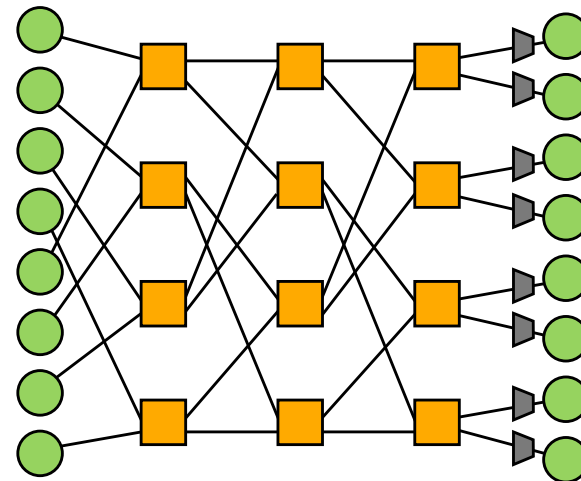
Properties of interconnect topology

■ Direct vs. indirect networks

- Direct network: endpoints sit “inside” the network
- e.g., mesh is direct network: every node is both an endpoint and a switch



Direct network



Indirect network

Properties of an interconnect topology

■ Bisection bandwidth:

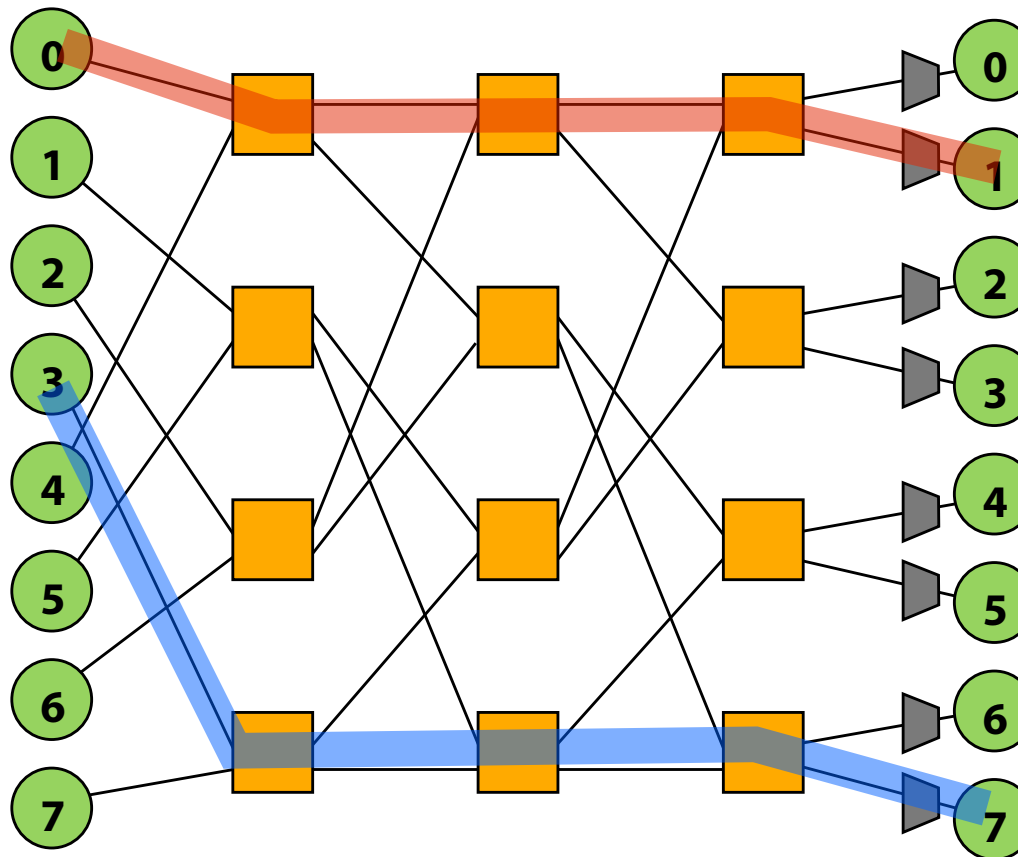
- Common metric of performance for recursive topologies
- Cut network in half, sum bandwidth of all severed links
- Warning: can be misleading as it does not account for switch and routing efficiencies

■ Blocking vs. non-blocking:

- If connecting any pairing of nodes is possible, network is non-blocking (otherwise, it's blocking)

Example: blocking vs. non-blocking

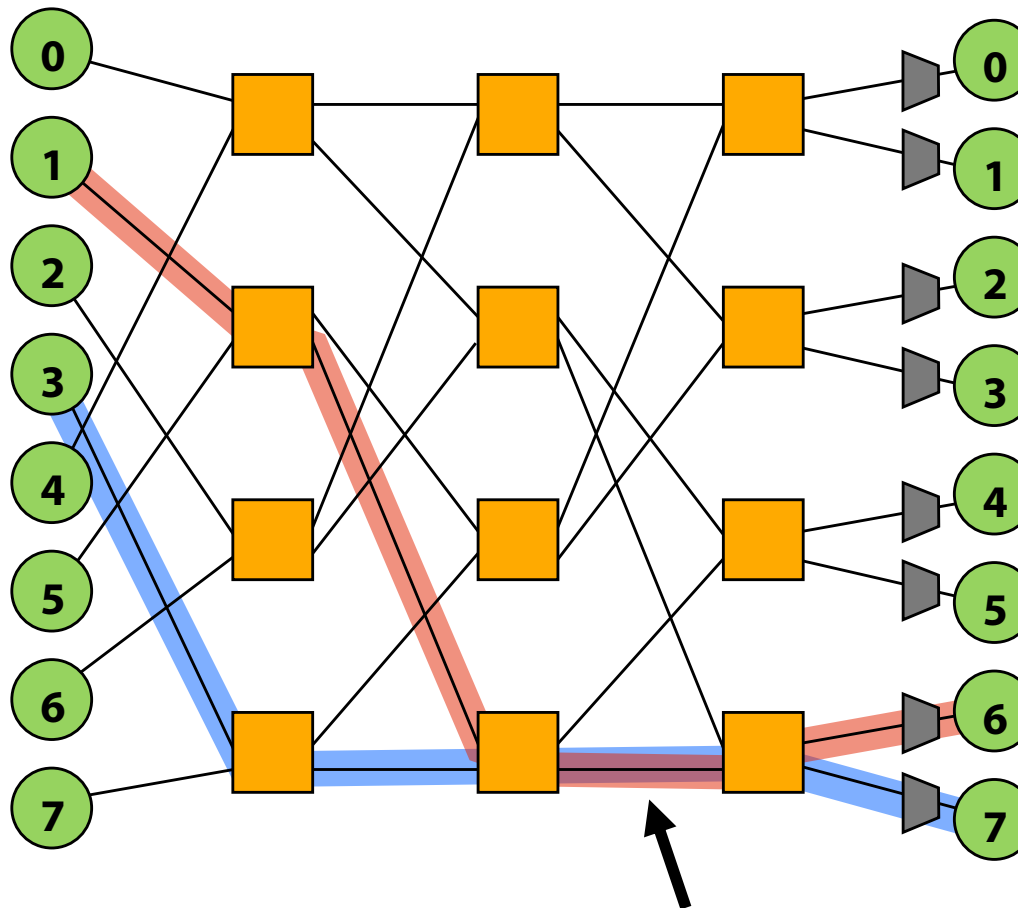
- Is this network blocking or non-blocking?
 - Consider simultaneous messages from 0-to-1 and 3-to-7.



Note: in this network illustration, each node is drawn twice for clarity (at left and at right)

Example: blocking vs. non-blocking

- Is this network blocking or non-blocking?
 - Consider simultaneous messages from 0-to-1 and 3-to-7.
 - Consider simultaneous messages from 1-to-6 and 3-to-7. **Blocking!!!**

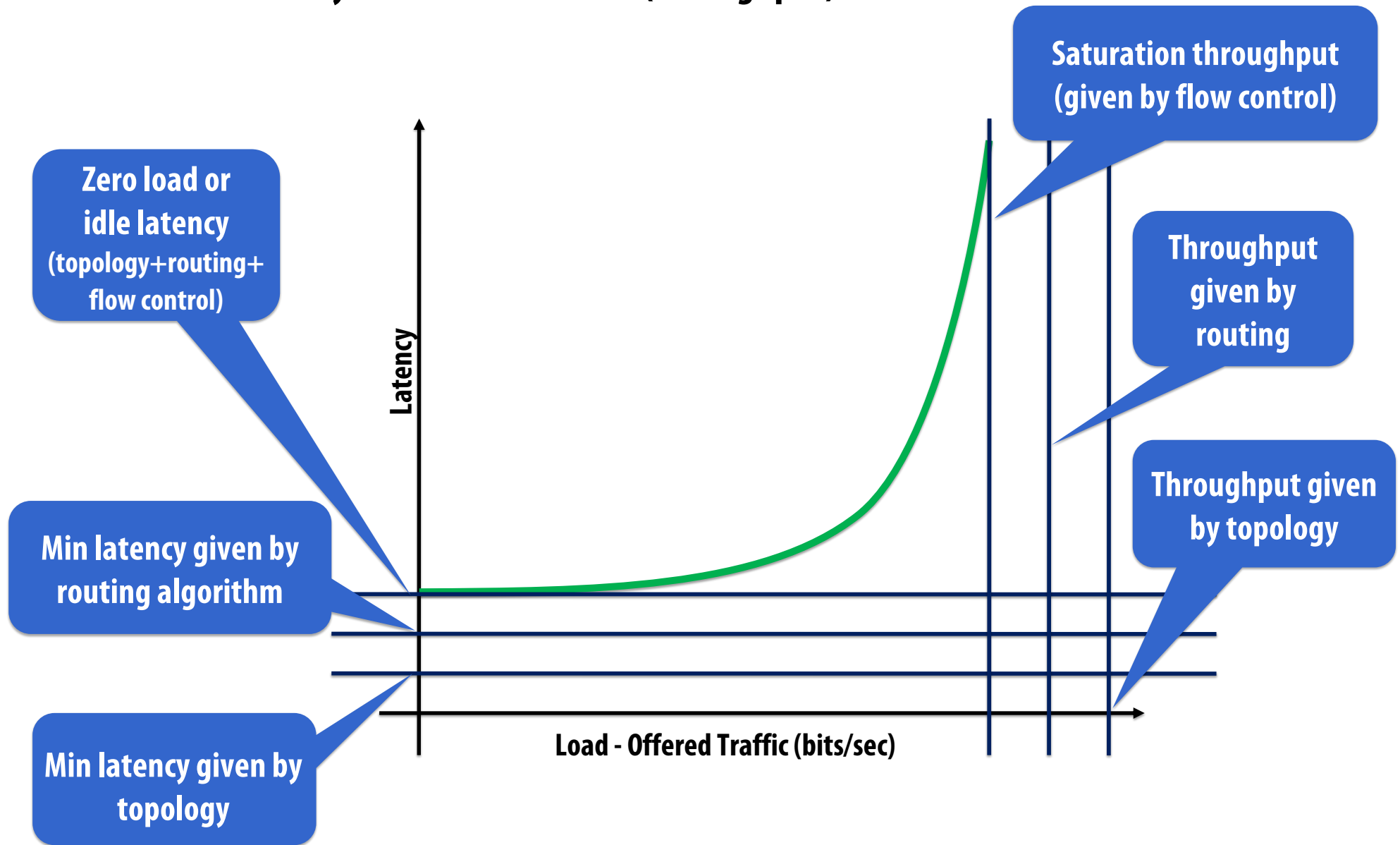


Note: in this network illustration, each node is drawn twice for clarity (at left and at right)

Conflict

Load-latency behavior of network

General rule: latency increases with load (throughput)



Interconnect topologies

Many possible network topologies

Bus

Crossbar

Ring

Tree

Omega

Hypercube

Mesh

Torus

Butterfly

...

Bus interconnect

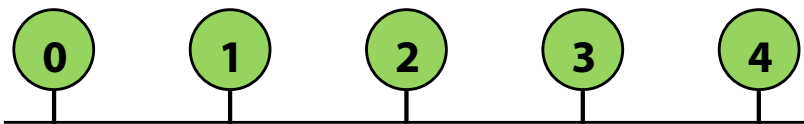
■ Good:

- Simple design
- Cost effective for a small number of nodes
- Easy to implement coherence (via snooping)

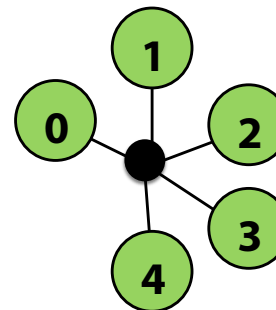
■ Bad:

- Contention: all nodes contend for shared bus
- Limited bandwidth: all nodes communicate over same wires (one communication at a time)
- High electrical load = low frequency, high power

Physical Structure



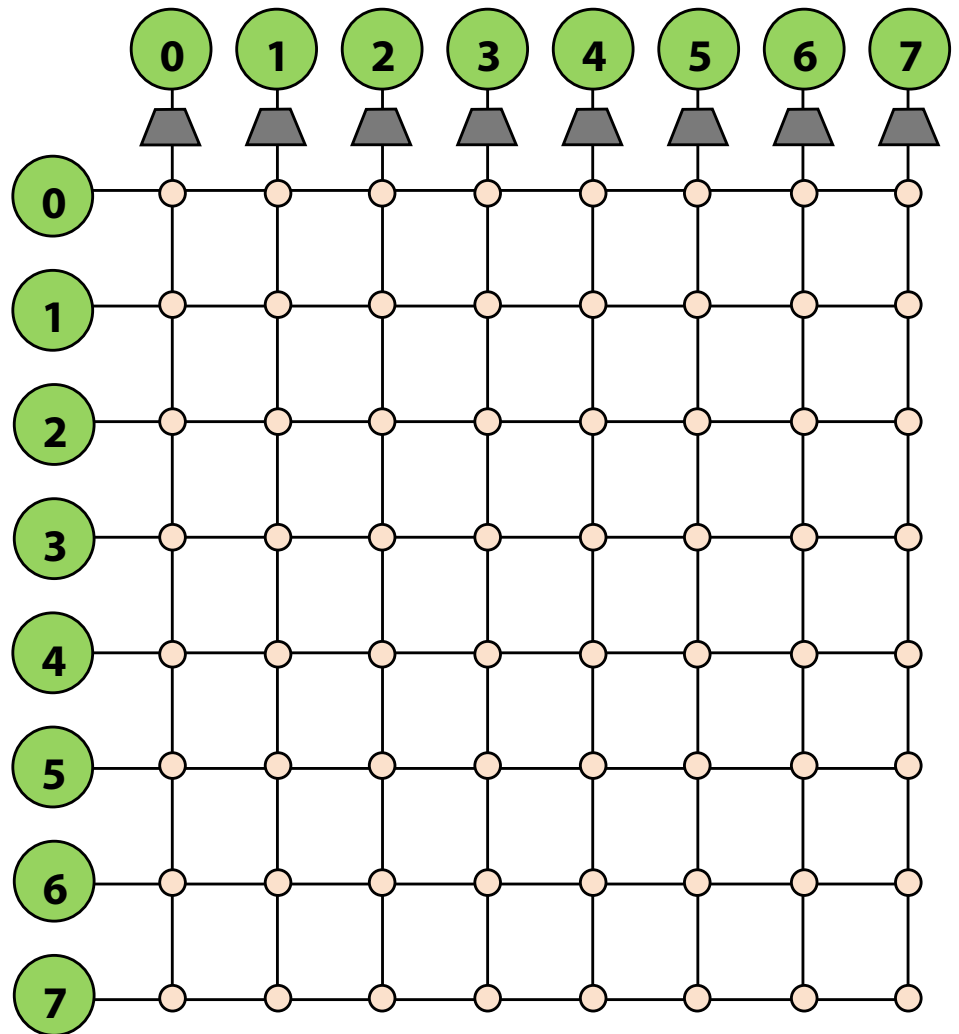
Logical Structure



Crossbar interconnect

- Every node is connected to every other node (non-blocking, indirect)
- Switch i,j provides direct connection from node i to node j
- Good:
 - $O(1)$ latency and high bandwidth
- Bad:
 - Not scalable: $O(N^2)$ switches
 - High cost
 - Difficult to arbitrate at scale

Crossbar scheduling algorithms / efficient hardware implementations are still active research areas.

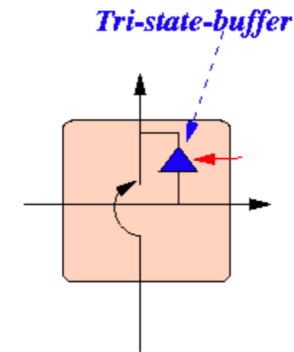
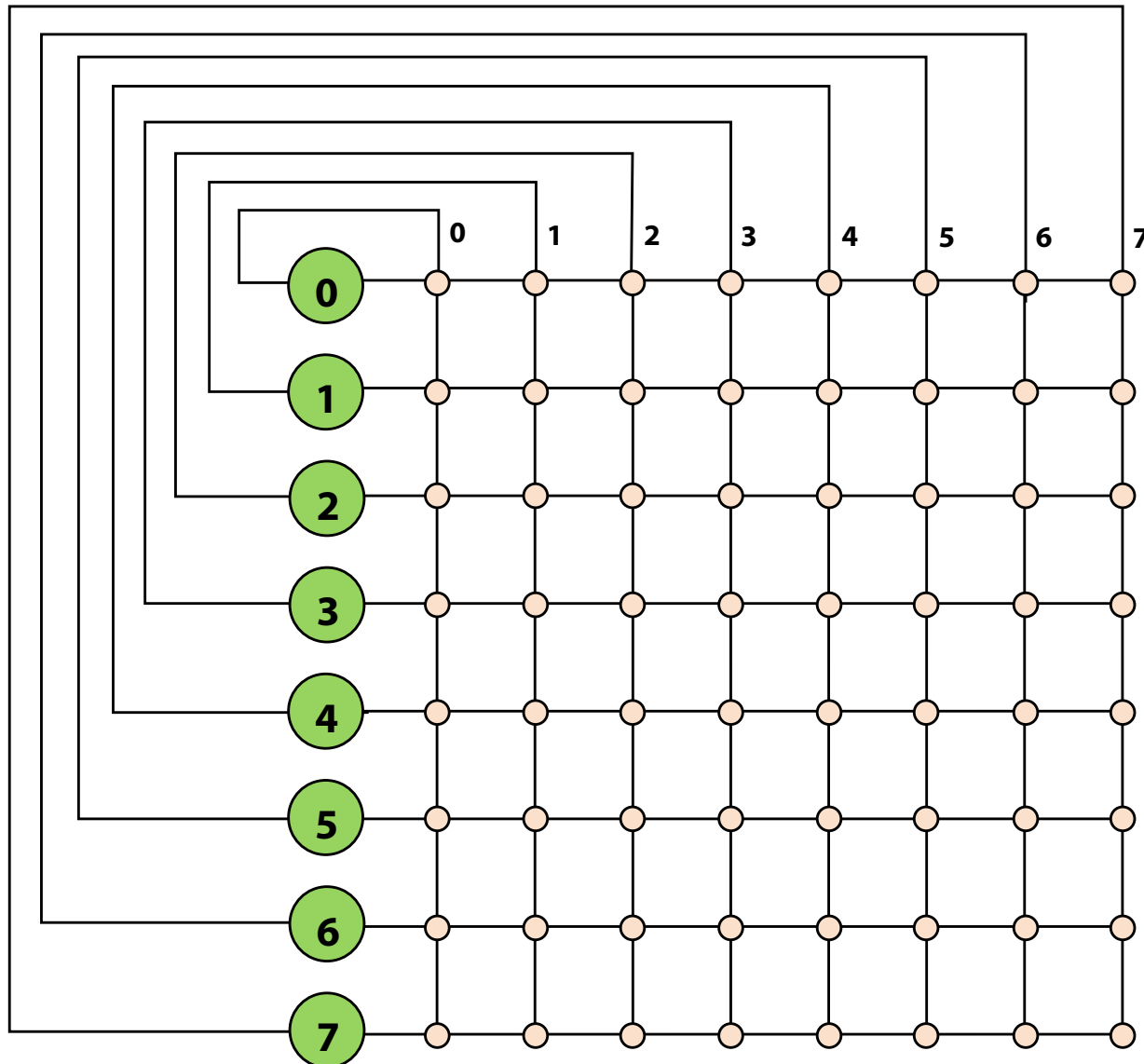


8-node crossbar network (N=8)

Note: in this network illustration, each node is drawn twice for clarity (at left and at top)

Crossbar interconnect

(Here is a more verbose illustration than that on previous slide)



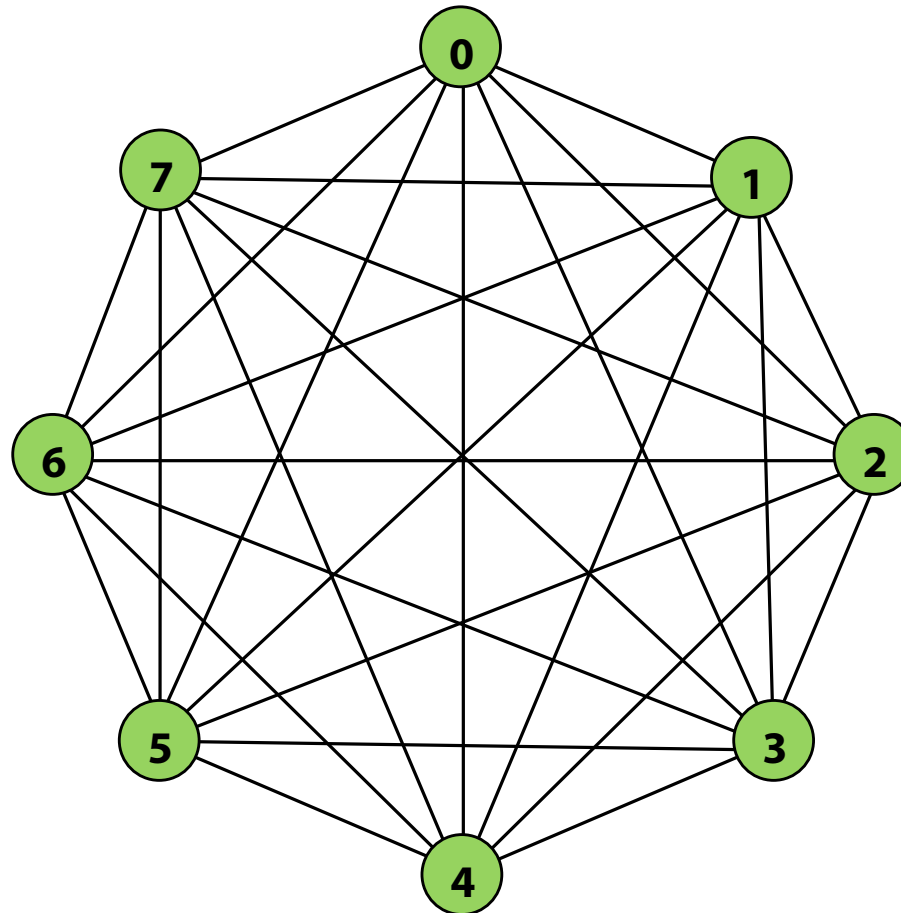
Horizontal/Vertical lines

- Continuous wires

Circles

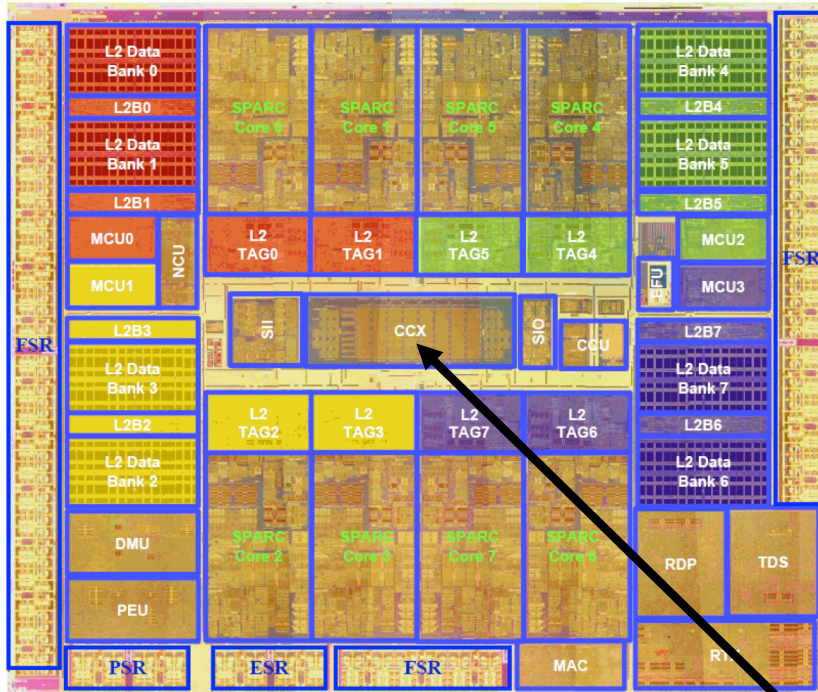
- Optionally connect horizontal wire to vertical

Crossbar Logical Structure

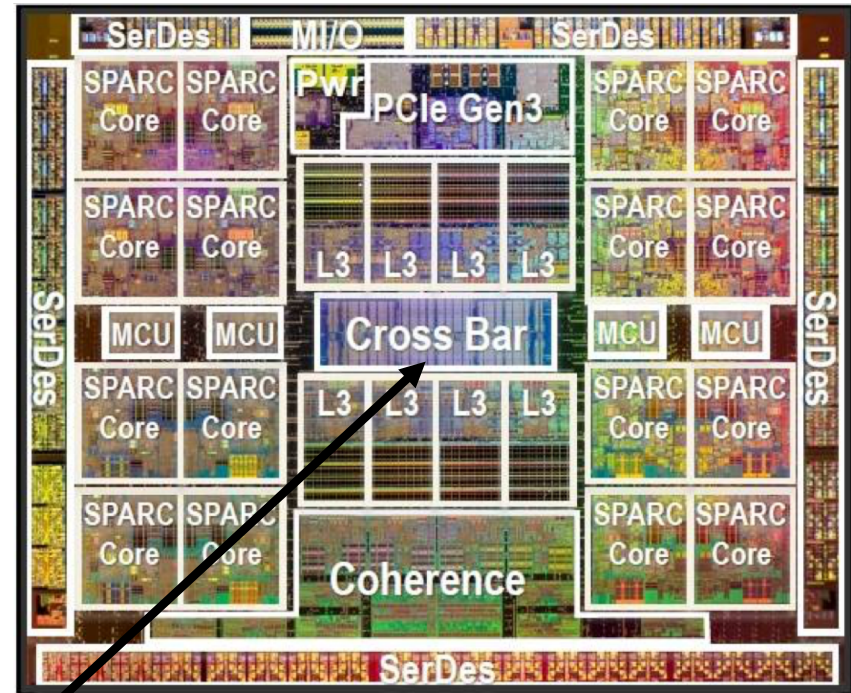


- **For each possible sender:**
 - **Can connect to any set of receivers simultaneously**
 - **Very general, but very expensive**

Crossbars were used in recent multi-core processing from Oracle (previously Sun)



Sun SPARC T2 (8 cores, 8 L2 cache banks)

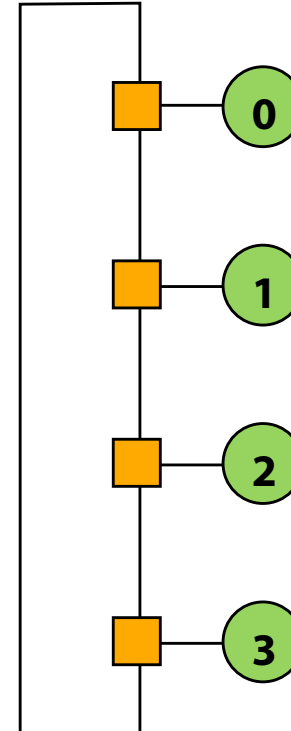


Oracle SPARC T5 (16 cores, 8 L3 cache banks)

Note that crossbar (CCX) occupies about the same chip area as a core

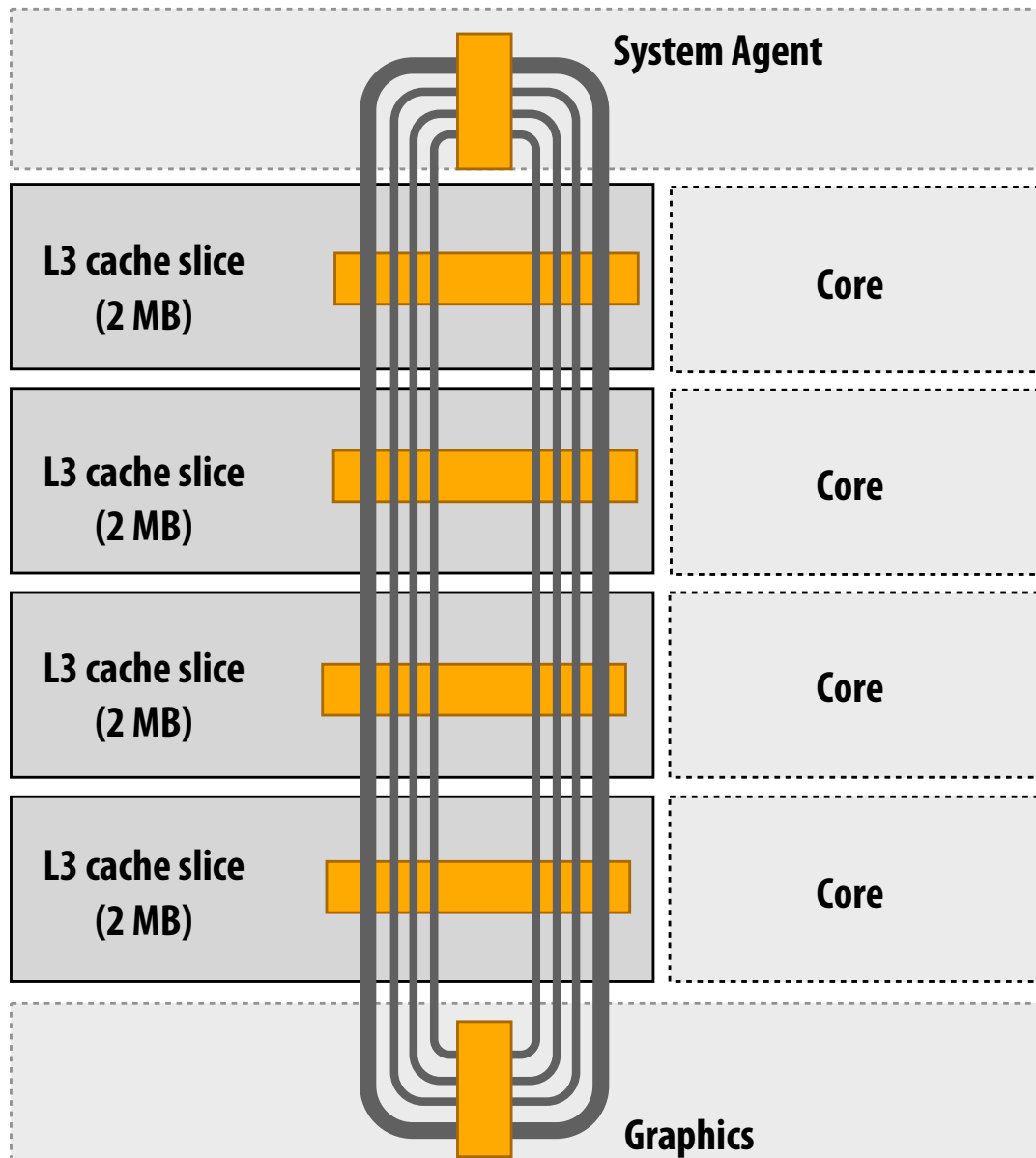
Ring

- **Good:**
 - Simple
 - Cheap: $O(N)$ cost
- **Bad:**
 - High latency: $O(N)$
 - Bisection bandwidth remains constant as nodes are added (scalability issue)
- **Used in recent Intel architectures**
 - Core i7
- **Also used in IBM CELL Broadband Engine (9 cores)**



Intel's ring interconnect

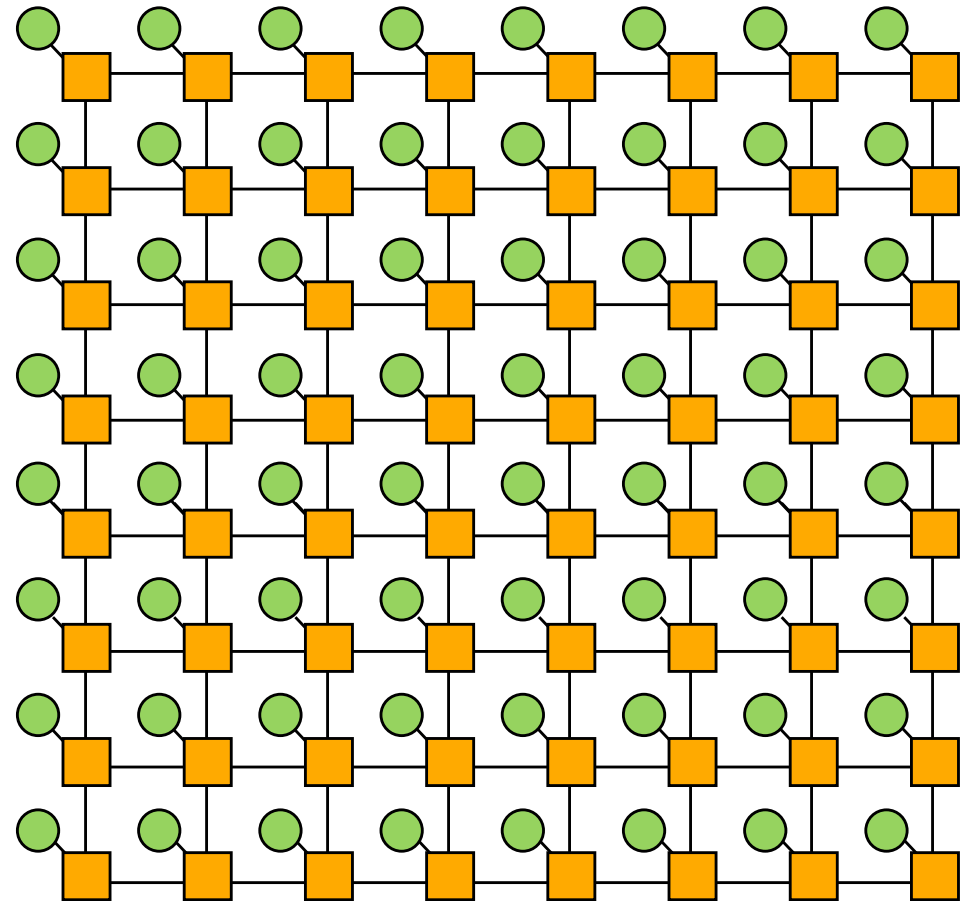
Introduced in Sandy Bridge microarchitecture



- **Four rings**
 - request
 - snoop
 - Ack
 - data (32 bytes)
- **Six interconnect nodes: four “slices” of L3 cache + system agent + graphics**
- **Each bank of L3 connected to ring bus twice**
- **Theoretical peak BW from cores to L3 at 3.4 GHz is approx. 435 GB/sec**
 - When each core is accessing its local slice

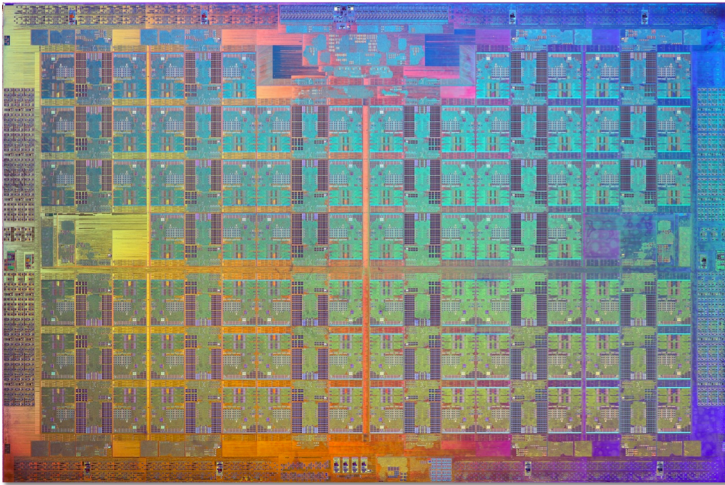
Mesh

- Direct network
- Echoes locality in grid-based applications
- $O(N)$ cost
- Average latency: $O(\sqrt{N})$
- Easy to lay out on chip: fixed-length links
- Path diversity: many ways for message to travel from one node to another
- Used by:
 - Tiler processors
 - Prototype Intel chips

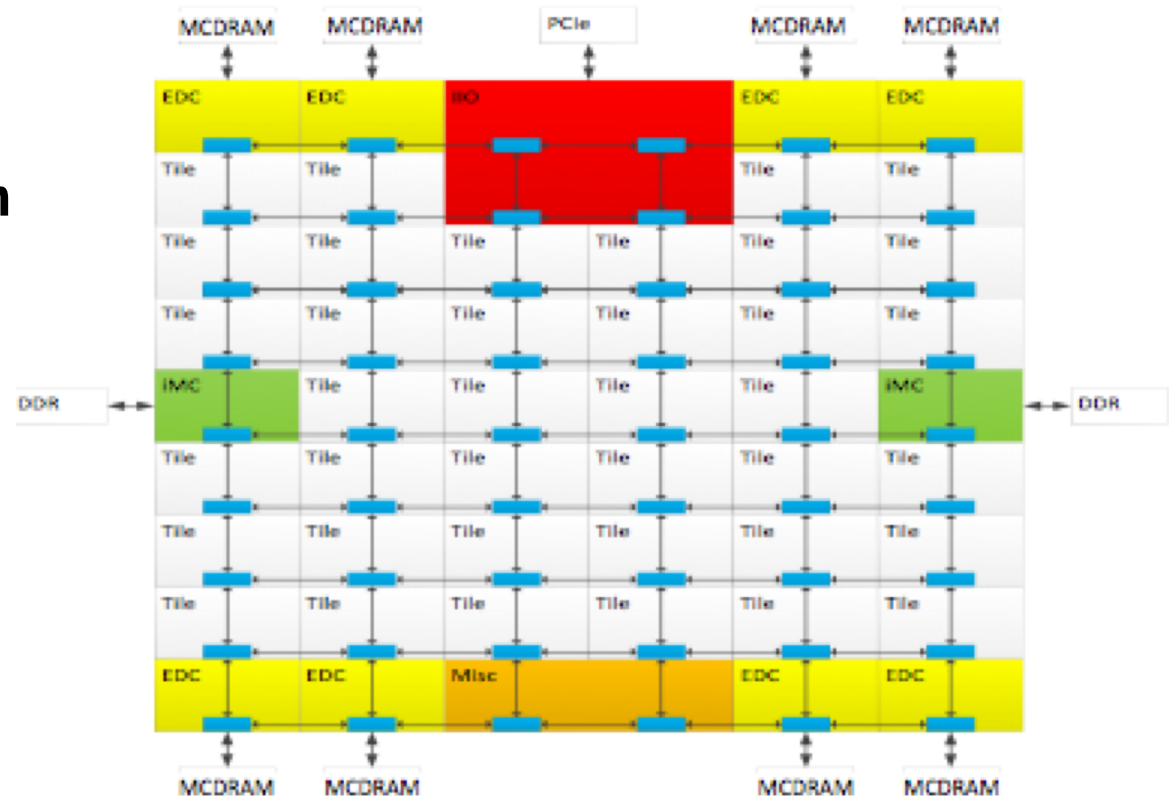


2D Mesh

Xeon Phi (Knights Landing)

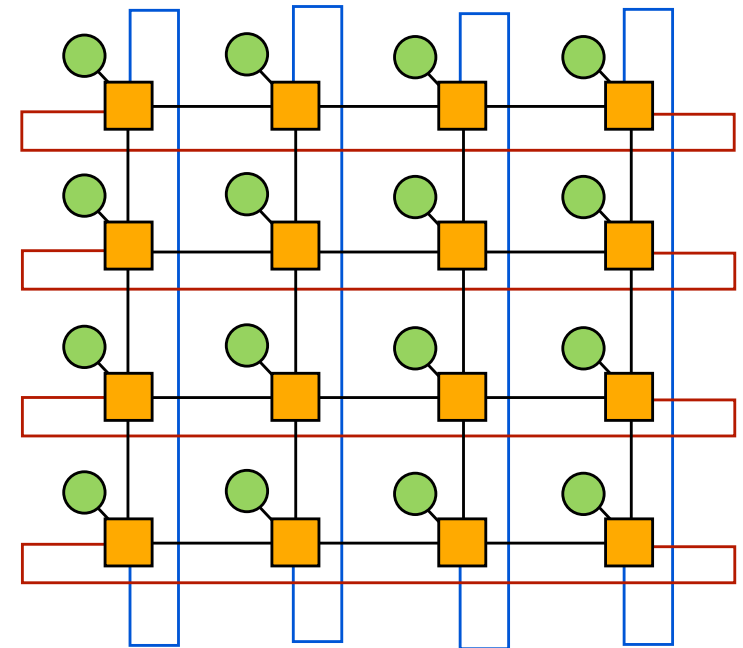


- 72 cores, arranged as 6 x 6 mesh of tiles (2 cores/tile)
- YX routing of messages:
 - Move in Y
 - "Turn"
 - Move in X



Torus

- Characteristics of mesh topology are different based on whether node is near edge or middle of network (torus topology introduces new links to avoid this problem)
- Still $O(N)$ cost, but higher cost than 2D grid
- Higher path diversity and bisection BW than mesh
- Higher complexity
 - Difficult to layout on chip
 - Unequal link lengths

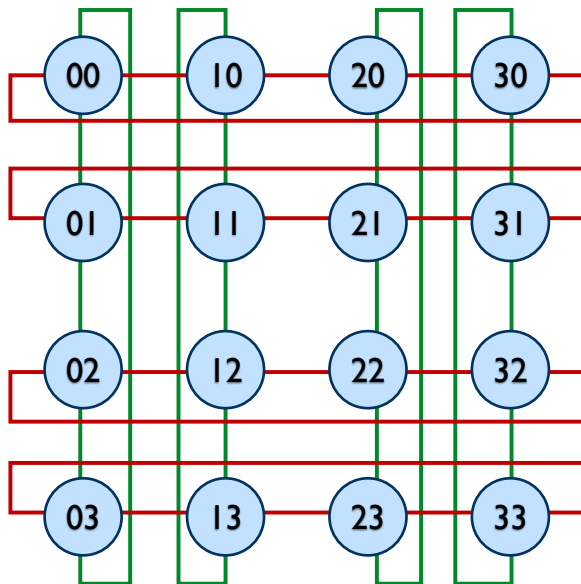


2D Torus

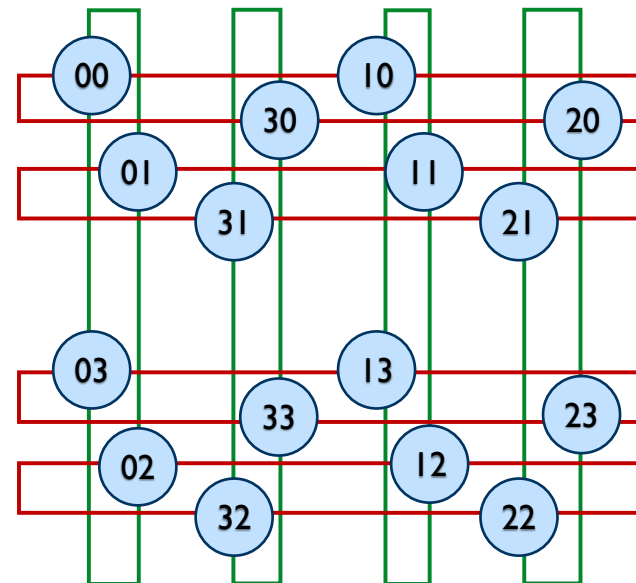
Folded Torus

- Interleaving rows & columns eliminates need for long connections
- All connections doubled in length

Torus

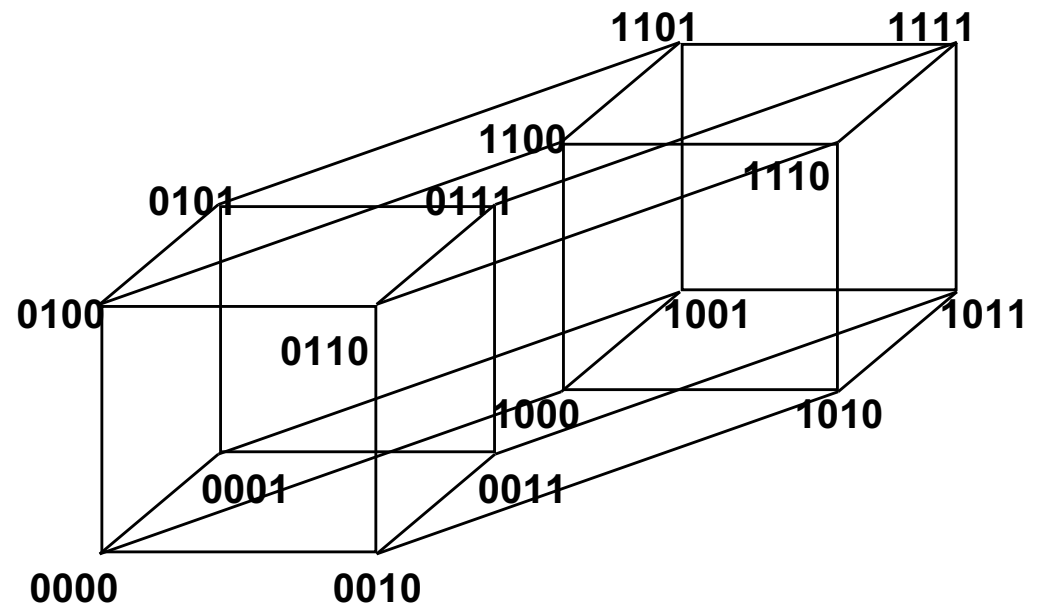
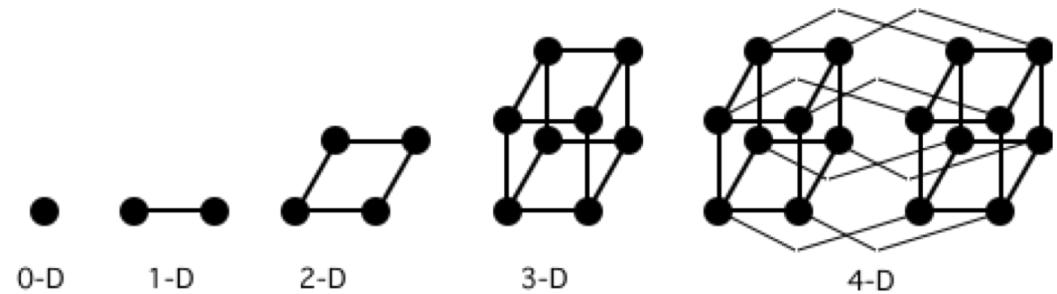


Folded Torus



Hypercube

- Low latency: $O(\lg N)$
- Radix: $O(\lg N)$
- Number of links $O(N \lg N)$

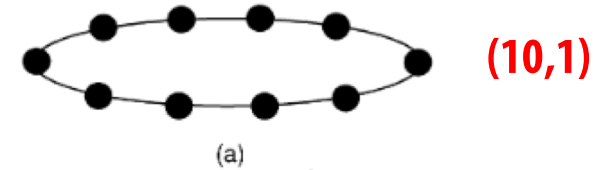


- 6D hypercube used in 64-core Cosmic Cube computer developed at Caltech in the 80s
- SGI Origin used a hypercube

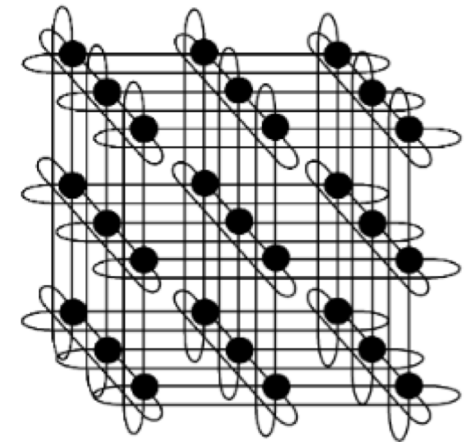
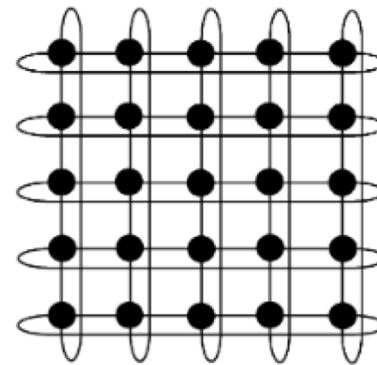
Generalizing Torii and Hypercubes

■ k-ary n-cube

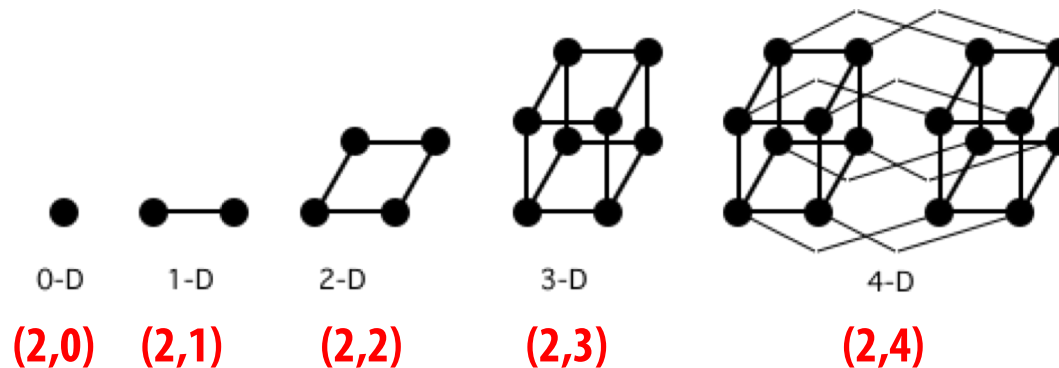
- Rings of k nodes
- Connected in n dimensions



$(5,2)$

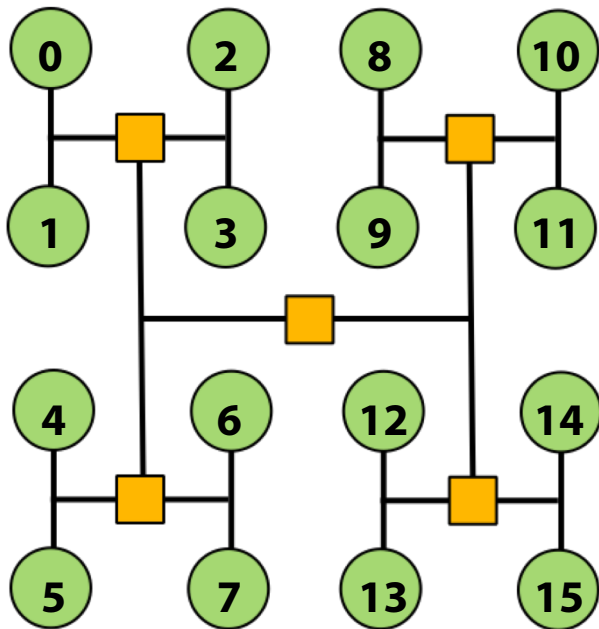


$(3,3)$

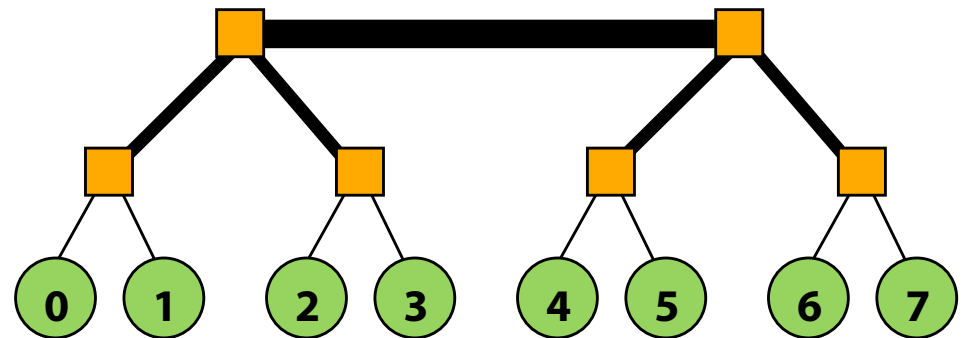


Trees

- Planar, hierarchical topology
- Like mesh/torus, good when traffic has locality
- Latency: $O(\lg N)$
- Use “fat trees” to alleviate root bandwidth problem (higher bandwidth links near root)



H-Tree



Fat Tree

Tree Routing

■ Getting from 1 to 2:

- $1 = 001_2$
- $2 = 010_2$

■ Getting from 3 to 6:

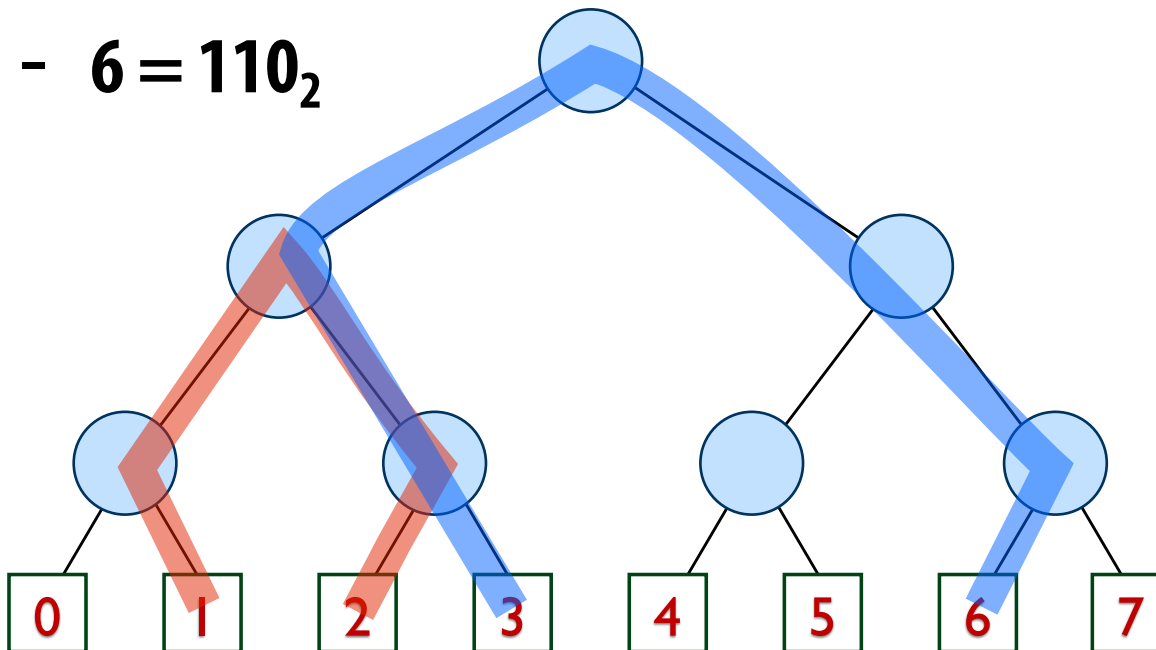
- $3 = 011_2$
- $6 = 110_2$

Upward:

- Until have common ancestor

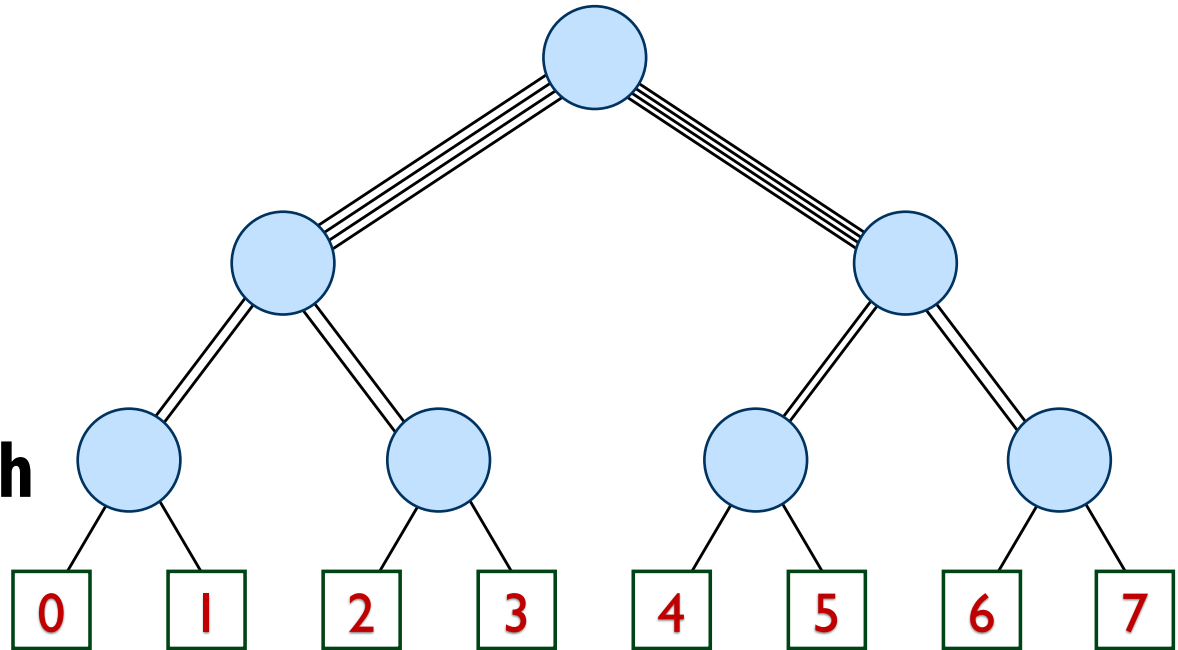
Downward:

- $0 \rightarrow \text{left}, 1 \rightarrow \text{right}$



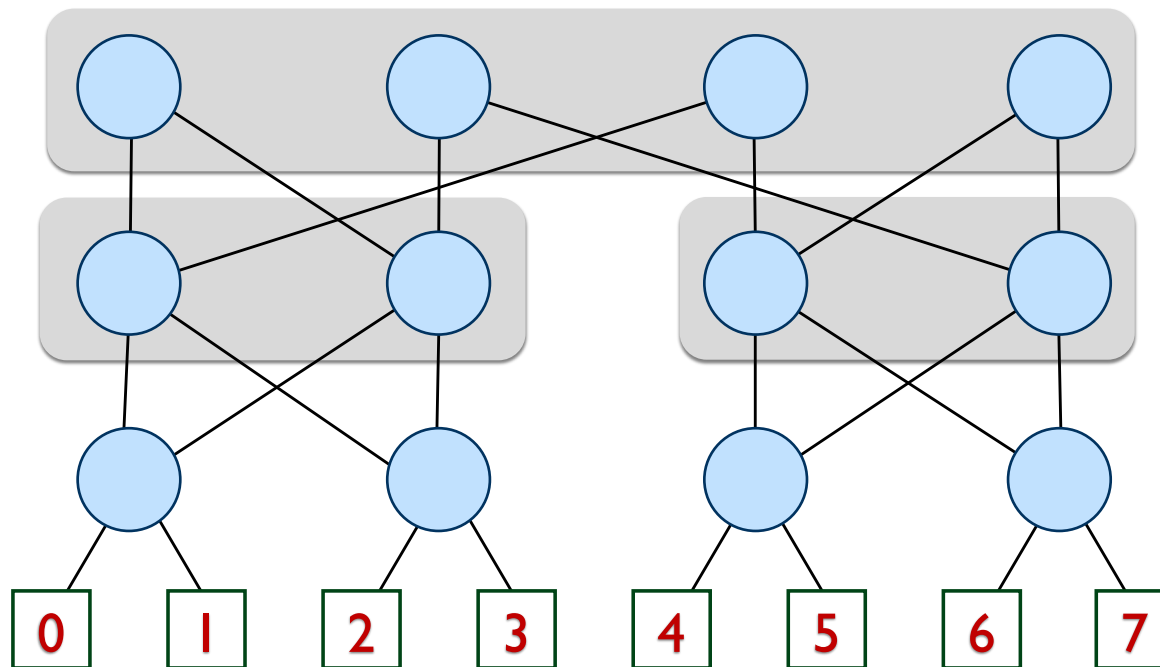
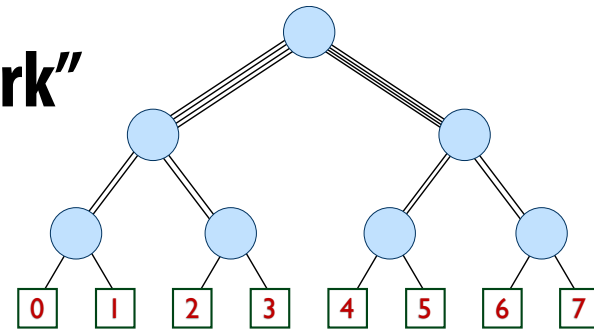
Fat Tree

- Charles Leiserson, 1985
- Increase bandwidth between nodes as move upward
- $O(N)$ bisection bandwidth
- Routing:
 - Like tree routing, but randomly choose when multiple links possible



Constant-Width Fat Tree

- Sometimes called “Folded Clos Network”
- All nodes fixed degree
 - Simpler hardware design
- Used in Infiniband networks

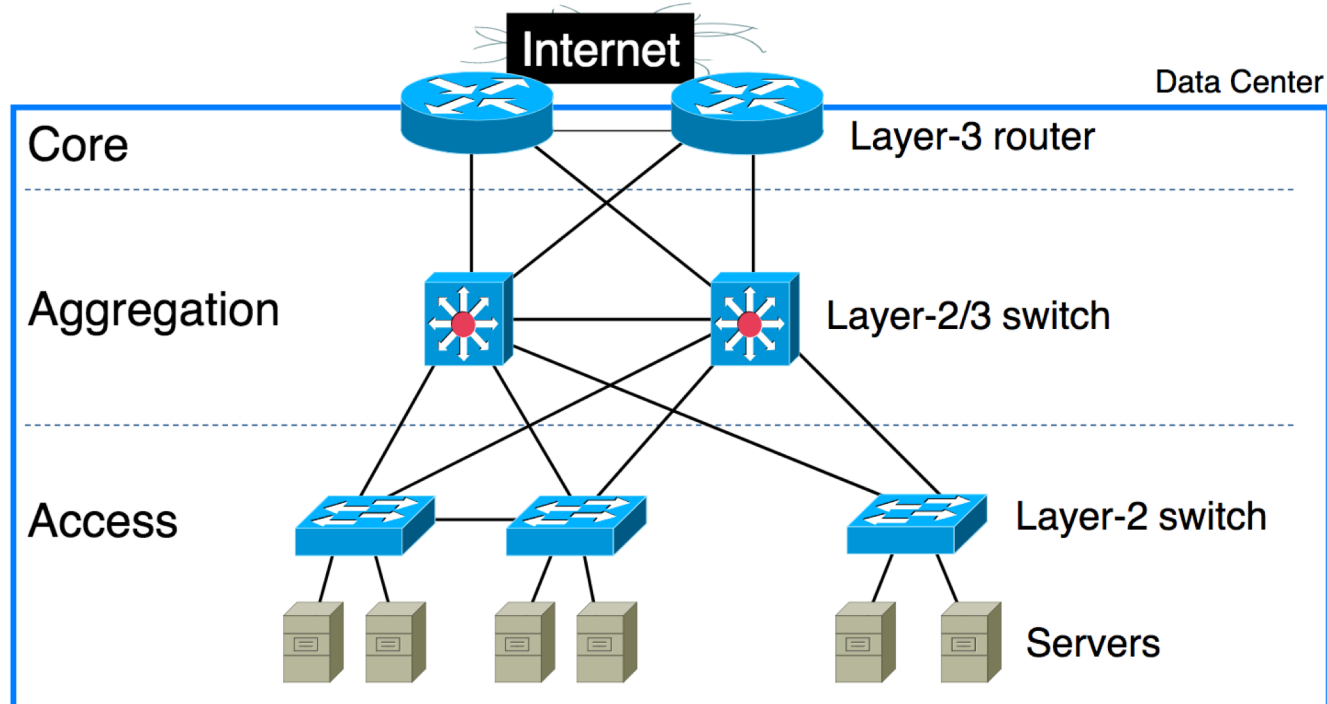


Data Center Networks

■ Requirements

- Provide connectivity between 1K–10K nodes in data center
- High bisection bandwidth
- Low cost

■ Traditional Design: Hierarchy of Ethernet Switches



Clos/Fat-Tree Networks for Data Centers

A Scalable, Commodity Data Center Network Architecture

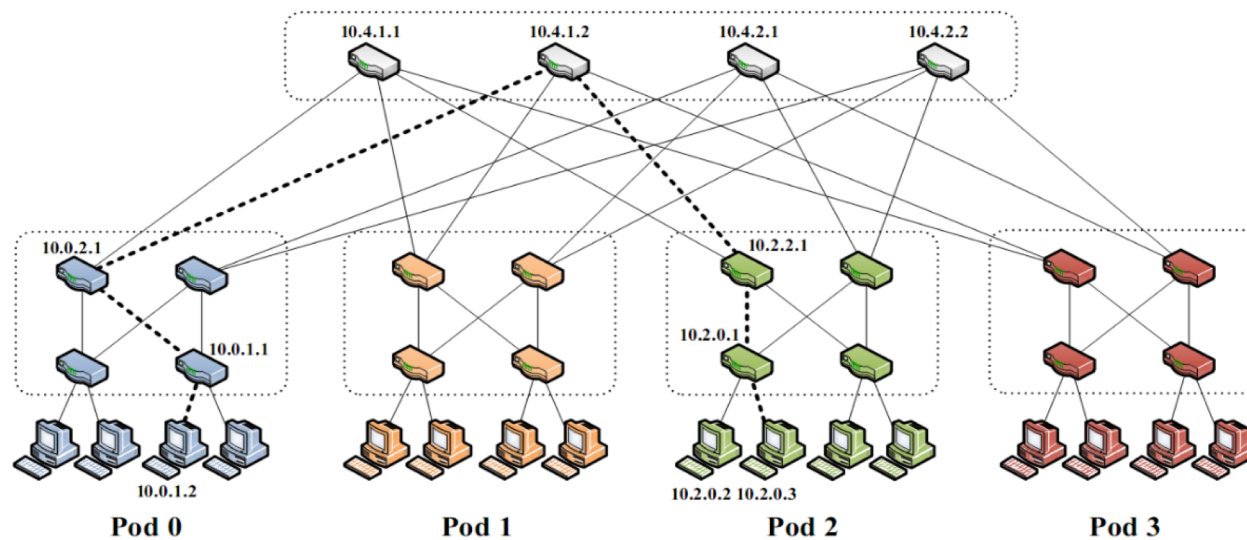
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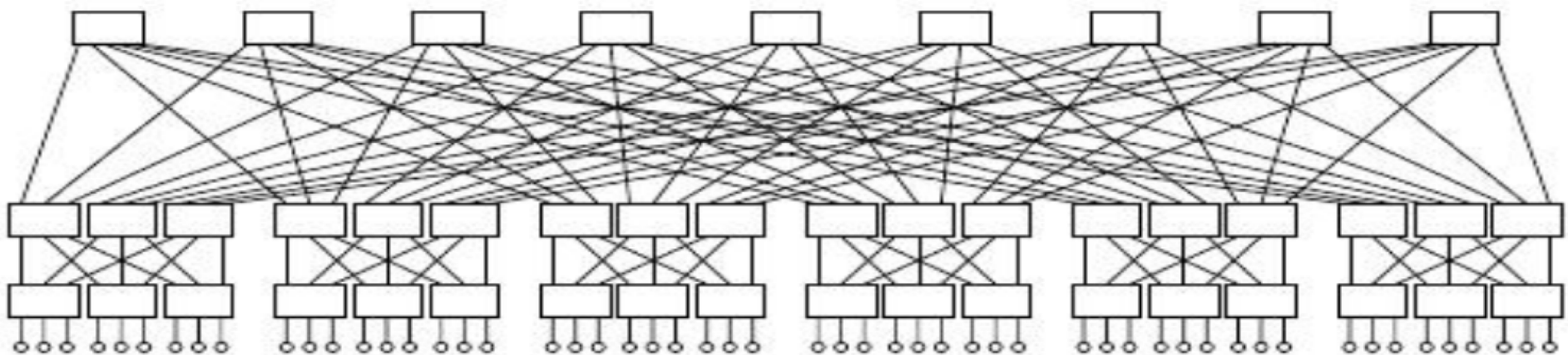
SIGCOMM'08, August 17–22, 2008, Seattle, Washington, USA.
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- Many copies of identical switches
- More tolerant of failures
- Can implement with IP-based protocols

Generalizing Clos Network

- **k-ary fat tree**
 - Basic unit is k-ported switch
 - E.g., $k = 6$:



- Connect $k^3/4$ hosts with $5k^2/4$ switches
- Bisection bandwidth = $k^3/4$

Supercomputer Networks

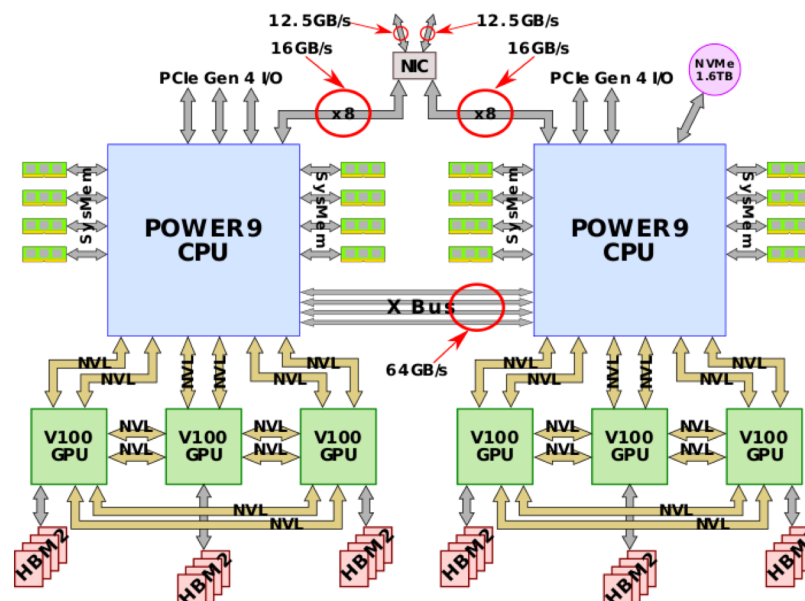
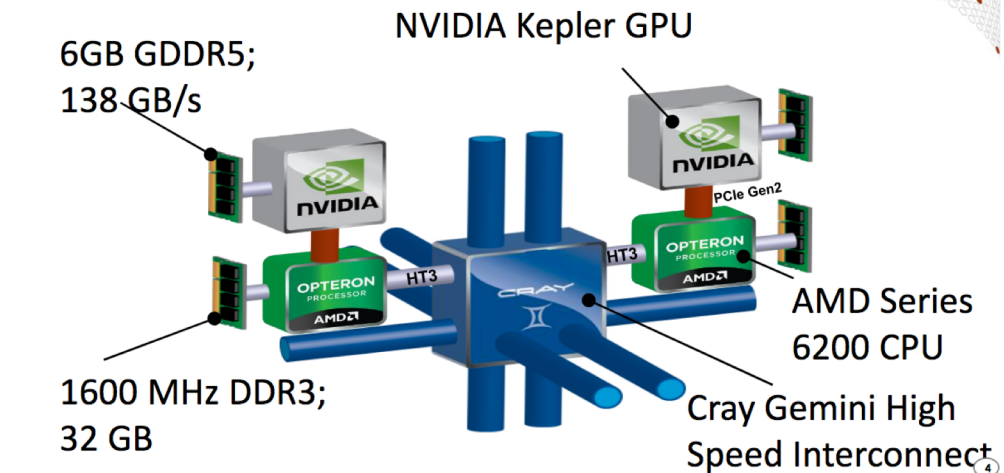
■ Oak Ridge Titan

- Fastest Computer in 2013
- 3D Torus Network
- 18,688 nodes
 - $\sim 26 \times 26 \times 28$

■ Oak Ridge Summit

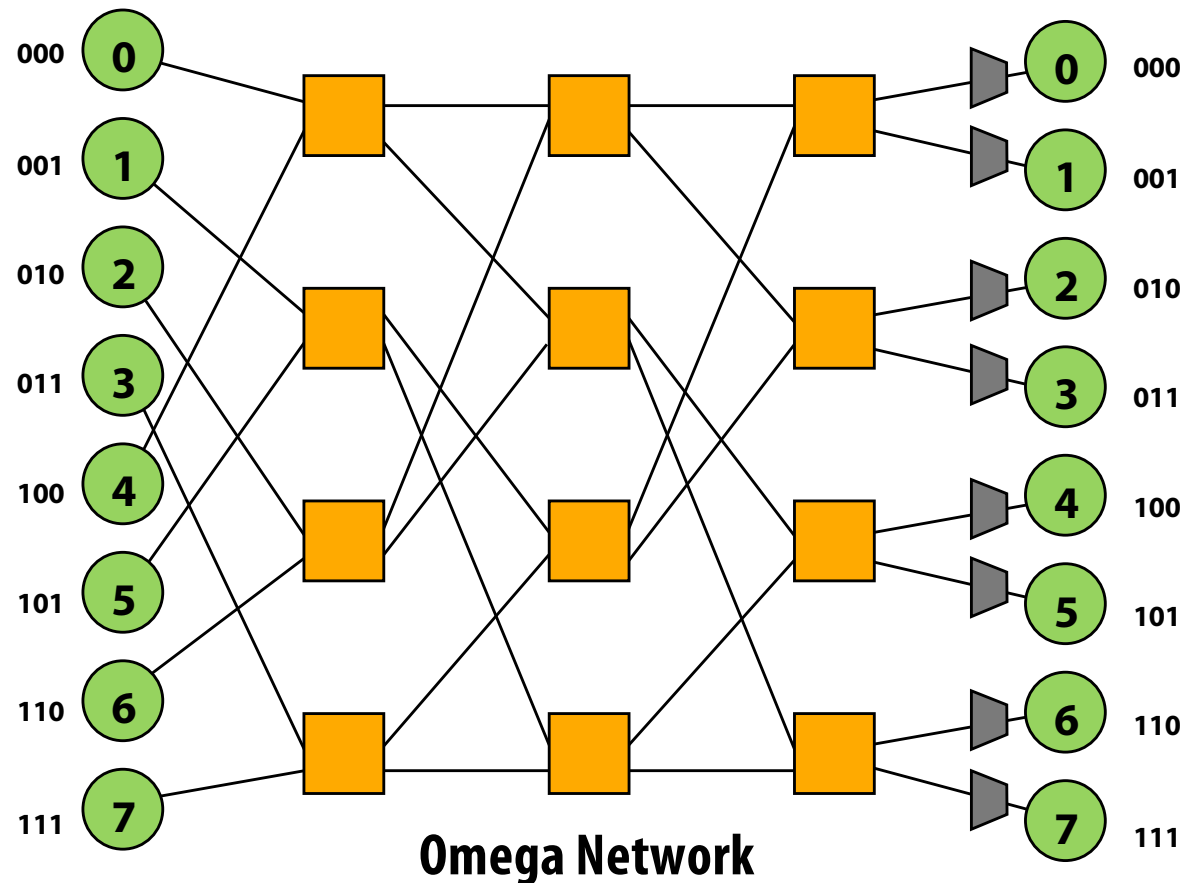
- Fastest in 2018
- 3-level fat tree
- 4,608 nodes
- $\sim k = 28$

Cray XK7 Architecture



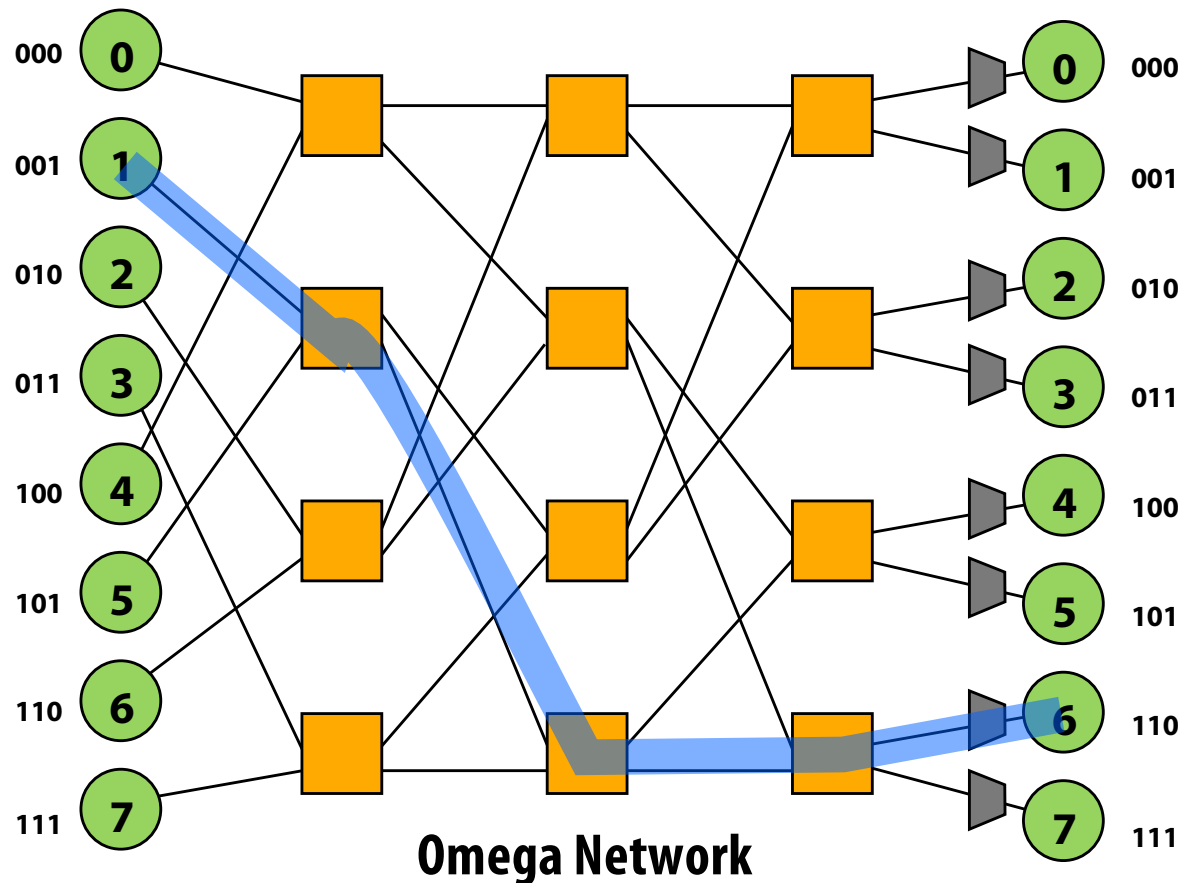
Multi-stage logarithmic

- Indirect network with multiple switches between terminals
- Cost: $O(N \lg N)$
- Latency: $O(\lg N)$
- Many variations: Omega, butterfly, etc...

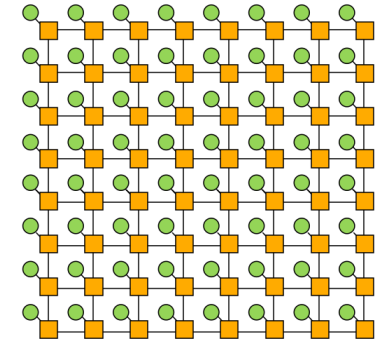
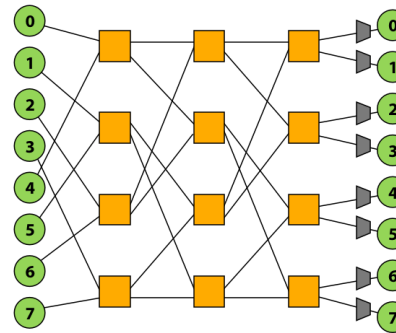
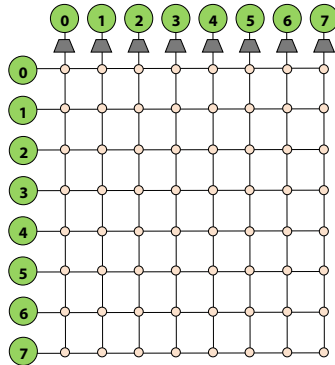


Multi-stage logarithmic Routing

- Route from 1 to 6
 - $6 = 110_2$
 - $1 \rightarrow \text{down}, 0 \rightarrow \text{up}$



Review: network topologies



Topology

Crossbar

Multi-stage log.

Mesh

Direct/Indirect

Indirect

Indirect

Direct

**Blocking/
Non-blocking**

Non-blocking

Blocking
(one discussed in class is, others
are not)

Blocking

Cost

$O(N^2)$

$O(N \lg N)$

$O(N)$

Latency

$O(1)$

$O(\lg N)$

$O(\sqrt{N})$
(average)

Buffering and flow control

Circuit switching vs. packet switching

■ Circuit switching sets up a full path (acquires all resources) between sender and receiver prior to sending a message

- Establish route (reserve links) then send all data for message
- Higher bandwidth transmission (no per-packet link mgmt overhead)
- Does incur overhead to set up/tear down path
- Reserving links can result in low utilization



■ Packet switching makes routing decisions per packet

- Route each packet individually (possibly over different network links)
- Opportunity to use link for a packet whenever link is idle
- Overhead due to dynamic switching logic during transmission
- No setup/tear down overhead



Granularity of communication

■ Message

- Unit of transfer between network clients (e.g., cores, memory)
- Can be transmitted using many packets

■ Packet

- Unit of transfer for network
- Can be transmitted using multiple flits (will discuss later)

■ Flit (flow control unit)

- Packets broken into smaller units called “flits”
- Flit: (“flow control unit”) a unit of flow control in the network
- Flits become minimum granularity of routing/buffering

Packet format

- A packet consists of:

- **Header:**

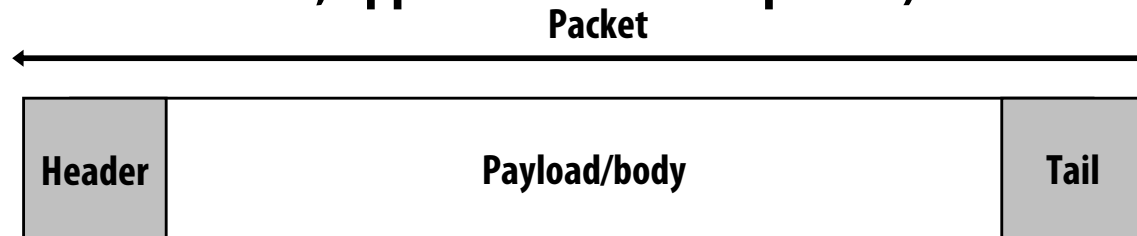
- Contains routing and control information
 - At start of packet to router can start forwarding early

- **Payload/body: containing the data to be sent**

- **Tail**

- Contains control information, e.g., checksum code for error detection
 - Generally located at end of packet so it can be generated “on the way out”

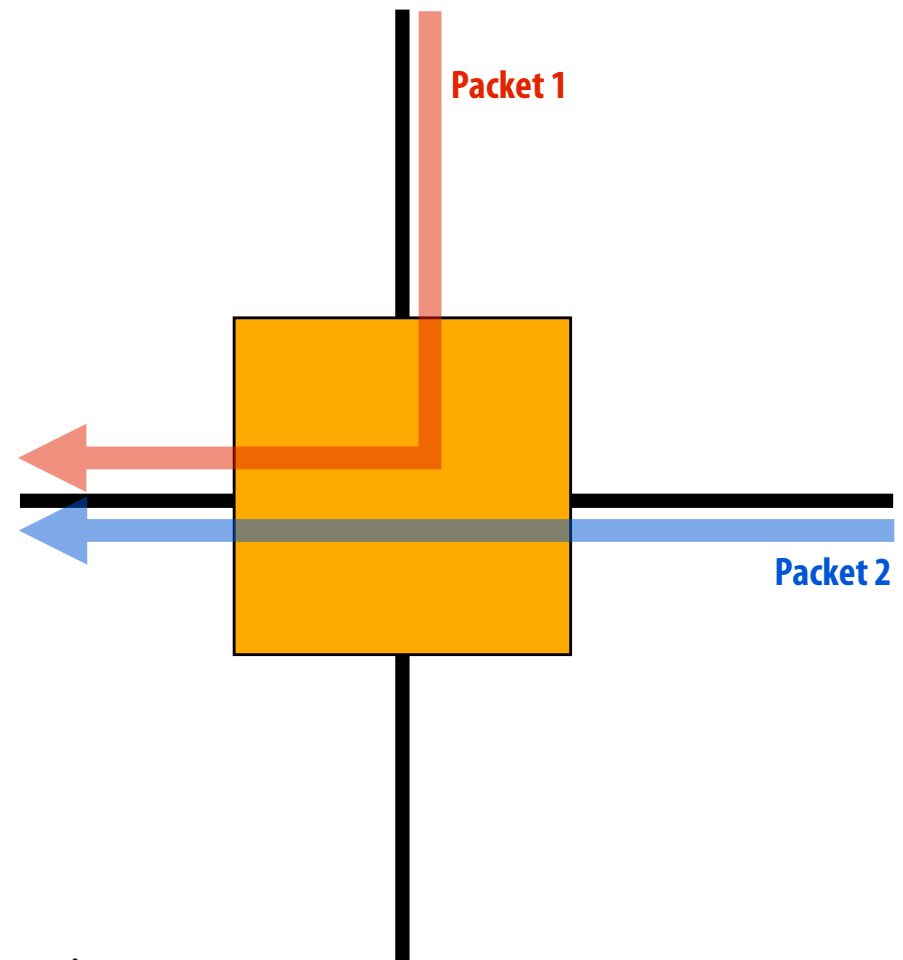
(sender computes checksum, appends it to end of packet)



Handling contention

Scenario: two packets need to be routed onto the same outbound link at the same time

- **Options:**
 - **Buffer one packet, send it over link later**
 - **Drop one packet**
 - **Reroute one packet (deflection)**
- **In this lecture: we only consider buffering ***

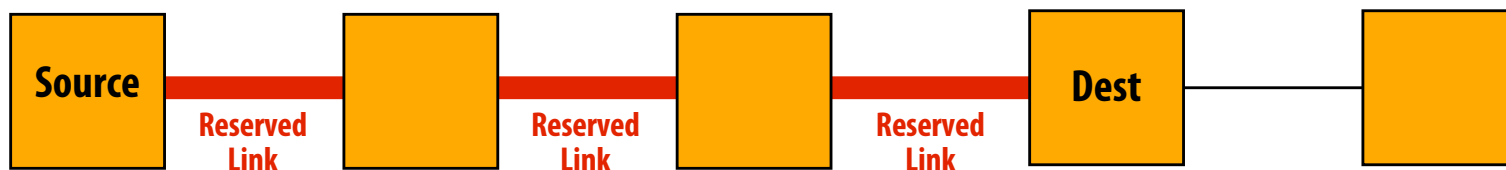


* But recent research has looked at using bufferless networks with deflection routing as a power-efficient interconnect for chip multiprocessors.

Circuit-switched routing

■ High-granularity resource allocation

- Main idea: pre-allocate all resources (links across multiple switches) along entire network path for a message (“setup a flow”)



■ Costs

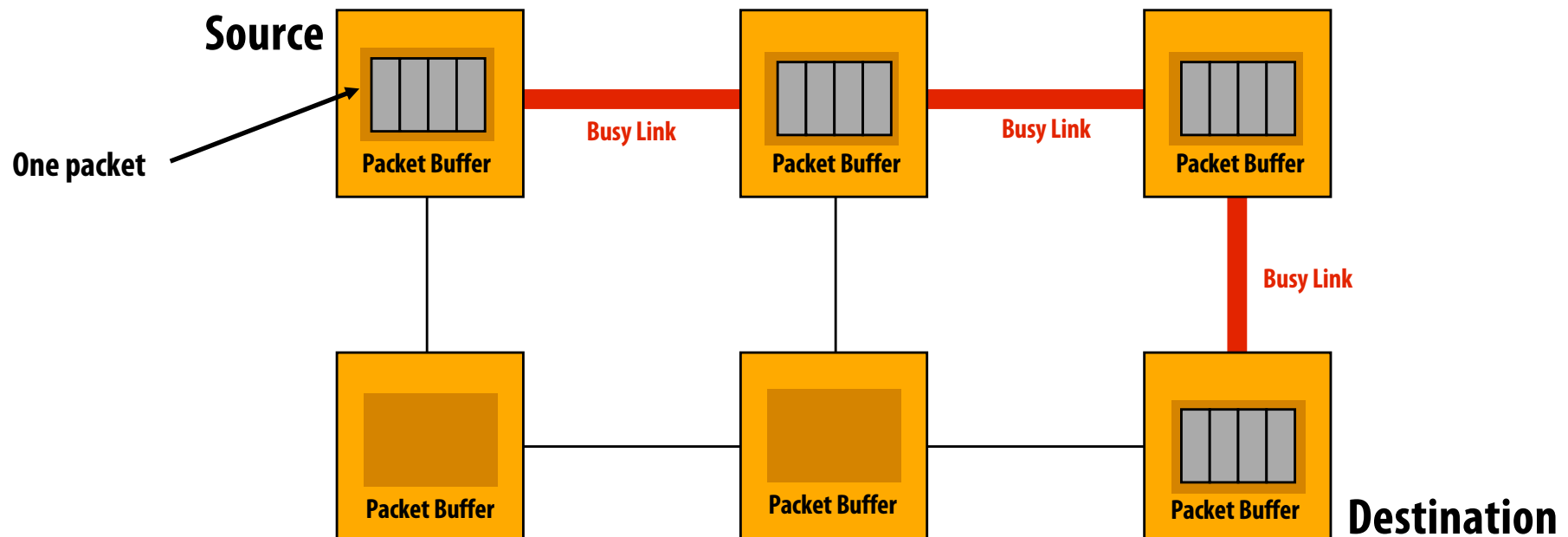
- Needs setup phase (“probe”) to set up the path (and to tear it down and release the resources when message complete)
- Lower link utilization. Transmission of two messages cannot share same link (even if some resources on a preallocated path are no longer utilized during a transmission)

■ Benefits

- No contention during transmission due to preallocation, so no need for buffering
- Arbitrary message sizes (once path is set up, send data until done)

Store-and-forward (packet-based routing)

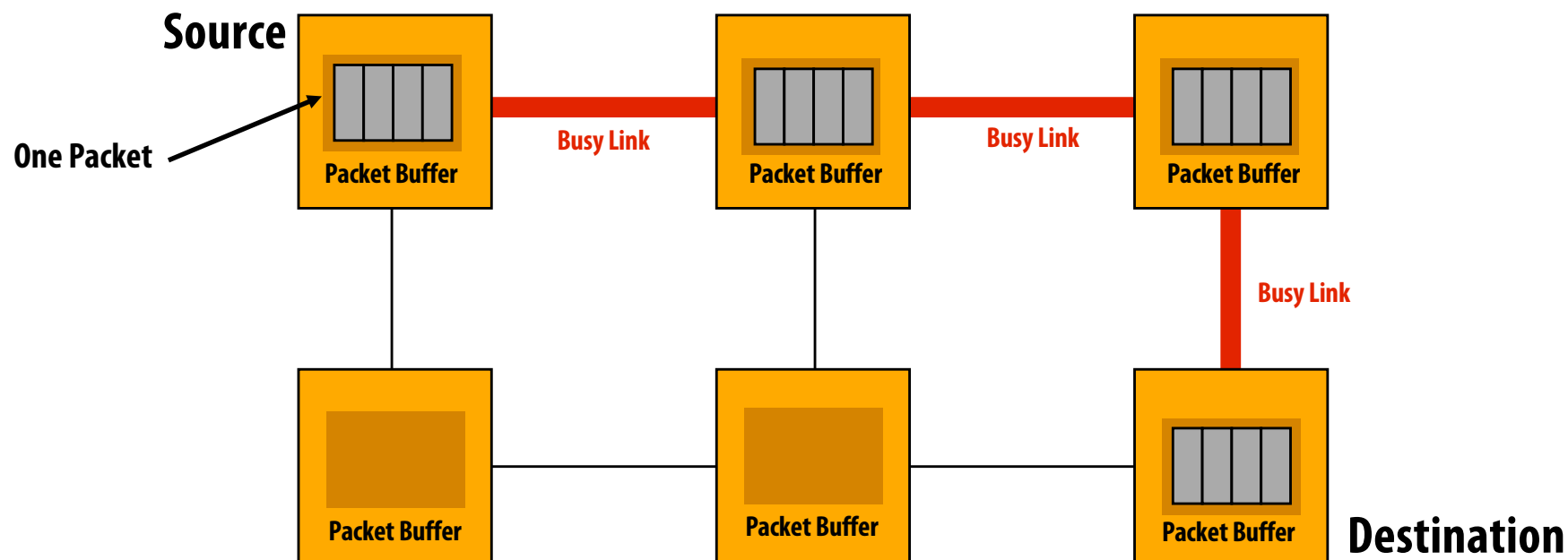
- Packet copied entirely into network switch before moving to next node
- Flow control unit is an entire packet
 - Different packets from the same message can take different routes, but all data in a packet is transmitted over the same route
- Requires buffering for entire packet in each router
- High per-packet latency (latency = packet transmission time on link x network distance)



Note to students: in lecture this slide was animated and the final build shown here is not illustrative of store-and-forward routing concept (please refer to lecture video)

Cut-through flow control (also packet-based)

- Switch starts forwarding data on next link as soon as packet header is received (header determines how much link bandwidth packet requires + where to route)
- Result: reduced transmission latency
 - Cut-through routing reduces to store-and-forward under high contention. Why?



Store and forward solution from previous slide: 3 hops x 4 units of time to transmit packet over a single link = 12 units of time

Cut-through solution: 3 steps of latency for head of packet to get to destination + 3 units of time for rest of packet = 6 units of time

Note to students: in lecture this slide was animated and the final build shown here is not illustrative of the cut-through routing concept (please refer to lecture video or Powerpoint version)

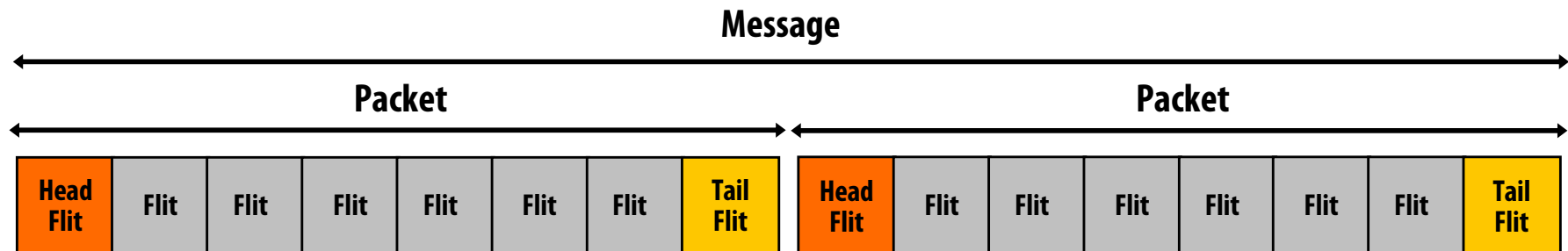
Cut-through flow control

- **If output link is blocked (cannot transmit head), transmission of tail can continue**
 - **Worst case: entire message is absorbed into a buffer in a switch (cut-through flow control degenerates to store-and-forward in this case)**
 - **Requires switches to have buffering for entire packet, just like store-and-forward**

Wormhole flow control

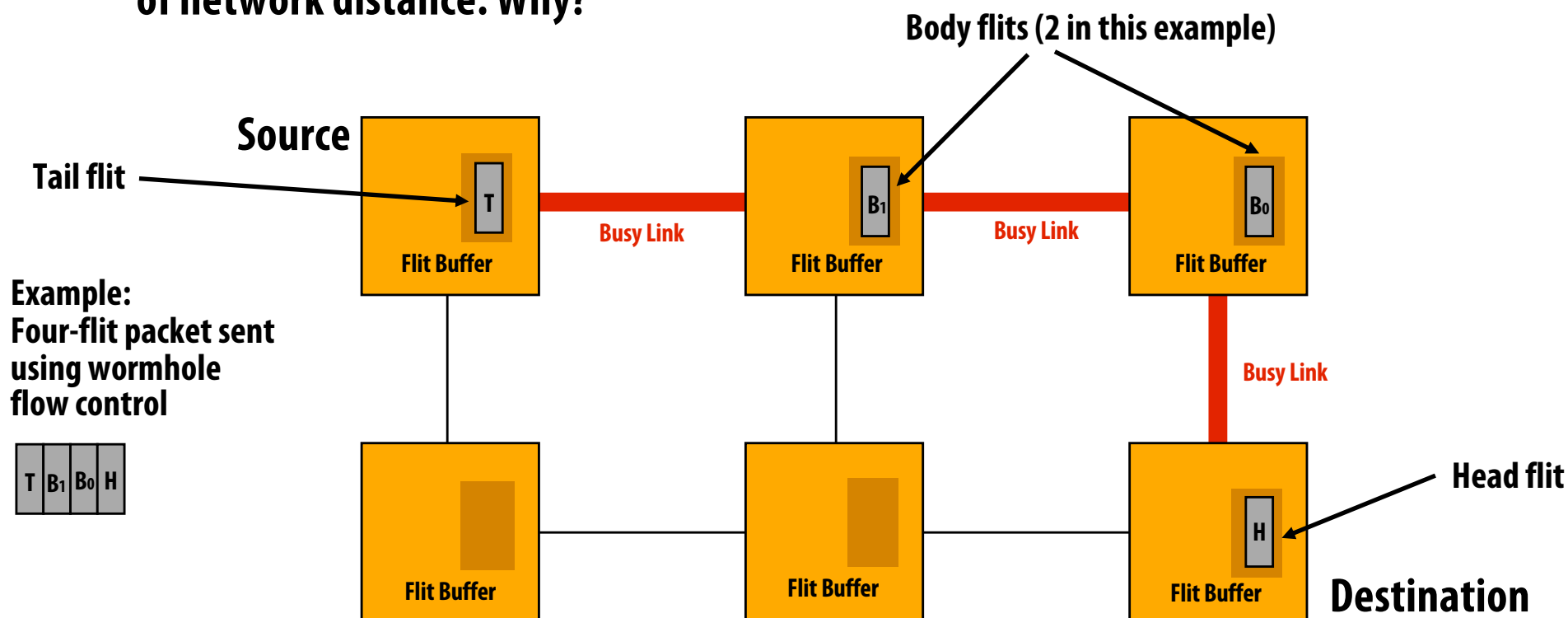
■ Flit (flow control unit)

- Packets broken into smaller units called “flits”
- Flit: (“flow control unit”) a unit of flow control in the network
- Flits become minimum granularity of routing/buffering
 - Recall: up until now, packets were the granularity of transfer AND flow control and buffering (store-and-forward, cut-through routing)

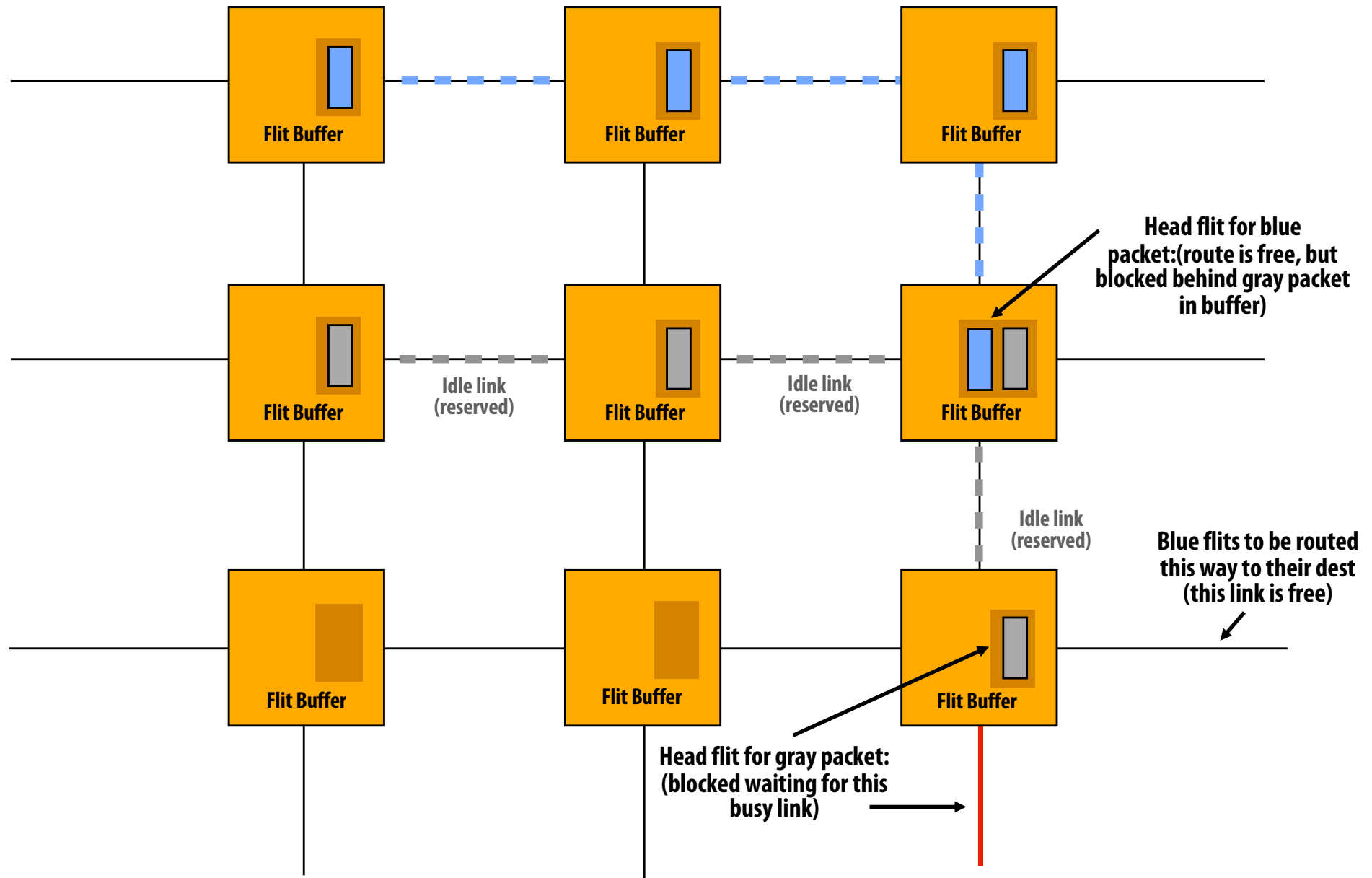


Wormhole flow control

- Routing information only in head flit
- Body flits follows head, tail flit flows body
- If head flit blocks, rest of packet stops
- Completely pipelined transmission
 - For long messages, latency is almost entirely independent of network distance. Why?

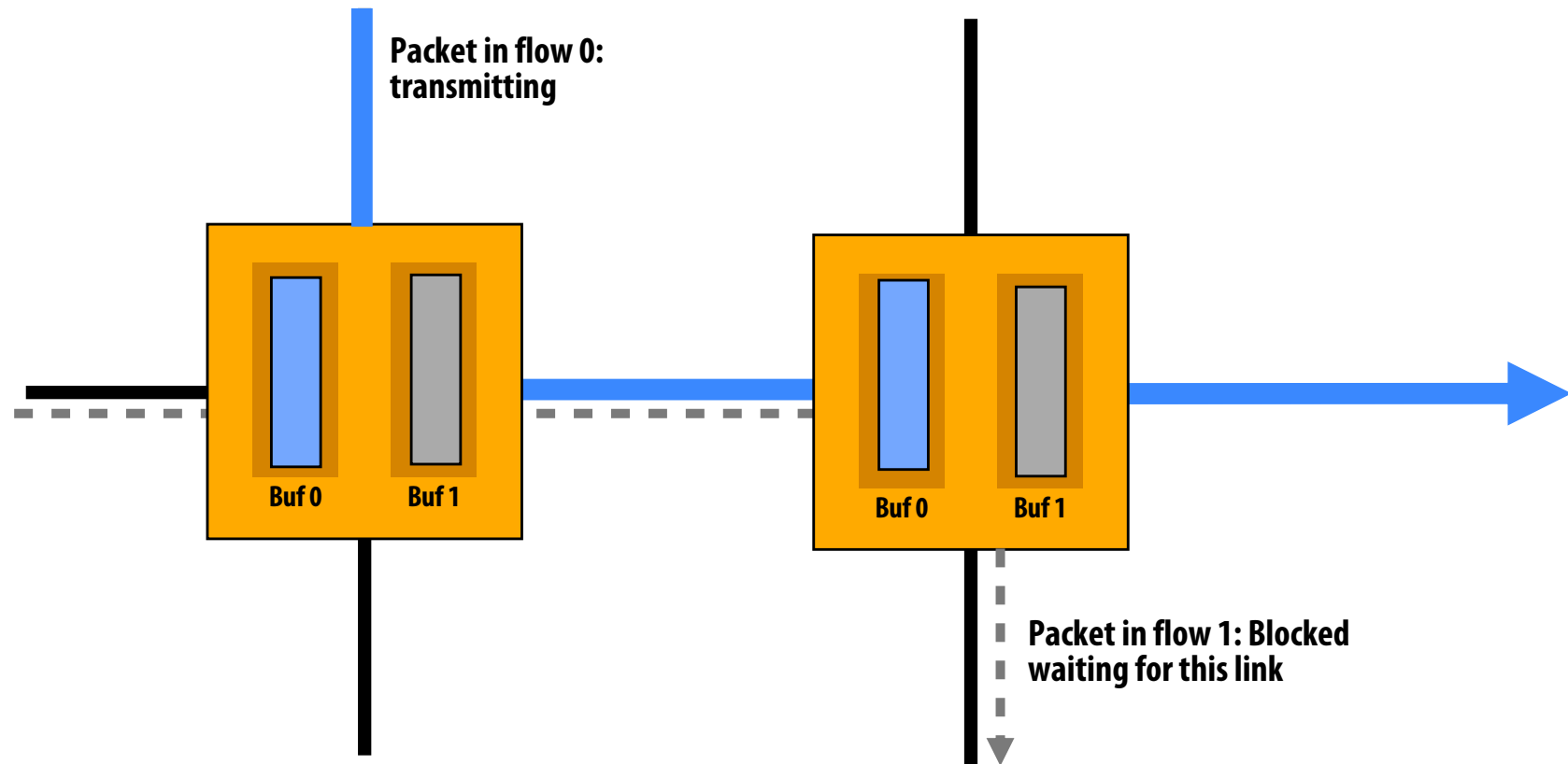


Problem: head-of-line blocking



Virtual channel flow control

- Multiplex multiple operations over single physical channel
- Divide switch's input buffer into multiple buffers sharing a single physical channel
- Reduces head-of-line blocking



Other uses of virtual channels

■ Deadlock avoidance

- Can be used to break cyclic dependency of resources
- Prevent cycles by ensuring requests and responses use different virtual channels
- “Escape” VCs: retain at least one virtual channel that uses deadlock-free routing

■ Prioritization of traffic classes

- Provide quality-of-service guarantees
- Some virtual channels have higher priority than others

Current research topics

- **Energy efficiency of interconnections**
 - **Interconnect can be energy intensive (~35% of total chip power in MIT RAW research processor)**
 - **Bufferless networks**
 - **Other techniques: turn on/off regions of network, use fast and slow networks**
- **Prioritization and quality-of-service guarantees**
 - **Prioritize packets to improve multi-processor performance (e.g., some applications may be more sensitive to network performance than others)**
 - **Throttle endpoints (e.g., cores) based on network feedback**
- **New/emerging technologies**
 - **Die stacking (3D chips)**
 - **Photonic networks-on-chip (use optical waveguides instead of wires)**
 - **Reconfigurable devices (FPGAs): create custom interconnects tailored to application (see CMU projects: CONNECT, CoRAM, Shrinkwrap)**

Summary

- **The performance of the interconnection network in a modern multi-processor is critical to overall system performance**
 - **Buses do not scale to many nodes**
 - **Historically interconnect was off-chip network connecting sockets, boards, racks**
 - **Today, all these issues apply to the design of on-chip networks**
- **Network topologies differ in performance, cost, complexity tradeoffs**
 - **e.g., crossbar, ring, mesh, torus, multi-stage network, fat tree, hypercube**
- **Challenge: efficiently routing data through network**
 - **Interconnect is a precious resource (communication is expensive!)**
 - **Flit-based flow control: fine-grained flow control to make good use of available link bandwidth**
 - **If interested, much more to learn about (not discussed in this class): ensuring quality-of-service, prioritization, reliability, deadlock, livelock, etc.**