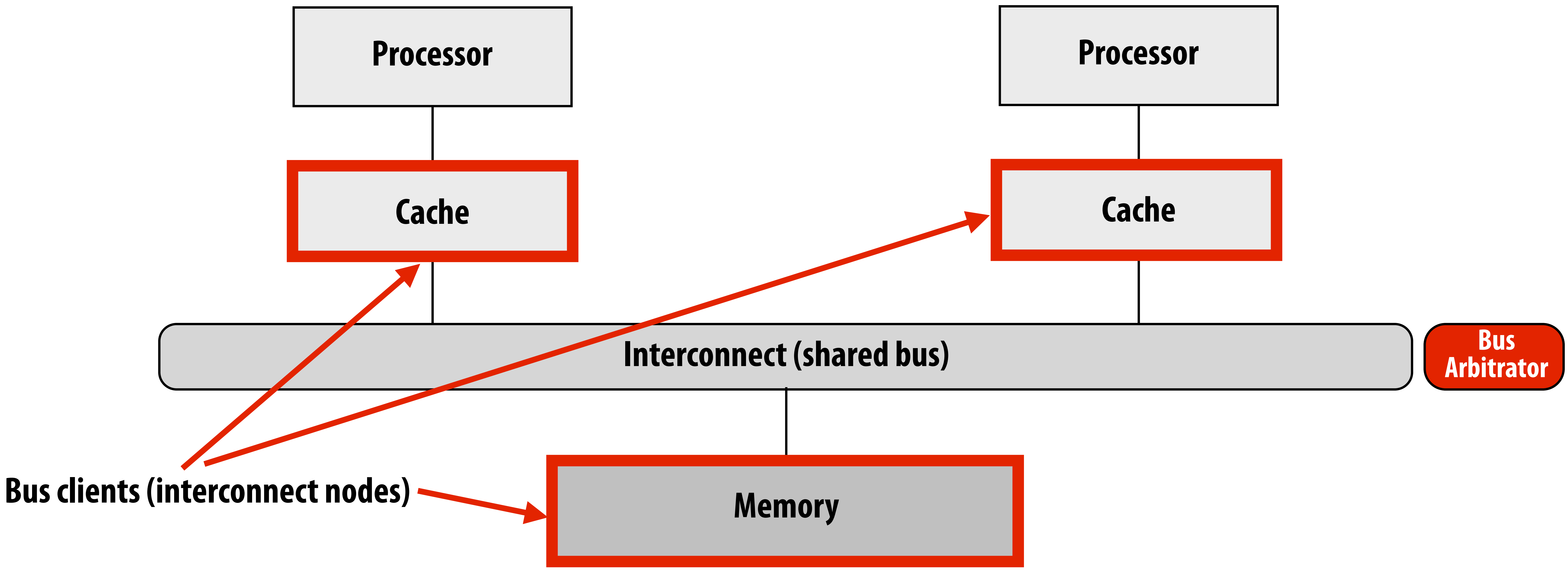
Lecture 14:

Interconnection Networks

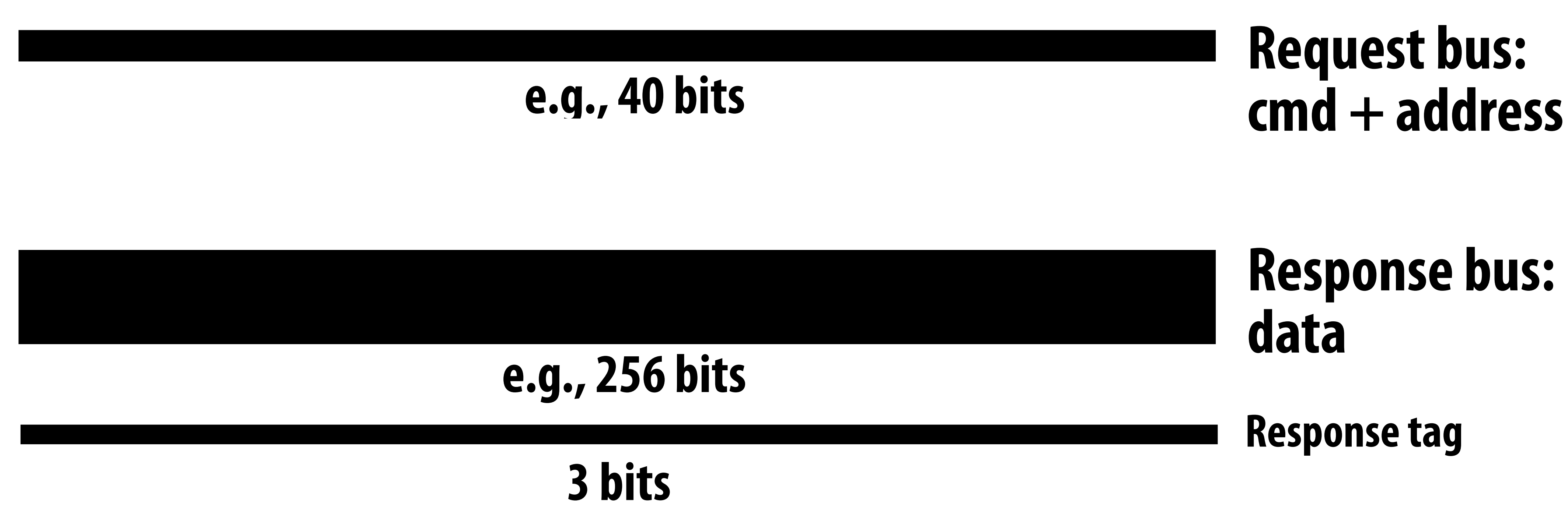
Parallel Computer Architecture and Programming
CMU 15-418/15-618, Spring 2023

Basic system design from previous lectures

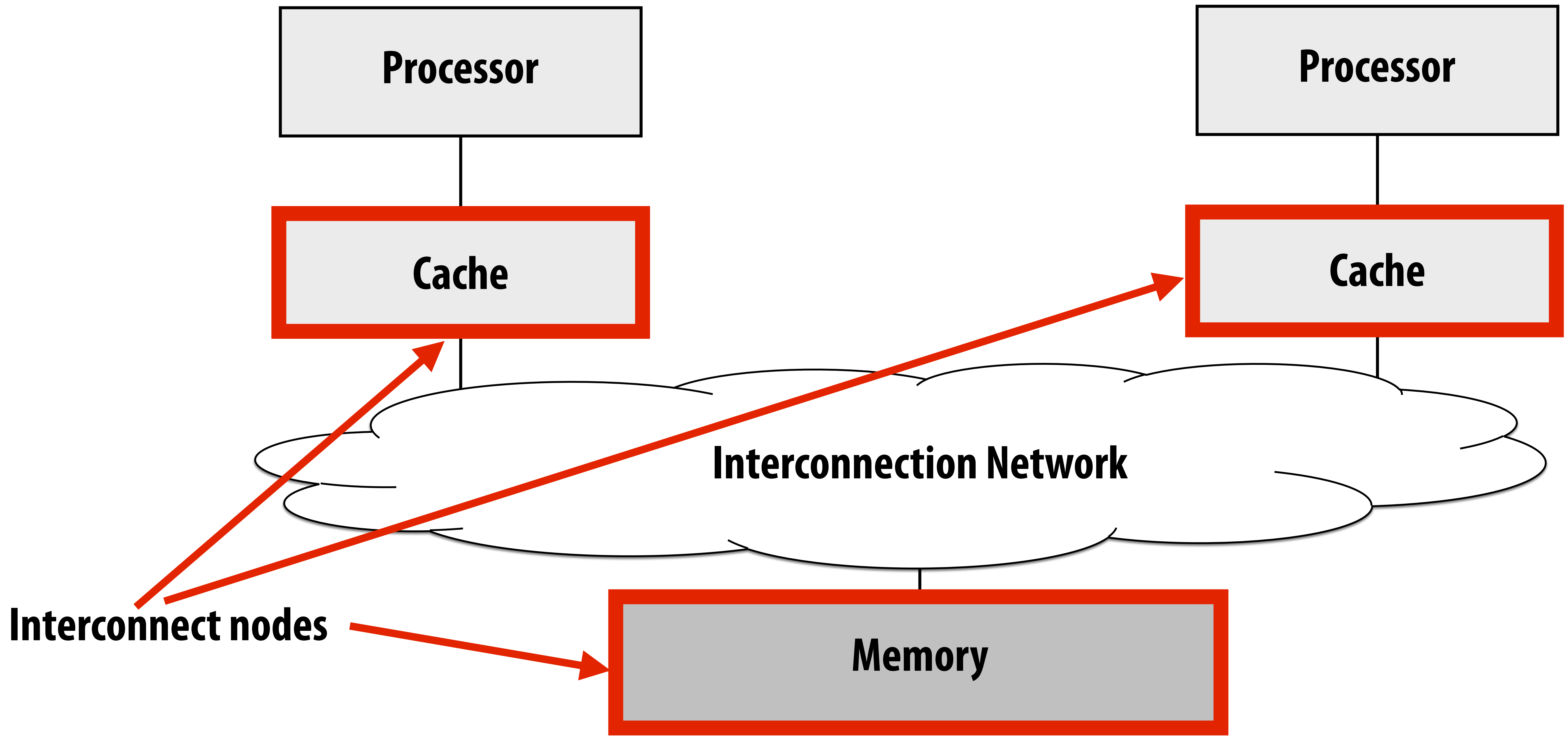


Bus interconnect:

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

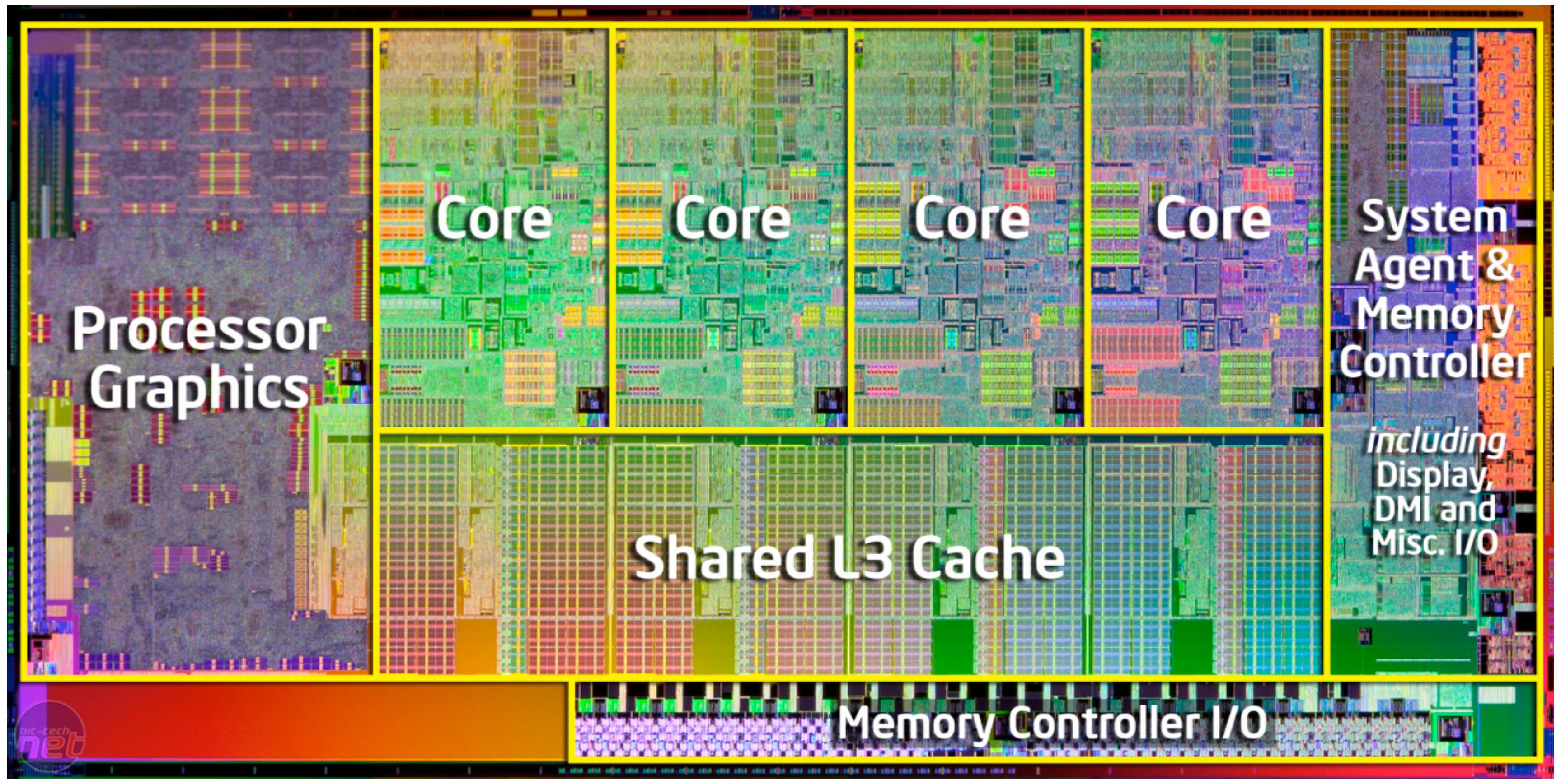
Why is the design of the interconnection network important?

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

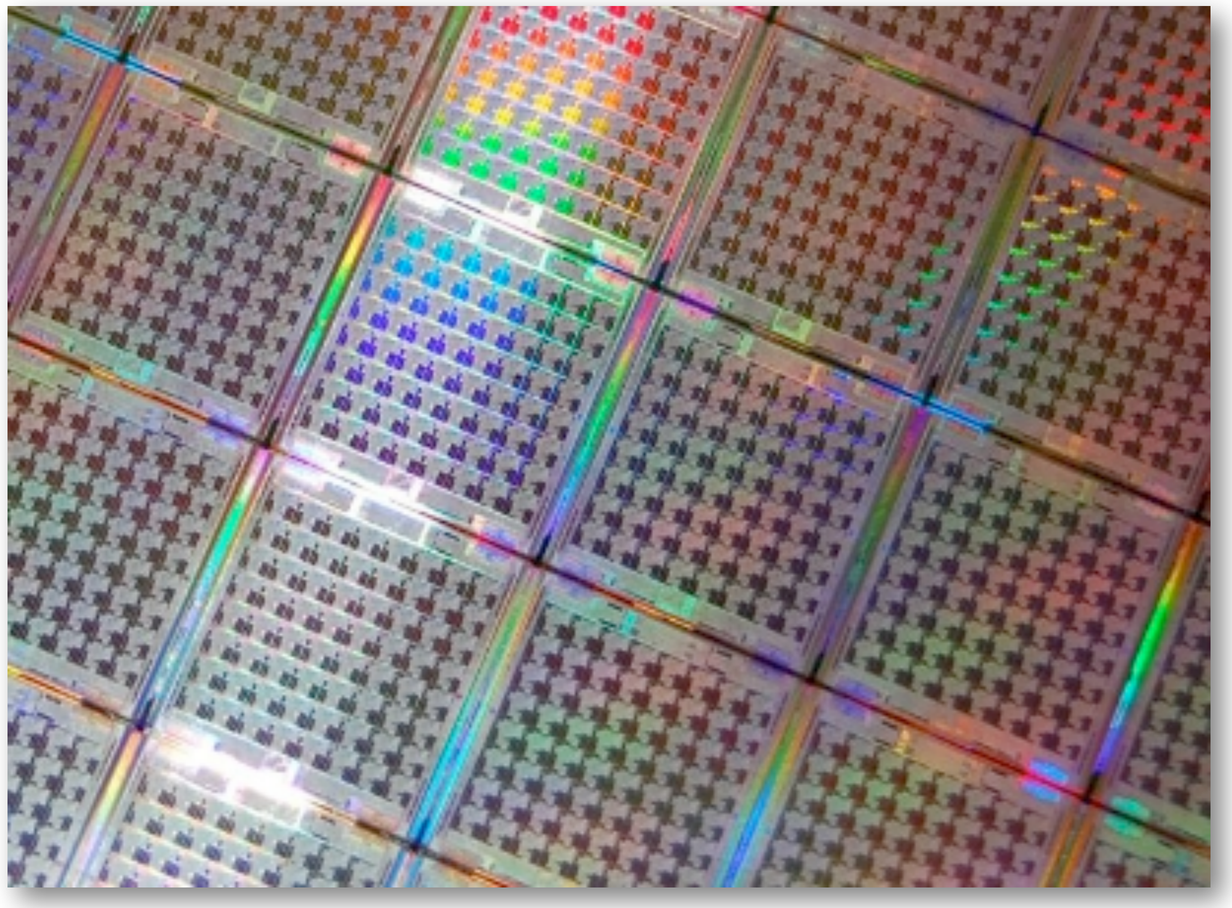
- **System performance and energy efficiency**
  - How fast can cores, caches, memory communicate
  - How long is latency to memory?
  - How much energy is spent on communication?

With increasing core counts…

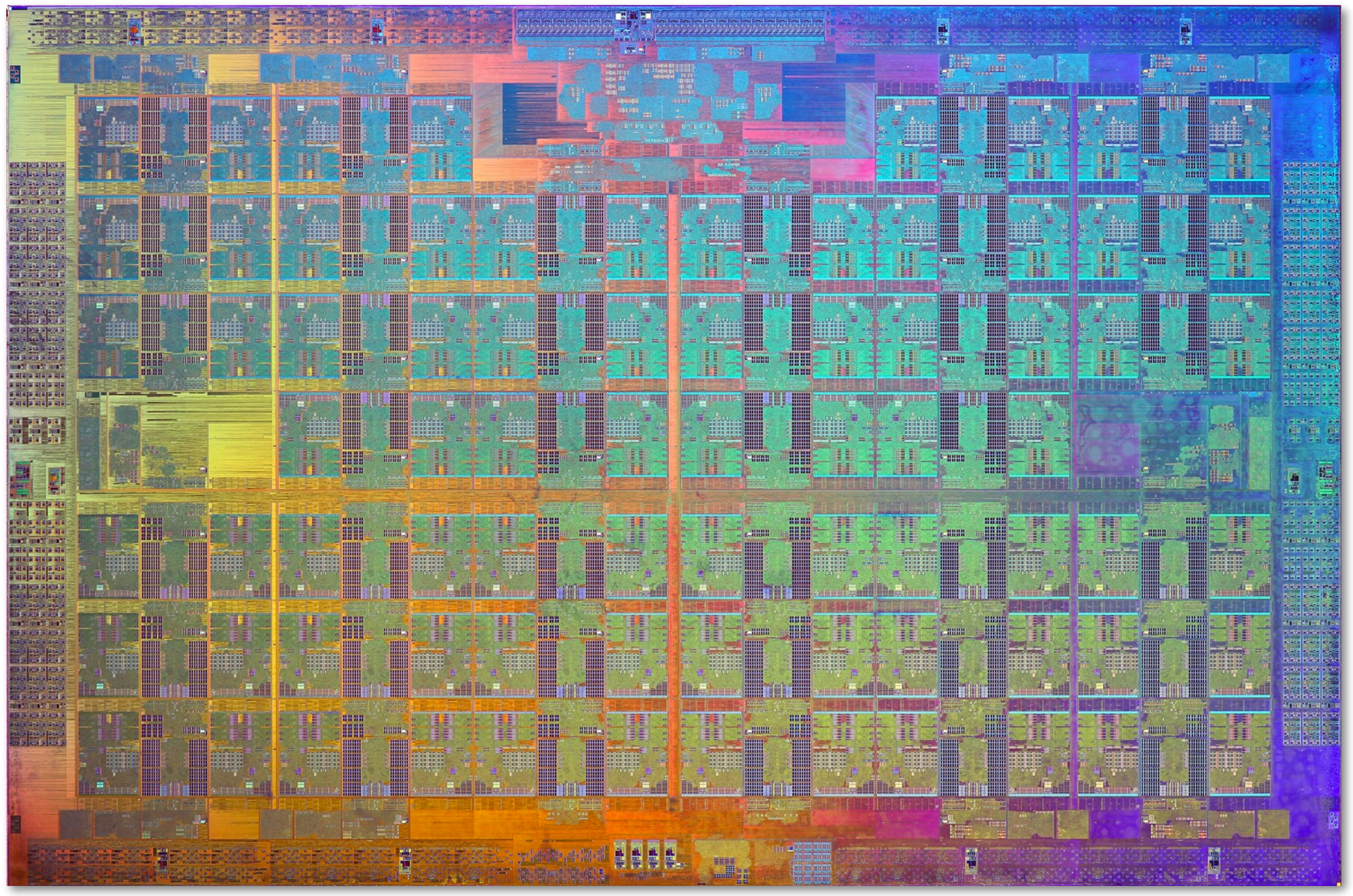
Scalability of on-chip interconnection network becomes increasingly important



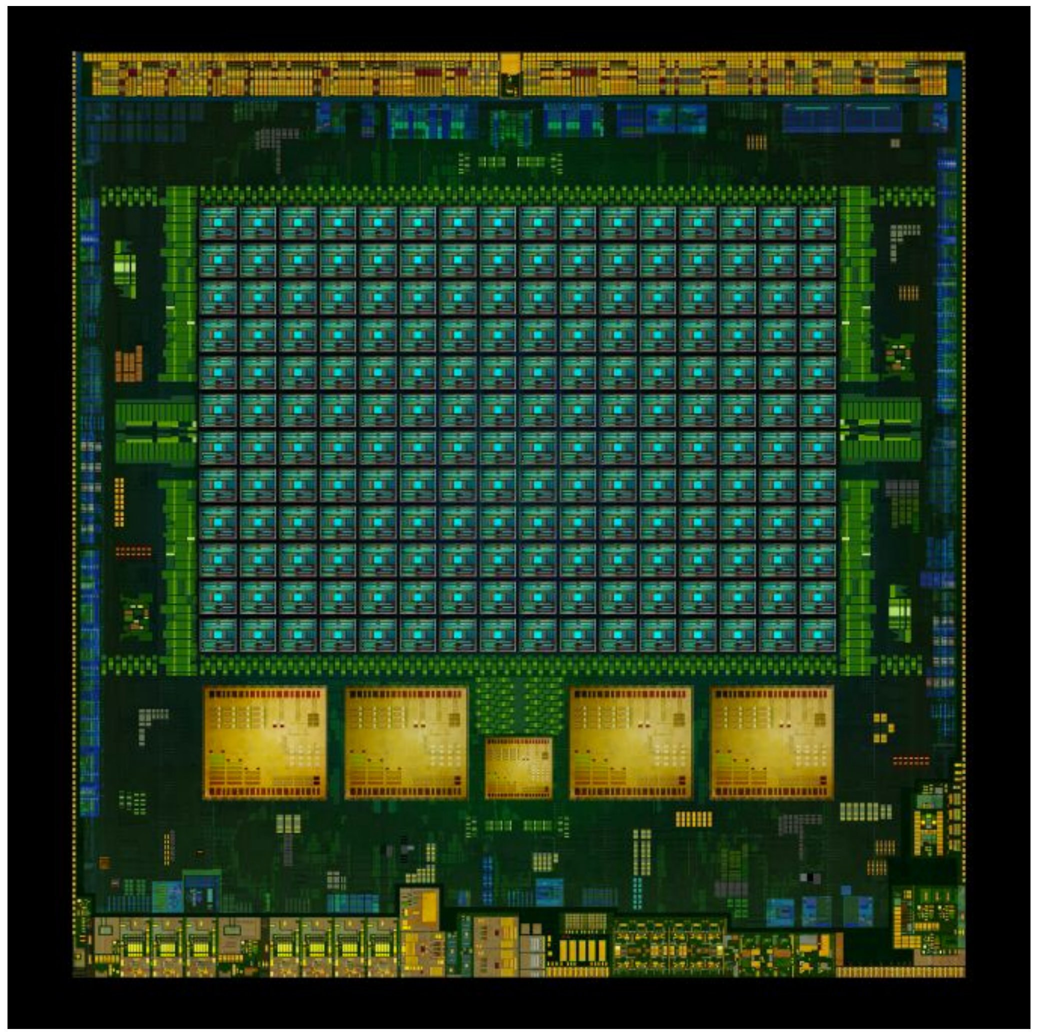
Intel core i7 (4-CPU cores, + GPU)



Tilera GX 64-core chip



Intel Xeon Phi (72-core x86)

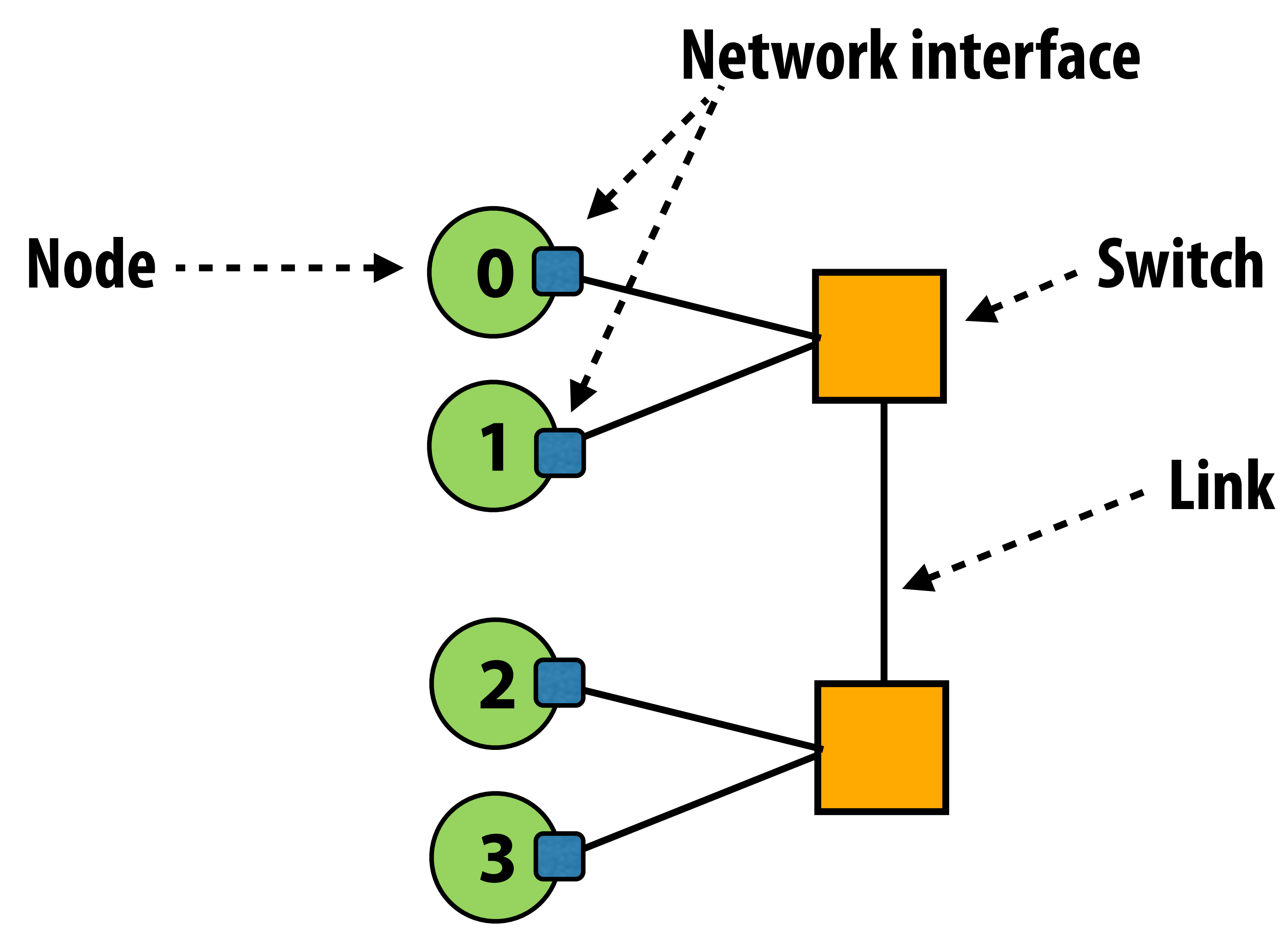


Tegra K1: 4 + 1 ARM cores + GPU cores

Interconnect terminology

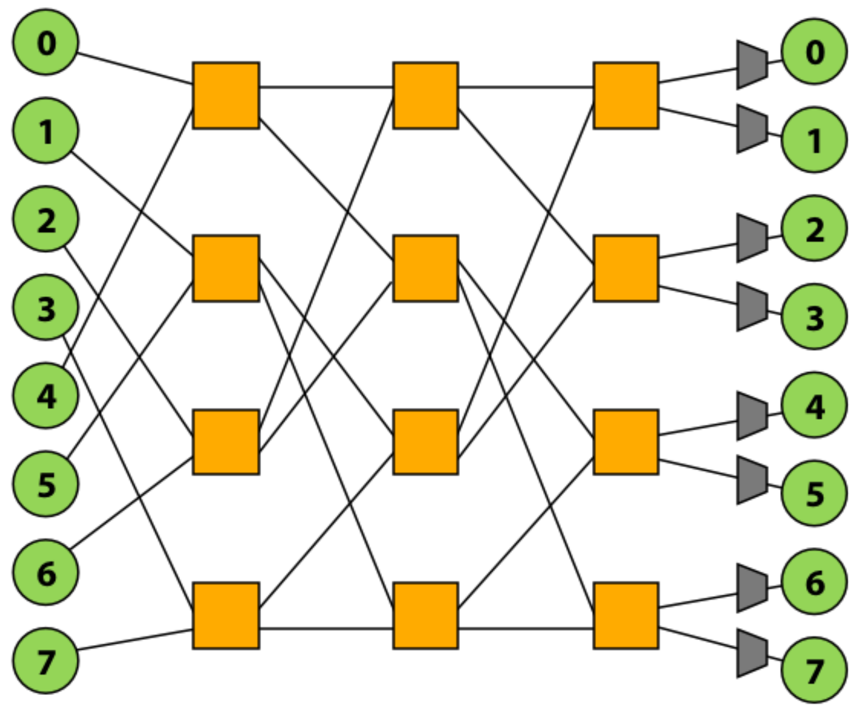
Terminology

- **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



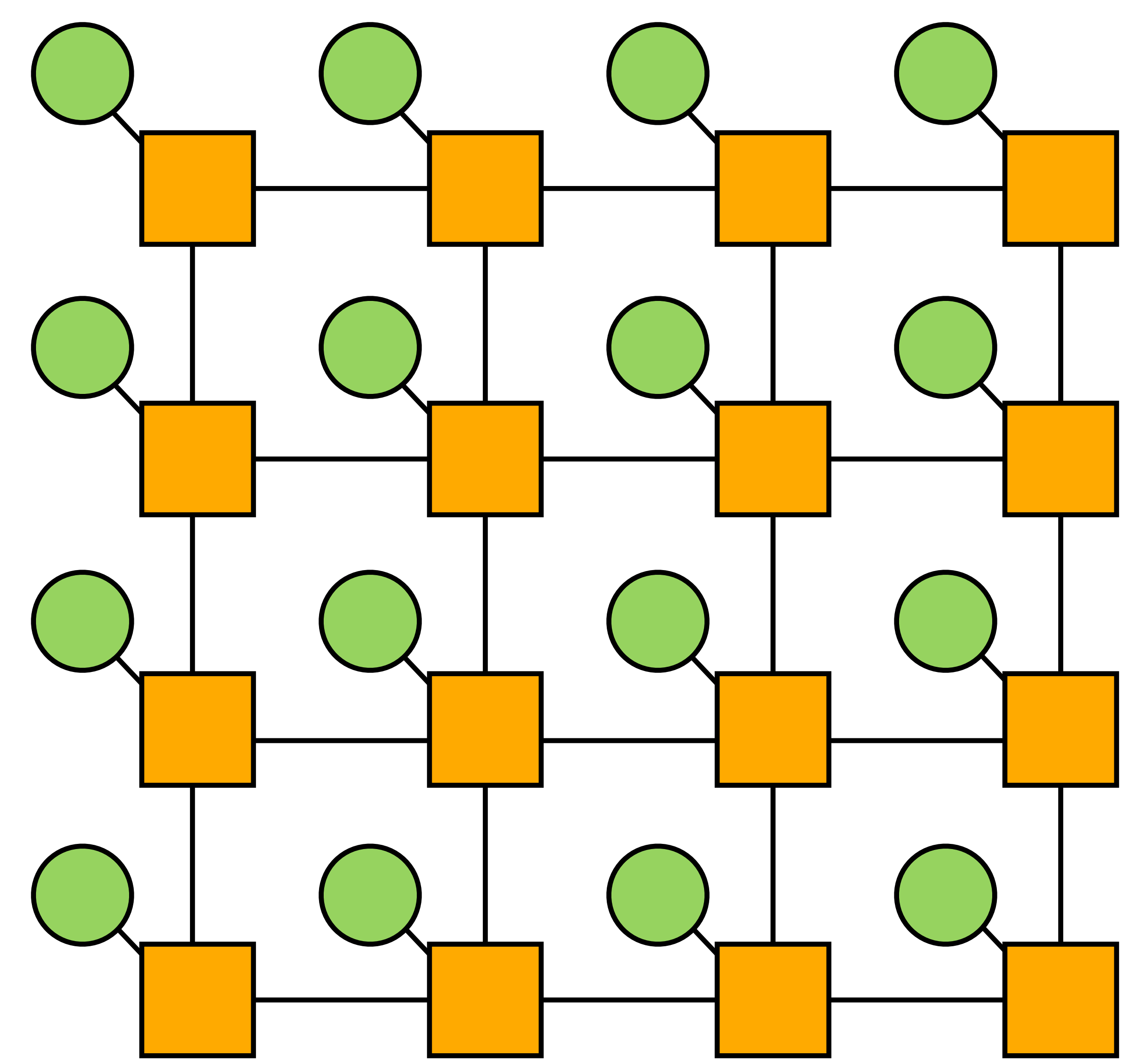
- **Routing: how a message gets from its source to its destination in the network**
  - Can be static (messages take a predetermined path) or adaptive based on load

- **Buffering and flow control**
  - What data is stored in the network? packets, partial packets? etc.
  - How does the network manage buffer space?

Properties of interconnect topology

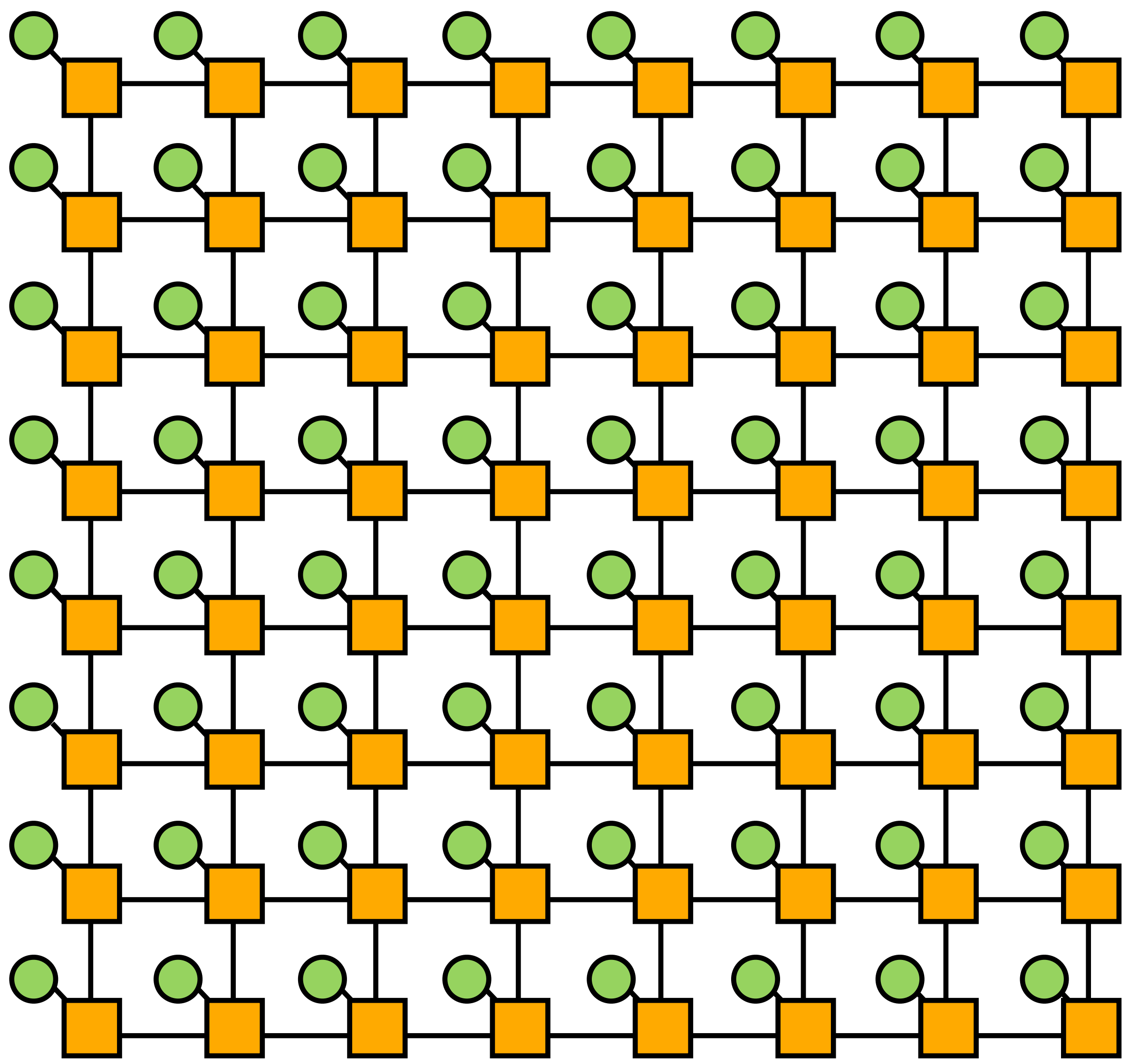
- **Routing distance**
  - Number of links ("hops") along a route between two nodes
- **Diameter: the maximum routing distance**
- **Average distance: average routing distance over all valid routes**

Example:
diameter = 6

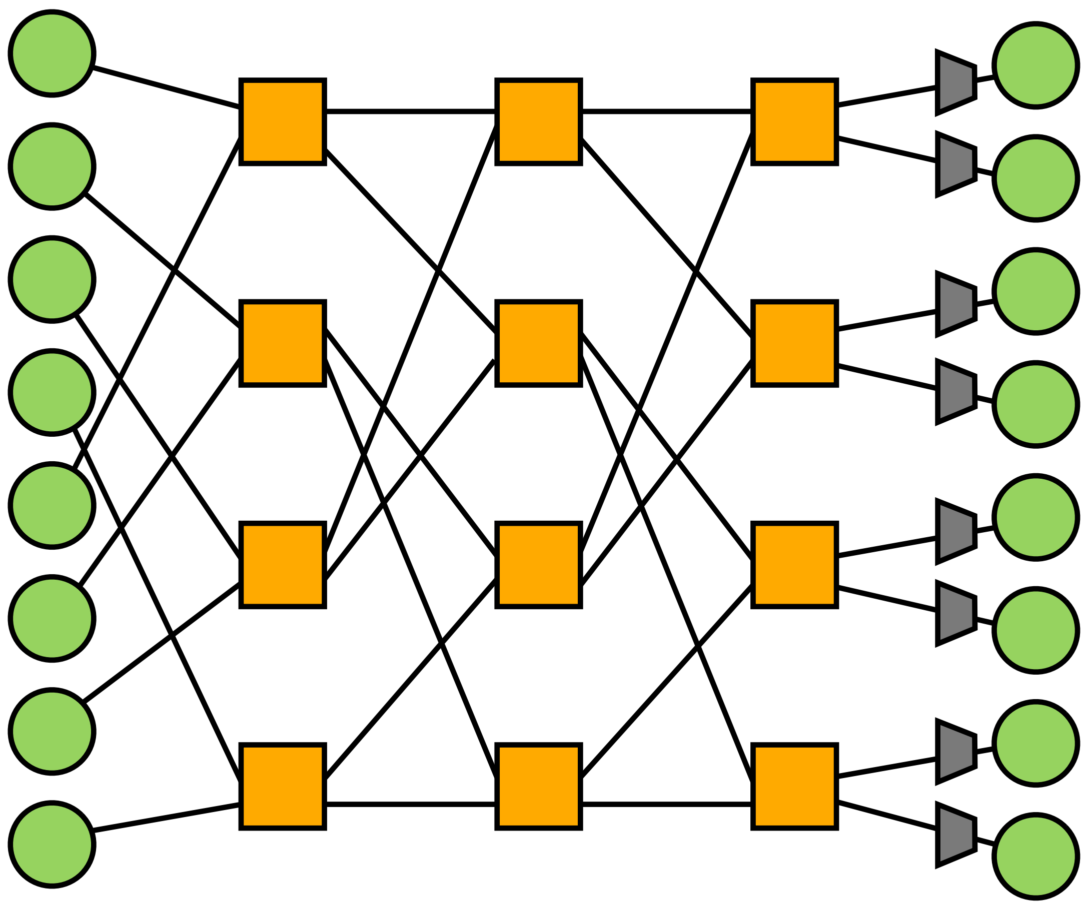


Properties of interconnect topology

- **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

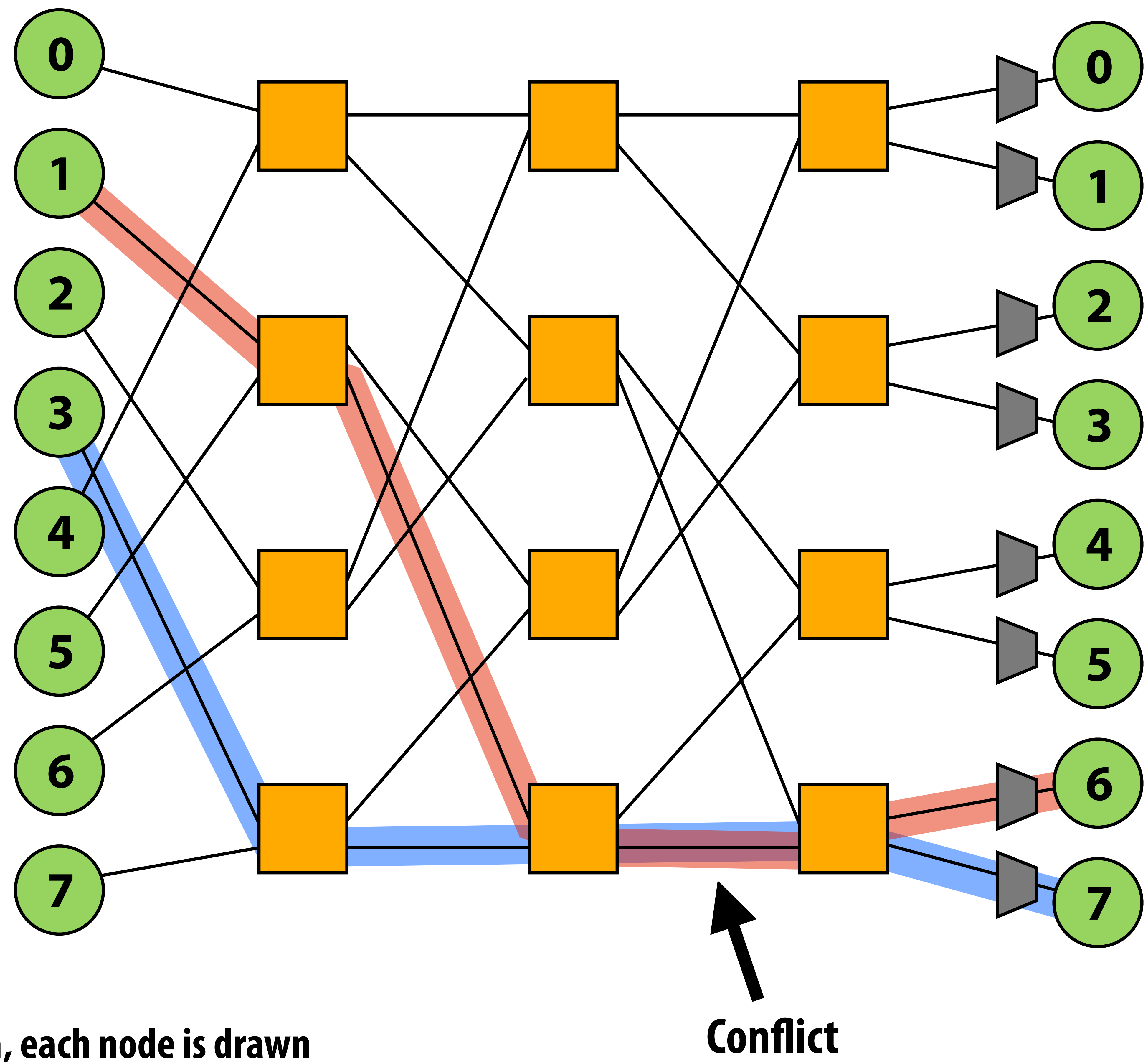
Properties of an interconnect topology

- **Bisection bandwidth:**
  - Common metric of performance for recursive topologies
  - Cut network in half, sum bandwidth of all severed links
    - Minimum cut that divides the network into two equal partitions
  - 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 without conflicts, network is non-blocking (otherwise, it's blocking)

Example: blocking vs. non-blocking

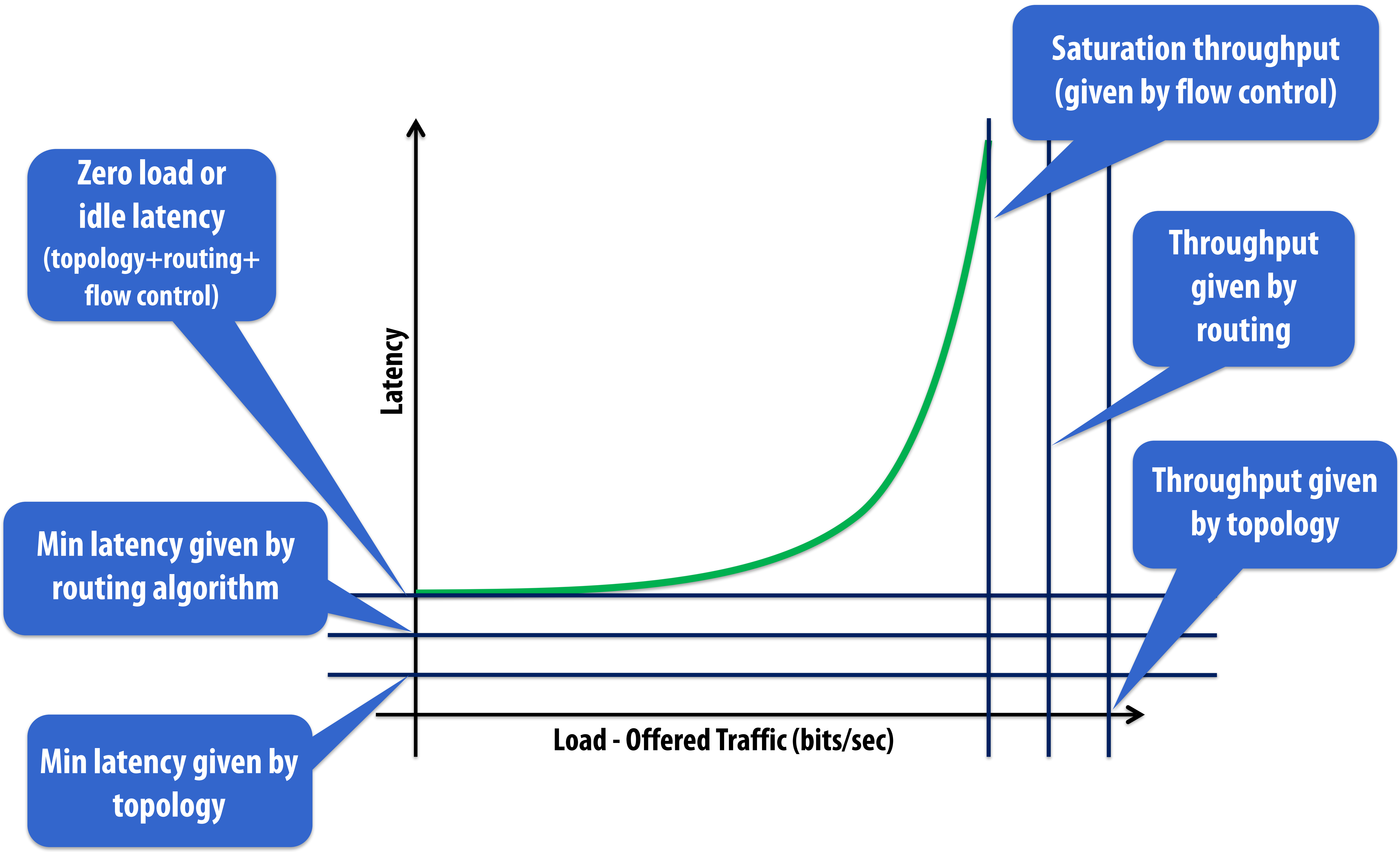
- Is this network blocking or non-blocking?
  - Consider simultaneous messages from 0-to-1 and 3-to-7.
  - Consider simultaneous messages from 1-to-6 and 3-to-7. Blocking!!!



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

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

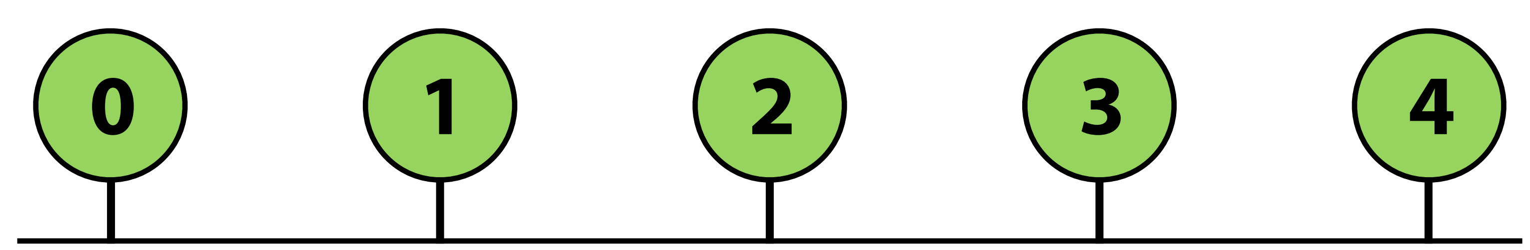
Torus

Butterfly

...

Bus interconnect

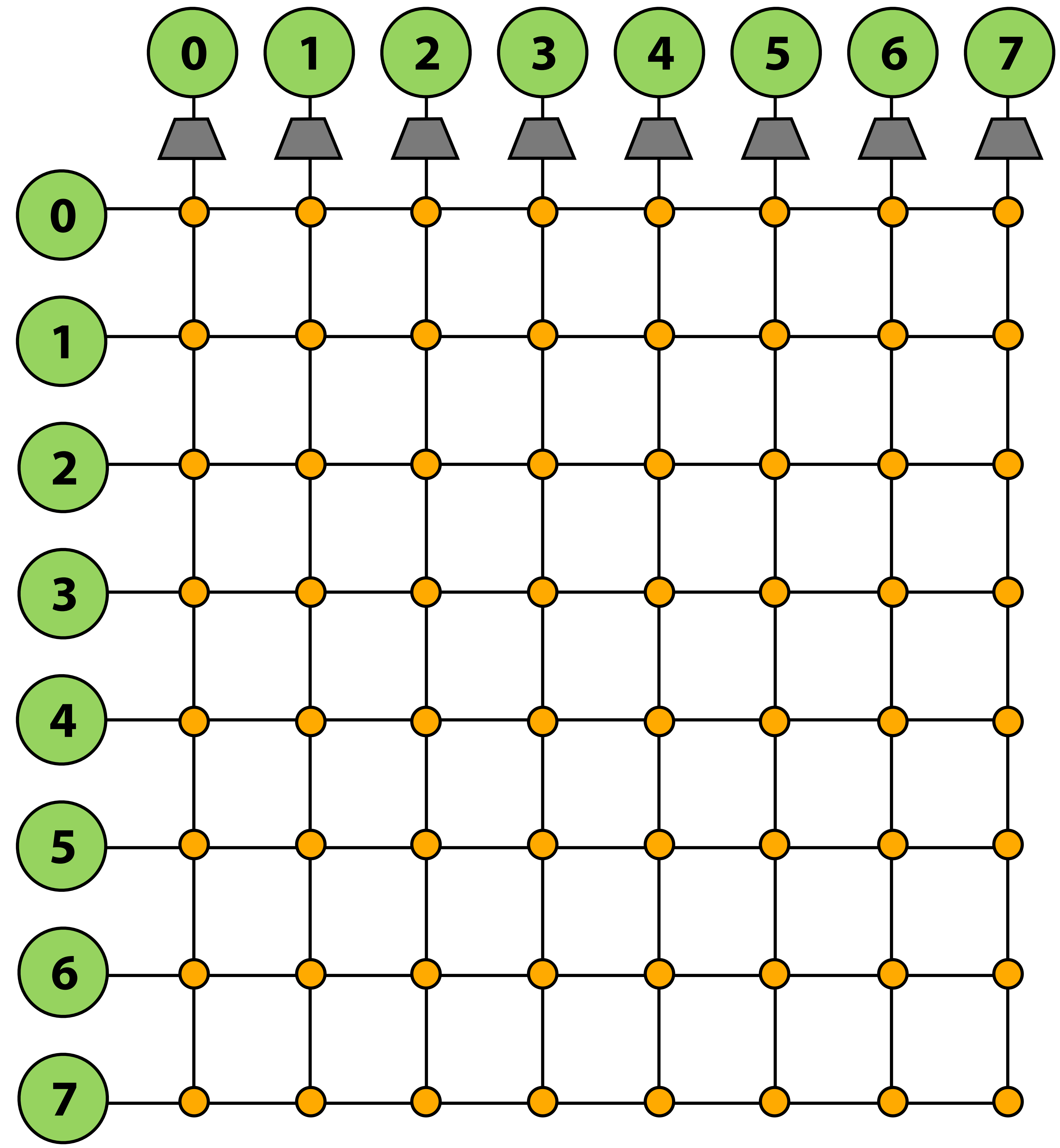
- **Good:**
  - Simple design
  - Cost effective for a small number of nodes
  - Easy to implement coherence (via snooping)
- **Bad:**
  - Contention: all nodes contend for shared bus
  - Limited bandwidth: all nodes communicate over same wires (one communication at a time)
  - High electrical load = low frequency, high power



Crossbar interconnect

- Every node is connected to every other node (non-blocking, indirect)
- 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.

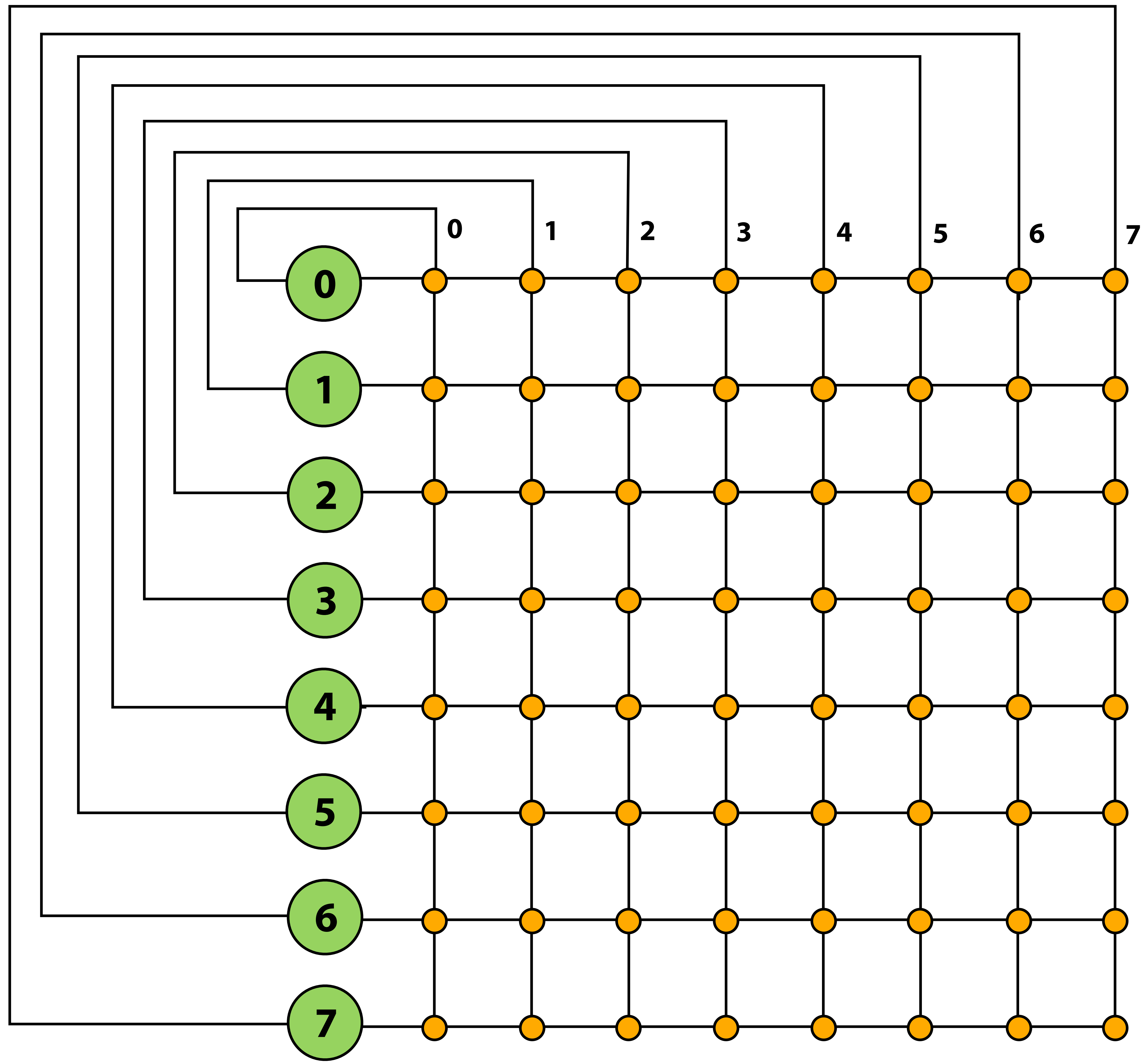


8-node crossbar network (N=8)

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

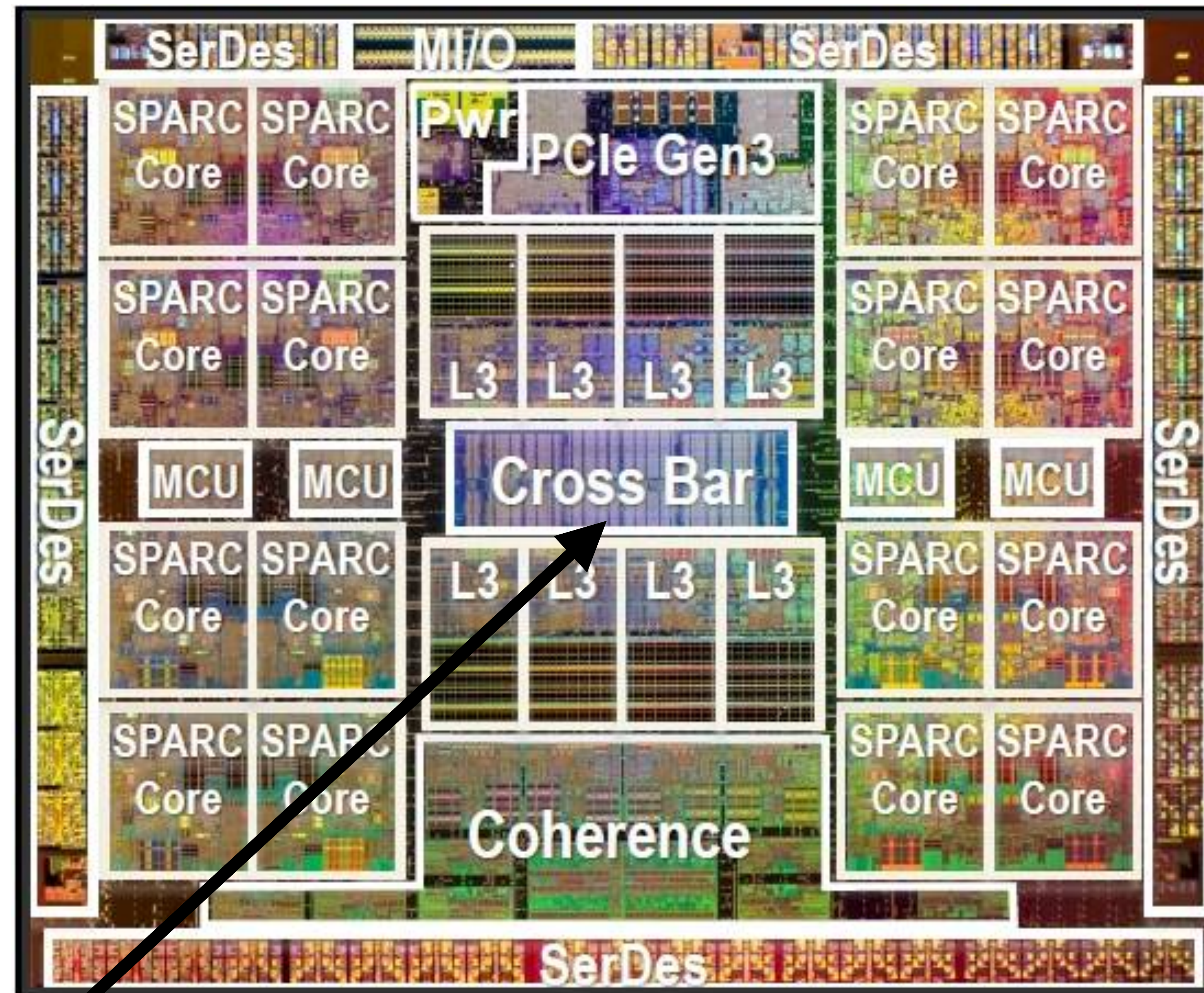
Crossbar interconnect

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



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

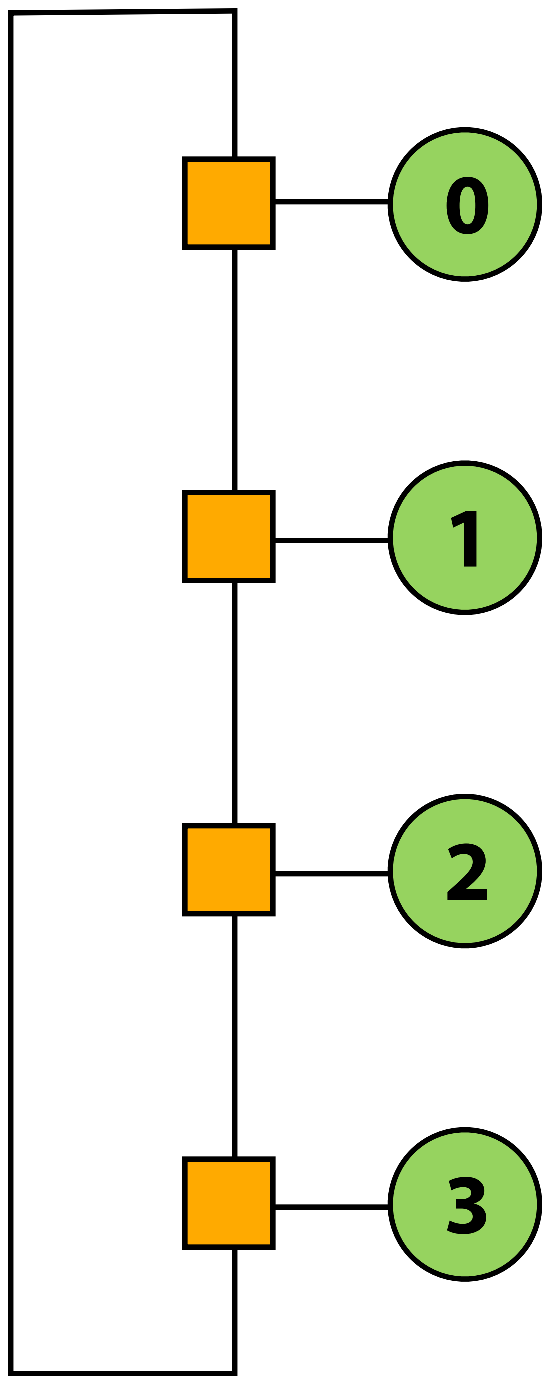
Ring

- **Good:**
  - Simple
  - Cheap: O(N) cost

- **Bad:**
  - High latency: O(N)
  - Bisection bandwidth remains constant as nodes are added (scalability issue)

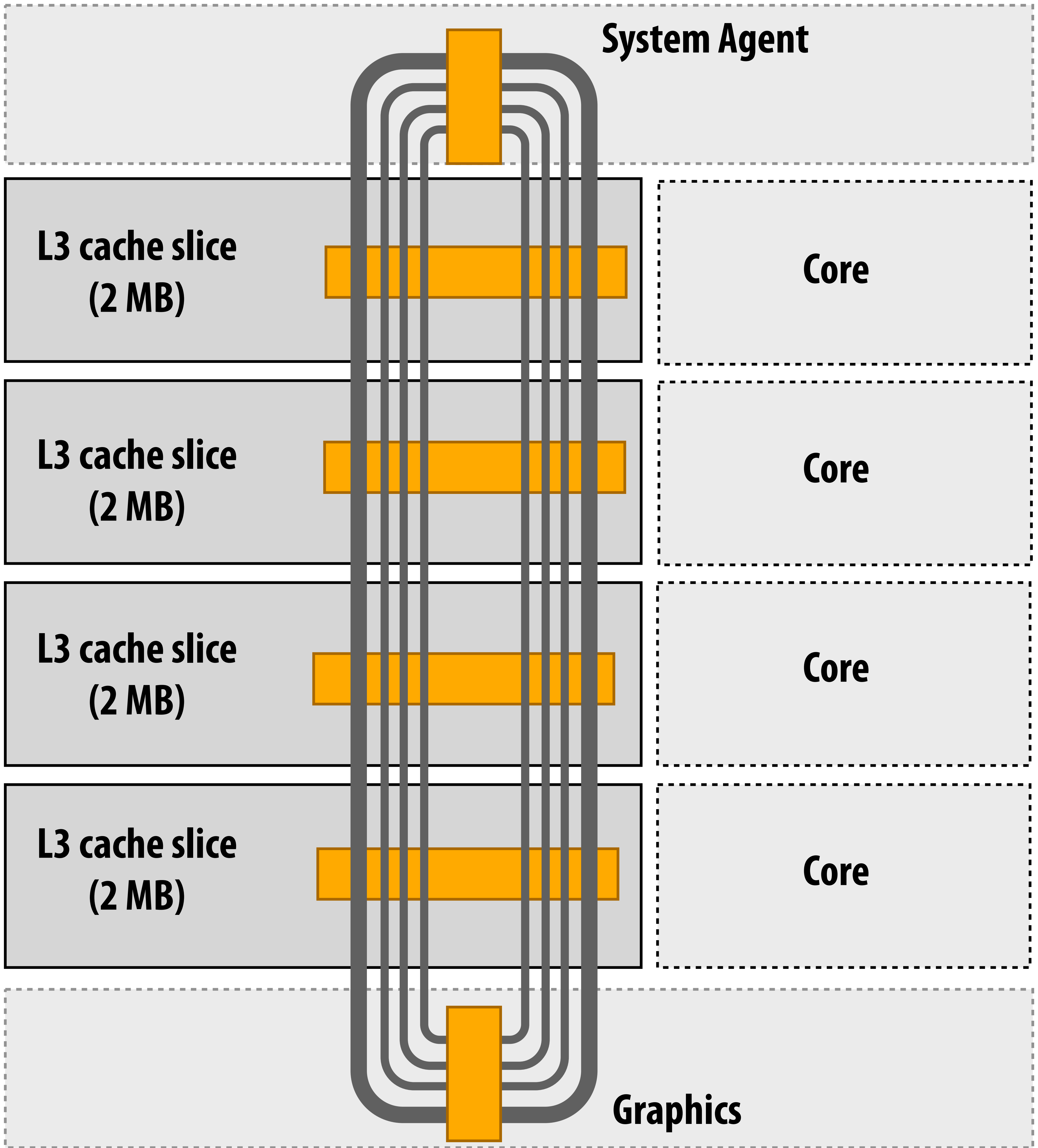
- **Used in recent Intel architectures**
  - Core i7

- **Also used in IBM CELL Broadband Engine (9 cores)**



Intel's ring interconnect

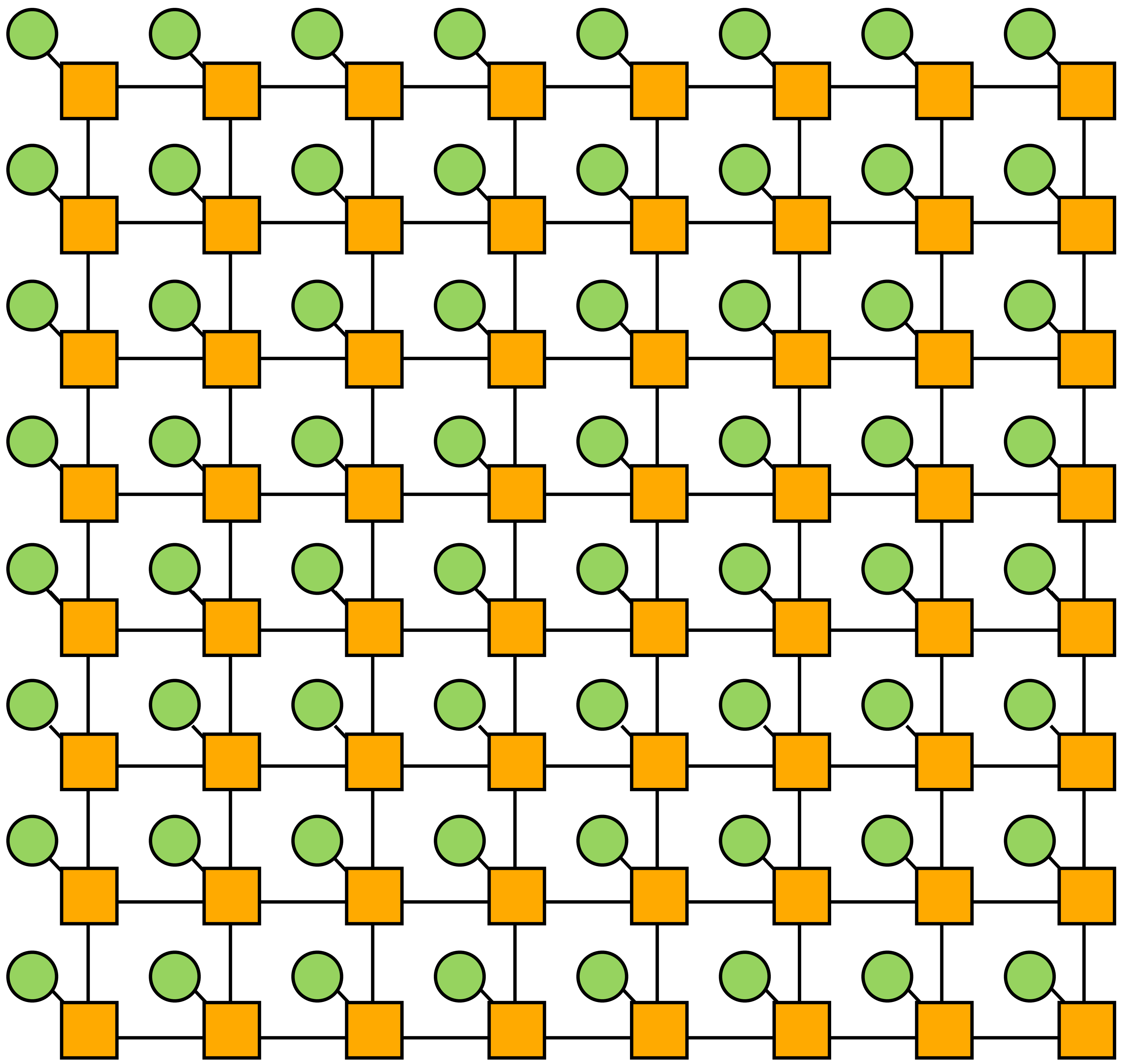
Introduced in Sandy Bridge microarchitecture



- **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

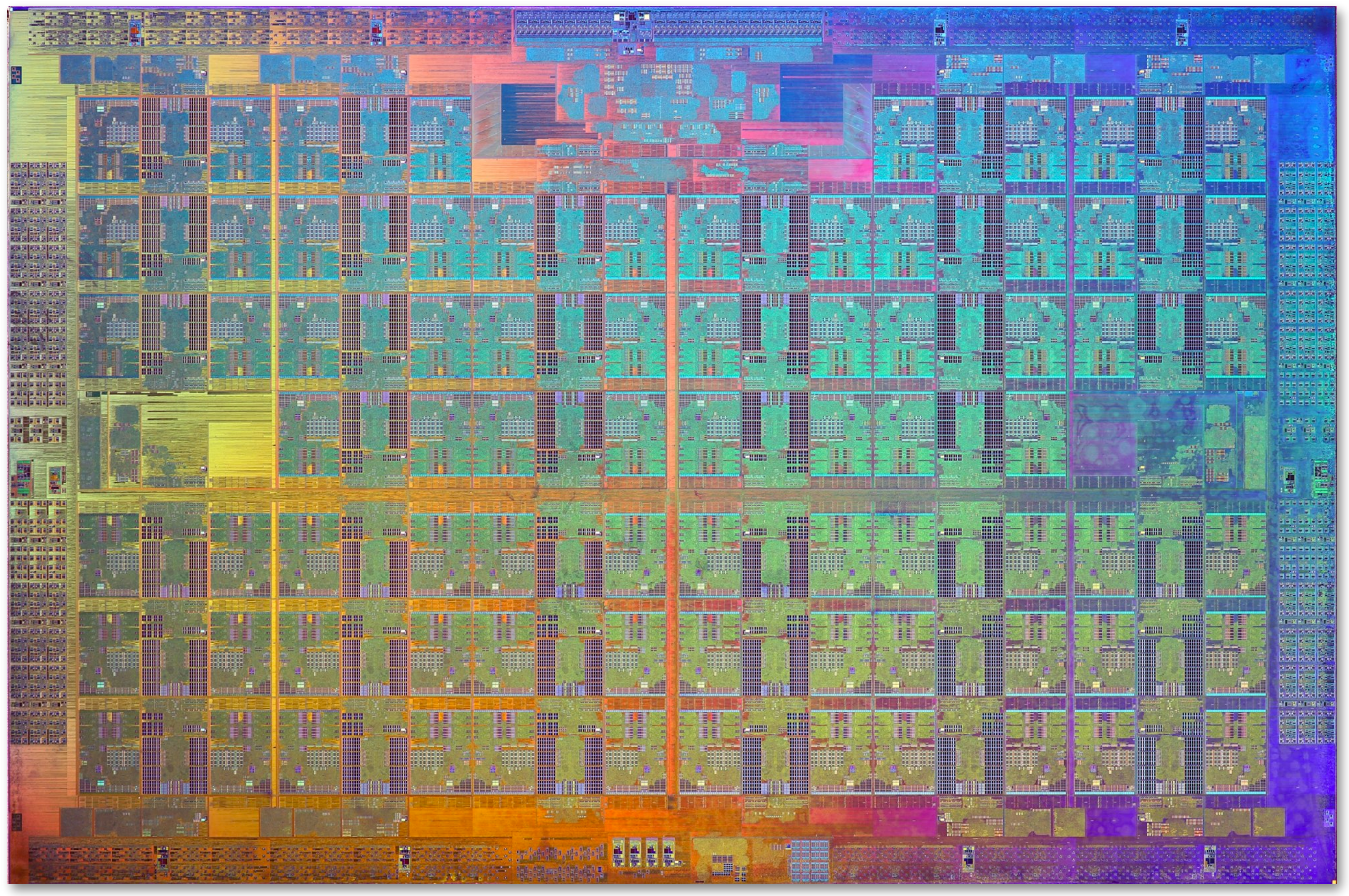
Mesh

- 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:
  - Tilera processors
  - Prototype Intel chips

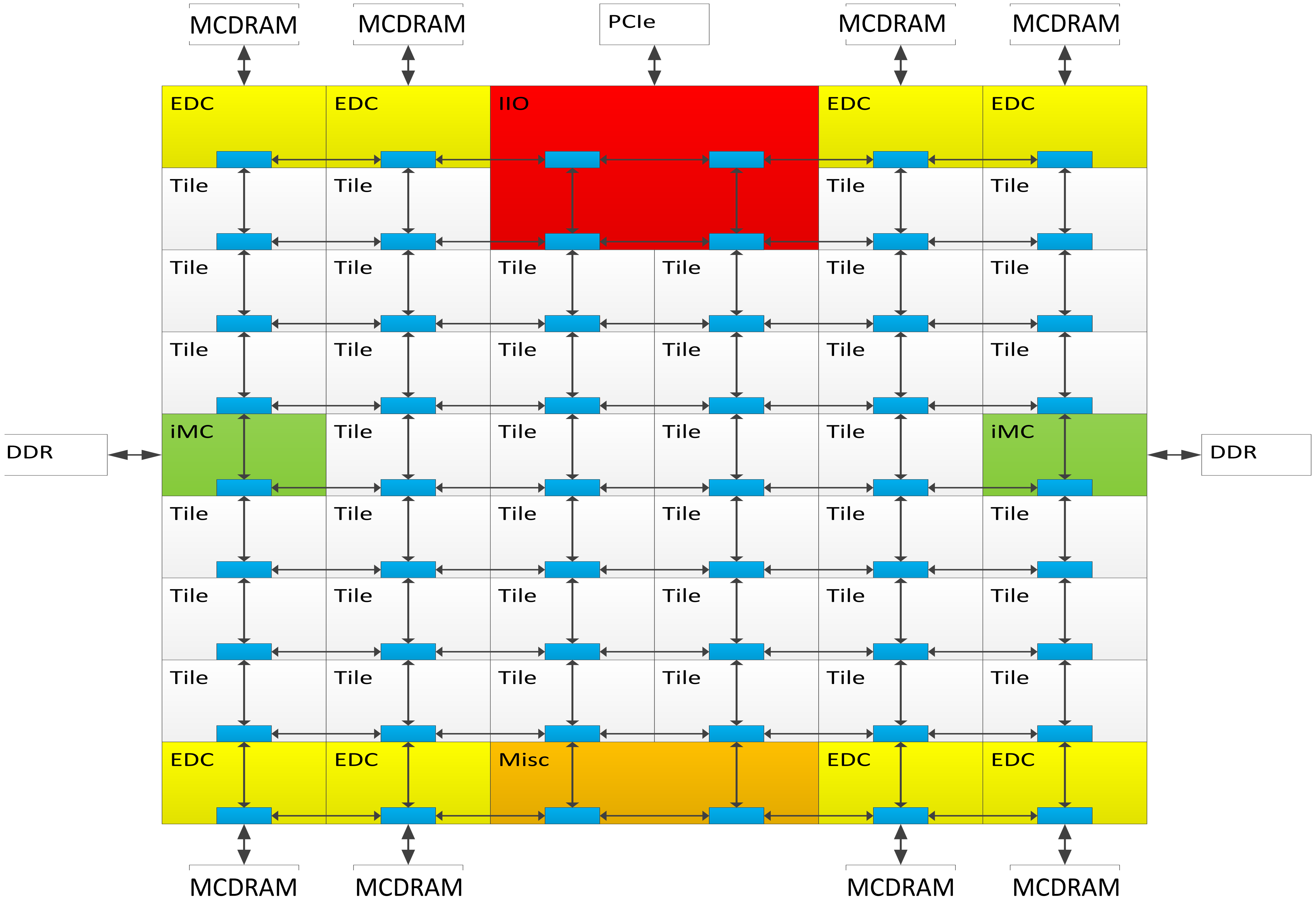


2D Mesh

Xeon Phi (Knights Landing)

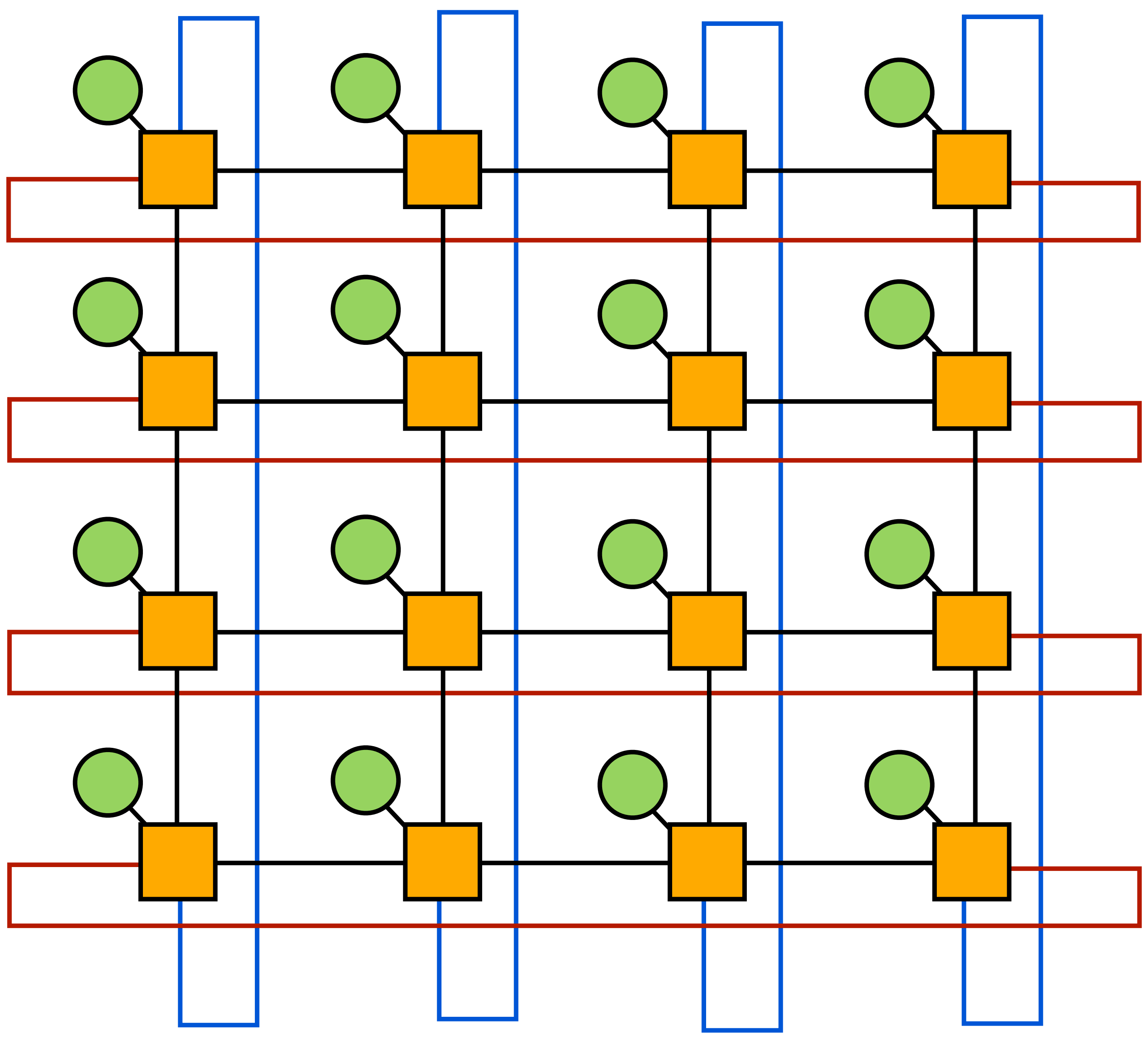


- 72 cores, arranged as 6 x 6 mesh of tiles (2 cores/tile)
- YX routing of messages:
  - Move in Y
  - "Turn"
  - Move in X



Torus

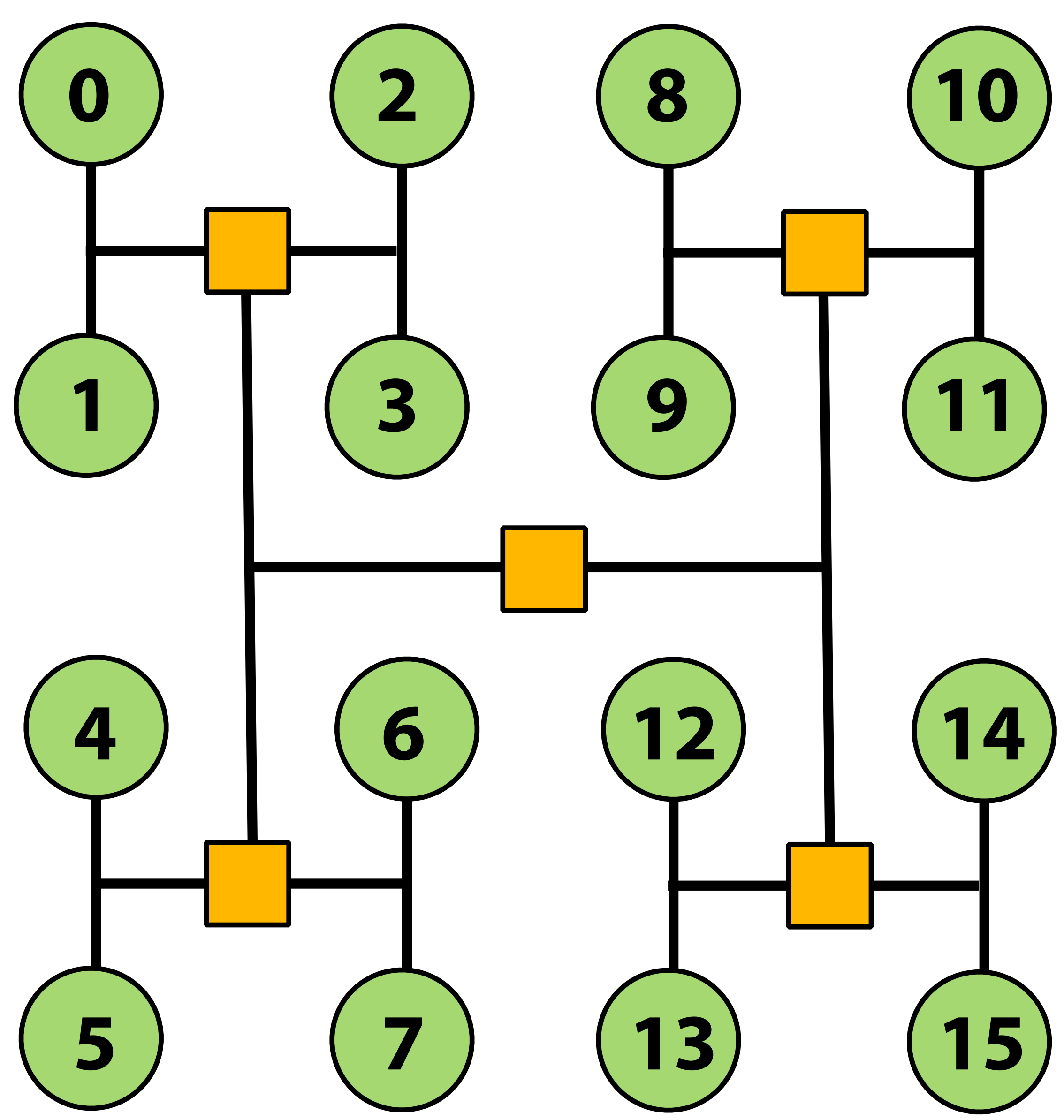
- Characteristics of mesh topology are different based on whether node is near edge or middle of network (torus topology introduces new links to avoid this problem)
- Still O(N) cost, but higher cost than 2D grid
- Higher path diversity and bisection BW than mesh
- Higher complexity
  - Difficult to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



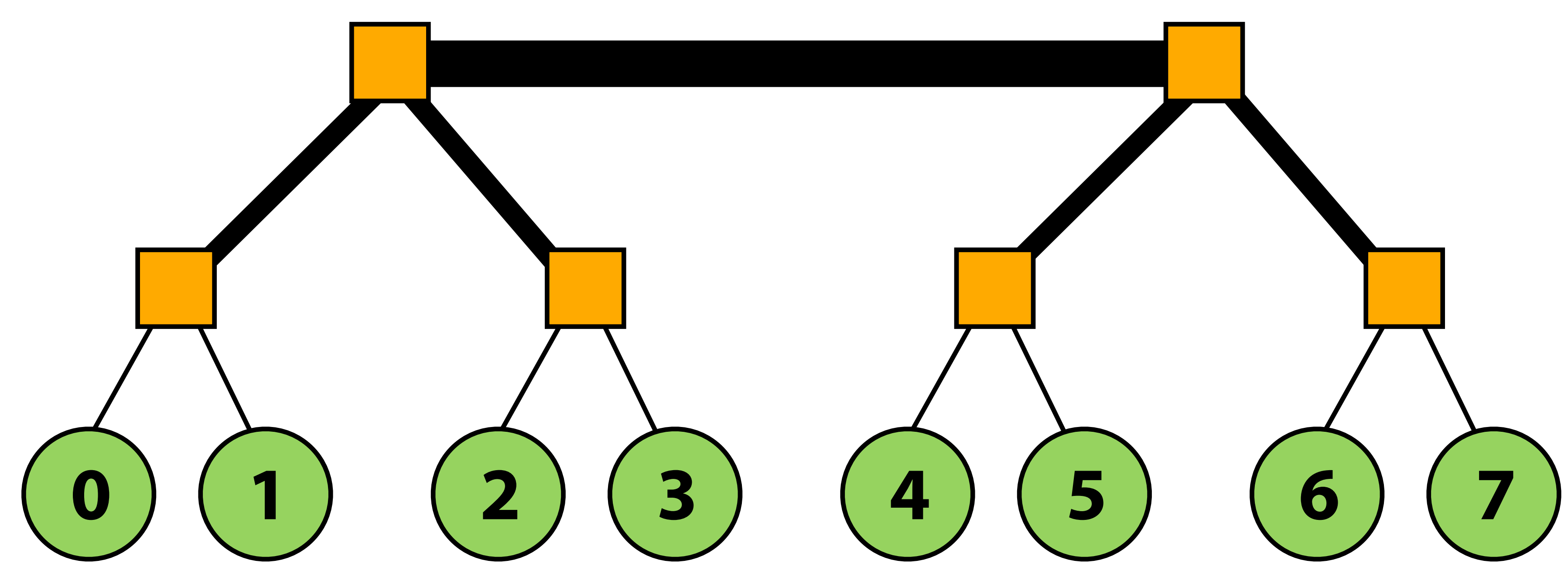
2D Torus

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)



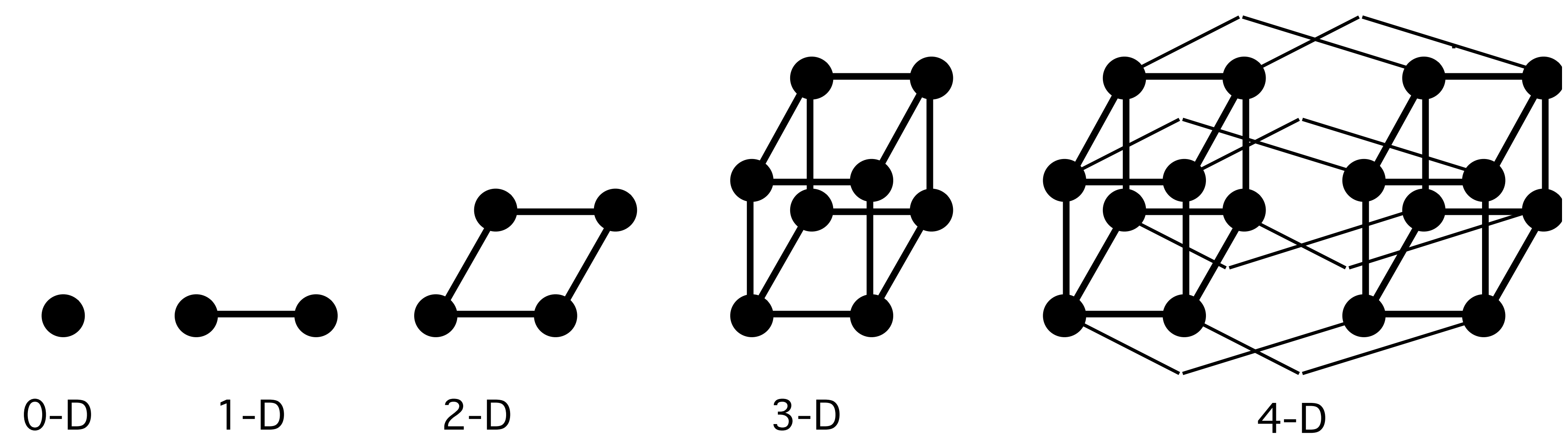
H-Tree

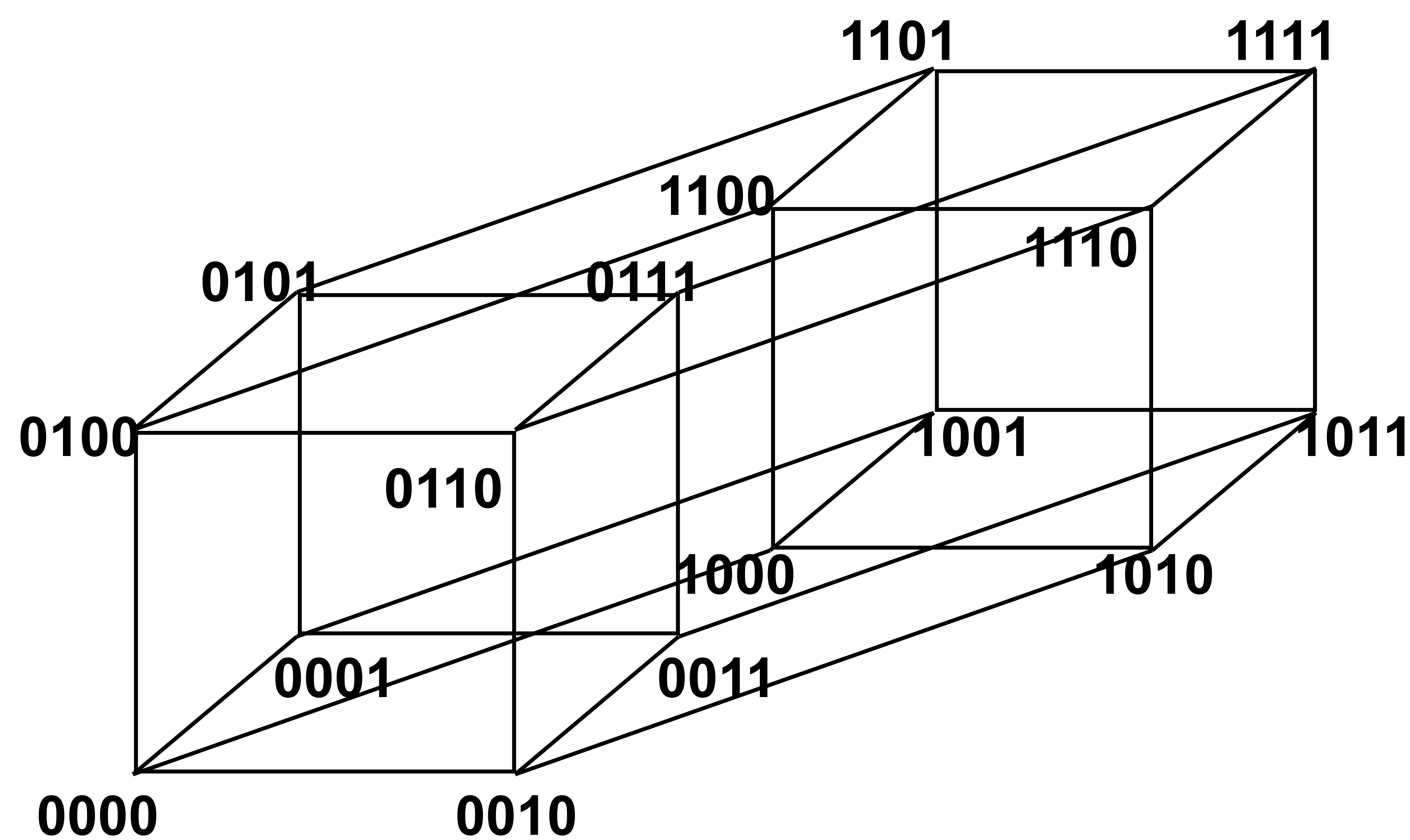


Fat Tree

Hypercube

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

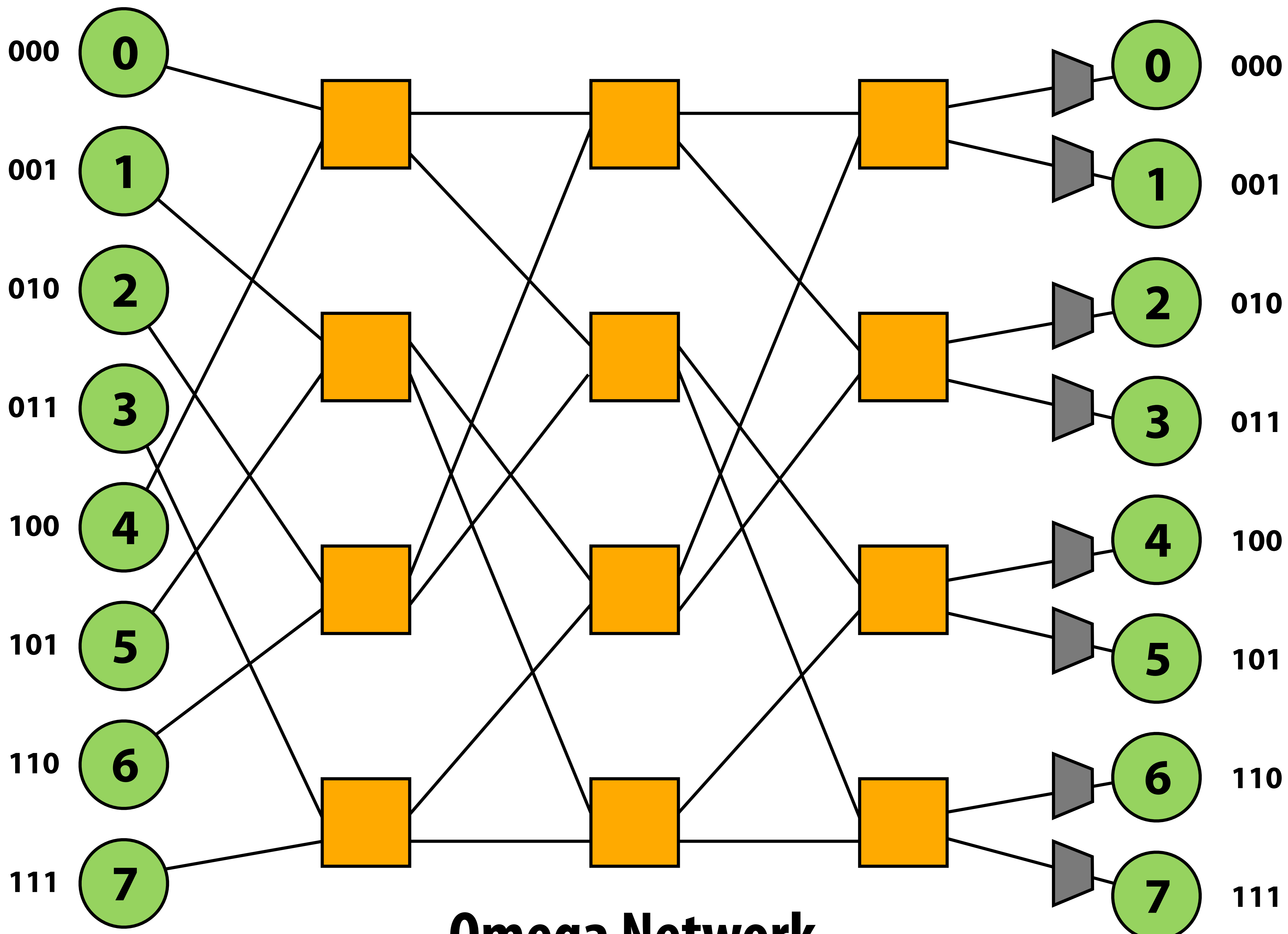




- 6D hypercube used in 64-core Cosmic Cube computer developed at Caltech in the 80s
- SGI Origin used a hypercube

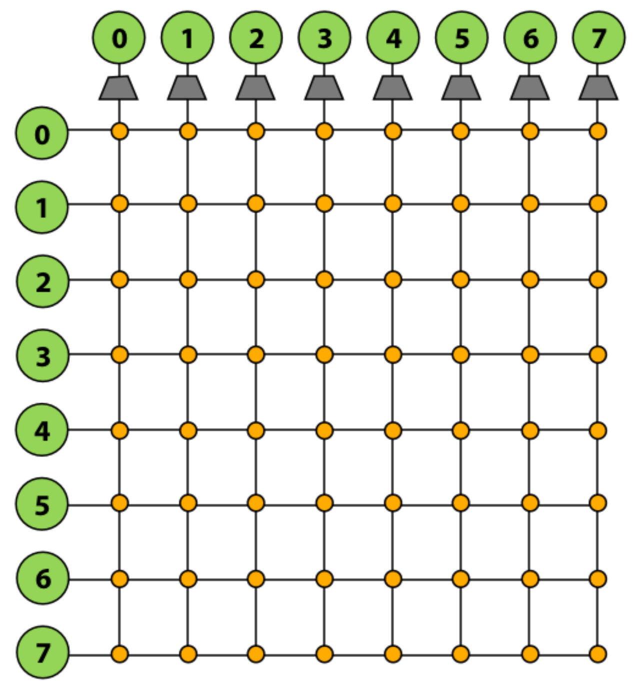
Multi-stage logarithmic

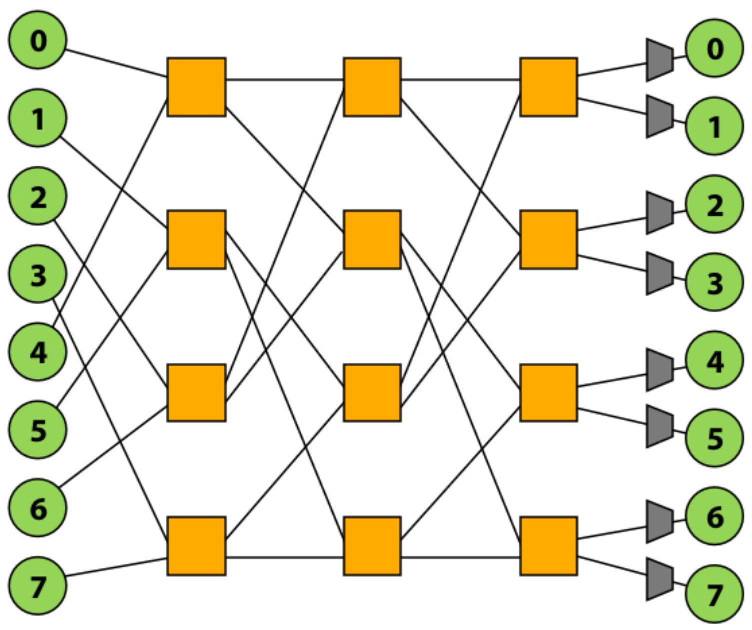
- Indirect network with multiple switches between terminals
- Cost: O(N lg N)
- Latency: O(lg N)
- Many variations: Omega, butterfly, Clos networks, etc…

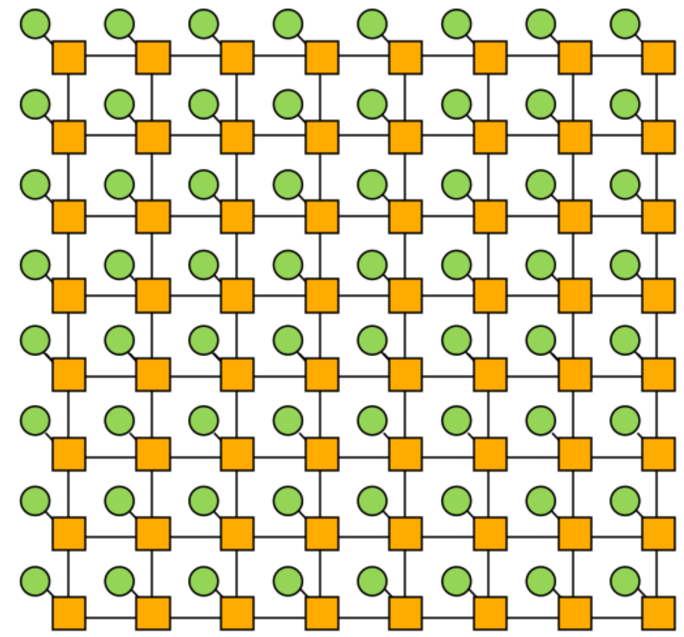


Omega Network

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

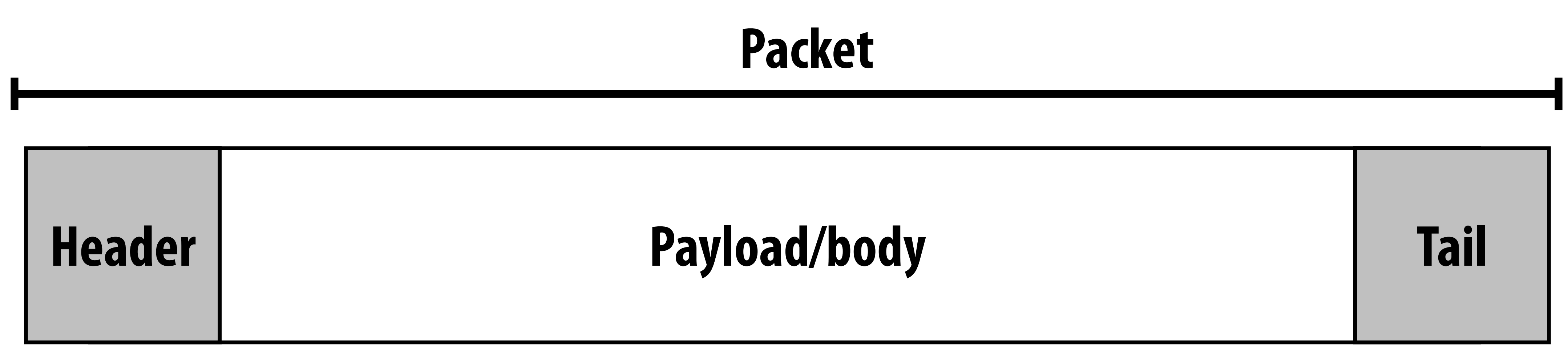
- **Message**
  - Unit of transfer between network clients (e.g., cores, memory)
  - Can be transmitted using many packets

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

- **Flit (flow control digit)**
  - Packets broken into smaller units called "flits"
  - Flit: ("flow control digit") 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., error code
    - Generally located at end of packet so it can be generated "on the way out" (sender computes checksum, appends it to end of packet)

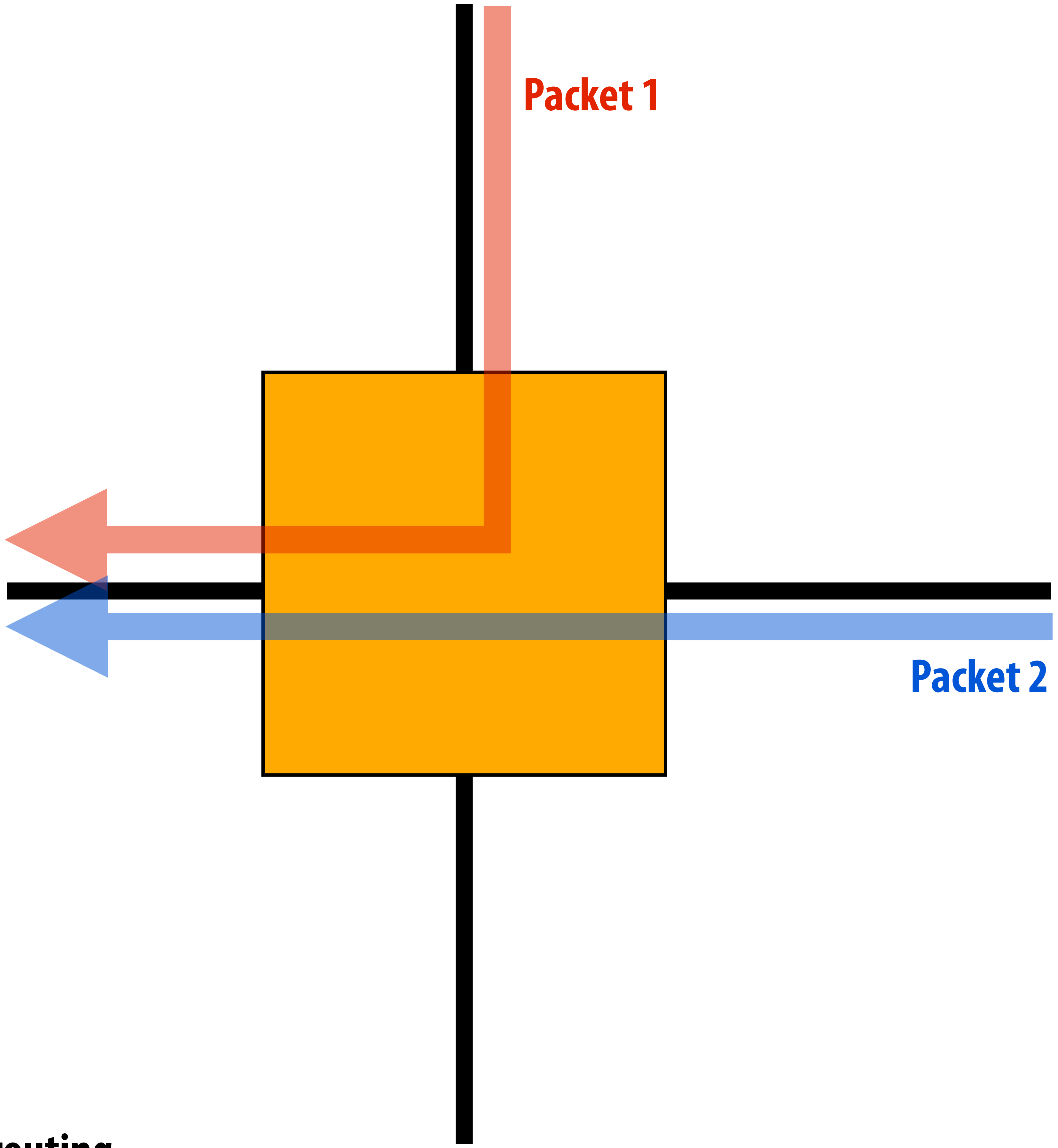


Handling contention

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)

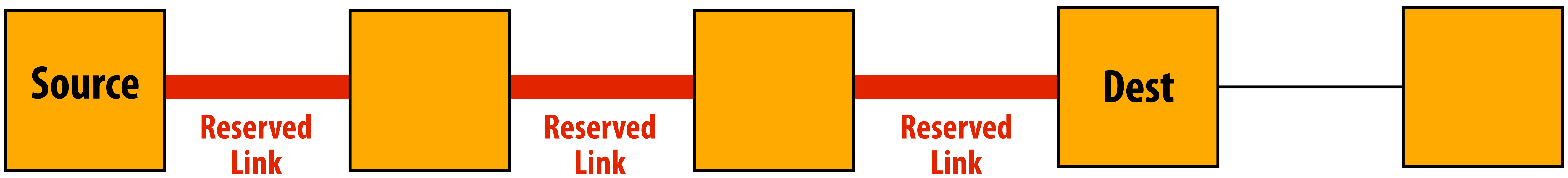
- In this lecture: we only consider buffering *



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

Circuit-switched routing

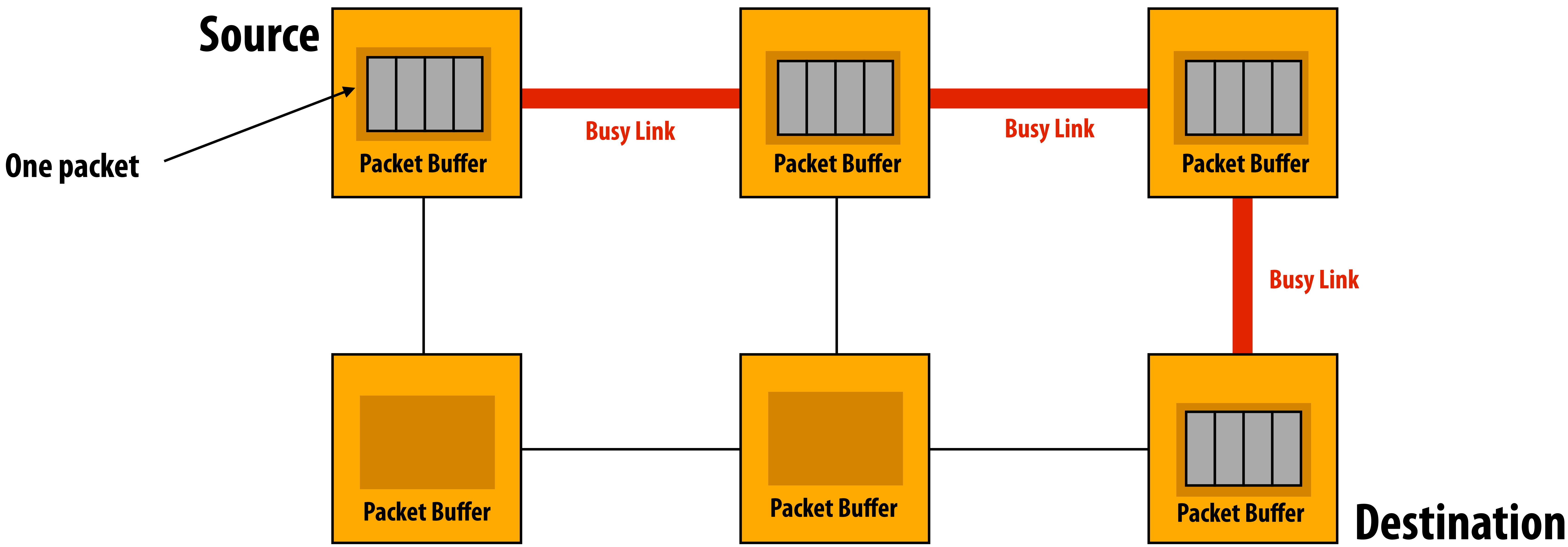
- **High-granularity resource allocation**
  - Main idea: <u>pre-allocate</u> all resources (links across multiple switches) along entire network path for a message ("setup a flow")



- **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)

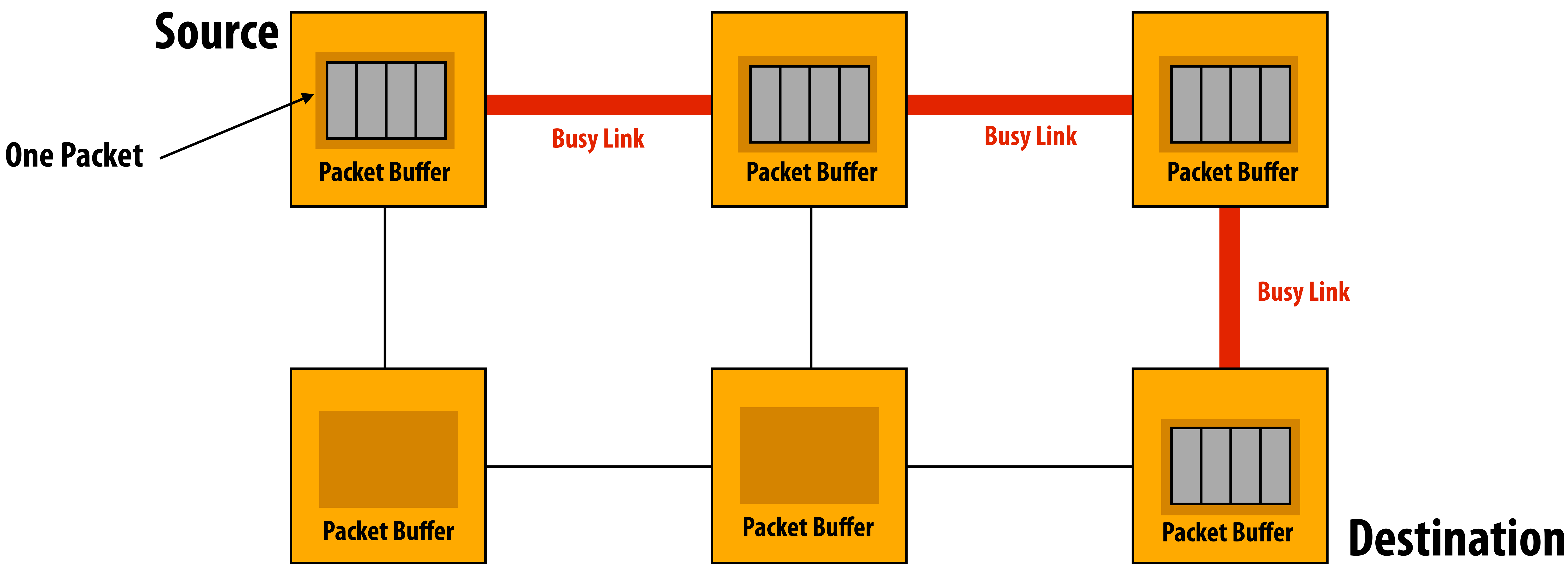
- Packet copied entirely into network switch before moving to next node
- Flow control unit is an entire packet
  - Different packets from the same message can take different routes, but all data in a packet is transmitted over the same route
- Requires buffering for entire packet in each router
- High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

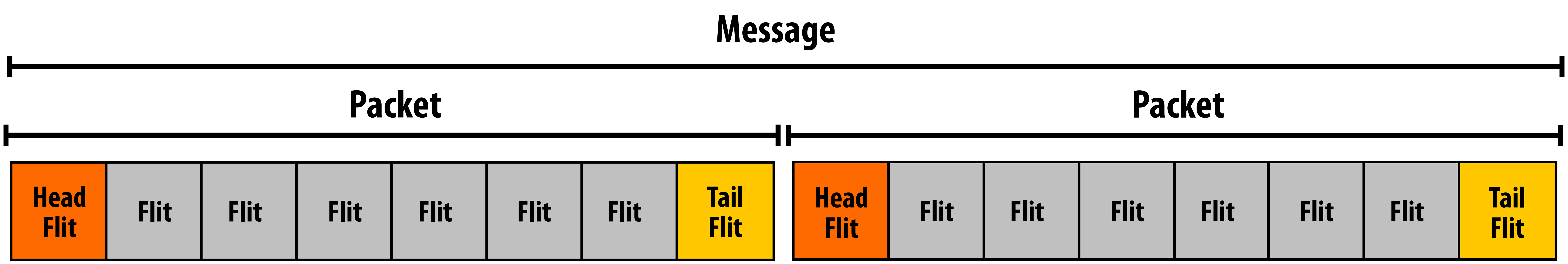
Note to students: in lecture this slide was animated and the final build shown here is not illustrative of the cut-through routing concept (please refer to lecture video)

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

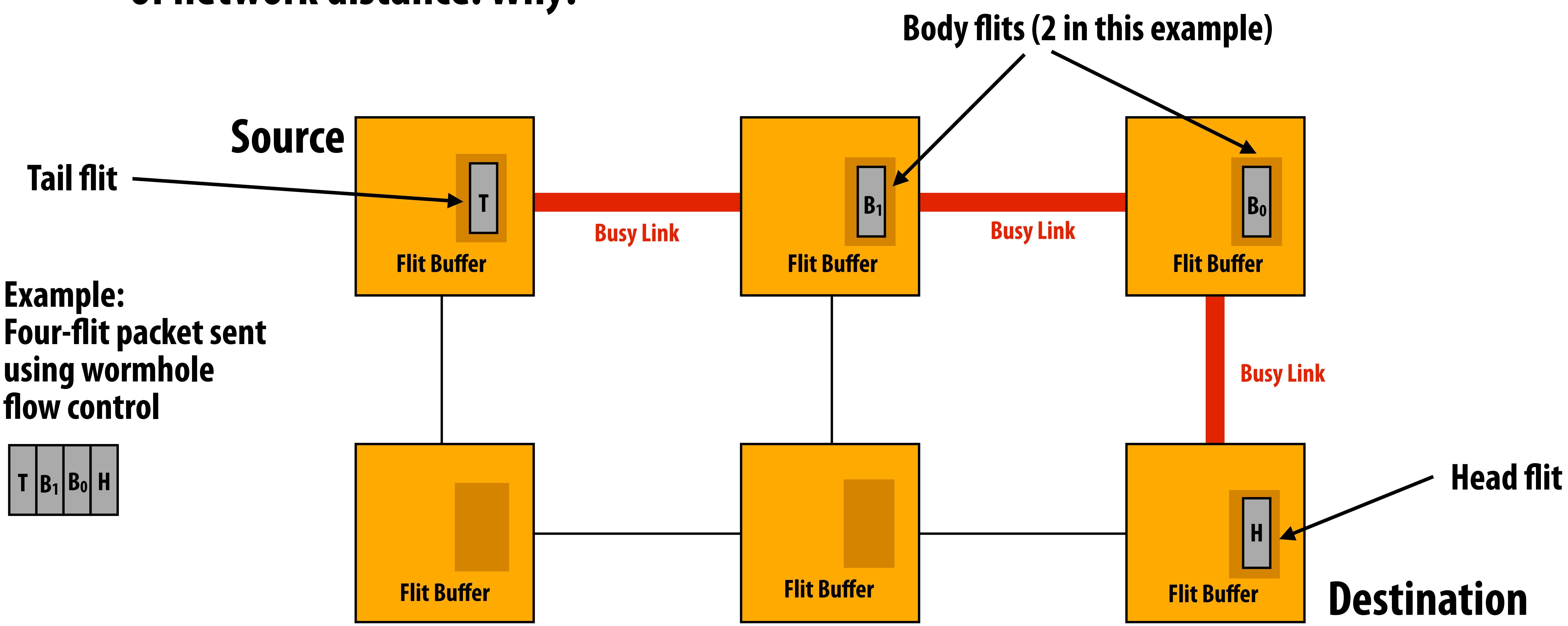
Wormhole flow control

- **Flit (flow control digit)**
  - Packets broken into smaller units called "flits"
  - Flit: ("flow control digit") 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)

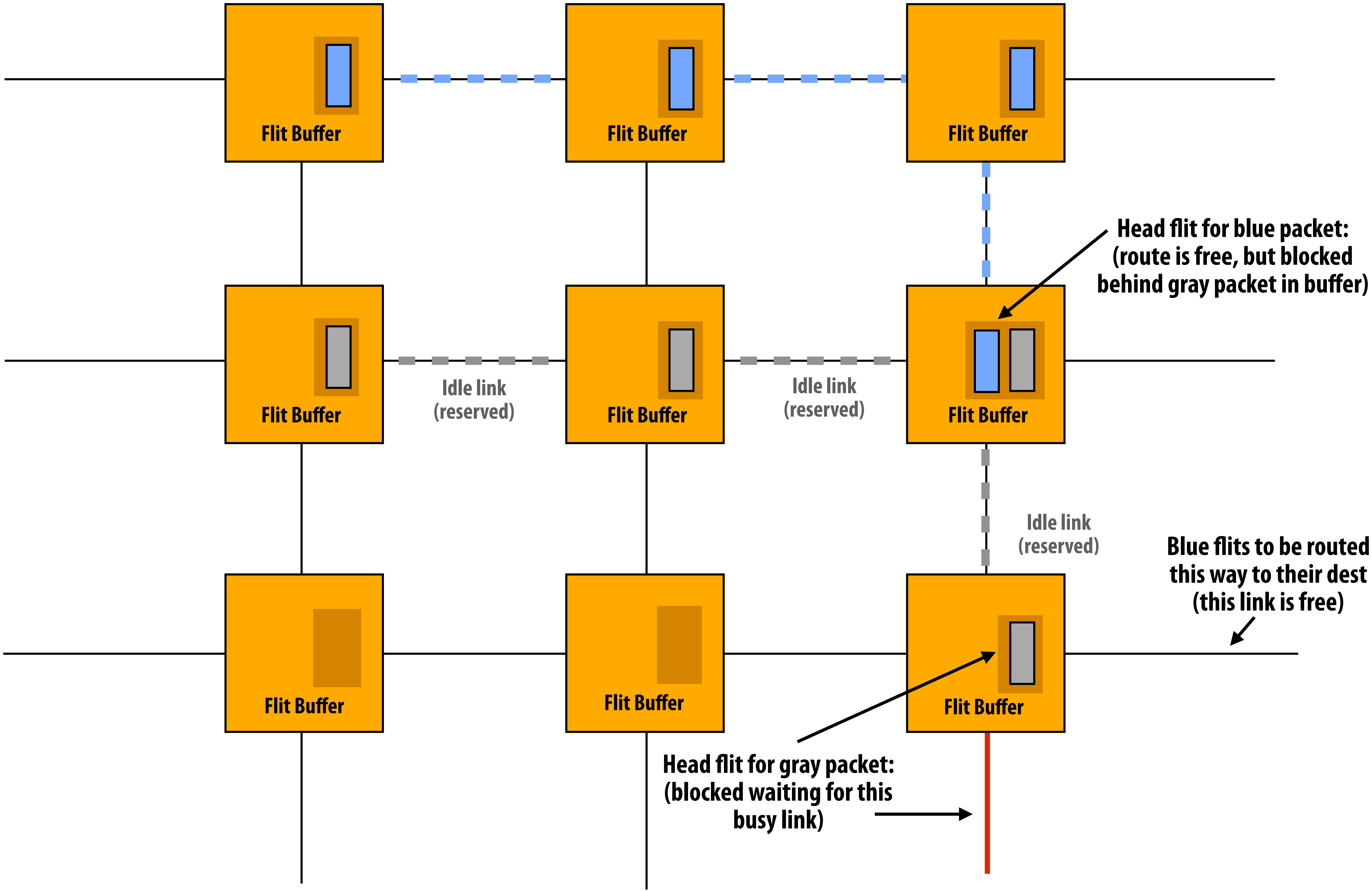


Wormhole flow control

- 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?

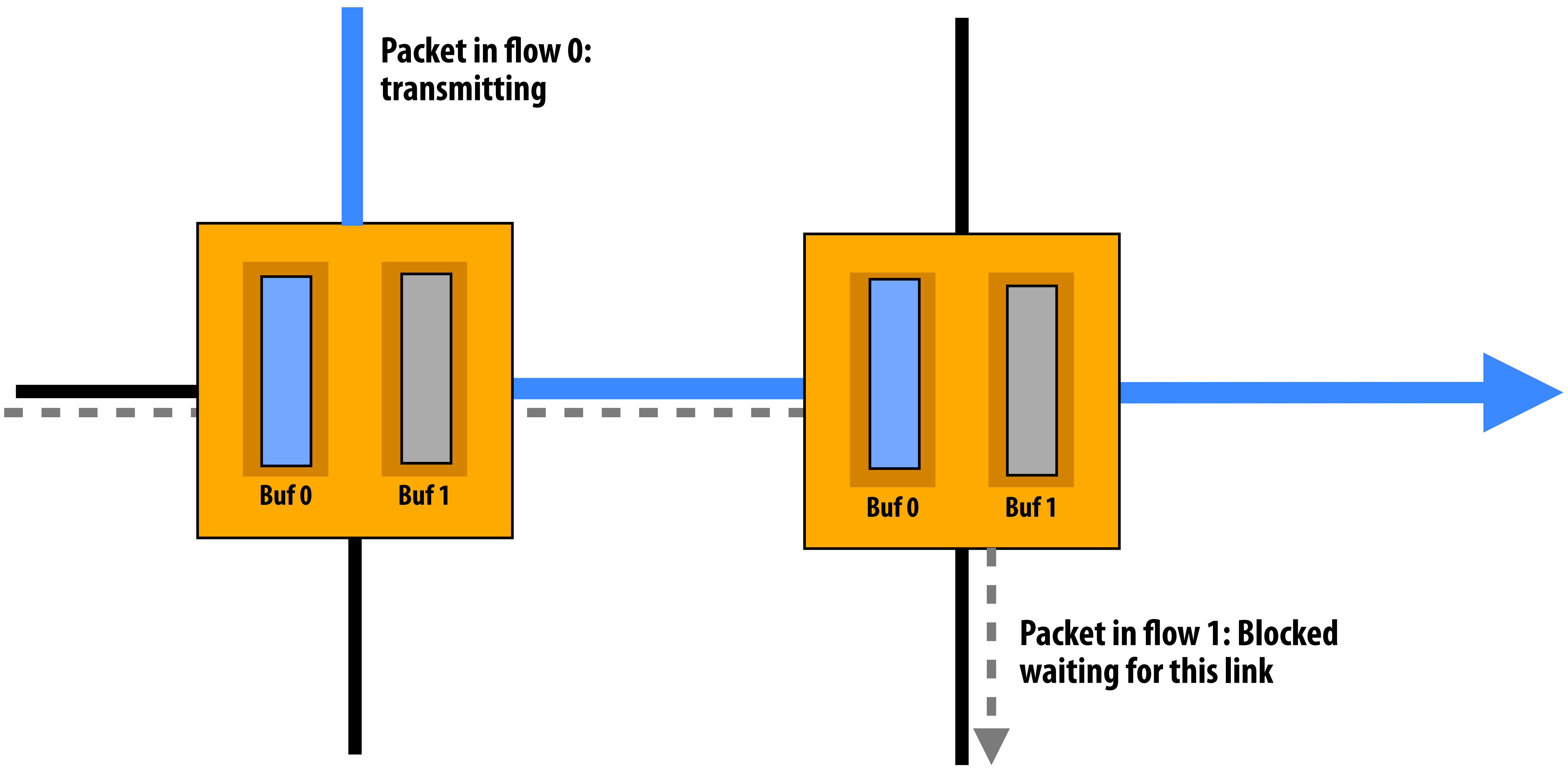


Problem: head-of-line blocking



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



See "Virtual Channel Flow Control," [Dally ISCA 1990]

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.