On-Chip Networks I: Topology/Flow Control

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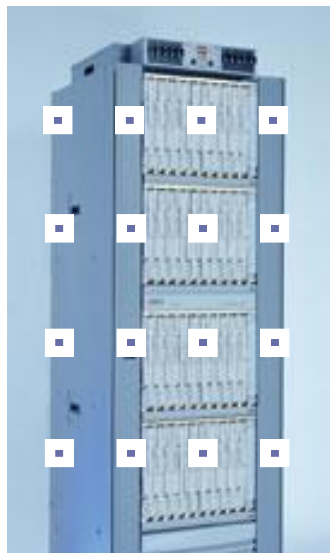
History: From interconnection networks to on-chip networks

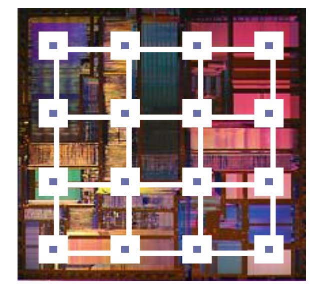
Box-to-box networks

Board-to-board networks



Chip-to-chip networks

On-chip networks

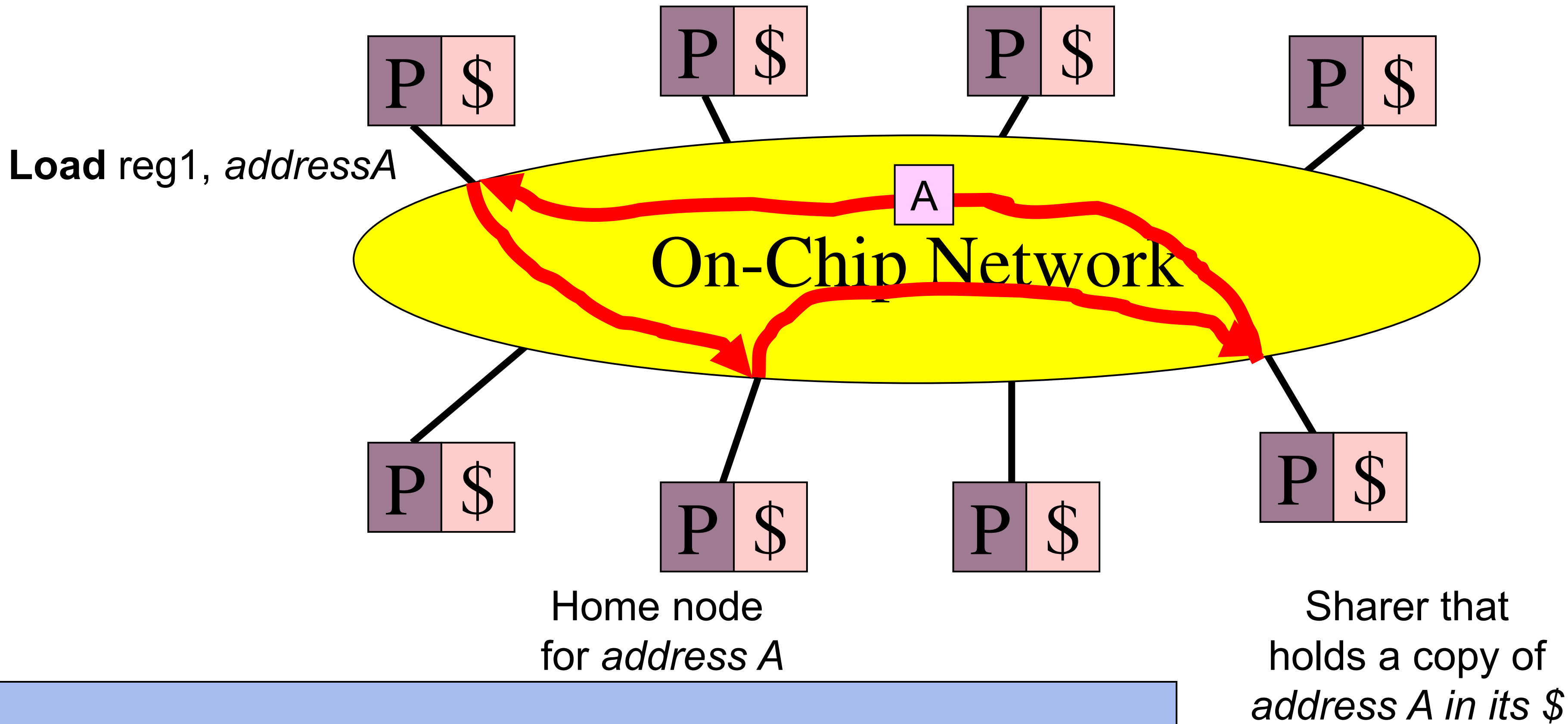


Focus on on-chip networks connecting caches in shared memory processors

Multi-Chip: Supercomputers, Data Centers, Internet Routers, Servers
On-Chip: Servers, Laptops, Phones, HDTVs, Access routers

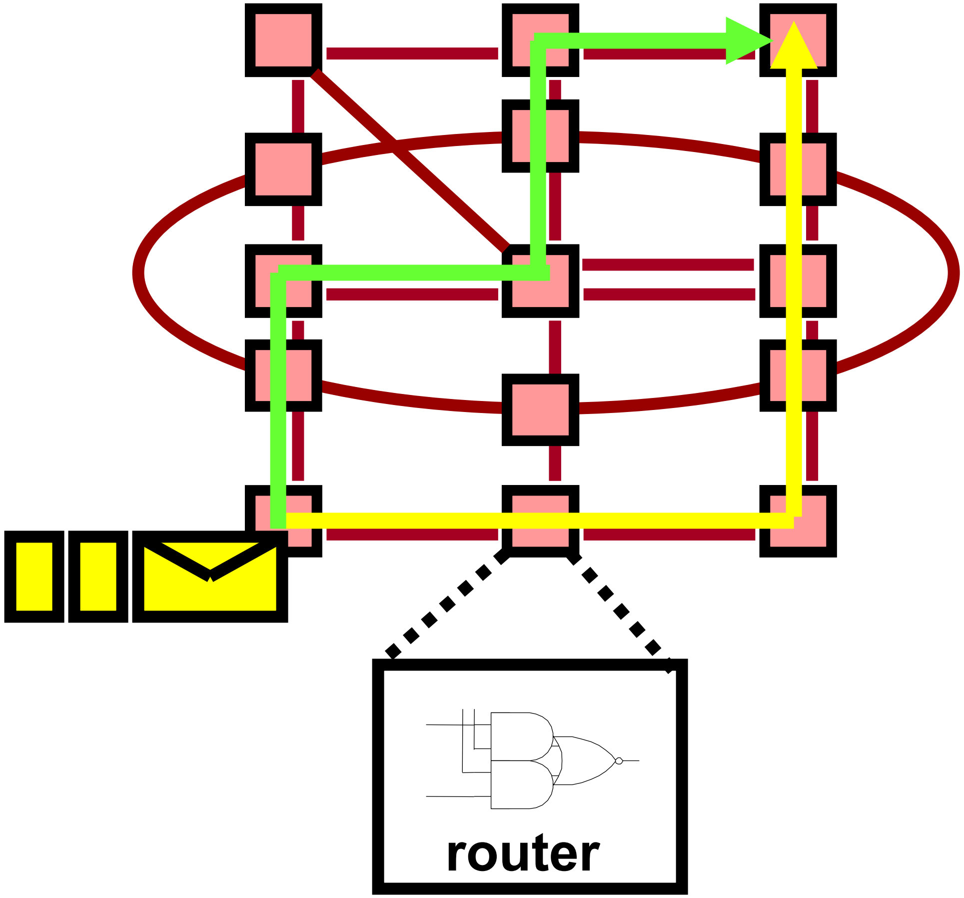
What's an on-chip network?

E.g. Cache-coherent chip multiprocessor



It transports cache coherence messages and cache lines between processor cores

Designing an on-chip network



- Topology
- Flow Control
- Router micro-architecture
- Routing

Interconnection Networks Architecture

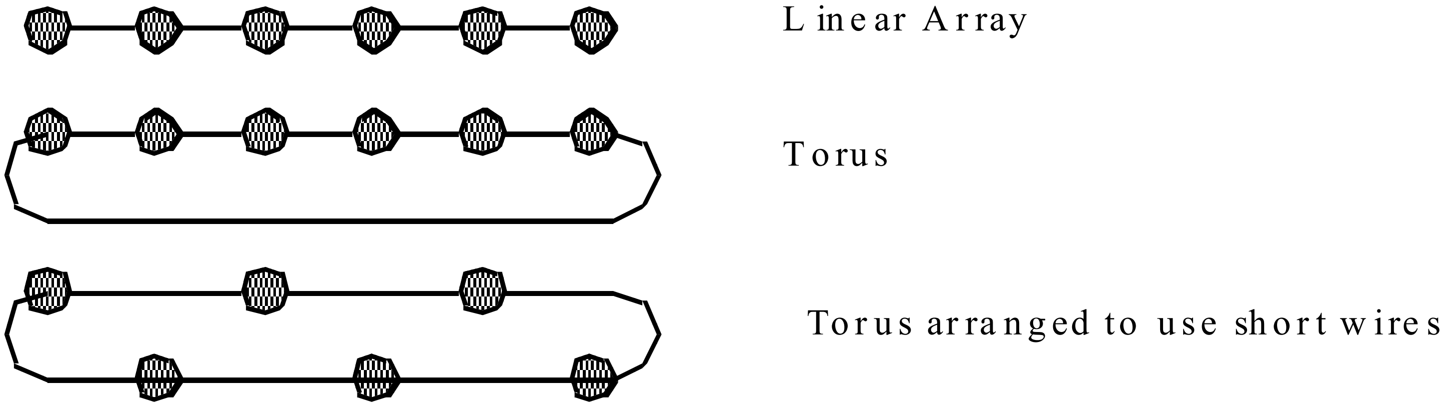
- How to connect the nodes up (processors, memories, router line cards, SoC modules) – TOPOLOGY
- Which path should a message take? – ROUTING
- How is the message actually forwarded from source to destination – FLOW CONTROL
- How to build the routers – ROUTER MICROARCHITECTURE
- How to build the links – LINK ARCHITECTURE
- How do nodes talk to the network – NETWORK INTERFACE

Topology

Topological Properties

- *Routing Distance* - number of links on route
- *Diameter* - maximum routing distance
- *Average Distance*
- A network is *partitioned* by a set of links if their removal disconnects the graph
- *Bisection Bandwidth* is the bandwidth crossing a minimal cut that divides the network in half

Linear Arrays and Rings

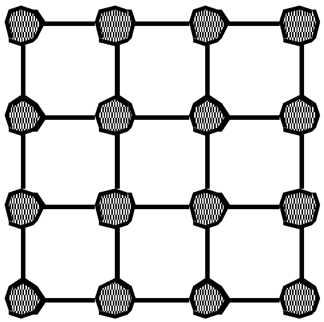


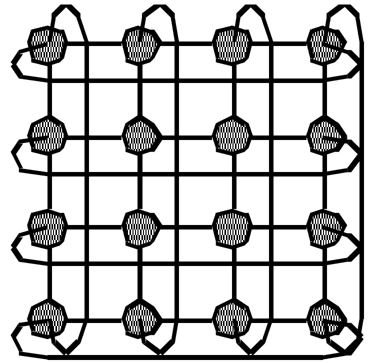
Route A -> B given by relative address R = B-A

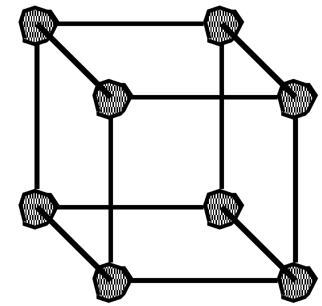
	Linear Array	Ring (1-D Torus)
Diameter?	N	N/2
Average Distance?	N/2	N/4
Bisection bandwidth?	1	2

- Torus Examples:
  - FDDI, SCI, FiberChannel Arbitrated Loop, Intel Xeon

Multidimensional Meshes and Tori



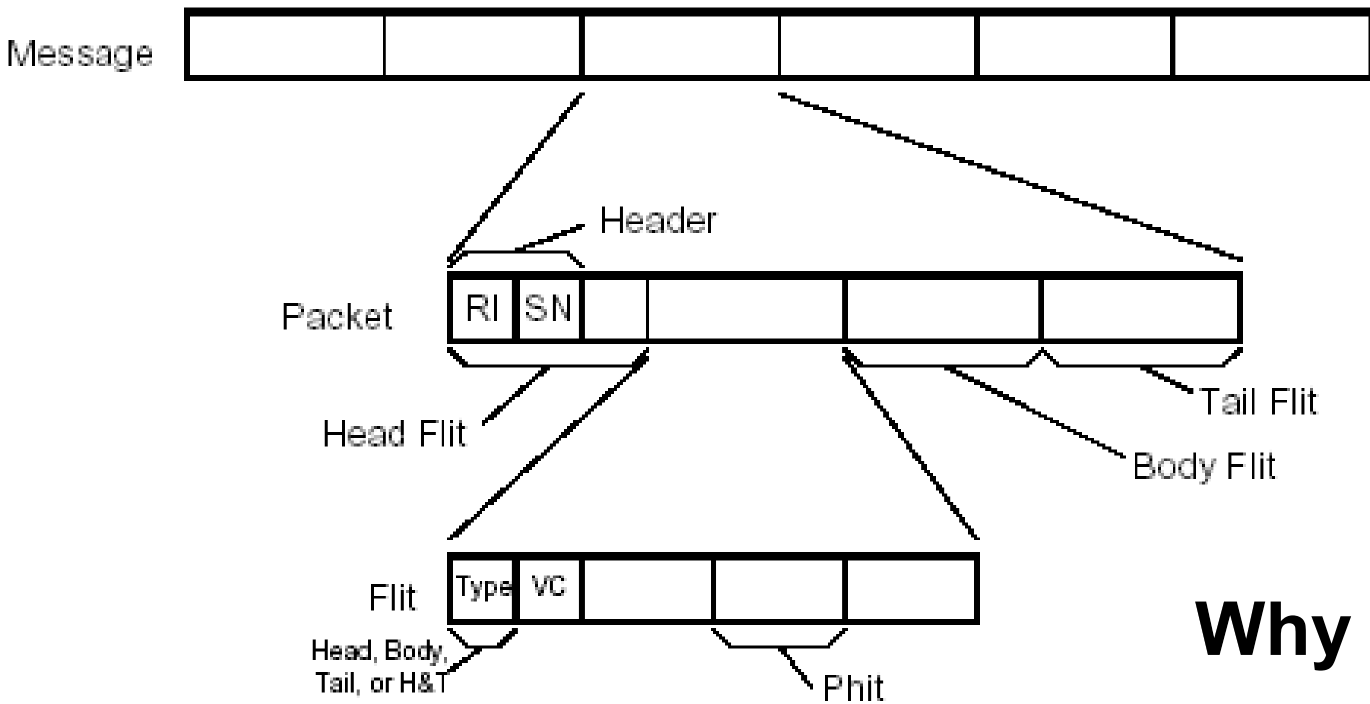




- *d*-dimensional array
  - $n = k_{d-1} \times \ldots \times k_O$ nodes
  - described by *d*-vector of coordinates $(i_{d-1}, \ldots, i_O)$
- *d*-dimensional *k*-ary mesh: $N = k^d$
  - $k = \sqrt[d]{N}$
  - described by *d*-vector of radix k coordinate
- *d*-dimensional *k*-ary torus (or *k*-ary *d*-cube)

Routing & Flow Control Overview

Messages, Packets, Flits, Phits



Why flits?

For variable packet sizes

Packet: Basic unit of routing and sequencing
- Limited size (e.g. 64 bits – 64 KB)

Flit (flow control digit): Basic unit of bandwidth/storage allocation
- All flits in packet follow the same path

Phit (physical transfer digit): data transferred in single clock

Routing vs Flow Control

- Routing algorithm chooses path that packets should follow to get from source to destination
- Flow control schemes allocate resources (buffers, links, control state) to packets traversing the network
- Our approach: Bottom-up
  - Today: Flow control, assuming routes are set
  - Next lecture: Routing algorithms

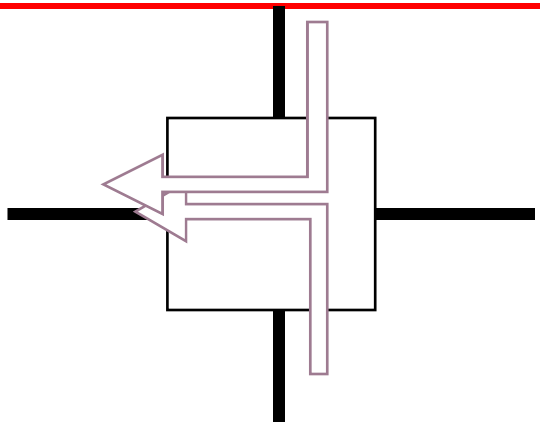
Properties of Routing Algorithms

- Deterministic/Oblivious
  - Route determined by (source, dest), not intermediate state (i.e. traffic)
- Adaptive
  - Route influenced by traffic along the way
- Minimal
  - Only selects shortest paths
- Deadlock-free
  - No traffic pattern can lead to a situation where no packets move forward

(more in next lecture)

Flow Control

Contention



- Two packets trying to use the same link at the same time
  - Limited or no buffering
- Problem arises because we are sharing resources
  - Sharing bandwidth and buffering

Flow Control Protocols

- Bufferless
  - Circuit switching
  - Dropping
  - Misrouting
- Buffered
  - Store-and-forward
  - Virtual cut-through
  - Wormhole
  - Virtual-channel

Complexity & Efficiency

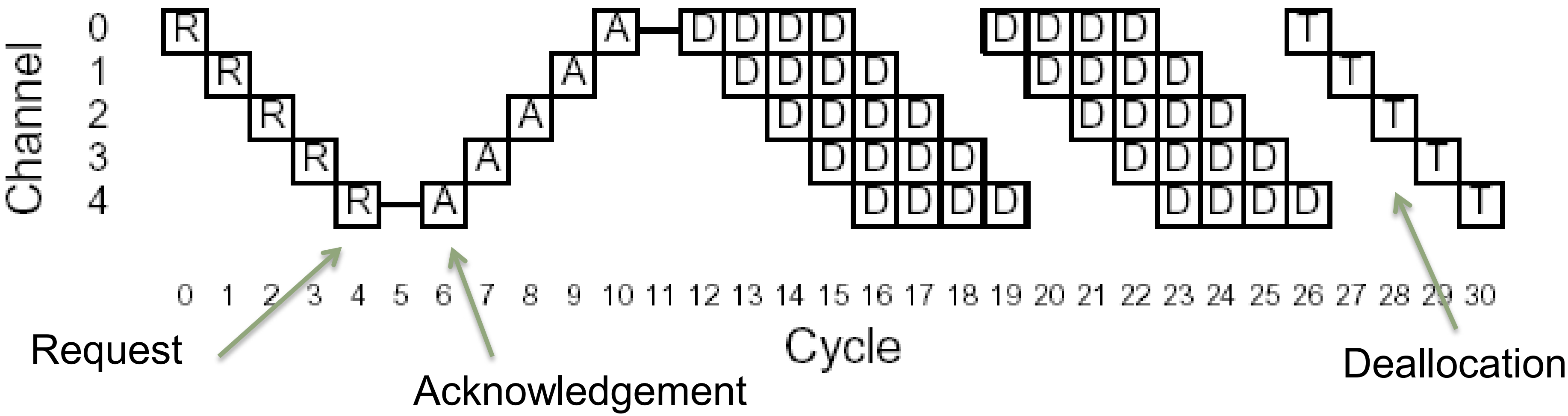
Circuit Switching

- Form a circuit from source to dest

- Probe to set up path through network
- Reserve all links
- Data sent through links

- Bufferless

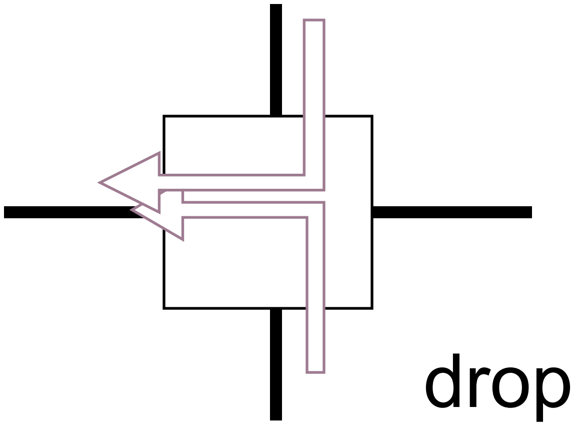
Time-space View: Circuit Switching



- Why is this good? Simple to implement
- Why is it not? Wasteful, increased 3X latency for short packets

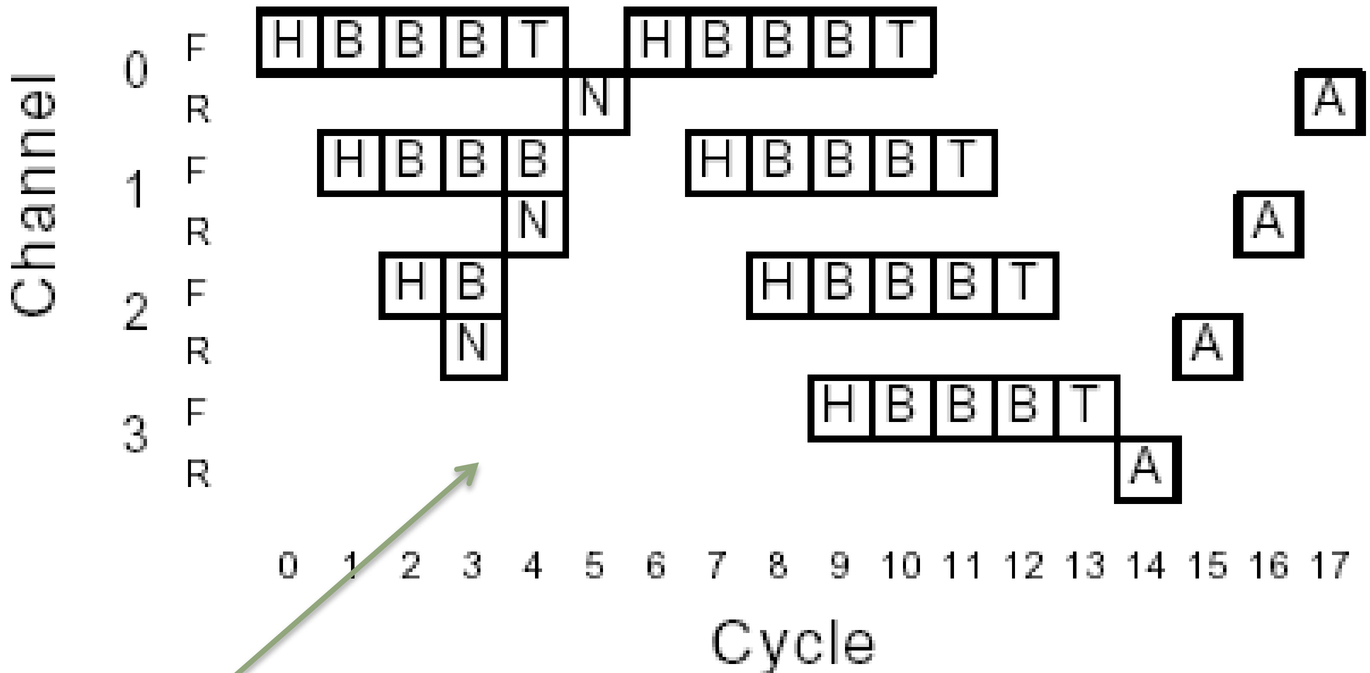
Speculative Flow Control: Dropping

- If two things arrive and I don't have resources, drop one of them
- Flow control protocol on the Internet



Time-space Diagram: Dropping

Retransmission



Unable to allocate channel 3

Disadvantages:

Poor tradeoff of traffic and buffering

Less Simple Flow Control: Misrouting

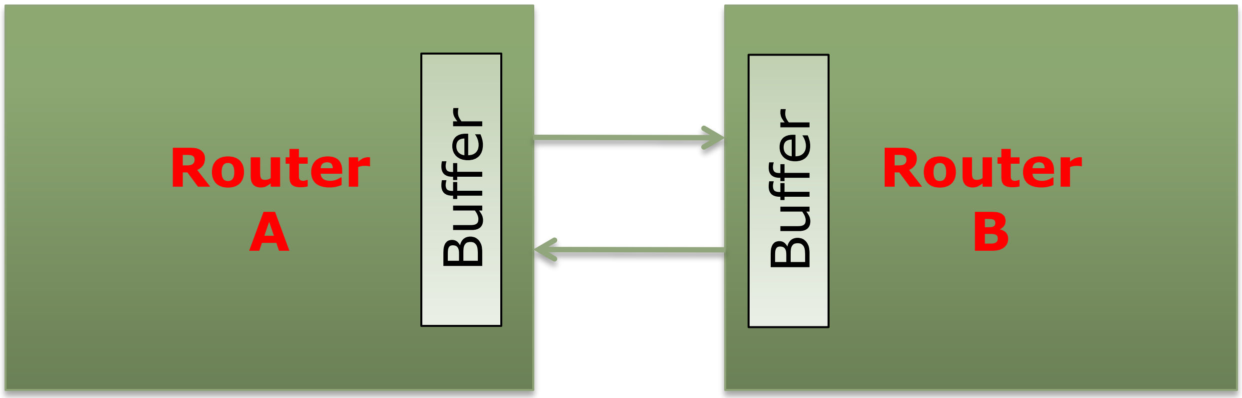
- If only one message can enter the network at each node, and one message can exit the network at each node, the network can never be congested. Right?

Wrong! Multiple hops cause congestion

- Philosophy behind misrouting: intentionally route away from congestion
- No need for buffering
- Problems?

Livelock: need to guarantee that progress is made

Buffered Routing



- Link-level flow control:
  - Given that you can't drop packets, how to manage the buffers? When can you send stuff forward, when not?
- Metrics of interest:
  - Throughput/Latency
  - Buffer utilization (turnaround time)

Techniques for link backpressure

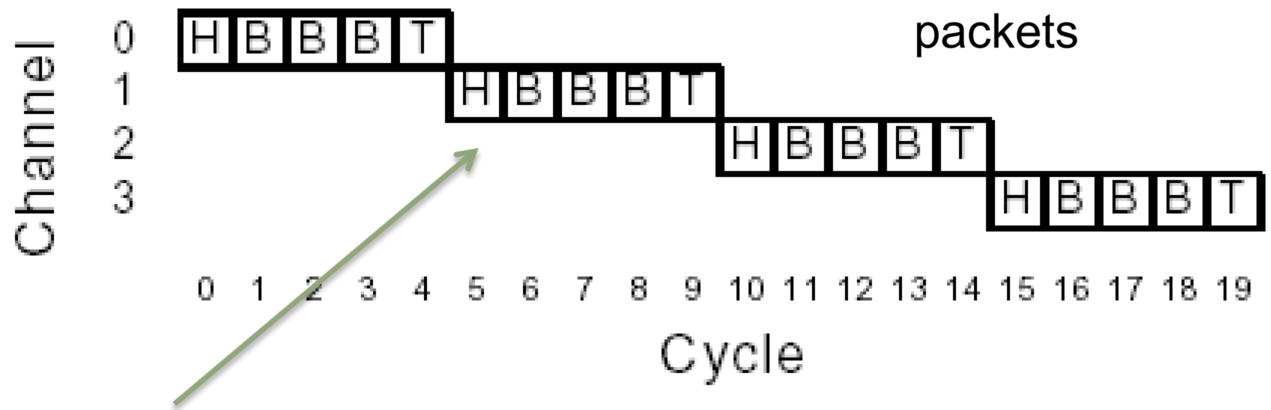
- Naïve stall-based (on/off):
  - Can source send or not?
- Sophisticated stall-based (credit-based):
  - How many flits can be sent to the next node?
- Speculative (ack/nack):
  - Guess can always send, but keep copy
  - Resolve if send was successful (ack/nack)
    - On ack – drop copy
    - On nack - resend

Packet-Buffer Flow Control: Store-and-Forward

- Strategy:
  - Make intermediate stops and wait until the entire packet has arrived before you move on
- Advantage:
  - Other packets can use intermediate links

Time-space View: Store-and-Forward

Flits only shown for consistency, allocation done in terms of packets



Could be allocated at a much later time without packet dropping

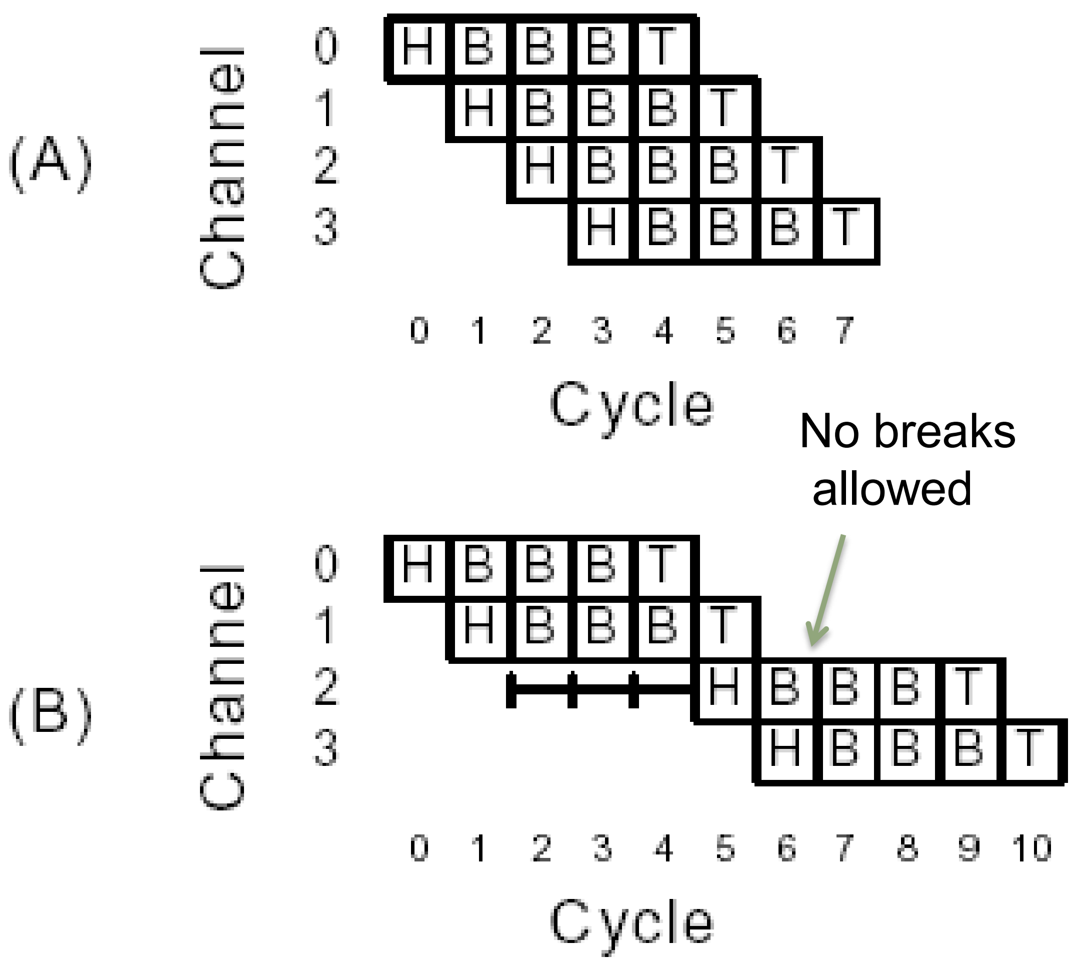
- Buffering allows packet to wait for channel
- Drawback?

Serialization latency experienced at each hop/channel

Virtual Cut-through

- Why wait till entire message has arrived at each intermediate stop?
- The head flit of the packet can dash off first
- When the head gets blocked, whole packet gets blocked at one intermediate node
- Used in Alpha 21364

Time-space View: Virtual Cut-through



- Advantages?

  Reduced latency

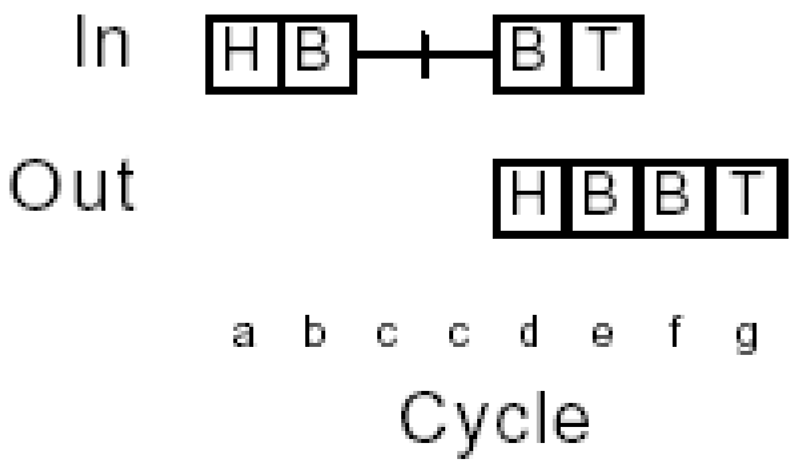
- Disadvantages?

  Allocates channels and buffers in terms of packets reducing utilization and increasing buffer contention

Flit-Buffer Flow Control: Wormhole

- When a packet blocks, just block wherever the pieces (flits) of the message are at that time.
- Operates like cut-through but with channel and buffers allocated to flits rather than packets
  - Channel state (virtual channel) allocated to packet so body flits can follow head flit

Time-space View: Wormhole



- Advantages?
- Disadvantages?

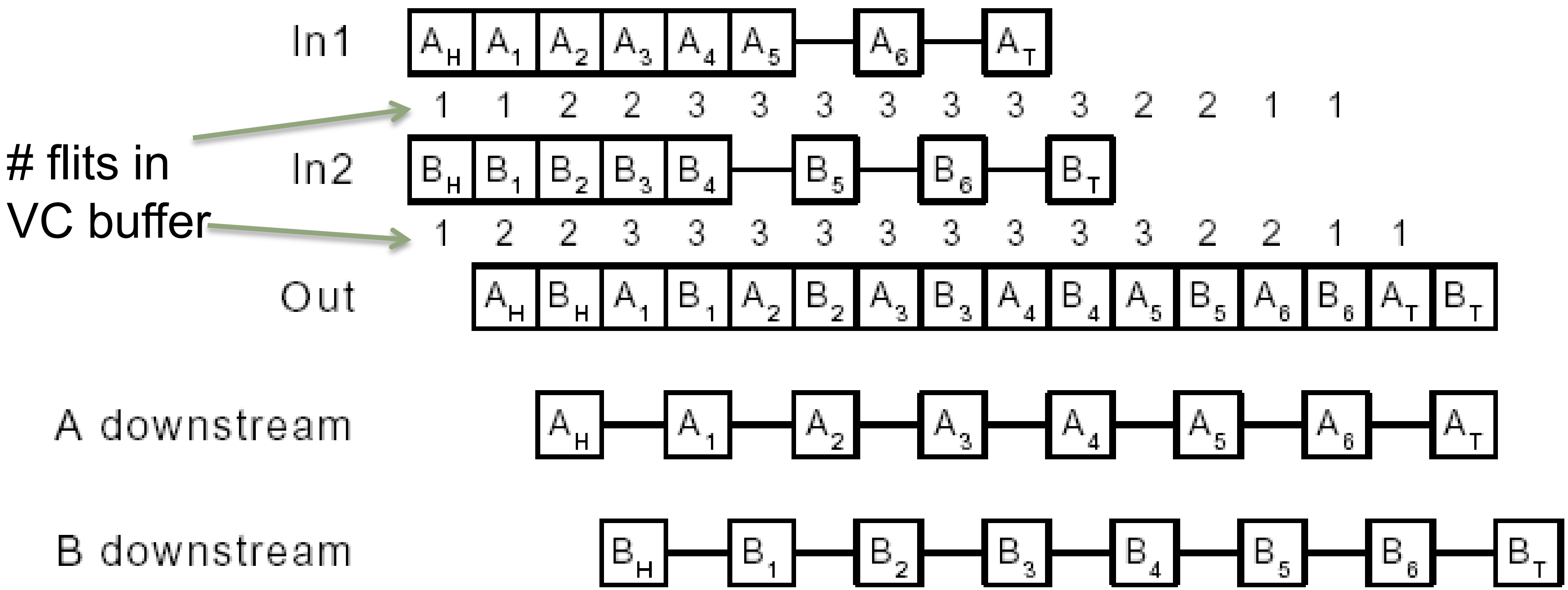
Smaller amount of buffer space required

May block a channel mid-packet, another packet cannot use bandwidth

Virtual-Channel (VC) Flow Control

- When a message blocks, instead of holding on to links so others can't use them, hold on to virtual links
- Multiple queues in buffer storage
  - Lanes on the highway
- Virtual channel can be thought of as channel state and flit buffers

Time-space View: Virtual-Channel



- Advantages? Significantly reduces blocking
- Disadvantages? More complex router, fair VC allocation required

Next Time:

Router (Switch) Microarchitecture

Routing Algorithms