On-Chip Networks I: Topology/Flow Control

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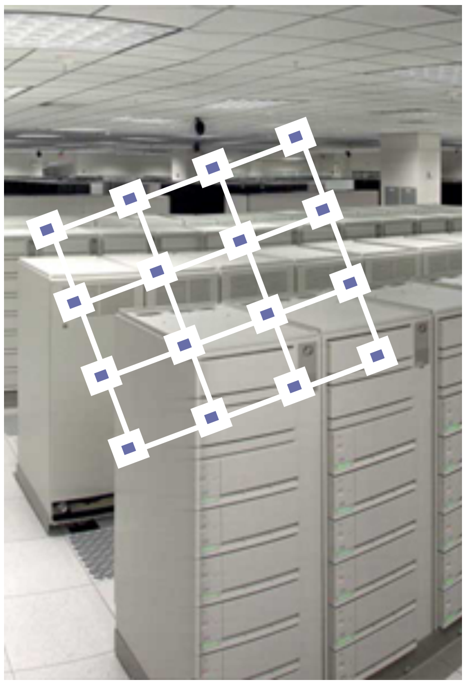
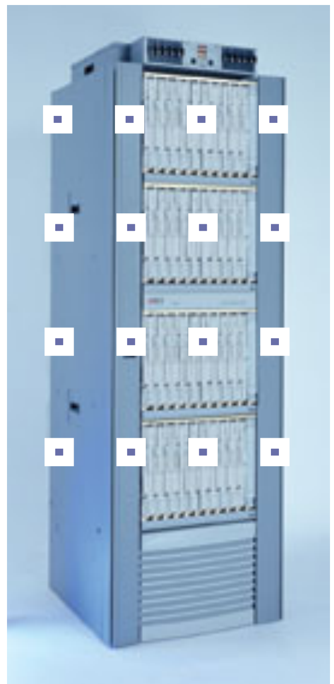
Based on slides from Daniel Sanchez and Onur Mutlu

History: From interconnection networks to on-chip networks

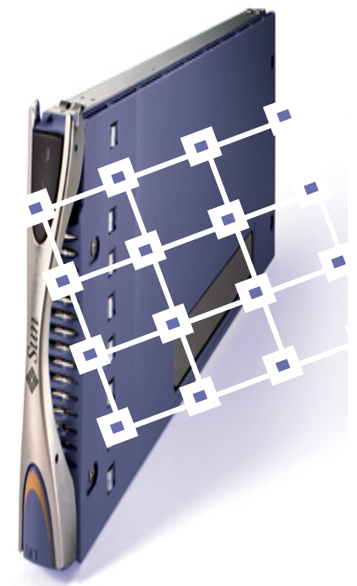
Box-to-box networks



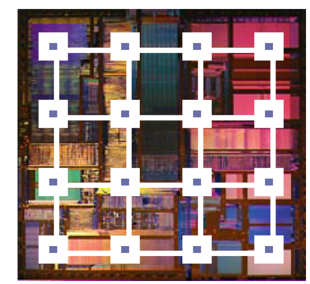
Board-to-board networks



Chip-to-chip networks



On-chip networks



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

History: From interconnection networks to on-chip networks

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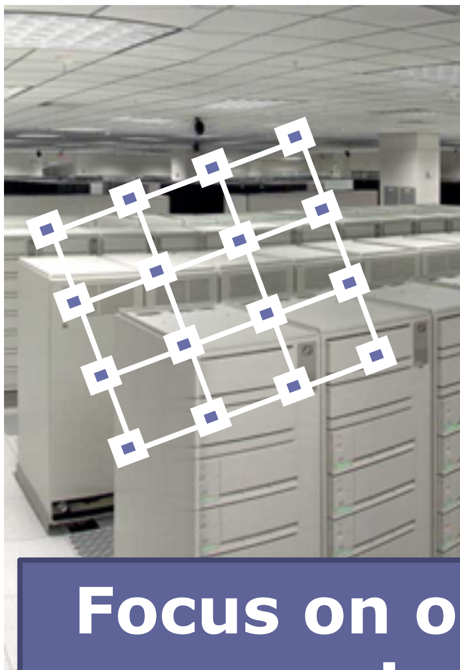

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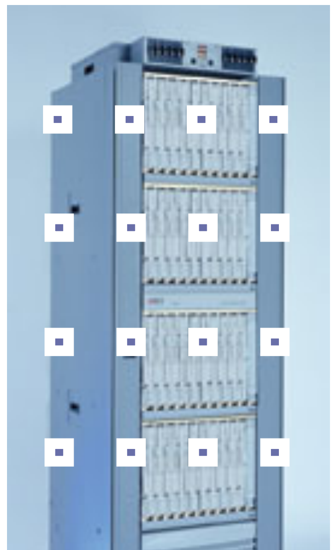

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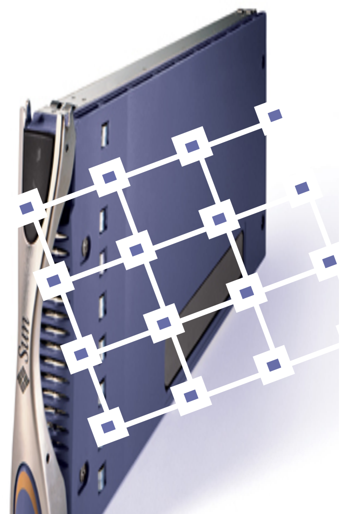

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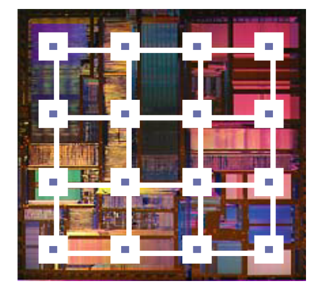
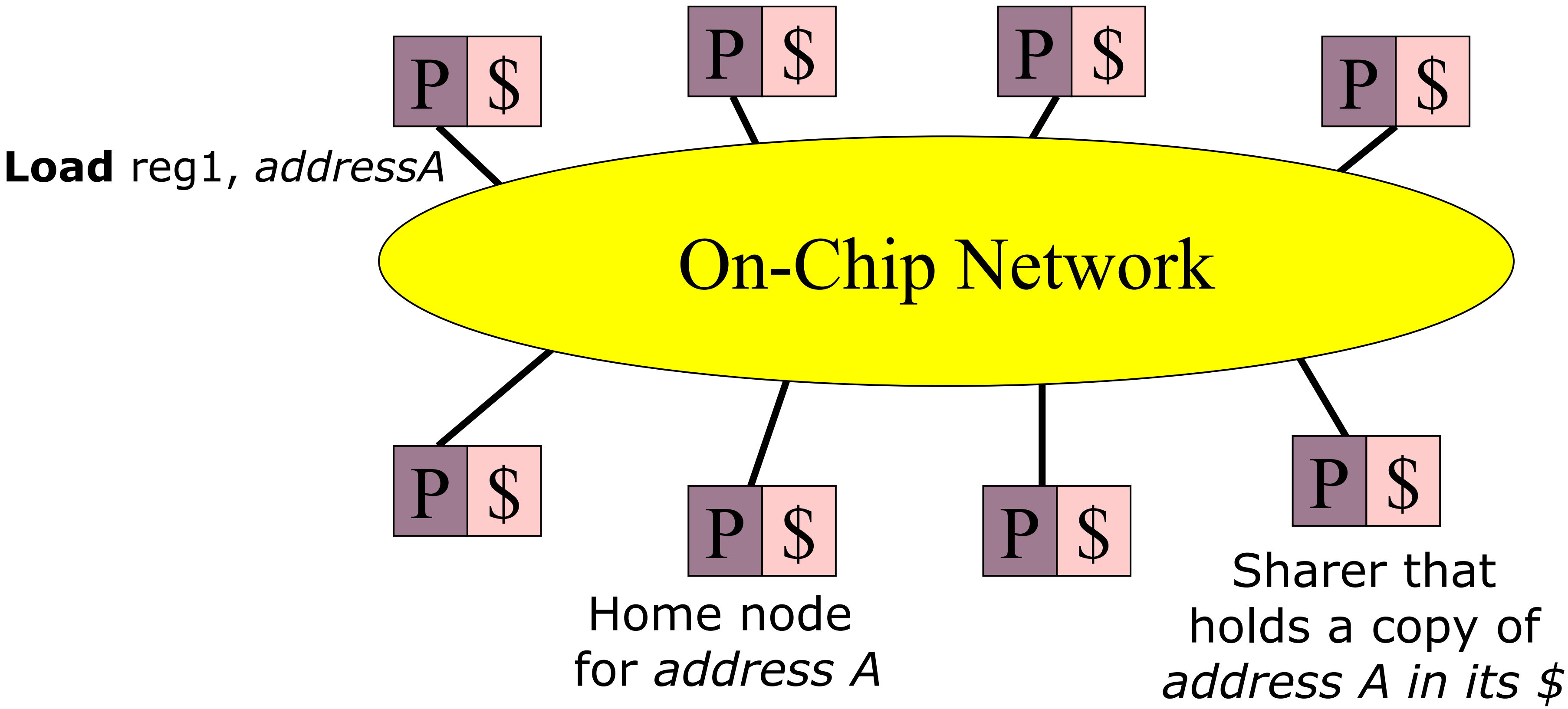


Focus on on-chip networks connecting caches in shared memory processors

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



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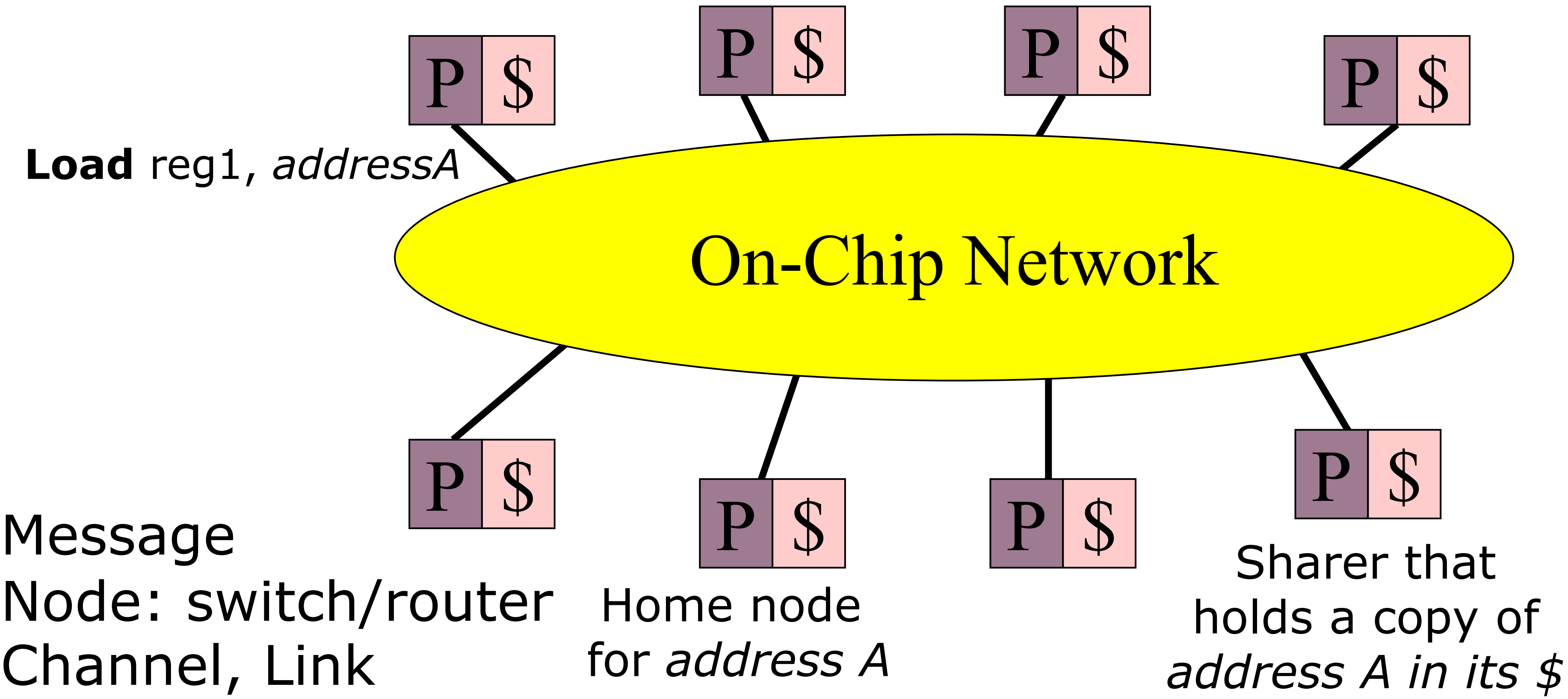

Message
Node: switch/router
Channel, Link

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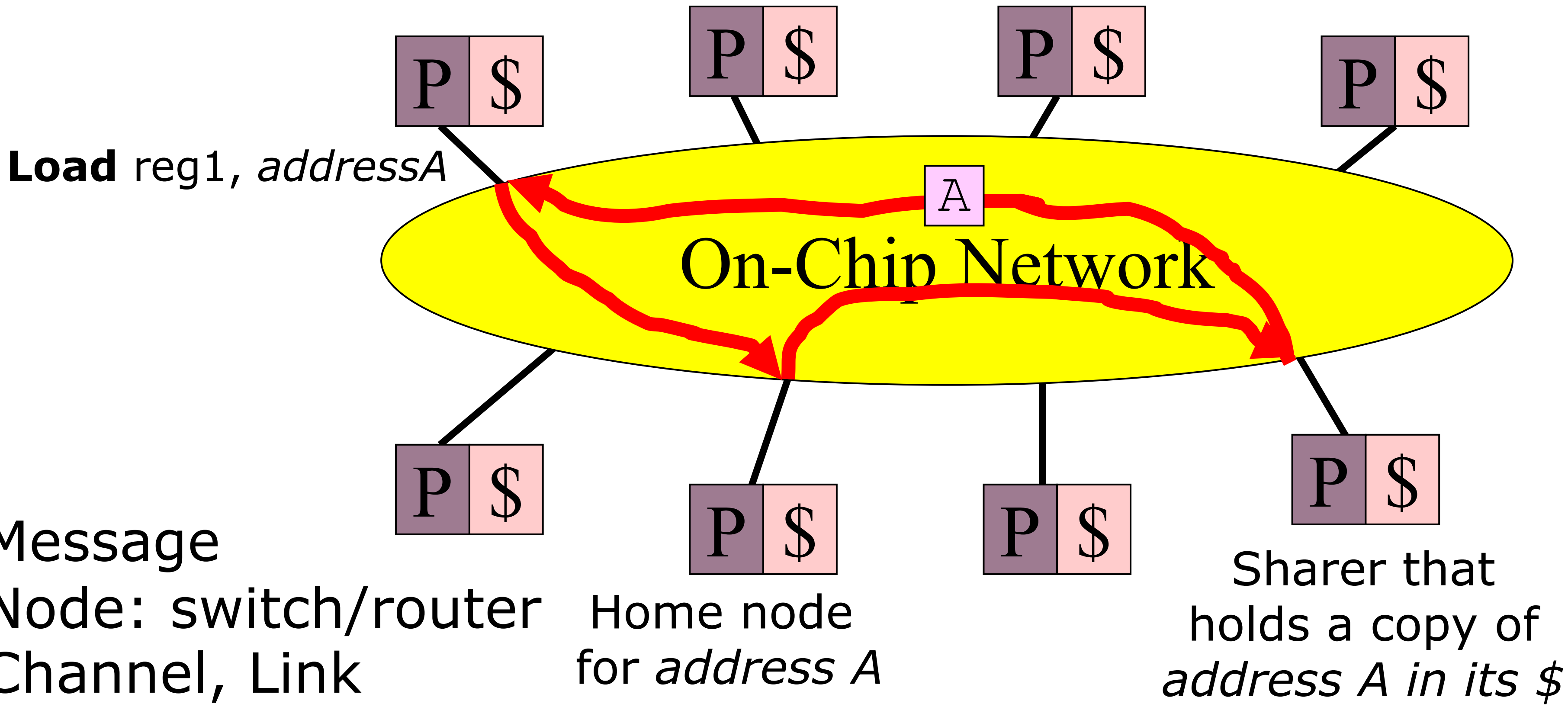

Message
Node: switch/router
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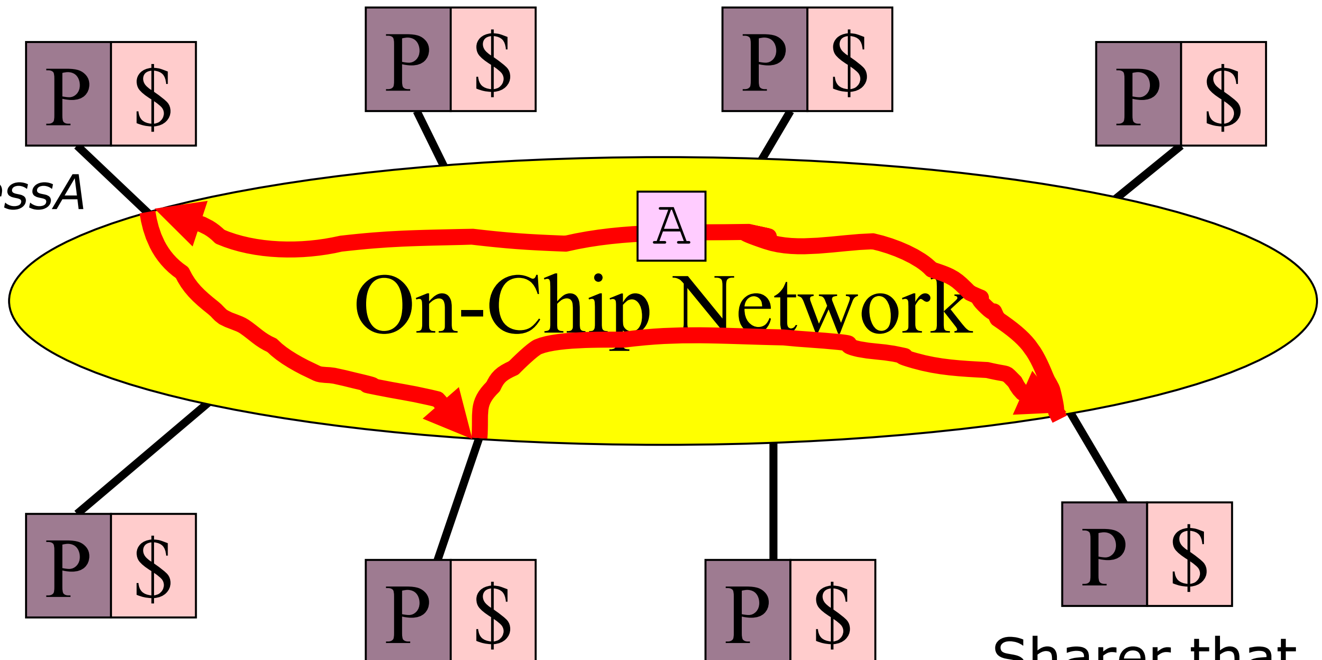
What’s an on-chip network?

E.g. Cache-coherent chip multiprocessor

Load reg1, *addressA*



Message
Node: switch/router
Channel, Link

Home node
for *address A*

Sharer that
holds a copy of
address A in its $

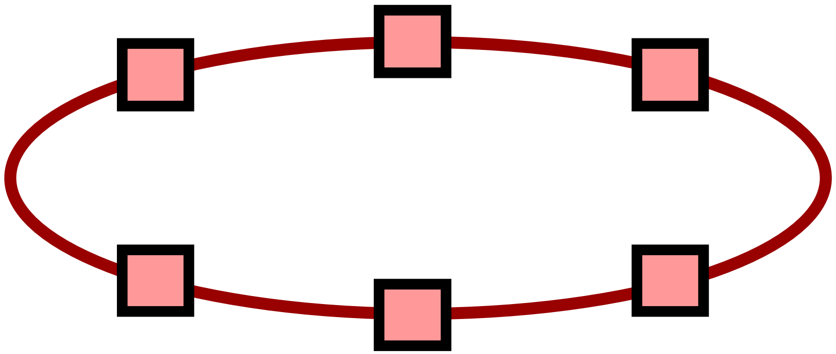
Network transports cache coherence messages and cache lines between processor cores

Designing an on-chip network

Designing an on-chip network

- Topology
  - Latency
  - Scalability

Designing an on-chip network



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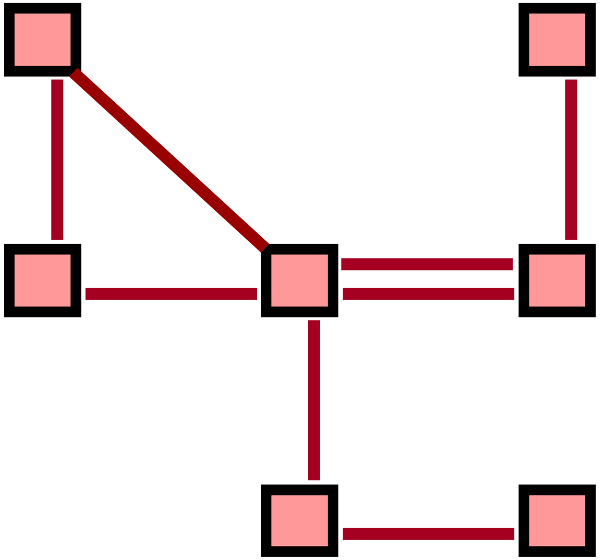

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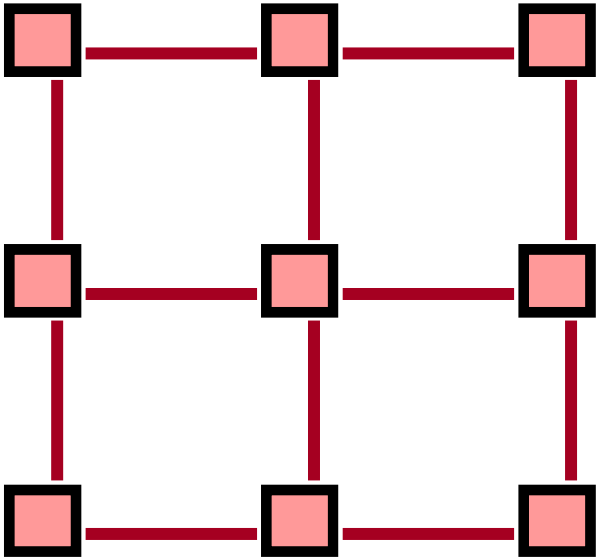

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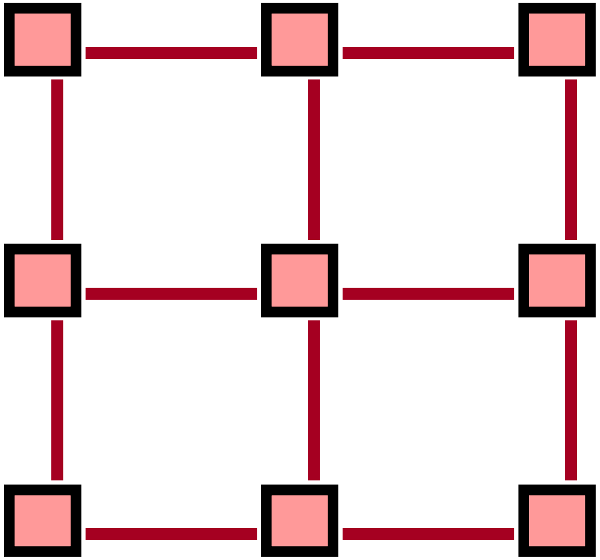

- Topology
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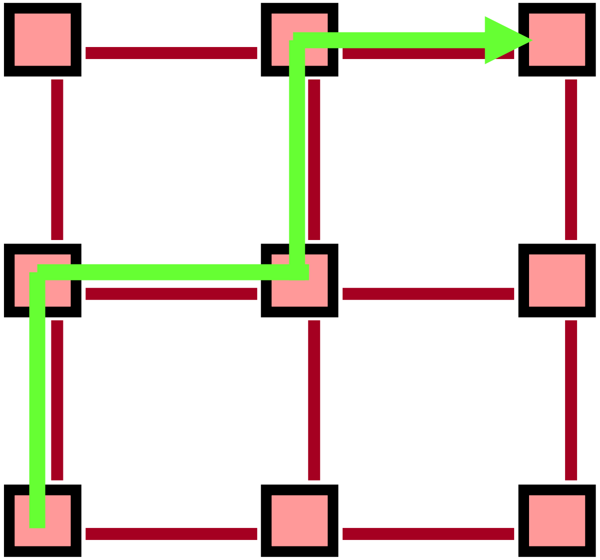
- Routing

Designing an on-chip network



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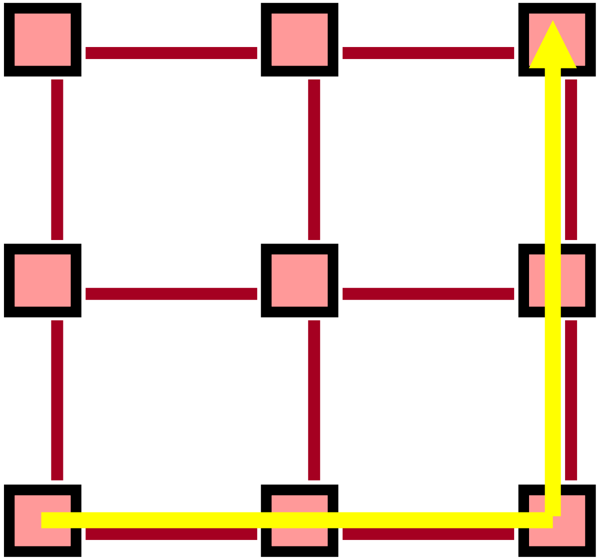

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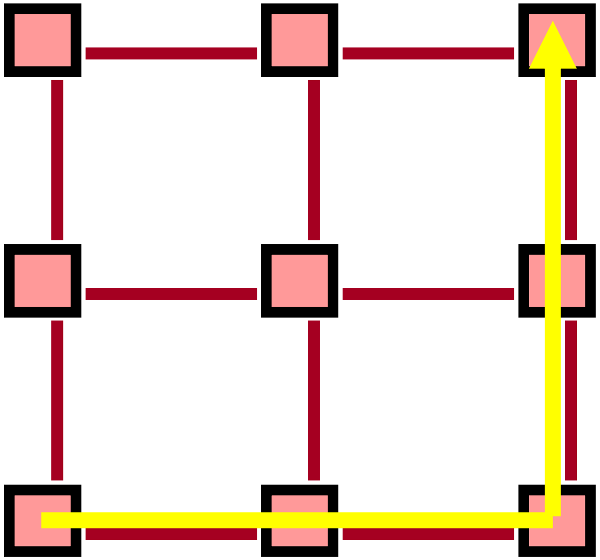

- Topology
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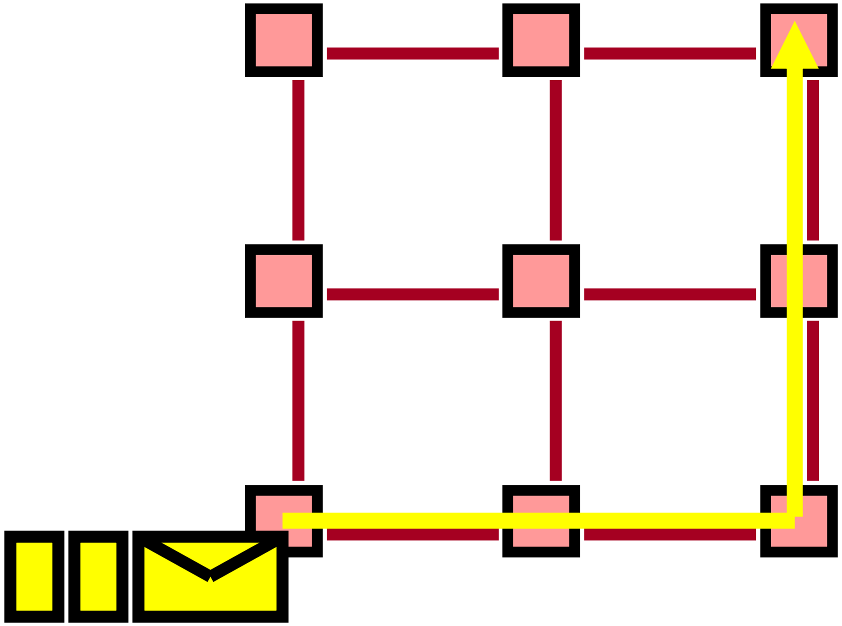
- Routing
- Flow control

Designing an on-chip network



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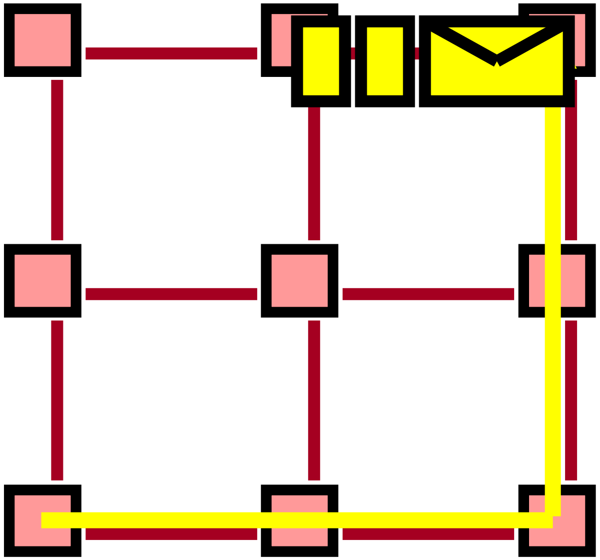

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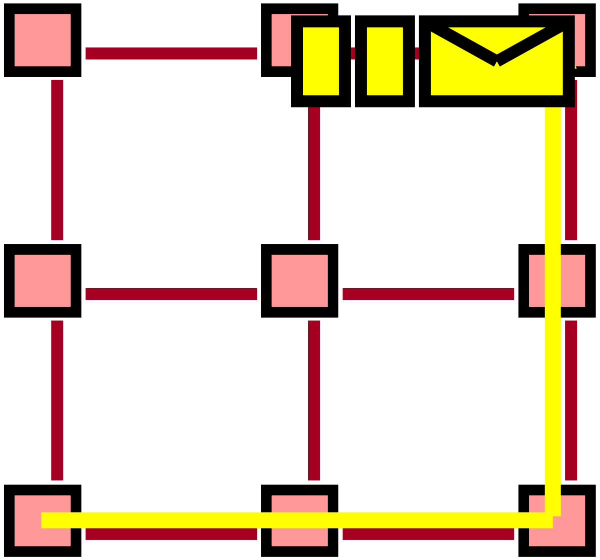
Designing an on-chip network



- Topology
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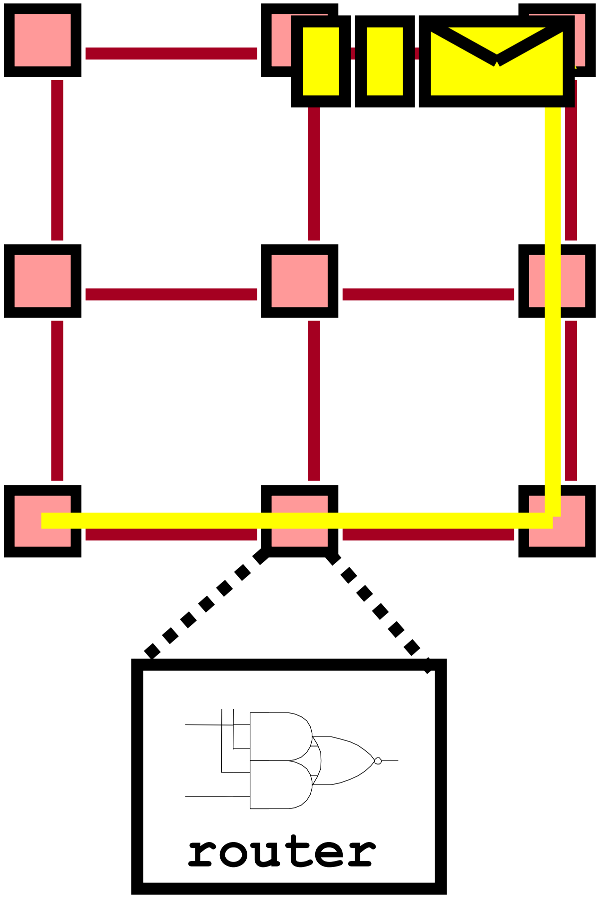
- Router/Link micro-architecture

Designing an on-chip network



- Topology
  - Latency
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- Routing
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Interconnection Network Architecture

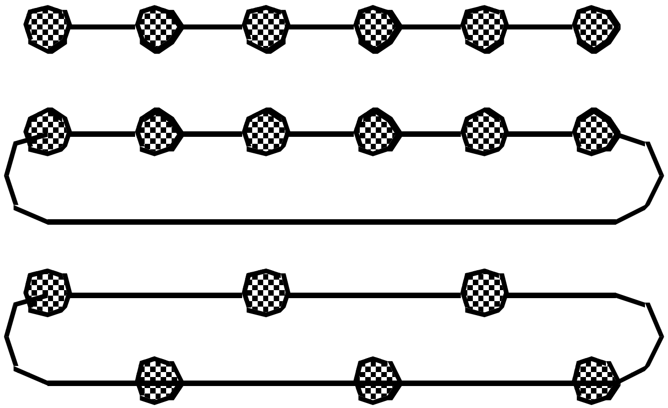
- *Topology*: How to connect the nodes up? (processors, memories, router line cards, …)
- *Routing*: Which path should a message take?
- *Flow control*: How is the message actually forwarded from source to destination?
- *Router microarchitecture*: How to build the routers?
- *Link microarchitecture*: How to build the links?

Topology

Topological Properties

- *Routing Distance* - number of links on route
- *Diameter* - maximum routing distance
- *Average Distance*
- *Bisection Bandwidth*
  - 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

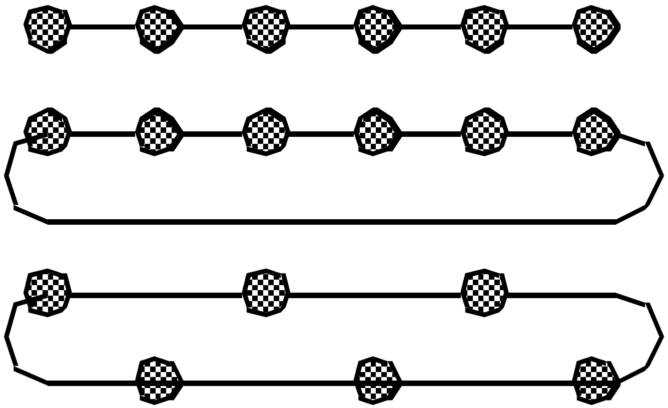


Route A -> B given by relative address R = B-A

	Linear Array	Ring (1-D Torus)
Diameter?		
Average distance?		
Bisection bandwidth?		

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

Linear Arrays and Rings



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

	Linear Array	Ring (1-D Torus)
Diameter?	N-1	
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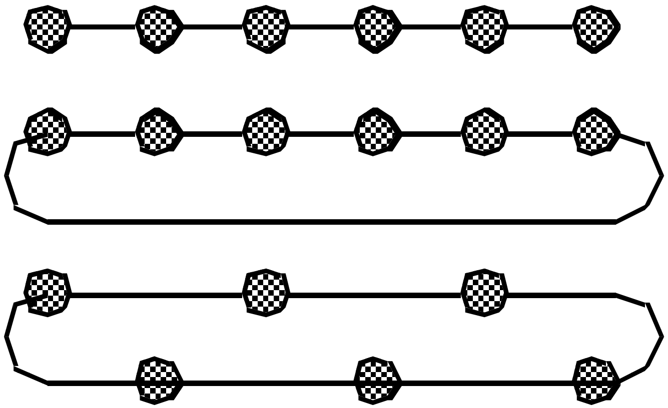
Linear Arrays and Rings



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

	Linear Array	Ring (1-D Torus)
Diameter?	N-1	
Average distance?	N/3-1/(3N)	
Bisection bandwidth?		

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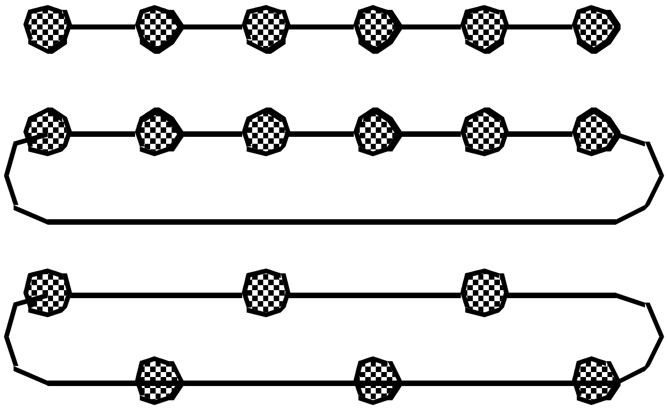
Linear Arrays and Rings



Linear Array

Torus

Torus arranged to use short wires

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

	Linear Array	Ring (1-D Torus)
Diameter?	N-1	
Average distance?	N/3-1/(3N)	
Bisection bandwidth?	1	

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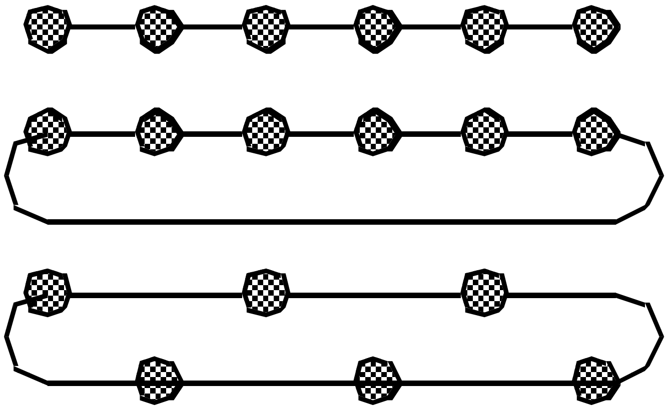
Linear Arrays and Rings



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

	Linear Array	Ring (1-D Torus)
Diameter?	N-1	N/2 (if even N)
Average distance?	N/3-1/(3N)	
Bisection bandwidth?	1	

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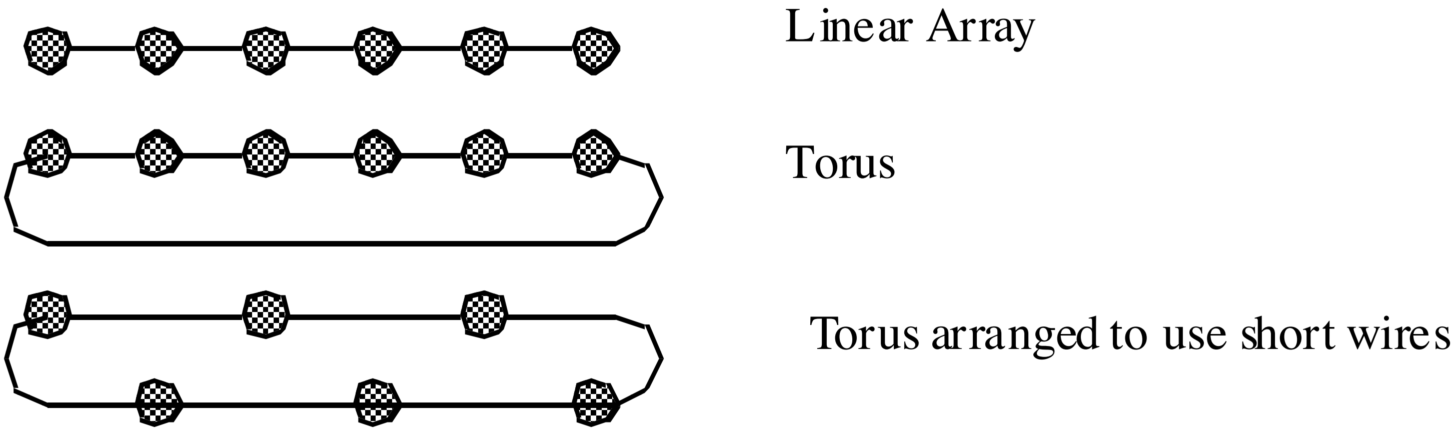
Linear Arrays and Rings



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

	Linear Array	Ring (1-D Torus)
Diameter?	N-1	N/2 (if even N)
Average distance?	N/3-1/(3N)	N/4 (if even N)
Bisection bandwidth?	1	

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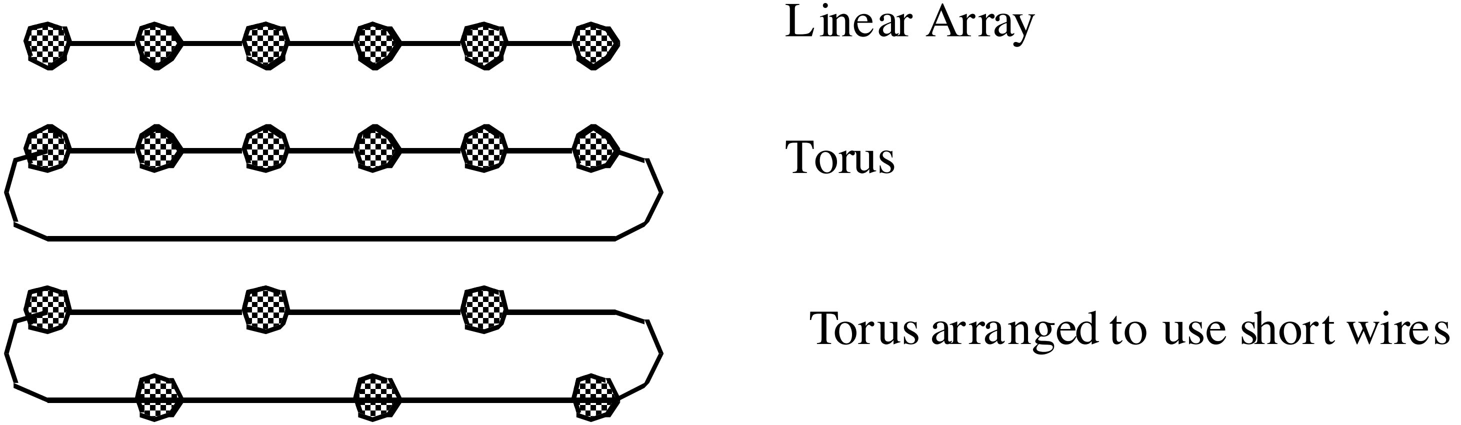
Linear Arrays and Rings



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	Linear Array	Ring (1-D Torus)
Diameter?	N-1	N/2 (if even N)
Average distance?	N/3-1/(3N)	N/4 (if even N)
Bisection bandwidth?	1	2

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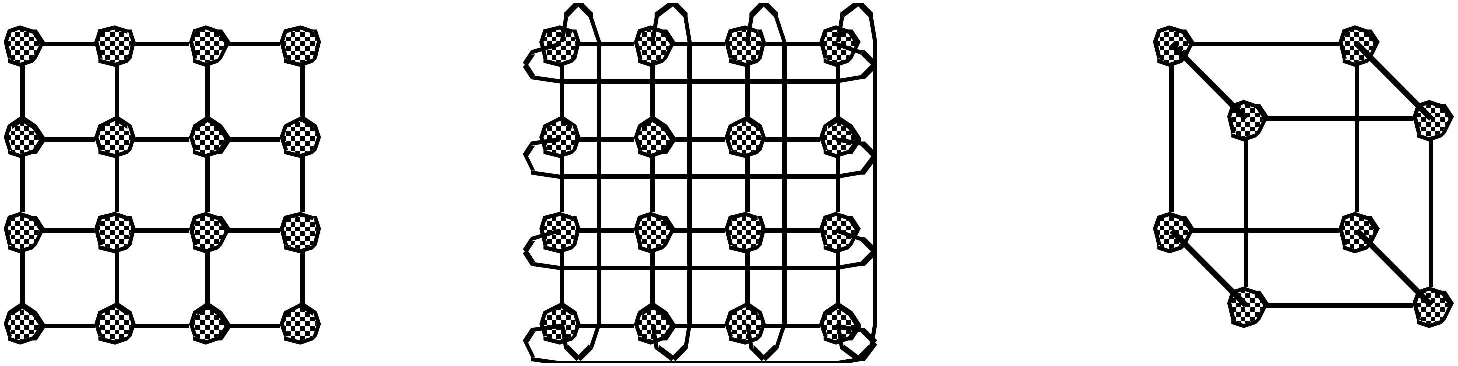
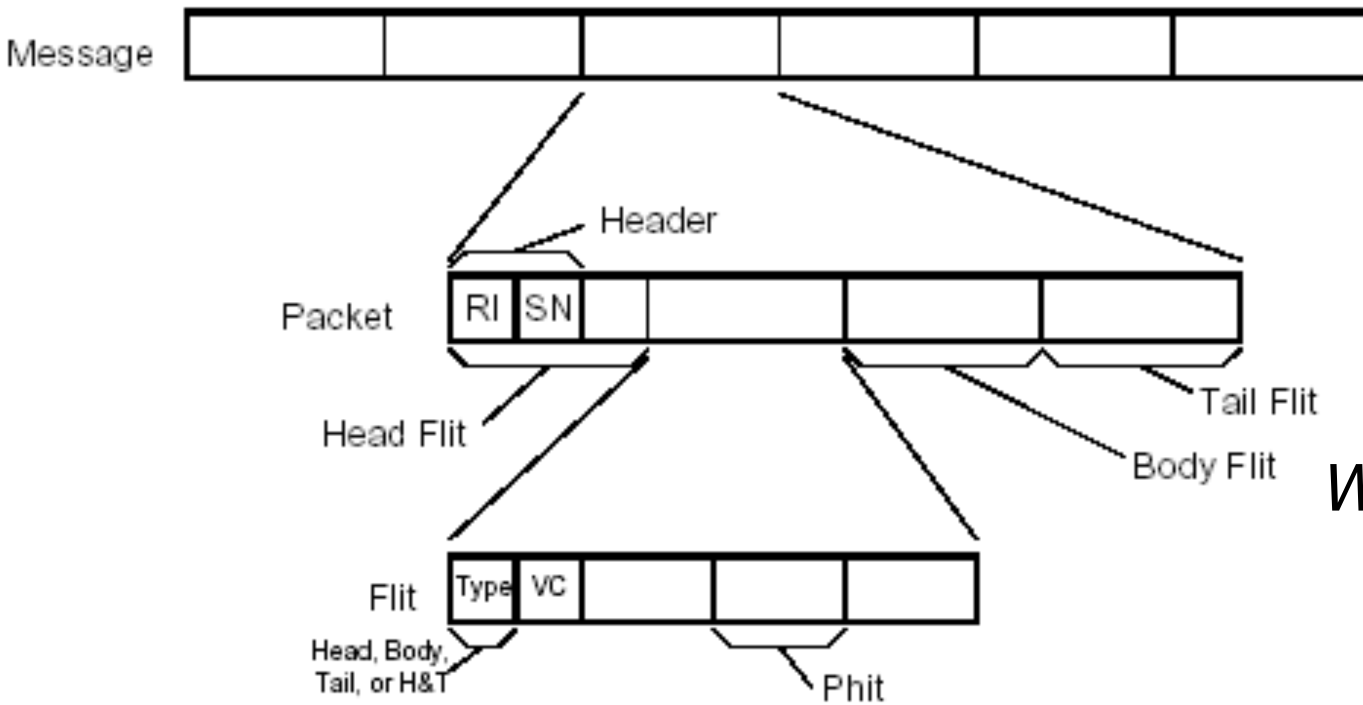
Multidimensional Meshes and Tori



- *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



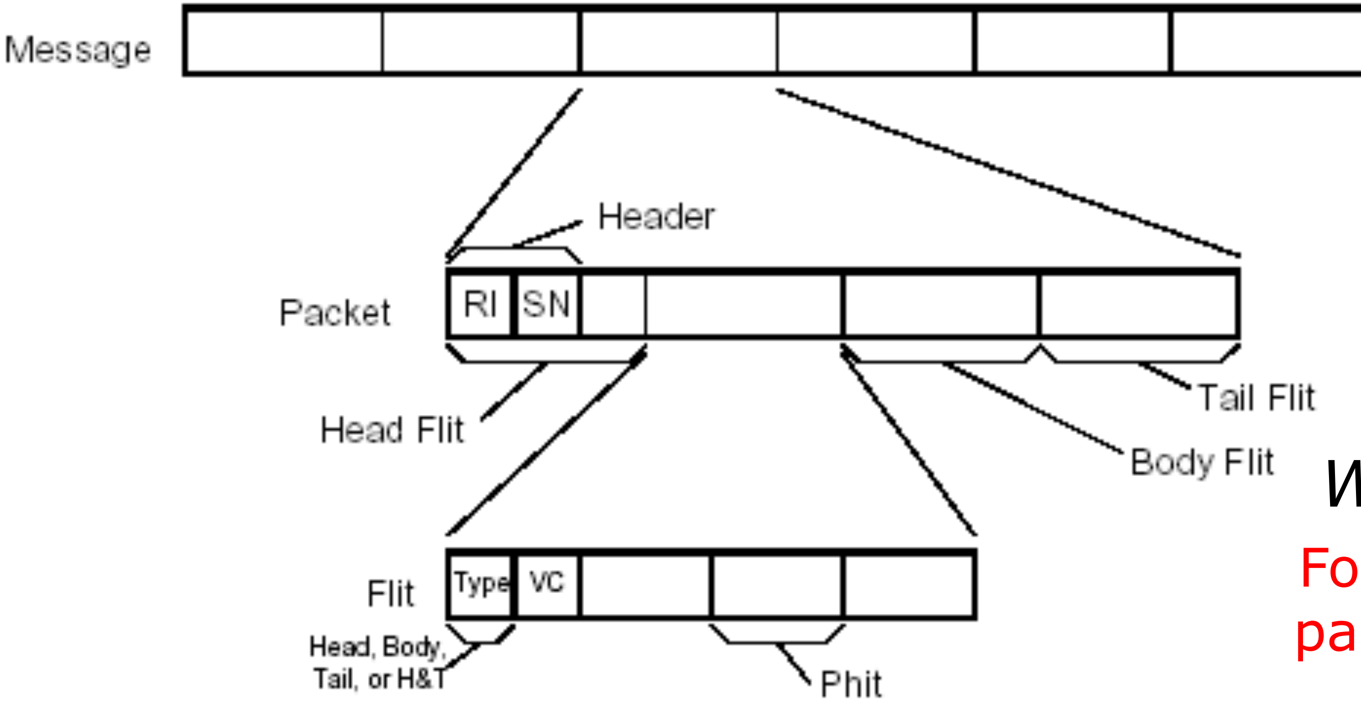
Why flits?

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

Flit: Basic unit of bandwidth/storage allocation
- All flits in packet follow the same path

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

Messages, Packets, Flits, Phits



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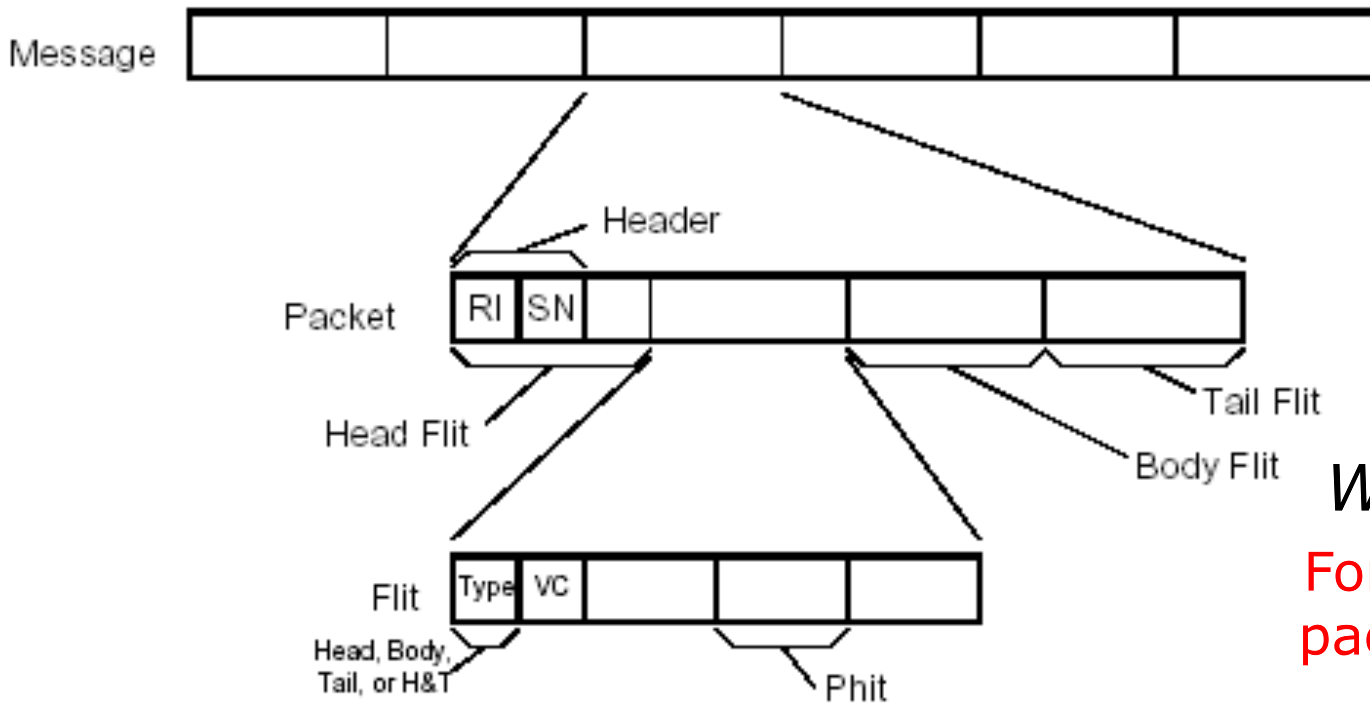


Why flits?

For variable packet sizes

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

Flit: Basic unit of bandwidth/storage allocation → Flow control
- All flits in packet follow the same path

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

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

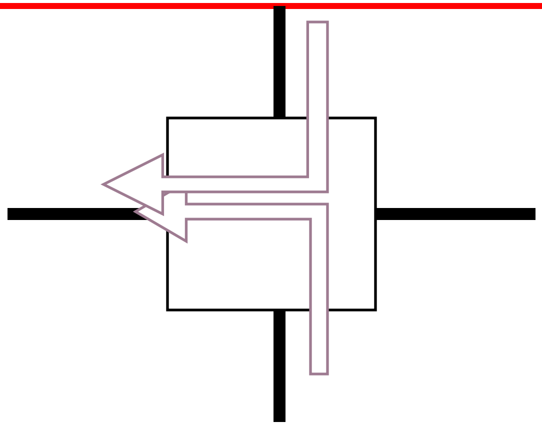
Properties of Routing Algorithms

- 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

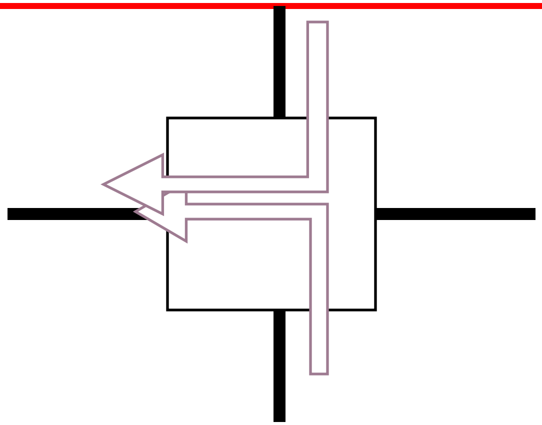
Contention



- Two packets trying to use the same link at the same time

- Problem arises because we are sharing resources
  - Sharing bandwidth and buffers

Contention



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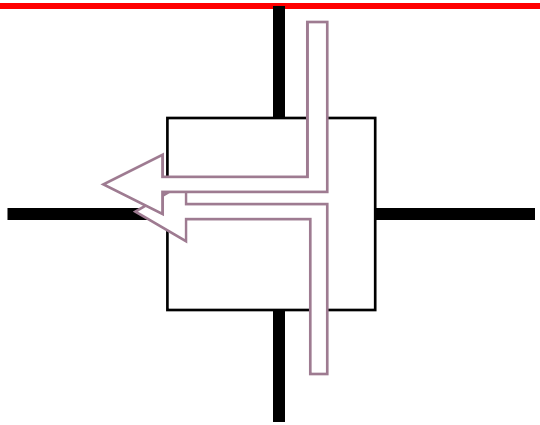

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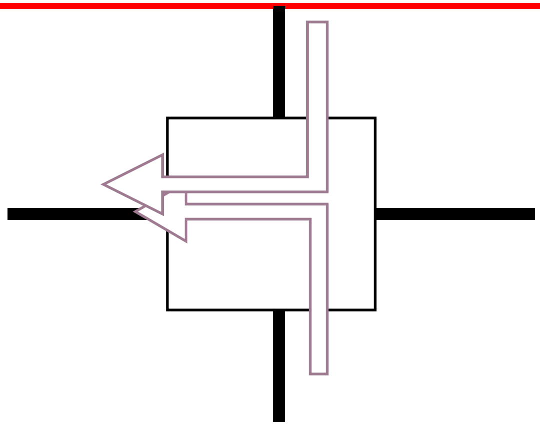

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  - Buffer one
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  - Misroute one (deflection)
- Problem arises because we are sharing resources
  - Sharing bandwidth and buffers

Flow Control Protocols

- Bufferless:

how to allocate channels

  - Circuit switching
  - Dropping
  - Misrouting

- Buffered:

how to allocate buffers and channels

  - Store-and-forward
  - Virtual cut-through
  - Wormhole
  - Virtual-channel

Flow Control Protocols

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−

Complexity & Efficiency

+

Circuit Switching

- Form a circuit from source to dest

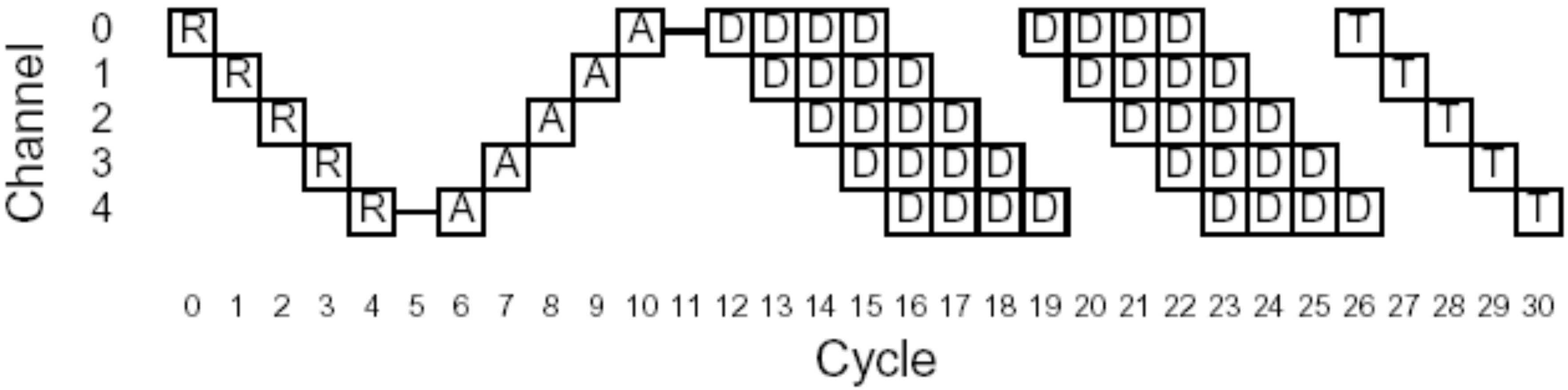
Circuit Switching

- 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?*
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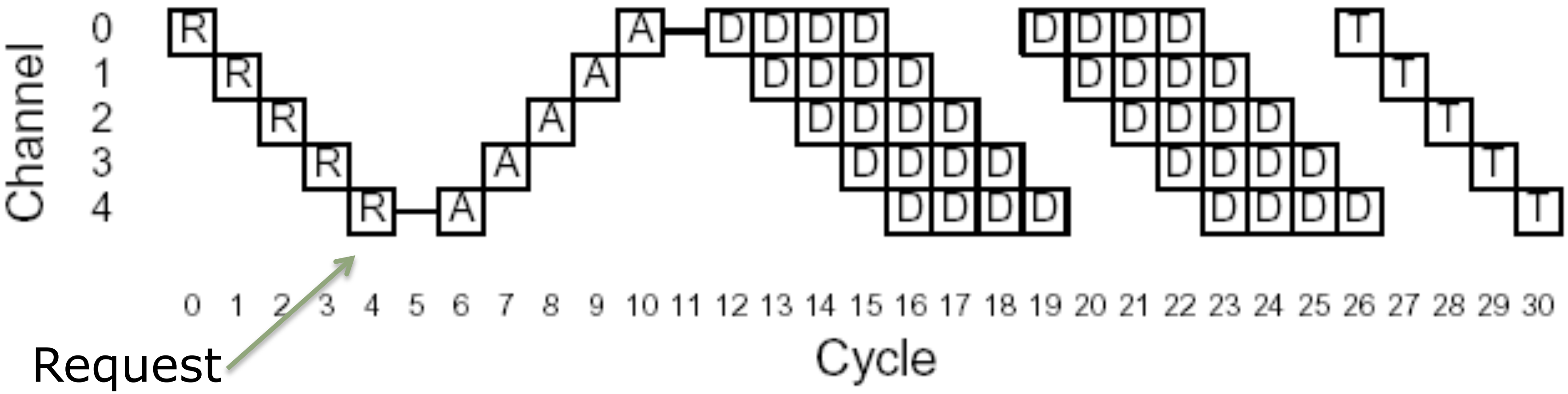

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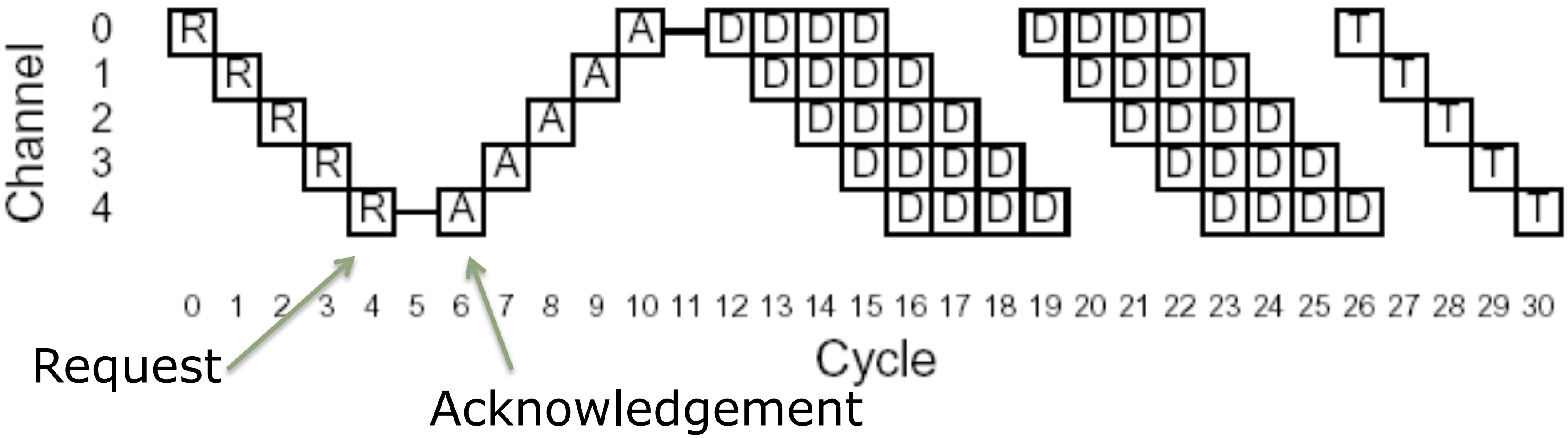

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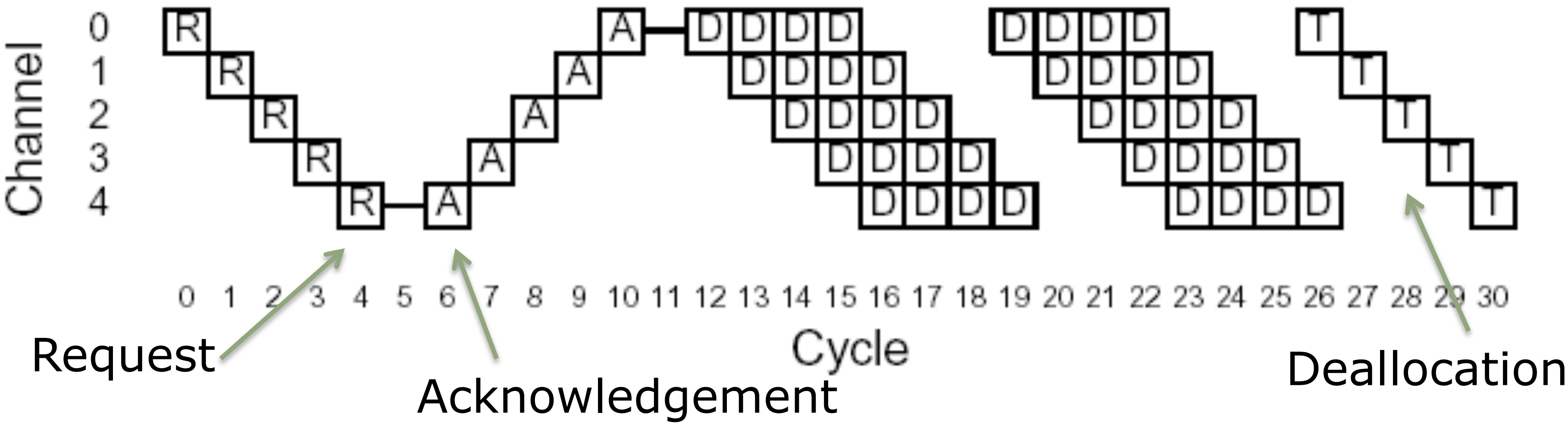

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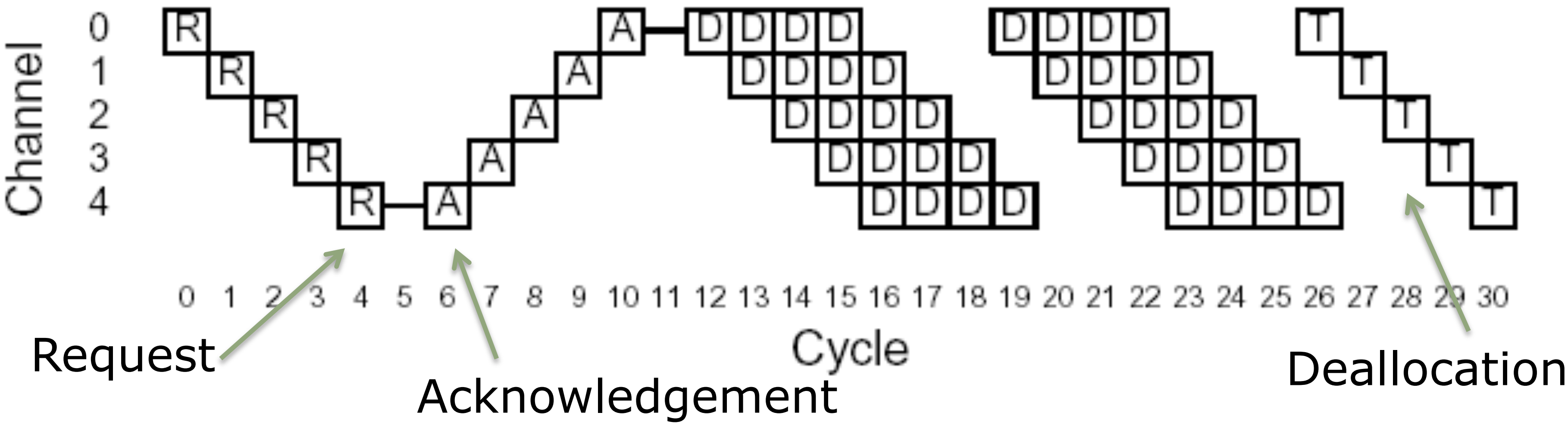

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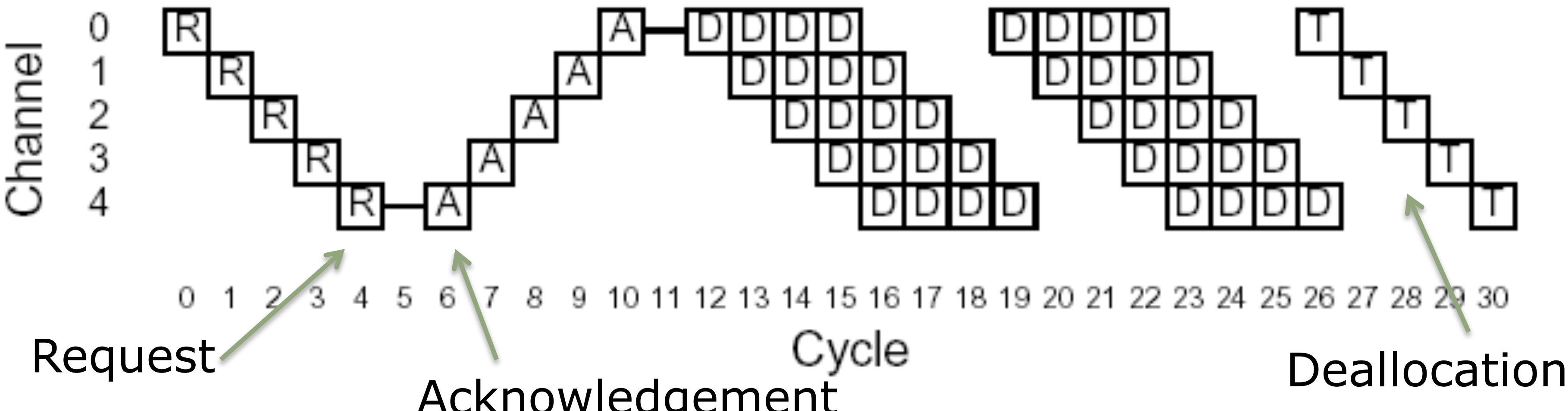
- *Why is it not?*

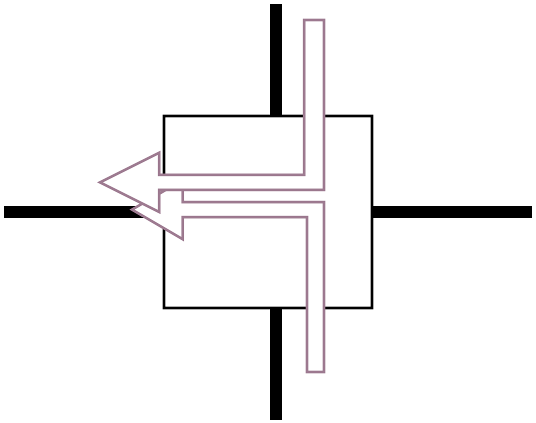
Time-space View: Circuit Switching



- *Why is this good?* Simple to implement
- *Why is it not?* Wasteful, 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



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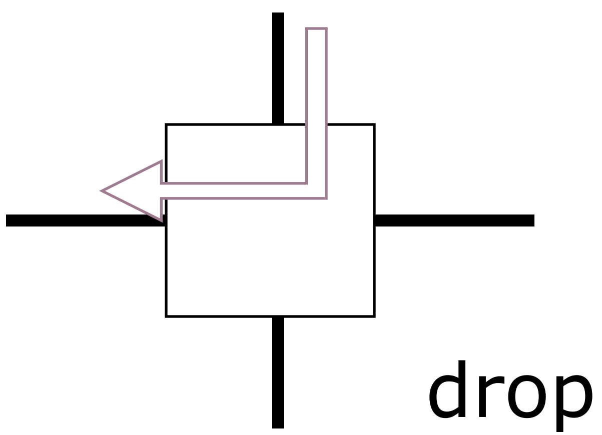
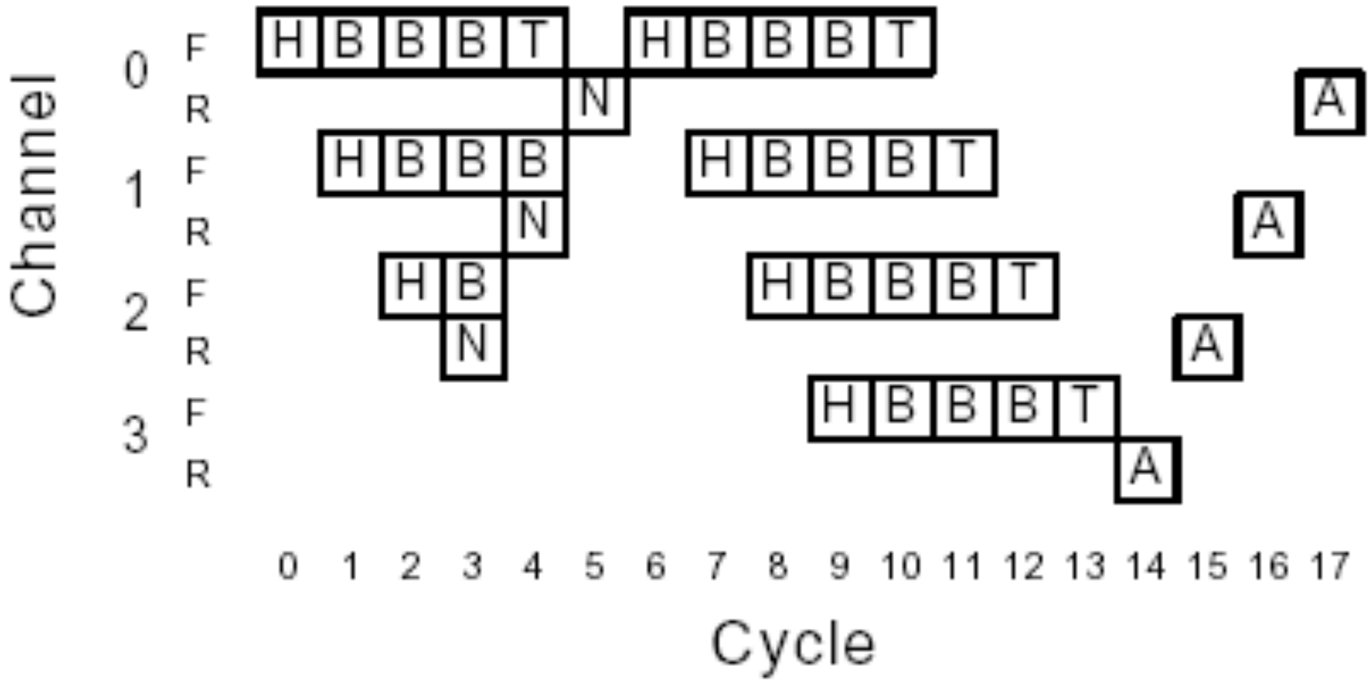
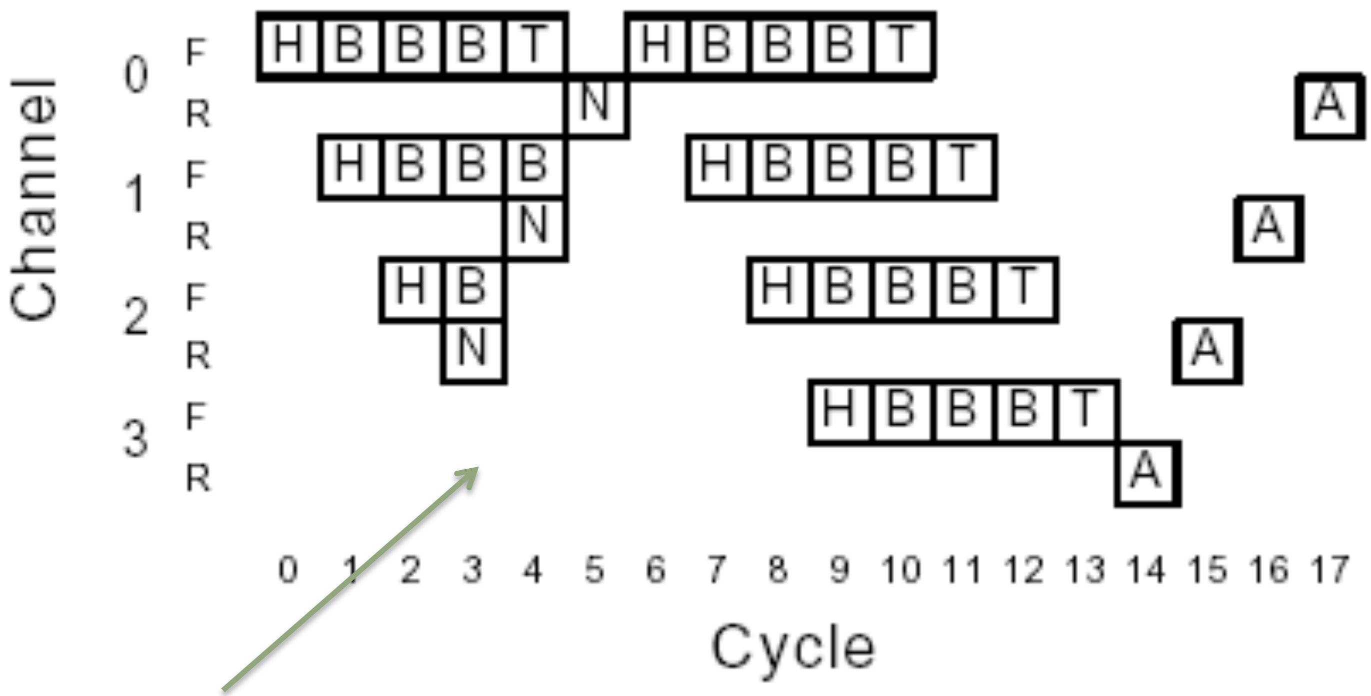


Time-space Diagram: Dropping



Disadvantages?

Time-space Diagram: Dropping

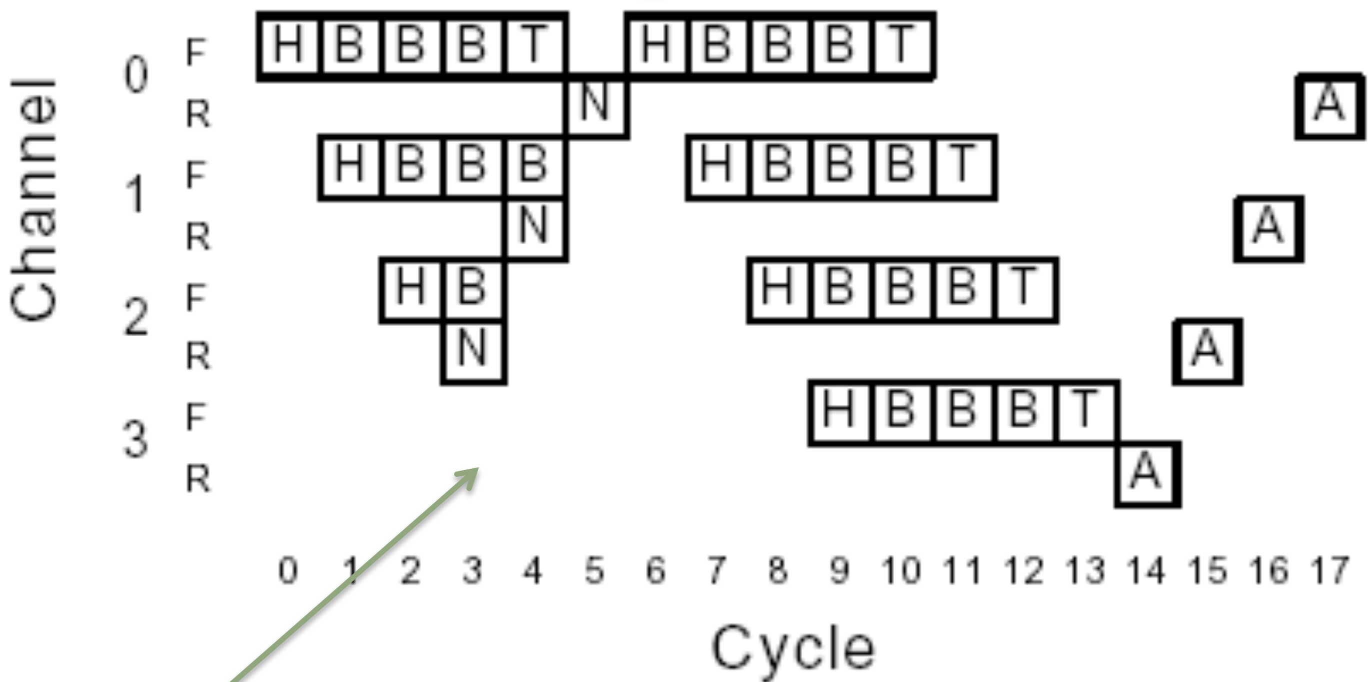


Unable to allocate channel 3

Disadvantages?

Time-space Diagram: Dropping

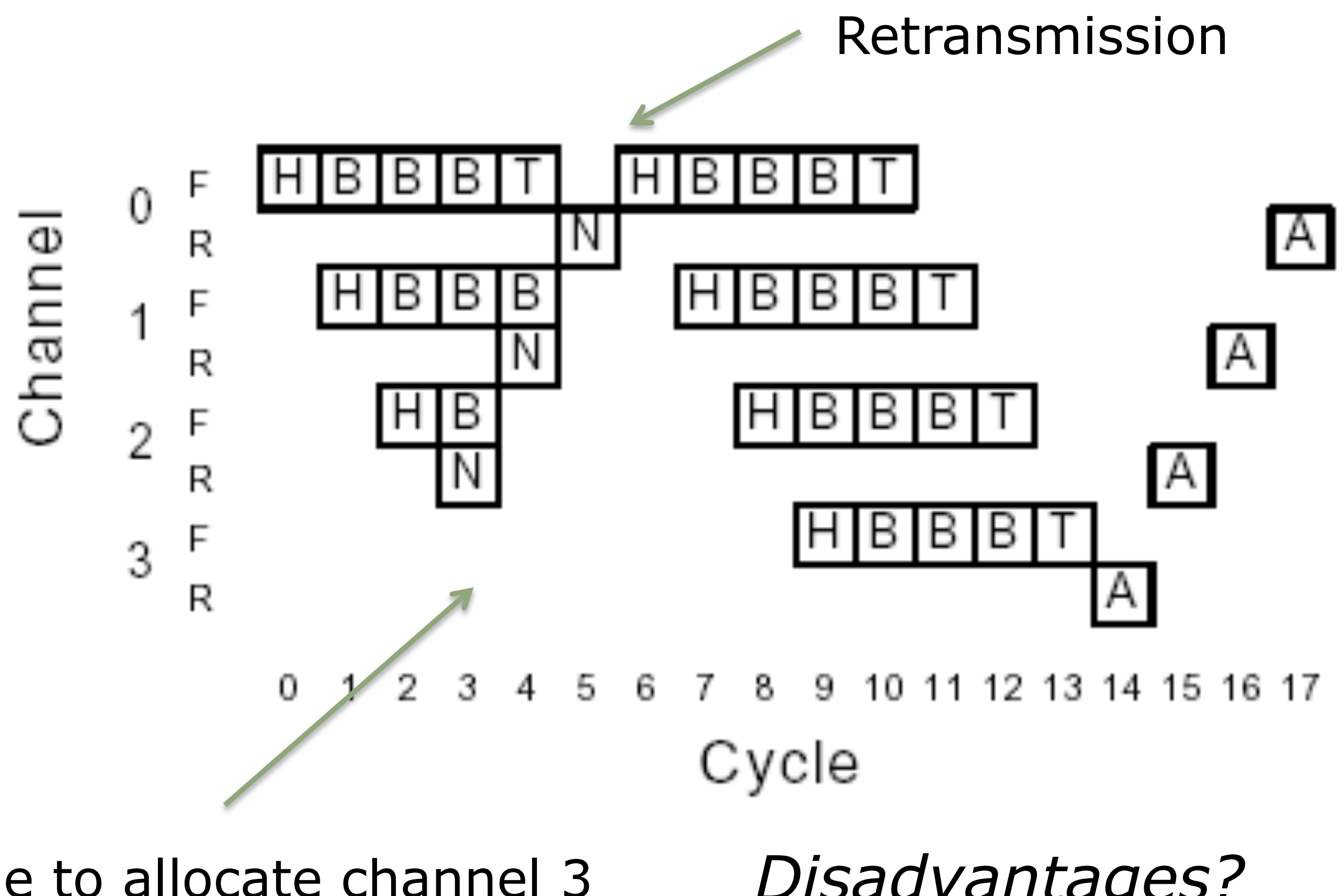
Retransmission



Unable to allocate channel 3

Disadvantages?

Time-space Diagram: Dropping

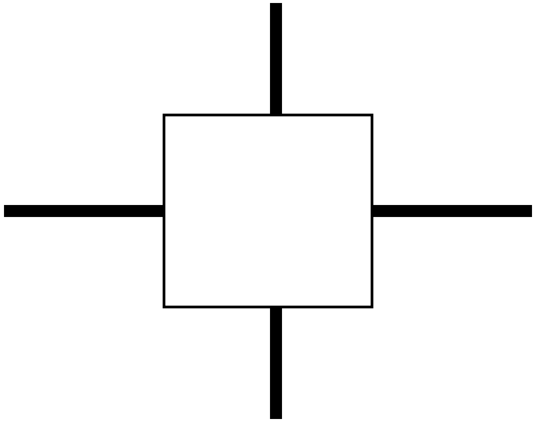


Disadvantages?

Poor tradeoff of traffic and buffering

Less Simple Flow Control: Misrouting

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



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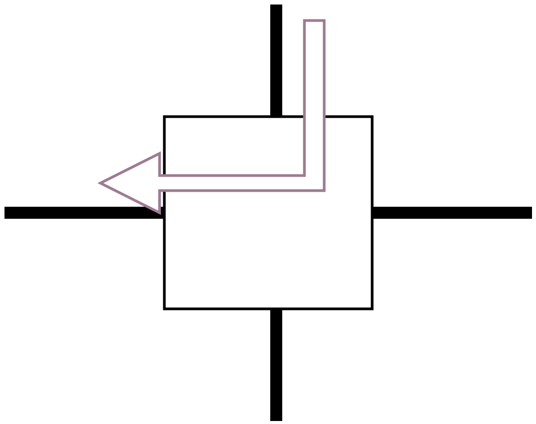

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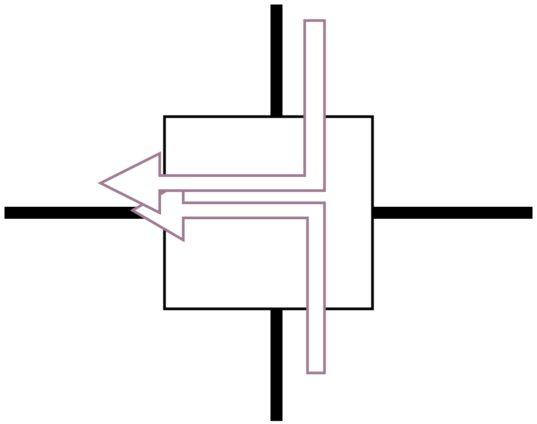

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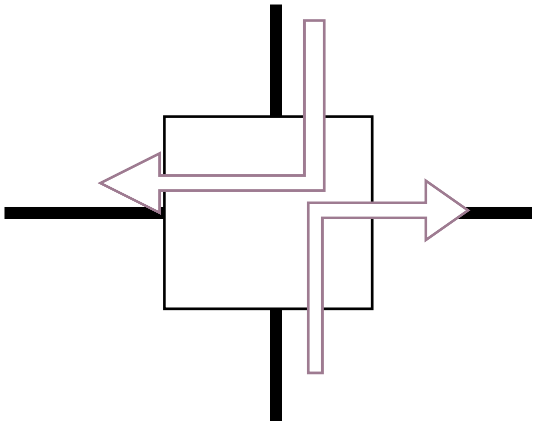

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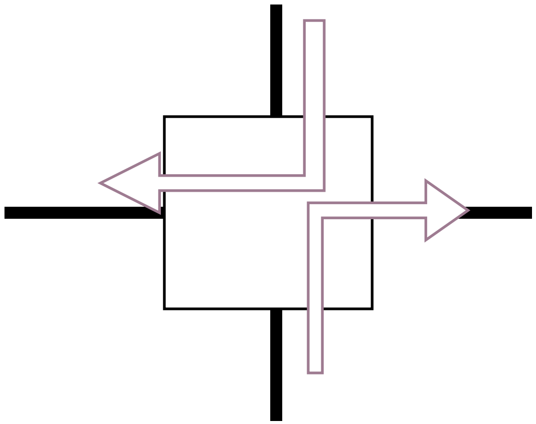

Less Simple Flow Control: Misrouting

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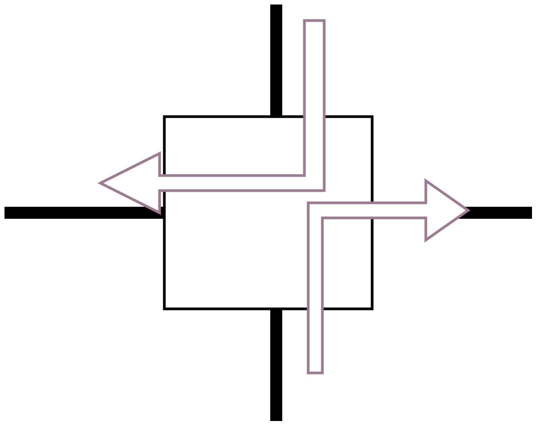
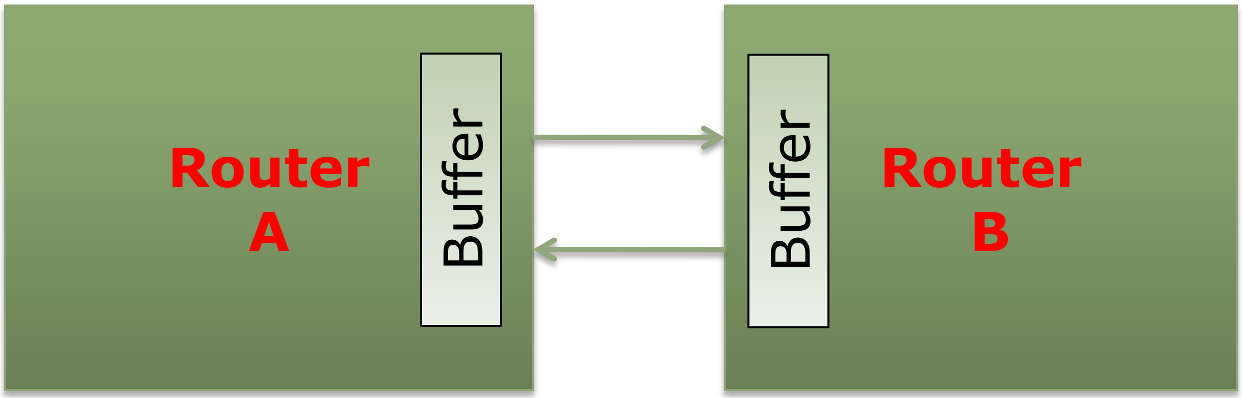
- No need for buffering
- Problems?

Livelock: need to guarantee that progress is made



Buffered Routing

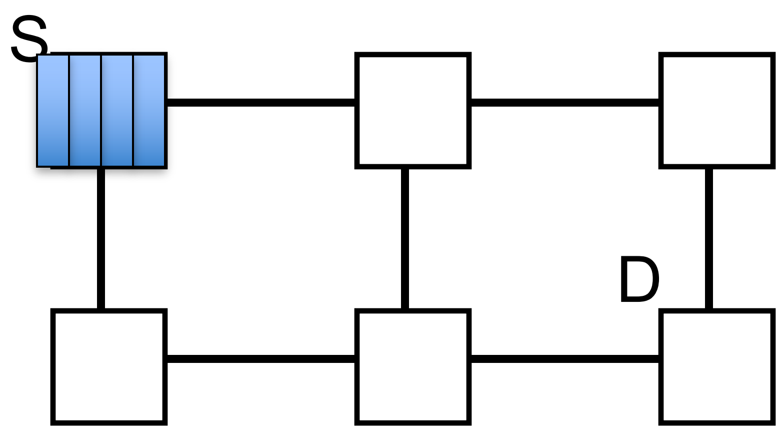


- Link-level flow control:
  - Given that you can’t drop packets, how to manage the buffers? When can you send stuff forward, when not?

- Metrics of interest:
  - Throughput/Latency
  - Buffer utilization (turnaround time)

Store-and-Forward (packet-based)

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



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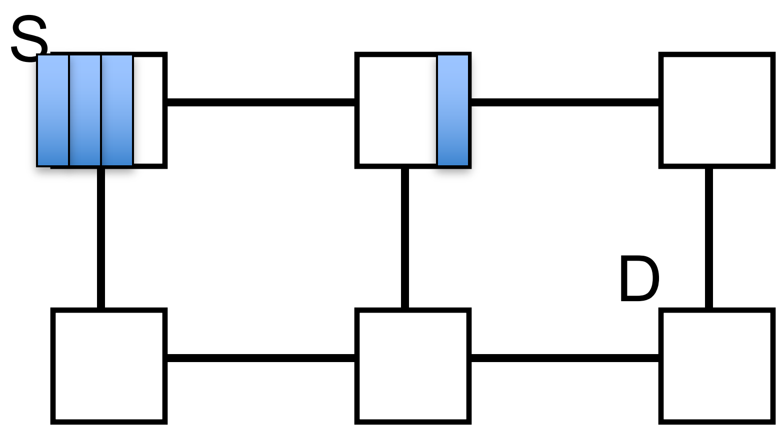

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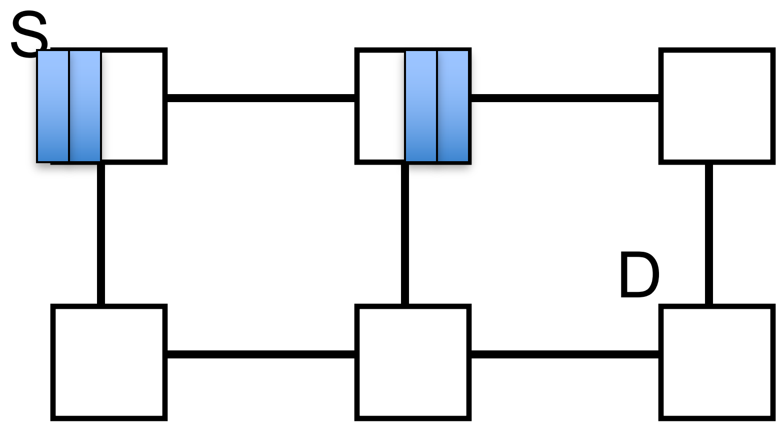

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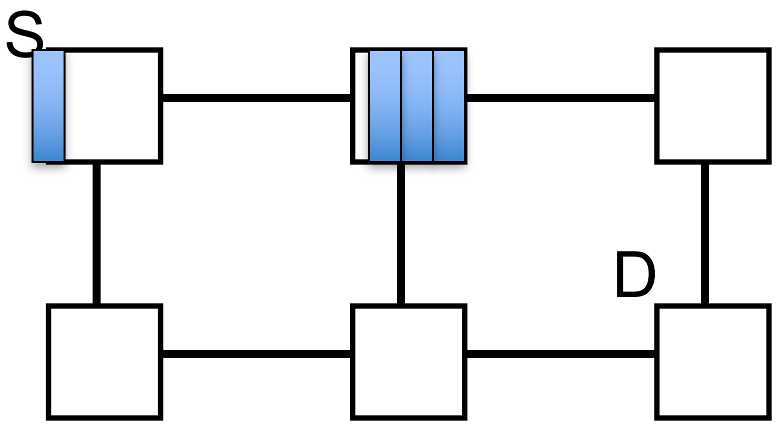

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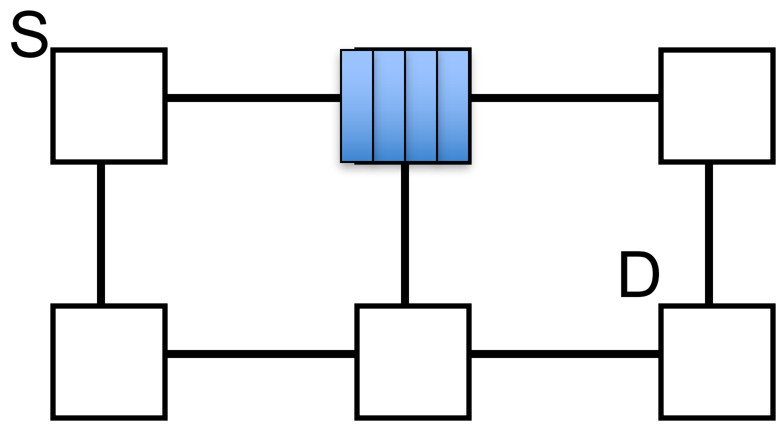

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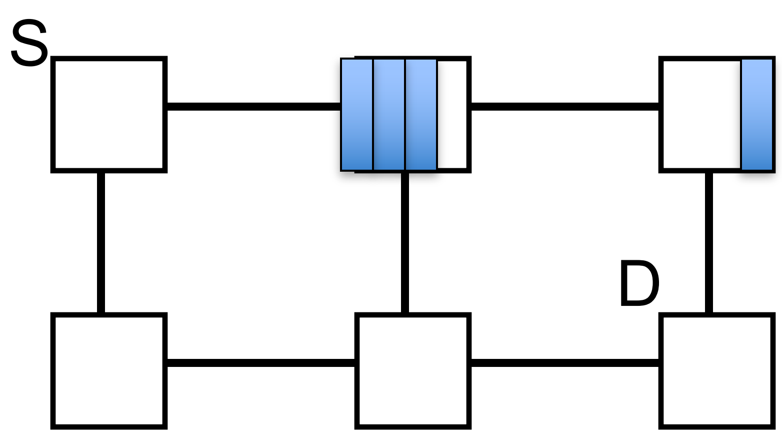

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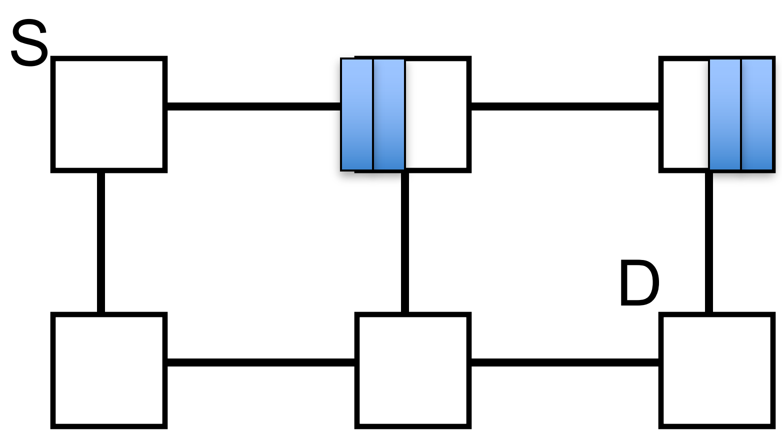

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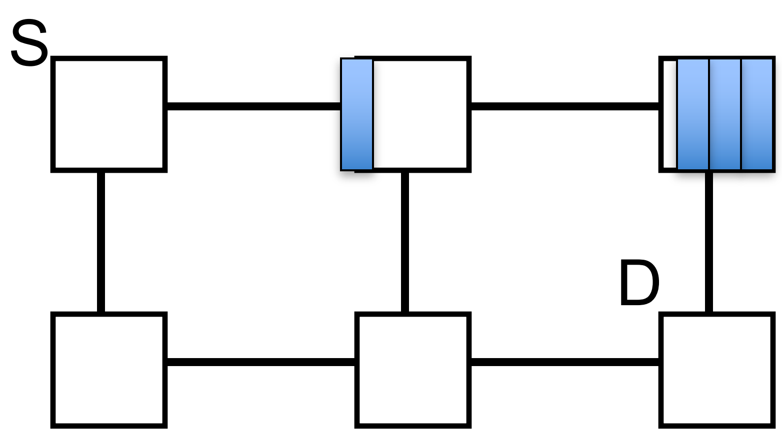

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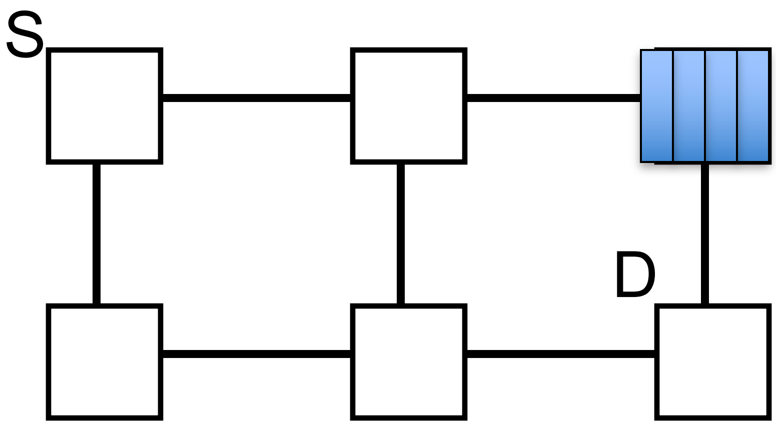

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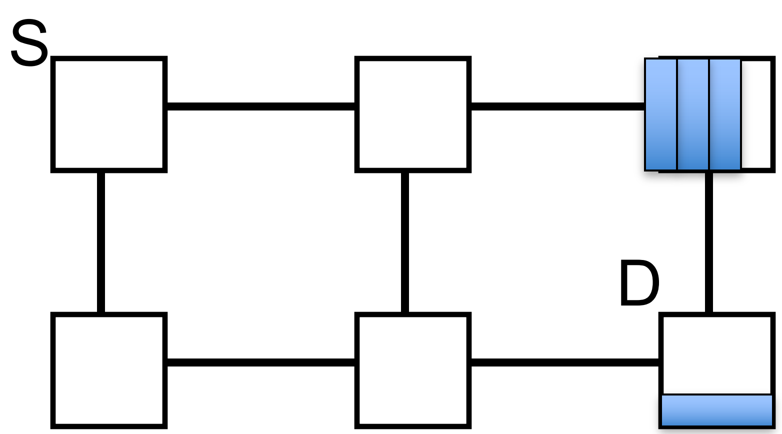

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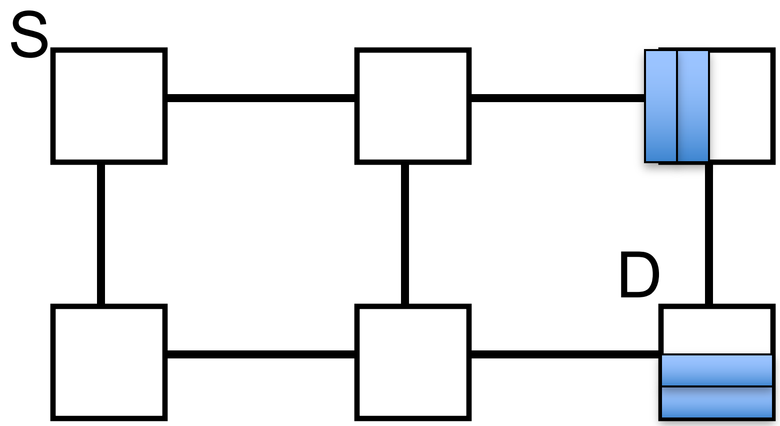

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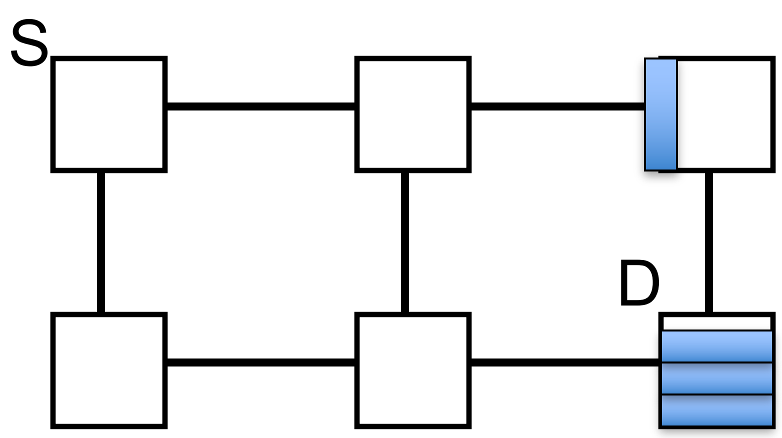

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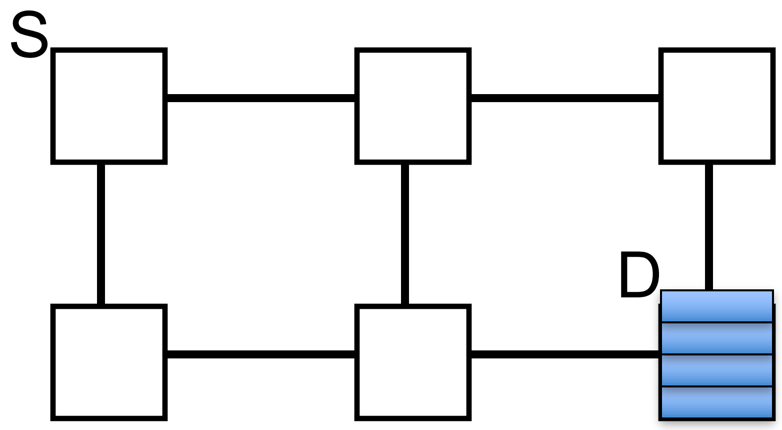
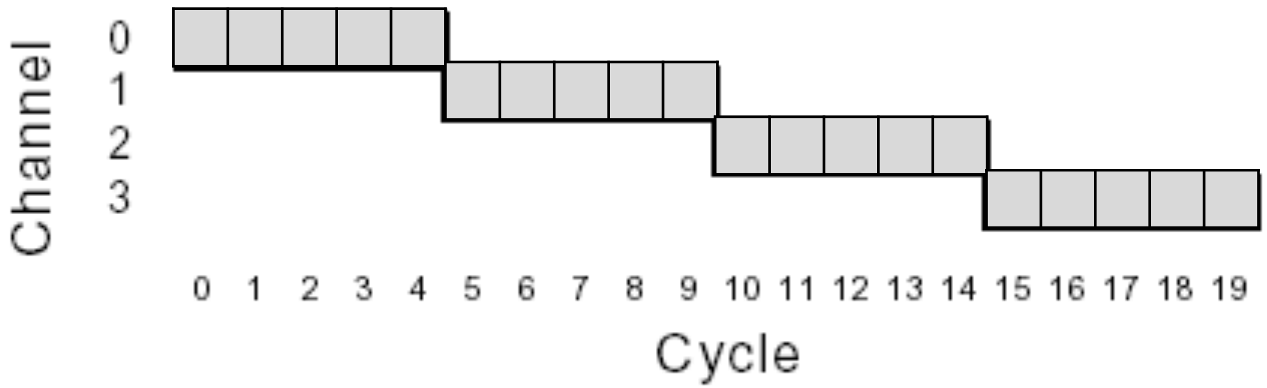


Time-space View: Store-and-Forward



- Buffering allows packet to wait for channel
- *Drawback?*

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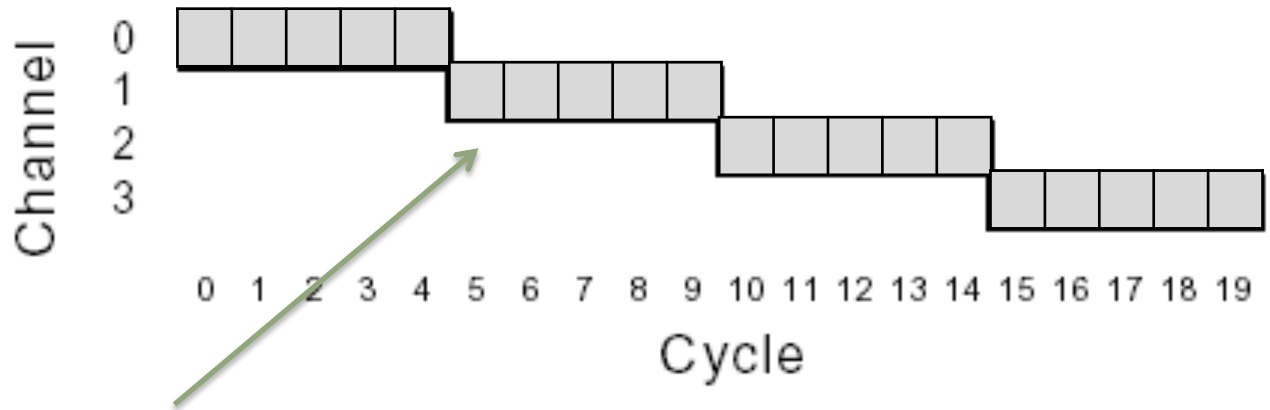

Could be allocated at a much later time without packet dropping

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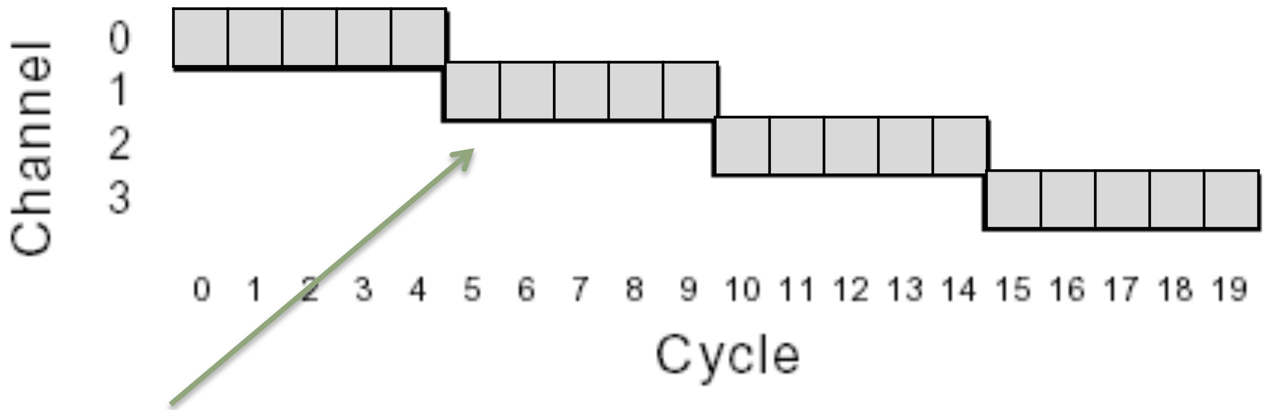
Time-space View: Store-and-Forward

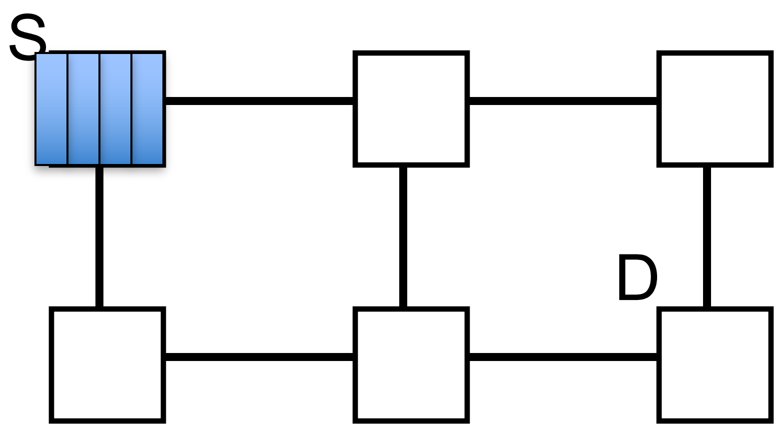


Could be allocated at a much later time without packet dropping

- Buffering allows packet to wait for channel
- *Drawback?* Serialization latency experienced at each hop/channel

Virtual Cut-through (packet-based)

- Why wait till entire message has arrived at each intermediate stop?
- Forward as soon as the flits are received and channels are allocated



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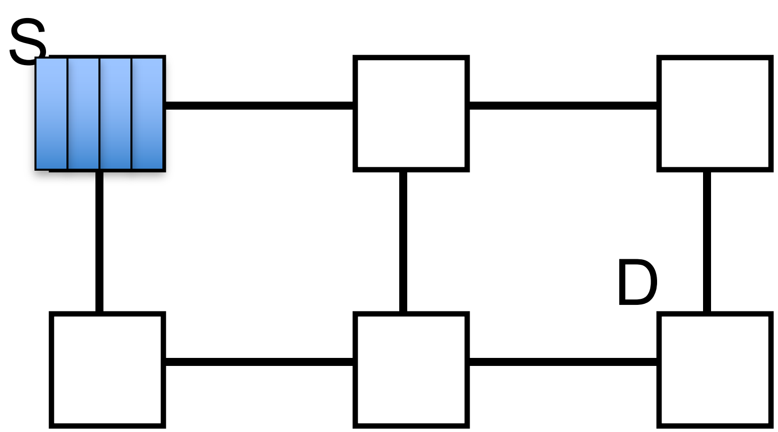

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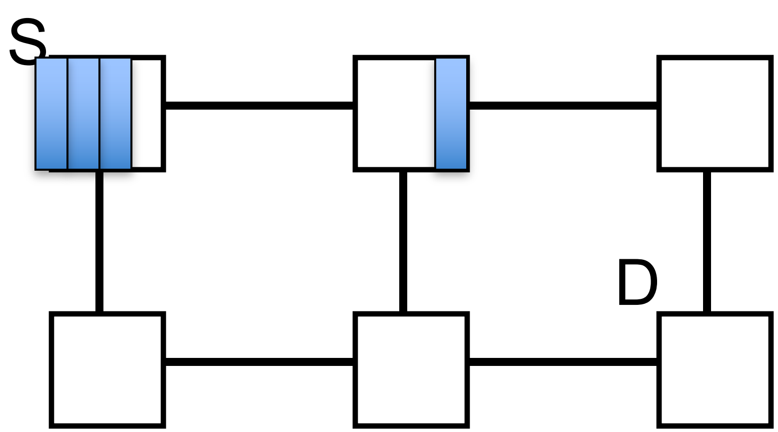

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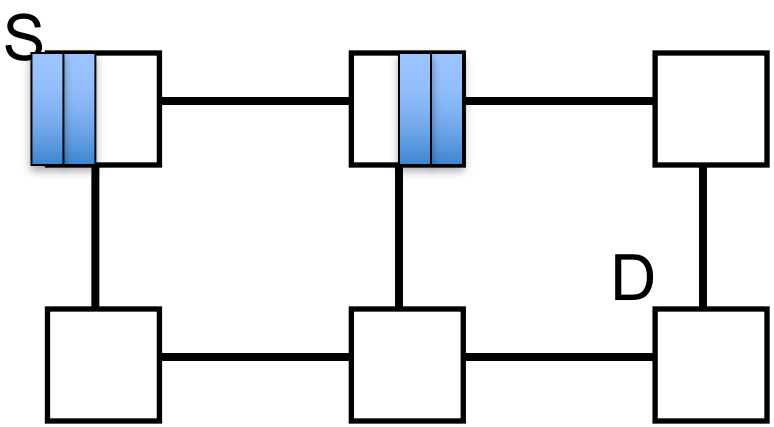

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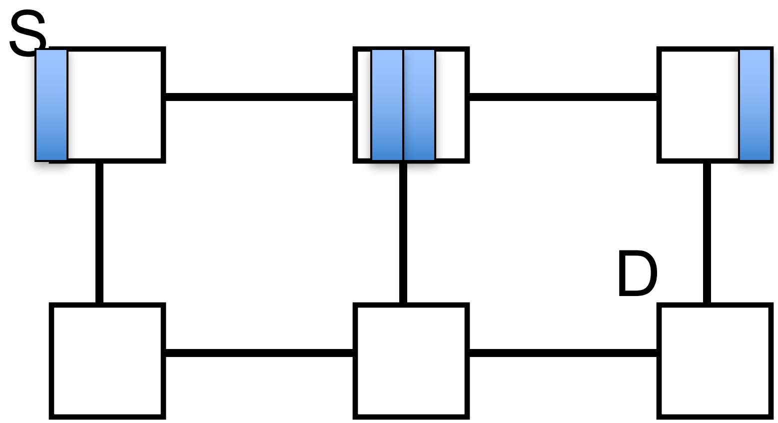

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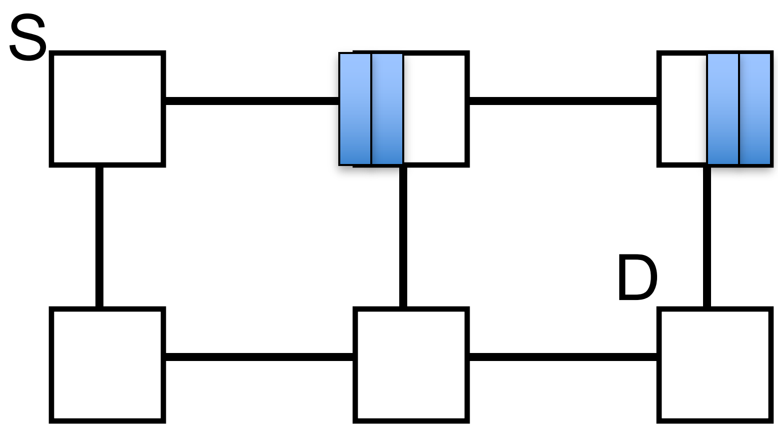

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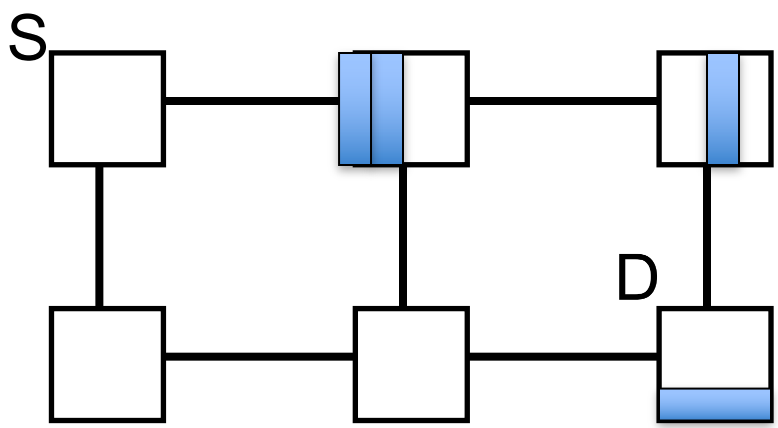

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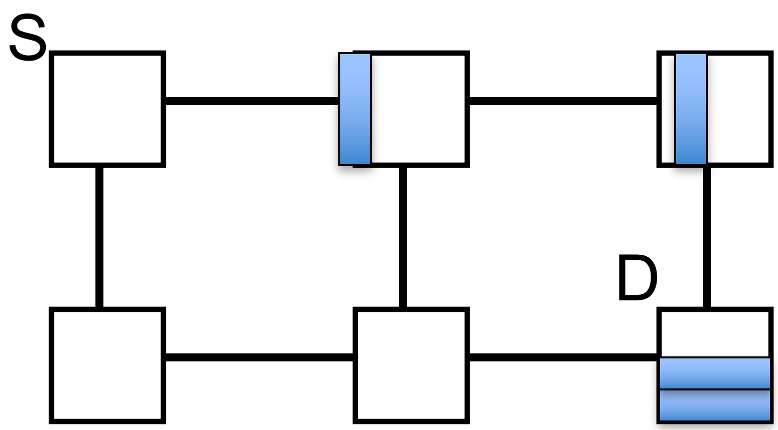

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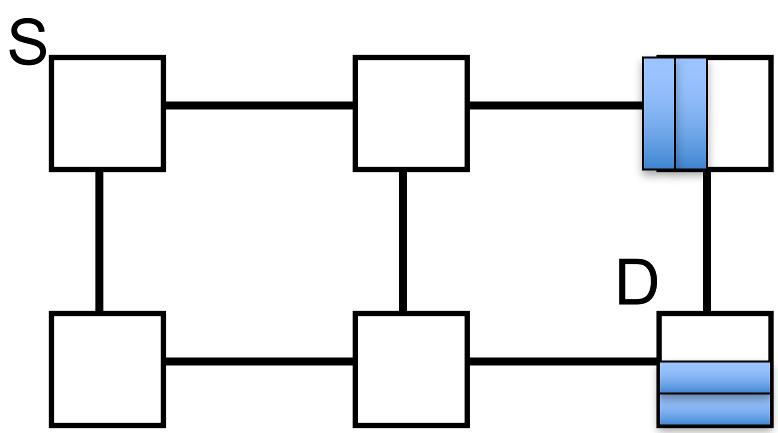

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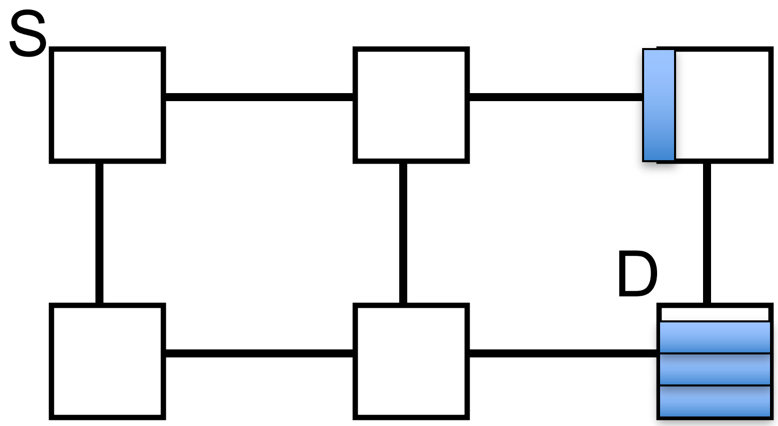

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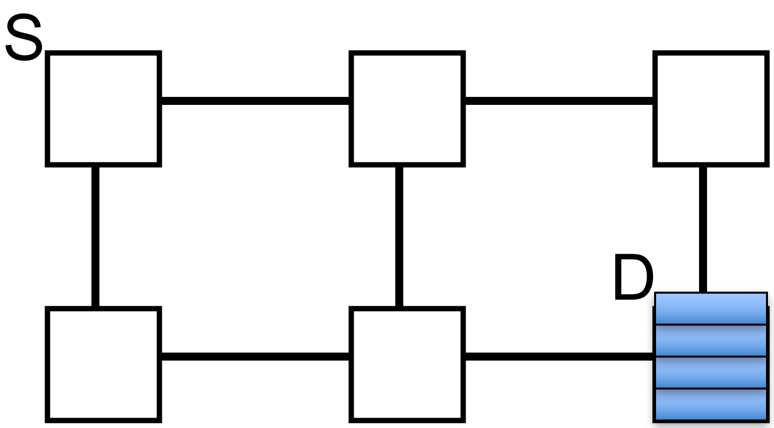
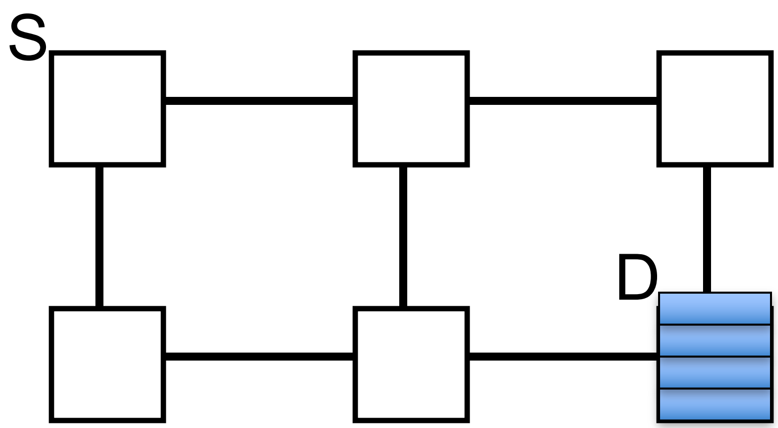
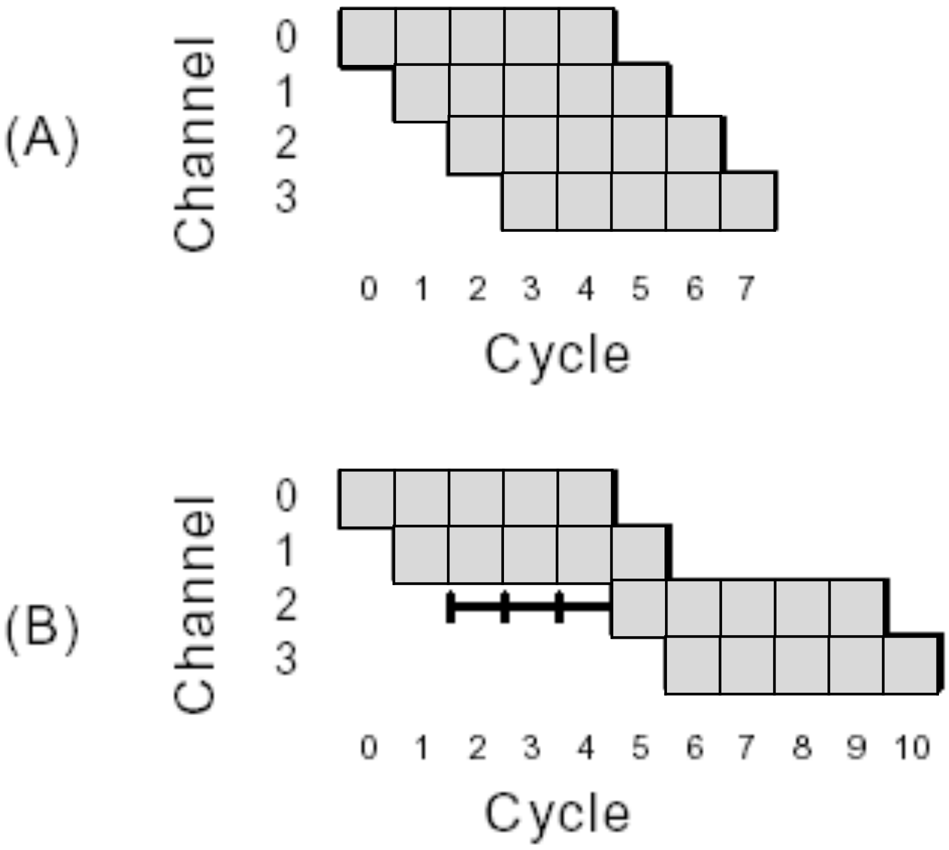


Virtual Cut-through (packet-based)

- Why wait till entire message has arrived at each intermediate stop?
- Forward as soon as the flits are received and channels are allocated
- Used in Alpha 21364
- When the head gets blocked, whole packet gets blocked at one intermediate node

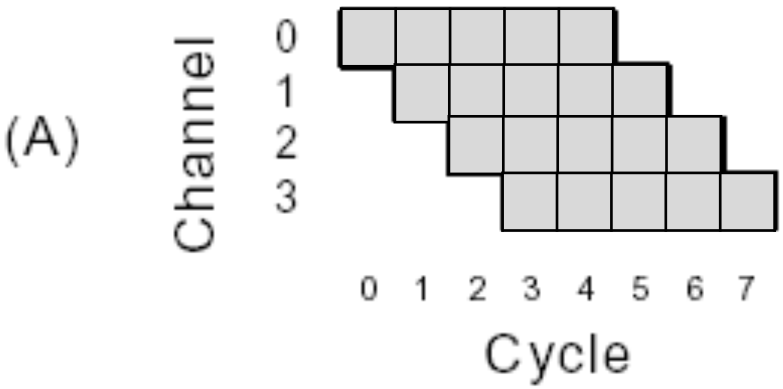


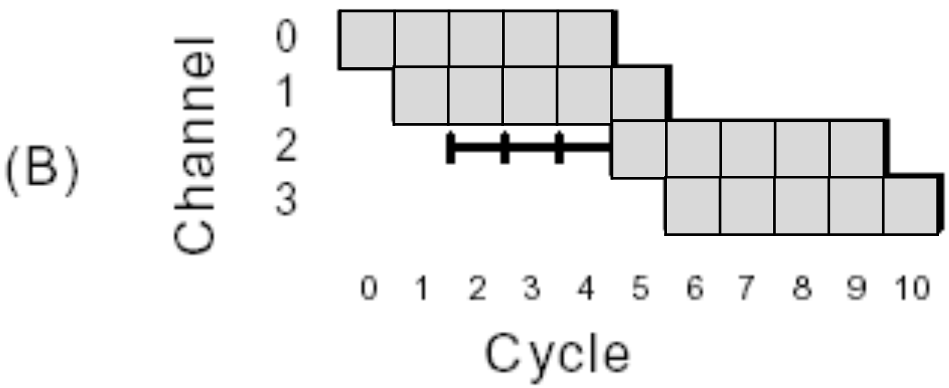
Time-space View: Virtual Cut-through



- *Advantages?*
- *Disadvantages?*

Time-space View: Virtual Cut-through



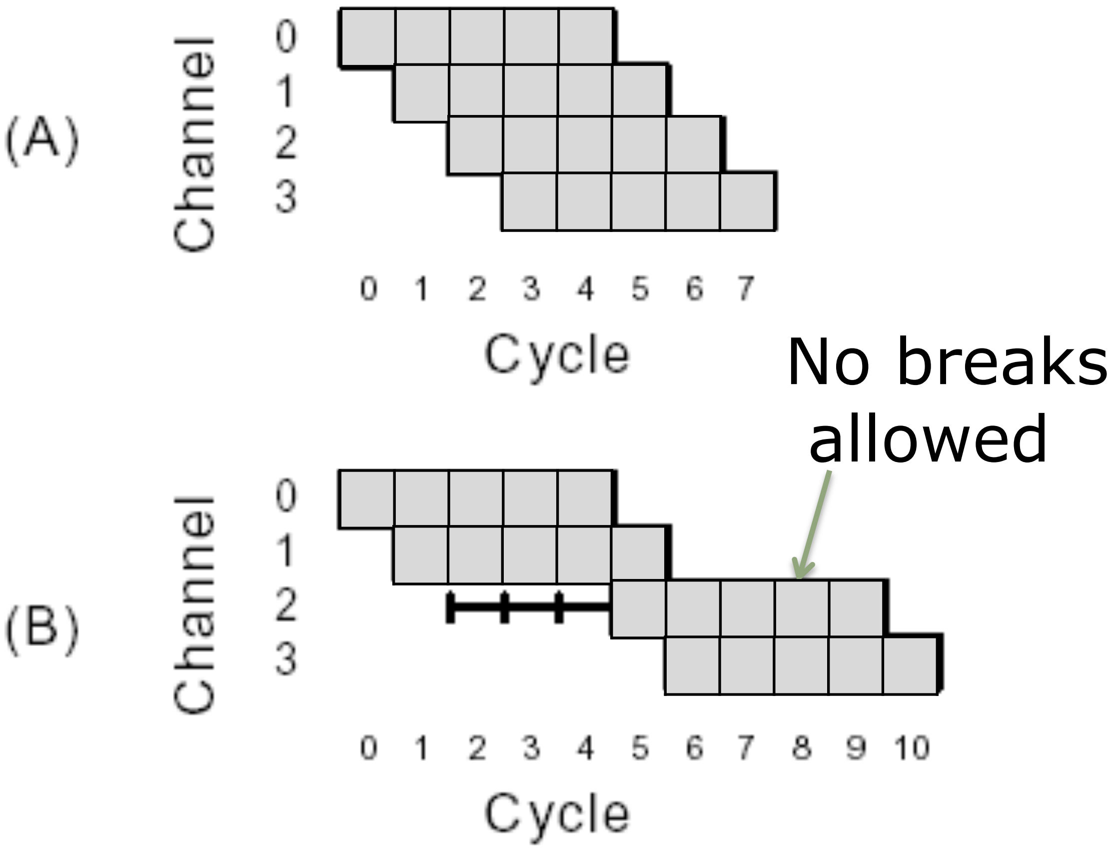


- *Advantages?*

  Lower latency

- *Disadvantages?*

Time-space View: Virtual Cut-through



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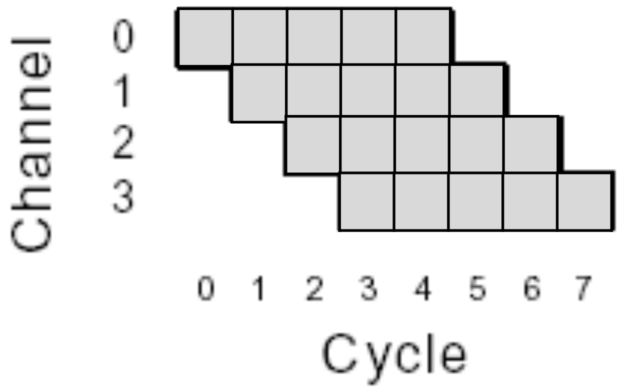
Time-space View: Virtual Cut-through

(A)

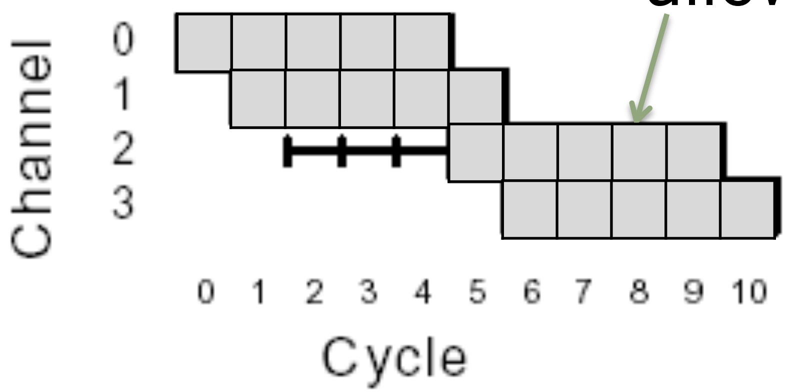


- *Advantages?*

Lower latency

No breaks allowed

(B)



- *Disadvantages?*

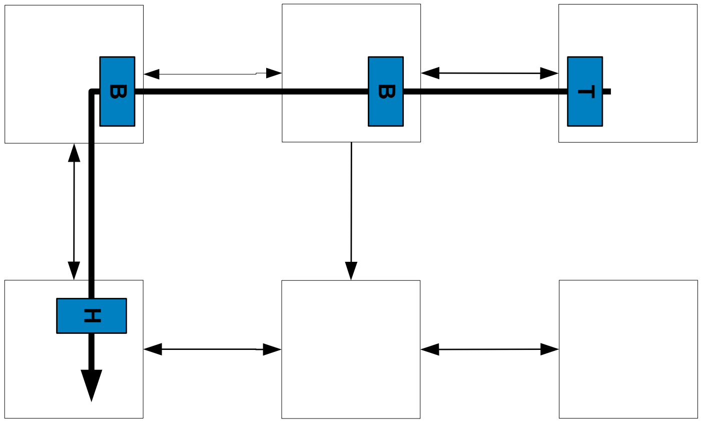
Buffers allocated in packets
→ large buffers & low utilization

Channels allocated in packets
→ unfairness & low utilization

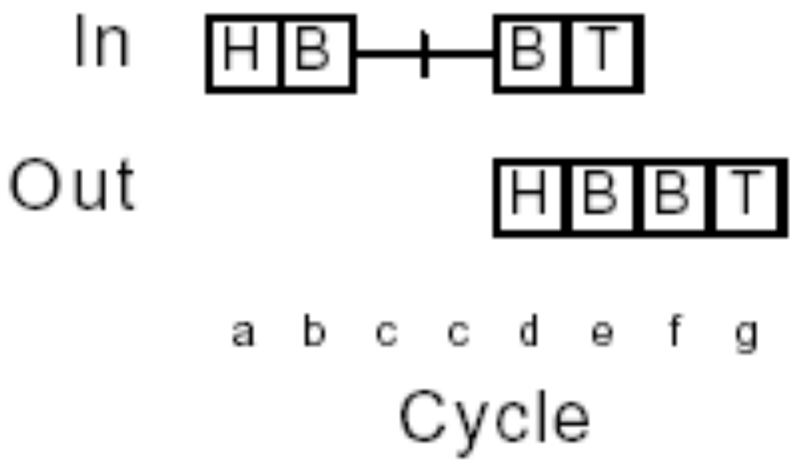
Flit-Buffer Flow Control: Wormhole

- 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

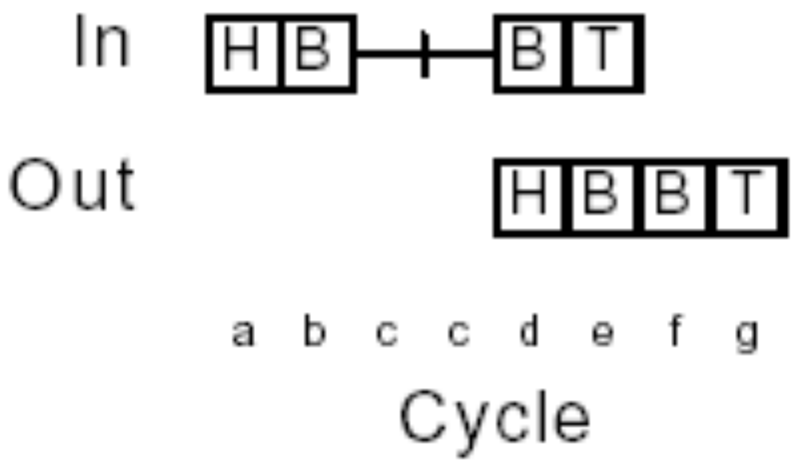


Time-space View: Wormhole



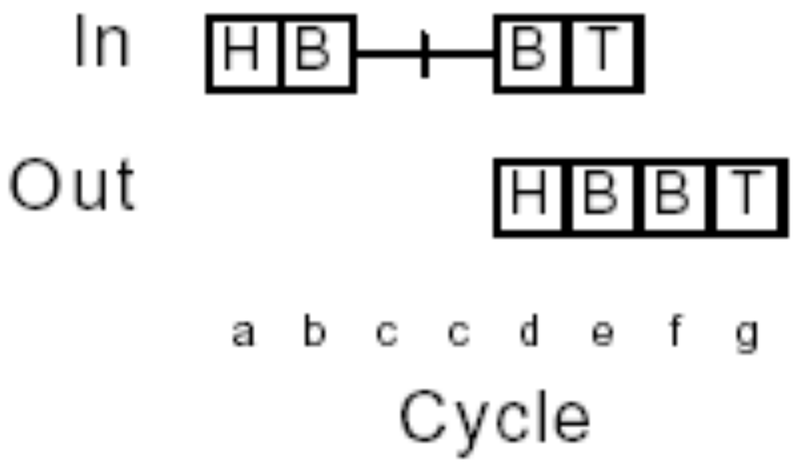
- *Advantages?*
- *Disadvantages?*

Time-space View: Wormhole



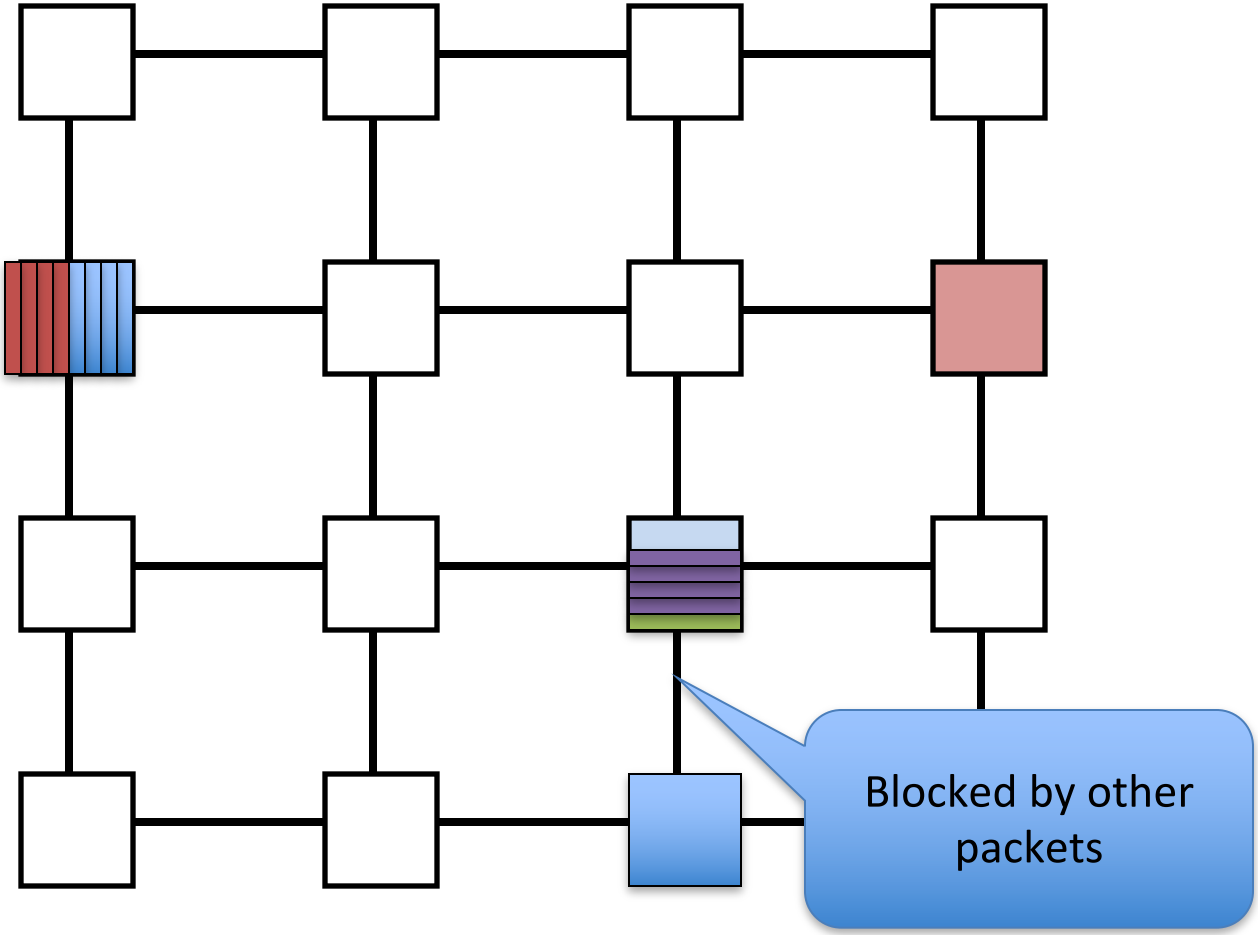
- *Advantages?* Smaller amount of buffer space required
- *Disadvantages?*

Time-space View: Wormhole



- *Advantages?* Smaller amount of buffer space required
- *Disadvantages?* May block a channel mid-packet, another packet cannot use bandwidth

Head of Line Blocking



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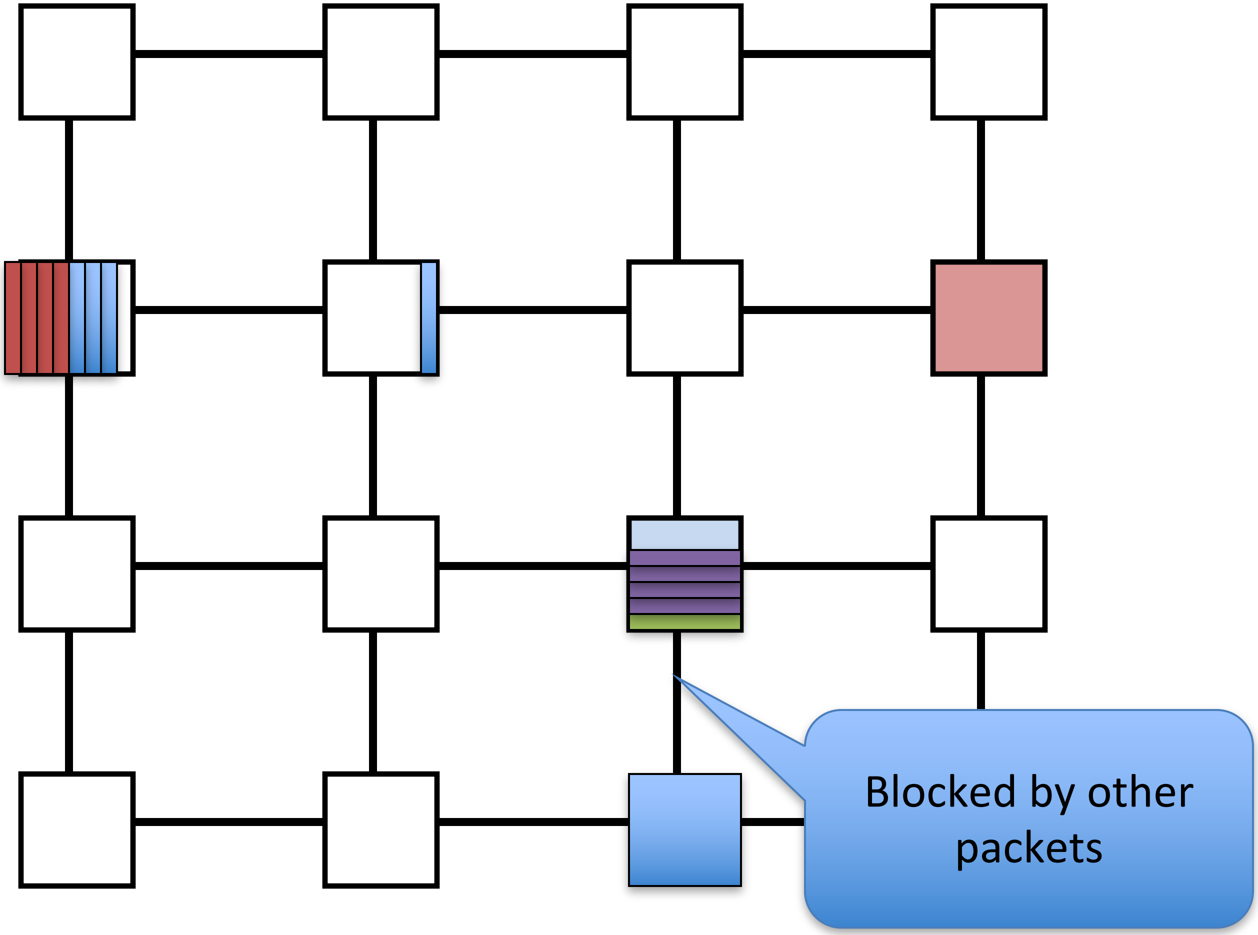

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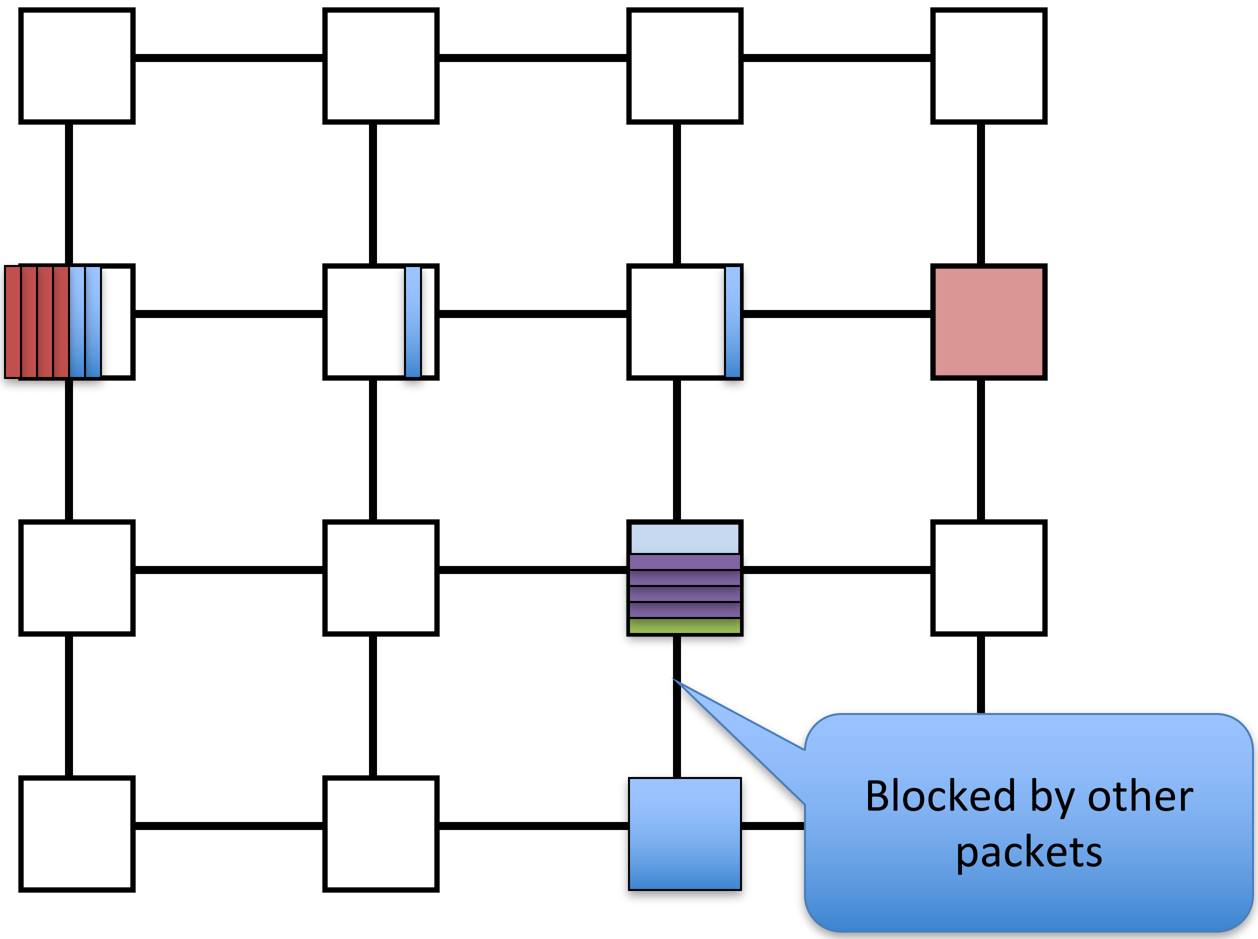

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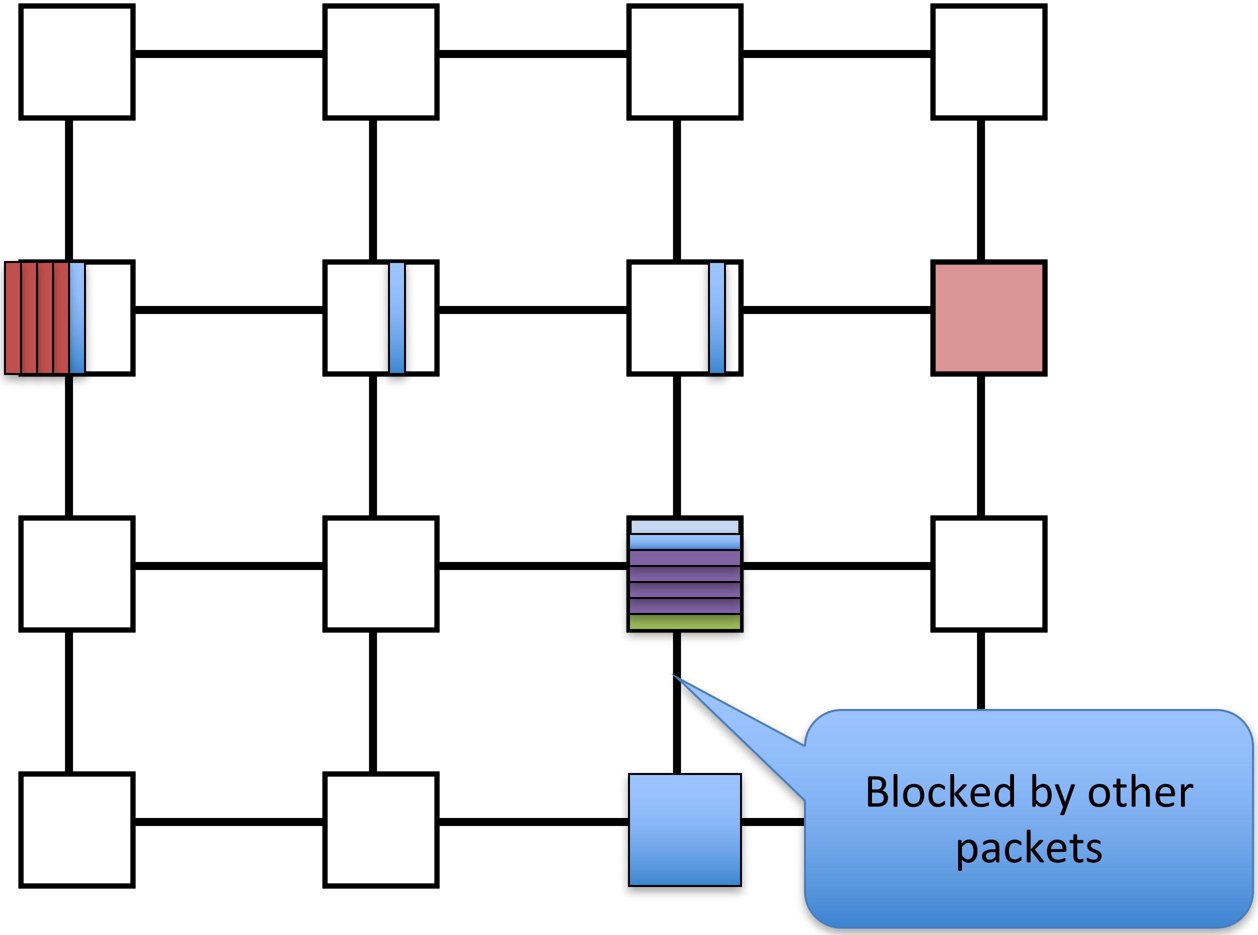

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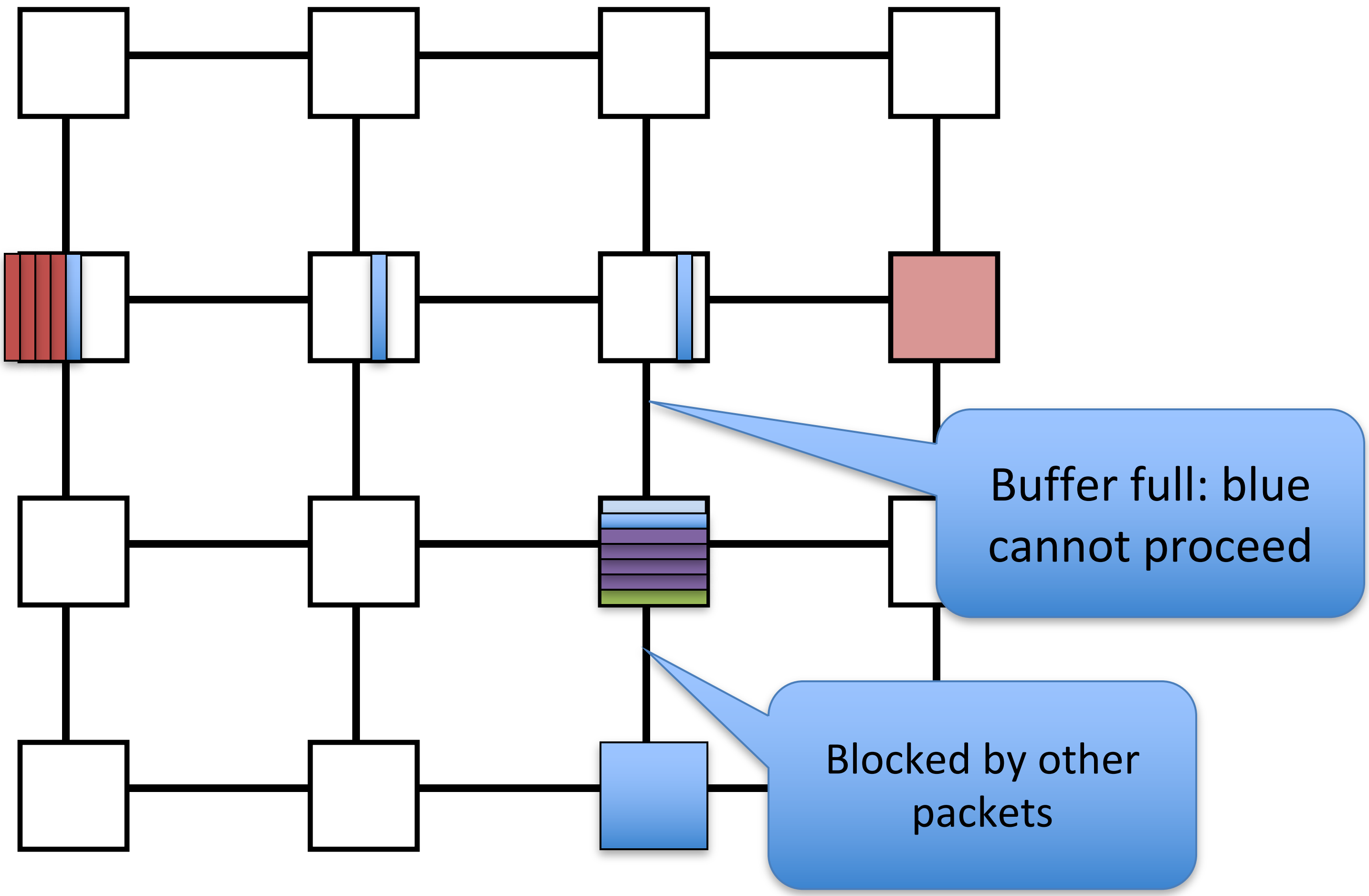

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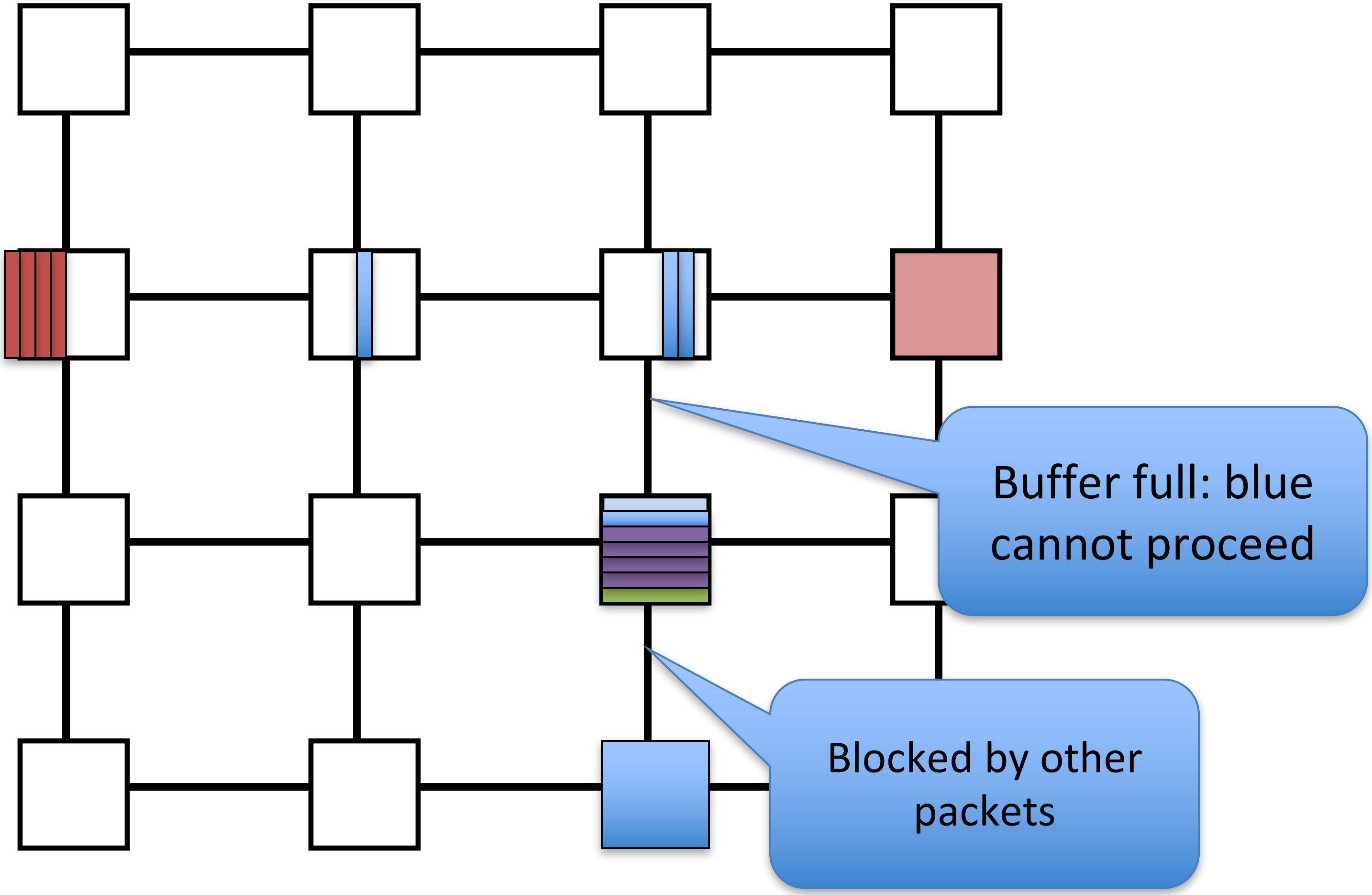

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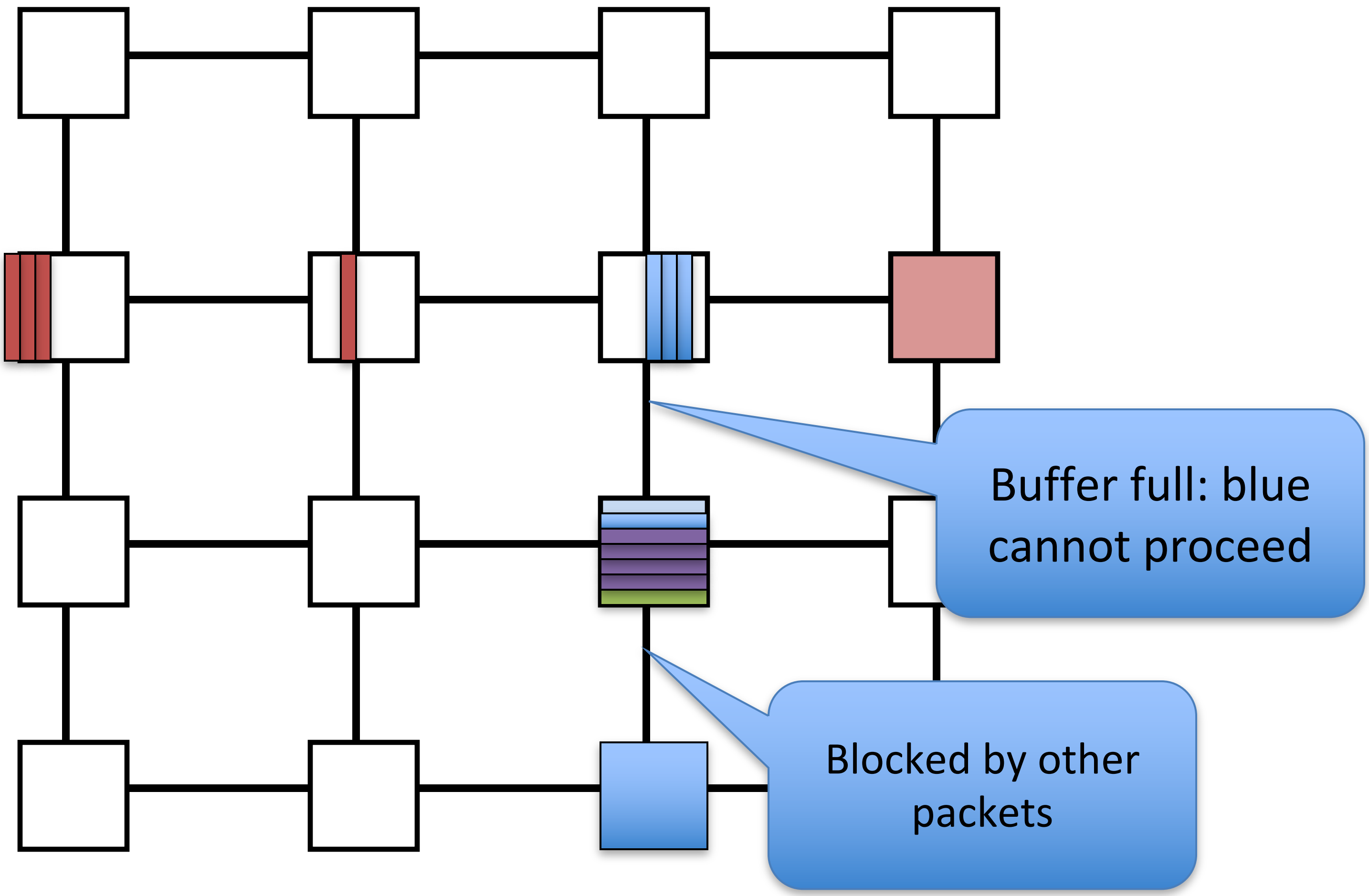

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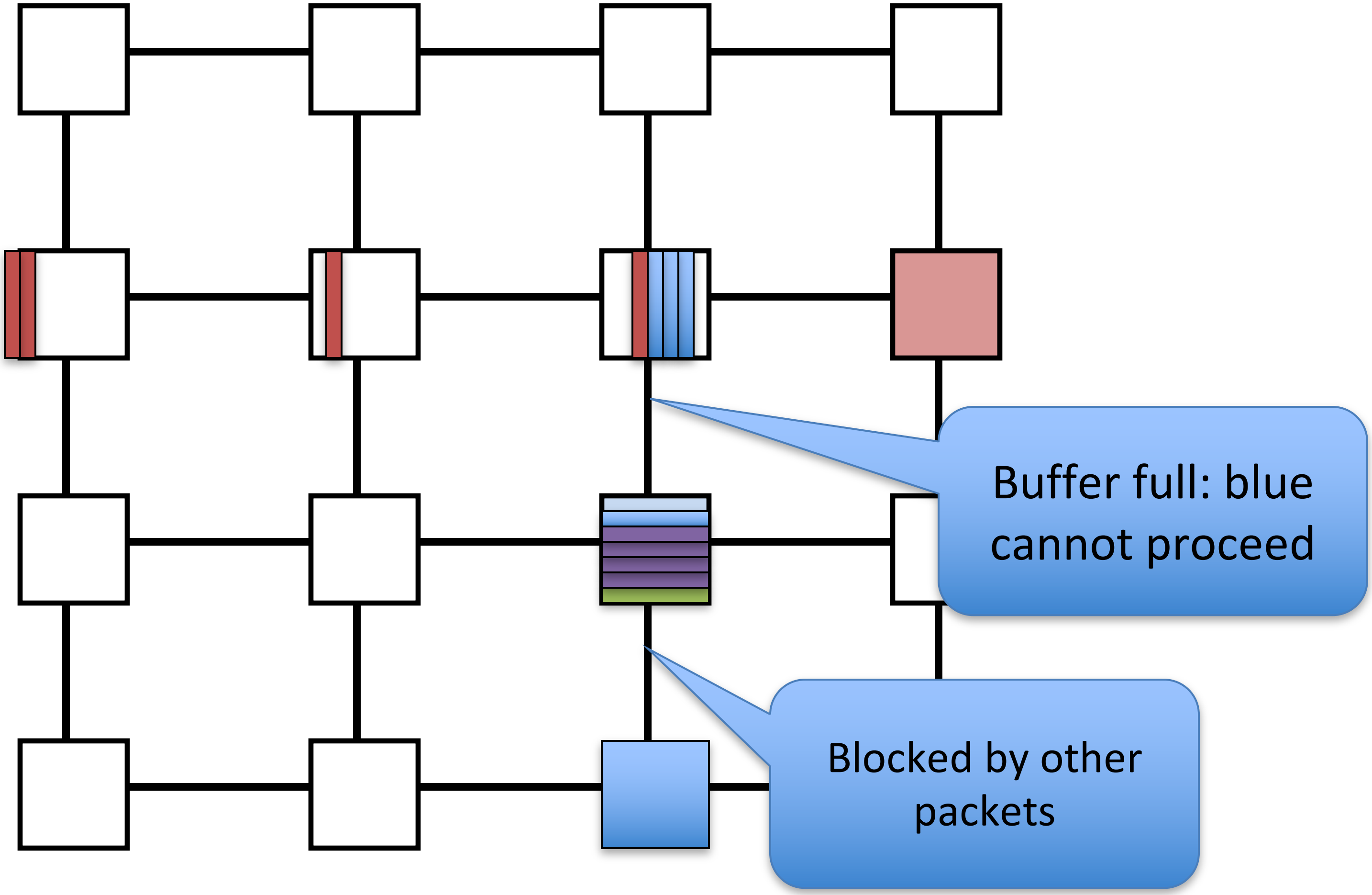

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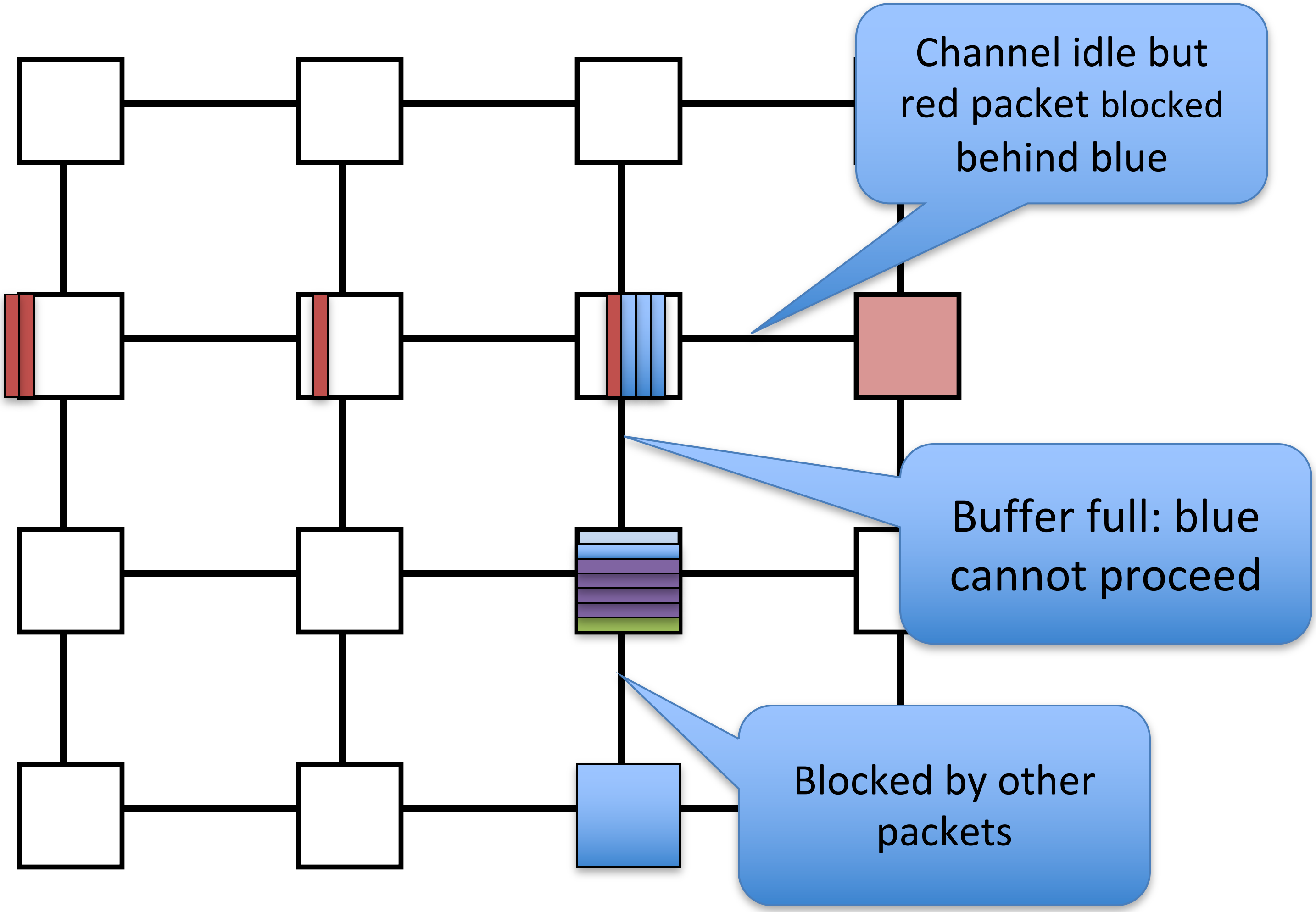
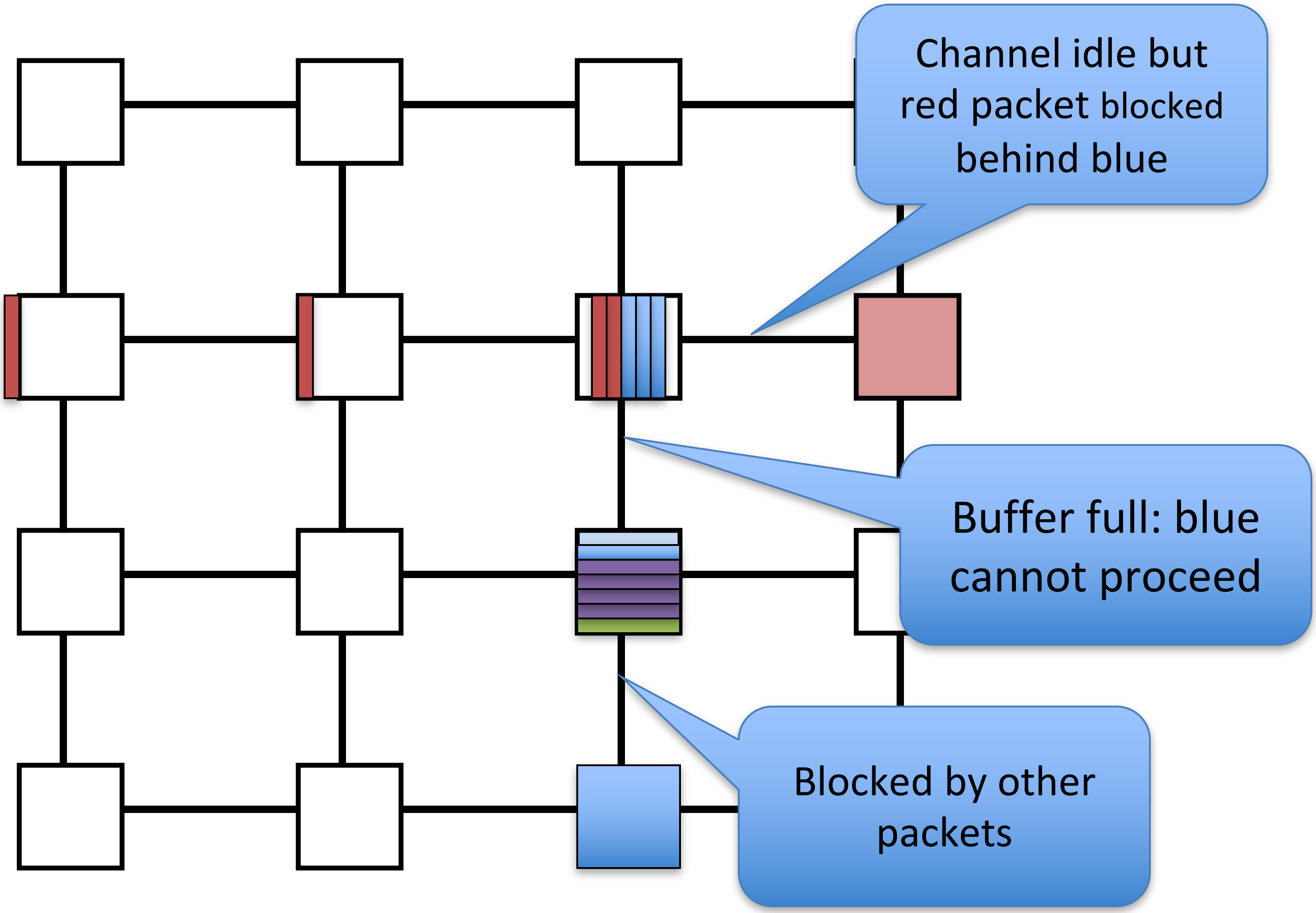


Head of Line Blocking



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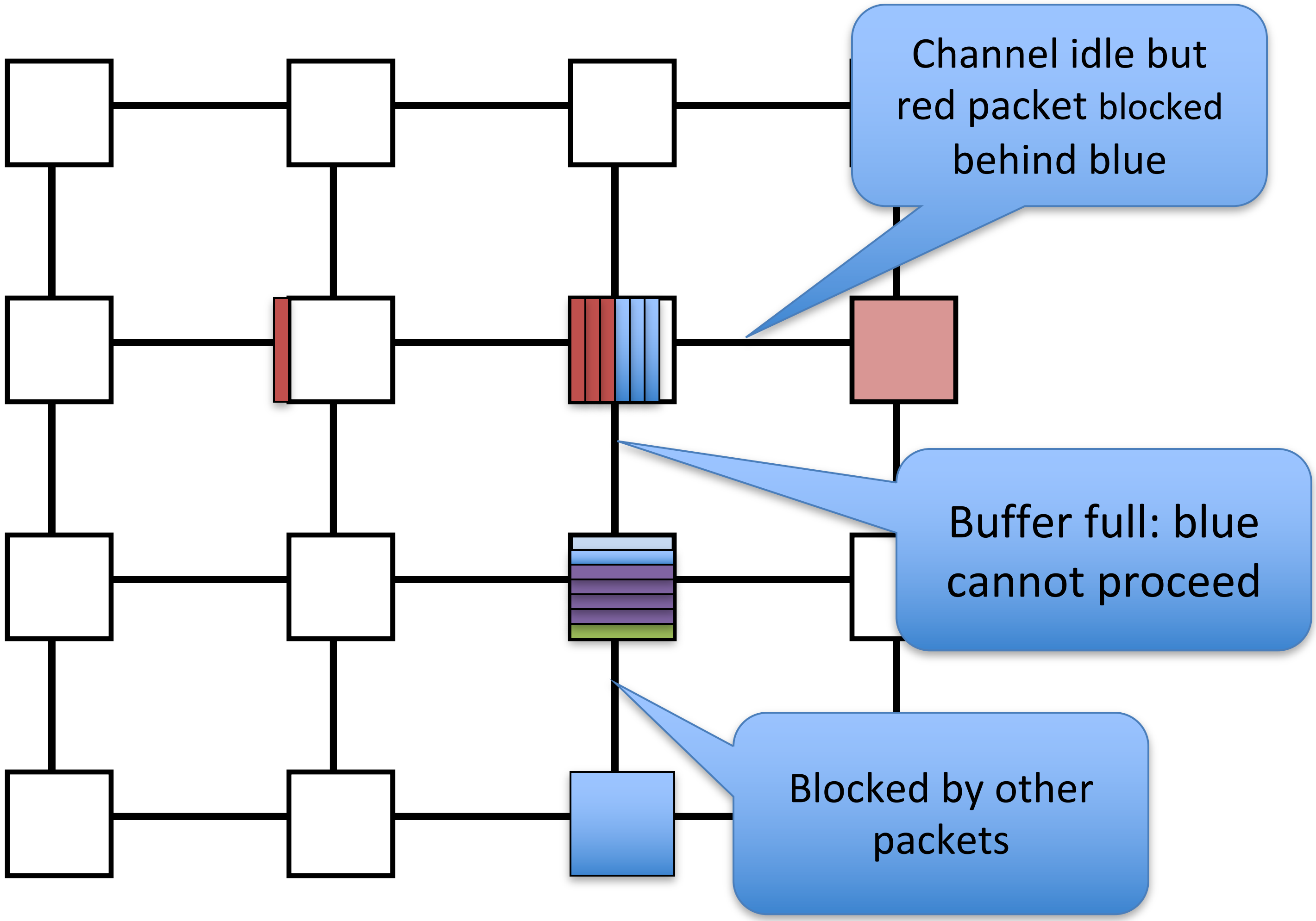

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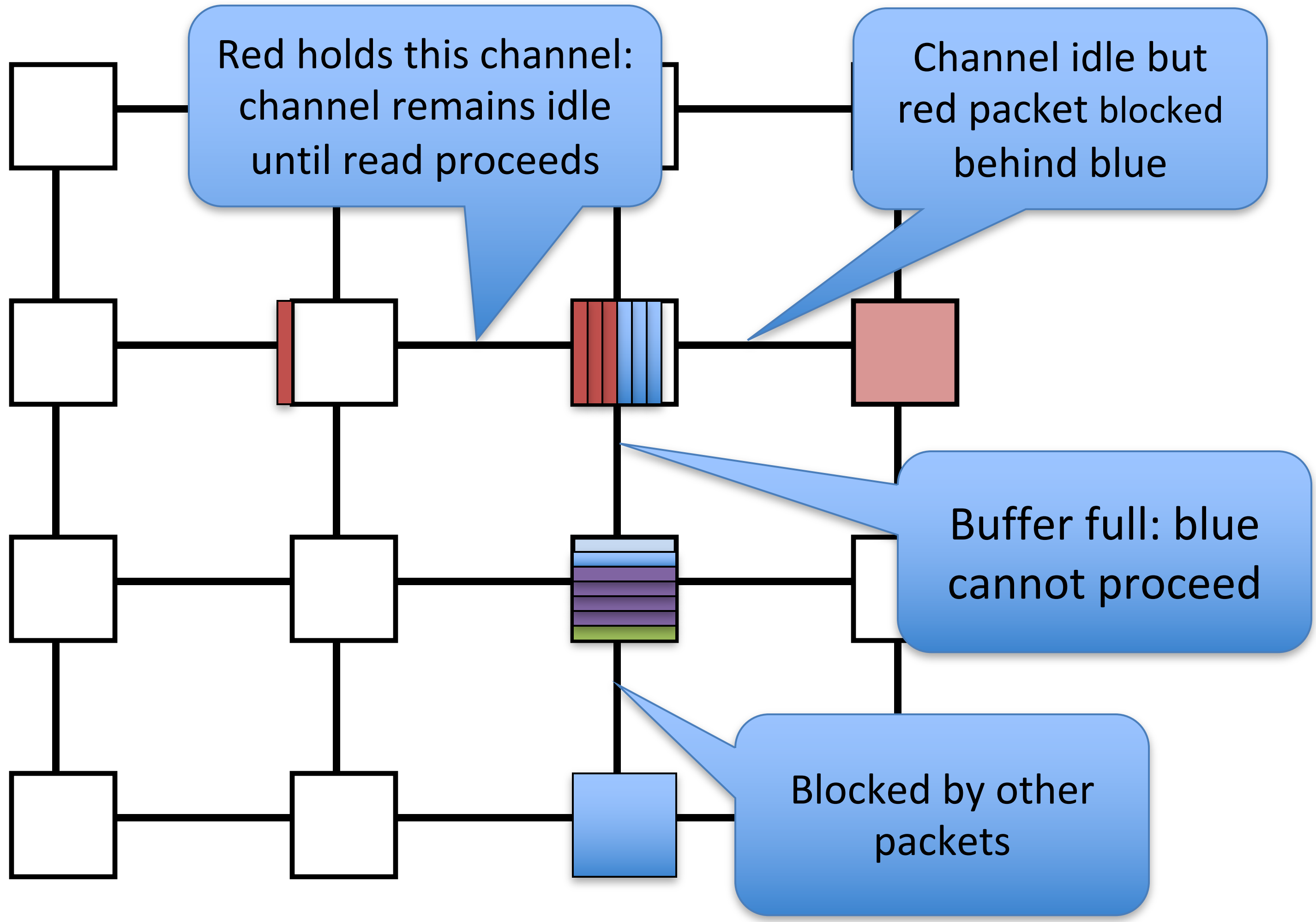

Virtual-Channel (VC) Flow Control

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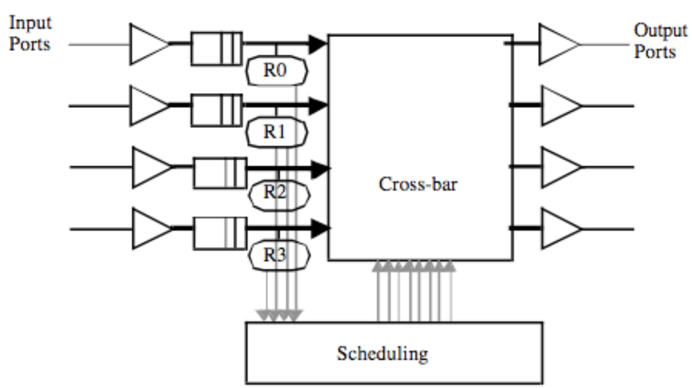

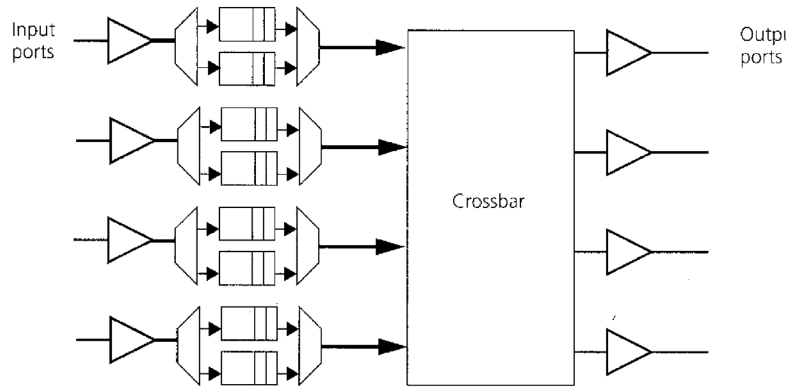

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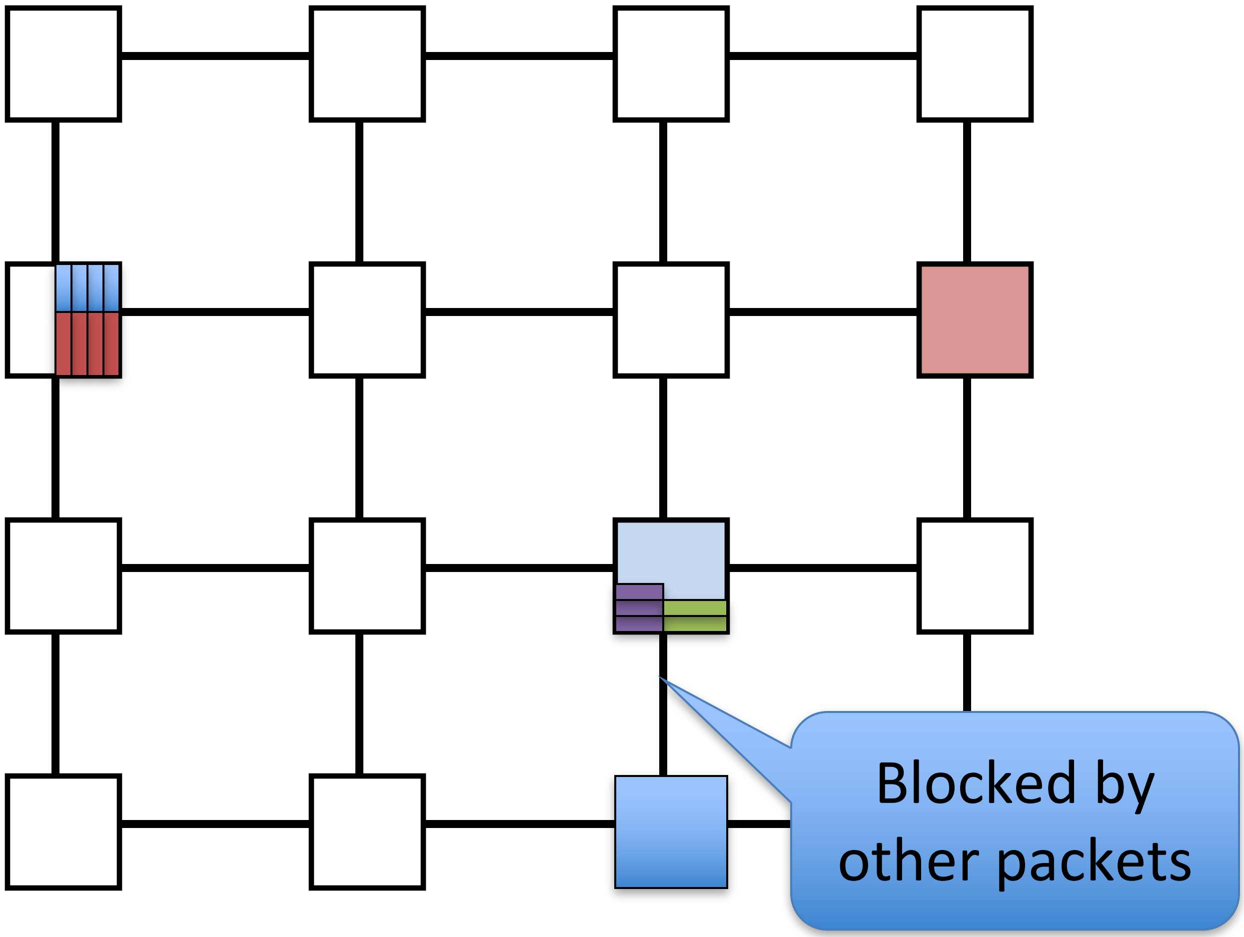

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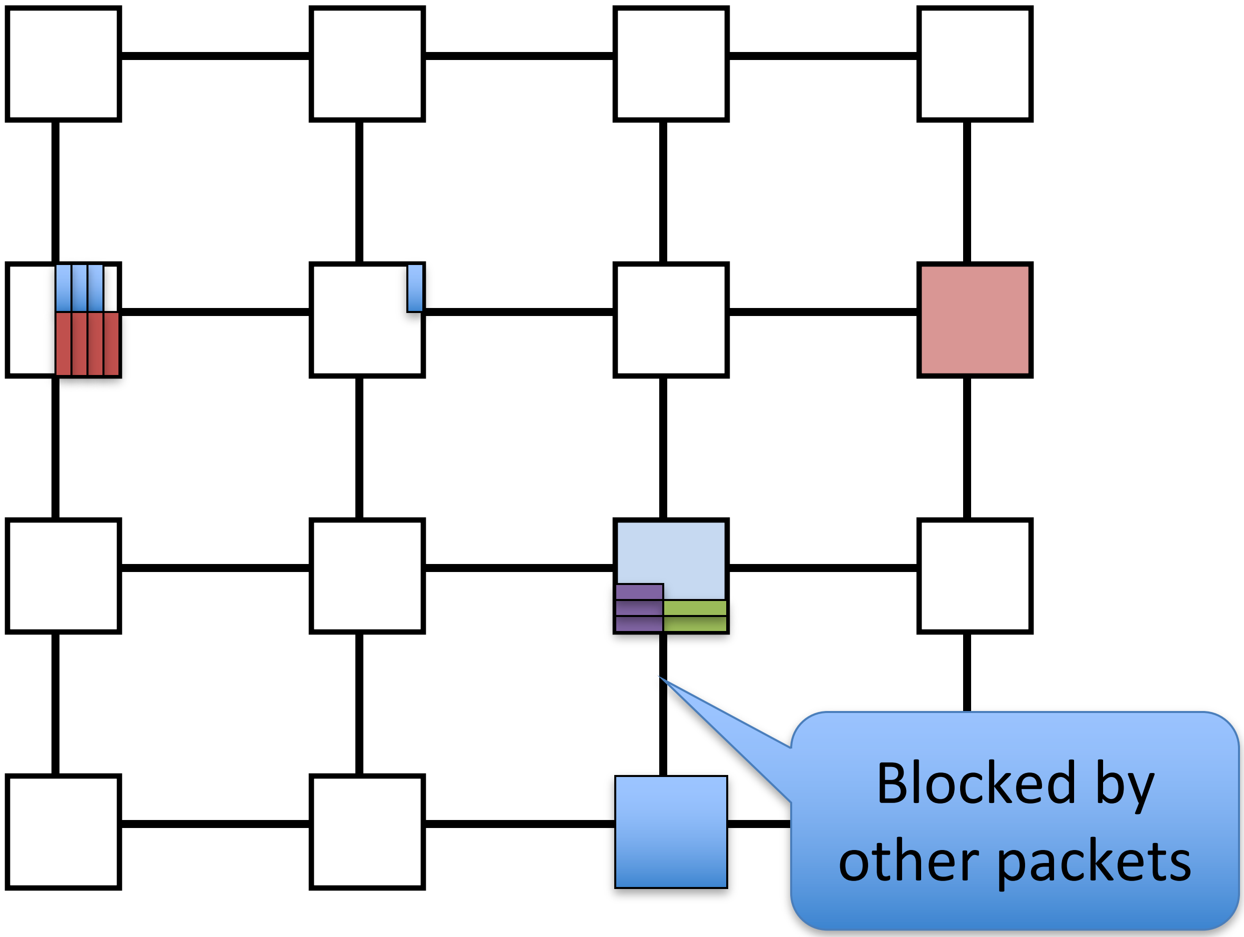

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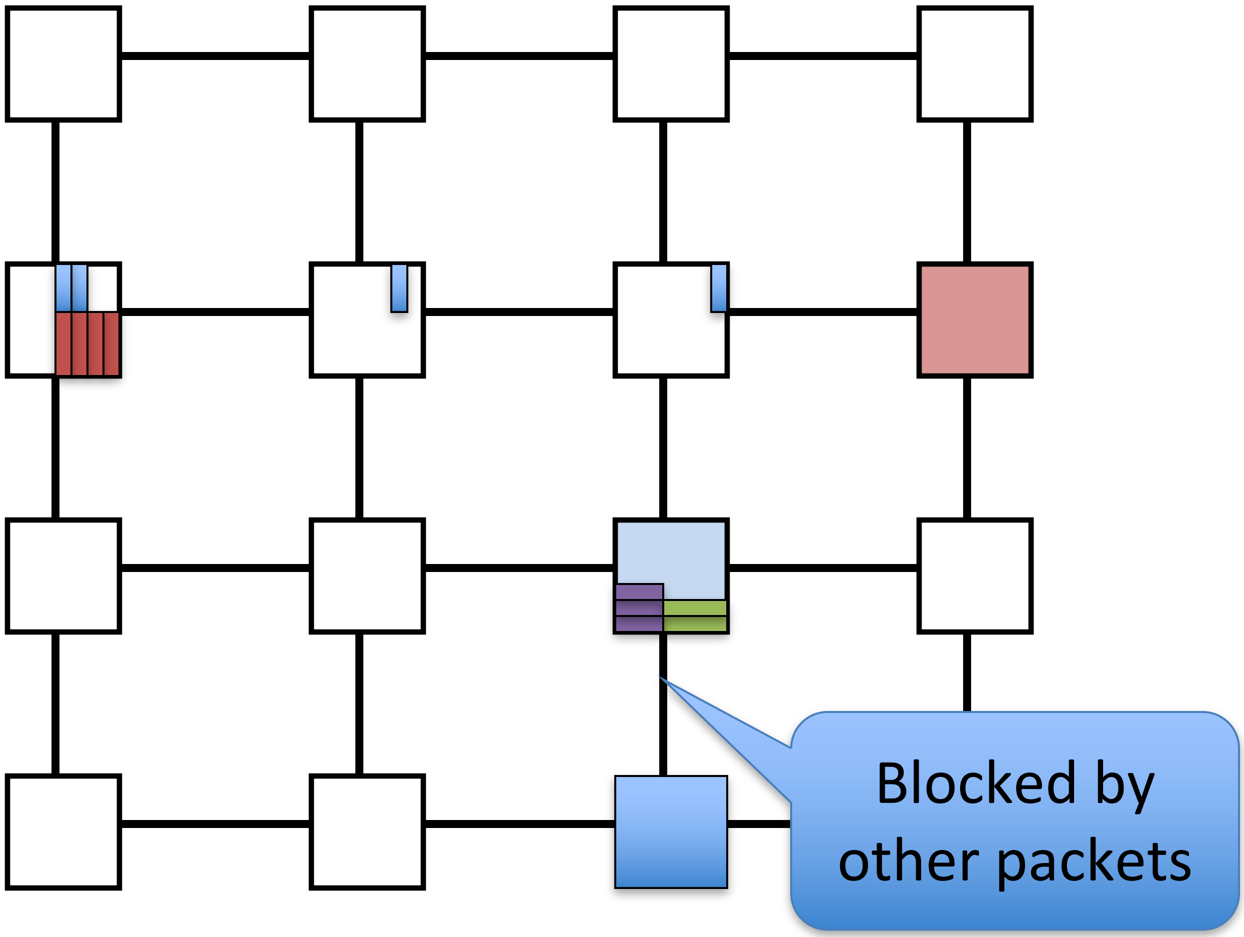

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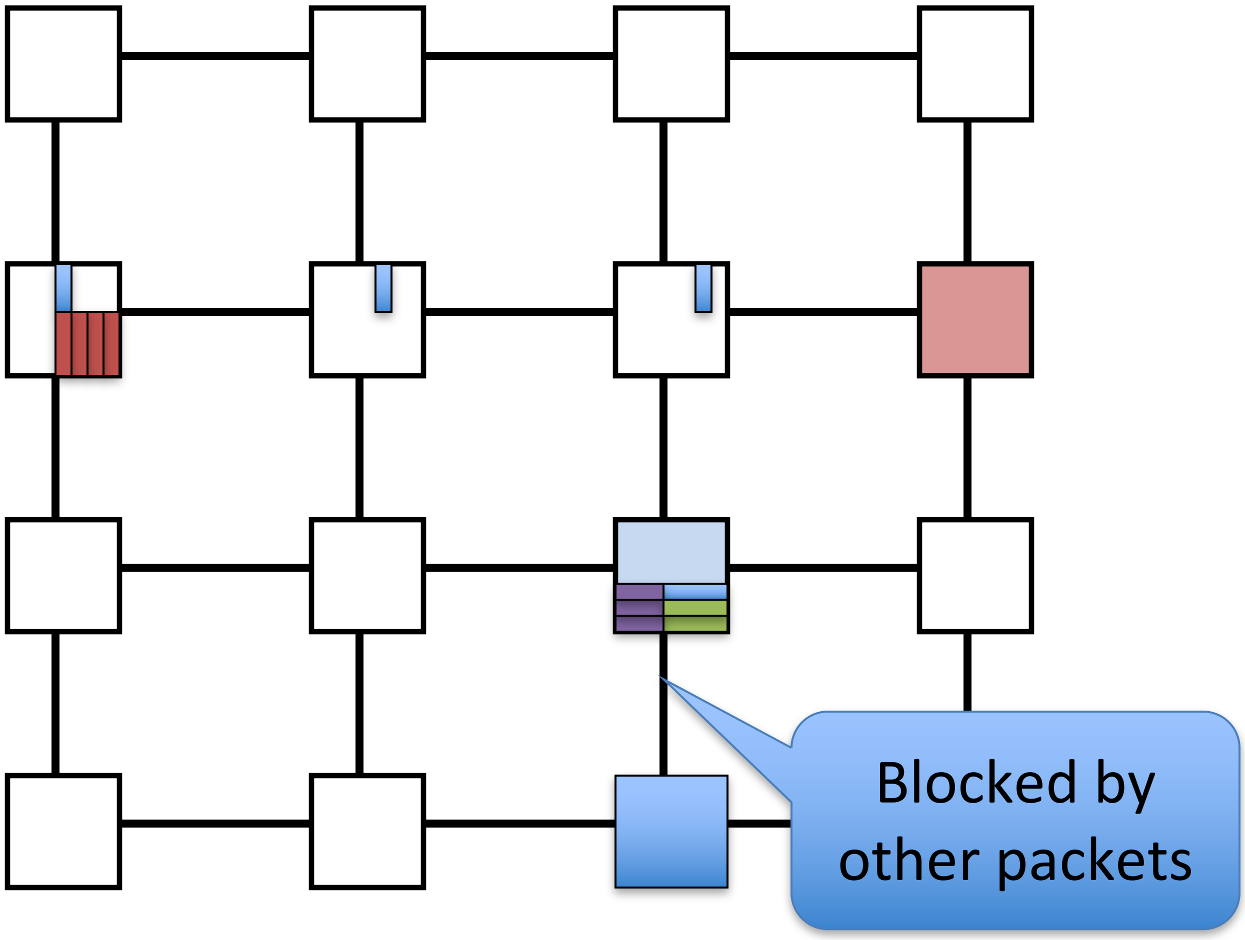

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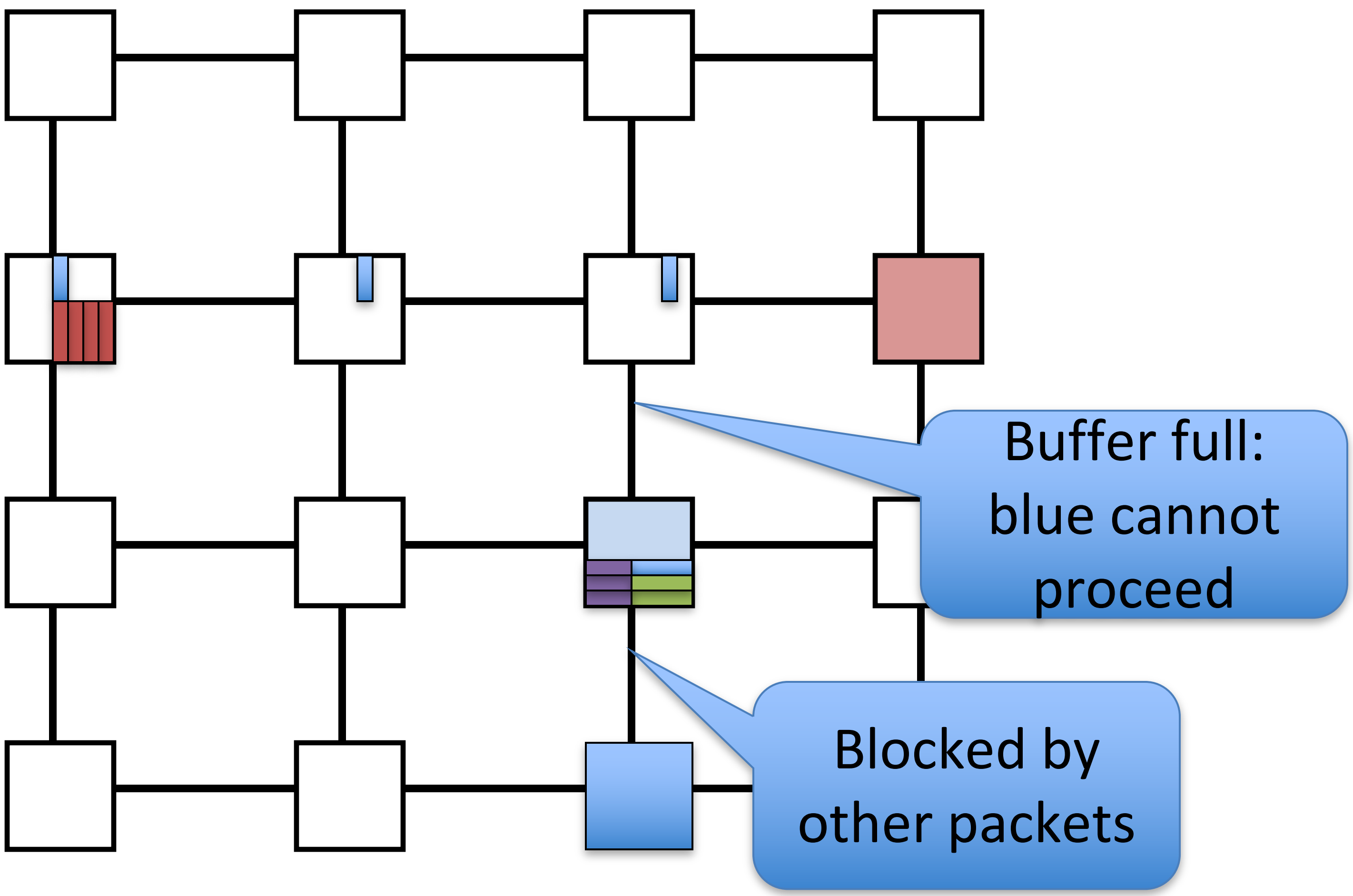

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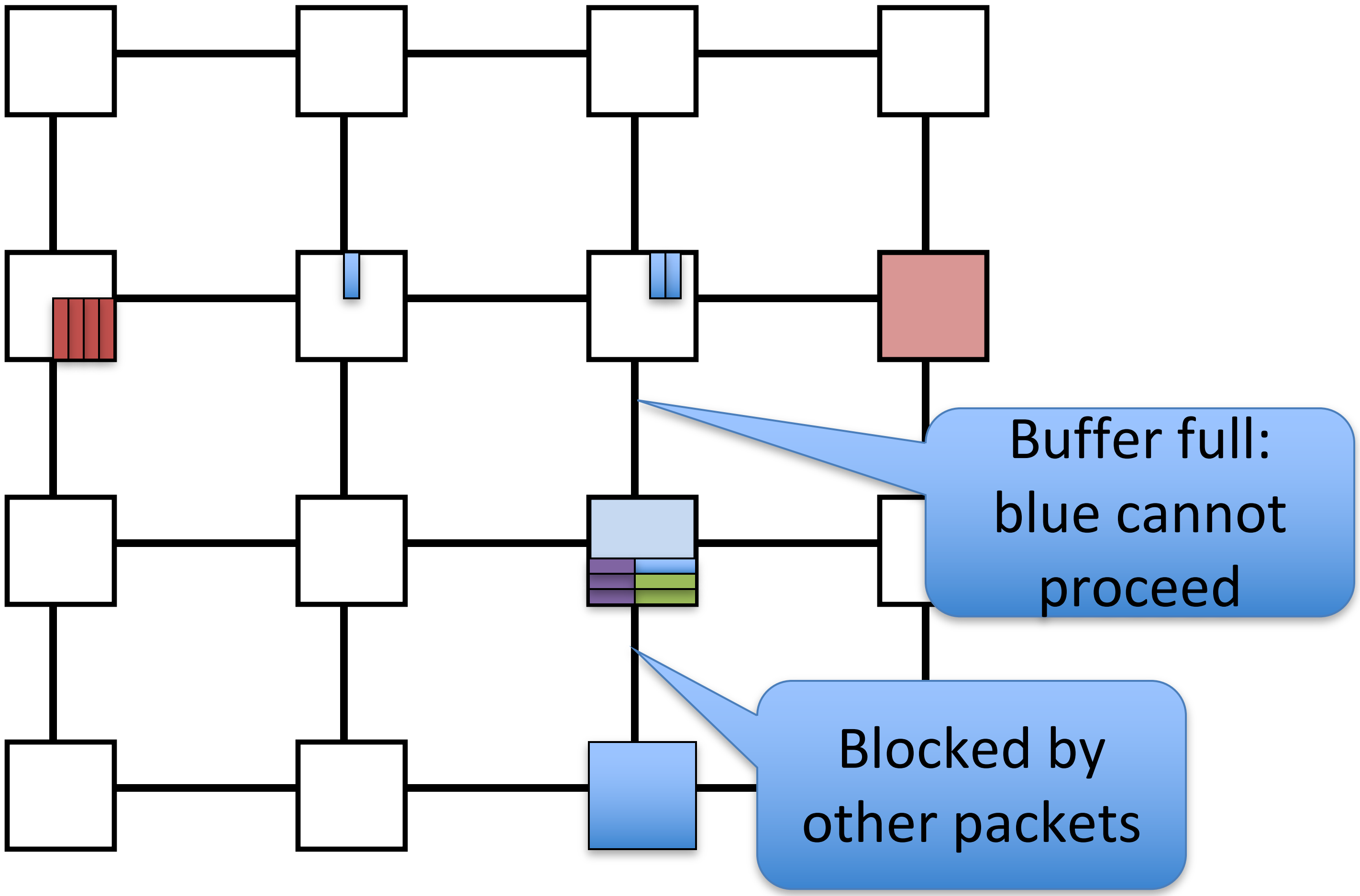

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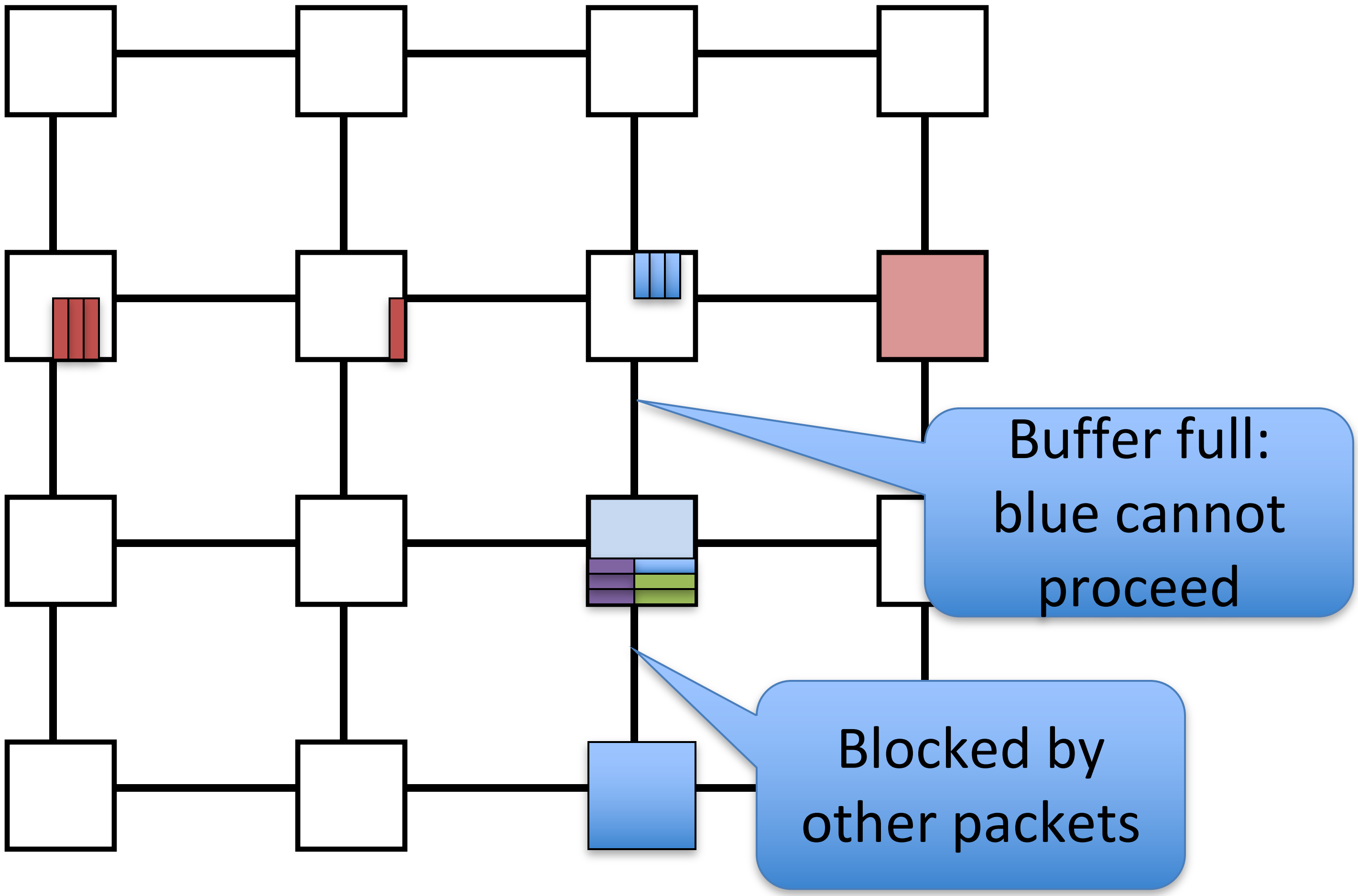

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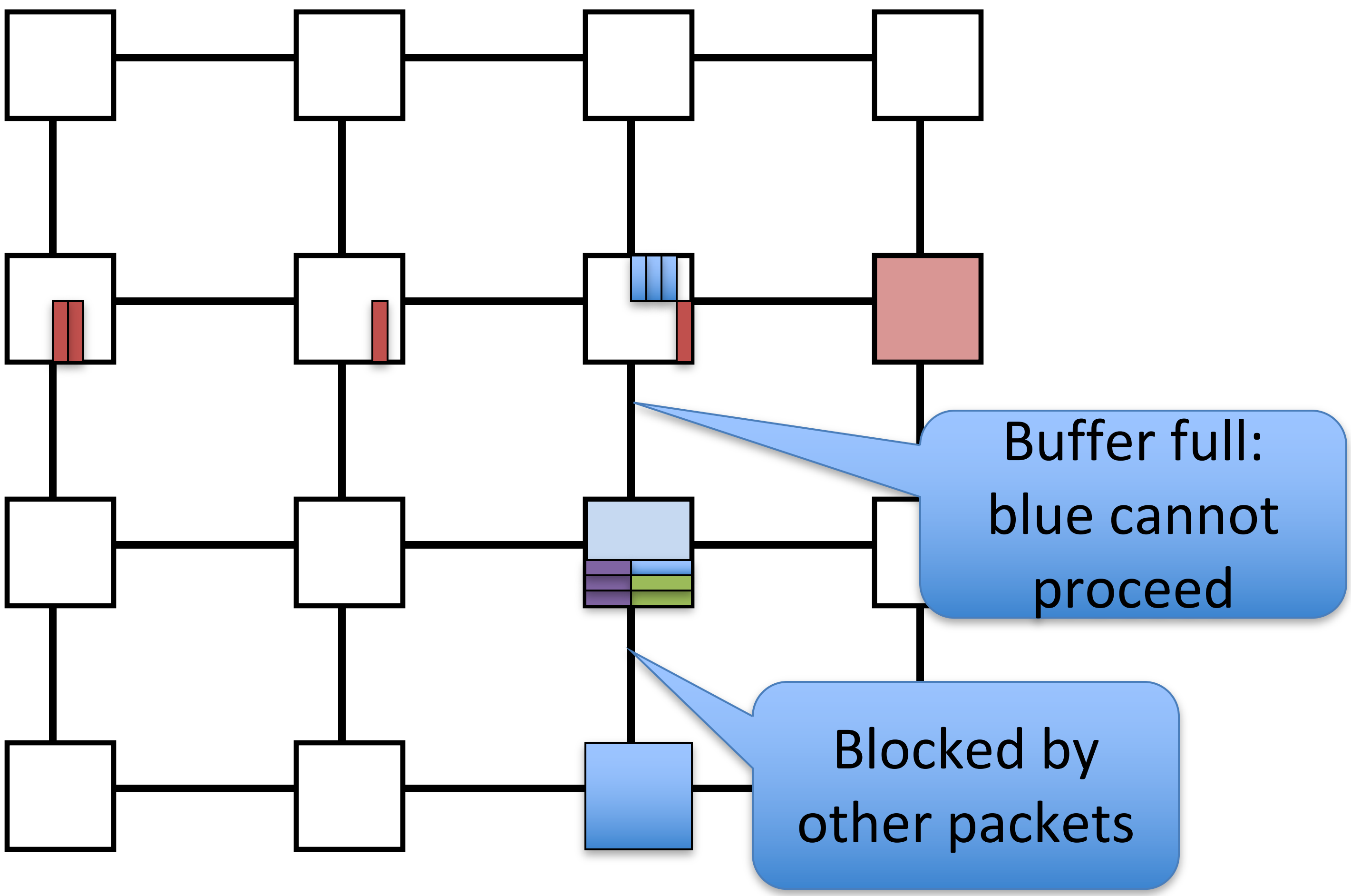

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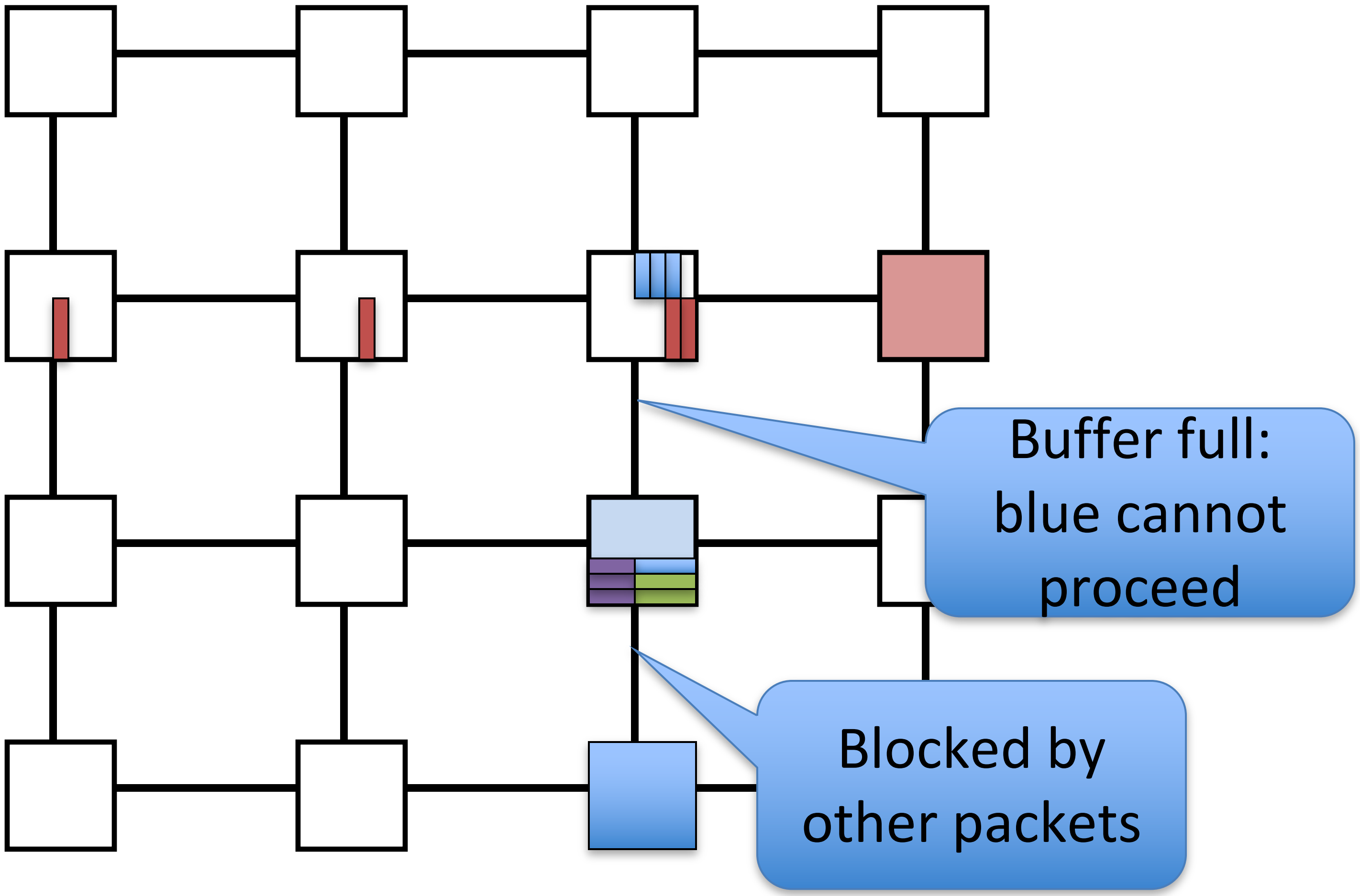

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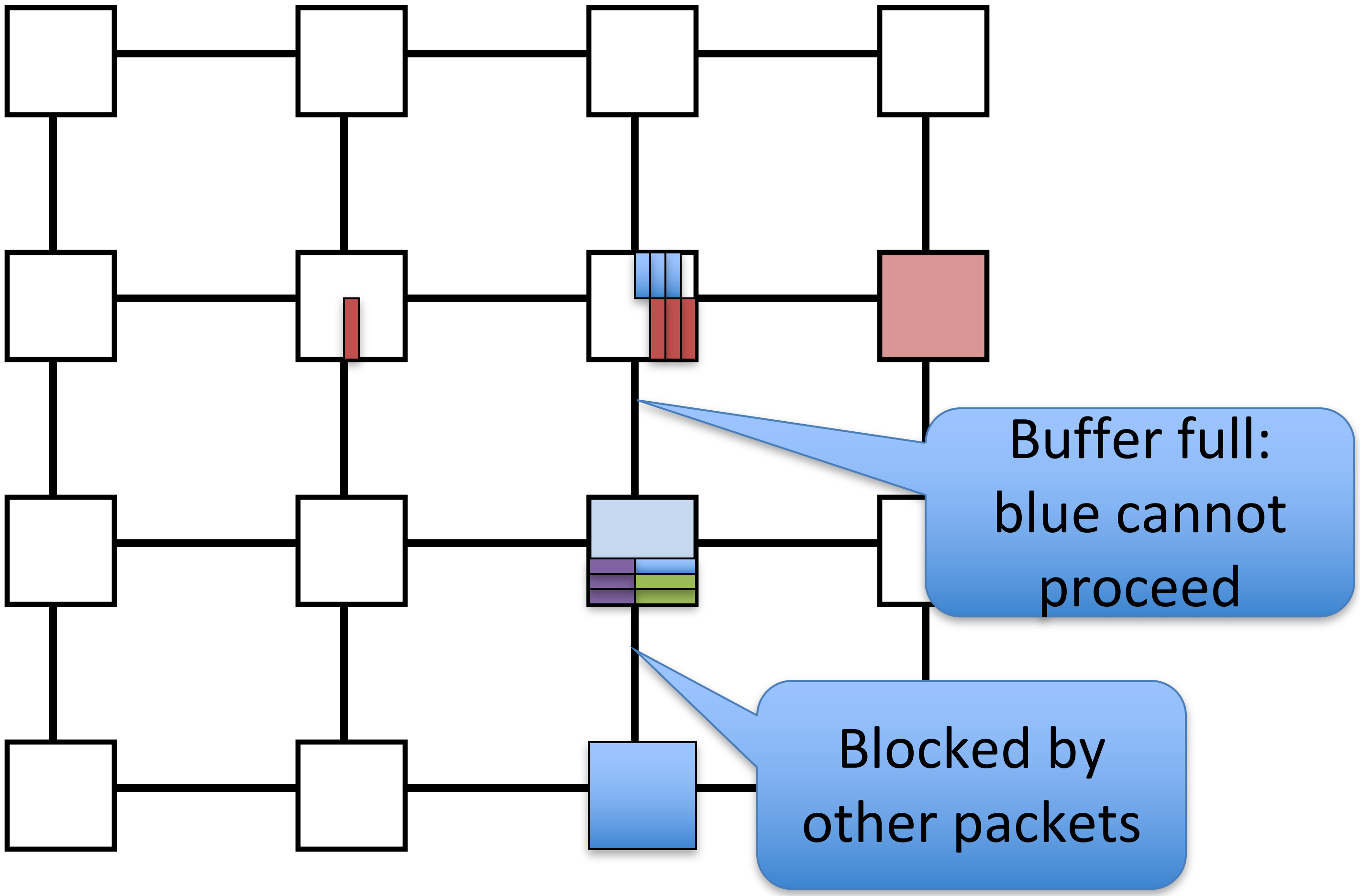

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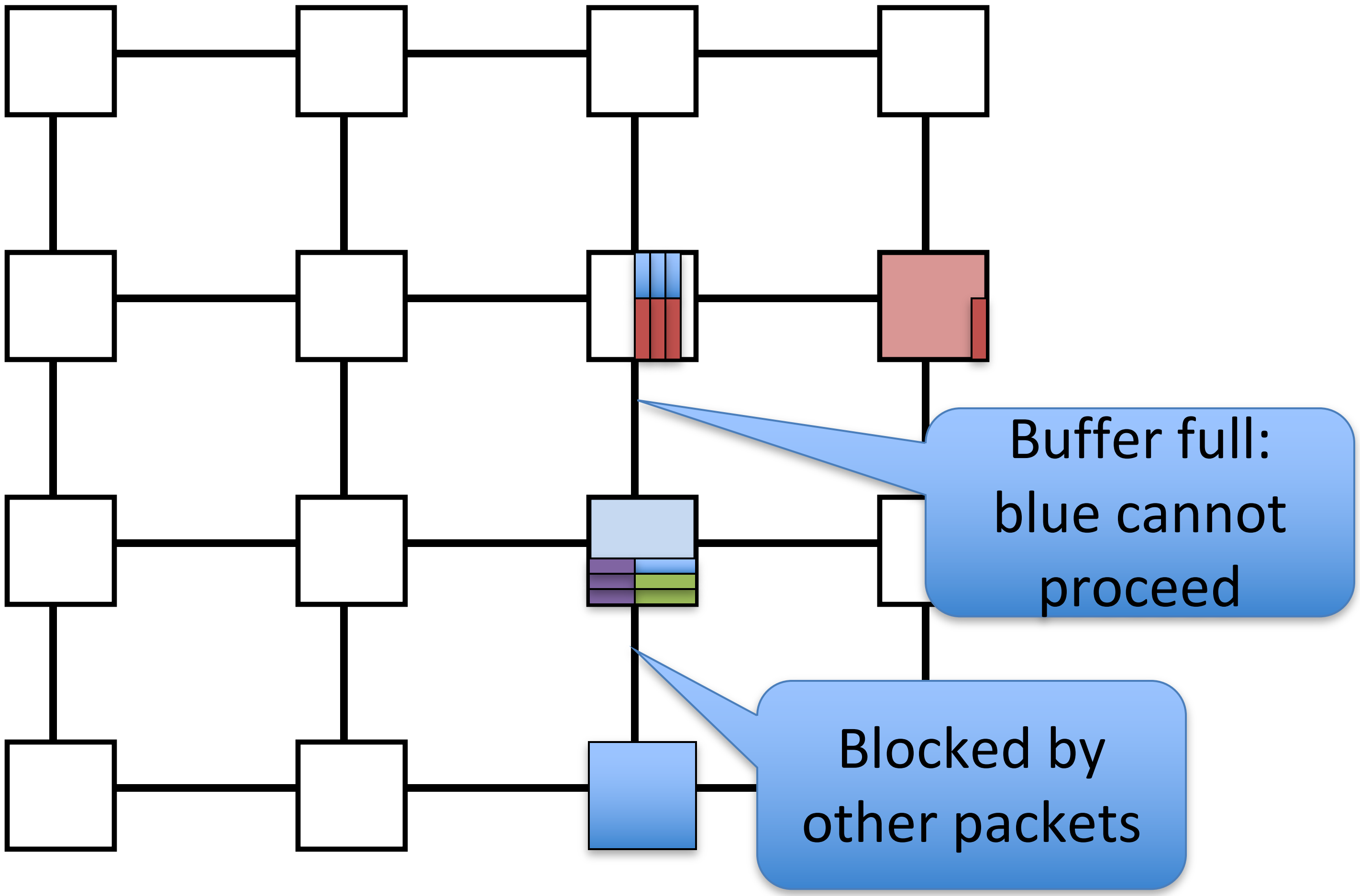

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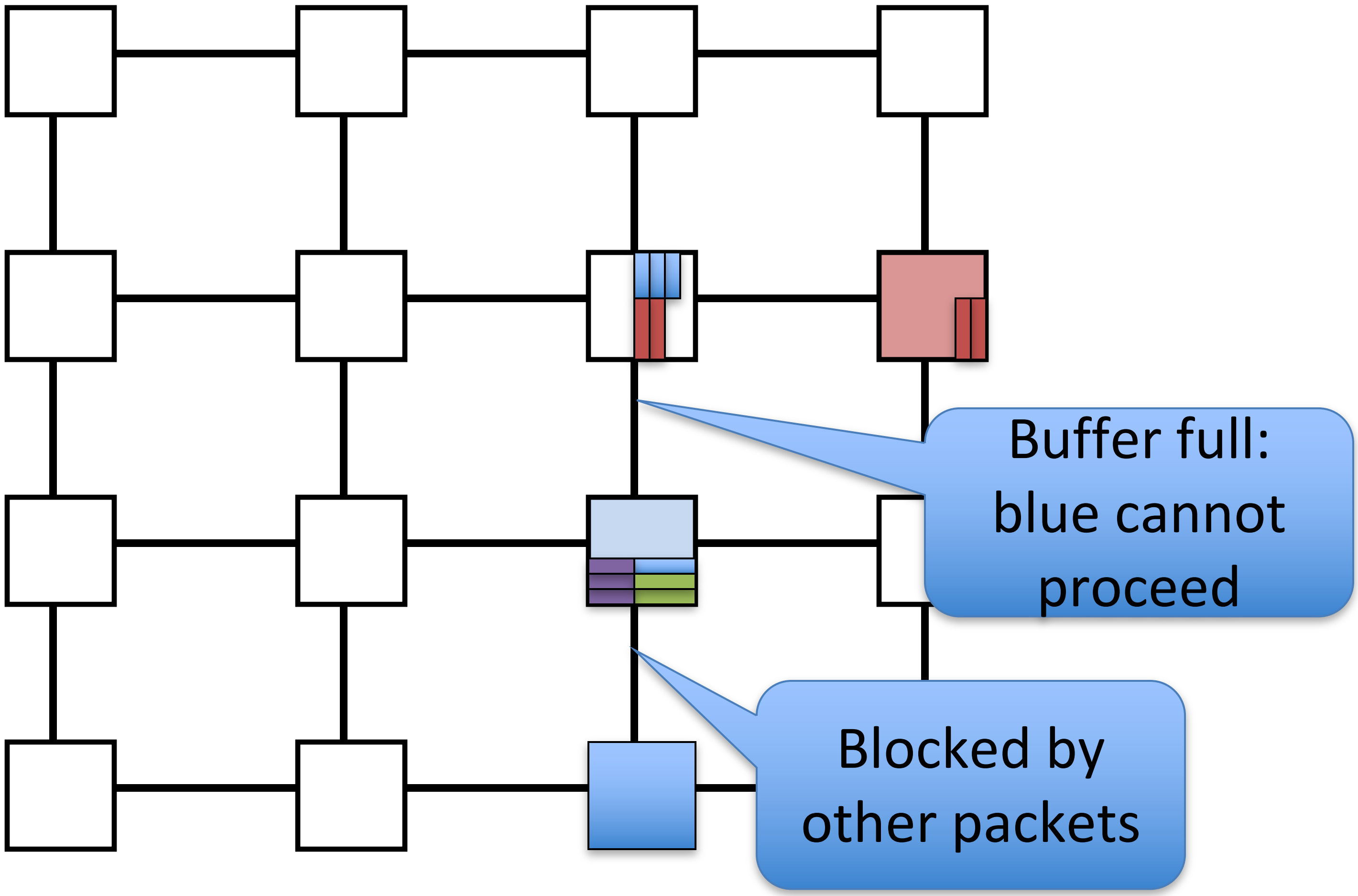

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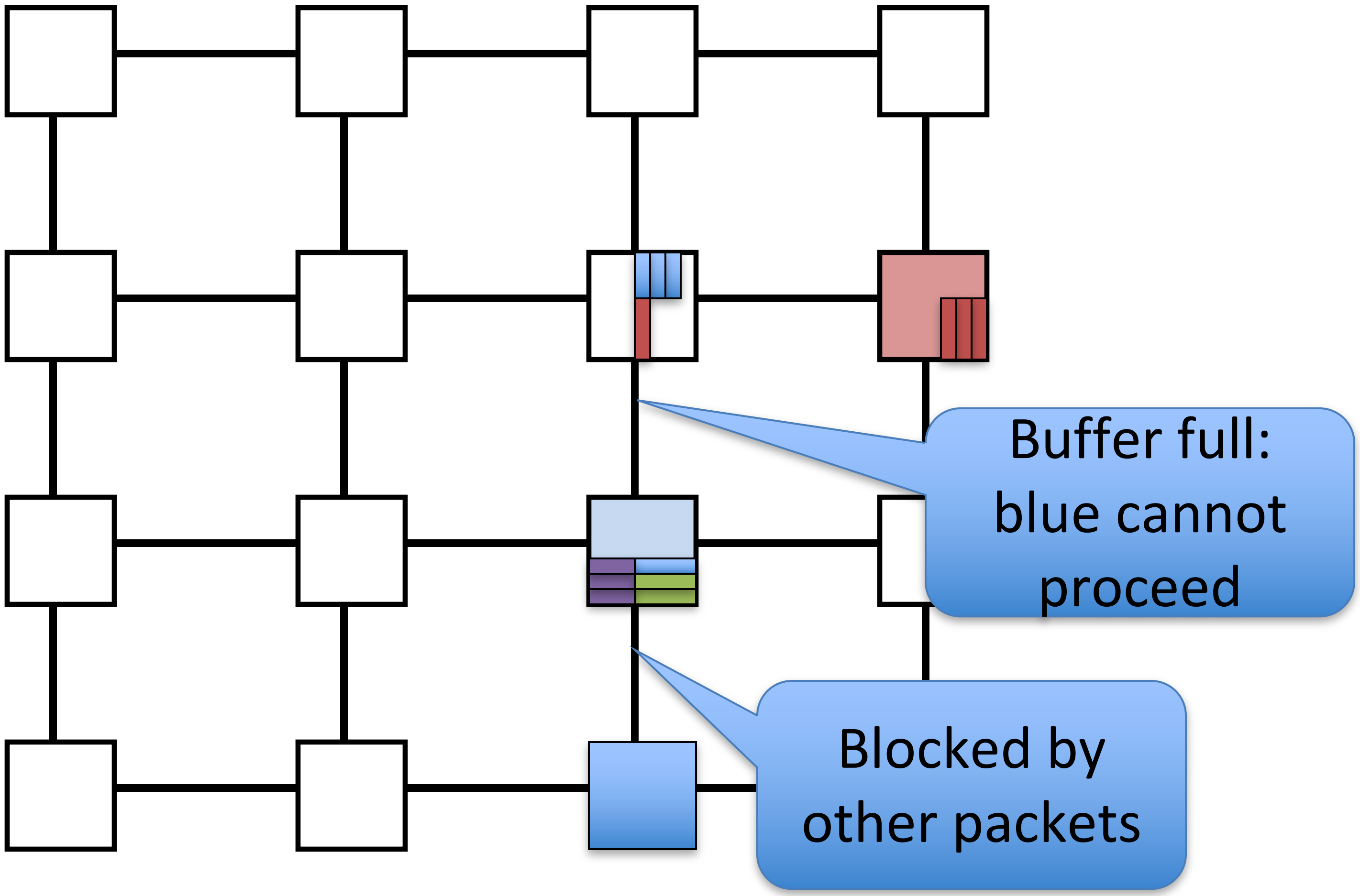
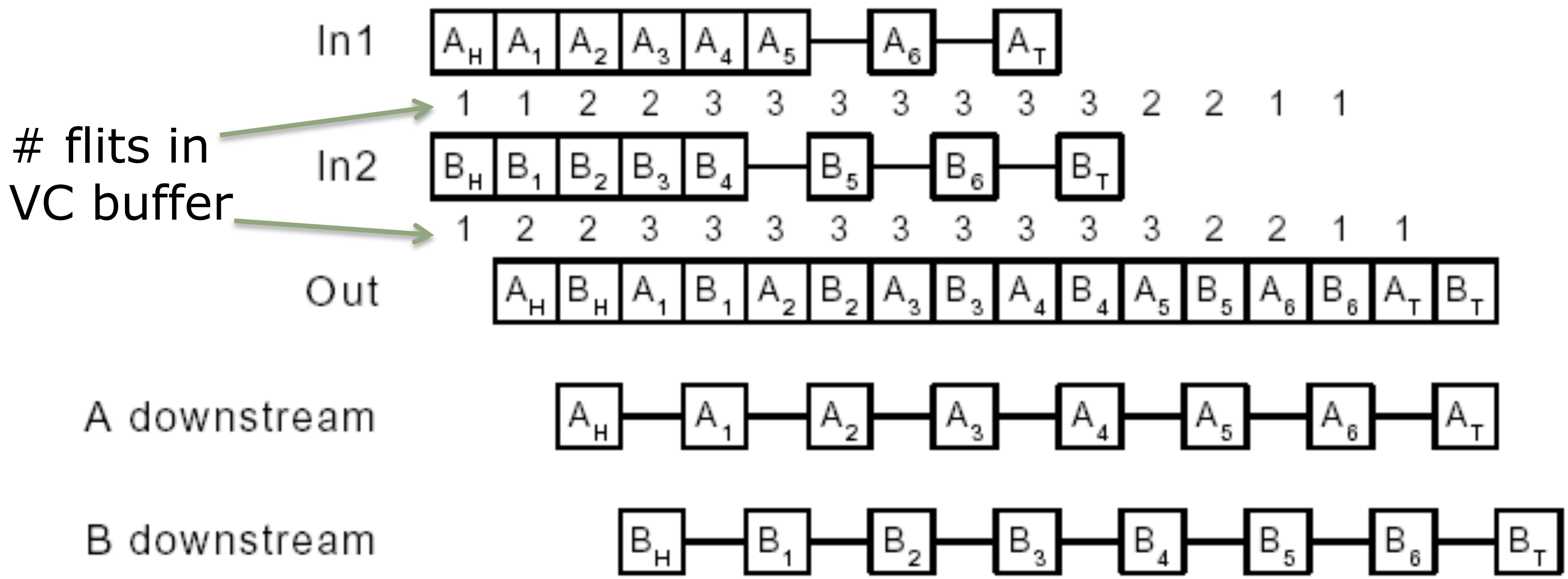
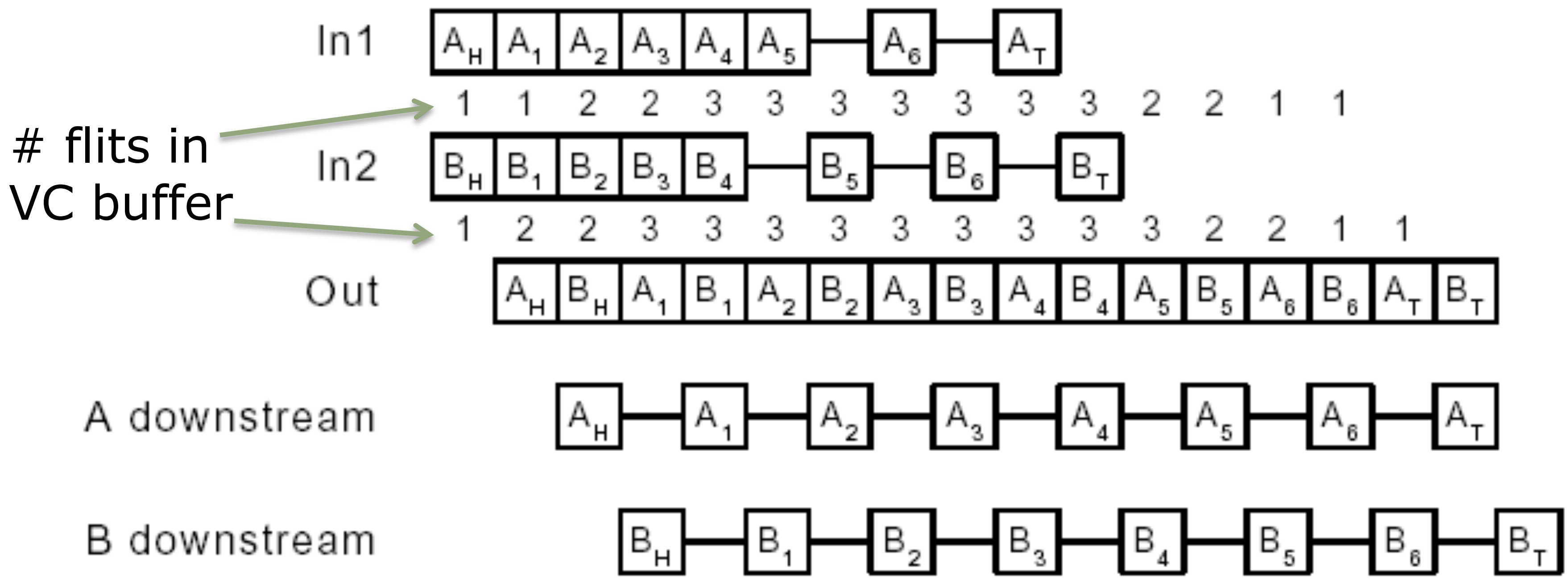


Time-space View: Virtual-Channel



- *Advantages?*
- *Disadvantages?*

Time-space View: Virtual-Channel



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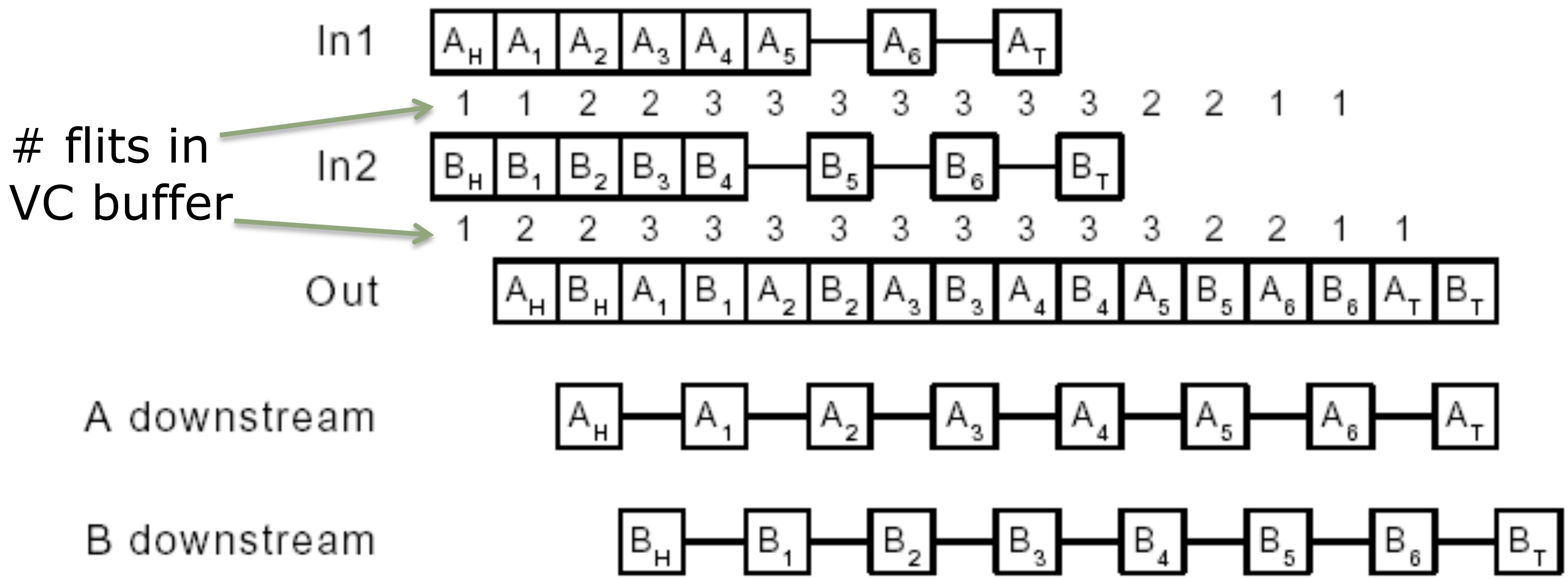
Time-space View: Virtual-Channel



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

Techniques for link backpressure

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- Naïve stall-based (on/off):
  - Can source send or not?

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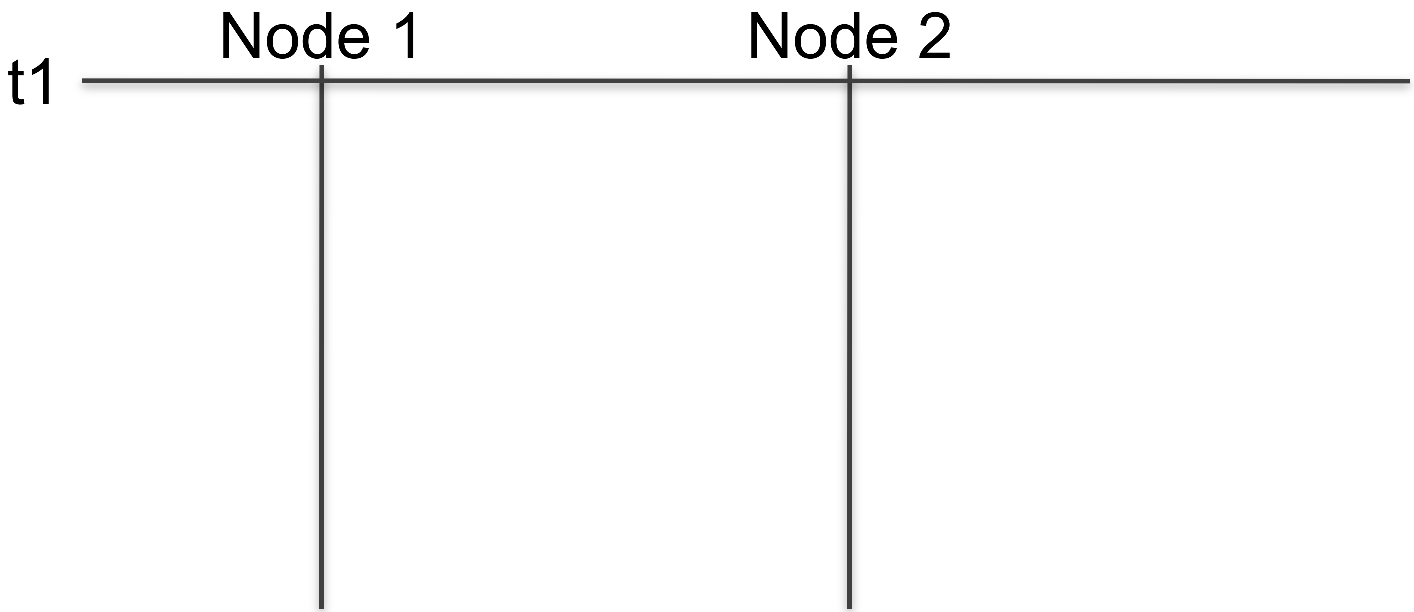
Techniques for link backpressure

- 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

Credit-based Flow Control



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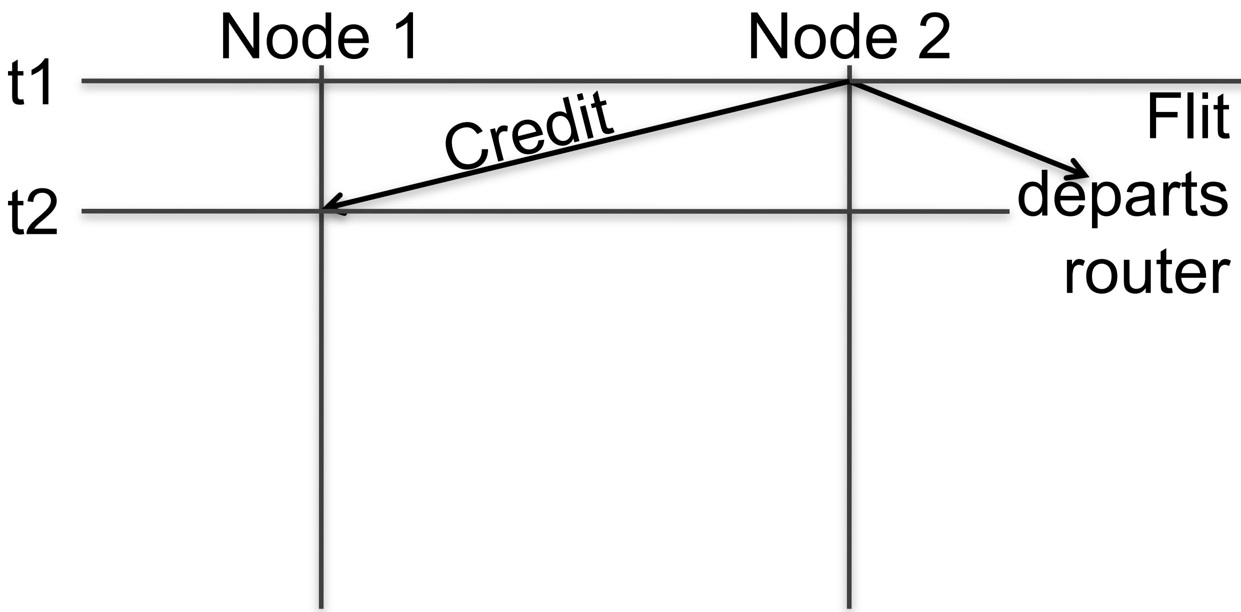

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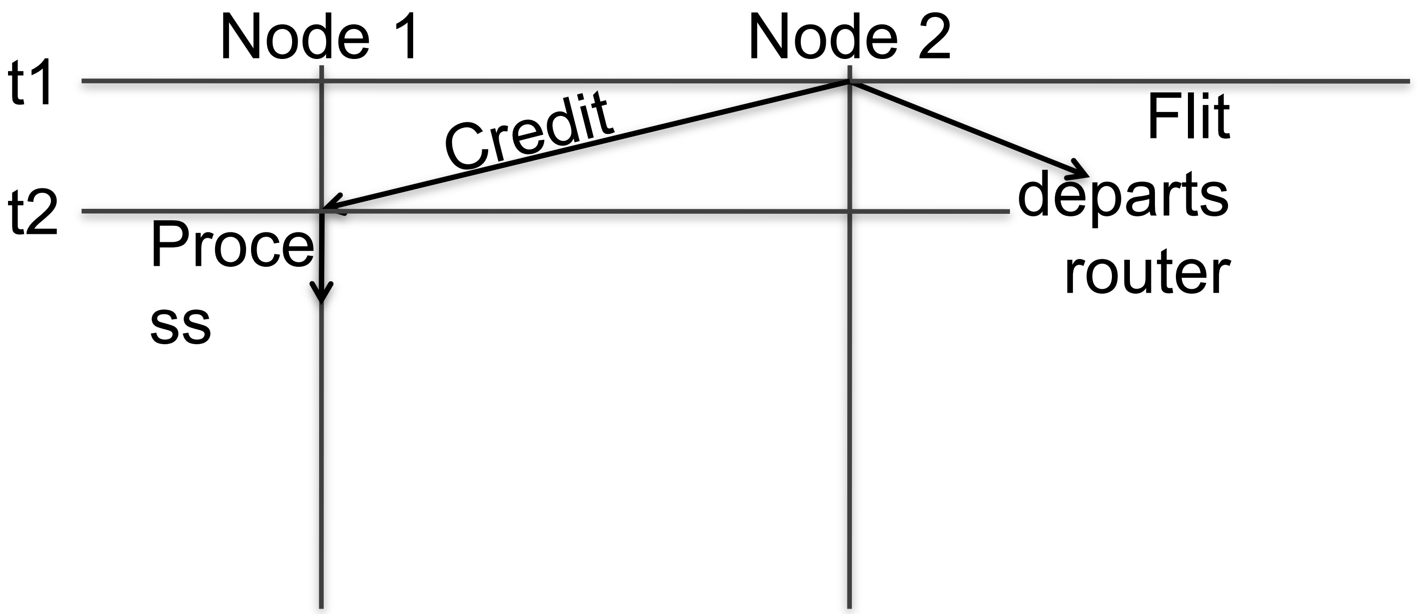

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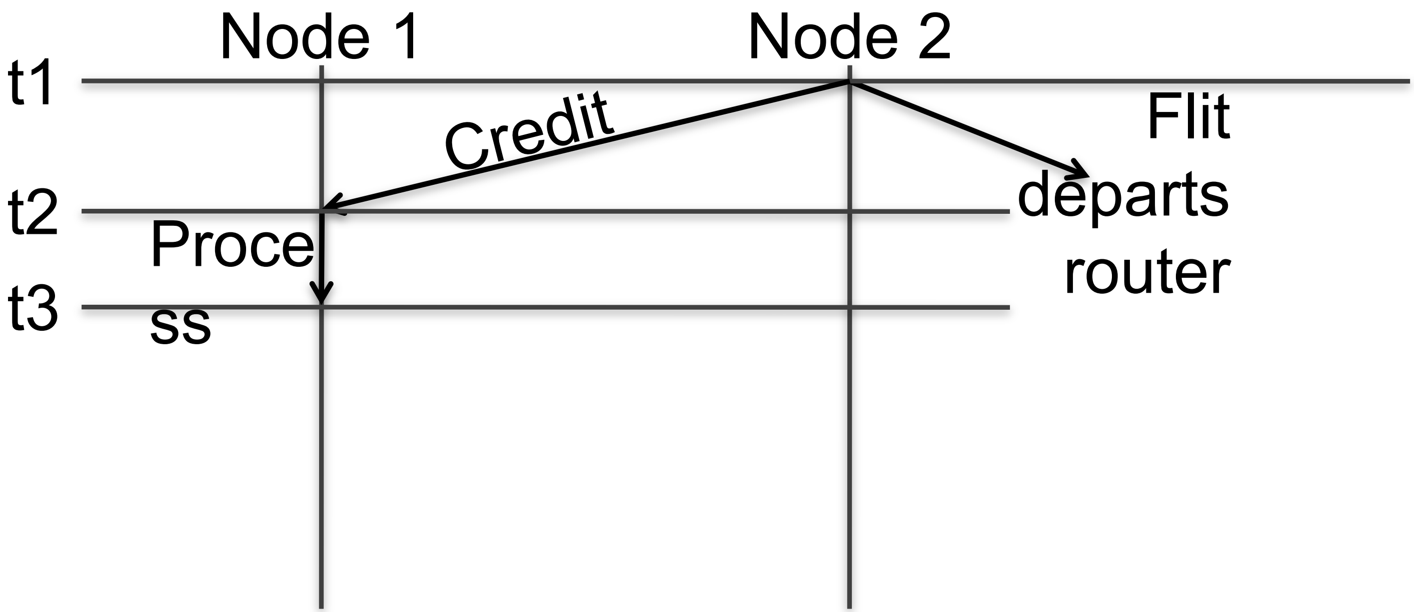

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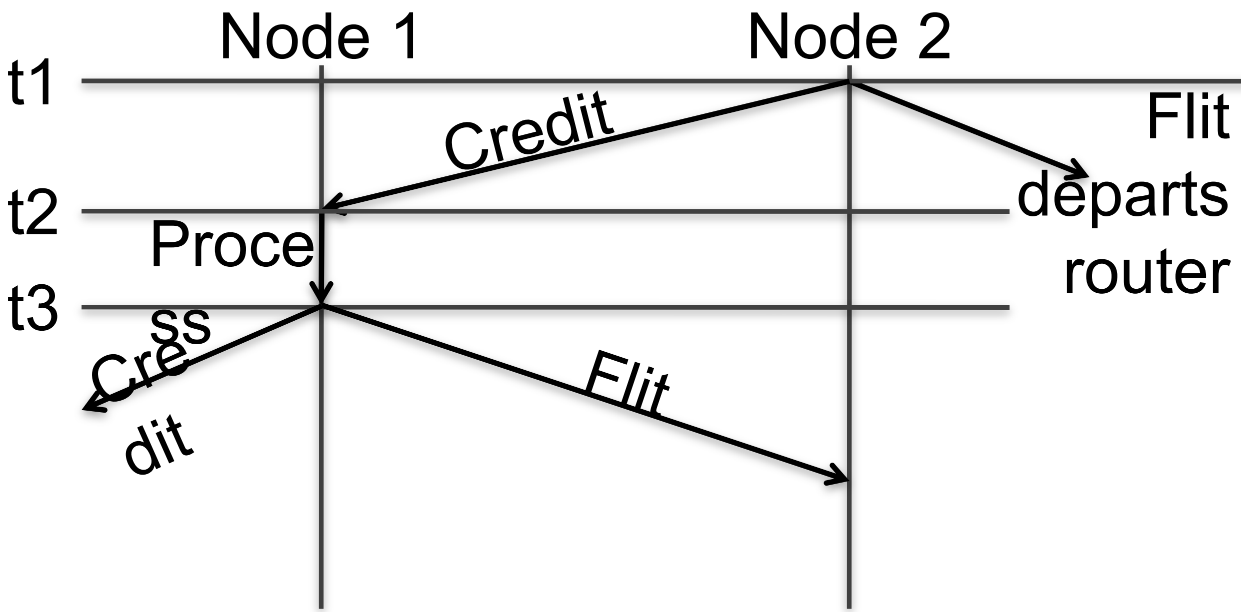

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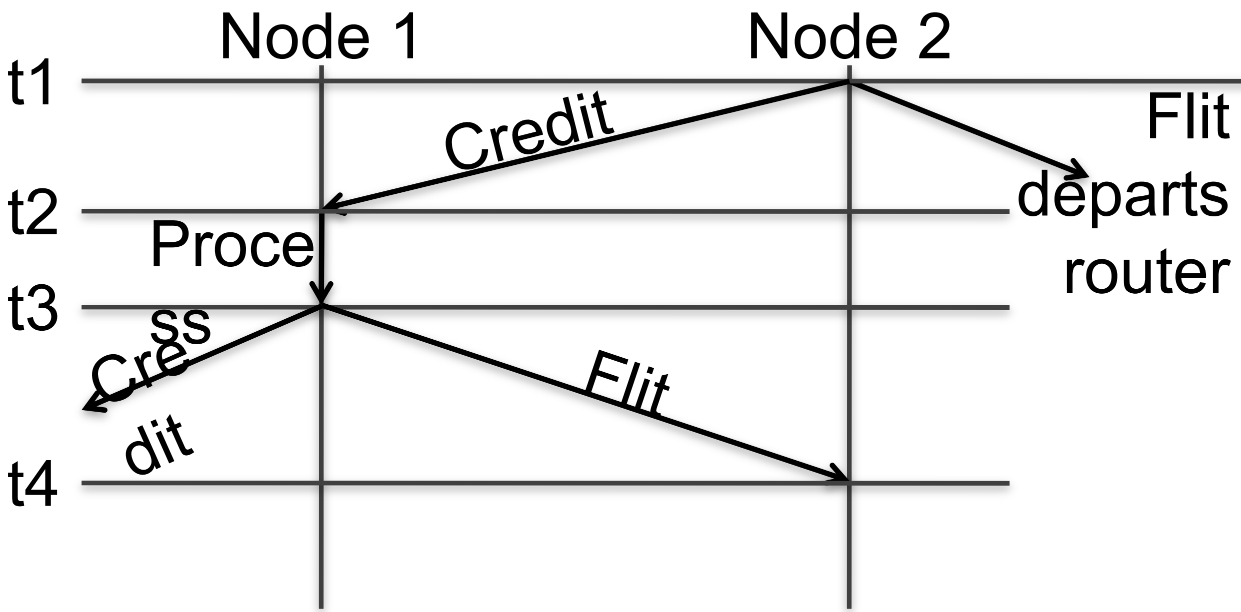

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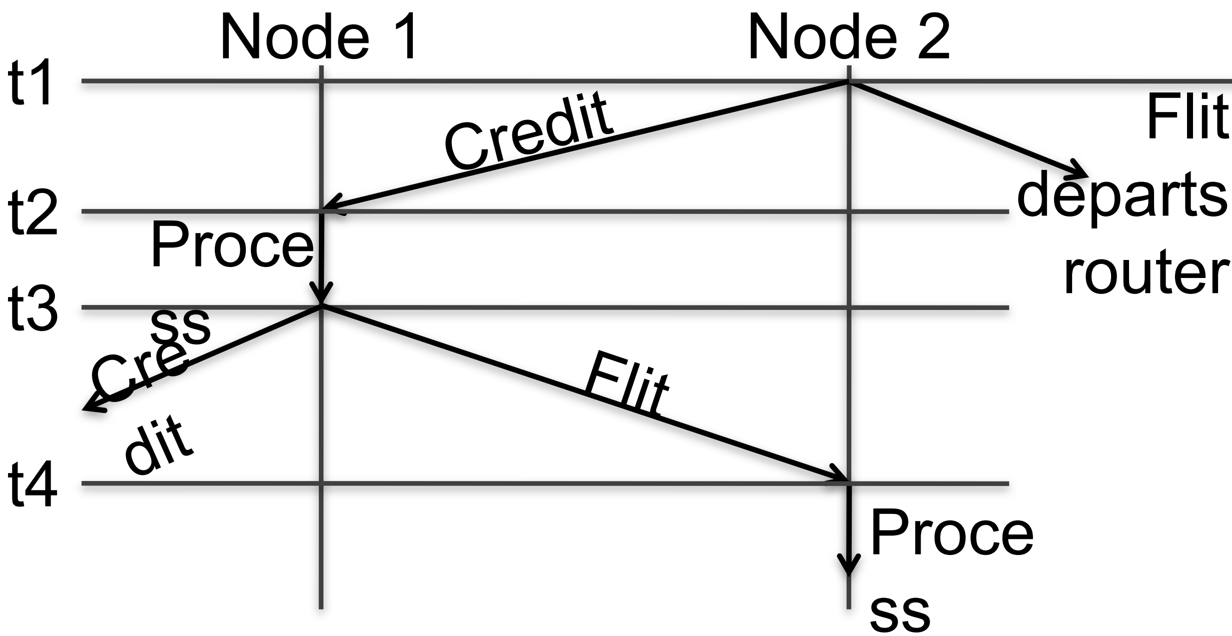

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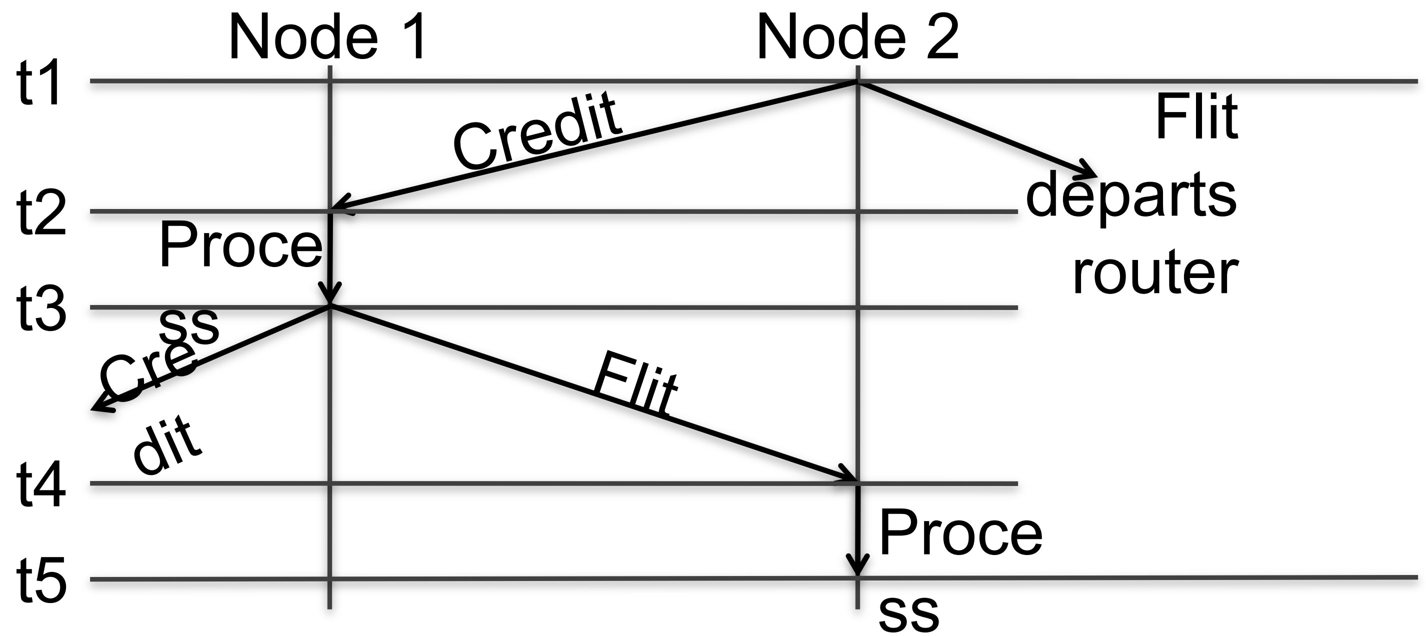

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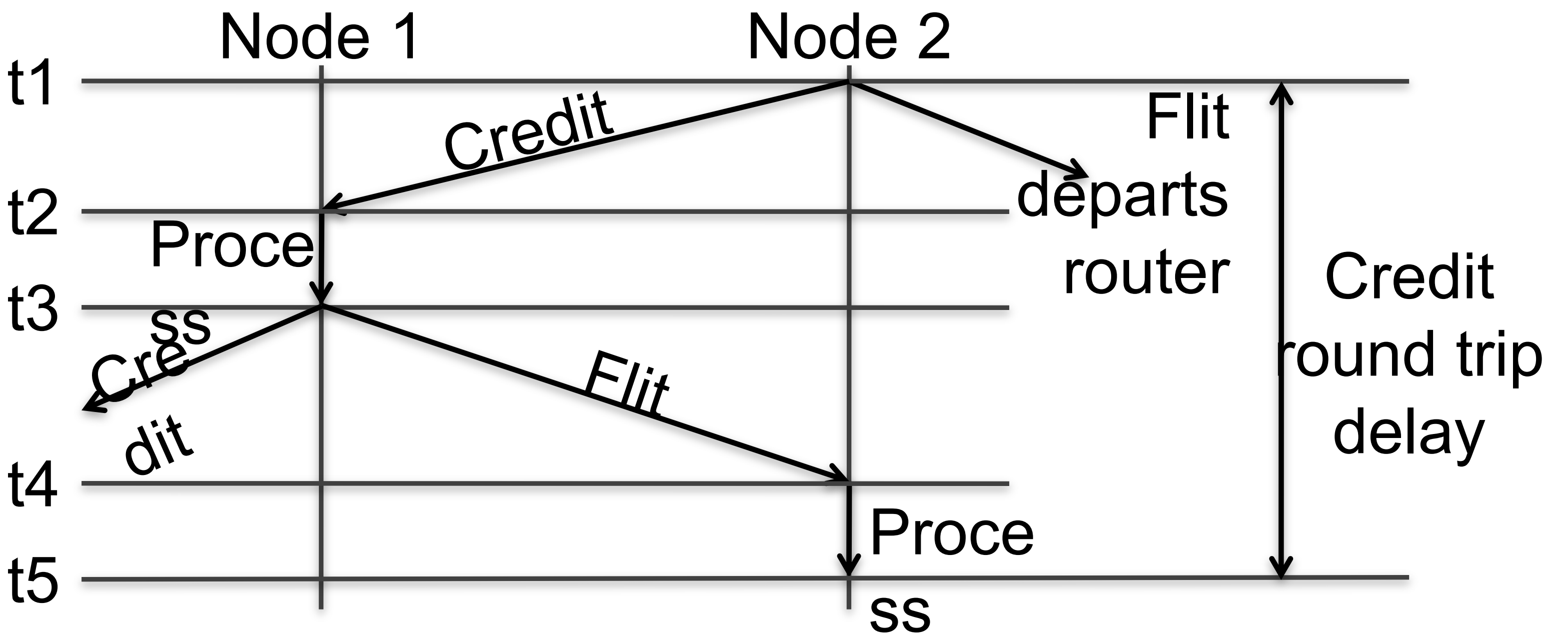

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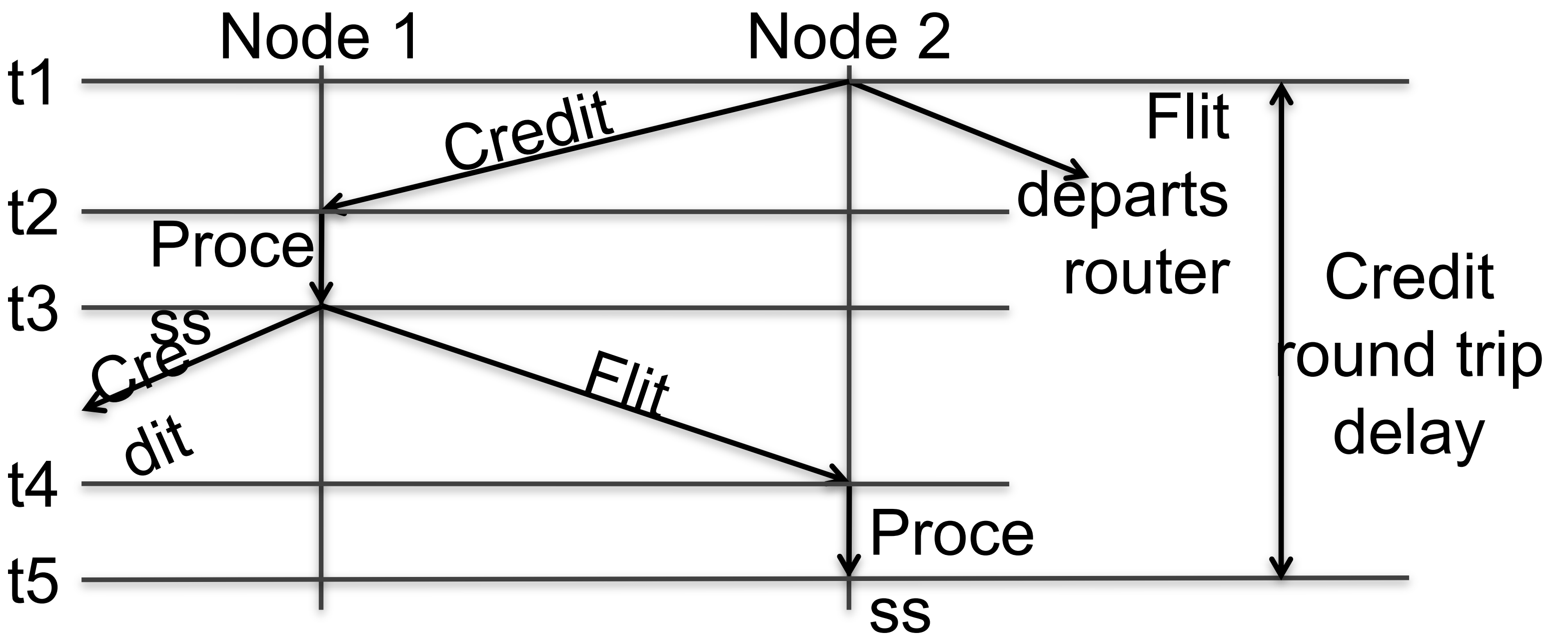

- Round-trip credit delay:
  - Time between when buffer empties and when next flit can be processed from that buffer entry

Thank you!

Next Lecture:

Router (Switch) Microarchitecture

Routing Algorithms