On-Chip Networks II: Router Microarchitecture & Routing

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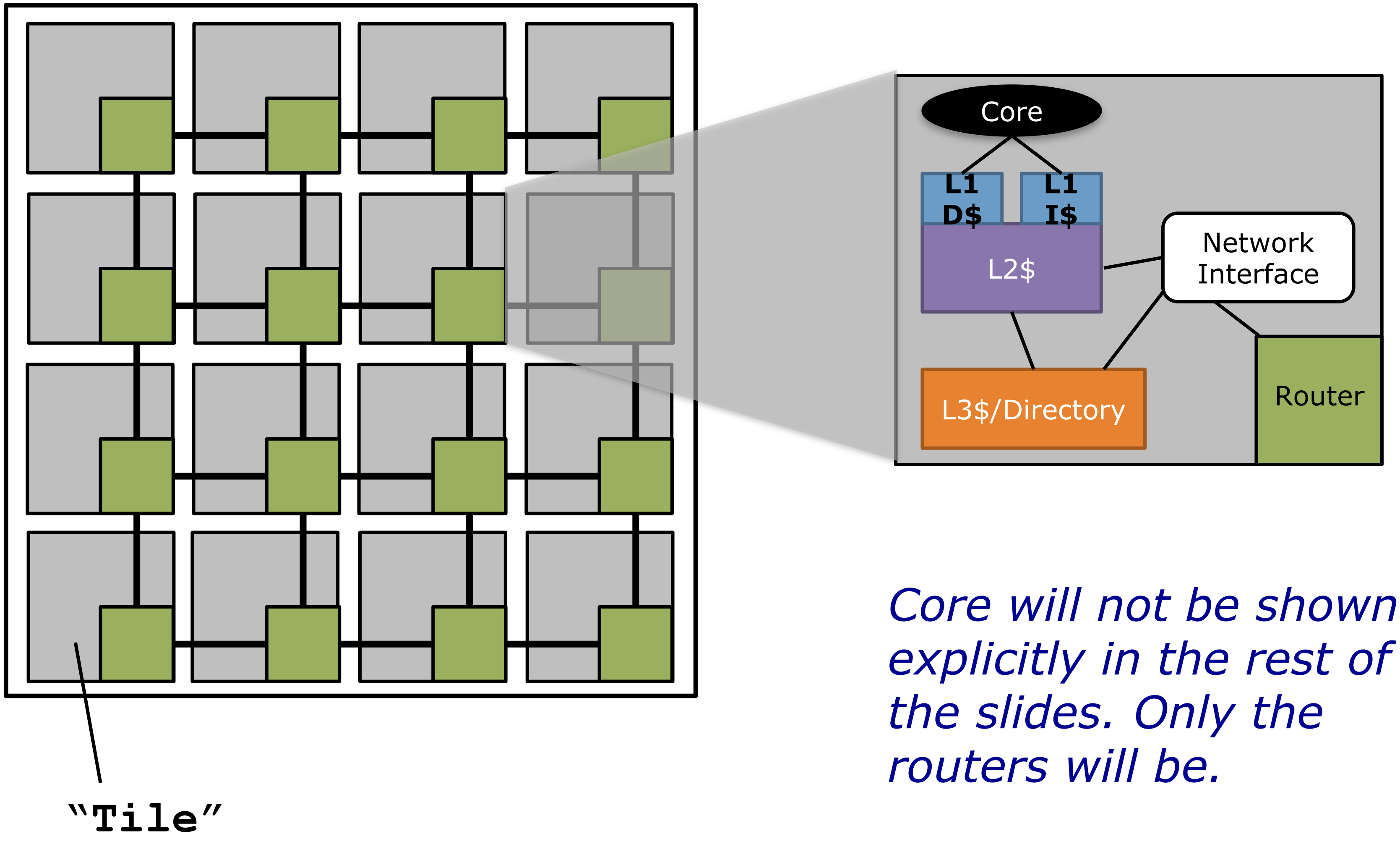
Interconnection Network Architecture

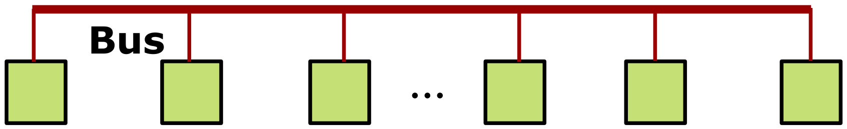
- *Topology*: How to connect the nodes up? (processors, memories, router line cards, …)
- *Routing*: Which path should a message take?
- *Flow control*: How is the message actually forwarded from source to destination?
- *Router microarchitecture*: How to build the routers?
- *Link microarchitecture*: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

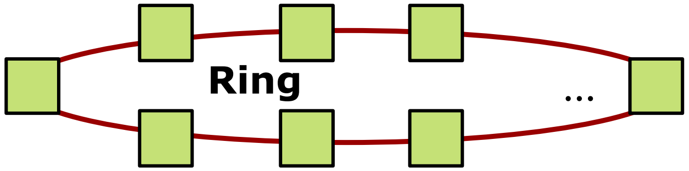
Recap: Modern on-chip networks

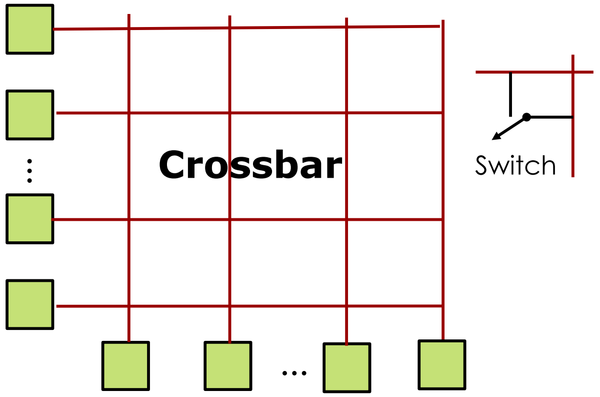


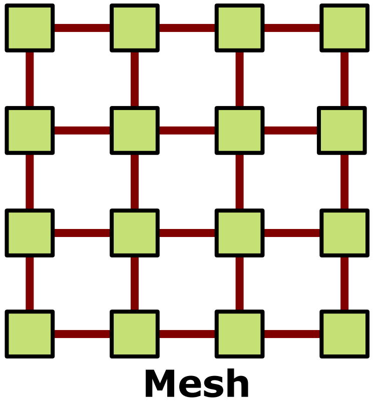
Core will not be shown explicitly in the rest of the slides. Only the routers will be.

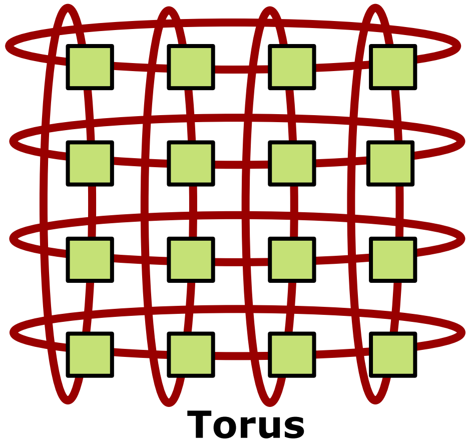
Recap: Topology

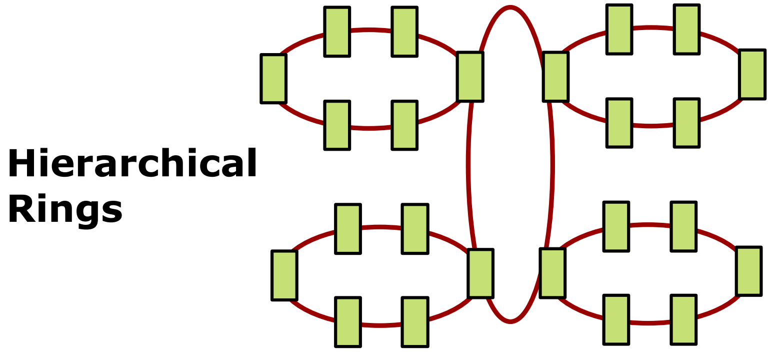


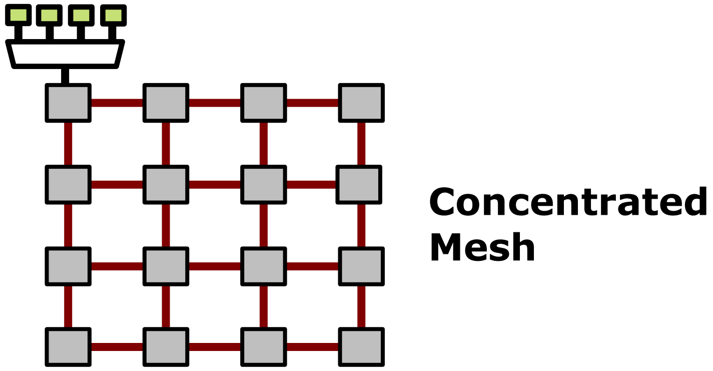












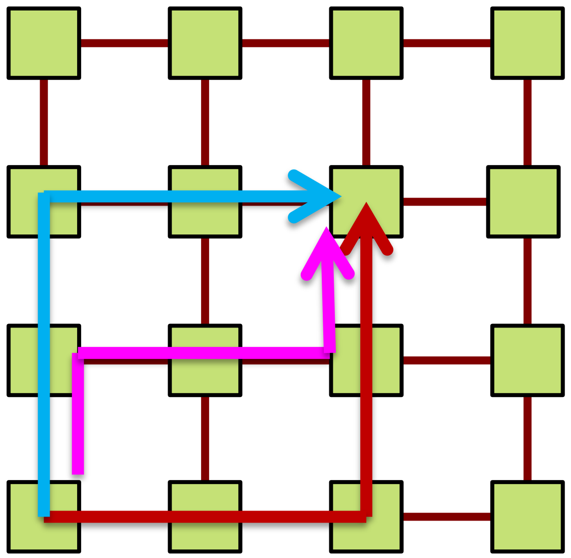
Today's Agenda

- *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?

Routing

Routing

- Once topology is fixed, routing determines exact path from source to destination
- Analogous to the series of road segments from source to destination

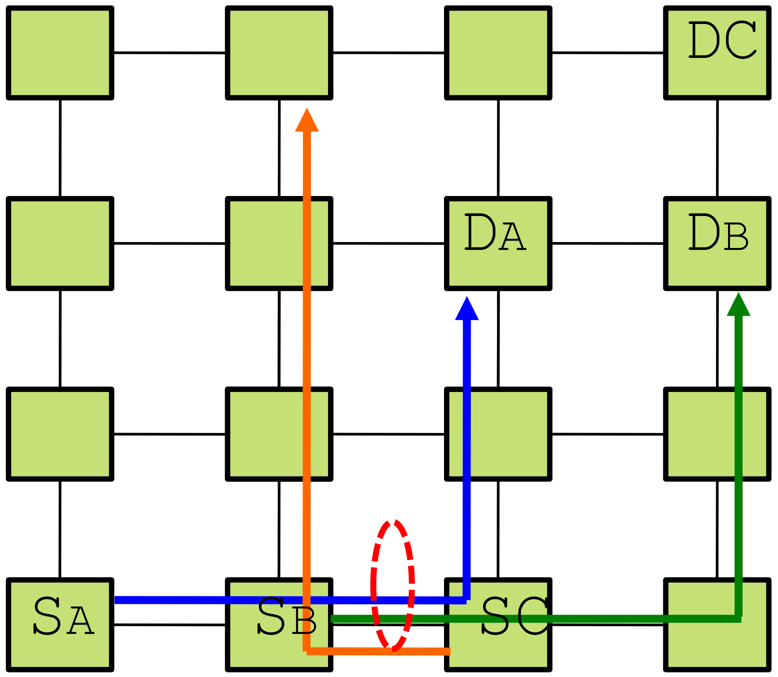


Routing Algorithms

- **Property**
  - Minimal or Non-Minimal
    - Minimal: only select shortest paths
    - Non Minimal: need not select shortest paths
  - Oblivious or Adaptive
    - Oblivious: routing decisions do not depend on network state (i.e., traffic), only depends on (src, dest)
      - ***Deterministic*** is a subset where is always chosen
    - Adaptive: uses different routes depending on trsame route affic
- **Design Considerations**
  - Deadlock Freedom
    - traffic pattern should not lead to a situation where no packets move forward
  - Implementation
    - Table-based or combination circuit

Dimension Ordered Routing

XY: Always go X first, then Y



Minimal and Deterministic

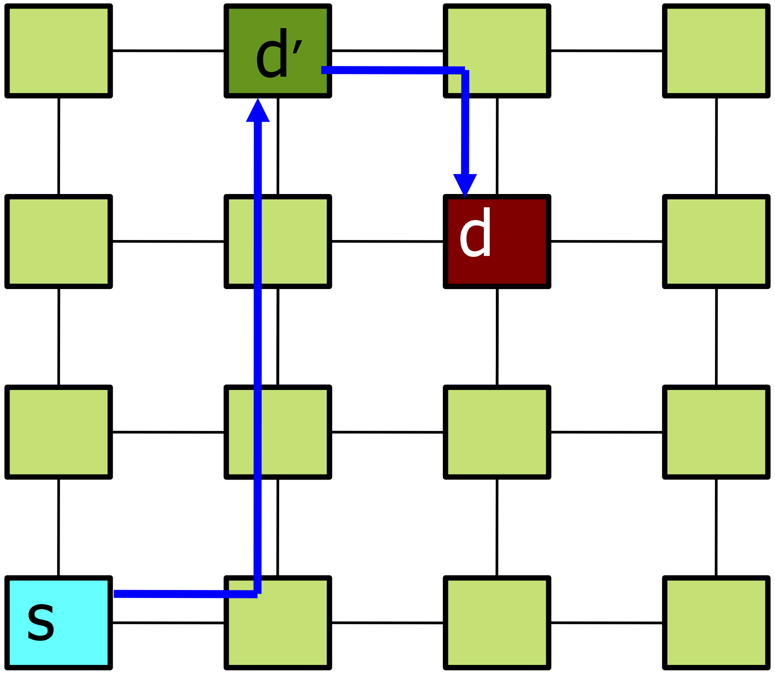
Cons of this approach?

- Eliminates any path diversity provided by topology
- Poor load balancing

And yet … This is the most common approach!

Valiant’s Routing Algorithm

- To route from s to d
  - Randomly choose intermediate node d’
  - Route* from s to d’ (Phase I), and d’ to d (Phase II)
- Pros
  - Randomizes any traffic pattern
    - All patterns appear uniform random
  - Balances network-load
    - Higher throughput
- Cons
  - Non-minimal
    - Higher latency and energy
  - Destroys locality

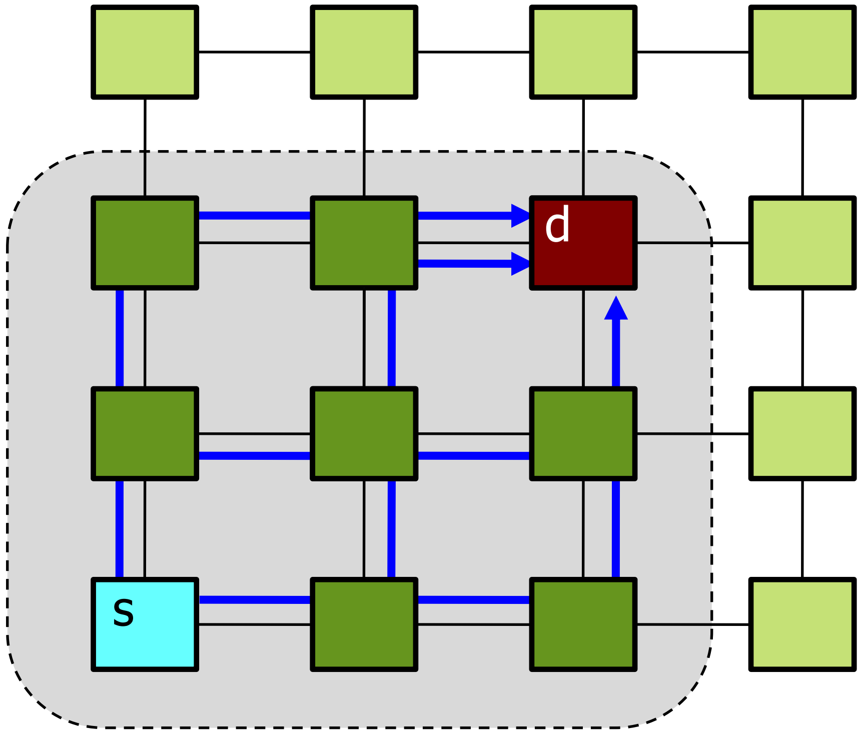


Non-Minimal and *Oblivious

can also be Adaptive

ROMM: Randomized, Oblivious Multi-phase Minimal Routing

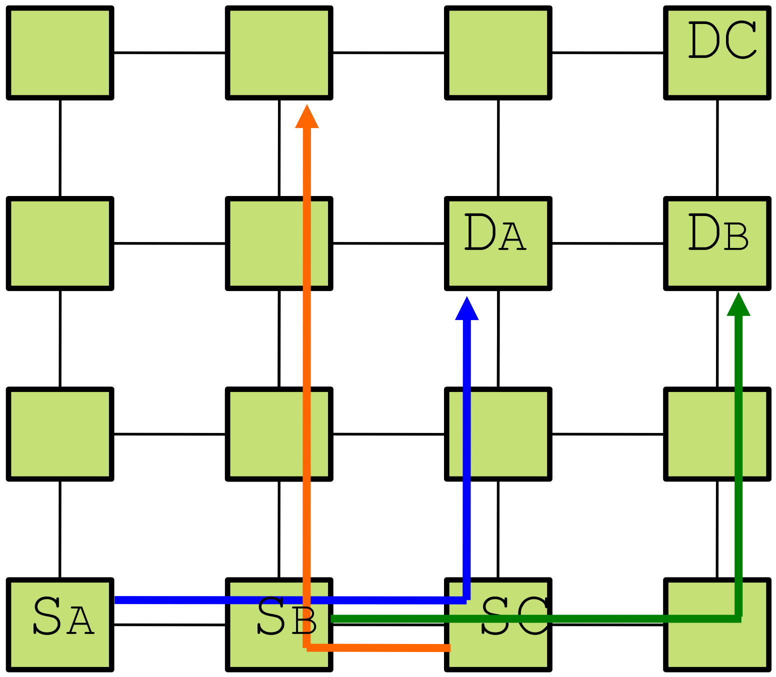
- Confine intermediate node to be within minimal quadrant
- Retain locality + some load-balancing
- This approach essentially translates to randomly selecting between all minimal paths from source to destination

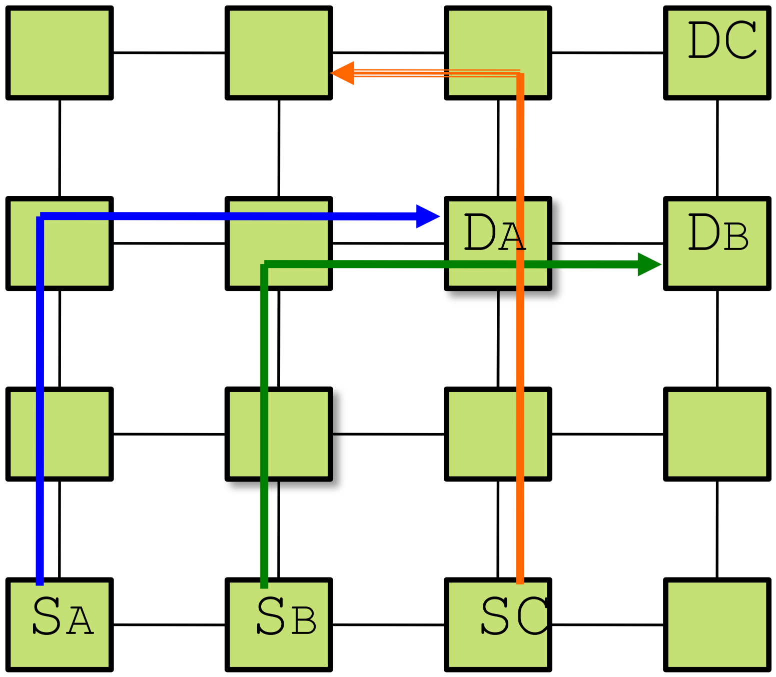


Minimal and Oblivious

Challenges with Minimal + Oblivious

XY Minimal and Oblivious ***YX***



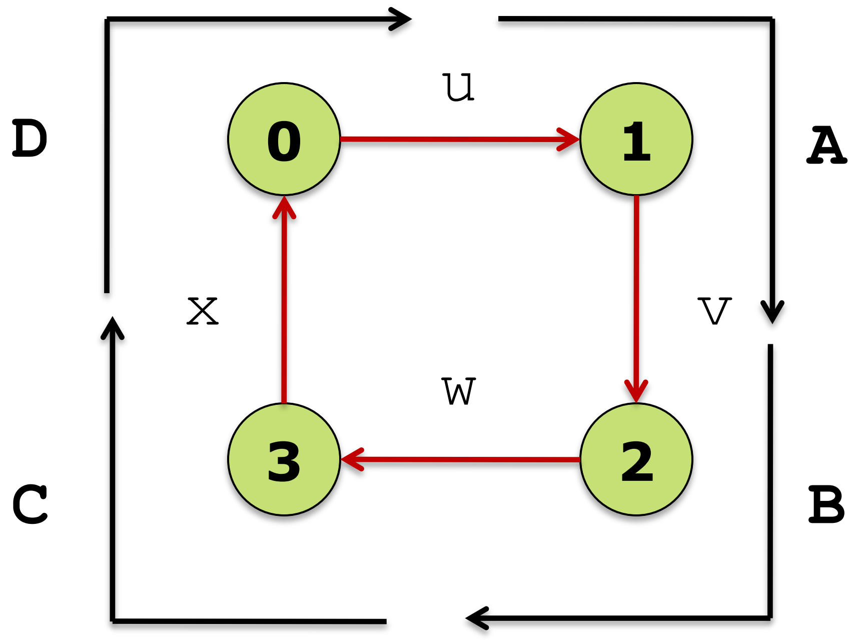


What happens if you use both simultaneously?
Suppose we toss a coin and send either XY or YX

Benefits?

Challenge?

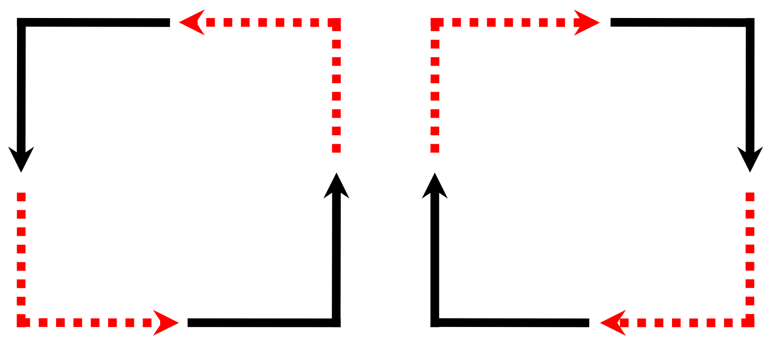
Network Deadlock



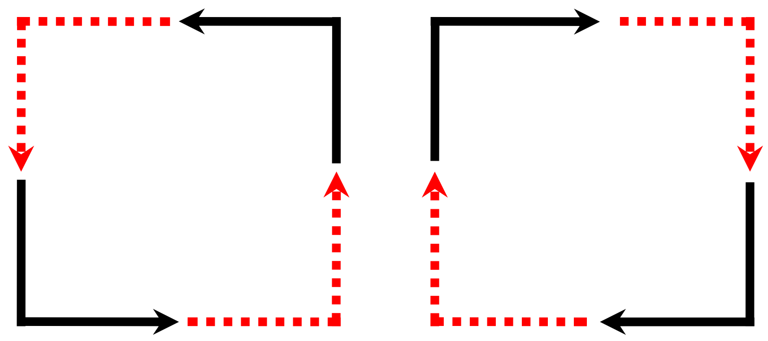
- Flow A holds u and wants v
- Flow B holds v and wants w
- Flow C holds w and wants x
- Flow D holds x and wants u

Turn Model (Glass and Ni 1994)

- One way of looking at whether a routing algorithm is deadlock free is to look at the turns allowed.
- Deadlocks may occur if turns can form a cycle
  - Removing some turns can make algorithm deadlock free

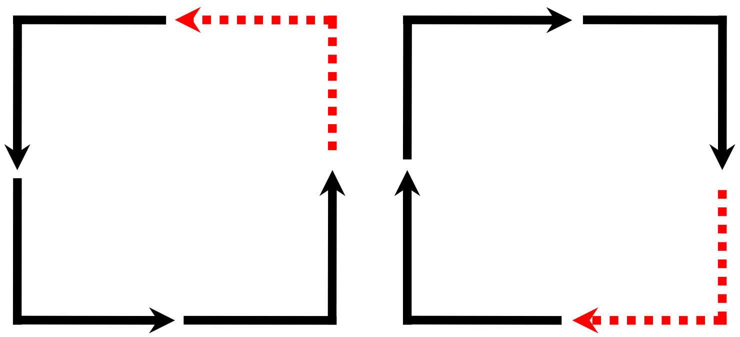


XY Model

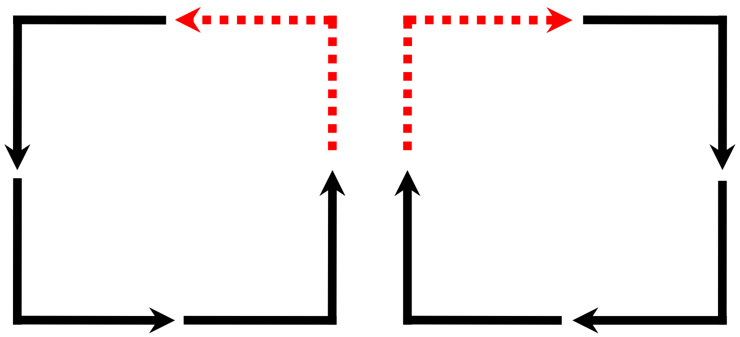


YX Model

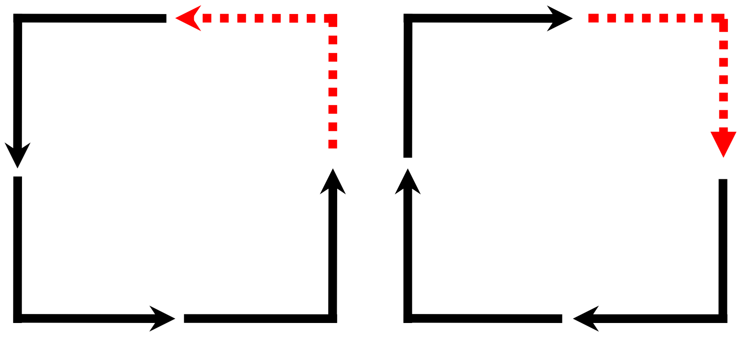
Deadlock-free Routing Algorithms



West-First Turn Model

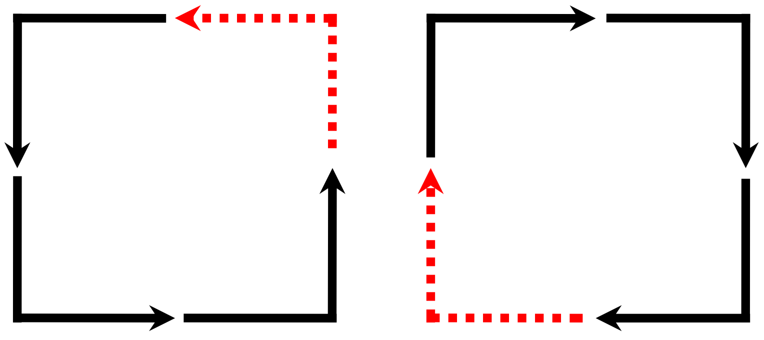


North-Last Turn Model

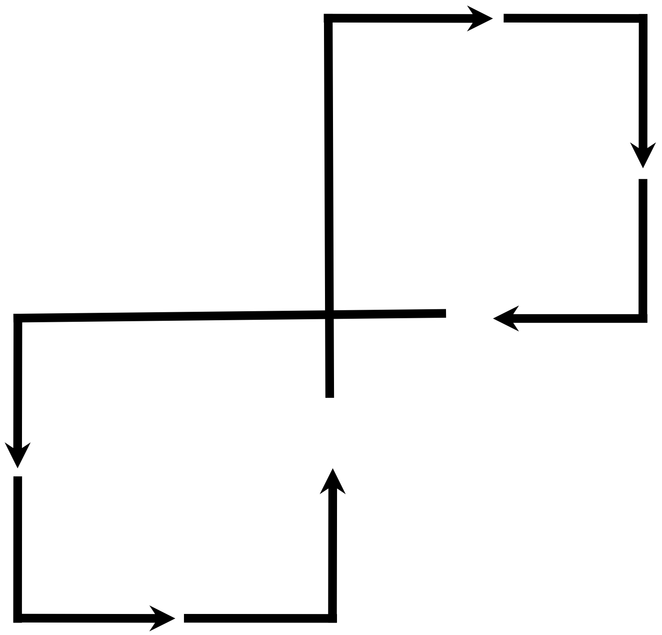


Negative-First Turn Model

Can we eliminate *any* 2 turns?



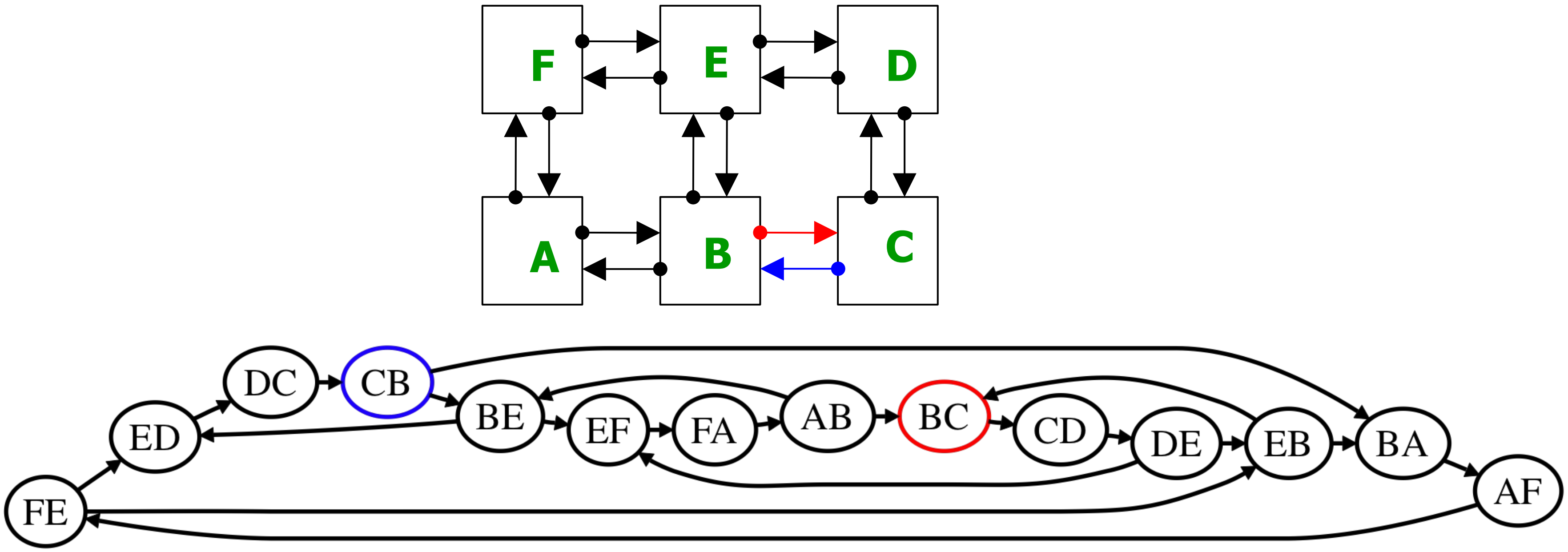
Six turn model



Deadlock!

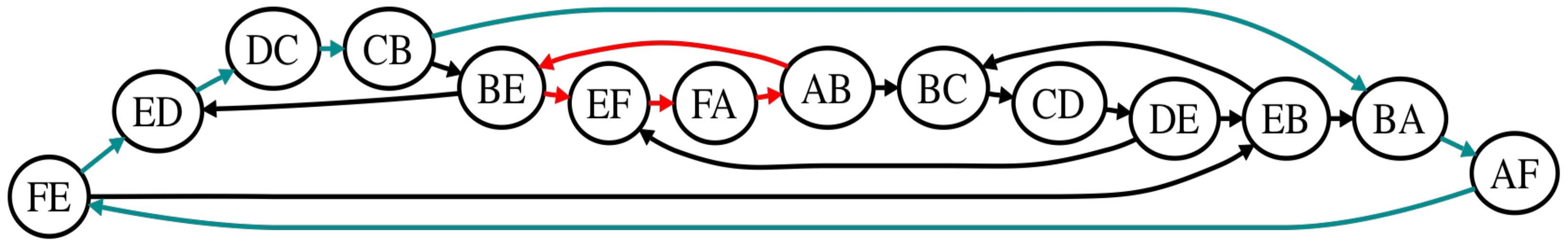
Channel Dependency Graph (CDG)

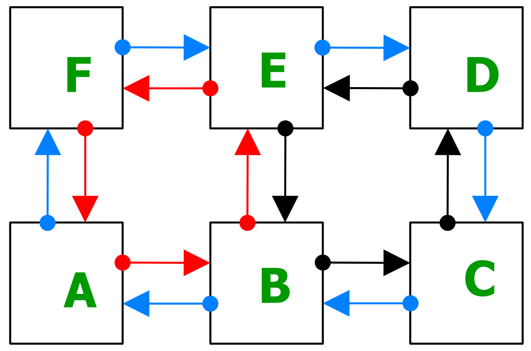
- Vertices represent network links (channels)
- Edges represent turns
  - *180^o turns not allowed, e.g., AB → BA*



Cycles in the CDG

The channel dependency graph D derived from the network topology may contain many *cycles*

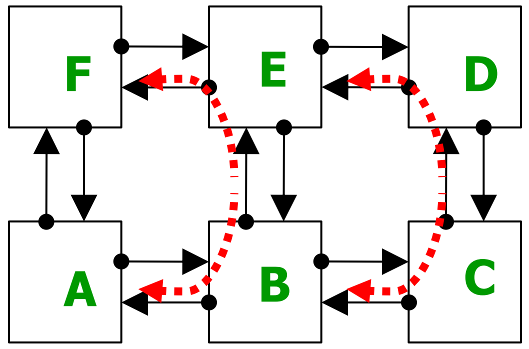




Flow routed through links AB, BE, EF
Flow routed through links EF, FA, AB
Deadlock!

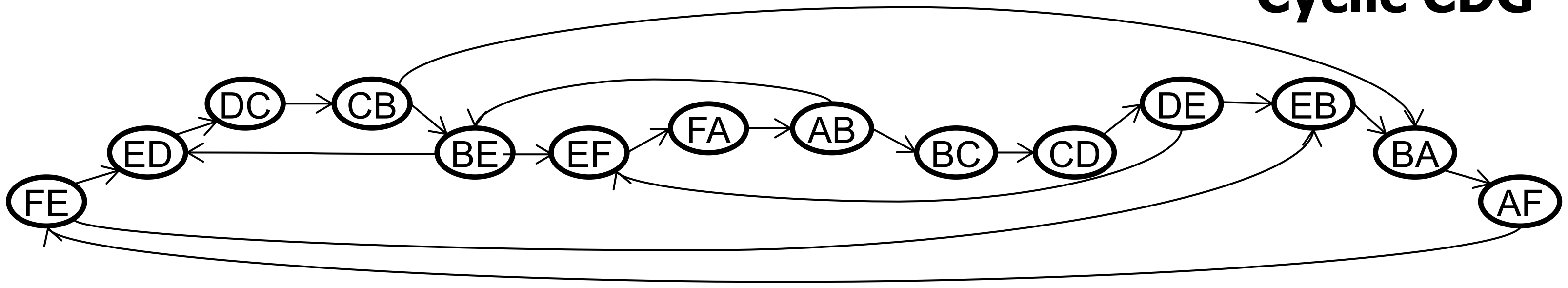
Edges in CDG = Turns in Network
➔ Disallow/Delete certain edges in CDG

Acyclic CDG

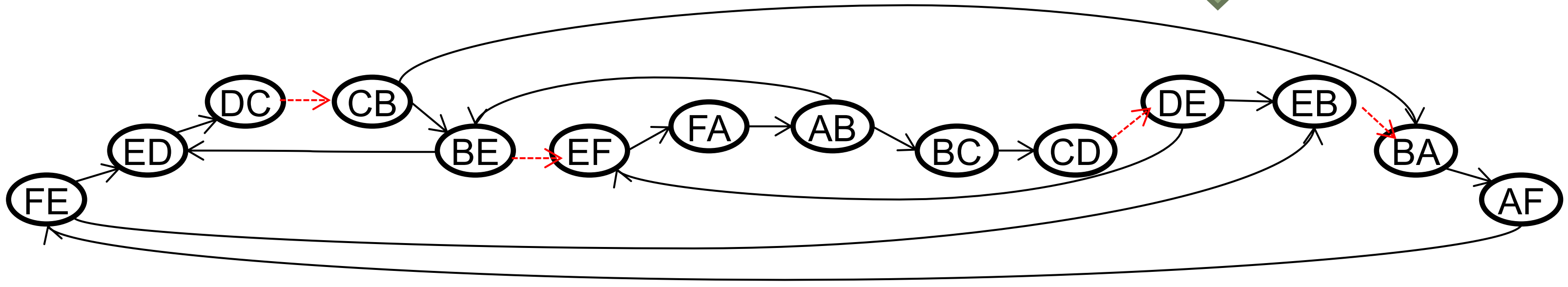


This is the West-first turn model!

Cyclic CDG



Disable certain edges



Acyclic CDG

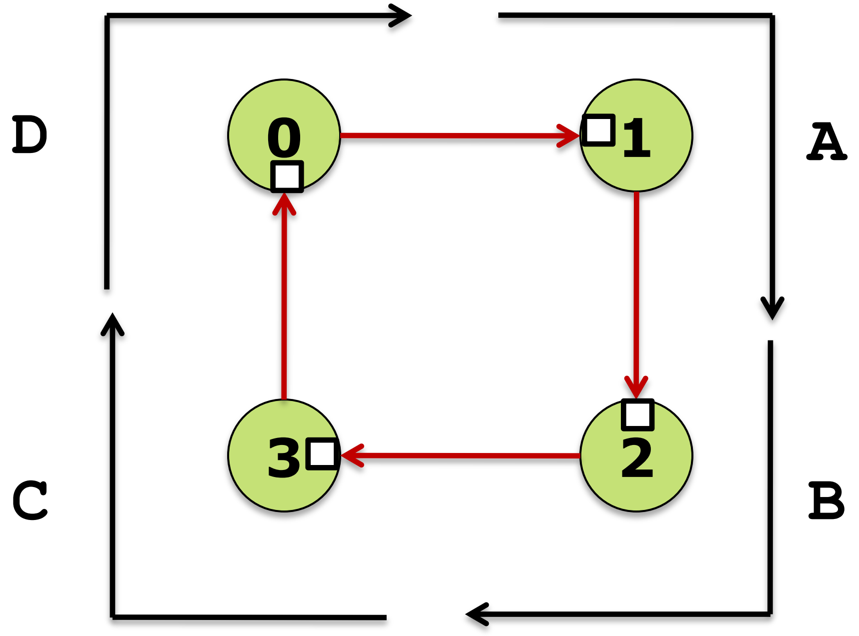
Path Diversity vs Deadlock

- Path diversity required for higher throughput
- Path restrictions because of deadlock-free routing requirement

- Can we allow all turns and still get deadlock freedom ?

Why do deadlocks occur?

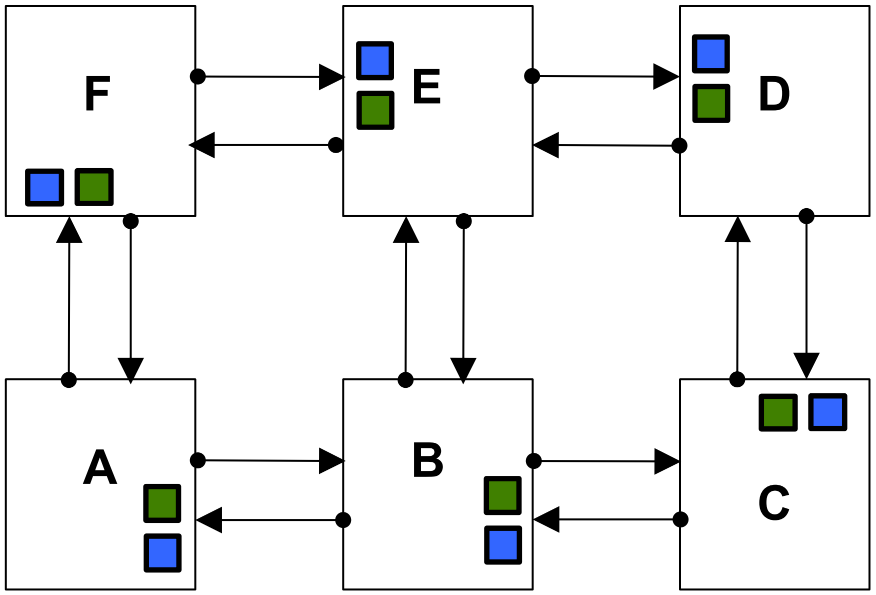
Resource conflicts! (i.e., structural hazard!)



- Flow A holds buffer in 1 and wants buffer in 2
- Flow B holds buffer in 2 and wants buffer in 3
- Flow C holds buffer in 3 and wants buffer in 0
- Flow D holds buffer in 0 and wants buffer in 1

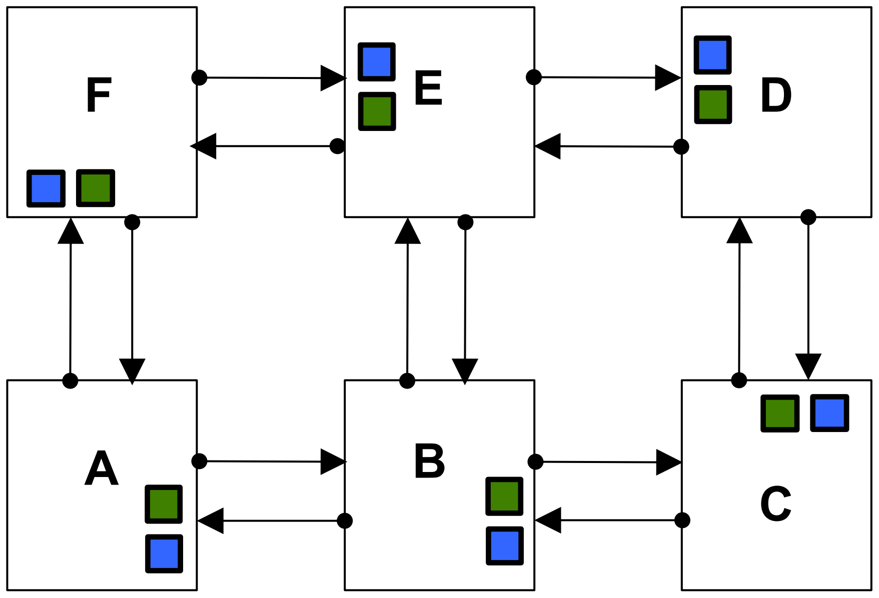
Virtual Channels

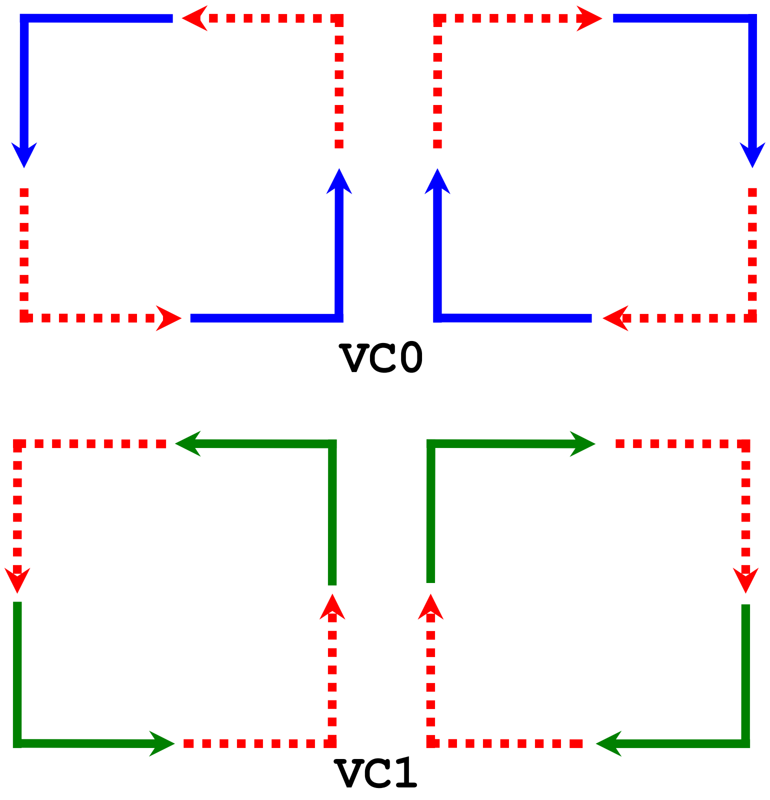
- Same physical link/channel between routers
  - additional buffers in each router to avoid deadlocks – called "virtual" channels



Example 1

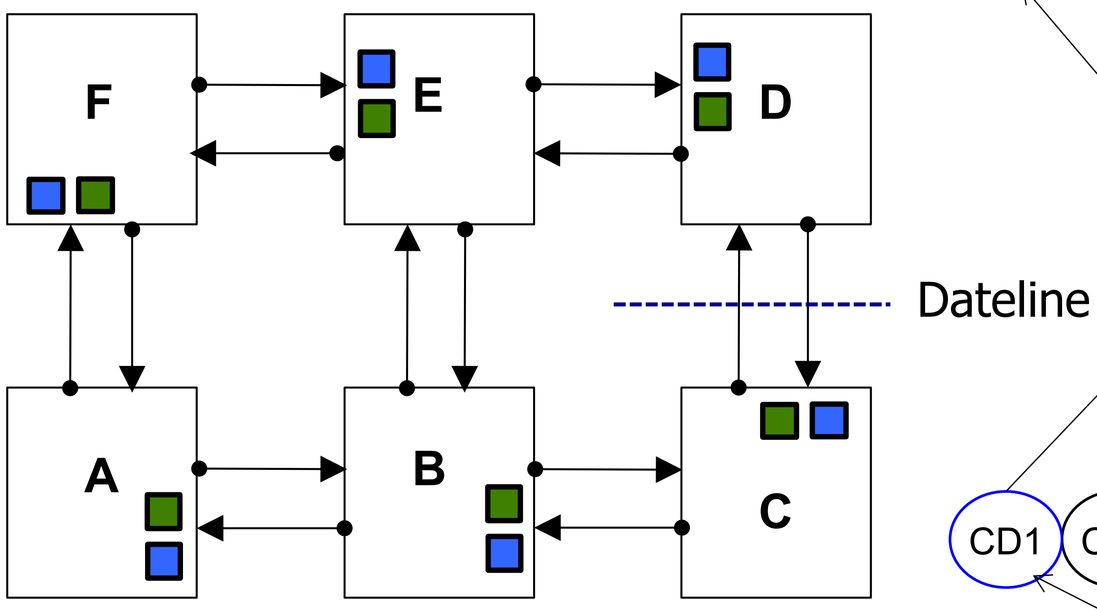
- Policy: XY in VC0, YX in VC 1

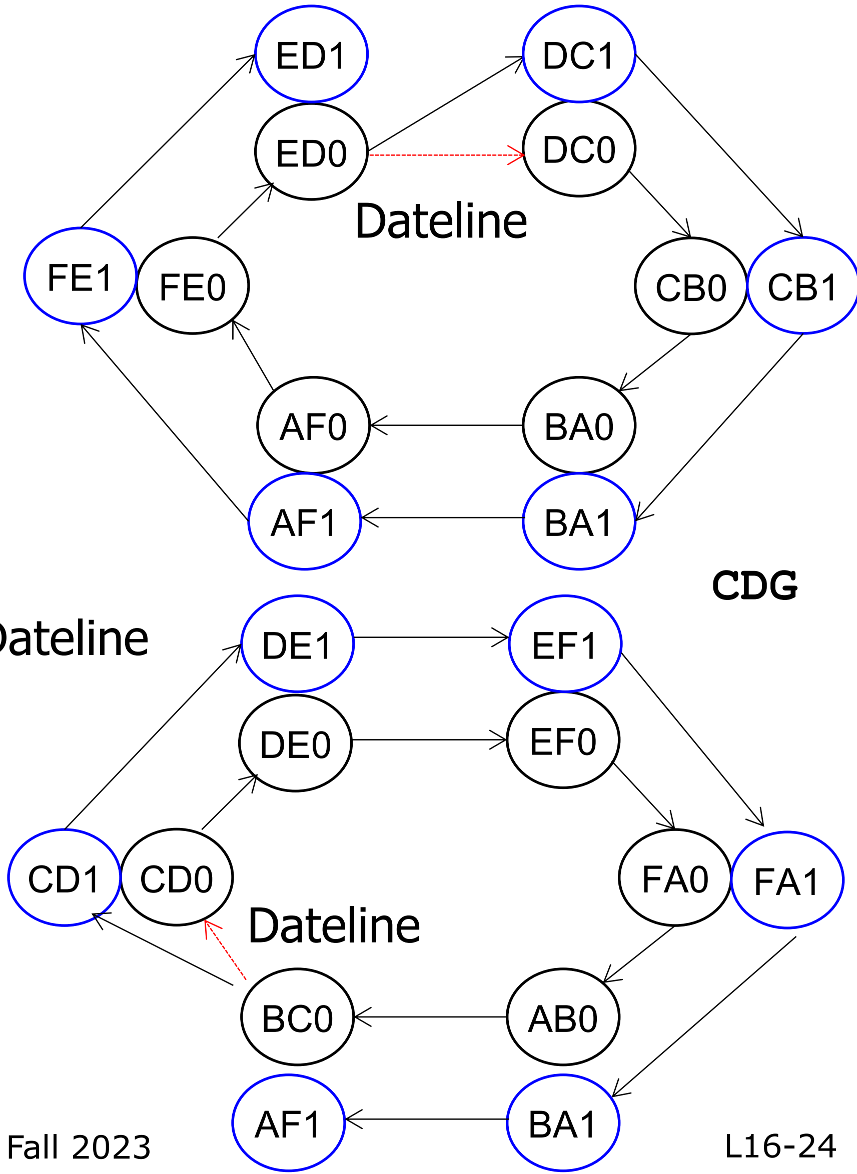




Example 2

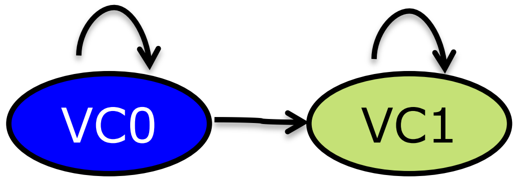
- Policy: Start in VC0, after Dateline jump to VC1



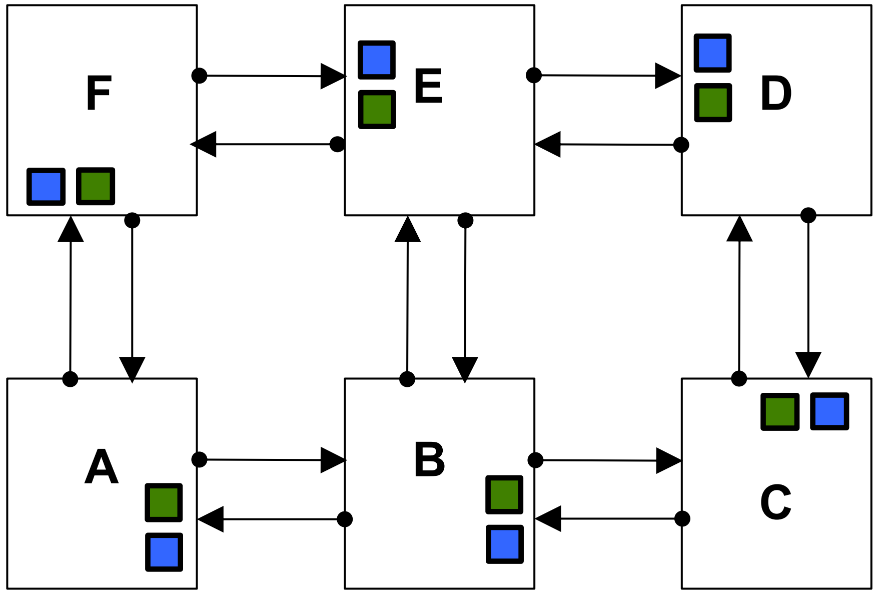


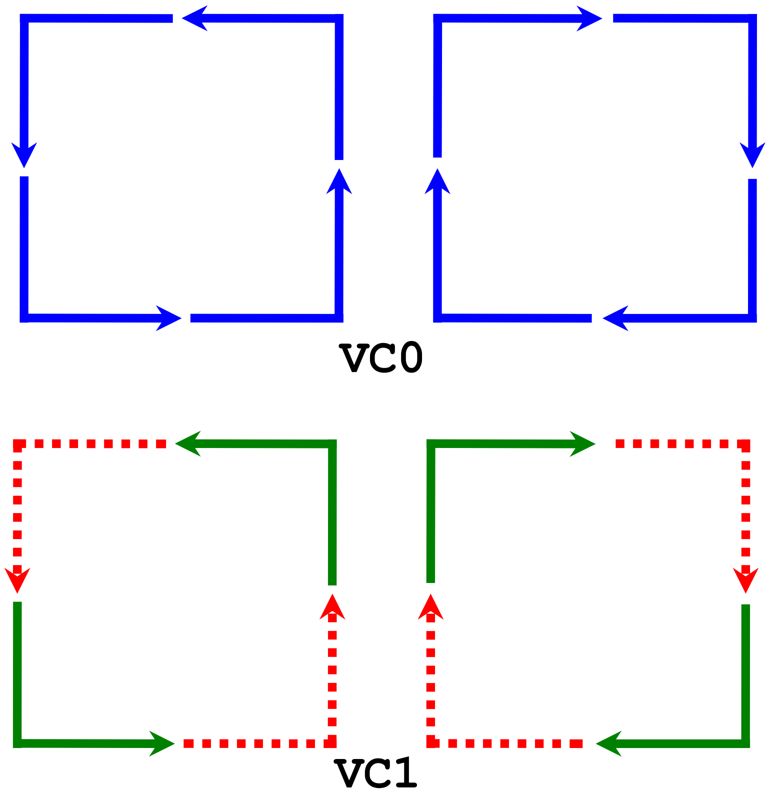
Escape Virtual Channels

- Policy:
  - Allow any turns across all VCs except one
    - **"Escape" VC** → deadlock-free route
  - If there is a deadlock, can jump into escape VC which is guaranteed to drain


$$\begin{tikzcd}
\text{VC0} \arrow[loop above] \arrow[r] & \text{VC1} \arrow[loop above]
\end{tikzcd}$$

Escape VC

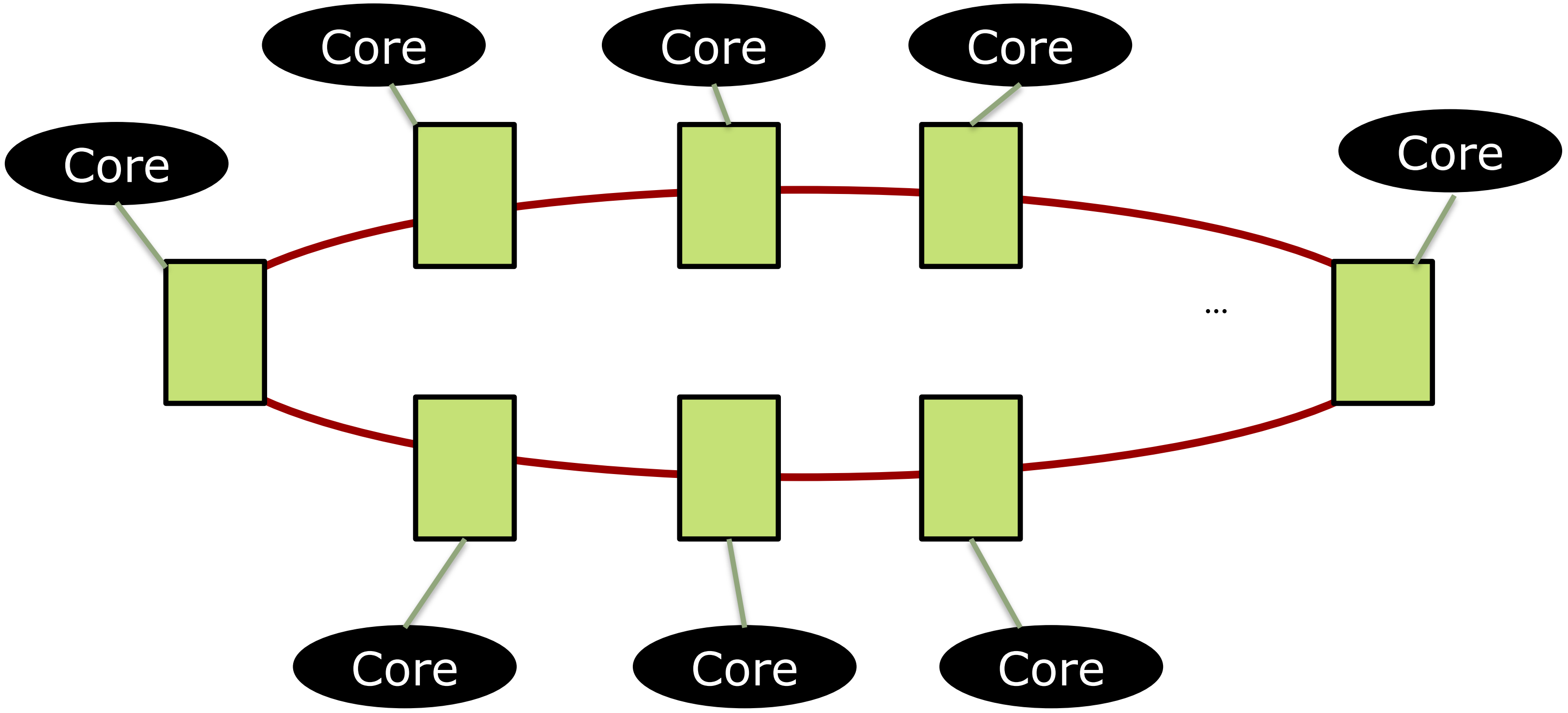




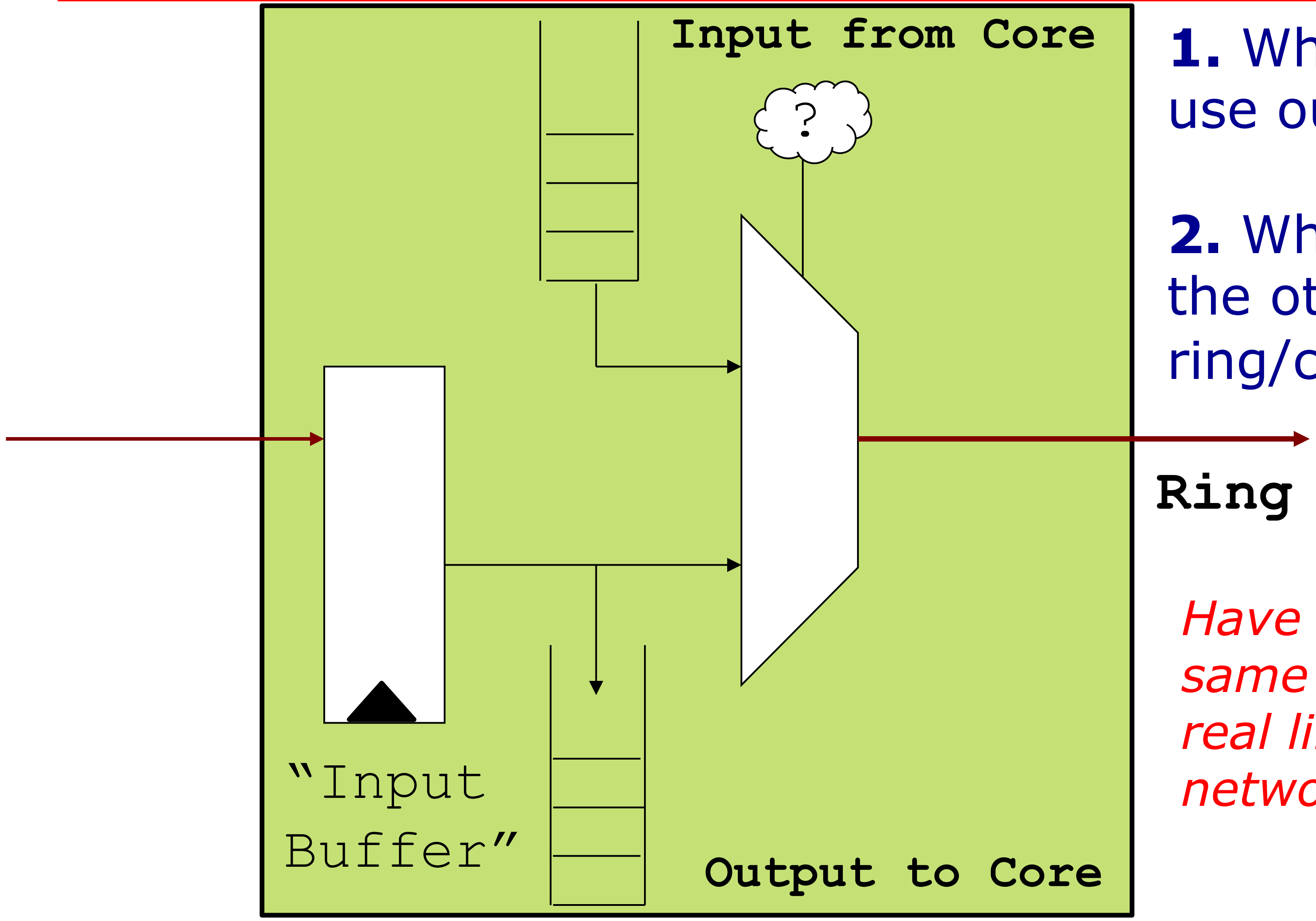
Router Microarchitecture

Example

- Suppose we have a Ring network



What does each "router" look like?



Note: only showing anti-clockwise ring for illustration

1. Who should use output link?

2. What to do with the other flit (from ring/core)

Have you seen this same situation in real life on a road network?

Link Arbitration

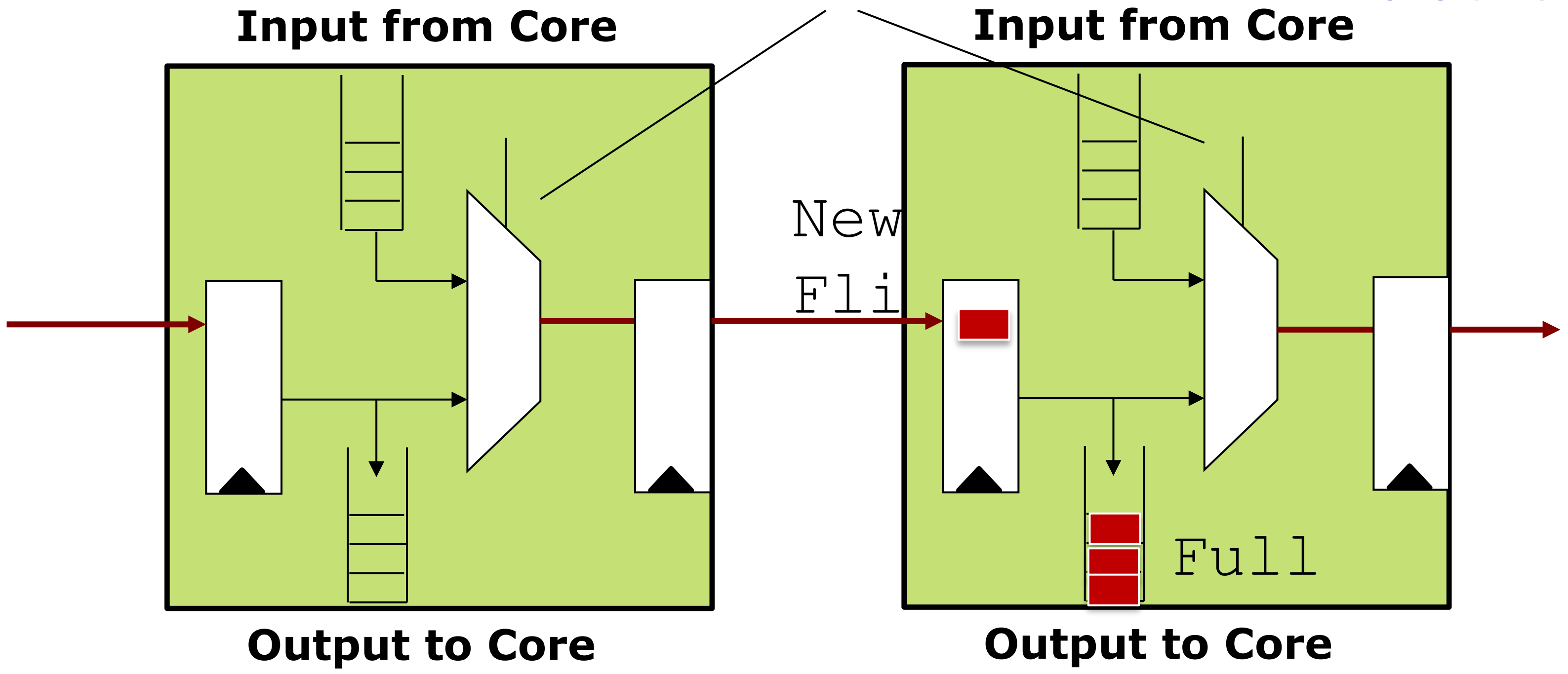
1. Who should use output link?

2. What to do with the other flit (from ring/core)

Arbitration Protocol

This is known as "arbitration"
The control structure is called an "arbiter"

3. What should a flit do if its output is blocked?



Buffer Management

- What should a flit do if its output is blocked?
  - **Option 1:** Drop!
    - Send a NACK back for dropped packet or have a timeout
      - Source retransmits
      - Implicit congestion control
    - Flow control protocol on the Internet
    - **Advantage: can be bufferless!**
    - Challenges?
      - Latency and energy overhead of re-transmitting more than that of buffering so not preferred on-chip

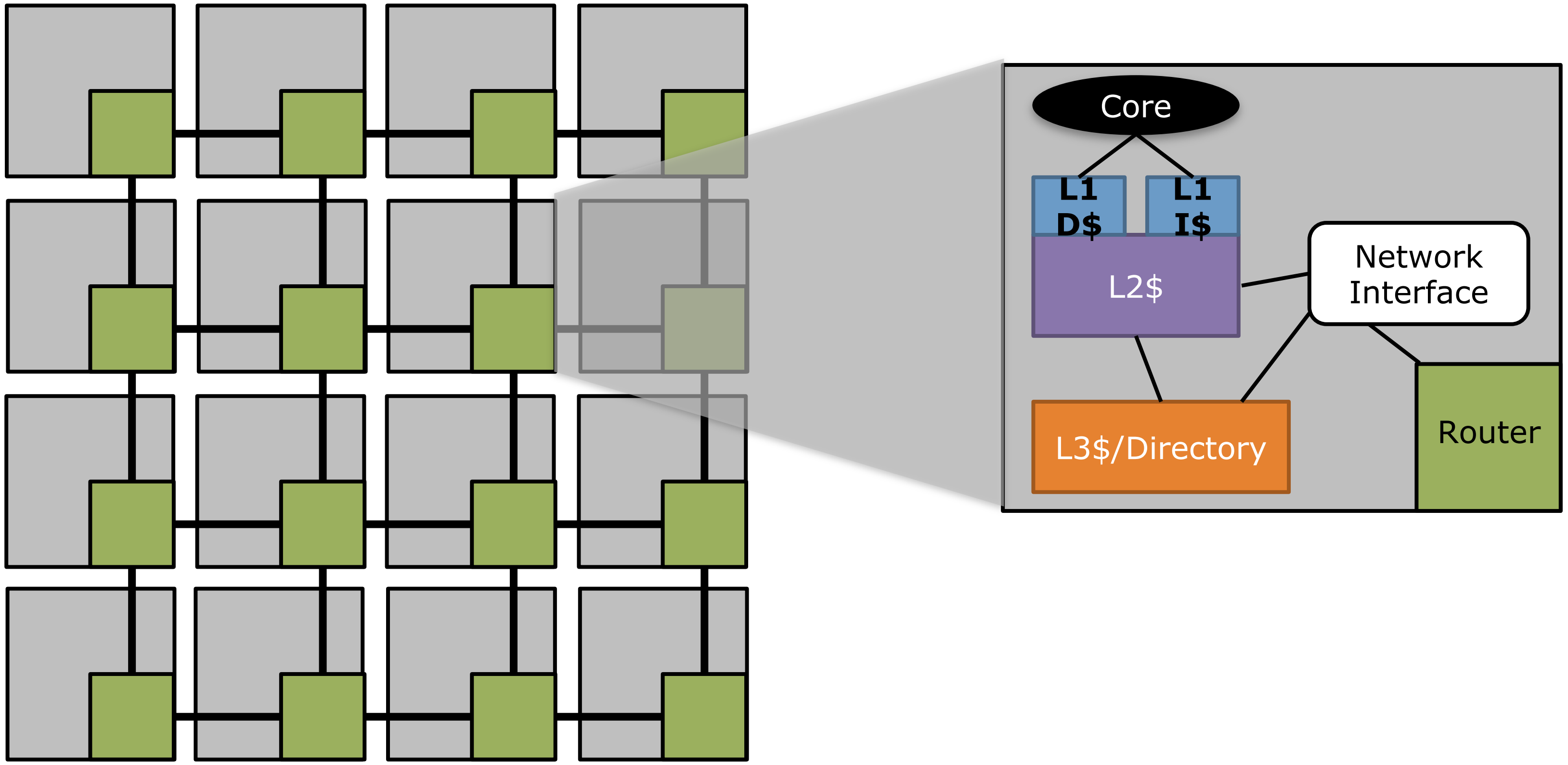
Buffer Management

- What should a flit do if its output is blocked?
  - **Option 2:** Misroute!
    - As long as N input ports and N output ports, can send flit out of some other output port
      - called "bouncing" on a ring
    - **Advantage: can be bufferless!**
    - Challenges
      - Energy
        - » Routes become non-minimal – more energy consumption at router latches and on links
      - Performance
        - » Non-minimal routes – can lead to longer delays
      - Correctness
        - » Livelock! – cannot *guarantee* forward progress
          - » Not the same as deadlock
          - » *Need to restrict number of misroutes of same packet*

Buffer Management

- What should a flit do if its output is blocked?
  - **Option 3:** Wait!
    - Signal to previous router to not send any more flits till the input at this router can be drained
    - **Backpressure** techniques
      - On/Off : one bit to signal if next router can receive or not
        - » Challenge: Delay of on/off signal
      - Credit-based : A count of how many flits can be sent to the next node?

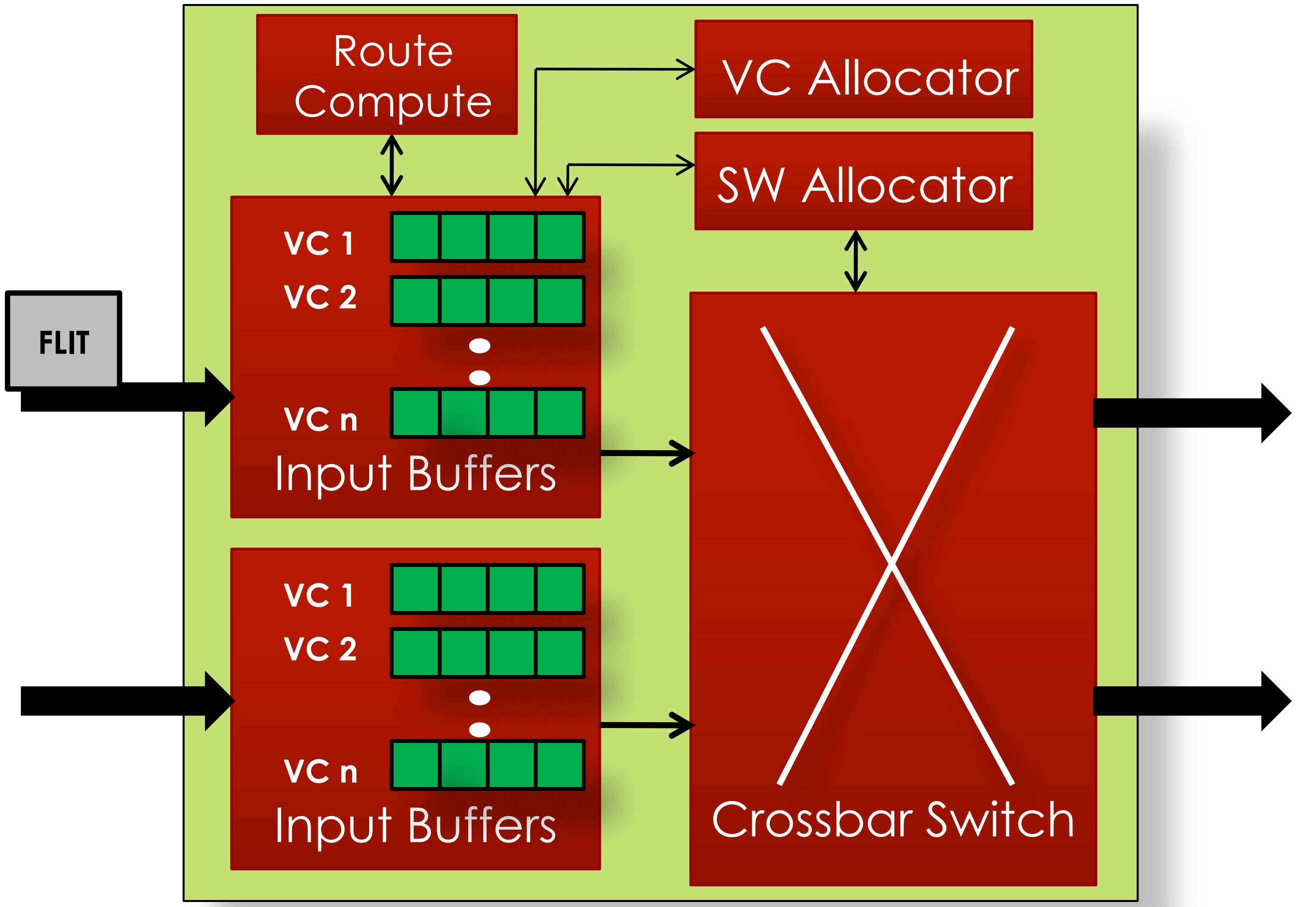
More general topology



What’s Inside A Router?

- It’s a system as well
  - Logic – State machines, Arbiters, Allocators
    - Control data movement through router
    - Idle, Routing, Waiting for resources, Active
  - Memory – Buffers
    - Store flits before forwarding them
    - SRAMs, registers, processor memory
  - Communication – Switches
    - Transfer flits from input to output ports
    - Crossbars, multiple crossbars, fully-connected, bus

Virtual-channel Router



BW: Buffer Write

RC: Route Compute

VA: VC Allocation
Input VCs arbitrate for "output" VCs (Input VCs at next router)

SA: Switch Allocation
Input ports arbitrate for output ports

BR: Buffer Read

ST: Switch Traversal

LT: Link Traversal

BW	**RC**	**VA**	**SA**	**BR**	**ST**	**LT**

Router Pipeline vs. Processor Pipeline

- Logical stages:
  - BW
  - RC
  - VA
  - SA
  - BR
  - ST
  - LT
- Different flits go through different stages
- Different routers have different variants
  - E.g. speculation, lookaheads, bypassing
- Different implementations of each pipeline stage

- Logical stages:
  - IF
  - ID
  - EX
  - MEM
  - WB
- Different instructions go through different stages
- Different processors have different variants
  - E.g. speculation, ISA
- Different implementations of each pipeline stage

Baseline Router Pipeline

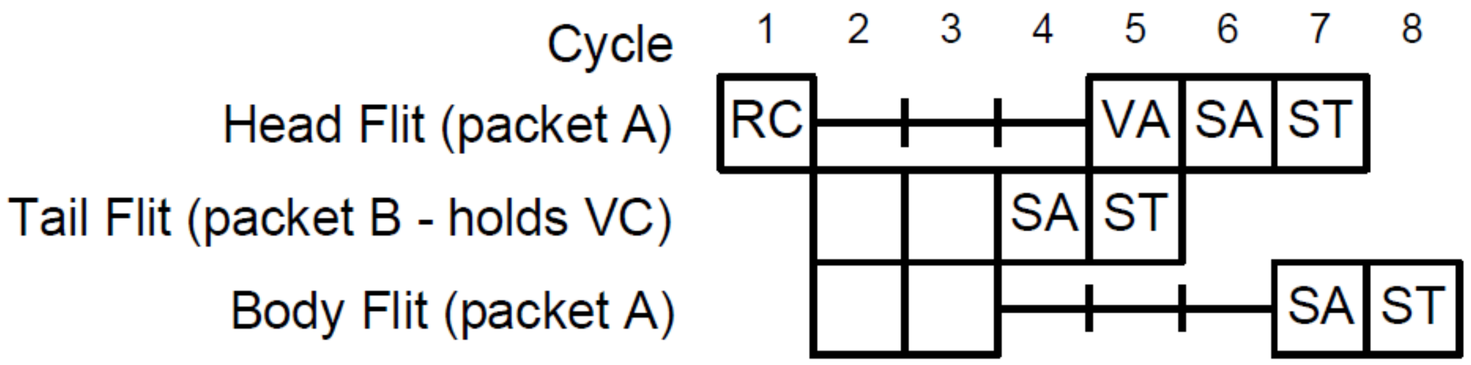
Head	BW	RC	VA	SA	ST	LT			
Body 1		BW	✗	✗	SA	ST	LT		
Body 2			BW	✗	✗	SA	ST	LT	
Tail				BW	✗	✗	SA	ST	LT

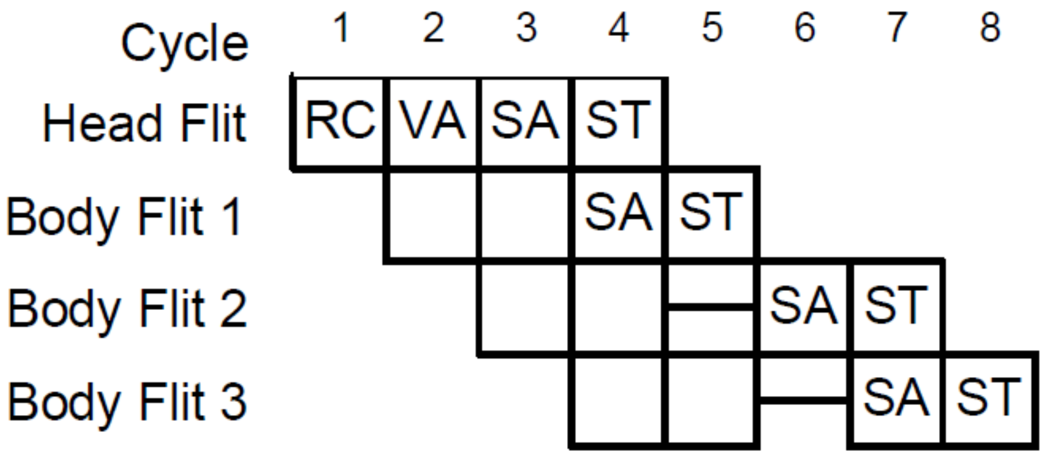
- Route computation performed once per packet
- Virtual channel allocated once per packet
- Body and tail flits inherit this info from head flit

Allocators In Routers

- VC Allocator
  - Input VCs requesting for a range of output VCs
  - Example: A packet of VC0 arrives at East input port. It’s destined for west output port, and would like to get any of the VCs of that output port.
- Switch Allocator
  - Input VCs of an input port request for different output ports (e.g., One’s going North, another’s going West)
- “Greedy” algorithms used for efficiency
- What happens if allocation fails on a given cycle?

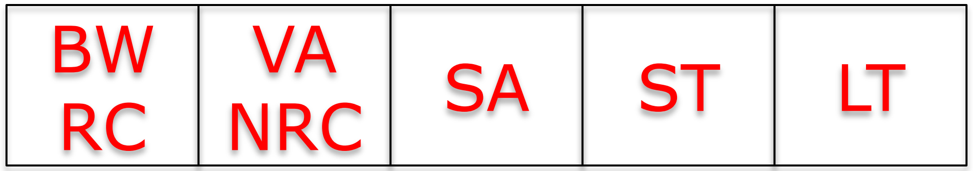
VC & Switch Allocation Stalls





Pipeline Optimizations: Lookahead Routing [Galles, SGI Spider Chip]

- At current router, perform route computation for next router

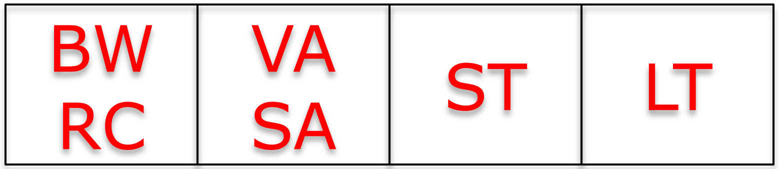


  - Head flit already carries output port for next router
  - RC just has to read output → fast, can be overlapped with BW
  - Precomputing route allows flits to compete for VCs immediately after BW
  - Routing computation for the next hop (NRC) can be computed in parallel with VA

- Or simplify RC (e.g., X-Y routing is very fast)

Pipeline Optimizations: Speculative Switch Allocation [Peh & Dally, 2001]

- Assume that Virtual Channel Allocation stage will be successful
  - Valid under low to moderate loads
- If both successful, VA and SA are done in parallel



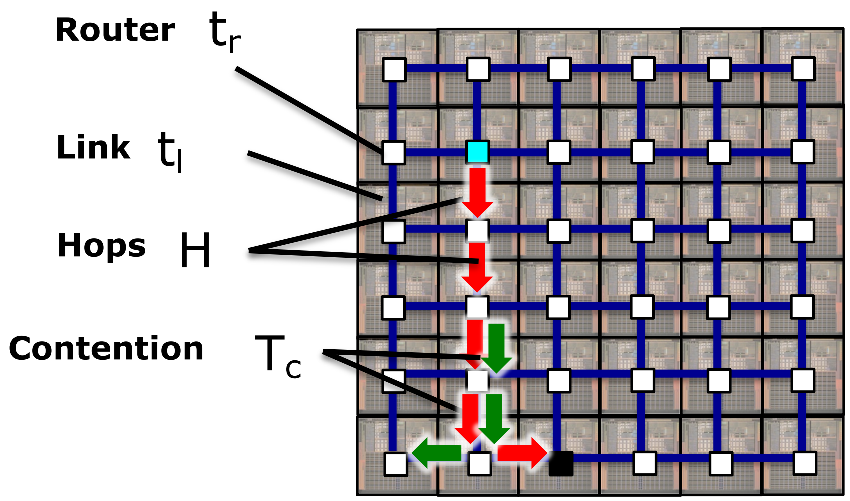
- If VA unsuccessful (no virtual channel returned)
  - Must repeat VA/SA in next cycle
- Prioritize non-speculative SA requests

Today: 1-2 cycles per router

Evaluating NoCs

Network Latency

$$T_N = (t_r + t_l) \times H + T_c + T_s$$

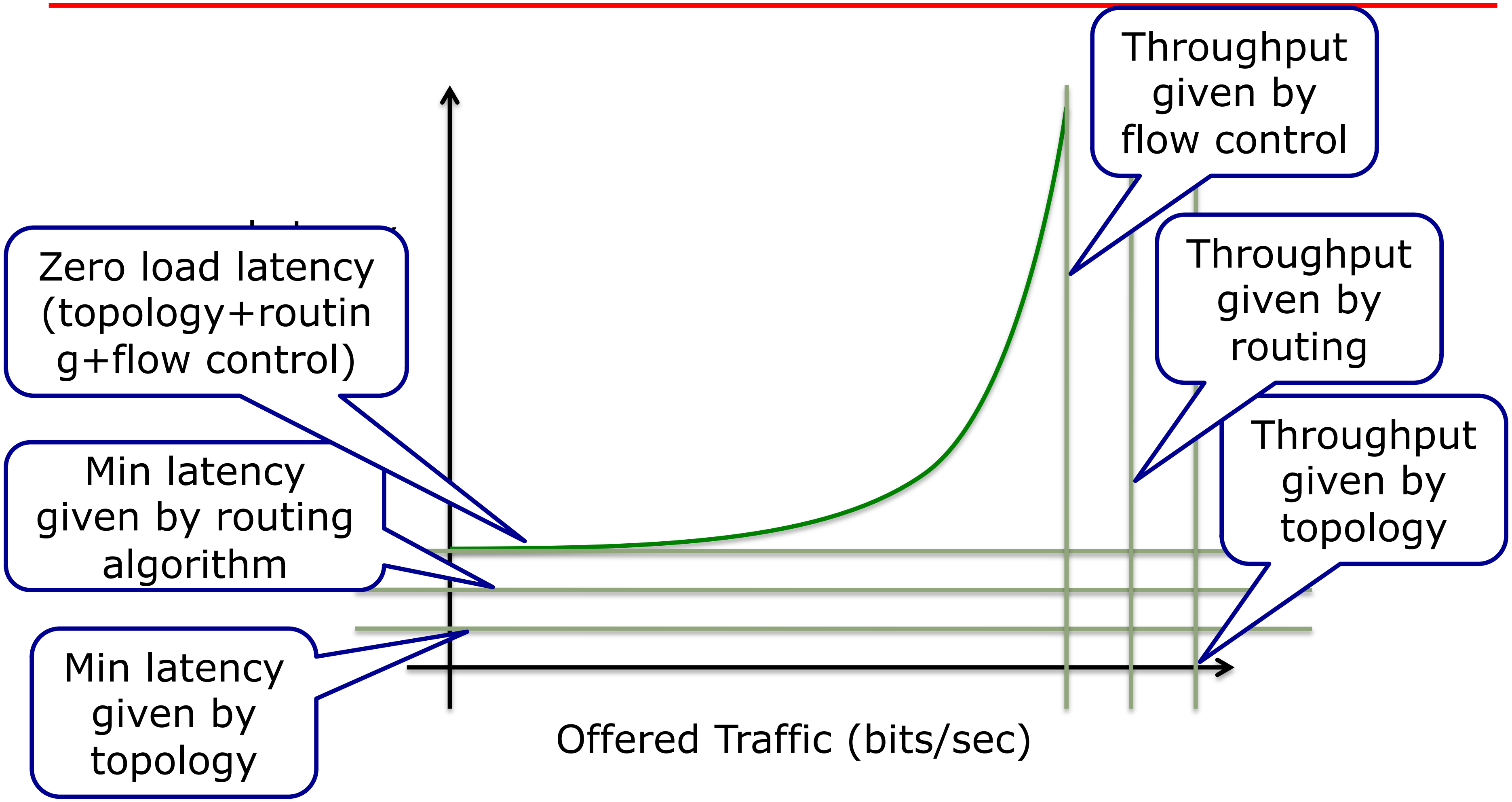


T_N	Network Latency
t_r	Router Latency
t_l	Link Latency
H	Hops
T_c	Contention Latency
T_s	Serialization Latency (for multi-flit packets)

Which of these is static? t_r t_w T_s

Which of these is dynamic (traffic-dependent)? H T_c

Evaluating NoCs



Open Research questions in NoCs

- "Best" *on-chip* topology
  - Uniform vs Hierarchical
  - Few routers with more ports ("High-Radix") or more routers with few ports ("Low-Radix")
- NoCs with unconventional interconnects
  - Photonic, RF, wireless
- Resilient NoCs
  - How to deal with run-time failures of links and routers
- NoCs for heterogeneous SoCs
  - Smartphones, IoT
- NoCs for Accelerators
  - NoCs for FPGAs
  - NoCs for deep learning accelerators
  - NoCs for database accelerators
  - NoCs for graph processing accelerators

} Surge of research in last few years

Thank you!

Next Lecture: VLIW