NOC
Deadlock and Livelock

Deadlock (When?)

- Deadlock can occur in an interconnection network, when a group of packets cannot make progress, because they are waiting on each other to release resource (buffers, channels)
- If a sequence of waiting agents form a cycle the network is deadlocked

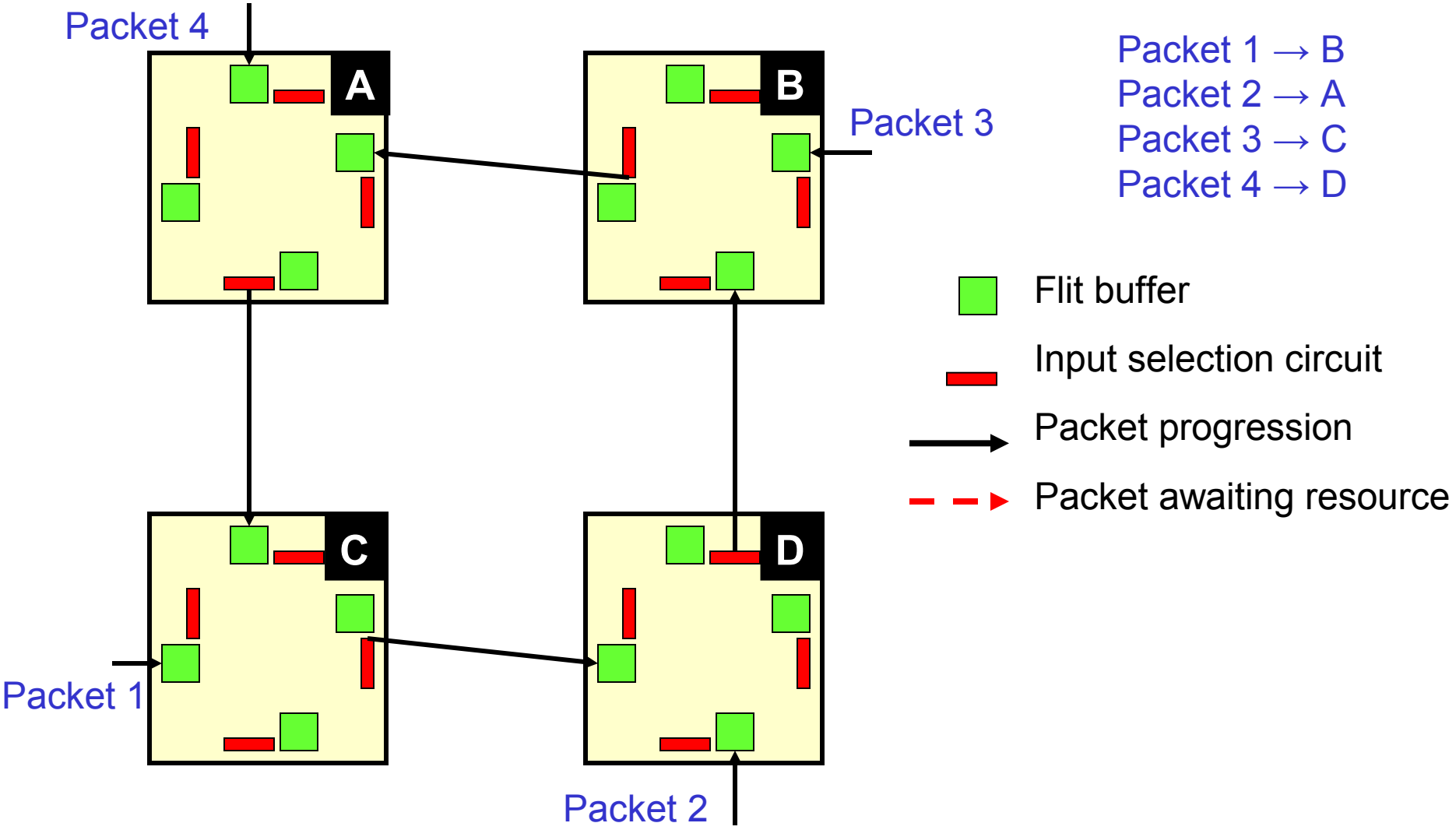
Deadlock (Why?)

- Deadlock can occur if packets are allowed to hold some resources while requesting others

Switching Technique	Resource
Store and Forward	Buffer
Virtual Cut-Through	Buffer
Wormhole	Channel

- Because blocked packets holding channels (and their corrisponding flit buffers) remain in the network
  - ➔ Wormhole routing is particularly susceptible to deadlock

Wormhole Routing Deadlock Example



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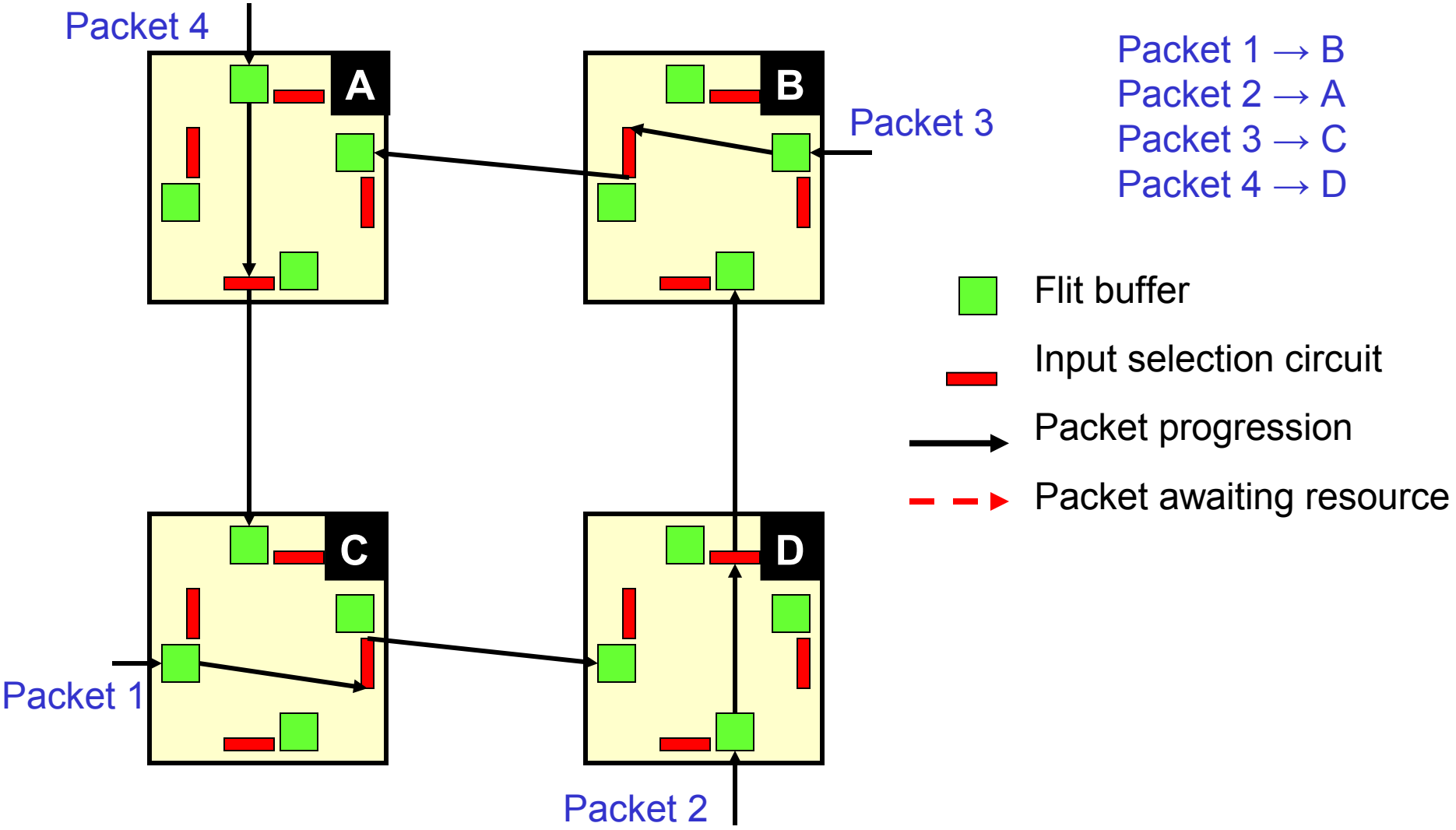

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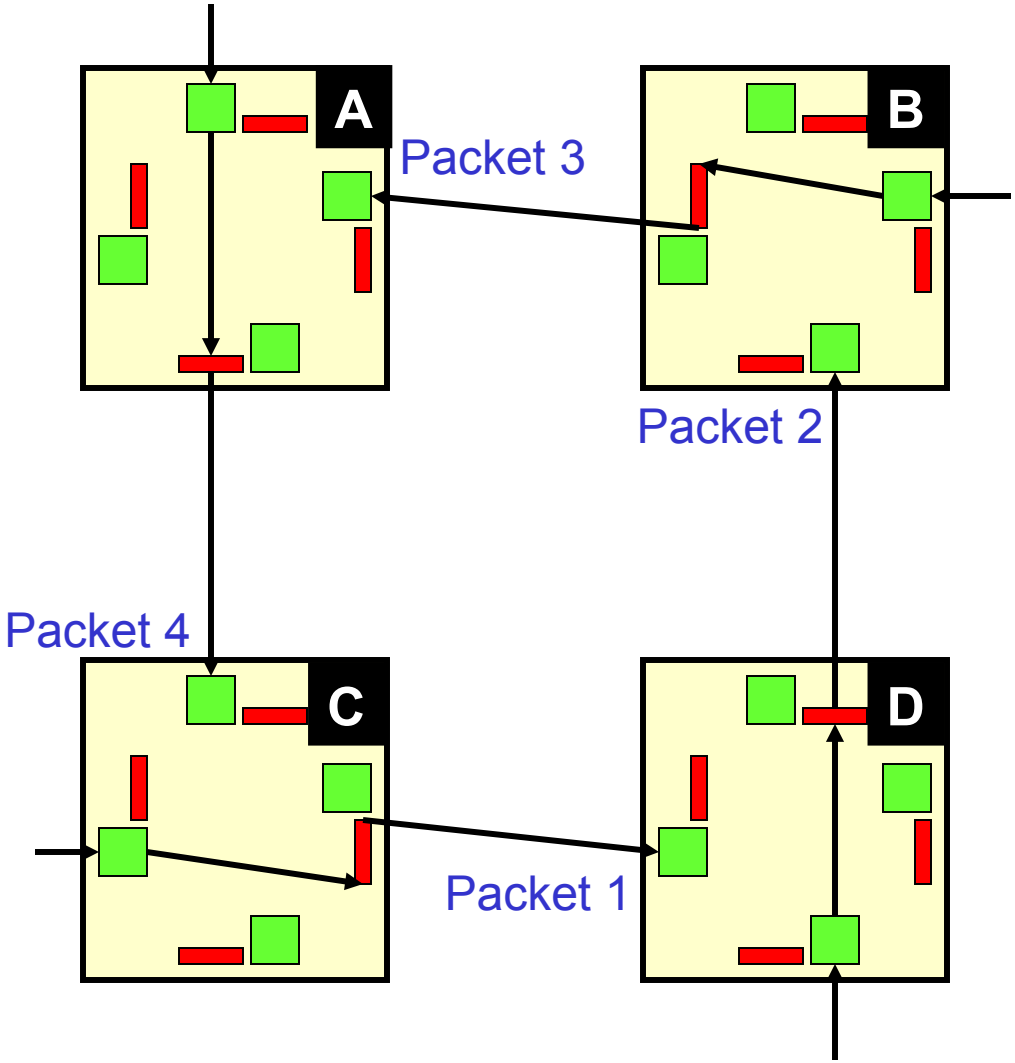


Packet 1 → B
Packet 2 → A
Packet 3 → C
Packet 4 → D

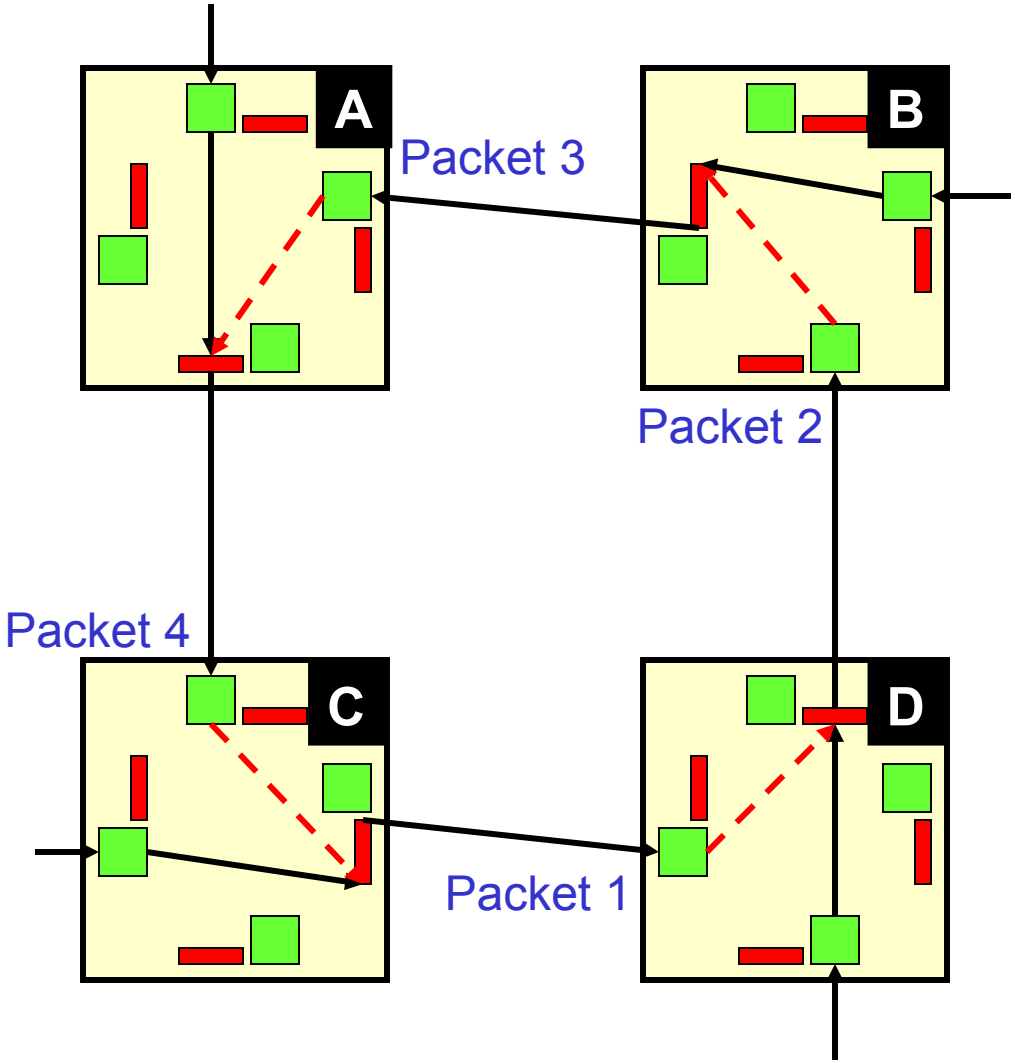
Flit buffer

Input selection circuit

Packet progression

Packet awaiting resource

Wormhole Routing Deadlock Example



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How to Solve Deadlock Problems

- Allow the preemption of packets involved in a potential deadlock situation
- Preemption packets can be
  - ➔ Rerouted
    - ✓ Adaptive nonminimal routing techniques
  - ➔ Discarded
    - ✓ Packets recovered at the source and restransmitted
- Not used in most direct networks architectures
  - ➔ Requirements of low-latency and reliability

How to Solve Deadlock Problems

- More commonly, deadlock is avoided by the routing algorithm
  - ➔ By ordering network resources and requiring that packets use these resources in strictly monotonic order
    - ✓ Circular wait is avoided

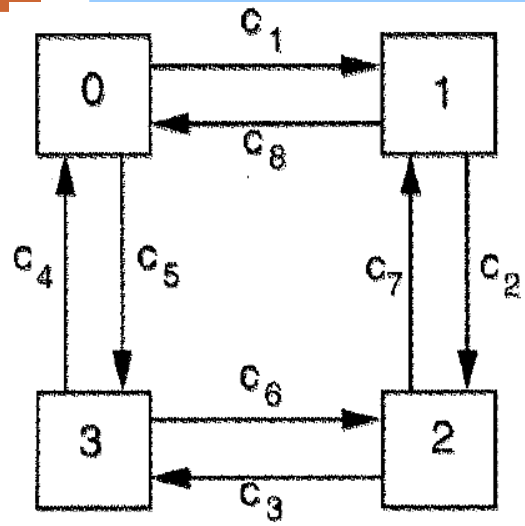
Channel Dependecy Graph

- In wormhole routing networks channels are the critical resources
- There is a *Direct Dependency* from l_i to l_j if l_j can be used immediately after l_i by messages destined to some node *n*
- The *Channel Dependency Graph* for a network and a routing algorithm is a direct graph *D=G(L,D)*
  - ➔ *L* consists of all the unidirectional channels in the network
  - ➔ *D* includes the pairs (l_i, l_j) if there is a direct dependency from l_i to l_j

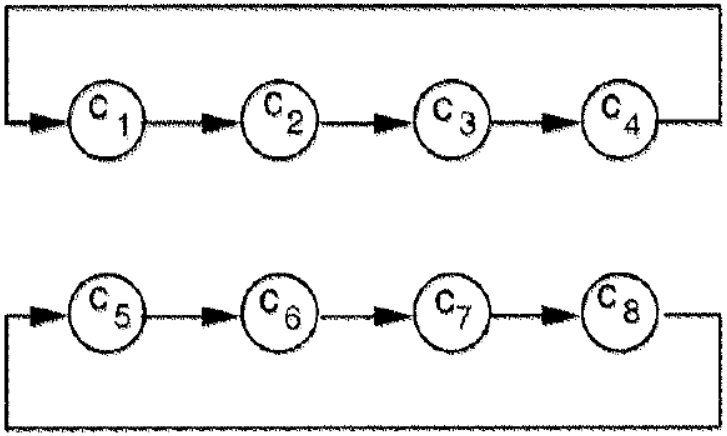
Duato's Theorem

- A routing function R is *deadlock-free* if there are no cycles in its channel dependency graph

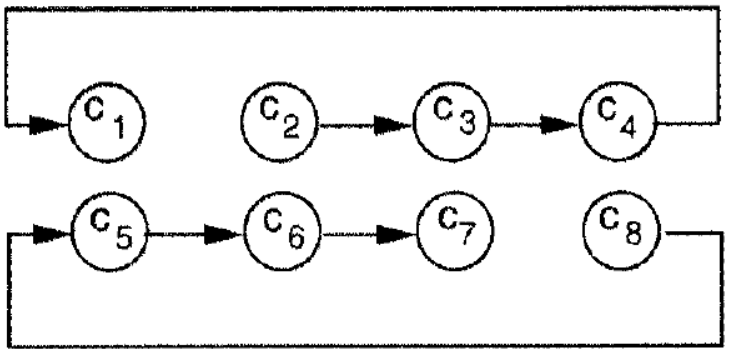
Channel Dependency Graph Method



(a)



(b)



(c)

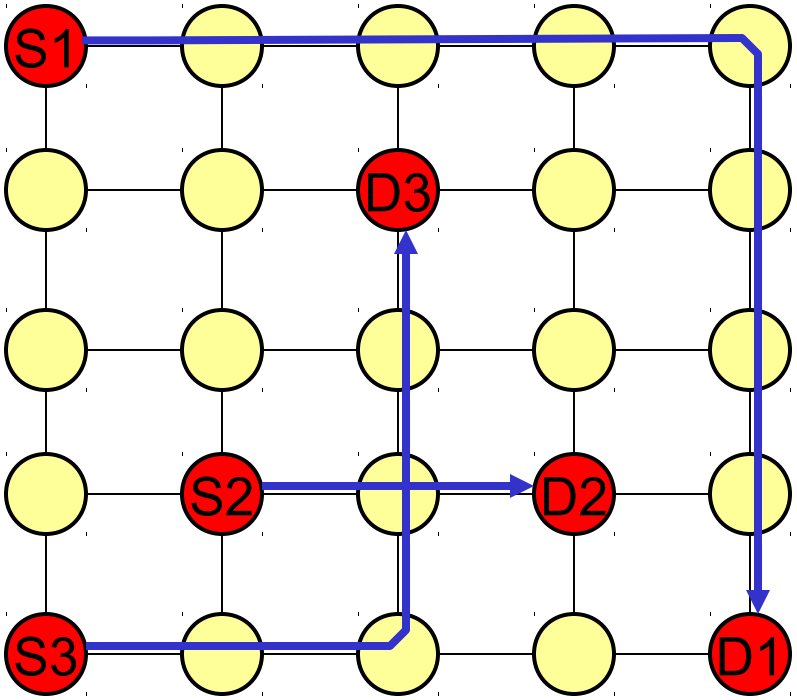
- The routing is still minimal
  - ➔ However, to send a packet from 0 to 2, the packet must be forwarded through node 3

Deterministic Routing

- An approach to designing a deadlock-free routing algorithm for a wormhole-routed network is to ensure that cycles are avoided in the channel dependency graph
  - ➔Assign a unique number to each channel
  - ➔Allocate channels to packets in strictly ascending (or descending) order
- If the behavior of the algorithm is independent of current network conditions
  - ➔Deterministic routing

Dimension-ordered Routing

- Each packet is routed in one dimension at a time
- Arriving at the proper coordinate in each dimension before proceeding to the next dimension
- Enforcing a strictly monotonic order on the dimension traversed



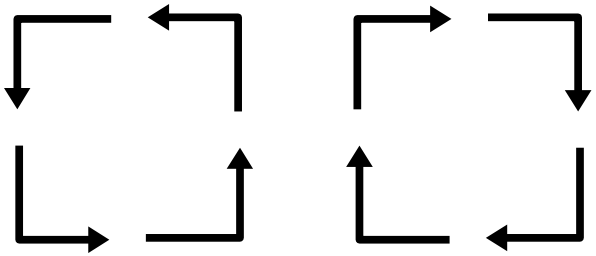
Adaptive Routing

- The main problem of a deterministic routing is that it cannot respond to dynamic network conditions
  - ➔Congestion
  - ➔Faults
- Adaptive routing must address deadlock issue

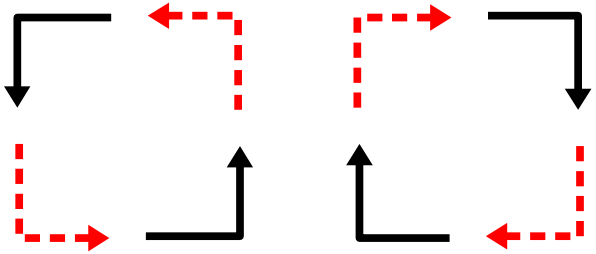
The Turn Model

- The *Turn Model* provide a systematic approach to the development of maximally adaptive routing algorithms
  1. Classify channels according to the direction in which they route packets
  2. Identify the turns that occur between one direction and another
  3. Identify the simple cycles these turns can forms
  4. Prohibit one turn in each cycle

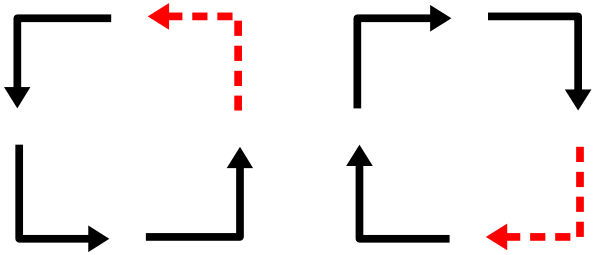
The Turn Model



Abstract cycles in a 2D mesh

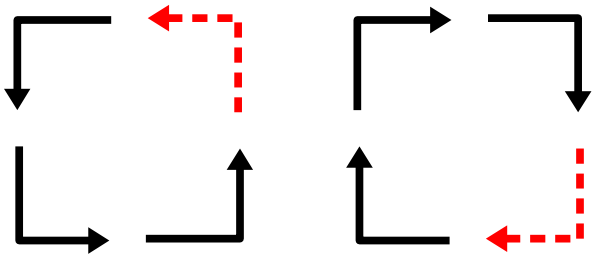


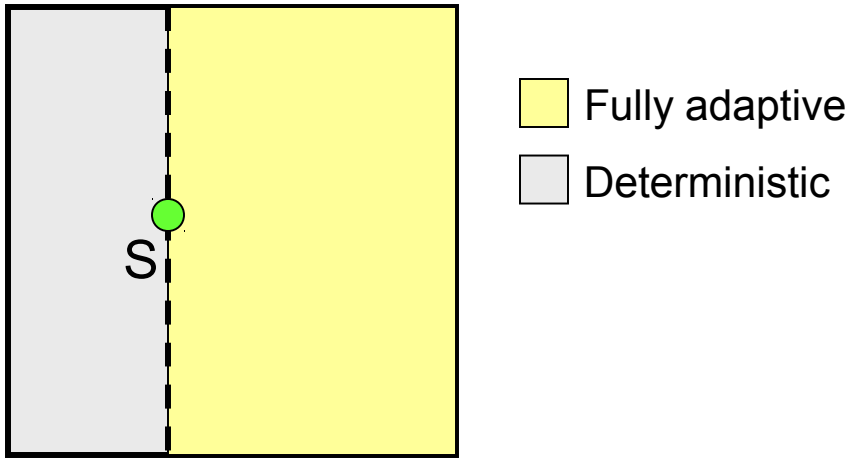
Four turns allowed in XY routing



Six turns allowed in *west-first* routing

West-First Routing

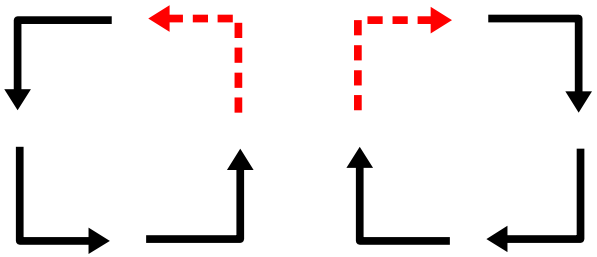


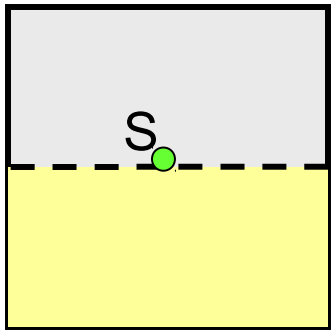


- First route a packet west, if necessary, and then adaptively south, east, and north
  - ➔ The algorithm is fully adaptive if the destination is on the right-hand side (east) of the source
    - ✓ Otherwise it is deterministic

Routing Algorithms based on Turn Model

North-last

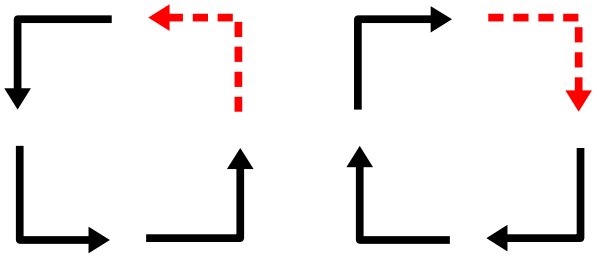


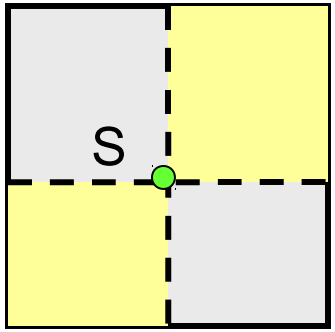


Fully adaptive

Deterministic

Negative-first





Fully adaptive

Deterministic