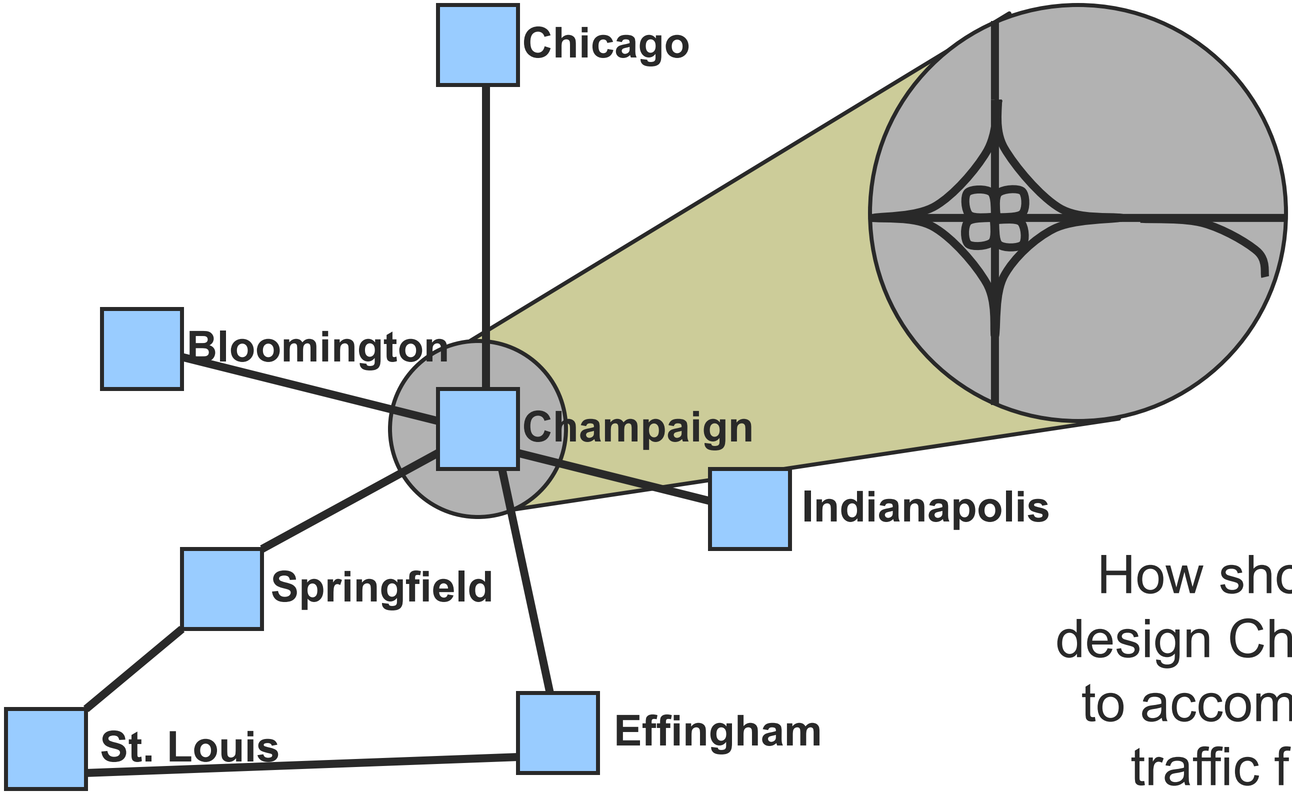
Switching Hardware

Where are we?

- Understand
  - Different ways to move through a network (forwarding)
    - Read signs at each switch (datagram)
    - Follow a known path (virtual circuit)
    - Carry instructions (source routing)
  - Bridge approach to extending LAN concept
- Next: how switches are built and contention within switches

Switch Design



How should we design Champaign to accommodate traffic flows?

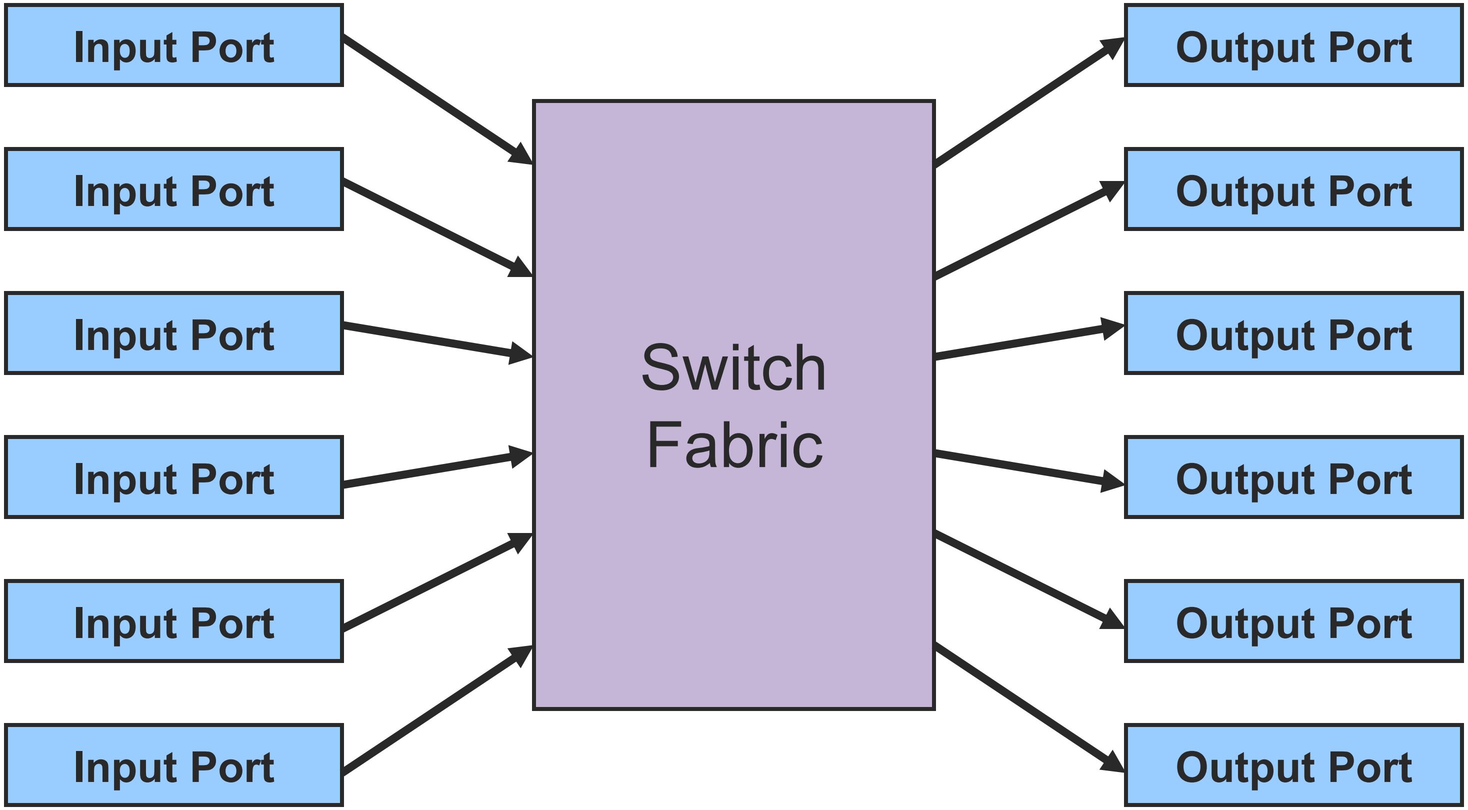
Switch architecture

Juniper EX2200

Juniper EX8200

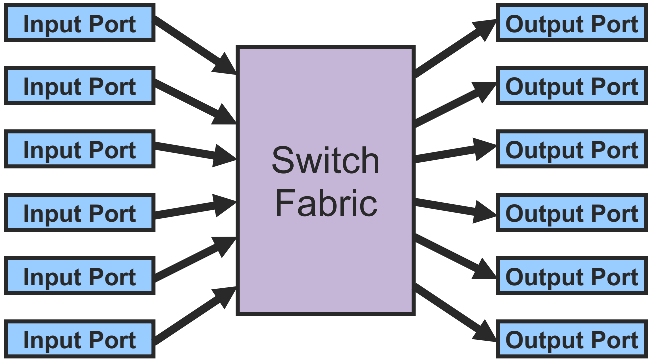
Cisco Catalyst 6500

Switch Design



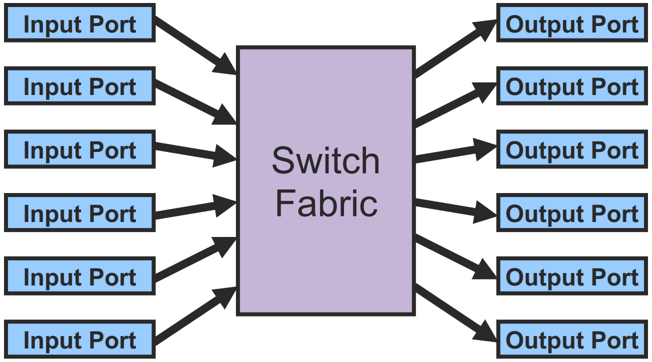
Switch Architecture

- Problem
  - Connect N inputs to M outputs
    - NxM ("N by M") switch
    - Common case: N = M
- Goals
  - Avoid contention
  - High throughput
  - Good scalability
    - Near-linear size/cost growth



Switch high level architecture

- Ports handle complexity
  - Forwarding decisions at input ports
  - Buffering at output and possibly input ports



- Simple fabric (it seems…)
  - Move packets from inputs to outputs
  - May have a small amount of internal buffering

Switch Design Goals

- Minimize Contention
  - Avoid contention through intelligent buffering
  - Use output buffering when possible
  - Apply back pressure through switch fabric
  - Improve input buffering through non-FIFO buffers
    - Reduces head-of-line blocking
  - Drop packets if input buffers overflow

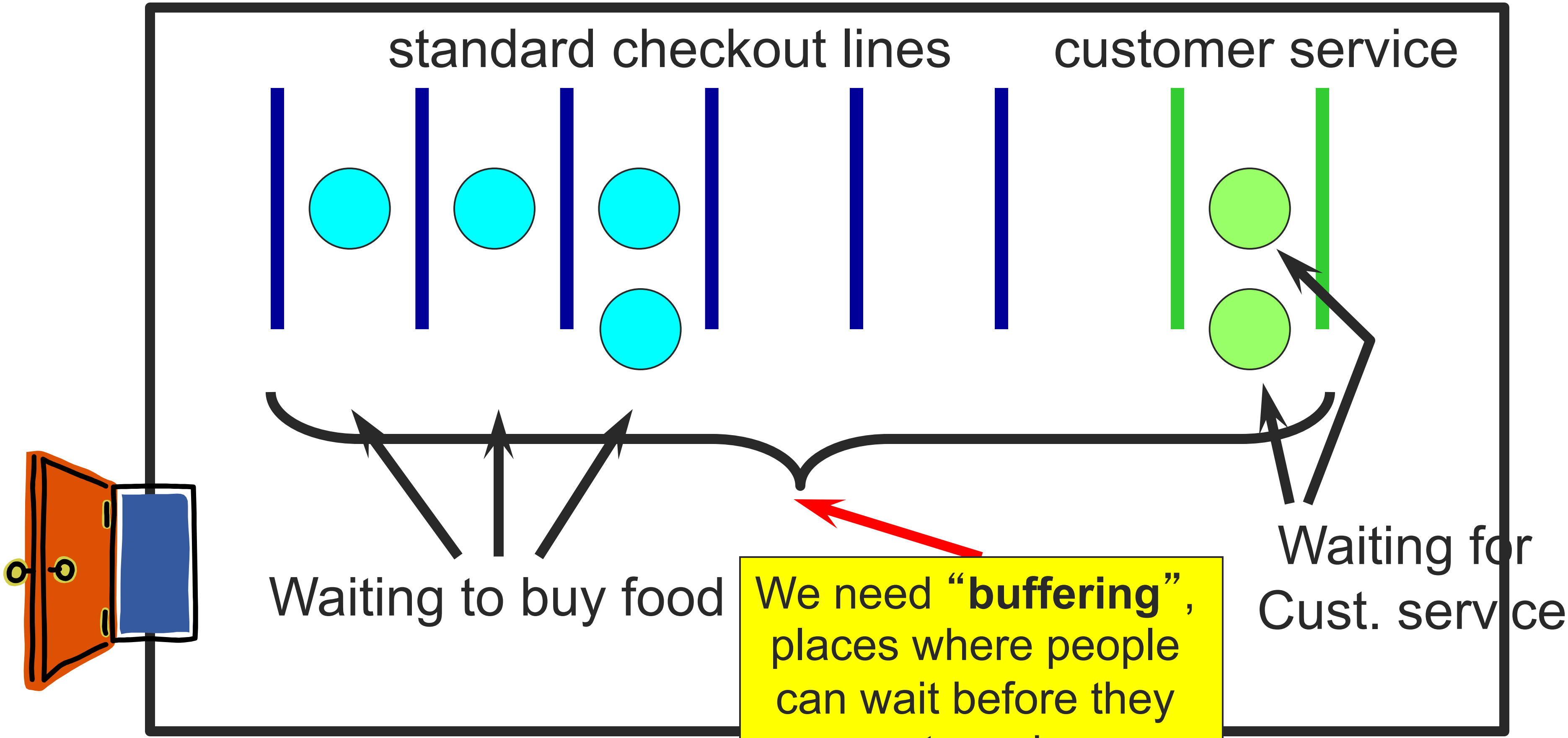
Switch Design Goals

- Maximize Throughput
  - Main problem is contention
  - Need a good traffic model
    - Arrival time
    - Destination port
    - Packet length
  - Telephony modeling is well understood
    - Until faxes and modems
  - Data traffic has different properties
    - E.g., phone call arrivals are “Poisson”, but packet arrivals are “heavy-tailed”

Contention

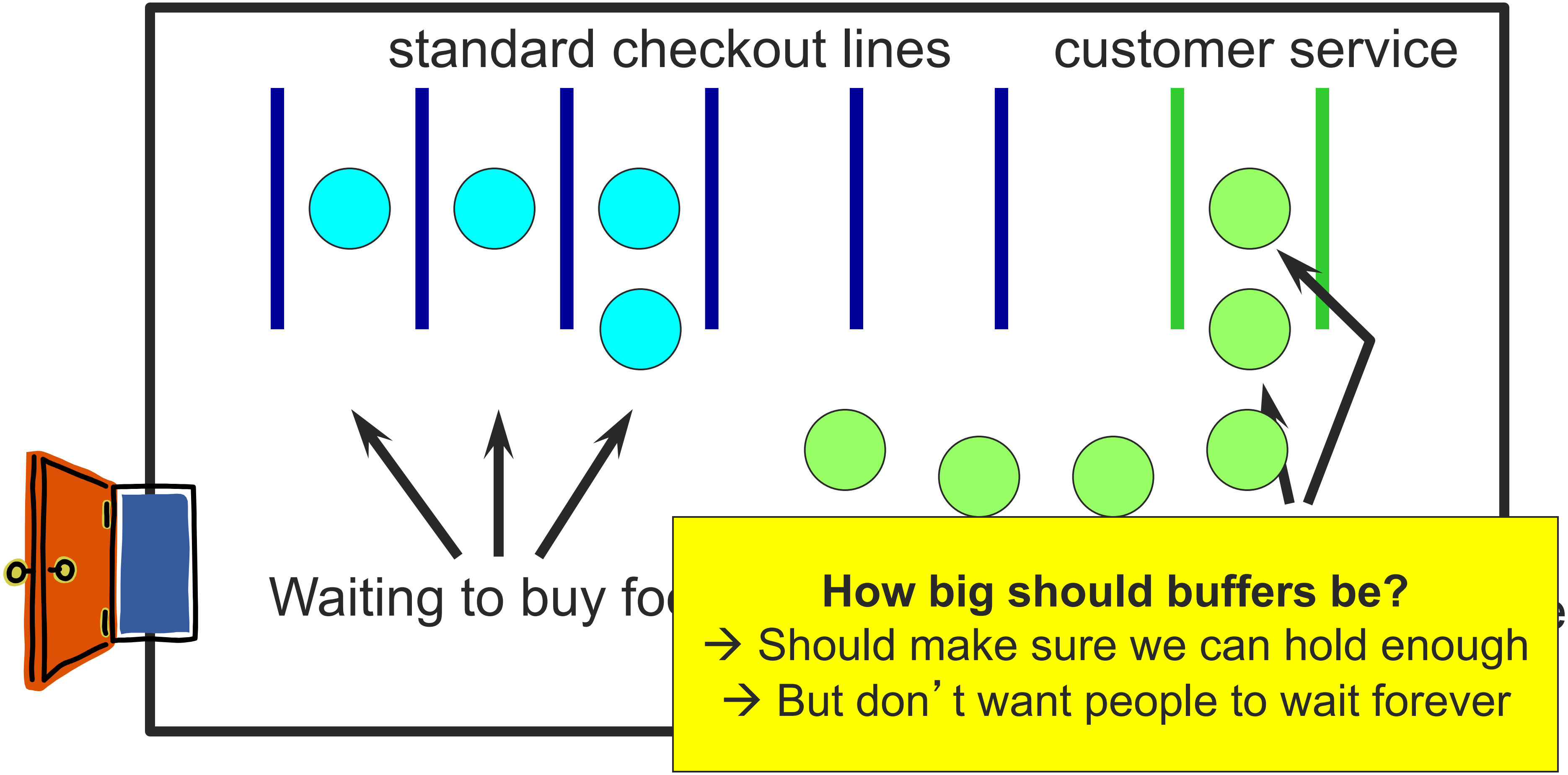
- Problem
  - Some packets may be destined for the same output port
- Solutions
  - One packet gets sent first
  - Other packets get delayed or dropped
- Delaying packets requires buffering
  - Buffers are finite, so we may still have to drop
  - Buffering at input ports
    - Increases, adds false contention
    - Sometimes necessary
  - Buffering at output ports
  - Buffering inside switch

Buffering



We need “**buffering**”, places where people can wait before they get service

Output Port Buffering

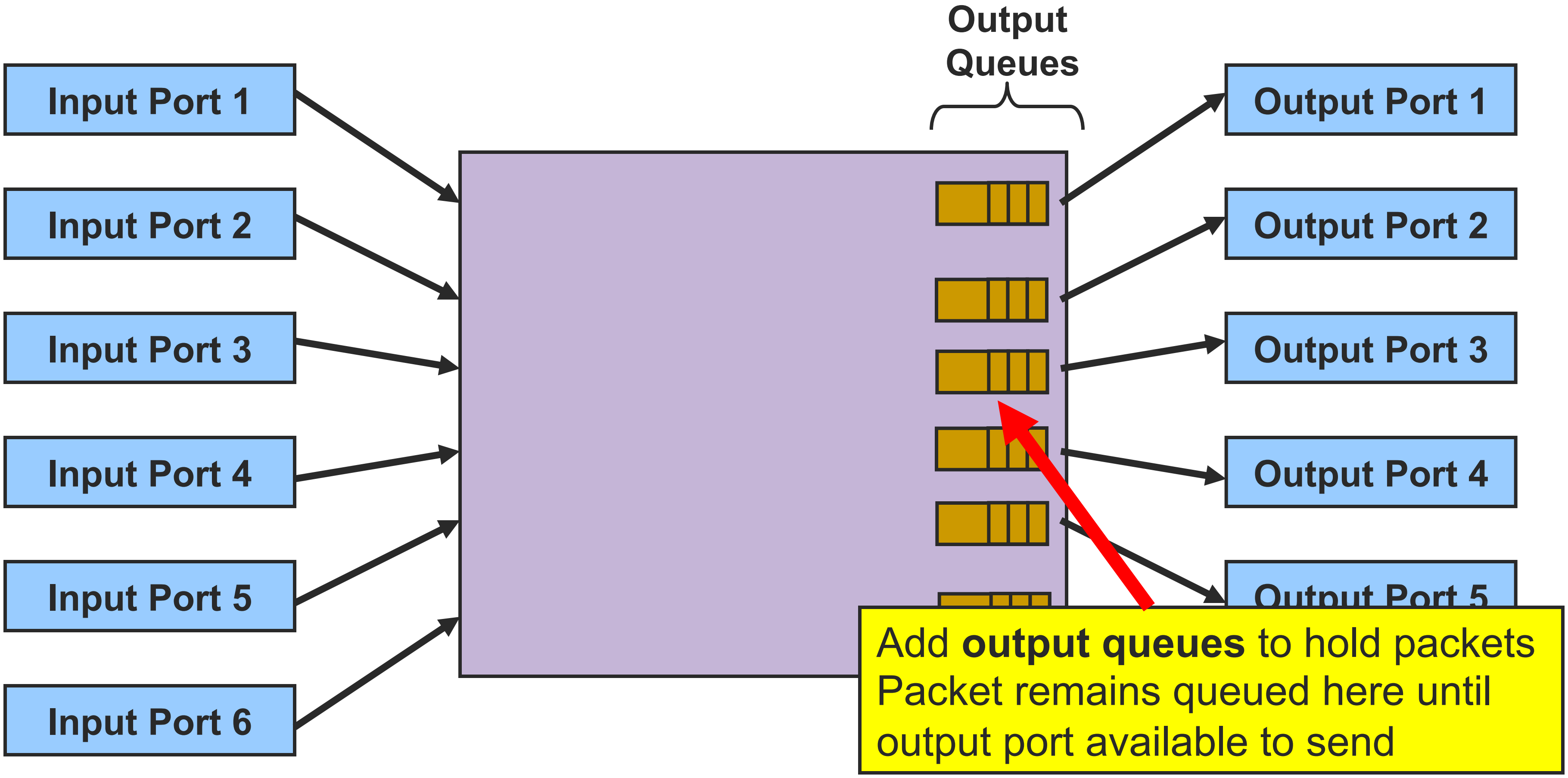


How big should buffers be?

→ Should make sure we can hold enough

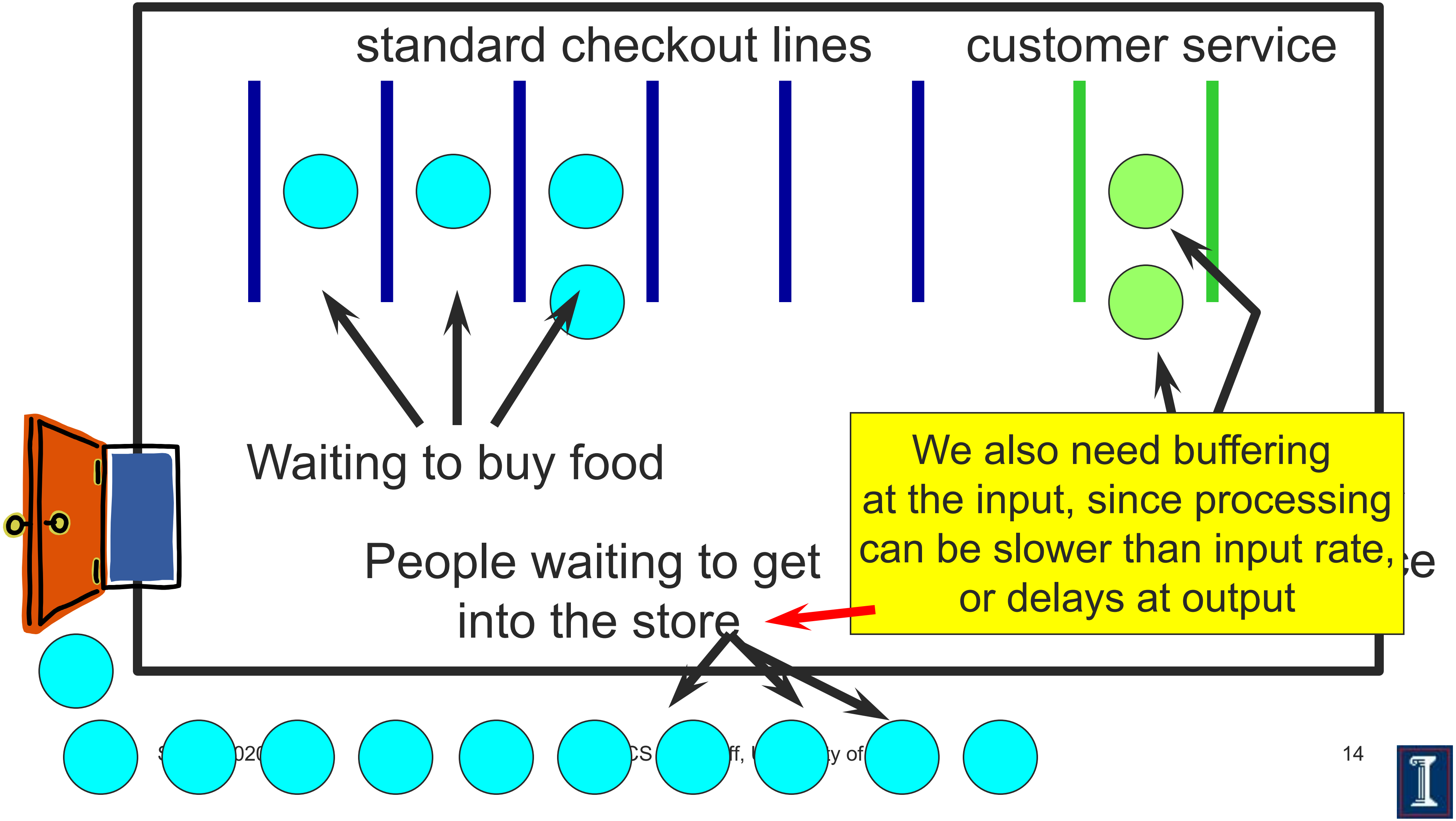
→ But don’t want people to wait forever

Switch Design



Add **output queues** to hold packets
Packet remains queued here until output port available to send

Input Port Buffering



standard checkout lines

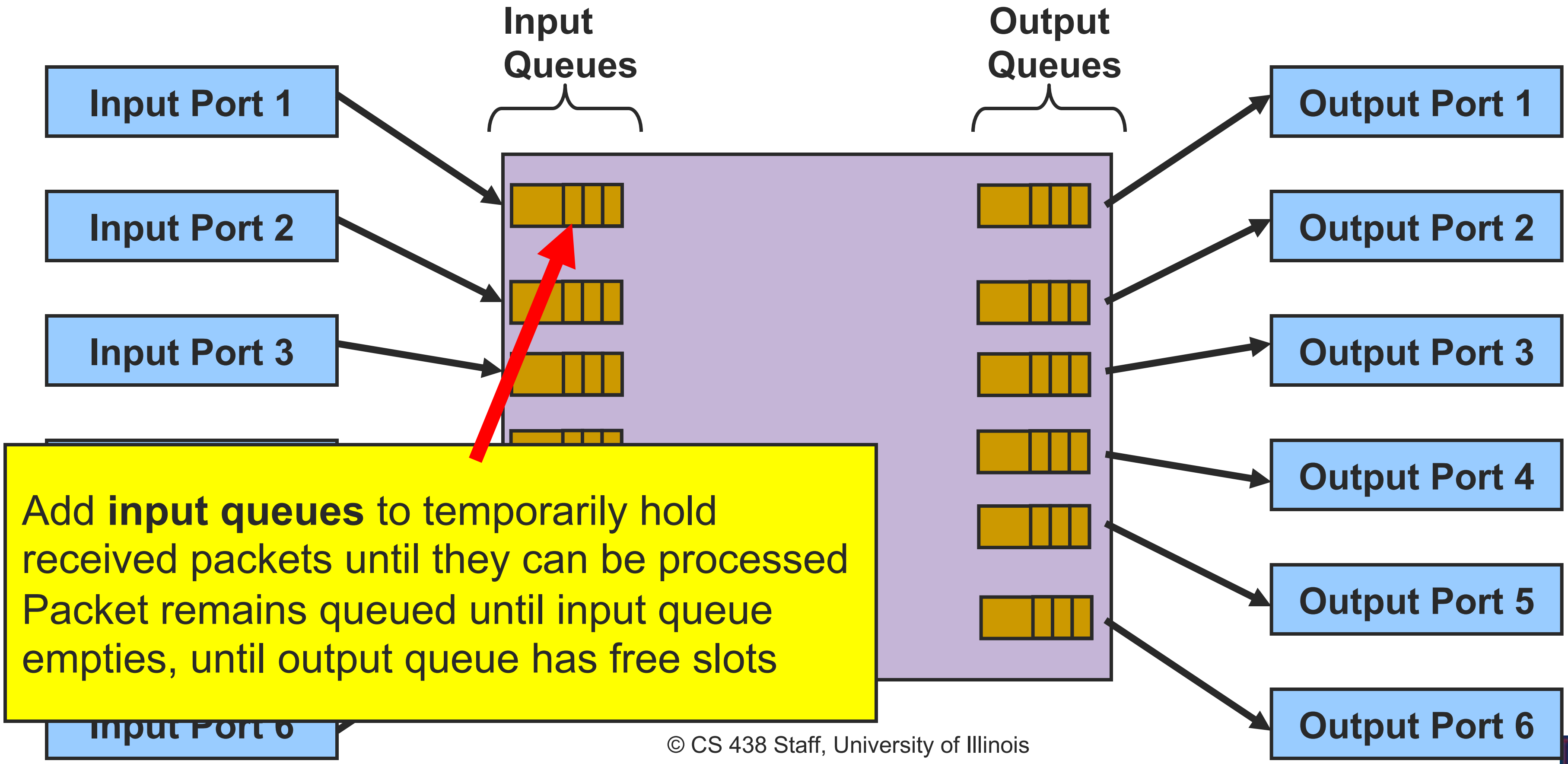
customer service

Waiting to buy food

People waiting to get into the store

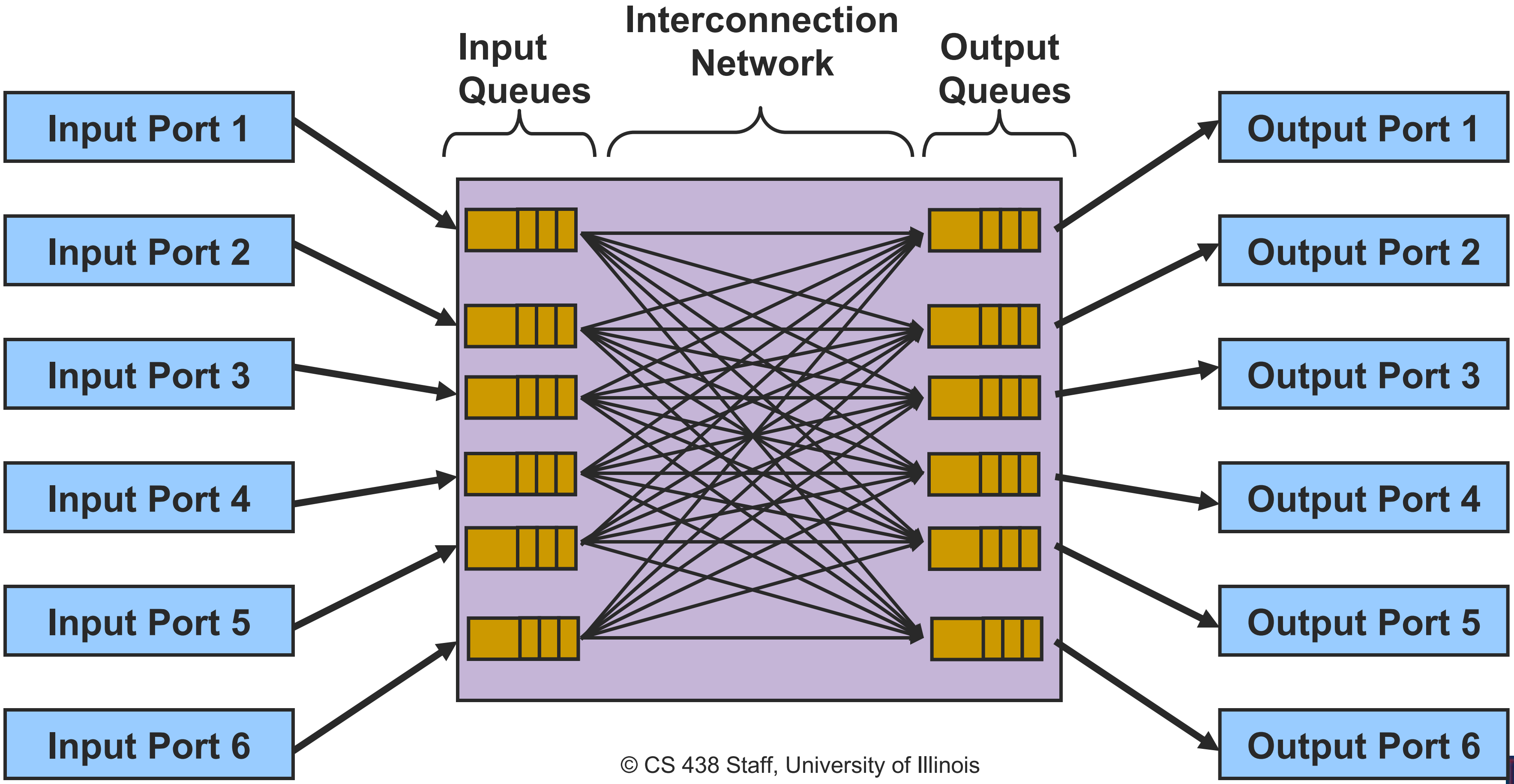
We also need buffering at the input, since processing can be slower than input rate, or delays at output

Switch Design



Add **input queues** to temporarily hold received packets until they can be processed
Packet remains queued until input queue empties, until output queue has free slots

Switch design: putting the pieces together



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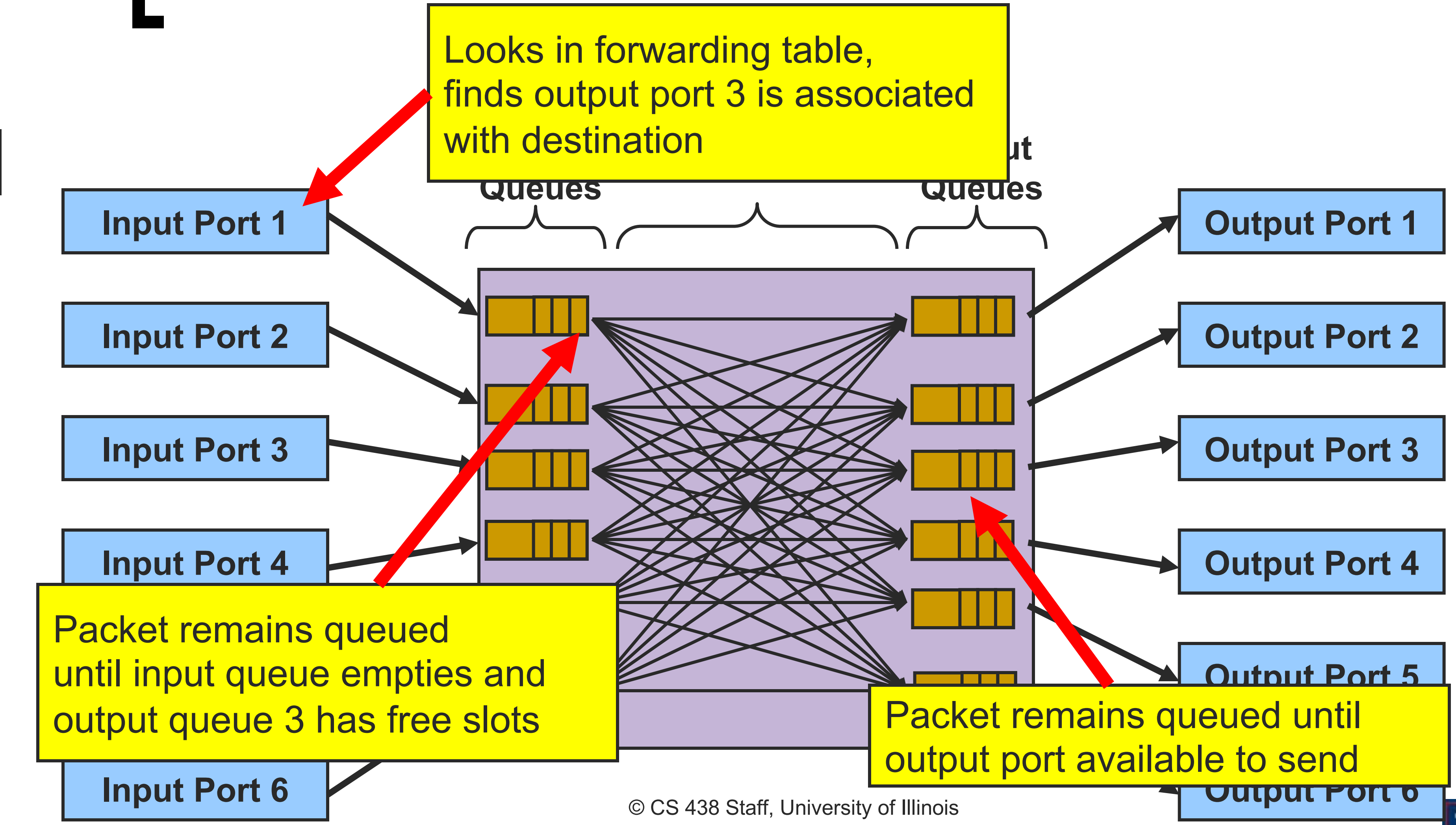
Switch design: putting the pieces together



Looks in forwarding table, finds output port 3 is associated with destination
ut
Queues
Queues
Input Port 1
Input Port 2
Input Port 3
Input Port 4
Input Port 6
Output Port 1
Output Port 2
Output Port 3
Output Port 4
Output Port 5
Output Port 6
Packet remains queued until input queue empties and output queue 3 has free slots
Packet remains queued until output port available to send

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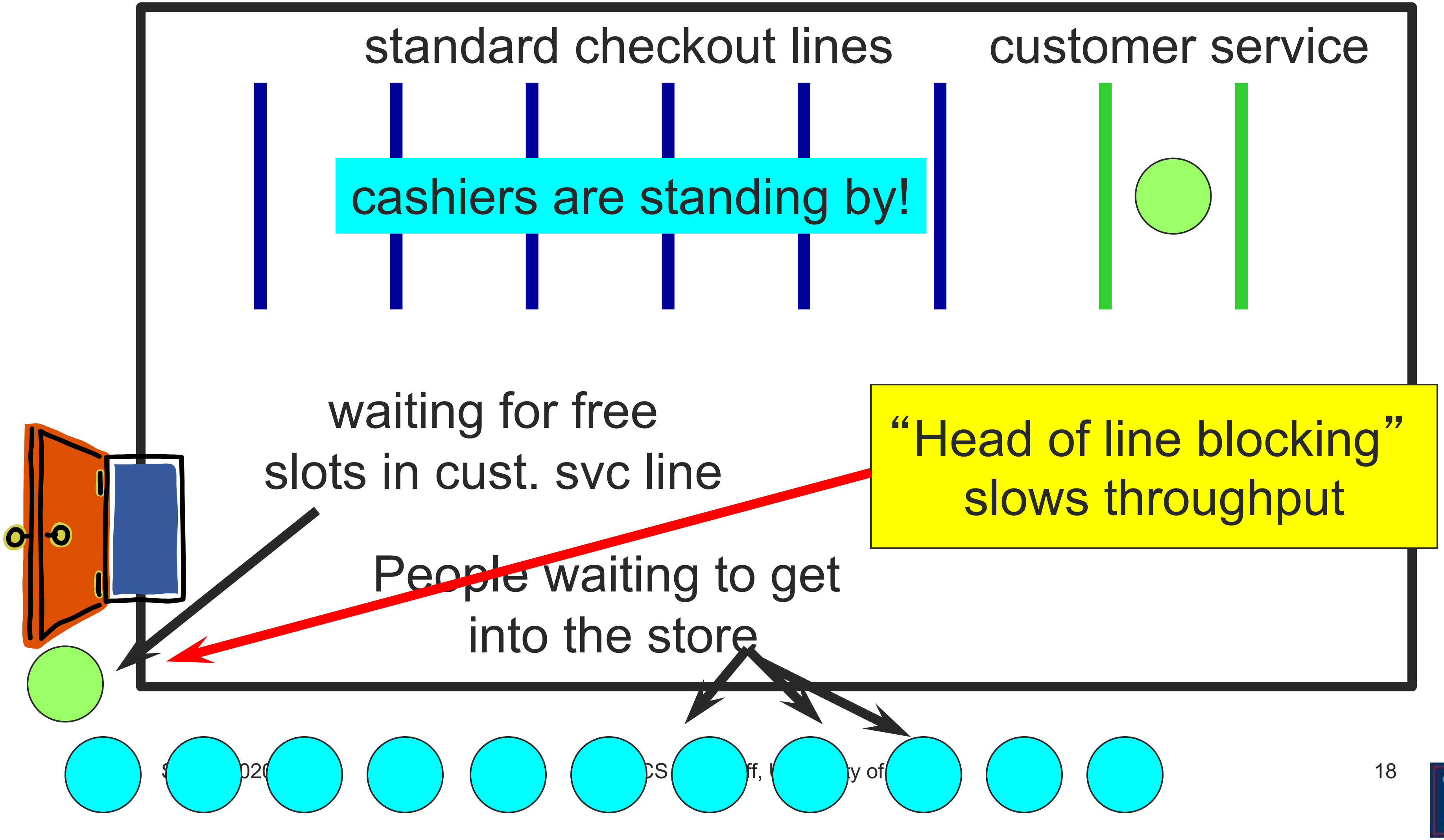
Contention – Head of Line Blocking



standard checkout lines

customer service

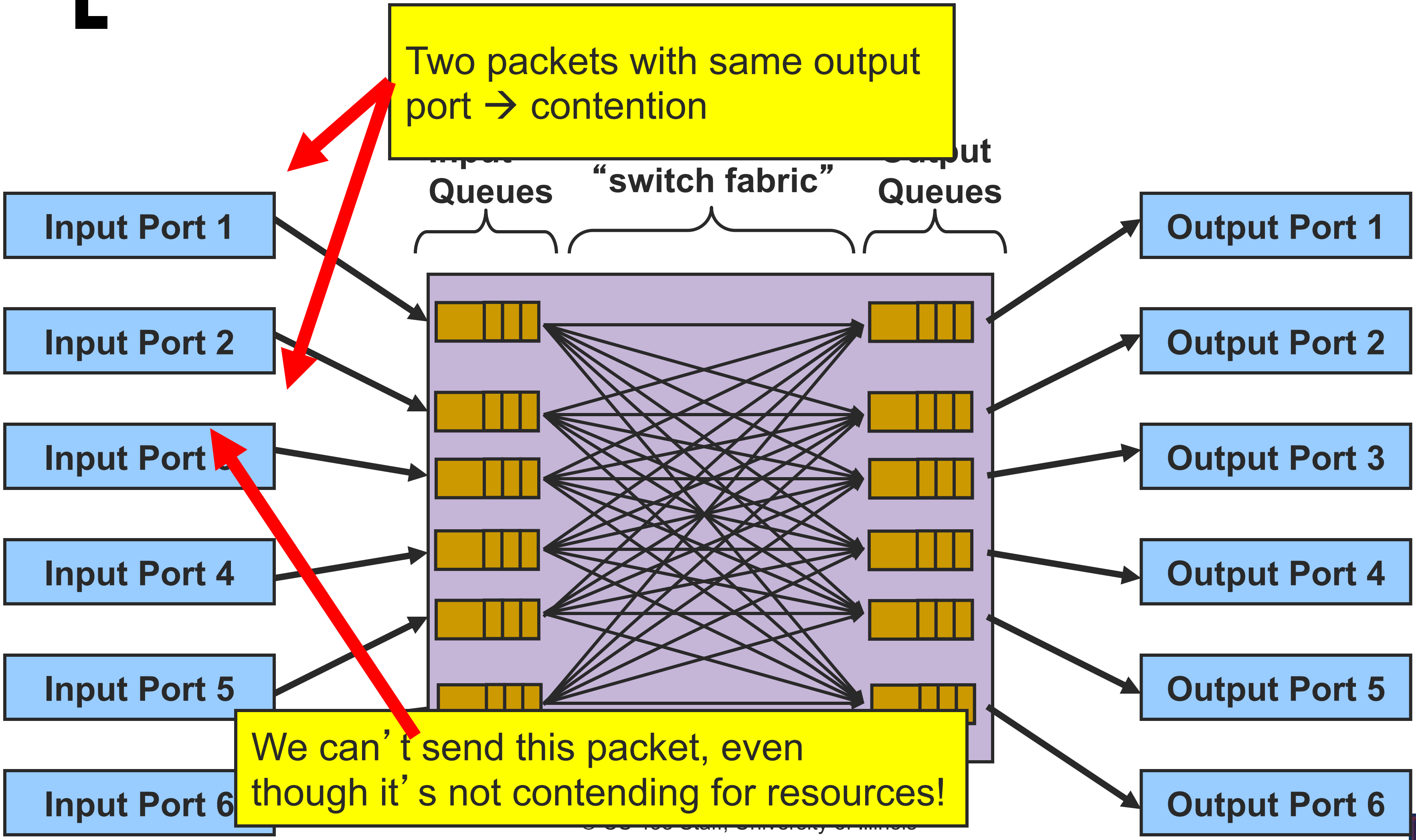
cashiers are standing by!

waiting for free slots in cust. svc line

“Head of line blocking” slows throughput

People waiting to get into the store

Head of Line Blocking



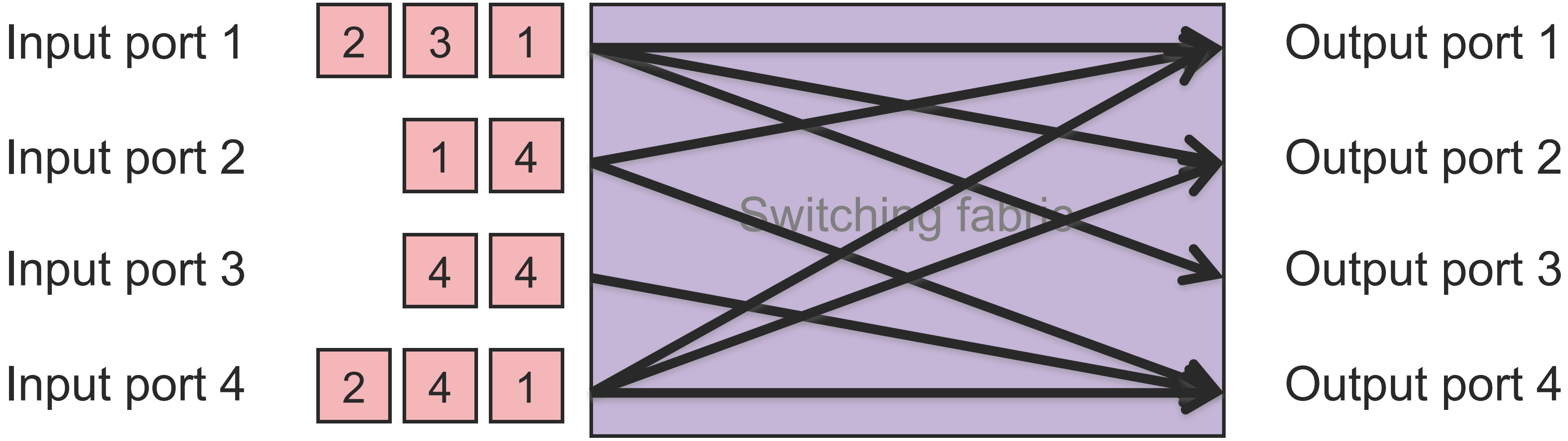
Two packets with same output port → contention

We can't send this packet, even though it's not contending for resources!

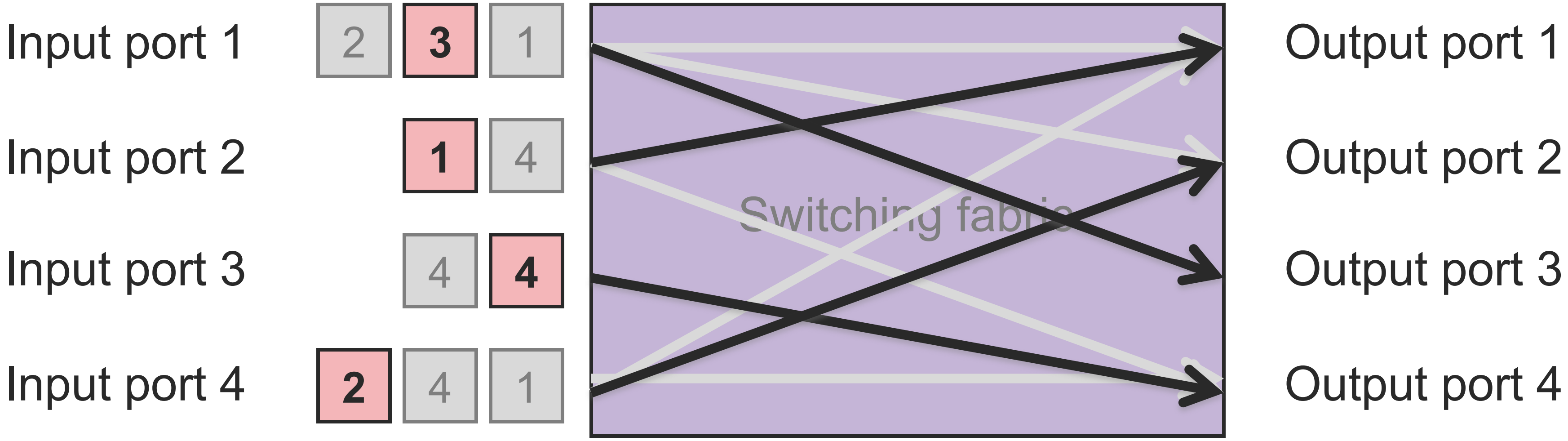
Unblocking head of line blocking

- Solution 1: No input queue
  - Switching fabric (hopefully) keeps up with input rate
- Solution 2: No need to always serve packet at head of queue. Could pick any!
  - Each input port has separate queue for each output port
- Next question: which packet do we pick?

Picking packets' ports

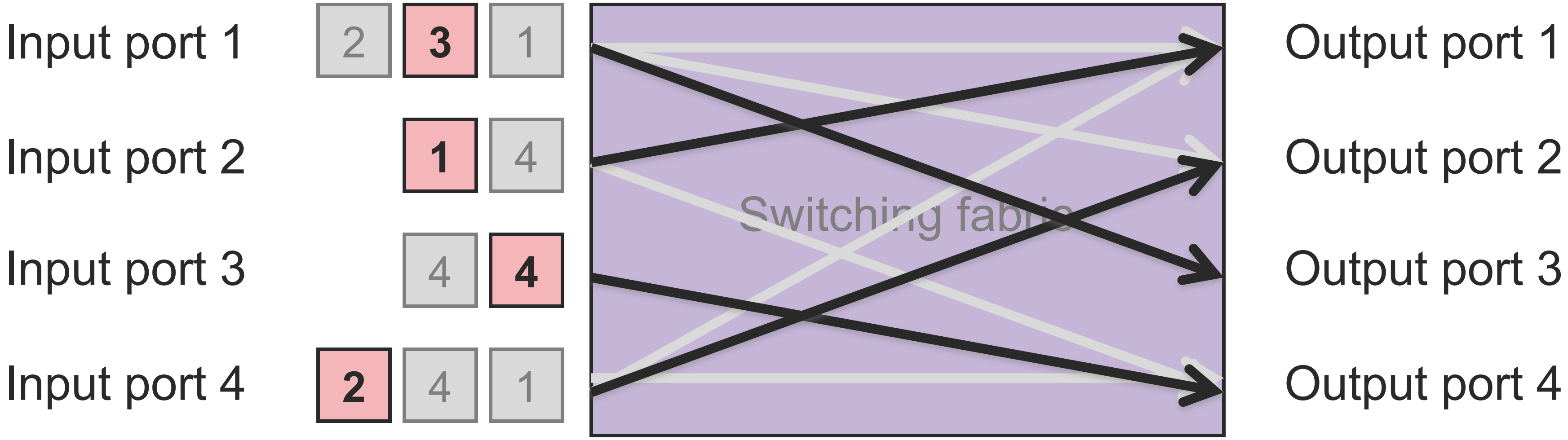


Picking packets' ports



- Underlying problem for max throughput in single timestep: bipartite matching
  - Pick max subset of edges using 1 edge per node

Picking packets' ports



- Switches may not find optimal solution: we also want
    - Fairness
    - Simplicity of implementation

What we know so far

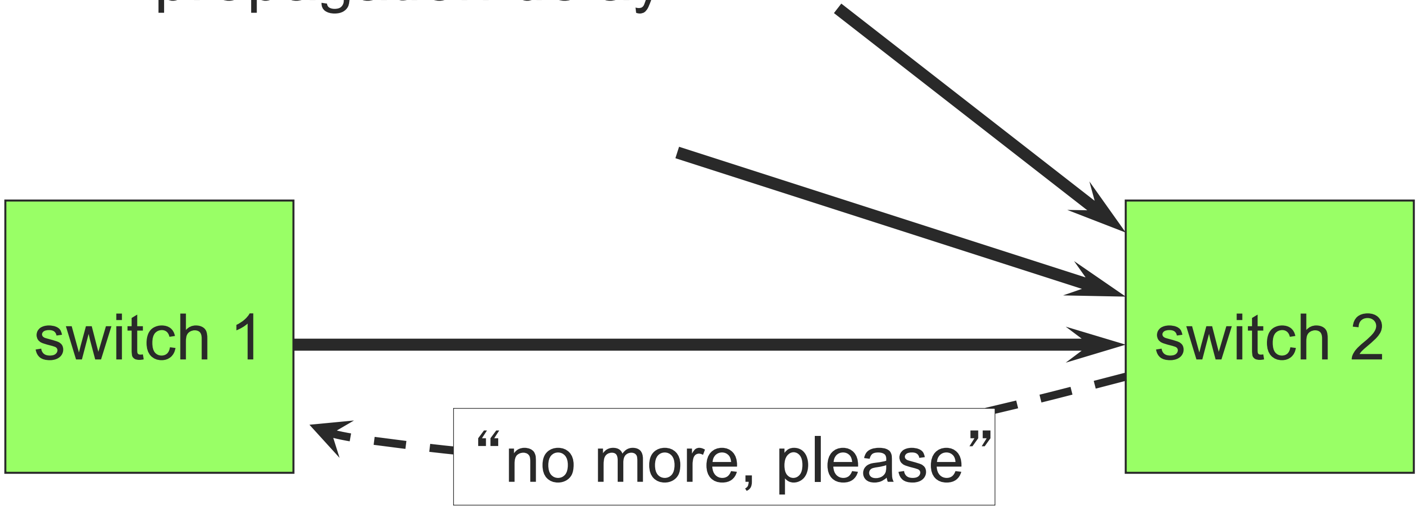
- Buffering masks temporary contention
- Need to carefully manage queues
  - Head-of-line blocking problem
  - Fairness
  - Throughput

What we know so far

- Did we completely solve contention problem? Could a packet ever be dropped?
  - Yes: queues can still overflow
  - Solution 1: plan allowed packet rates in advance – virtual circuit switching
  - Solution 2: dynamically request rate reduction – backpressure

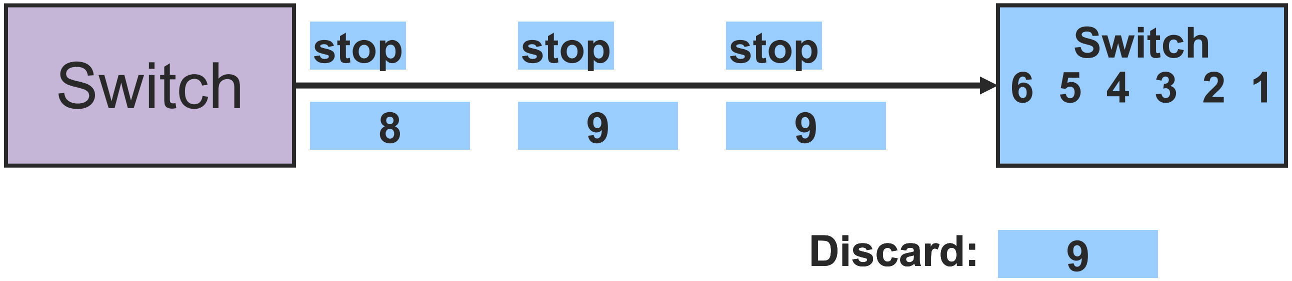
Contention – Back Pressure

- Let the receiver tell the sender to slow down
  - Propagation delay requires that the receiver react before the buffer is full
  - Typically used in networks with small propagation delay



Contention – Back Pressure

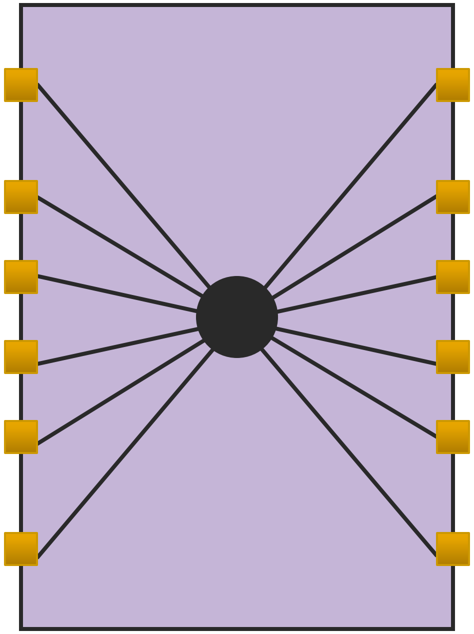
- Need to send backpressure *before* queue fills
- So, better when propagation delay small
  - e.g., switch fabrics
  - e.g., Ethernet pause-based flow control (IEEE 802.3x) used to run FibreChannel over Ethernet



Switch Design Goals

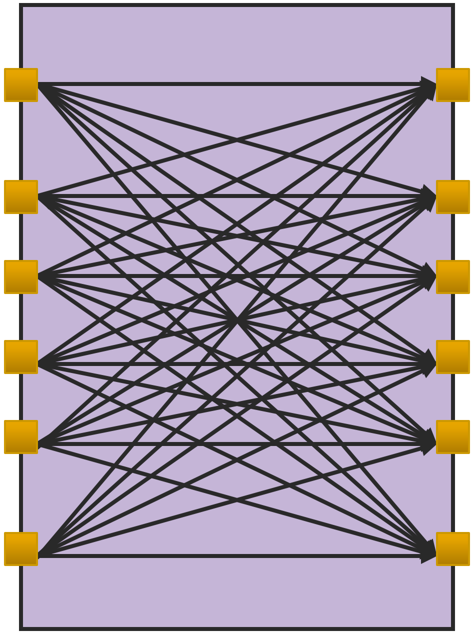
- High Throughput
  - Number of packets a switch can forward per second
- High Scalability
  - How many input/output ports can it connect
- Low Cost
  - Per port monetary costs

Two simple fabrics



Shared bus or memory:
Low $, low throughput

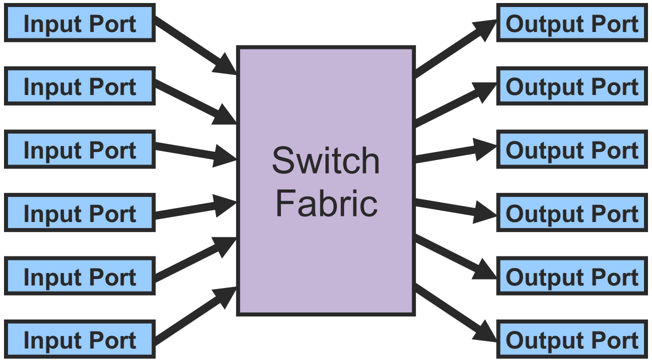
Two simple fabrics for very large high-performance switches!



Full mesh:
High $, high throughput

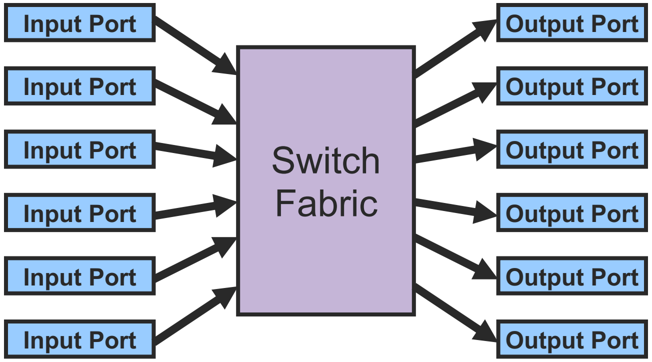
Special Purpose Switches

- Problem
  - Connect N inputs to M outputs
    - NxM (“N by M”) switch
    - Often N = M
- Goals
  - High throughput
    - Best is MIN(sum of inputs, sum of outputs)
  - Avoid contention
  - Good scalability
    - Linear size/cost growth



Switch Design

- Ports handle complexity
  - Forwarding decisions
  - Buffering
- Simple fabric
  - Move packets from inputs to outputs
  - May have a small amount of internal buffering



Switch Design Goals

- Throughput
  - Main problem is contention
  - Need a good traffic model
    - Arrival time
    - Destination port
    - Packet length
  - Telephony modeling is well understood
    - Until faxes and modems
  - Modeling of data traffic is new
    - Not well understood
    - Will good models help?

Switch Design Goals

- Contention
  - Avoid contention through intelligent buffering
  - Use output buffering when possible
  - Apply back pressure through switch fabric
  - Improve input buffering through non-FIFO buffers
    - Reduces head-of-line blocking
  - Drop packets if input buffers overflow

Switch Design Goals

- Scalability
  - O(N) ports
  - Port design complexity O(N) gives O(N^2) for entire switch
  - Port design complexity of O(1) gives O(N) for entire switch

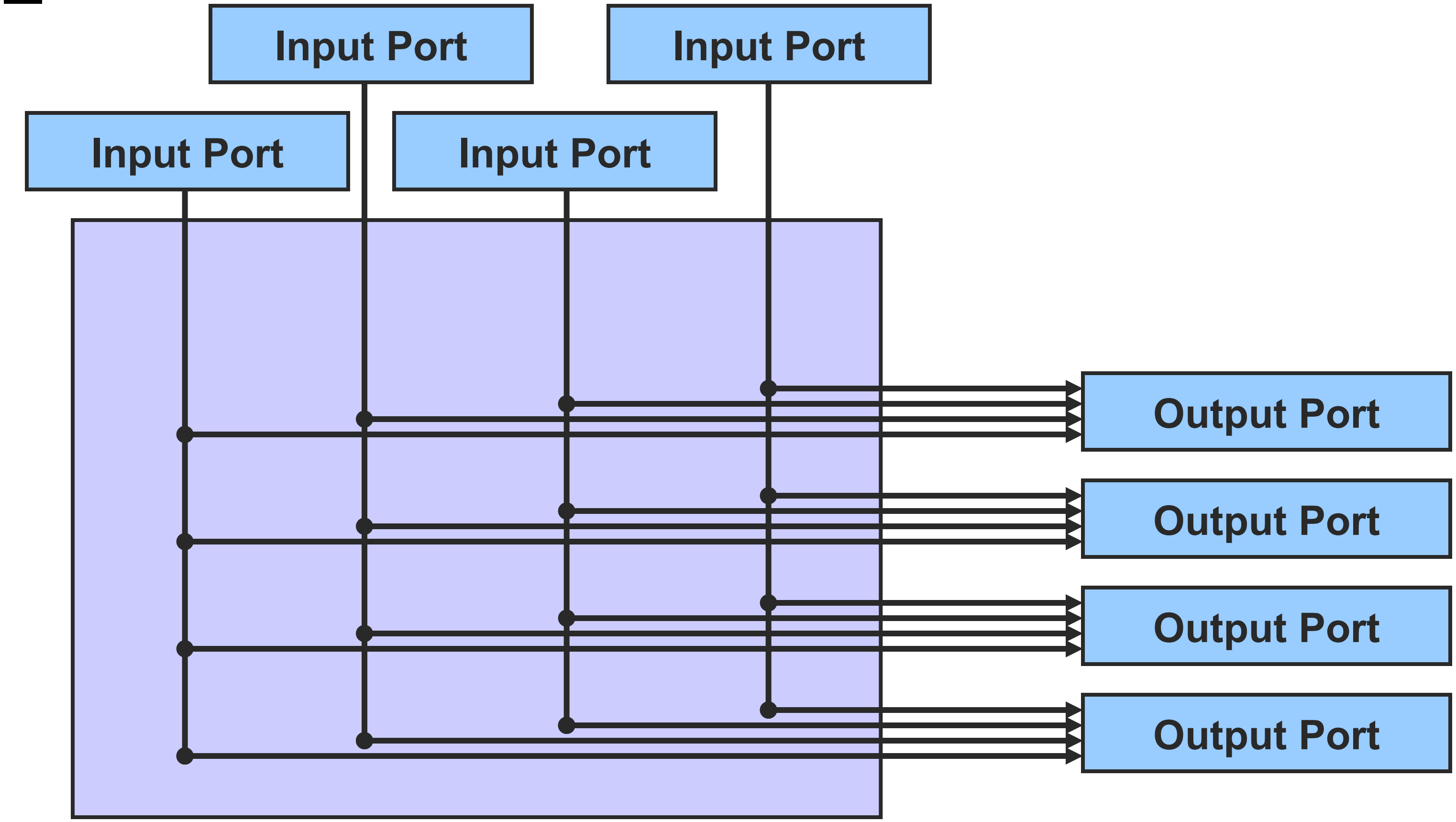
Switch Design

- Crossbar Switches
- Banyan Networks
- Batcher Networks
- Sunshine Switch

Crossbar Switch

- Every input port is connected to every output port
  - NxN
- Output ports
  - Complexity scales as O(N^2)

Crossbar Switch



Knockout Switch

- Problem
  - Full crossbar requires each output port to handle up to N input packets
- Assumption
  - It is unlikely that N inputs will have packets destined for the same output port
- Instead
  - implement each port to handle L<N packets at the same time
- Challenges
  - What value of L to use
  - Managing hotspots

Knockout Switch

- Output port design
  - Packet filters
    - Recognize packets destined for a specific port
  - Concentrator
    - Selects up to L packets from those destined for this port
    - “Knocks out” (discards) excess packets
  - Queue
    - Length L

Knockout Switch

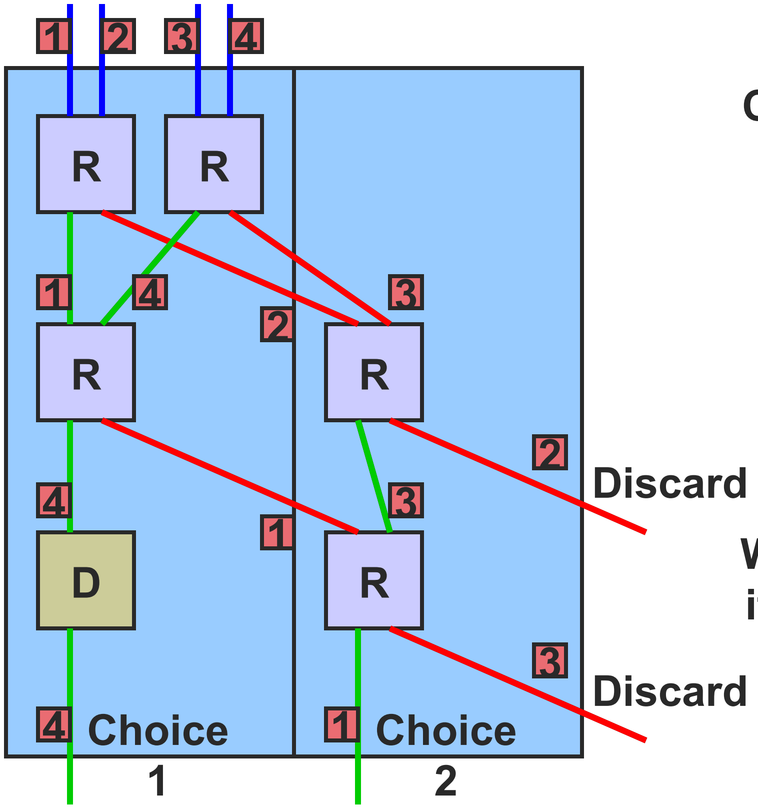
- Goal
  - Want some fairness
  - No single input should have its packets always "knocked out"
- Approach
  - Essentially a "knock out" tennis tournament with each game of 2 players (packets) chosen randomly
  - Overall winner is selected by playing log N rounds, and keeping the winner

Knockout Switch

- Pick L from N packets at a port
  - Output port maintains L cyclic buffers
  - Shifter places up to L packets in one cycle
  - Each buffer gets only one packet
  - Output port uses round-robin between buffers
  - Arrival order is maintained

- Output ports scale as O(N)

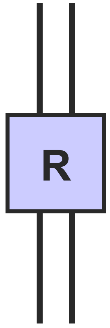
Knockout Switch



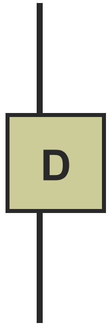
Choose L of N

Ex: 2 of 4

What happens if more than L arrive?



2x2 random selector



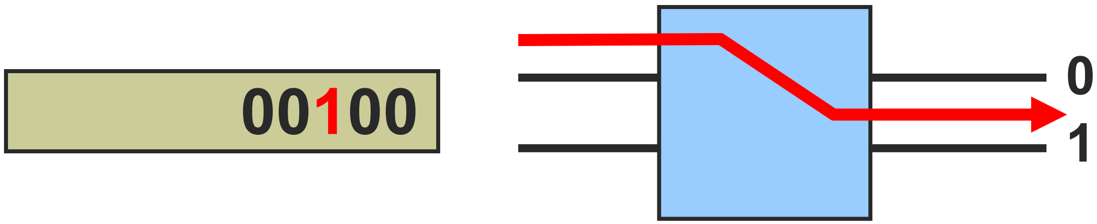
Delay unit

Self-Routing Fabrics

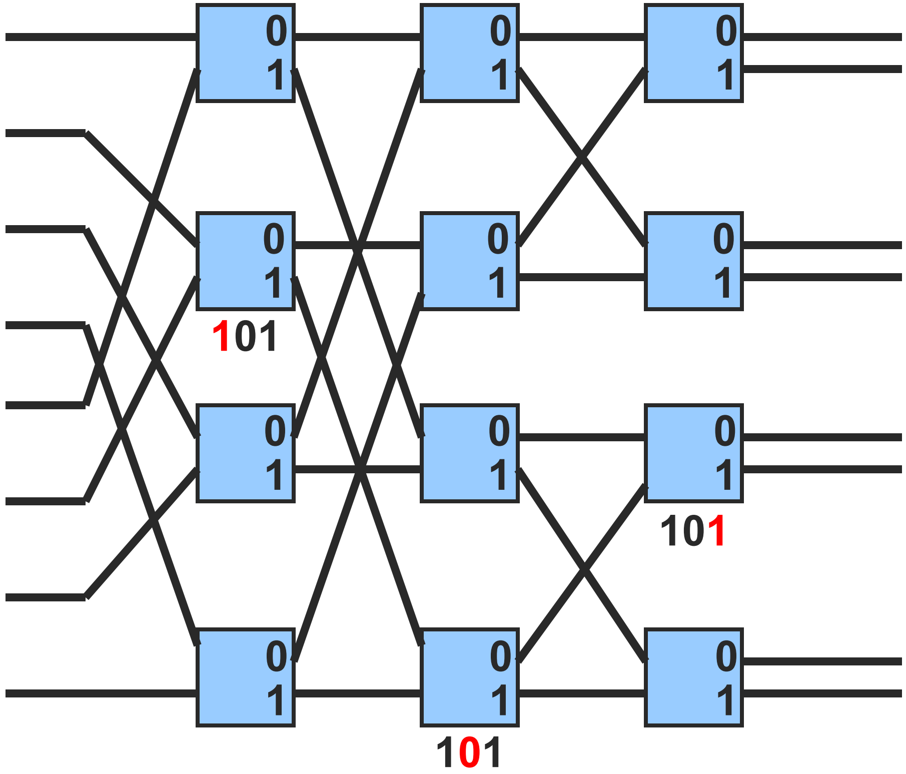
- Idea
  - Use source routing on “network” in switch
  - Input port attaches output port number as header
  - Fabric routes packet based on output port
- Types
  - Banyan Network
  - Batcher-Banyan Network
  - Sunshine Switch

Banyan Network

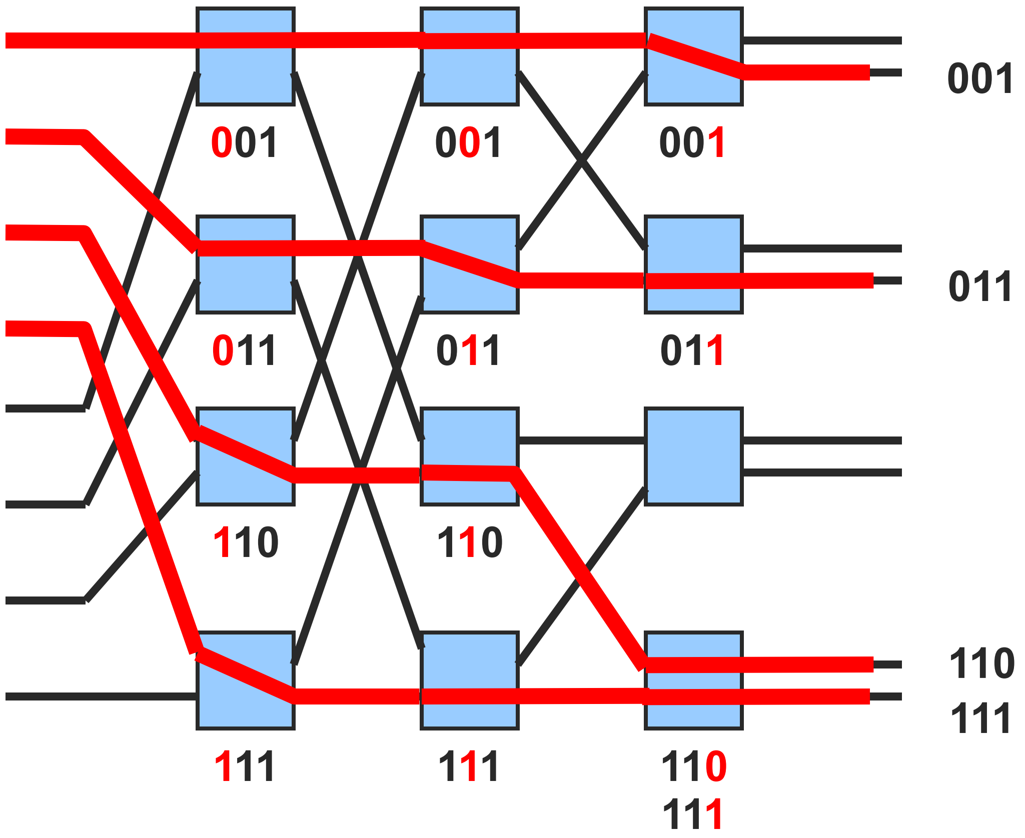
- A network of 2x2 switches
  - Each element routes to output 0 or 1 based on packet header
  - A switch at stage i looks at bit i in the header



Banyan Network



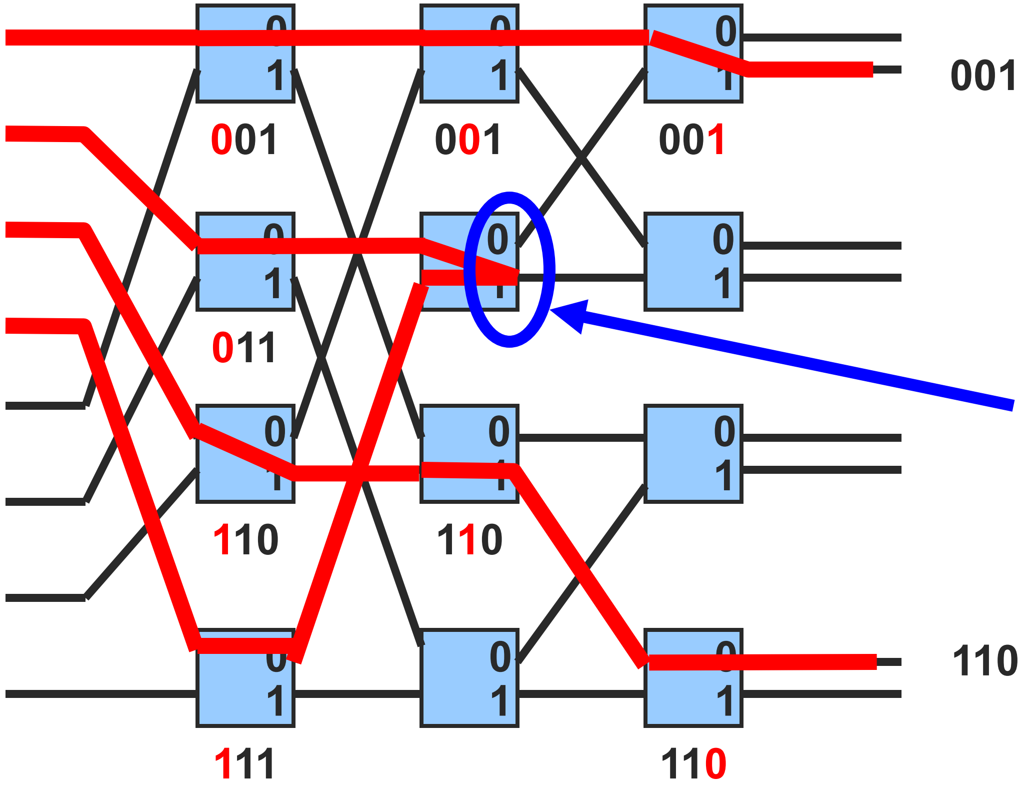
Banyan Network



Banyan Network

- Perfect Shuffle
  - N inputs requires $\log_2 N$ stages of N/2 switching elements
  - Complexity on order of N $\log_2 N$
- Collisions
  - If two packets arrive at the same switch destined for the same output port, a collision will occur
  - If all packets are sorted in ascending order upon arrival to a banyan network, no collisions will occur!

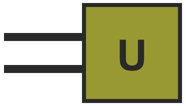
Collision in a Banyan Network



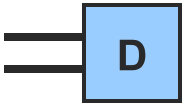
Collision!
Happens because input is unsorted

Batcher Network

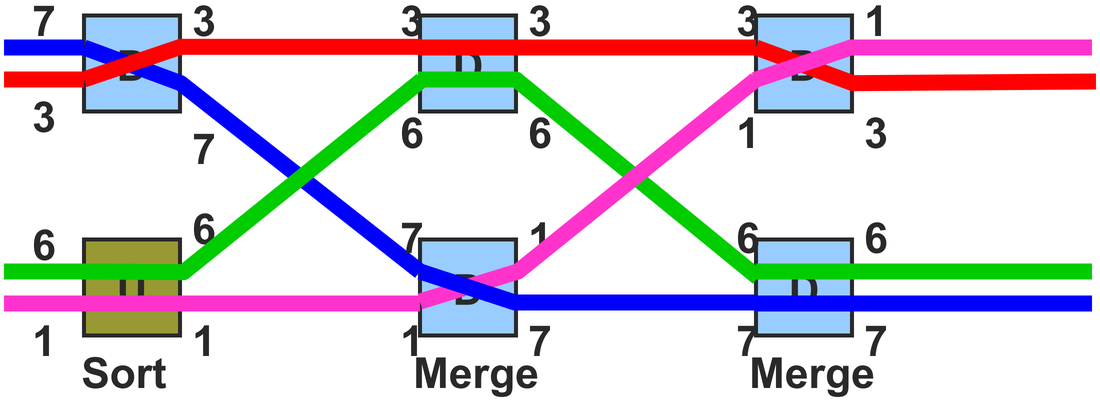
- Performs merge sort
- A network of 2x2 switches
  - Each element routes to output 0 or 1 based on packet header
  - A switch at stage i looks at the whole header
  - Two types of switches
    - Up switch
      - Sends higher number to top output (0)



    - Down switch
      - Sends higher number to bottom output (1)

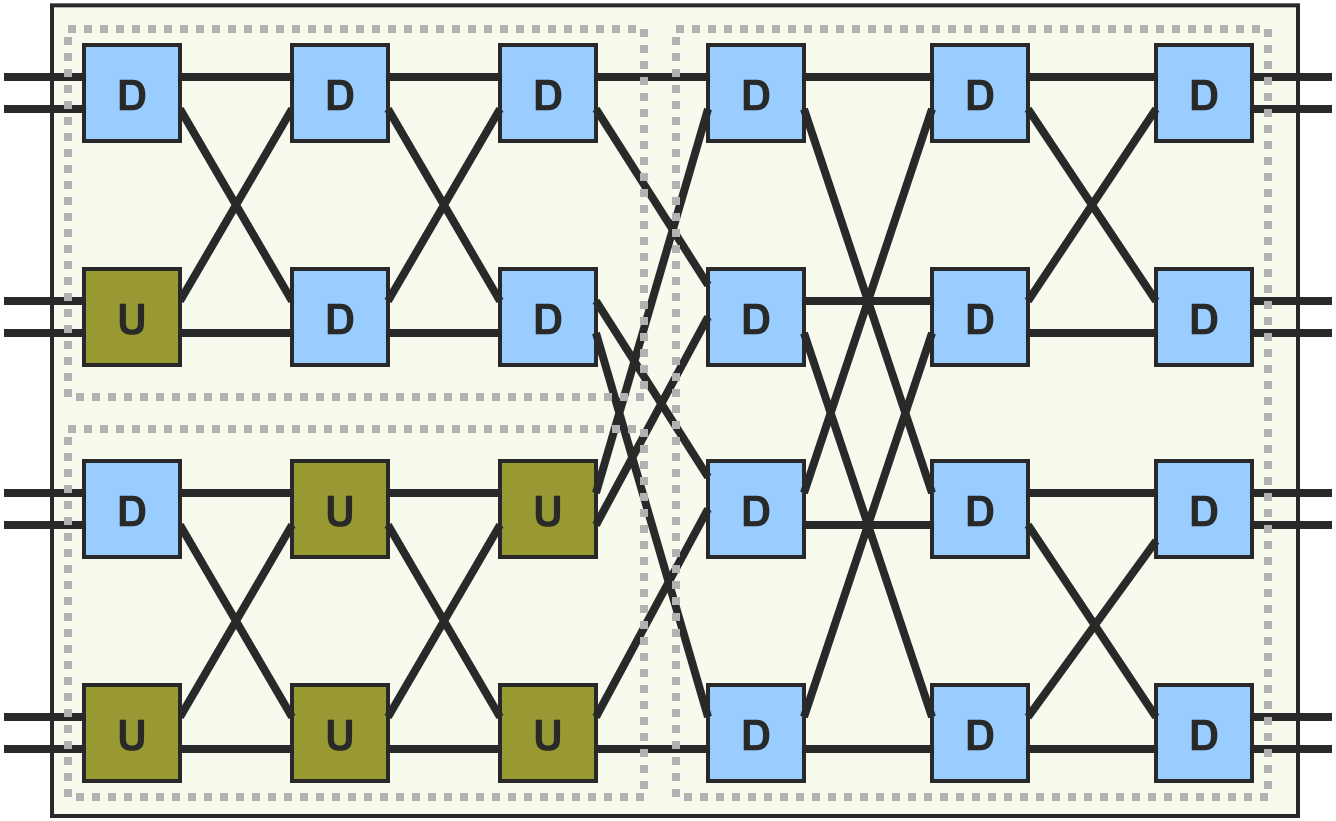


Batcher Network



Batcher Network

Sort inputs 0 – 3 in ascending order



Merge 0 – 3 with 4 – 7

8x8 Switch

Sort inputs 4 – 7 in descending order

Batcher Network

- How it really works
  - Merger is presented with a pair of sorted lists, one in ascending order, one in descending order
  - First stage of merger sends packets to the correct half of the network
  - Second stage sends them to the correct quarter
- Size
  - N/2 switches per stage
  - $\log_2 N$ x $(1 + \log_2 N)/2$ stages
  - Complexity = $N \log_2^2 N$

Batcher-Banyan Network

- Idea
  - Attach a batcher network back-to-back with a banyan network
  - Arbitrary unique permutations can be routed without contention