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 Fabric

Input Port

Output Port

Input Port

Output Port

Input Port

Output Port

Input Port

Output Port

Input Port

Output Port

Input Port

Output Port
Switch Architecture

- Problem
  - Connect N inputs to M outputs
    - N x M (“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

standard checkout lines

customer service

Waiting to buy food

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

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

- Waiting to buy food
- People waiting to get into the store

standard checkout lines  customer service

Waiting for Cust. service

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.
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
Switch design: putting the pieces together

- Input Port 1
- Input Port 2
- Input Port 3
- Input Port 4
- Input Port 5
- 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.

Looks in forwarding table, finds output port 3 is associated with destination.

Packet remains queued until output port available to send data to dst.

Looks in forwarding table, finds output port 3 is associated with destination.
Contestation – Head of Line Blocking

standard checkout lines

cashiers are standing by!

customer service

waiting for free slots in cust. svc line

People waiting to get into the store

“Head of line blocking” slows throughput
Head of Line Blocking

Two packets with same output port → contention

Input Port 1
Input Port 2
Input Port 3
Input Port 4
Input Port 5
Input Port 6

Output Port 1
Output Port 2
Output Port 3
Output Port 4
Output Port 5
Output Port 6

Queues
“switch fabric”
Queues

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

Input port 1  2  3  1  
Input port 2  1  4  
Input port 3  4  4  
Input port 4  2  4  1  

Switching fabric

Output port 1
Output port 2
Output port 3
Output port 4
## Picking packets’ ports

<table>
<thead>
<tr>
<th>Input port 1</th>
<th>2</th>
<th>3</th>
<th>1</th>
<th>Output port 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input port 2</td>
<td>1</td>
<td>4</td>
<td></td>
<td>Output port 2</td>
</tr>
<tr>
<td>Input port 3</td>
<td>4</td>
<td></td>
<td>4</td>
<td>Output port 3</td>
</tr>
<tr>
<td>Input port 4</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>Output port 4</td>
</tr>
</tbody>
</table>

- **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

```
  switch 1
    “no more, please”
  switch 2
```
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

```
8 9 9
```

Stop: 8 9 9

```
6 5 4 3 2 1
```

Discard: 9
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 for very large high-performance switches!

- Shared bus or memory: Low $, low throughput
- Full mesh: High $, high throughput
Special Purpose Switches

- **Problem**
  - Connect \( N \) inputs to \( M \) outputs
    - \( N \times M \) (“\( N \) by \( M \)” ) switch
    - Often \( N = M \)

- **Goals**
  - High throughput
    - Best is \( \text{MIN}(\text{sum of inputs, sum of outputs}) \)
  - 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
  - \( N \times N \)
- 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

```
00100
```
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

Sort inputs 4 – 7 in descending order

Merge 0 – 3 with 4 – 7

8x8 Switch
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
  - $\log_2 N \times (1 + \log_2 N)/2$ 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
Sunshine Switch

- Sunshine Switch
  - Like a knockout switch
    - Can handle up to $L$ packets per output port
  - Recirculates overflow packets
    - If more than $L$ packets arrive for any output port in one cycle
Sunshine Switch

- Elements
  - Multiple Banyan networks
    - Enables multiple packets per output port
  - Delay Box
    - Excess (K) packets are recirculated and resubmitted to the switch
  - Batcher network
    - N new packets
    - K delayed packets
  - Trap
    - Identifies packets destined for banyan
    - Identifies excess packets
  - Selector
    - Routes multiple packets for same output on separate banyans
Sunshine Switch

Diagram: Batcher, Trap, Selector, L Banyans
Sunshine Switch

- Can packets circulate for ever?
  - Priority bit is used to favor older packets
  - Priority bit also ensure packet order is preserved through the switch