# CS 5114
# Network Programming Languages
# Data Plane

http://www.flickr.com/photos/rofi/2097239111/

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Based on lecture notes by Jennifer Rexford and Michael Freedman

# Announcements

## Overview

- Last lecture today
- Start with SDNs on Tuesday

## Homework #1

- Goes out next Tuesday
- Due two weeks later
- Topic: OpenFlow programming

# Data Plane

## Streaming algorithms that act on packets

- Matching on some bits, taking a simple action
- … at behest of control and management plane

## Wide range of functionality

- Forwarding
- Access control
- Mapping header fields
- Traffic monitoring
- Buffering and marking
- Shaping and scheduling
- Deep packet inspection

# Packet Forwarding

# Packet Forwarding

## Control plane computes a forwarding table

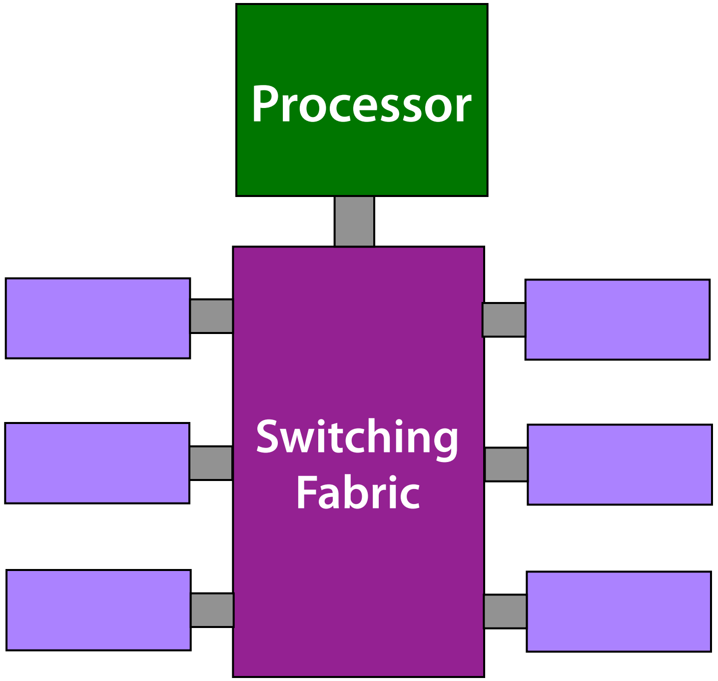
- Maps destination address(es) to an output link

## Handling an incoming packet

- Match: destination address
- Action: direct the packet to the chosen output link

## Switching fabric

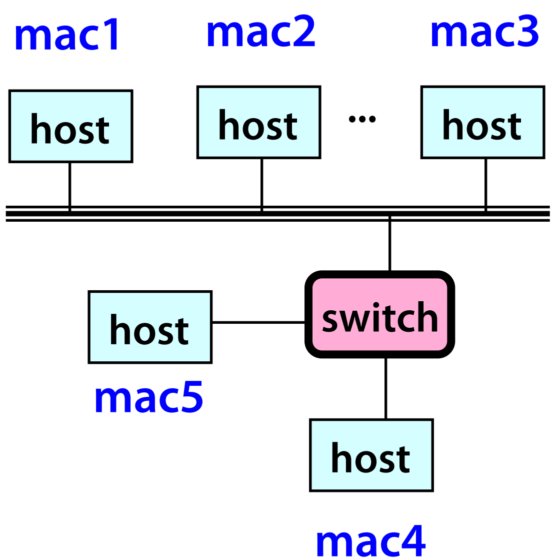
- Directs packet from input link to output link



# Switch: Match on Destination MAC

## MAC addresses are location independent

- Assigned by the vendor of the interface card
- Cannot be aggregated across hosts in the LAN



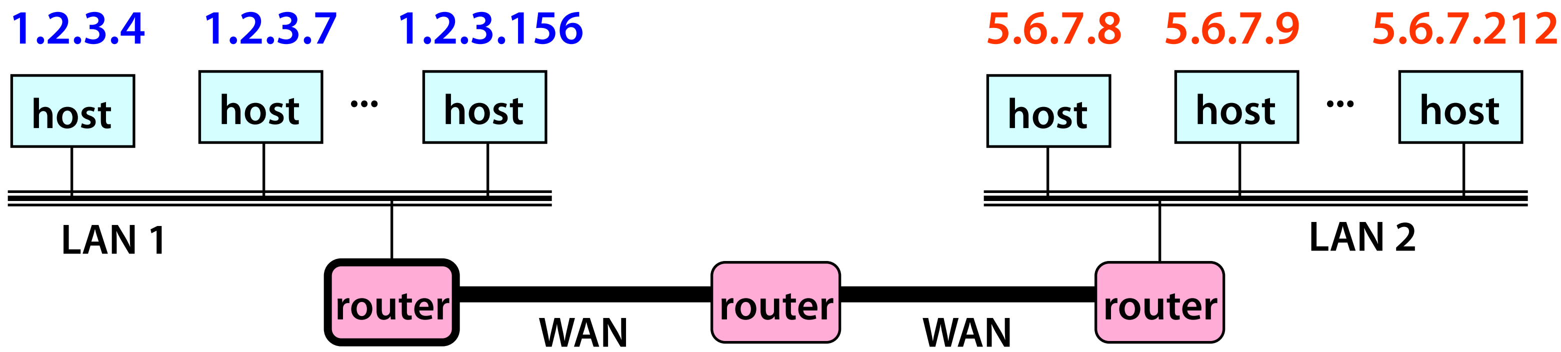

| | |
|---|---|
| mac1 | ↑ |
| mac2 | ↑ |
| mac3 | ↑ |
| mac4 | ← |
| mac5 | ↓ |

**Implemented using a hash table or a content addressable memory.**

# IP Routers: Match on IP Prefix

## IP addresses grouped into common subnets

- Allocated by ICANN, regional registries, ISPs, and within individual organizations
- Variable-length prefix identified by a mask length

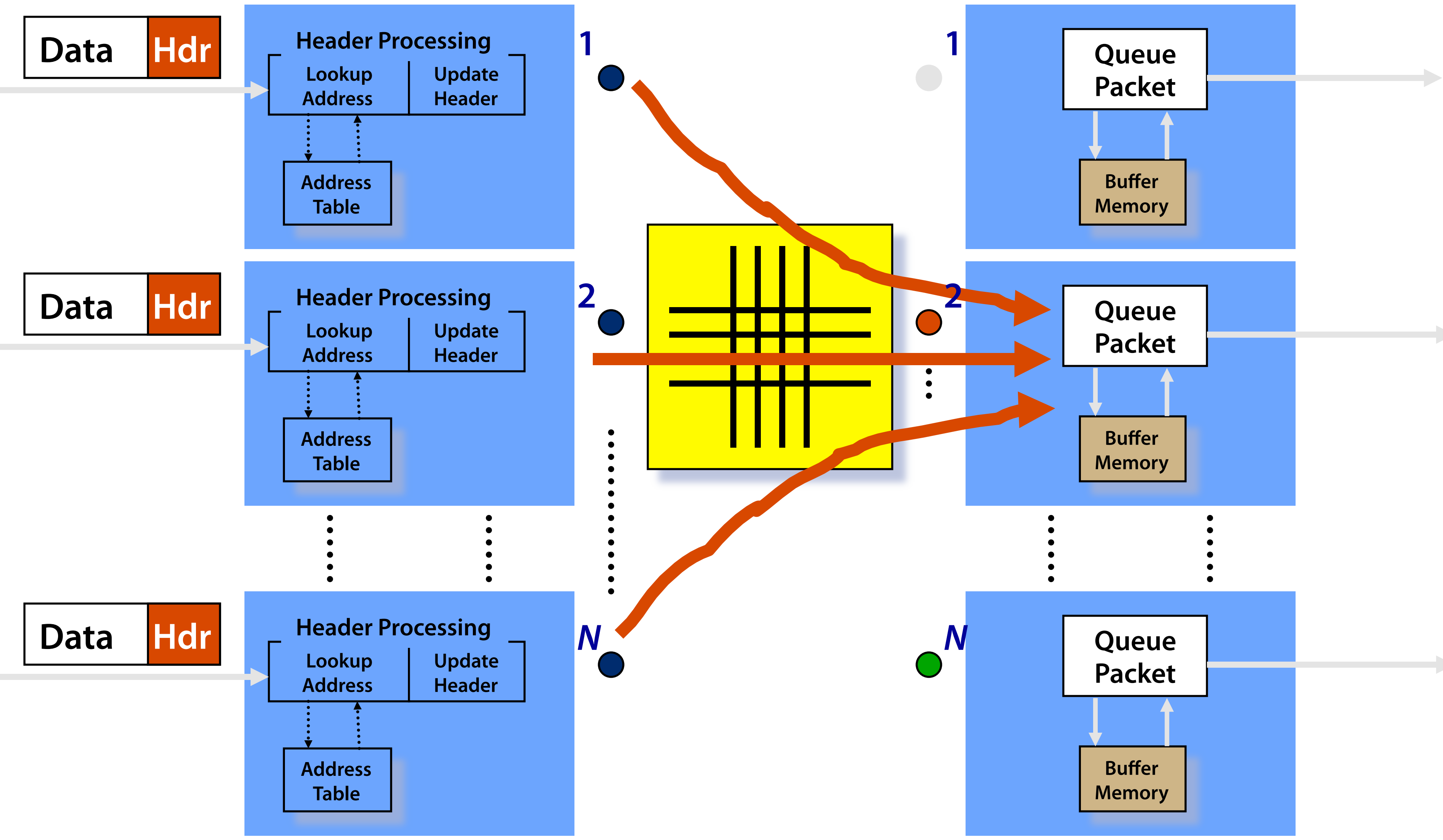



| | |
|---|---|
| 1.2.3.0/24 | ← |
| 5.6.7.0/24 | → |

**forwarding table**

- **Prefixes may be nested.**
- **Routers identify the *longest matching* prefix.**

# Switch Fabric: From Input to Output



# Access Control

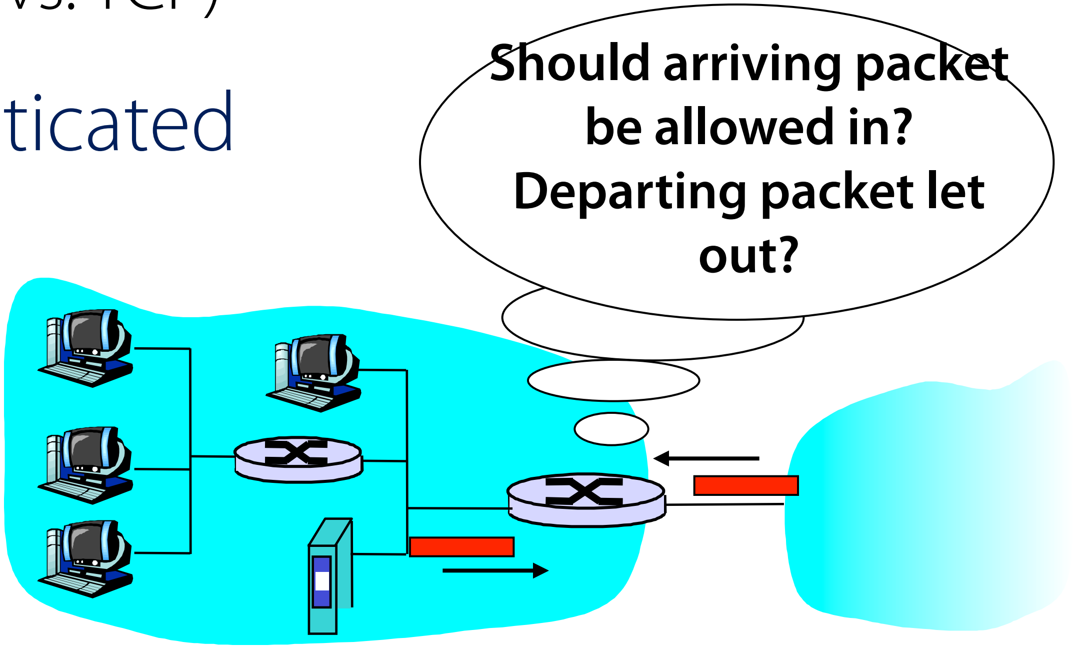
# Access Control: Packet Filtering

## "5-tuple" for access control lists (ACLs)

- Source and destination IP addresses
- TCP/UDP source and destination ports
- Protocol (e.g., UDP vs. TCP)

## Can be more sophisticated

- E.g., block all TCP SYN packets from outside hosts



# Applying Access Control Lists

## Ordered list of "accept/deny" clauses

- Clauses can have wild cards
- Clauses can overlap
- … so order matters

## Packet classification

- Given all of the fields
- … identify the match with the highest priority

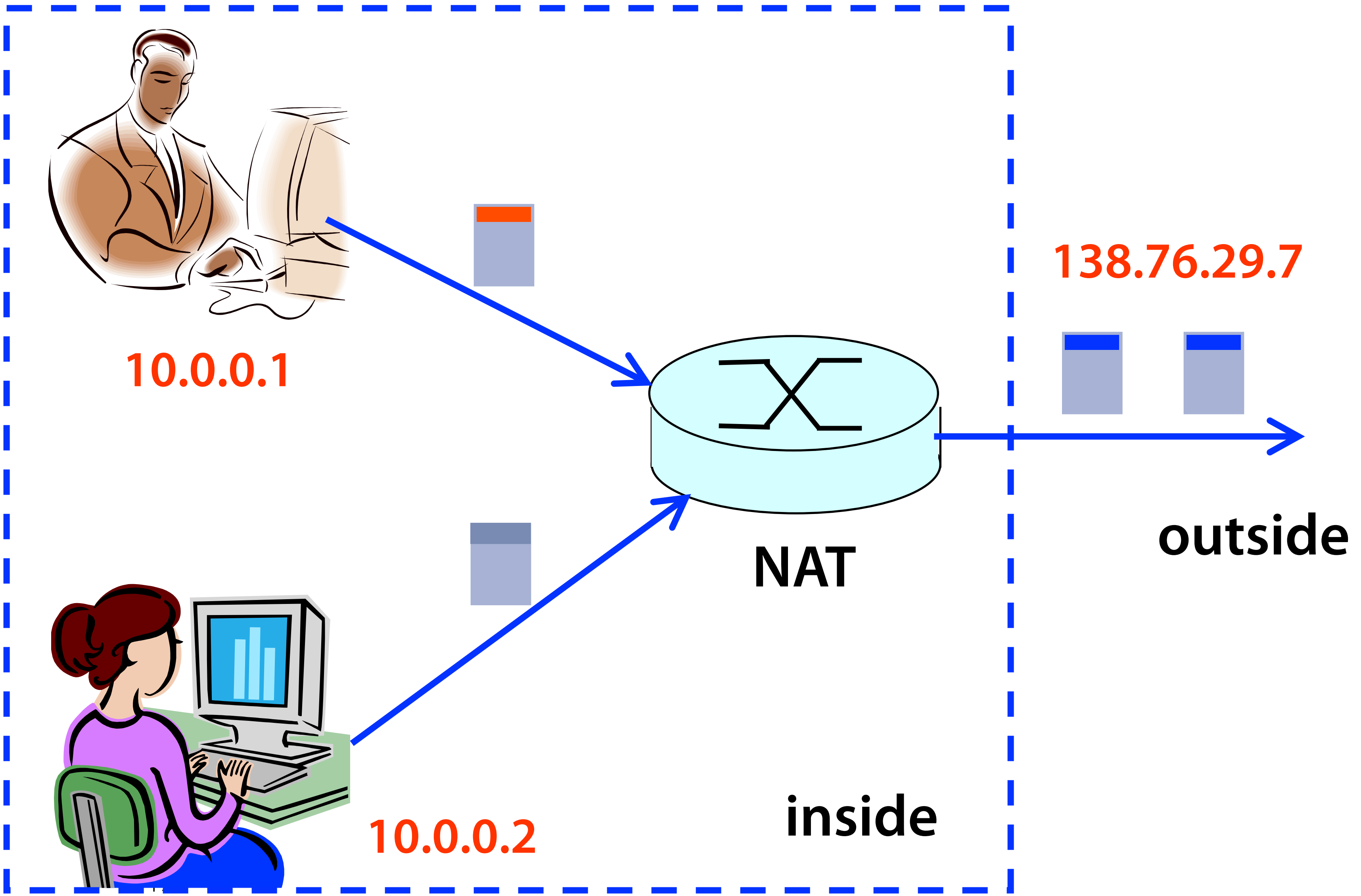
| | |
|---|---|
| Src=1.2.3.4, Dest=5.6.7.8 | Deny |
| Dest=1.2.3.* | Allow |
| Dest=1.2.3.8, Dport!=53 | Deny |
| Src=1.2.3.7, Dport=100 | Allow |
| Dport=100 | Deny |

## Approaches

- Clever algorithms for multi-dimensional classification
- Ternary Content Addressable Memories (TCAMs)

# Mapping Header Fields

# Network Address Translation (NAT)



# Mapping Addresses and Ports

## Remap IP addresses and TCP/UDP port numbers

- Addresses: between end-host and NAT addresses
- Port numbers: to ensure each connection is unique

## Create table entries as packets arrive

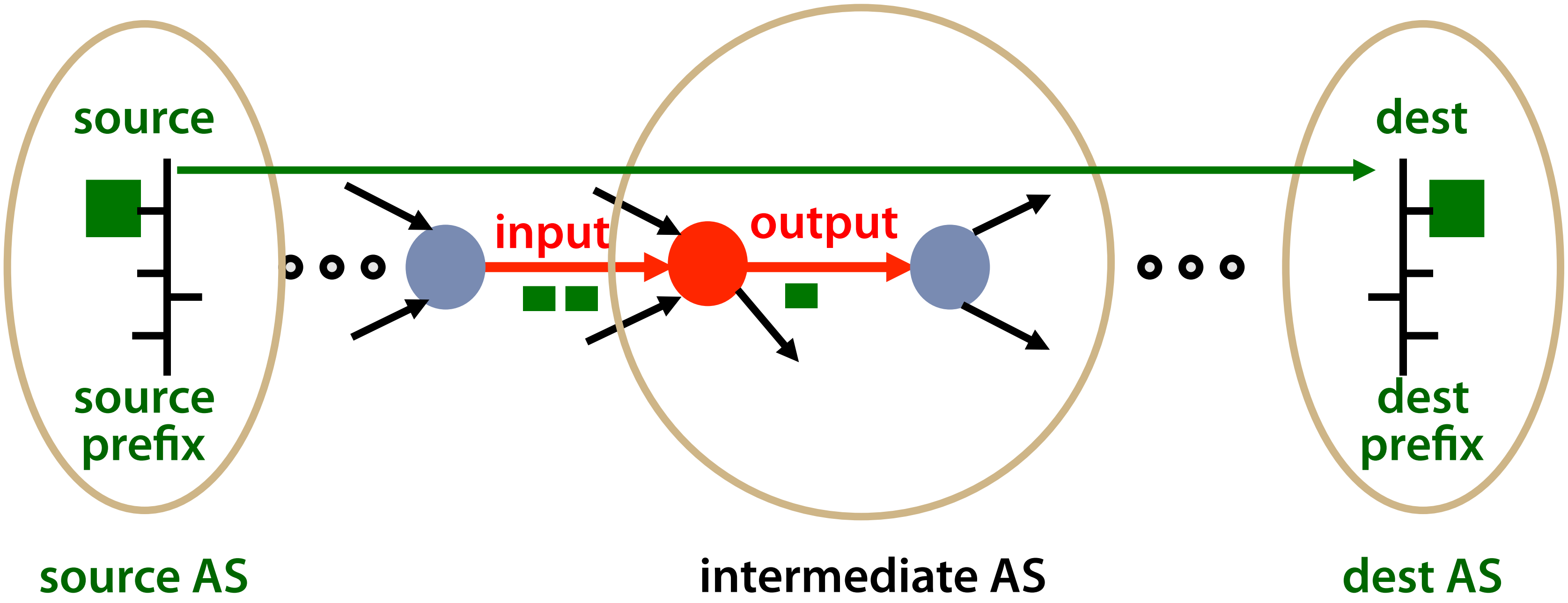
- Src 10.0.0.1, SPort 1024, Dest 1.2.3.4, DPort 80
  - Map to Src 138.76.29.7, Sport 1024, Dest 1.2.3.4, Dport 80
- Src 10.0.0.2, SPort 1024, Dest 1.2.3.4, DPort 80
  - Map to Src 138.76.29.7, Sport 1025, Dest 1.2.3.4, Dport 80

## Challenges

- When do we remove entries?
- How do we run services behind a NAT?
- What if both ends of a connection are behind NATs

# Traffic Monitoring

# Observing Traffic Passing Through




## Applications of traffic measurement

- Usage-based billing
- Network engineering
- Detecting anomalous or malicious traffic

# Passive Traffic Monitoring

## Counting the traffic

- Match based on fields in the packet header
- … and update a counter of # bytes and # packets

## Examples

- Link
- IP prefixes
- TCP/UDP ports
- Individual "flows"

| Dest Prefix | # Packets | # Bytes |
|---|---:|---:|
| 1.2.3.0/24 | 3 | 1500 |
| 7.8.0.0/16 | 10 | 13000 |
| 8.0.0.0/8 | 100 | 85020 |
| 7.7.6.0/23 | 1 | 40 |

## Challenges

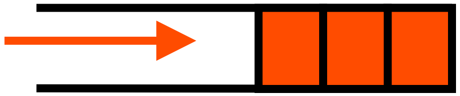
- Identify traffic aggregates in advance vs. reactively
- Summarizing other information (e.g., time, TCP flags)
- Not knowing if you see all packets in a connection

# Resource Allocation

# Buffering

## Drop-tail FIFO queue

- Packets served in the order they arrive
- … and dropped if queue is full

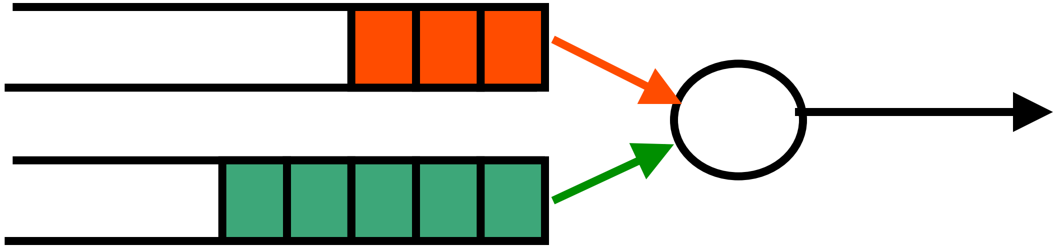


## Random Early Detection (RED)

- When the buffer is nearly full
- … drop or mark some packets to signal congestion

## Multiple classes of traffic

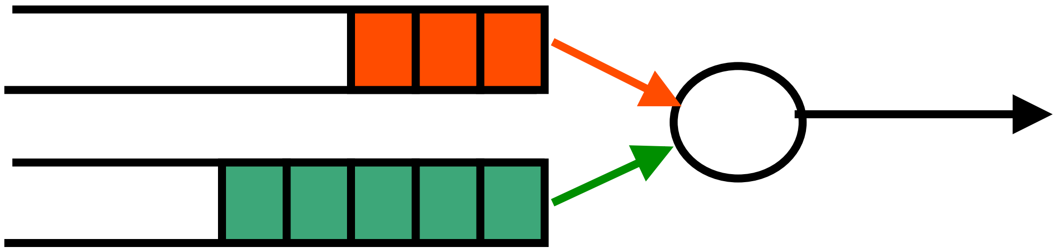
- Separate FIFO queue for each flow or traffic class
- … with a link scheduler to arbitrate between them



# Link Scheduling

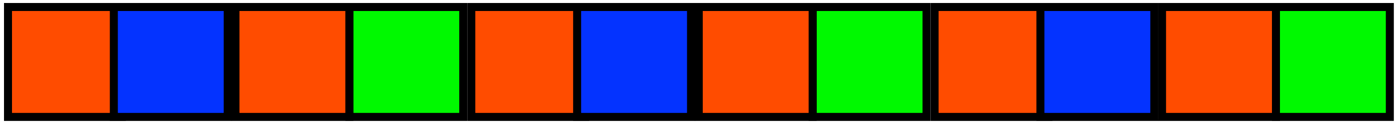
## Strict priority

- Assign an explicit rank to the queues
- … and serve the highest-priority backlogged queue



## Weighted fair scheduling

- Interleave packets from different queues
- …in proportion to weights



**50% red, 25% blue, 25% green**

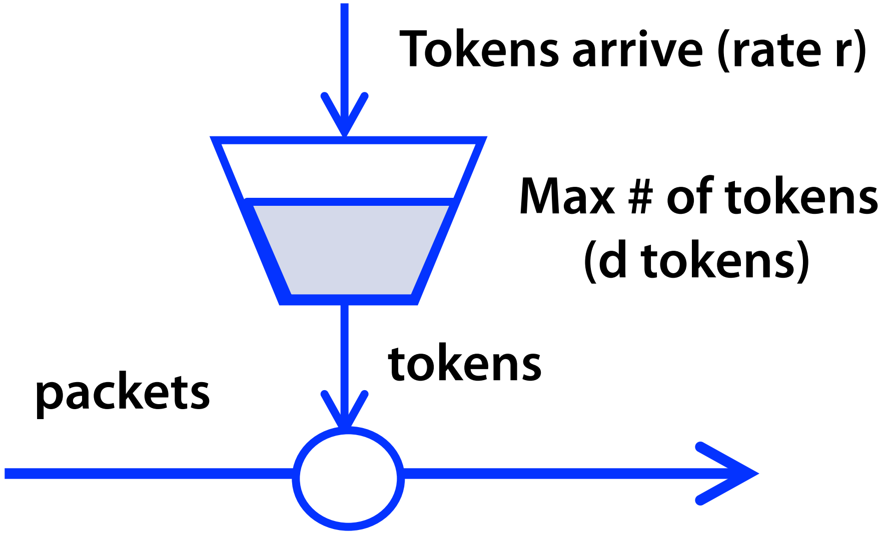
# Traffic Shaping

## Force traffic to conform with a profile

- To avoid congesting downstream resources
- To enforce a contract with the customer

## Leaky-bucket shaping

- Can send at rate r and intermittently burst
- Parameters: token rate r and bucket depth d




**A leaky-bucket shaper for each flow or traffic class**

# Traffic Classification and Marking

## Mark a packet to influence handling downstream

- Explicit Congestion Notification (ECN) flag
- Type-of-Service (ToS) bits

## Ways to set the ToS bits

- End host sets the bits based on the application
  - But, then the network must trust (or bill!) the end host
- Network sets the bits based on traffic classes
  - But, then the network needs to know how to classify packets

## Identifying traffic classes

- Packet classification based on the "five tuple"
- Rate limits, with separate mark for "out of profile" traffic

# Generalizing the Data Plane

# Many Boxes, But Similar Functions

Router
- Forward on destination IP address
- Access control on "5-tuples"
- Link scheduling and marking
- Monitoring traffic
- Deep packet inspection

Switch
- Forward on destination MAC address

Firewall
- Access control on "five tuple" (and more)

NAT
- Mapping addresses and port numbers

Shaper
- Classify packets
- Shape or schedule

Packet sniffer
- Monitoring traffic

OpenFlow

## Match

- Match on a subset of bits in the packet header
- E.g., key header fields (addresses, port numbers, etc.)
- Well-suited to capitalize on TCAM hardware

## Action

- Perform a simple action on the matching packet
- E.g., forward, flood, drop, rewrite, count, etc.

## Controller

- Software that installs rules and reads counts
- ... and handles packets the switch cannot handle

# Programmable Data Plane

## Programmable data plane

- Arbitrary customized packet-handling functionality
- Building a new data plane, or extending existing one

## Speed is important

- Data plane in hardware or in the kernel
- Streaming algorithms the handle packets as they arrive

## Two open platforms

- Click: software data plane in user space or the kernel
- NetFPGA: hardware data plane based on FPGAs

## Lots of ongoing research activity…

# Click Modular Router (backup slides)

# Click Motivation

Flexibility

- Add new features and enable experimentation

Openness

- Allow users/researchers to build and extend
- (In contrast to most commercial routers)

Modularity

- Simplify the composition of existing features
- Simplify the addition of new features

Speed/efficiency

- Operation (optionally) in the operating system
- Without the user needing to grapple with OS internals

# Router as a Graph of Elements

Large number of small elements

- Each performing a simple packet function
- E.g., IP look-up, TTL decrement, buffering

Connected together in a graph

- Elements inputs/outputs snapped together
- Beyond elements in series to a graph
- E.g., packet duplication or classification

Packet flow as main organizational primitive

- Consistent with data-plane operations on a router
- (Larger elements needed for, say, control planes)

# Click Elements: Push vs. Pull

## Packet hand-off between elements

- Directly inspired by properties of routers
- Annotations on packets to carry temporary state

## Push processing

- Initiated by the source end
- E.g., when an unsolicited packet arrives (e.g., from a device)

## Pull processing

- Initiated by the destination end
- E.g., to control timing of packet processing (e.g., based on a timer or packet scheduler)

# Click Language

## Declarations

- Create elements

## Connections

- Connect elements

```
src :: FromDevice(eth0);
ctr :: Counter;
sink :: Discard;

src -> ctr;
ctr -> sink;
```

## Compound elements

- Combine multiple smaller elements, and treat as single, new element to use as a primitive class

## Language extensions through element classes

- Configuration strings for individual elements
- Rather than syntactic extensions to the language

# Handlers and Control Socket

## Access points for user interaction

- Appear like files in a file system
- Can have both read and write handlers

## Examples

- Installing/removing forwarding-table entries
- Reporting measurement statistics
- Changing a maximum queue length

## Control socket

- Allows other programs to call read/write handlers
- Command sent as single line of text to the server
- http://read.cs.ucla.edu/click/elements/controlsocket?s=llrpc

# Example: EtherSwitch Element

## Ethernet switch

- Expects and produces Ethernet frames
- Each input/output pair of ports is a LAN
- Learning and forwarding switch among these LANs

## Element properties

- Ports: any # of inputs, and same # of outputs
- Processing: push

## Element handlers

- Table (read-only): returns port association table
- Timeout (read/write): returns/sets TIMEOUT

**http://read.cs.ucla.edu/click/elements/etherswitch**

# An Observation…

## Click is widely used

- And the paper on Click is widely cited

## Click elements are created by others

- Enabling an ecosystem of innovation

## Take-away lesson

- Creating useful systems that others can use and extend has big impact in the research community
- And brings tremendous professional value
- Compensating amply for the time and energy ☺