CS168
How the Internet Works:
A bottom-up view

Sylvia Ratnasamy

Spring 2020

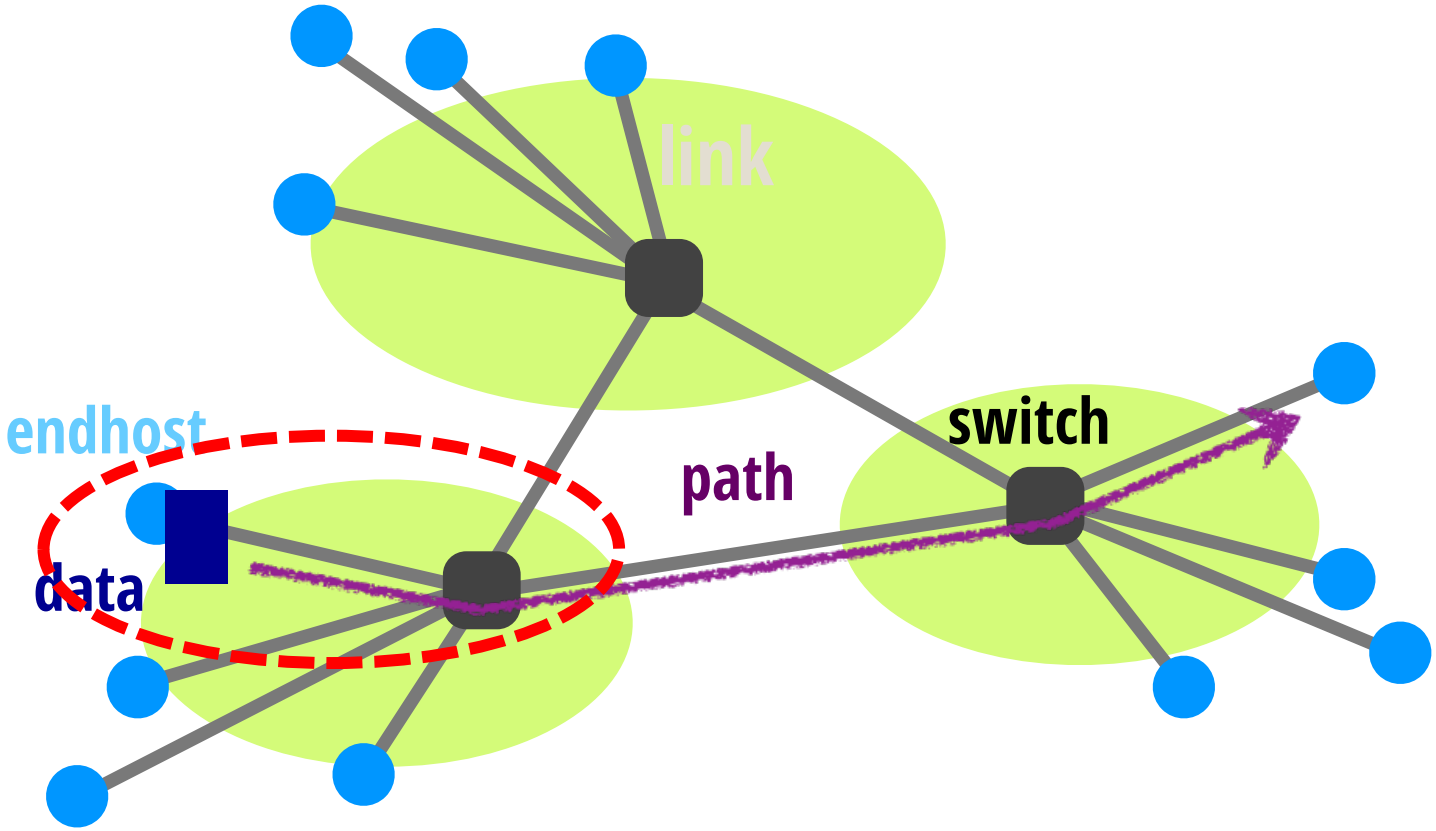
Goal for the next two lectures is to give you a broad overview of how the Internet works*

- This lecture: bottom-up
  - Identify the fundamental pieces that make up the overall picture
- Next lecture: top-down
  - Identify the important architectural choices involved in the picture together

Today

- How is data transferred across the Internet?
- How are network resources shared?
- Start understanding of the “life of a packet” through the network
- Along the way: identify the key topics we’ll be studying this semester

Recall, from last lecture



The goal of the Internet is to transfer data between end hosts

How is data organized (in the network)?

Application data

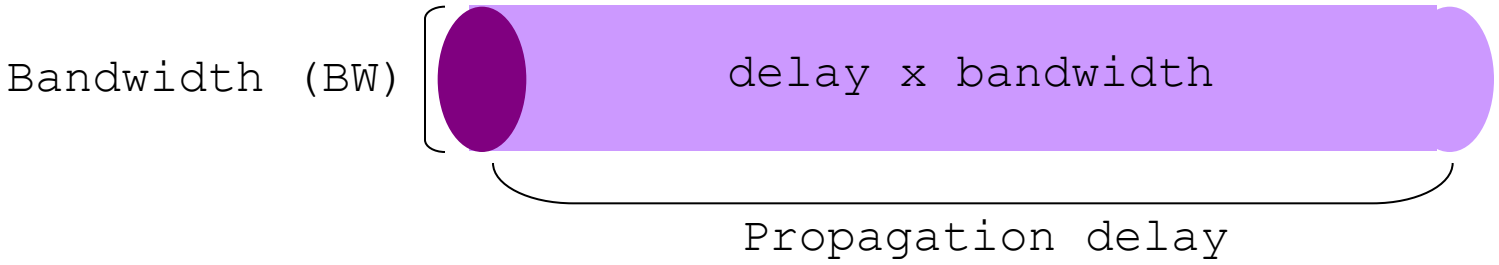
Recap: packets

- Packets are a chunk of bits with:
  - **Payload:** meaningful only to the endpoints
    - Bits from a file, video, etc.
  - **Header**: meaningful to the network *and* endpoint
    - What information must a header contain? The destination address!
- In practice, a packet has multiple headers (next lecture)
- And communication between a pair of endhosts involves multiple packets
  - "Flow": stream of packets exchanged between two endpoints (more on this later)

Packets on a link

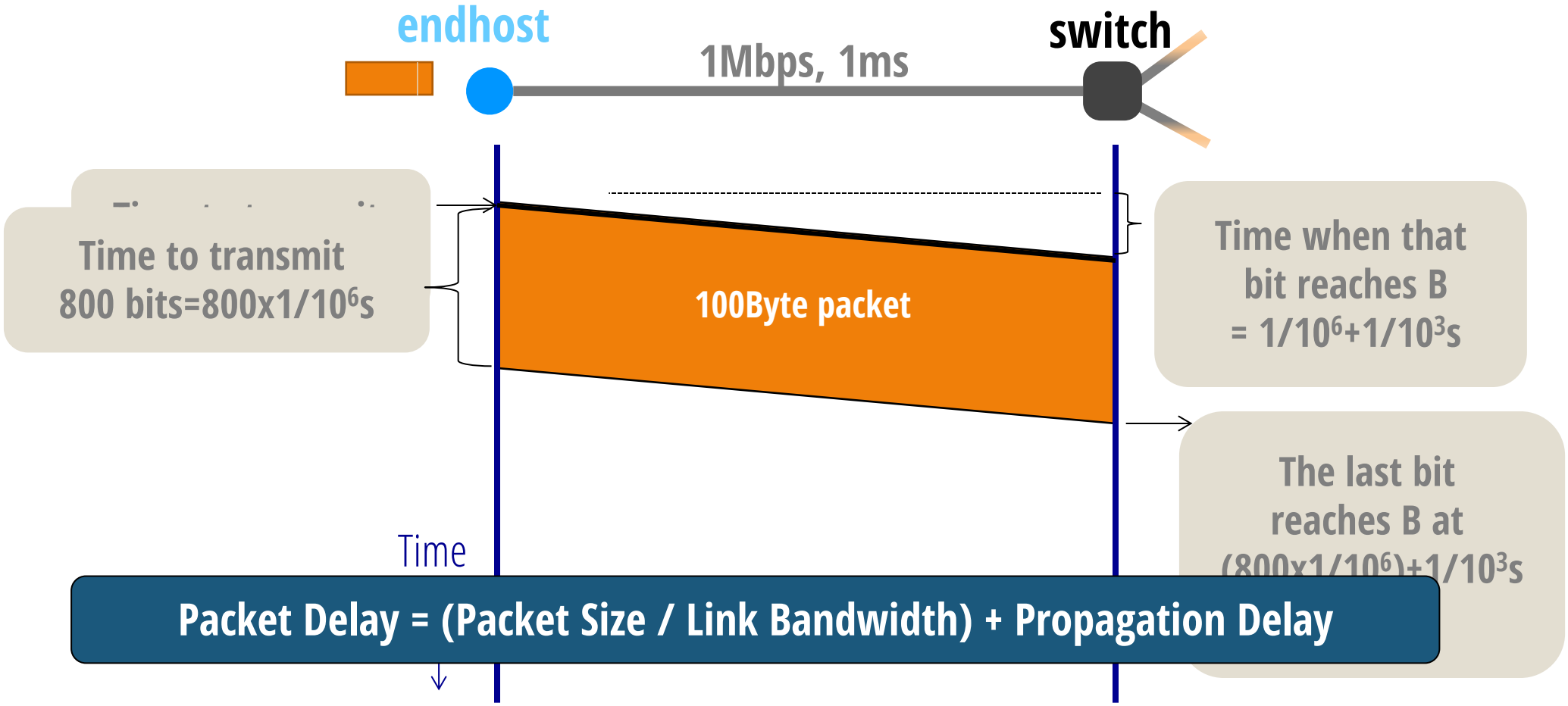
Application data

Properties of links



- **Bandwidth**: number of bits sent (or received) per unit time (bits/second or bps)
  - "width" of the link
- **Propagation delay**: time it takes a bit to travel along the link (seconds)
  - "length" of the link
- **Bandwidth-Delay Product (BDP):** bits/time `x` propagation delay (bits)
  - "capacity" of the link

Packets on a link: sending a 100B packet



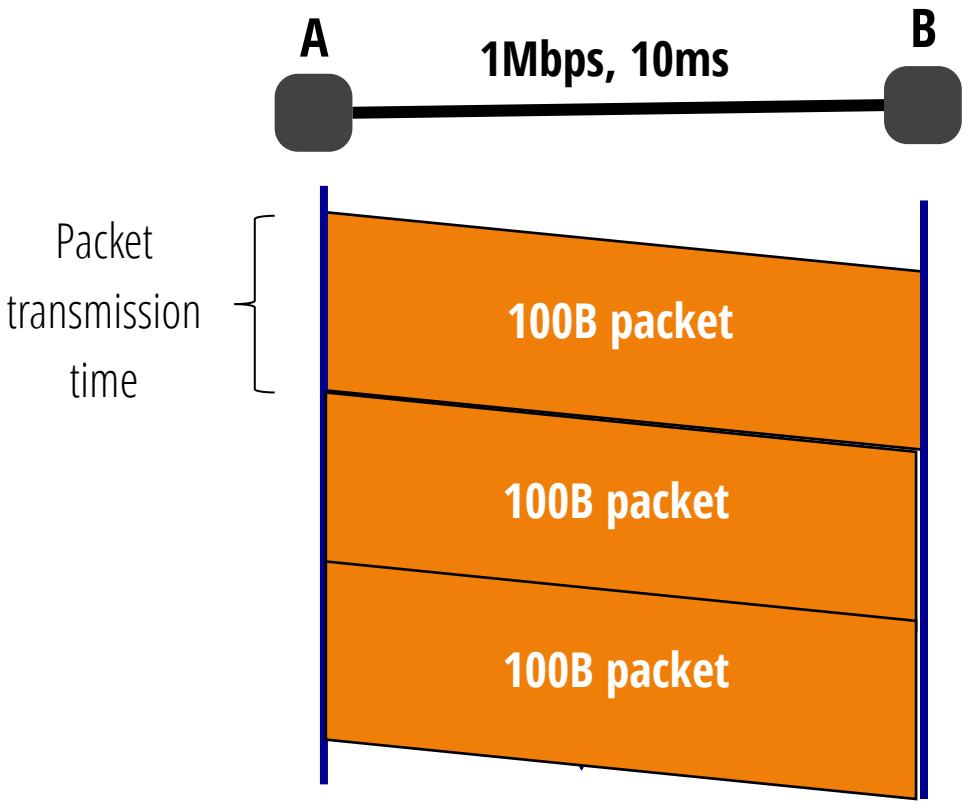
Question: which link is better?

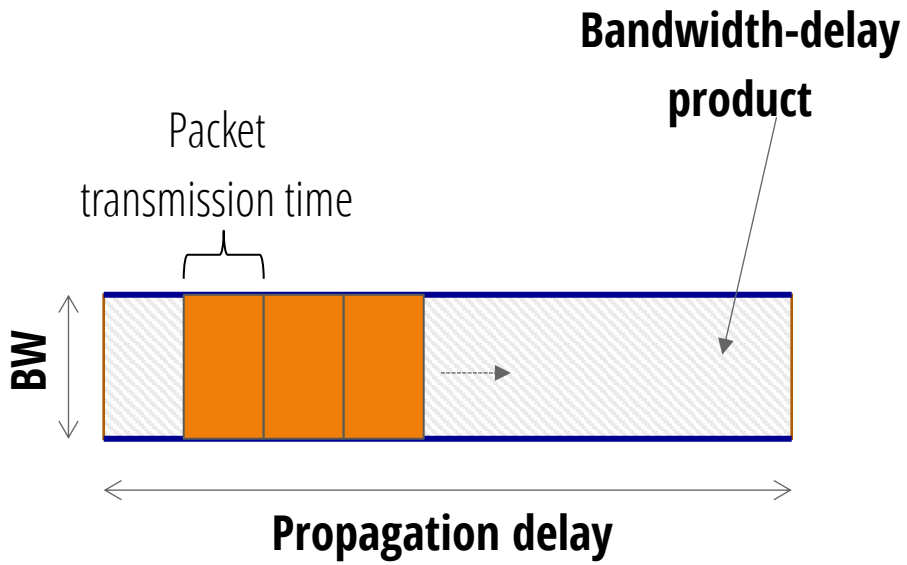
- Link-1: bandwidth=10Mbps and propagation delay = 10ms
- Link-2: bandwidth=1Mbps and propagation delay = 1ms

- Packet delay for a **10B** packet:
  - With link 1: ~10ms
  - With link 2: ~1ms
- For a **10,000B** packet:
  - Link 1: ~18ms
  - Link 2: ~81ms

Sections will cover packet delay calculations in detail

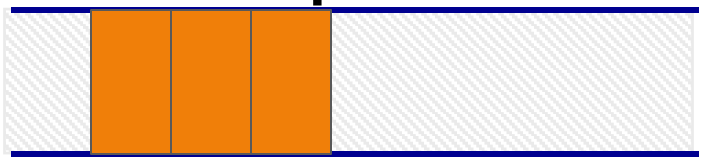
Packets on a link: an alternate “pipe” view

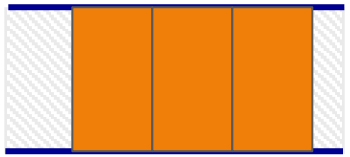




Packets on a link: an alternate “pipe” view

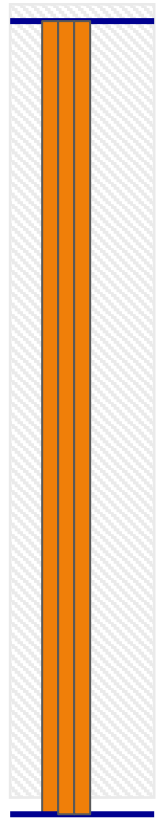
1Mbps, 10ms





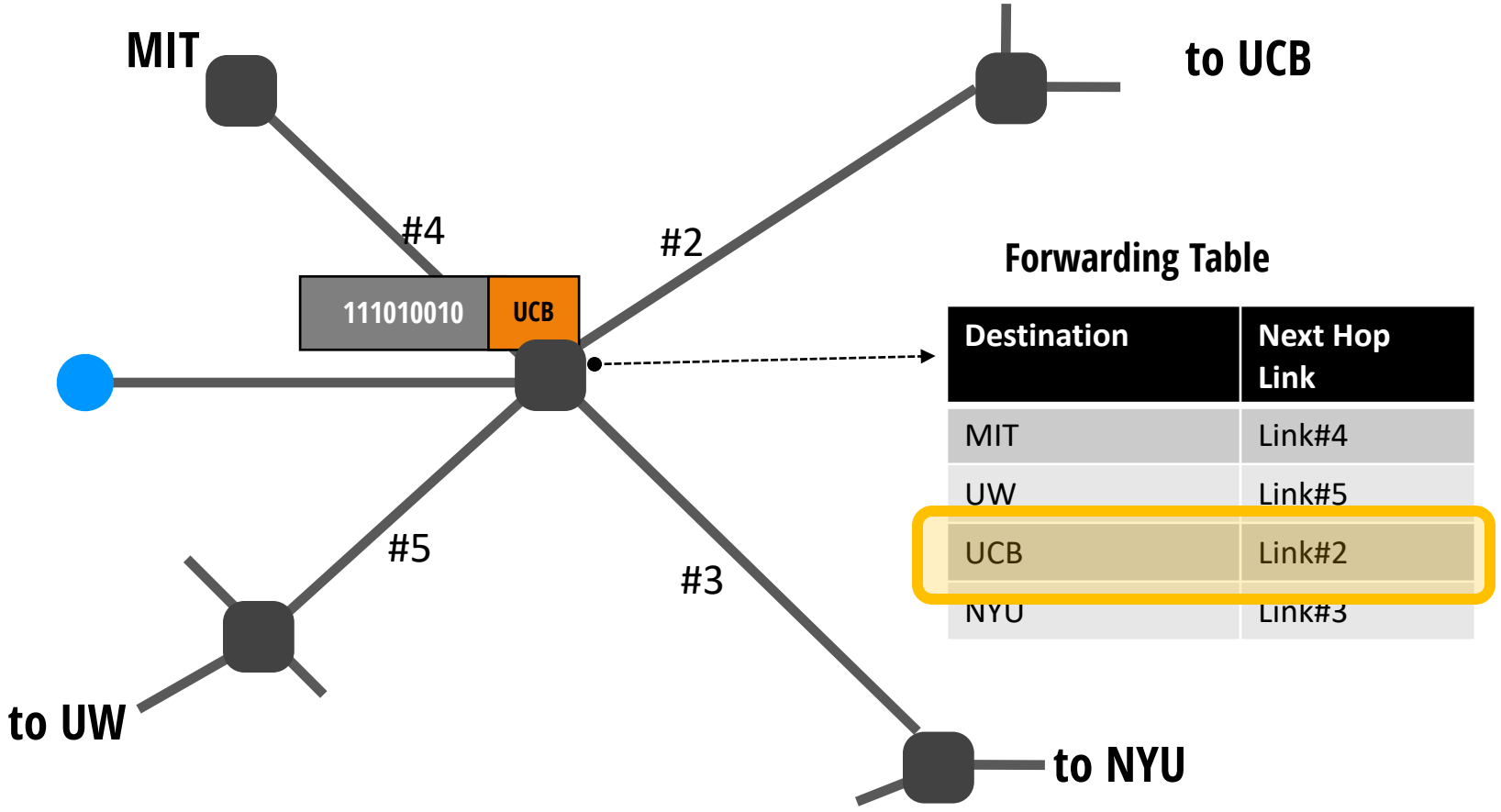
1Mbps, 5ms ?

10Mbps, 1ms ?



Recap: packet on a link

Switches “forward” packets



Forwarding Table

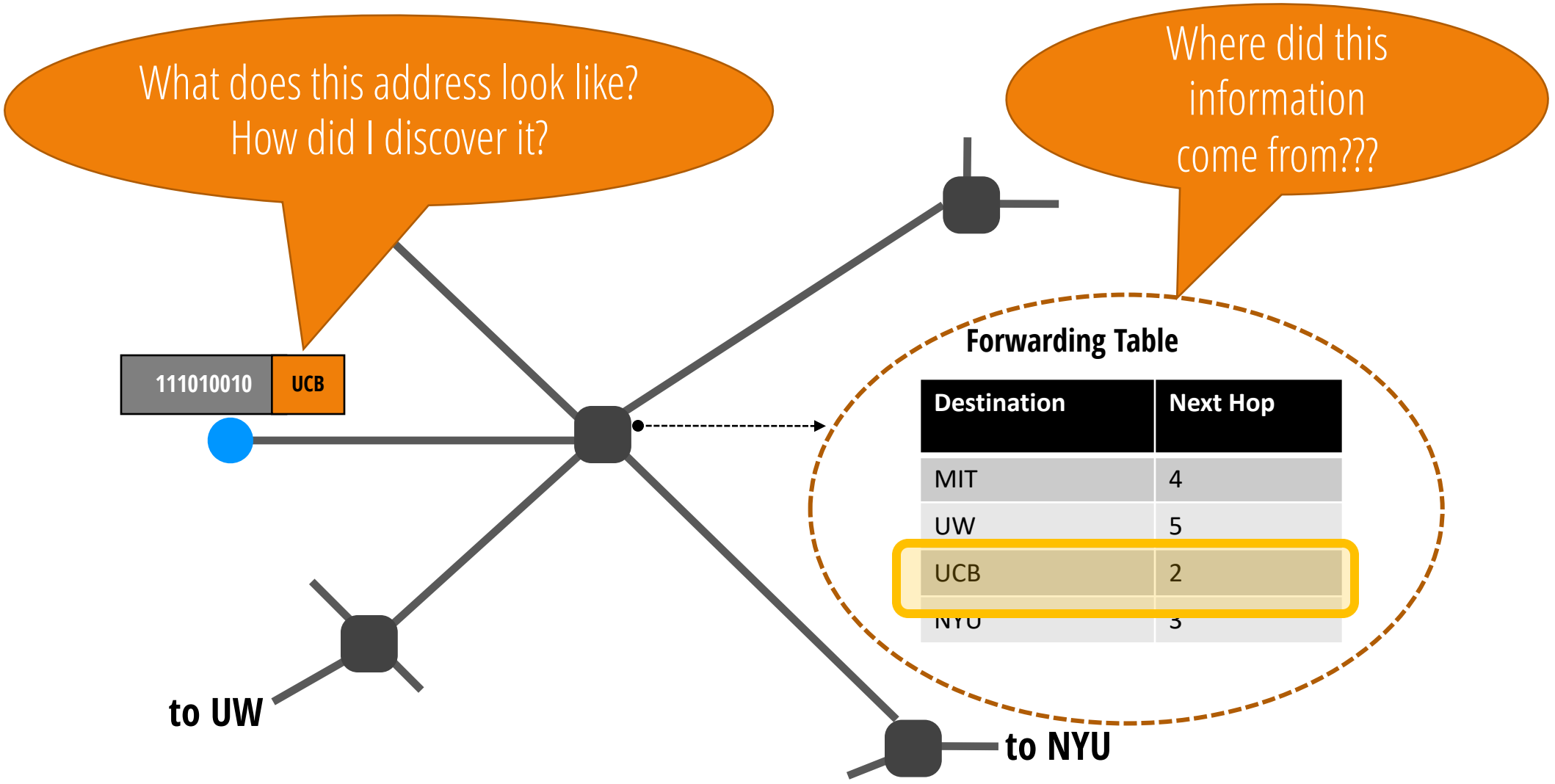
Destination	Next Hop Link
MIT	Link#4
UW	Link#5
UCB	Link#2
NYU	Link#3

Recap: life of a packet so far…

- Source has some data to send to a destination
- Chunks it up into packets: each packet has a payload and a header
- Packet travels along a link
- Arrives at a switch; switch forwards the packet to its next hop

And the last two steps repeat until we reach the destination…

What are the fundamental challenges in this?



What are the fundamental challenges in this?

Challenge: addressing and naming

- Network **address**: where host is located
- Network **name**: which host it is
- Similar to your own name and address
  - E.g., my name is Sylvia; my address is 413 Soda Hall
  - When I move to a new building: my name doesn't change but my address does
- Need an addressing and naming scheme that works at Internet scale!

Will discuss IP addressing a few lectures from now

Challenge: mapping names to addresses

- Consider when you access a web page
  - Insert URL into browser (e.g., cnn.com)
  - You send request packets to the server hosting cnn.com content and receive response packets
- How do you get to the web site?
  - URL is user-level ***name*** (e.g., cnn.com)
  - Network needs **address** (e.g., where is cnn.com?)
- Must map names to addresses….

Challenge: mapping names to addresses

- Before you can send packets to cnn.com, you must **resolve** names into the host's address

- Done by the **Domain Name System (DNS)**

Will cover DNS in a later lecture (second half of semester)

Challenge: Routing

- When a packet arrives at a router, the **forwarding table** determines which outgoing link the packet is sent on

- How do you compute the forwarding tables necessary to deliver packets?

Will devote multiple lectures (and one project) to this question!

Routing (Conceptually)

- Distributed **routing algorithm** run between switches/routers
- Gather information about the network topology
- Compute paths through that topology
- Store forwarding information in each router:
  - If packet is destined for X, send it on this link
  - If packet is destined for Y, send it on that link
  - …
- This is the **forwarding table**

Control Plane *vs* Data Plane

- Control plane: mechanisms used to compute forwarding tables
  - Inherently **global:** must know topology to compute
  - *Routing algorithm is part of the control plane*
  - Time scale: per network event

- Data plane: using those tables to actually forward packets
  - Inherently **local**: depends only on arriving packet and local routing table
  - *Forwarding mechanism is part of data plane*
  - Time scale: per packet arrival

Control Plane: Challenge

- Computing routes at scale
- In the face of network failures and topology changes

(Will study routing algorithms starting week#3)

- While respecting ISPs' need for autonomy
  - Internet is comprised of many different ISPs
  - They each get to make their own decisions about how to do routing *within* their networks
  - And they typically do not want to reveal the internals of this decision making
  - Can we ensure that ISPs' independent decisions result in usable end-to-end routes?

  (Will study BGP in depth later in the semester)

Data Plane: Challenge

- Consider a 1 Tbps link (10^{12}) receiving 10,000 bit packets
  - New packet arrives every 10 nanoseconds (10^{-8})
- The following operations must be done after packet arrives (in ~10 nanoseconds or less)
  - Parse packet (extract address, etc.)
  - Look up address in forwarding table
  - Update other fields in packet header (if needed)
  - Update relevant internal counters, etc.
  - Send packet to appropriate output link

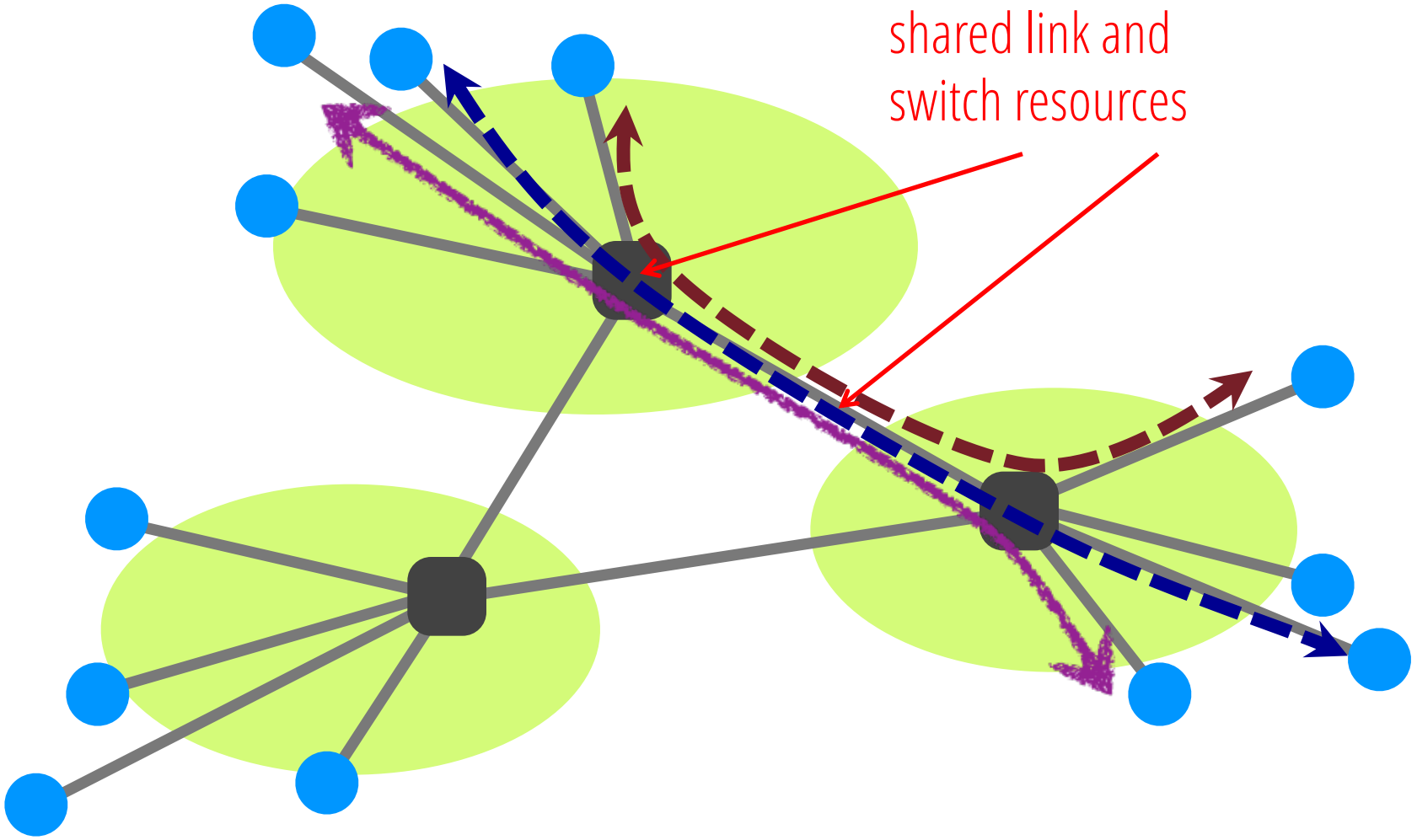
(Will study router designs and IP forwarding lookup algorithms.)

Hence, our important topics (so far)

- How do we name endhosts on the Internet? **(naming)**
- How do we address endhosts? **(addressing)**
- How do we map names to addresses? **(mapping names to addresses)**
- How do we compute forwarding tables? **(routing control plane → project 1)**
- How do we forward packets? **(routing data plane)**

Questions??

Let's back up a level...



Fundamental Fact About Networks

- Network must support many simultaneous flows at the same time
  - Recall, flow = stream of packets sent between two end hosts

- Which means network resources (links and switches) are **shared** between end hosts

Network resources (i.e., bandwidth) are statistically multiplexed

Statistical Multiplexing

- Combining demands to **share** resources efficiently
  - vs. statically partitioning resources
- Long history in computer science
  - Processes on an OS (*vs.* every process has own core)
  - Cloud computing (*vs.* everyone has own datacenter)
- Based on the premise that: peak of aggregate load is << aggregate of peak loads

Aggregates, Peaks, etc....

- Average rate of flow f: A(f)
  - Average rate of set of flows f1, f2: A(f1+f2)
- Peak rate of flow f: P(f)
  - Peak rate of set of flows f1, f2: P(f1+f2)
- Aggregate of peaks: $\Sigma_{\{f\}}$[P(f)]
- Peak of aggregate: P($\Sigma_{\{f\}}$f)
- Typically: $\Sigma_{\{f\}}$[P(f)] >> P($\Sigma_{\{f\}}$f) and P($\Sigma_{\{f\}}$f) ~ A($\Sigma_{\{f\}}$f)

Statistical Multiplexing

- Statistical multiplexing merely means that you don't provision for absolute worst case
  - When everything peaks at the same time

- Instead, you share resources and hope that peak rates don't occur at same time

How would you share network resources?

Two approaches to sharing

- **Reservations**: end-hosts explicitly reserve BW when needed (e.g., at the start of a flow)
  - Request/reserve resources
  - Send data
  - Release resources

- **Best-effort**: just send data packets when you have them and hope for the best …
  - Also known as "on demand"

How would you implement these?

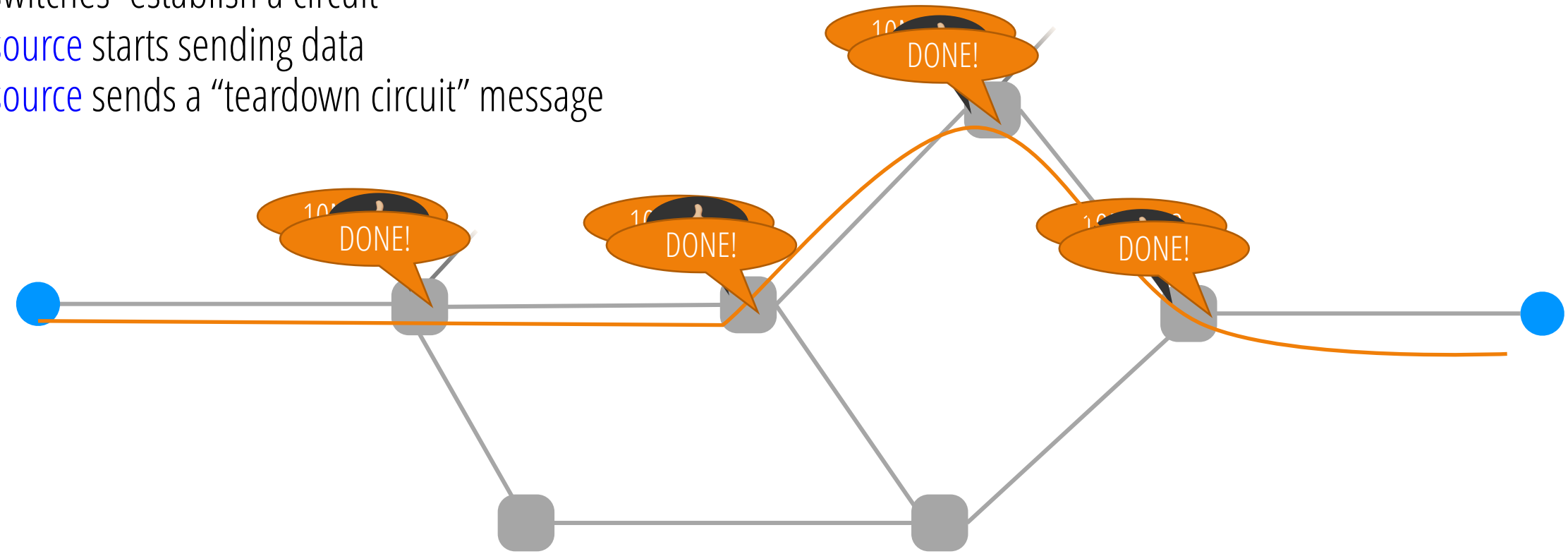
Implementing reservations / best-effort sharing

- Many possible approaches!

- Two canonical designs explored in research and industry
  - Reservations via **circuit switching**
  - Best-effort via **packet switching**

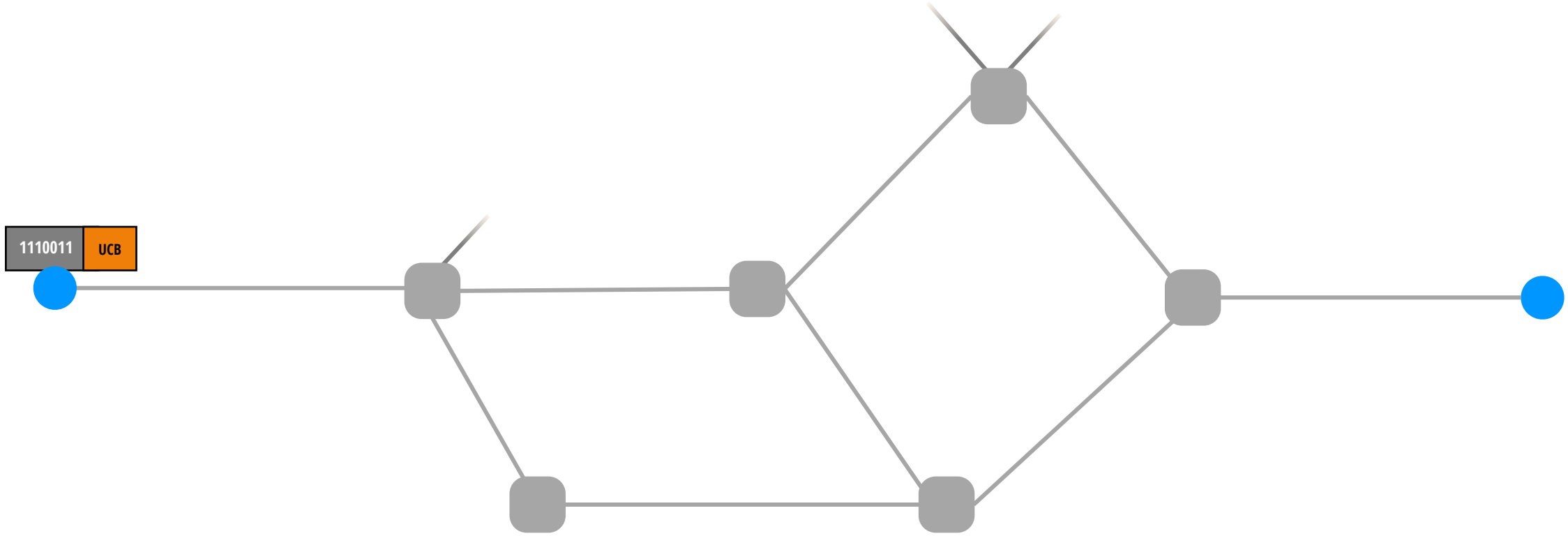
Reservations: e.g., circuit switching

(1) source sends a reservation request to the destination
(2) switches "establish a circuit"
(3) source starts sending data
(4) source sends a "teardown circuit" message



Idea: **Reserve** network capacity for all packets in a flow

Best-effort: e.g., packet switching



Allocate resources to each packet independently
(independent across switches and across packets)

Both approaches embody statistical multiplexing!

- Circuit switching: resources shared between *flows* currently in system
  - Reserve the peak demand for a flow
  - But don't reserve for all flows that might ever exist

- Packet switching: resources shared between *packets* currently in system
  - Resources given out on packet-by-packet basis
  - Never reserve resources

Circuit *vs.* Packet switching: which is better?

- What are the dimensions along which we should compare?
  - As an abstraction to applications (endhosts)
  - Efficiency
  - Handling failures
  - Complexity of implementation

From an application viewpoint

- Circuits offer better application performance (reserved bandwidth)
- More predictable and understandable (w/o failures)
- Also a very intuitive abstraction in support of business models!

Which makes more efficient use of network capacity?

- To be continued…