Today

• Wrap up our discussion of circuit & packet switching

• Start our top-down overview
Recall, from last lecture...
Recall, from last lecture...

Two canonical approaches to sharing
Recall, from last lecture...

Two canonical approaches to sharing

- Reservations: end-hosts explicitly reserve BW when needed (e.g., at the start of a flow)
Recall, from last lecture...

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• Best-effort: just send data packets when you have them and hope for the best...
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Two canonical designs to implementing these approaches
Recall, from last lecture...

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- Reservations via circuit switching
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Two canonical designs to implementing these approaches

- Reservations via circuit switching
- Best-effort via packet switching
Recall, from last lecture: circuit switching

Idea: Reserve network capacity for all packets in a flow
Recall, from last lecture: circuit switching

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Recall, from last lecture: circuit switching
Recall, from last lecture: circuit switching

Idea: Reserve network capacity for all packets in a flow
Recall, from last lecture: e.g., packet switching

Allocate resources to each packet independently
Recall, from last lecture: e.g., packet switching

Allocate resources to each packet independently
Circuit vs. Packet switching: which is better?

• What are the dimensions along which we should compare?
  • As an abstraction to applications
  • Efficiency (at scale)
  • Handling failures (at scale)
  • Complexity of implementation (at scale)
From an application viewpoint
From an application viewpoint

- Circuits offer better application performance (reserved bandwidth)
From an application viewpoint

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- More predictable and understandable behavior (w/o failures)
From an application viewpoint

• Circuits offer better application performance (reserved bandwidth)

• More predictable and understandable behavior (w/o failures)

• Also a very intuitive abstraction in support of business models
Which makes more efficient use of network capacity?
Which makes more efficient use of network capacity?

Answer: Packet switching is typically more efficient
Which makes more efficient use of network capacity?

Answer: Packet switching is typically more efficient

• But how much better depends on the “burstiness” of the traffic sources
Example#1: Three constant sources

Link capacity = 30Mbps

- Source A: 10Mbps
- Source B: 10Mbps
- Source C: 10Mbps
Example#2: Three “bursty” sources

Link capacity = 30Mbps
What happens with reservations?

Link capacity = 30Mbps

Time

12Mbps

11Mbps

13Mbps
What happens with reservations?

Allow two flows to reserve peak rate

Link capacity = 30Mbps

Time
What happens with reservations?

Allow two flows to reserve peak rate

Link capacity = 30Mbps

Must turn away third flow!
What happens with best-effort?

Link capacity = 30Mbps
What happens with best-effort?

Link capacity = 30Mbps
What happens with best-effort?

All good! No overloading

Link capacity = 30Mbps

Time
Smooth vs. Bursty Applications
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- Characterized by the ratio between an app’s peak to average transmission rate
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- Some apps have relatively small peak-to-average ratios
  - Voice might have a ratio of 3:1 or so
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  • E.g., ratios of 100 or greater are common when web browsing
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• That’s why the phone network used reservations and the Internet does not!
Which makes more efficient use of network capacity?

Answer: Packet switching is typically more efficient

• But how much better depends on the “burstiness” of the traffic sources
Other differences in efficiency?
Other differences in efficiency?

• Circuit switching spends some time to setup / teardown circuits
  • Very inefficient when you don’t have much data to send! (short flows)
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 (at scale)
  • Complexity of implementation (at scale)
What happens in the event of a failure?
What happens in the event of a failure?
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With packet switching?
What happens in the event of a failure?

With circuit switching?
What happens in the event of a failure?

With circuit switching?
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With circuit switching?
Recap: Failure Recovery in Packet Switching
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• Link goes down, then what?

• Network must detect failure
Recap: Failure Recovery in Packet Switching

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• Network recalculates routes
  • (Job of the routing control plane)
Recap: Failure Recovery in Packet Switching

- Link goes down, then what?
- Network must detect failure
- Network recalculates routes
  - (Job of the routing control plane)
- Endhosts and individual flows do nothing special
  - Except cope with the temporary loss of service
Recap: Failure Recovery in Circuit Switching

• Network must do all the things needed for packet switching
Recap: Failure Recovery in Circuit Switching

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• And in addition, endhosts must
  • detect failure
  • teardown old reservations
  • send a new reservation request
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• If millions of flows were going through a switch, then millions of reservation requests are being simultaneously re-established!
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Recall...
(1) source sends a reservation request to the destination
Recall...

(1) **source** sends a reservation request to the **destination**
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How do switches know that the reservation went through?
Recall...

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How do switches know that the reservation went through?

What happens if the reservation request is lost mid way?
Recall...

(1) source sends a reservation request to the destination

What happens if the confirmation that the reservation made it is lost?
Recall...

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What happens if the reservation request is lost mid way?

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What should the endhost do if the reservation is declined?
Recall...

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How do switches know that the reservation went through?

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What happens if the confirmation that the reservation made it is lost?

What should the endhost do if the reservation is declined?

What happens if the underlying route changes?
(1) source sends a reservation request to the destination

And on and on....
Recap: Circuit vs. Packet Switching
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• Pros for circuit switching:
  • Better application performance (reserved bandwidth)
  • More predictable and understandable (w/o failures)
Recap: Circuit vs. Packet Switching

• Pros for circuit switching:
  • Better application performance (reserved bandwidth)
  • More predictable and understandable (w/o failures)

• Pros for packet switching:
  • Better efficiency
  • Faster startup to first packet delivered
  • Easier recovery from failure
  • Simpler implementation (avoids dynamic per-flow state management in switches)
What does the Internet use today?
What does the Internet use today?

• Packet switching is the default
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• Packet switching is the default
  • Some use of RSVP (“Resource Reservation Protocol”) within one domain
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  • Often statically set up (manually), long-lived (e.g., years), and per user (vs. per flow)
  • So, a far cry from the vision of dynamic reservations that we just discussed
Circuit vs. Packet Switching: A bit of history
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A lesson in how technology can transform user behavior!
Let’s take a closer look at packet switching ....
Recall, packets in flight: “pipe” view
No Overload!
Transient Overload

Not a rare event!
Transient Overload
Not a rare event!
Queue
Queues absorb transient bursts!
What about persistent overload?
What about persistent overload?
What about persistent overload?
Will eventually drop packets
Queues introduce queuing delays

- Recall, packet delay = transmission delay + propagation delay

- With queues: packet delay = transmission delay + propagation delay + queueing delay
Recall: 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 step repeats until we reach the destination...
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• 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
  • switch may buffer, or even drop, the packet
• And the last step repeats until we reach the destination ...
  • or the packet is dropped
Hence, our fundamental topics [updated]

• 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)
• How do hosts communicate reliably? (reliable packet delivery → project 2)
• How do sources know at what rate they can send packets? (congestion control)
• Plus advanced topics (the web, SDN, cellular, datacenters, etc.)
Recap: key takeaways from our bottom-up overview

• What is a packet?

• Approaches to sharing the network – circuit vs. packet switching -- and their tradeoffs

• An overall sense of the life of a packet
  • We’ll continue to refine this picture over the course of the semester

• An overall sense of the topics we’ll be studying and why they’re fundamental
Questions??
Changing Perspective

- Designing the Internet: a top-down approach

- In the process, discuss a few enduring ideas:
  - Layering
  - The end-to-end principle
  - Fate sharing
The Internet’s problem definition

- Support the transfer of data between endhosts
- ... across multiple networks
  - The Internet
How do you solve a problem?
How do you solve a problem?

1. Decompose it (into tasks and abstractions)
How do you solve a problem?

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How do you solve a problem?

1. Decompose it (into tasks and abstractions)
2. Assign tasks to entities (who does what)
Modularity

*Modularity based on abstraction is the way things are done*

– Barbara Liskov, Turing lecture
What is Modularity?
What is Modularity?

- Decomposing systems into smaller units
  - Providing a “separation of concerns”
What is Modularity?

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- Plays a crucial role in computer science...
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- Decomposing systems into smaller units
  - Providing a “separation of concerns”

- Plays a crucial role in computer science…

- The challenge is to find the right modularity
Network Modularity
Network Modularity

- The need for modularity still applies
Network Modularity

- The need for modularity still applies
  - And is even more important!
Network Modularity

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- Normal modularity organizes code
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  • Also distributed across many devices (hosts, routers)
Network Modularity

• The need for modularity still applies
  • And is even more important!

• Normal modularity organizes code

• But network implementations are not just distributed across many lines of code…
  • Also distributed across many devices (hosts, routers)
  • … and different players (clients, server, ISPs)
How do we decompose the job of transferring data between end-hosts?
Inspiration…
Inspiration...

- CEO A writes letter to CEO B
  - Folds letter and hands it to administrative aide

  Dear Sundar,

  Your days are numbered.

  -- Satya
Inspiration…

- CEO A writes letter to CEO B
  - Folds letter and hands it to administrative aide
Inspiration…

- **CEO A writes letter to CEO B**
  - Folds letter and hands it to administrative aide

- **Aide:**
  - Puts letter in envelope with CEO B’s full name
  - Takes to FedEx
Inspiration…

- **CEO A writes letter to CEO B**
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- **Aide:**
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- **FedEx Office**
  - Puts letter in larger envelope
  - Puts name and street address on FedEx envelope
  - Puts package on FedEx delivery truck
Inspiration…

- **CEO A writes letter to CEO B**
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- **FedEx Office**
  - Puts letter in larger envelope
  - Puts name and street address on FedEx envelope
  - Puts package on FedEx delivery truck
- **FedEx delivers to other company**
The Path of the Letter

CEO
Aide
FedEx

CEO
Aide
FedEx
The Path of the Letter

CEO

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• “Peers” understand the same things
The Path of the Letter

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- “Peers” understand the same things
The Path of the Letter

- “Peers” understand the same things
- No one else needs to

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The Path of the Letter

- “Peers” understand the same things
- No one else needs to
- Lowest level has most “packaging”
Thought Experiment
Thought Experiment

- How would you break the Internet into tasks?
- Just focus on what is needed to get packets between processes on different hosts....
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Thought Experiment

- How would you break the Internet into tasks?

- Just focus on what is needed to get packets between processes on different hosts....

- Do not consider application or control tasks
  - Naming, computing forwarding tables, etc.
Breakdown into Tasks
Breakdown into Tasks

- Bits across a link
Breakdown into Tasks

- Bits across a link
- Packets across a link
Breakdown into Tasks

- Bits across a link
- Packets across a link
- Deliver packets across local network
  - Local addresses
Breakdown into Tasks

- Bits across a link
- Packets across a link
- Deliver packets across local network
  - Local addresses
- Deliver packets across multiple networks
  - Global addresses
Breakdown into Tasks

- Bits across a link
- Packets across a link
- Deliver packets across local network
  - Local addresses
- Deliver packets across multiple networks
  - Global addresses
- Deliver data reliably
Breakdown into Tasks

- Bits across a link
- Packets across a link
- Deliver packets across local network
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- Deliver packets across multiple networks
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- Deliver data reliably
- Do something with the data
Breakdown into Tasks

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Breakdown into Tasks

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  - Local addresses
- Deliver packets across multiple networks
  - Global addresses
- Deliver data reliably
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In the Internet: organization
In the Internet: organization

Physical transfer of bits
In the Internet: organization

- Best-effort local *packet* delivery
- Physical transfer of bits
In the Internet: organization

Best-effort *global* packet delivery

Best-effort local *packet* delivery

Physical transfer of bits
In the Internet: organization

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A layered architecture

- Layer = a part of a system with well-defined interfaces to other parts
A layered architecture

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- One layer interacts only with layer above and layer below
A layered architecture

- Layer = a part of a system with well-defined interfaces to other parts
- One layer interacts only with layer above and layer below
- Two layers interact only through the interface between them
In the Internet: organization

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In the Internet: organization

Applications

...built on...

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Physical transfer of bits
In the Internet: organization

Applications
  ...built on...
Reliable (or unreliable) data delivery
  ...built on...
Best-effort global packet delivery
  ...built on...
Best-effort local packet delivery
  ...built on...
Physical transfer of bits

L7
Application
L4
Transport
L3
Network
L2
Datalink
L1
Physical

nope, not a typo
The Open Systems Interconnect (OSI) model developed by the International Organization for Standardization (ISO) included two additional layers that are often implemented as part of the application.
Questions?