CS 43: Computer Networks
The Network Layer

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Some background...

• 1968: DARPA.net/ARPAnet (precursor to Internet)
  – (Defense) Advanced Research Projects Agency Network
  – Bob Taylor, Larry Roberts create program to build first wide-area packet-switched network

• Mid 1970’s: new networks emerge
  – SATNet, Packet Radio, Ethernet
  – All “islands” to themselves – didn’t work together

• Big question: how to connect these networks?
Internetworking

• Cerf & Kahn, in 1974, “A Protocol for Packet Network Intercommunication” – Foundation for the modern Internet

• **Routers** forward **packets** from source to destination – May cross many separate networks along the way

• All packets use a common **Internet Protocol** – *Any* underlying data link protocol – *Any* higher layer transport protocol
DARPAnet Primary Goal: Connect Stuff

• “Effective technique for multiplexed utilization of existing interconnected networks” – David Clark (1988)

  – Minimal assumptions about underlying networks
    • No support for broadcast, multicast, real-time, reliability
    • Extra support could actually get in the way
  – Packet switched, store and forward
    • Matched application needs, nets already packet switched
    • Enables efficient resource sharing/high utilization
  – “Gateways” interconnect networks
    • Routers in today’s nomenclature
Internet Protocol Stack

- Application: Email, Web, ...
- Transport: TCP, UDP, ...
- Network: IP
- Link: Ethernet, WiFi, ATM, ...
- Physical: copper, fiber, air, ...

- “Hourglass” model, “thin waist”, “narrow waist”
Internet Protocol Stack

• This should seem weird.

• *Everyone* uses IP?

• “Hourglass” model, “thin waist”, “narrow waist”
Example of Internet Routing

Network layer involved at every hop along the path.
Network Layer Functions

- **Forwarding:** move packets from router’s input to appropriate router output (“data plane”)

- **Routing:** determine route taken by packets from source to destination. (“control plane”)

When should a router perform routing? Forwarding?

A. Do both when a packet arrives.

B. Route in advance, forward when a packet arrives.

C. Forward in advance, route when a packet arrives.

D. Do both in advance.

E. Some other combination
Network Layer Functions

- **Forwarding**: move packets from router’s input to appropriate router output
  - Look up in a table

- **Routing**: determine route taken by packets from source to destination.
  - Populating the table
Each packet is forwarded independently. Does it have to be that way?
Circuit Switching

- Reserve path in advance

- (Old) telephone system
Why doesn’t the Internet (typically) use circuits?

A. It’s too slow to establish a connection.

B. It doesn’t offer good enough performance.

C. It wastes resources.

D. It requires too many resources.

E. Some other reason.
Packet Switching

• Do we always need to reserve a link?

• **Statistical multiplexing**
  – Assign multiple conversations to a physical path
  – At any given time, one will have something to say
Which of the following is/are generally true of packet vs. circuit switching?

1. Packet switching has less variance in performance.
2. Circuit switching is less reliable.

A. Only 1 is true.
B. Only 2 is true.
C. Both 1 and 2 are true.
D. Neither 1 nor 2 are true.
Circuit-switching vs. Packet switching

- Circuit switching: establish path, send data
  - Reserve resources, provide performance control
  - Example: telephone system
- Packet switching: forward packets hop by hop
  - Fair sharing despite bursts, statistical multiplexing
  - Example: postal system
Datagram vs. “Virtual Circuit”

• *Datagram* network provides network-layer *connectionless* service (packet switching)

• *Virtual-circuit* network provides network-layer *connection* service (like circuit switching)
Virtual circuits: Signaling Protocols

- Used to setup, maintain, teardown VC
- Used in ATM, frame-relay, X.25
- Less common in today’s Internet
Datagram Networks

• No call setup at network layer
• Routers: no state about end-to-end connections
  ▪ no network-level concept of “connection”
• Packets forwarded individually towards destination

1. send datagrams
2. receive datagrams
How do we populate a router’s forwarding table?

A. A person adds entries to the table.

B. A program external to the router adds entries to the table.

C. Routers communicate with each other to add entries to the table.

D. Some other mechanism.
Routing

**Traditional**

- Routers run a *routing protocol* to exchange state.

- Use state to build up the forwarding table.

Assume this is the type of routing we’re talking about unless we explicitly say otherwise!
Routing

Traditional

• Routers run a routing protocol to exchange state.

• Use state to build up the forwarding table.

“Software-Defined”

• Routers are dumb, just do what they’re told.

• Controller service explicitly tells each router what to do.

• Rare on the Internet, hot topic in data centers.
Datagram Forwarding

• Routers periodically exchange state.

• Use the state to build a forwarding table (FIB)
Datagram forwarding table

- IP destination address in arriving packet’s header
- Local forwarding table
<table>
<thead>
<tr>
<th>dest address</th>
<th>output link</th>
</tr>
</thead>
<tbody>
<tr>
<td>?</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Routing algorithm
Routers exchange state (we’ll save the what and when for later). They decide, for each destination, how to get there, and build a lookup structure. What should they build?

A. A list – scan for the destination.

B. A hash table – look up the destination.

C. A tree – Follow branches that lead to the destination.

D. Some other software structure.

E. We can’t do this in software, we need special hardware.
Datagram forwarding table

- IP destination address in arriving packet’s header

Local forwarding table:

<table>
<thead>
<tr>
<th>dest address</th>
<th>output link</th>
</tr>
</thead>
<tbody>
<tr>
<td>address-range 1</td>
<td>3</td>
</tr>
<tr>
<td>address-range 2</td>
<td>2</td>
</tr>
<tr>
<td>address-range 3</td>
<td>2</td>
</tr>
<tr>
<td>address-range 4</td>
<td>1</td>
</tr>
</tbody>
</table>

Routing algorithm

4 billion IP addresses, so rather than list individual destination address, list range of addresses (aggregate table entries)
### Datagram forwarding table

<table>
<thead>
<tr>
<th>Destination Address Range</th>
<th>Link Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111</td>
<td>0</td>
</tr>
<tr>
<td>11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111</td>
<td>1</td>
</tr>
<tr>
<td>11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111</td>
<td>2</td>
</tr>
<tr>
<td>Otherwise (default gateway)</td>
<td>3</td>
</tr>
</tbody>
</table>

**Q:** but what happens if ranges don’t divide up so nicely?
Longest prefix matching

When looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

<table>
<thead>
<tr>
<th>Destination Address Range</th>
<th>Link interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>11001000 00010111 00010*** **********</td>
<td>0</td>
</tr>
<tr>
<td>11001000 00010111 00011000 **********</td>
<td>1</td>
</tr>
<tr>
<td>11001000 00010111 00011*** **********</td>
<td>2</td>
</tr>
<tr>
<td>Otherwise (default gateway)</td>
<td>3</td>
</tr>
</tbody>
</table>

Examples:

DA: 11001000 00010111 00010110 10100001 which interface?
DA: 11001000 00010111 00011000 10101010 which interface?
Routing

Traditional
- Routers run a **routing protocol** to exchange state.
- Use state to build up the forwarding table.

“Software-Defined”
- Routers are dumb, just do what they’re told.
- Controller service explicitly tells each router what to do.
- Rare on the Internet, hot topic in data centers.

Coming up in ~1 week.
Software-Defined Networking (SDN)

Traditional Hardware

SDN Hardware

You can't read this. It's too small. Seriously, stop trying to read this. More important things are happening elsewhere!
Software-Defined Networking (SDN)

Traditional Hardware

SDN Hardware

Controller

Right
Right

You can't read this, it's too small! Seriously, stop trying to read this, more important things are happening elsewhere!
Summary

- Forwarding: moving packet from one interface to another (table lookup)
- Routing: Populating the table in advance
- On the Internet, best effort packet switching is the norm
- Hardware helps with quick forwarding using longest prefix matching