The Internet (part 1 of 2)

Global Internet: One of Humanity’s Greatest Achievements

We looked at Wifi and cellular. Now we know how our data get to the Internet.

But what is the Internet?

How does information pass through it?

In a list of human accomplishments in the last century, the Internet is probably near the top.

Tradeoffs: Pros and Cons of a Design

Today, you get to be an engineer!

Actually,

• today we will focus on

• design tradeoffs

• as we consider different ways

• in which communication networks can be connected.

View Internet Development in Terms of Tradeoffs

Organization of a network—

• which machine connects to which other machine—

• called the topology of the network.

We’ll compare benefits and disadvantages of different topologies

• to understand how Internet developed

• and what problems it solves.
From Computation to Communication

We will talk about the Internet from the ground up.
In our first week,
◦ we talked about bits
◦ and the emergence of computing.
At the same time,
◦ other people were wondering
◦ how results could be communicated.

Physical Layer (Wiring) Took Substantial Effort

A lot of research went into developing the physical wires needed to communicate.

Modern Ethernet Leveraged the Telephone Infrastructure

Today’s Ethernet is much easier to use.
Ethernet cable contains ◦ four twisted pairs of copper wire.
◦ Each pair carries a voltage (bits).
For decades, telephones
◦ used a single pair of the same type
◦ to connect phones throughout the home.

How Do We Connect Many Computers?

Why not just connect everyone?
How Many “Wires” Needed for a Clique?

Connecting everyone to everyone else produces a topology known as a clique. How many “wires” do we need?

- 6 “wires”
- 12 “wires”

2 “wires” (one in each direction)

Requirements and Limitations for a Clique Topology

Generalize: how many “wires” for N computers?

To count,
1. choose one computer (N choices), then
2. choose a different computer (N – 1 choices).

Total possible choices? \(N(N – 1)\) “wires” *

Limitations of a clique? Too many wires! And too many network interfaces.

*Wires usually only used in one direction, but two can be packaged in one cable, so divide by two for the number of cables.

Sharing Reduces Wire and Interface Count

Ethernet was originally a shared medium. Just 1 “wire”—in yellow, labeled “The Ether”—in the diagram—for all computers!

The Same Six Computers on a Shared Ethernet

The Ether
Which is Better? A Shared Network or a Clique?

Consider a small group (10-20 computers).

**Build a clique or a shared network?**

**Pros of sharing:**
- cheaper wiring
- fewer network interfaces
  (one per computer instead of 9-19)

**Pros of a clique:**
- simpler physical protocols
- no need to take turns
- simultaneous all-to-all communication

Ethernet solved these issues.

Neither Technique Scales to Large Numbers

What if we have 1,000 computers?

Neither clique topologies nor shared networks scale to large numbers.

**Don’t want to pay for a clique** (999 wires and 999 network cards per computer!)

But **sharing is also not viable:**
- imagine a room with 1,000 people all speaking
- with voices amplified to be audible to all.

**What has been done in other contexts?**

Airline Routes Must Also be Efficient

I fly from Champaign.
I need to go to many large cities.
And many smaller ones.
I want to fly directly.

**Why can’t I?**

*Hint: everyone wants to fly directly!*

**Not enough passengers for flights!**

Hierarchy Connects All Cities More Efficiently

What do the airlines do instead?
Use a hierarchy.

Designate hub cities.
Route flights hierarchically.
Champaign to Chicago (hub) to Denver (hub) to Dallas (hub) to Columbia
User of Hierarchy Permeates Natural and Human Systems

Hierarchy used ubiquitously in large systems.
Examples in nature include:
- trees (trunk, branch, smaller branch, leaf),
- roots (main root, smaller, and smaller), and
- blood vessels.
Examples in human-made systems include:
- airline routes (international, domestic, regional),
- corporate structures (CEO, VPs, directors, managers, workers) and
- power networks.

One Level of Hierarchy: a Star Topology

Instead of a clique, let’s use a hierarchy.

We’ll build a “star”.

Star Topology Between Shared Network and a Clique

In a star, all data pass through the hub.
Benefits (relative to clique or shared):
- fewer wires and interfaces than a clique, but
- no sharing required.
Disadvantages (to clique):
- paths a little slower than a clique (longer, and require processing by hub), and
- hub may still be a bottleneck to communication.

The “Hub” in a Computer Network is a Router

But we don’t need a monitor nor a keyboard.

A router forwards data packets (routes).
Hierarchies Can be Organized Hierarchically!

But why stop there?

We can use several levels of hierarchy.

More Levels of Hierarchy are Possible

Tradeoffs: One Level or Two Levels?

Why bother?

Compared with a single level of hierarchy,

- the main benefit is that
  - delay gets better for close nodes.

The disadvantages include:

- more routers (more cost),
- more interfaces (routers need them, too),
- and longer paths have more delay.

Can Keep Adding Layers of Hierarchy

We can do it recursively! (over and over)
Deep Hierarchies Enable Networks to Span the Globe

If we keep adding levels, the network can get really huge!

What Happens When We Want to Join?
Imagine a hierarchical network here on campus.
We connect the top of our hierarchy to a router in the bigger network in Chicago.
Not just one link!
We connect to two routers instead—maybe a second node in Indianapolis.

Making Connections from UIUC to the World

The Valley

d Build locally, then connect to someone else.

Design Topologies to Minimize the Impact of Failures

What about failures?
Which link failures in the previous diagram disconnect groups of computers?
Lots!
But not all.
How can we connect our networks so that the network is reliable?
Real topologies are designed to reduce the impact of failures.
Real Failures Can Still be Catastrophic

In practice, it's not as reliable as one hopes.

About 15 years ago, a backhoe dug up (and broke) the optical fibers running from our campus to Chicago.

Internet traffic almost instantly shifted to route through Indianapolis.

Although we had paid for that connection, the router in Indianapolis didn’t expect any traffic.

After all, UIUC never sent any traffic that way.

The Internet was down for days at UIUC.

One More Link Can Have a Huge Impact

Now astronauts can watch Netflix!

Plumbing: the Invisible Infrastructure

Do you care about your plumbing?

You should say, “Absolutely!”

But how often do you think about your plumbing?

Plumbing is an invisible infrastructure: you only think about it when it fails.

So we often talk about infrastructure that works well as “plumbing.”

Optical Fiber and Tier 1 ISPs Form the Backbone

What about the “plumbing” in the Internet?

Governments (in the US, for example)

- own* the right-of-ways along which companies lay bundles of optical fiber.

Tier 1 Internet Service Providers (ISPs)

- build or lease these fibers
- to carry traffic
- across the Internet.

These form the backbone of the Internet.

*Purchased in the 19th century to lay railroads across the continent.
Tier 1 ISPs Carry Transit Traffic for Lower Tiers

Tier 1 ISPs cover
- different parts of the country
- and/or world (sometimes overlapping).

They peer with one another:
- connect in several places and
- agree to carry data traffic for one another.

Tier 2 and 3 ISPs Connect Directly to Customers

Tier 2 ISPs
- connect to Tier 1 ISPs and
- provide service in smaller regions,
- carrying some transit traffic, but
- not as much as Tier 1.

Tier 3 ISPs
- connect to Tier 2 ISPs and are fairly local.
- They do not carry transit traffic, only passing packets from their customers up to the Tier 2 ISPs (and back).

Send Data Packets Across the Internet!

Once it’s all connected,
- you can send packets of bits
- to any machine on the Internet!

How?
You just need an IP address!
For example, here’s one for ece.illinois.edu

Every Computer Has a Unique IP Address

An Internet Protocol (IP) address
- is 4 Bytes (32 bits)
- Humans write 130.126.151.19,
- but in the computer, it’s
- 1000 0010 0111 1110 1001 0111 0001 0011
- (without the spaces).

Every computer in the Internet has an IP address.*

*Sort of. Today, a household usually shares one public address.
Sending is Easy: Attach an Address and Send it Off!

To send a birthday photo to your friend in Tokyo, your computer finds their computer's IP address and puts it into a packet with the photo, then pushes the packet into the Internet.

Each router along the way sees the IP address and knows where to send it until it arrives at your friend's computer!

Then their computer unpacks the photo bits.

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Routers Forward Data Packets Based on IP Address

When a data packet arrives at a router, the router must decide on which outgoing link/network interface to forward the packet.

The router looks at two things:
1. destination IP address in packet,
2. and its forwarding table (also called a routing table).

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Routers Advertise IP Addresses They Can Reach

A forwarding table maps
- IP addresses into interface numbers (1, 2, or 3, for example).

Routers periodically advertise IP address ranges that they can reach to their other links.

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Forwarding Table Built from Advertisements

Each router builds its forwarding table based on the advertisements it hears from its neighbors.

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An organization’s network—including ISPs—is called an Autonomous System (AS).

### Forwarding Between ASs Considers Only Reachability

**Routing between ASs**
- uses the Border Gateway Protocol (BGP),
- but each AS measures cost differently.

So BGP makes **forwarding decisions**
- based on reachability:
  - can I get to the destination?

Full paths (hop-to-hop AS routes) are advertised to avoid loops.

### Let’s Try Some Forwarding Together

A packet arrives for Northwestern University (in Chicago, IL, USA).
**Which interface?** 2

A packet arrives for Tokyo University (in Tokyo, Japan).
**Which interface?** 1

A packet arrives for UIUC.
**Which interface?** 3? Or 2? 3

Usually, the more specific answer is chosen.

### Routing Within AS Based on Link Costs

Within an AS, **each link** can be assigned a cost.

Link cost may reflect
- length (delay),
- link capacity,
- congestion (queueing delay),
- any combination of those metrics,
- or just the AS’s preferences.
To construct a forwarding table, a router must **decide** which path to follow to reach each other node.

The **cost of a path** is the **sum of the costs of the links** in the path.

And the **desired path** is the path with the **smallest cost**.

**Routing Within AS Based on Link Costs**

Let's Find Routes Together!

Complete the forwarding table for the node S.

(by "hops": all link costs are 1)

<table>
<thead>
<tr>
<th>dest</th>
<th>interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>2</td>
</tr>
<tr>
<td>M</td>
<td>1</td>
</tr>
</tbody>
</table>

Let's Find Routes Together!

Complete the forwarding table for the node S.

A little trickier this time?

<table>
<thead>
<tr>
<th>dest</th>
<th>interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>?</td>
</tr>
</tbody>
</table>

How Many Paths Must We Consider?

How many paths are possible? 4

- Path cost = 3 + 8 + 5 = 16
- Path cost = 4 + 8 + 7 = 19
- Path cost = 3 + 7 = 10
- Path cost = 4 + 5 = 9
Let’s Find Routes Together!

Complete the forwarding table for the node S.
A little trickier this time?

Build a Spanning Tree for Each Destination

In practice, we build a tree starting from the destination.
What node is closest to D?
F at distance 3
And the closest to that pair?
B at distance 4
And …

Let’s Find Routes Together!

Complete the forwarding table for destination D from the node S.
(Prof. Roy Choudhury made it!)

Let’s Find Routes Together!

Complete the forwarding table for destination D from the node S.
(Prof. Roy Choudhury made it!)
**Logically Separated Data and Control Planes**

Routers forward packets.
- Packets with data are said to be passing through the data plane.

In addition to forwarding packets,
- routers exchange information about routes available to them.
- These coordination messages travel through the control plane.

The two planes
- use the same physical network
- (except within a single router),
- but are logically separate.

**Terminology You Should Know from These Slides**

- design tradeoffs
- network topology
- Ethernet
- clique topology
- network interface
- shared network
- hierarchy
- star topology
- router
- Internet Service Providers (ISPs; Tier 1,2,3)
- Internet backbone
- peering
- Transit traffic
- IP address
- forwarding
- Route advertisements
- Routing (building forwarding table)
- Autonomous System (AS)
- Border Gateway Protocol (BGP)
- Internet backbone
- peering
- Transit traffic
- In addition to forwarding packets,
- routers exchange information about routes available to them.
- These coordination messages travel through the control plane.

The two planes
- use the same physical network
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**Internet Plumbing: Routing and Forwarding**

Routers have established a control plane between themselves.

And have populated their forwarding tables.

This is the plumbing in the Internet.

**Concepts You Should Know from These Slides**

- engineers must consider tradeoffs between alternative designs
- number of “wires” needed for a clique
- tradeoffs: clique vs. shared vs. hierarchy
- hierarchy appears in all large systems, both natural and human-made
- how topology affects tolerance to failures
- packets only allowed to cross Tier 1 & 2 ISPs (transit traffic)
- each computer has a 4B IP address
- how a router uses its forwarding table
- routers forward packets in data plane and send route advertisements in control plane
- how to find shortest paths in small graphs