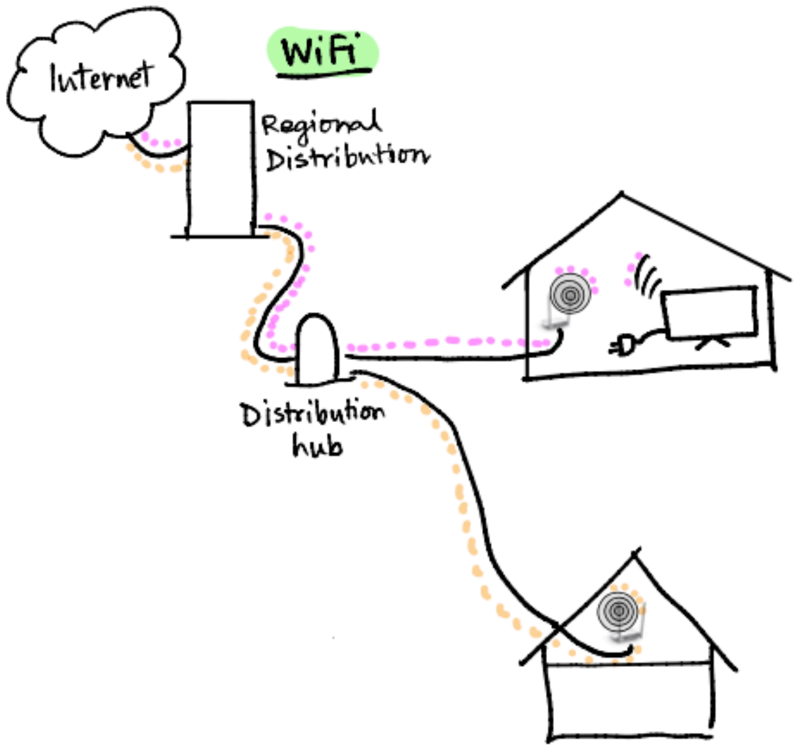
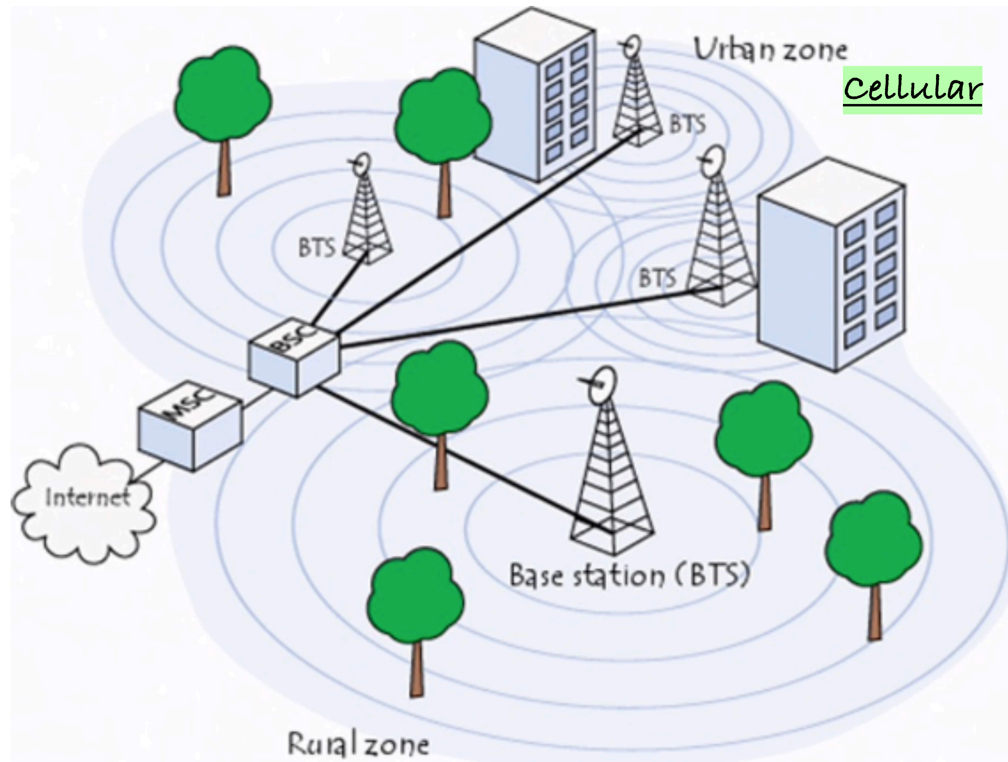
University of Illinois at Urbana-Champaign
Dept. of Electrical and Computer Engineering

ECE 101: Exploring Digital Information Technologies

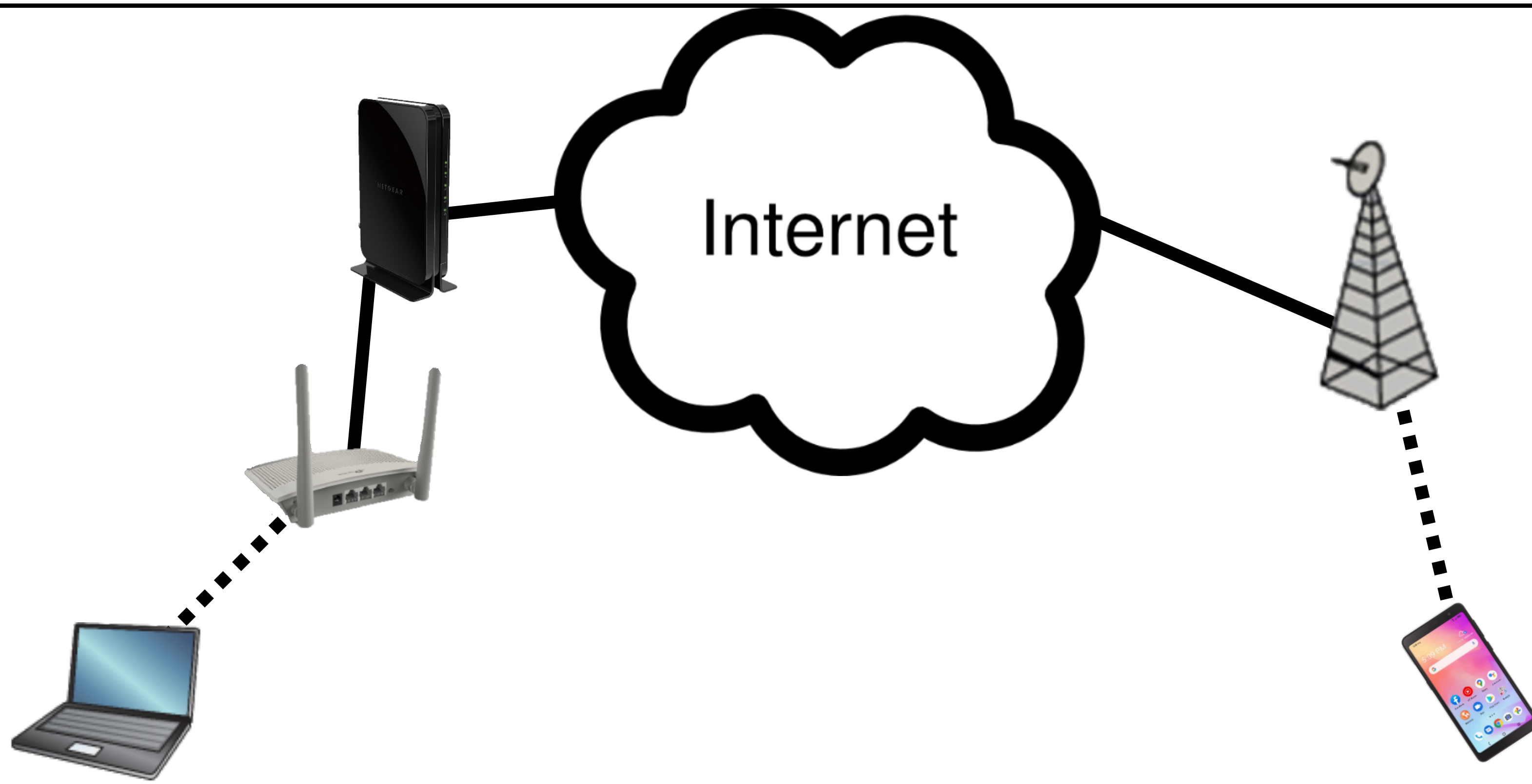
The Internet
(part 1 of 2)

So far we've looked at …





Basically two ways for you two connect to the …



Global Internet: One of Humanity's Greatest Achievements

"The internet is a design philosophy
and architecture
expressed as a set of protocols"

-Vint Cerf

How do you connect a network?

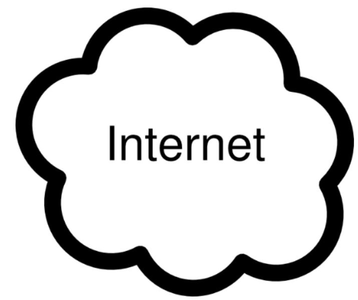
Let's

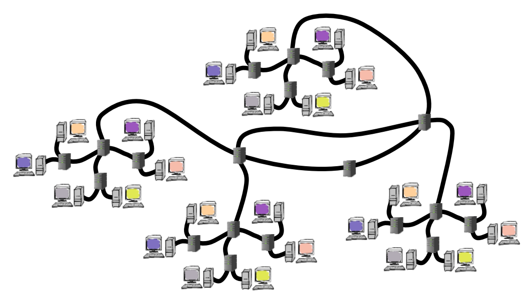
- **focus on design tradeoffs**
- as we consider different ways
- in which communication networks can be connected.

Design Problem

To create a network, we must decide—

- **How to connect one machine to another**
- Design the **topology of the network**.





From Computation to Communication

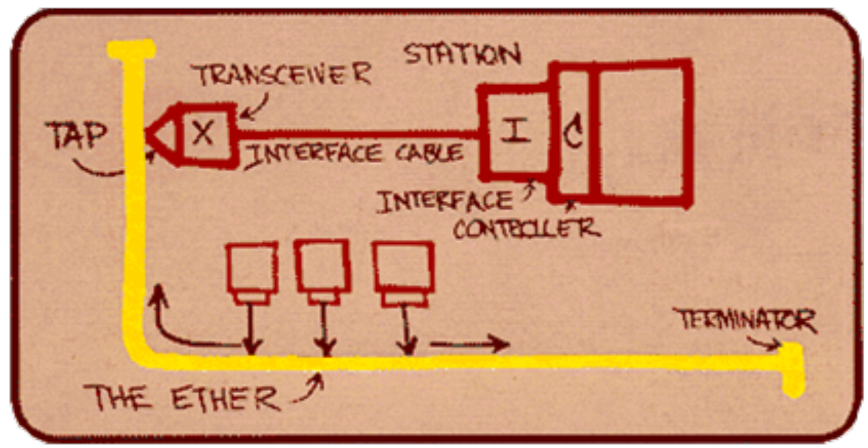
In our first week,
- we talked about bits
- and the emergence of computing.

At the same time,
- other people were wondering
- how computation results could be communicated.

Physical Layer (Wiring) Took Substantial Effort

A lot of research went into developing the physical wires needed to connect computers so they could communicate.

early Ethernet cable

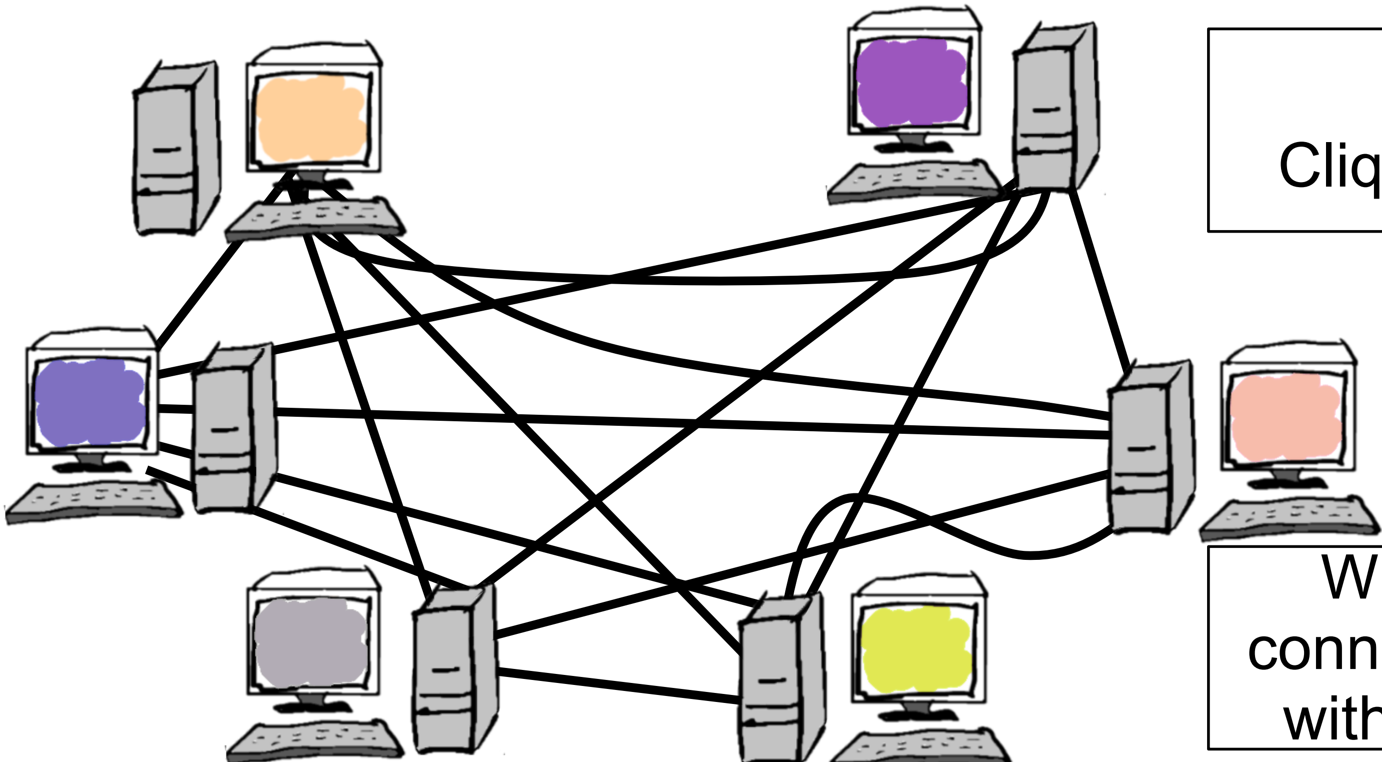


shared Ethernet topology

Network Topologies

Once we could connect computers….

The question was “How do we connect many computers?”



Make a Clique topology

Why not just connect everyone with everyone?

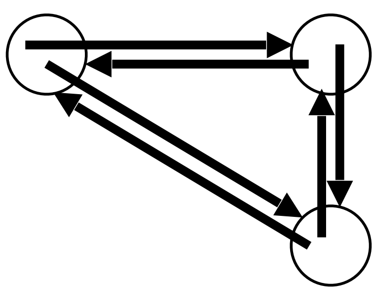
How Many "Wires" Needed for a Clique?

How many "wires" do we need?

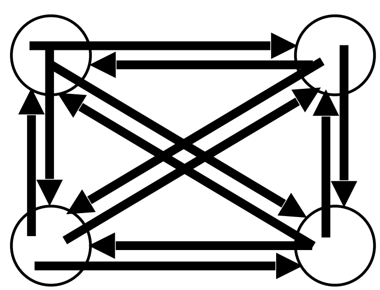
2 "wires"

(one in each direction)

6 "wires"



12 "wires"



How many "wires" for 6 computers?

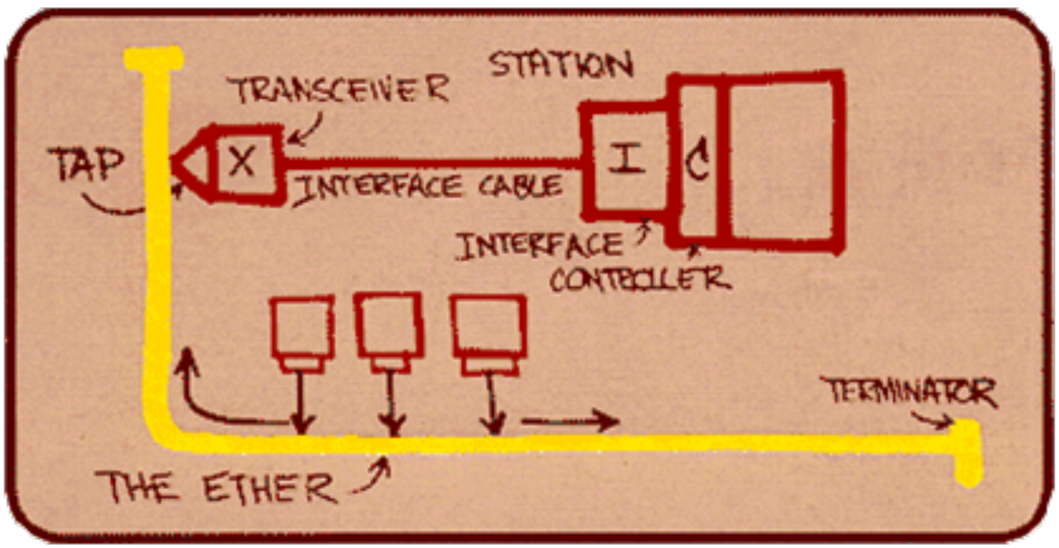
30

Too many!!

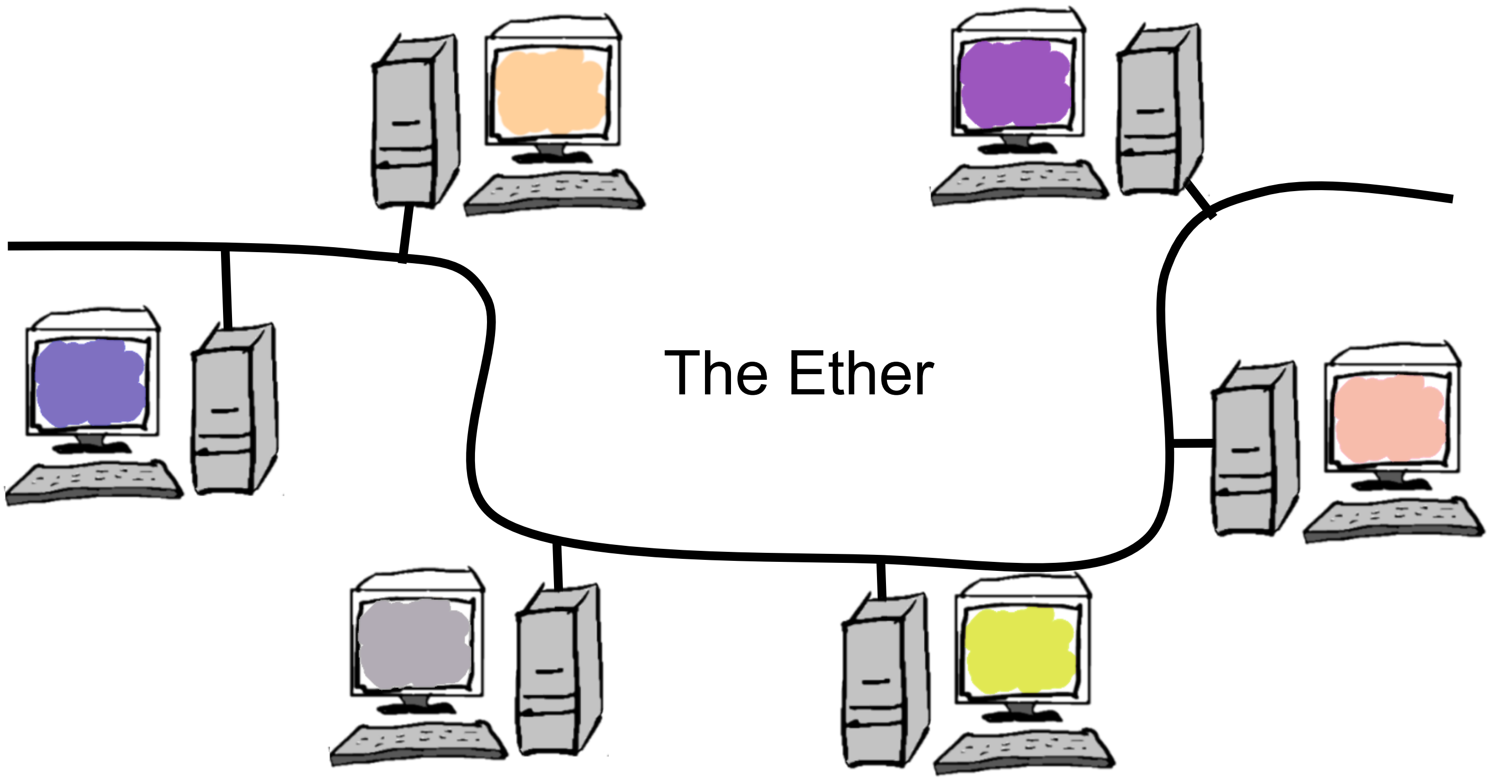
Sharing Reduces Wire and Interface Count

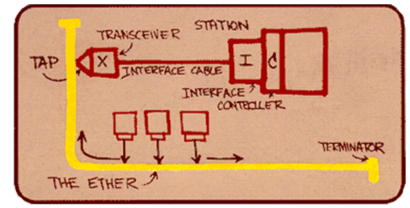
Ethernet was originally a **shared medium**.

- Just **1 "wire"**—in yellow, labeled "The Ether" in the diagram
- **for all computers**!



The Same Six Computers on a Shared Ethernet

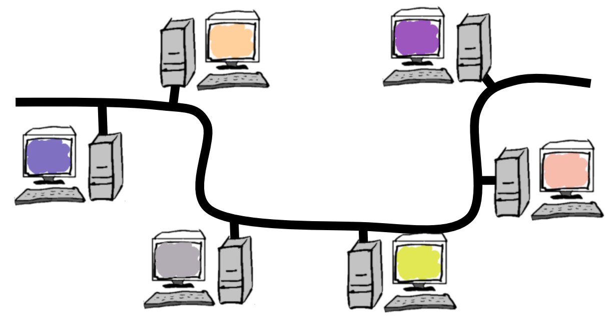




Which is Better? A Shared Network or a Clique?

Consider a small group (~~10-20 computers~~). 1000

Build a clique or a shared network?



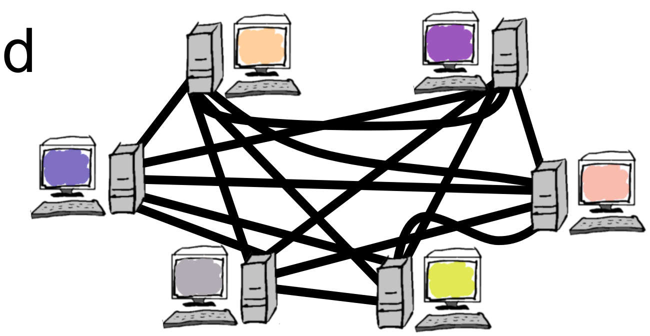
pros of sharing:

- 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

With 1,000 computers …

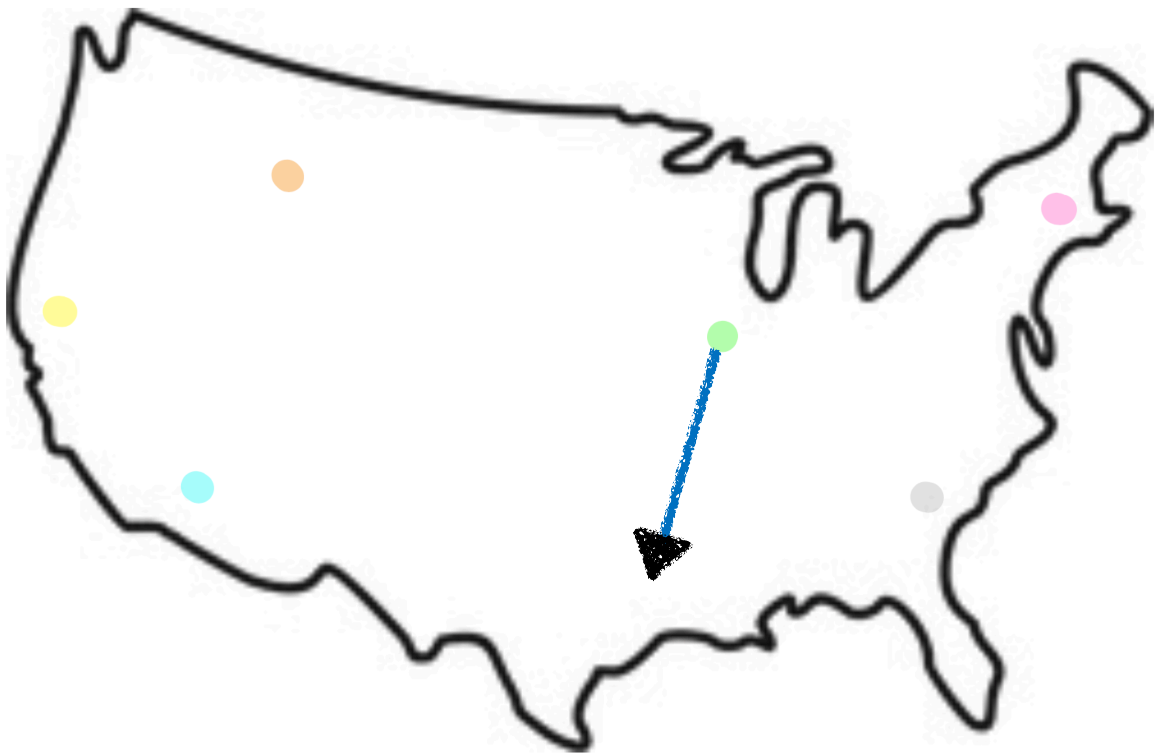
Neither **clique topologies** nor **shared networks** scale to large numbers.

- **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 could be done?

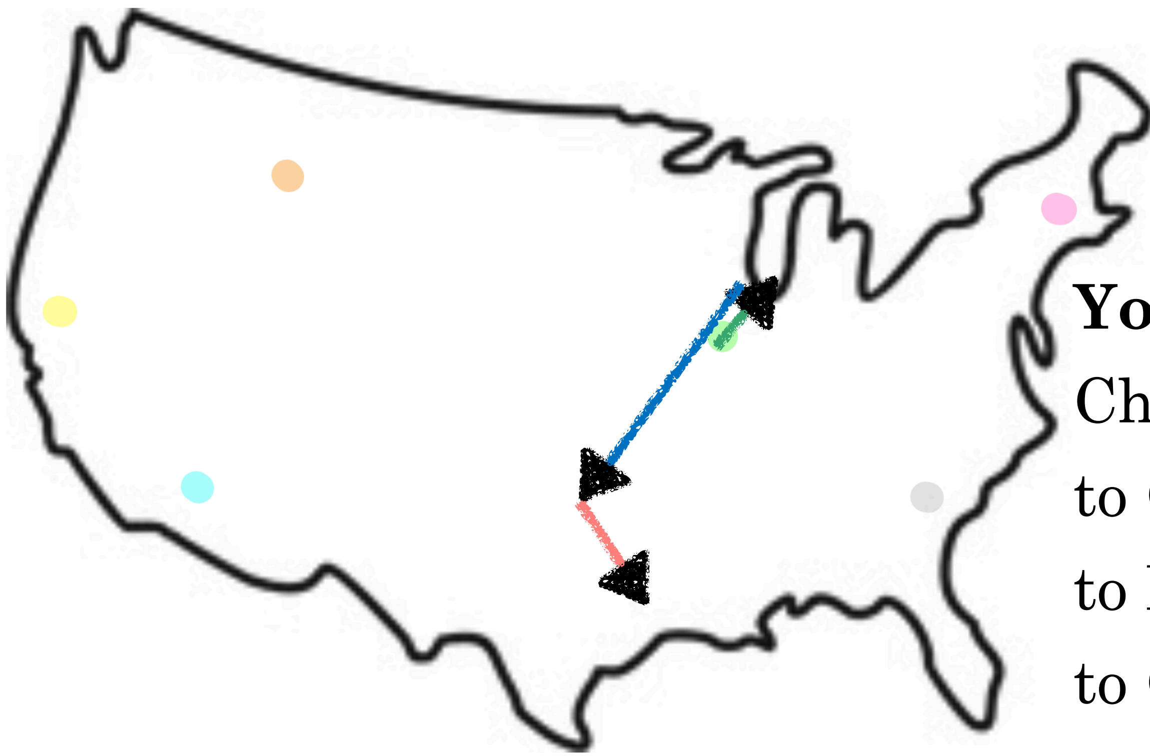
What comes to your mind looking at this picture?

Direct flights would be nice!!



Not enough passengers for flights!

Instead …



You fly from …

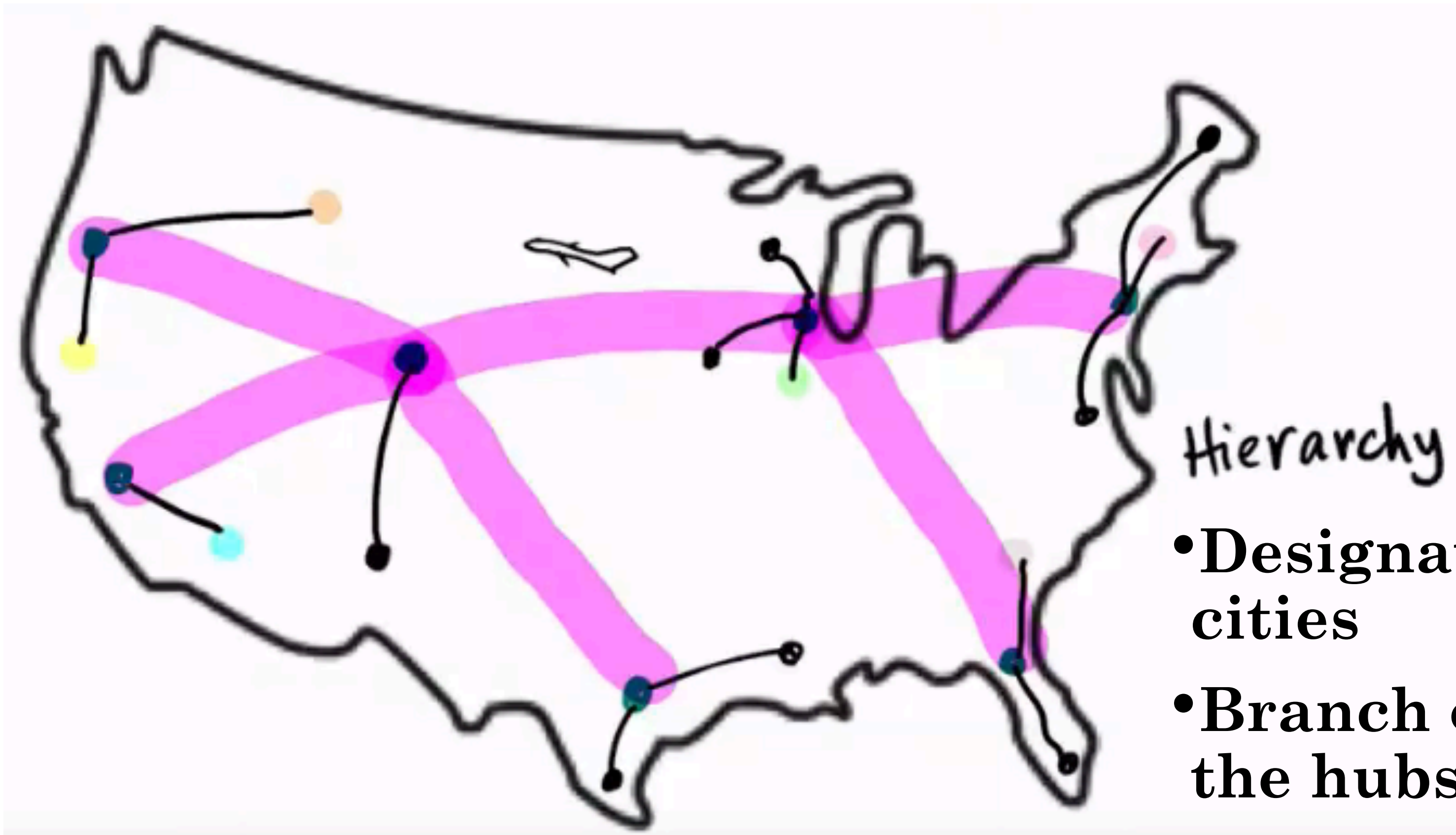
Champaign

to Chicago (hub)

to Dallas (hub)

to College Station

The solution is in creating a ….

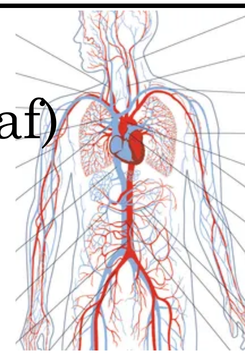


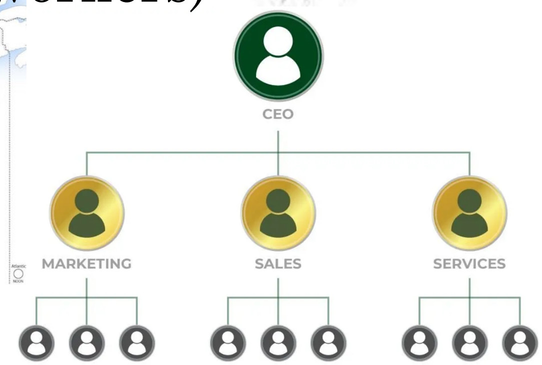
- Designate hub cities
- Branch off from the hubs

Use of Hierarchy Permeates Natural and Human Systems

Examples in nature include:
- tree branches (trunk, branch, smaller branch, leaf)
- roots (main root, smaller, and smaller)
- blood vessels.

Examples in man-made systems include:
- airline routes (international, domestic, regional),
- corporate structures (CEO, VPs, directors, managers, workers)
- power supply networks.





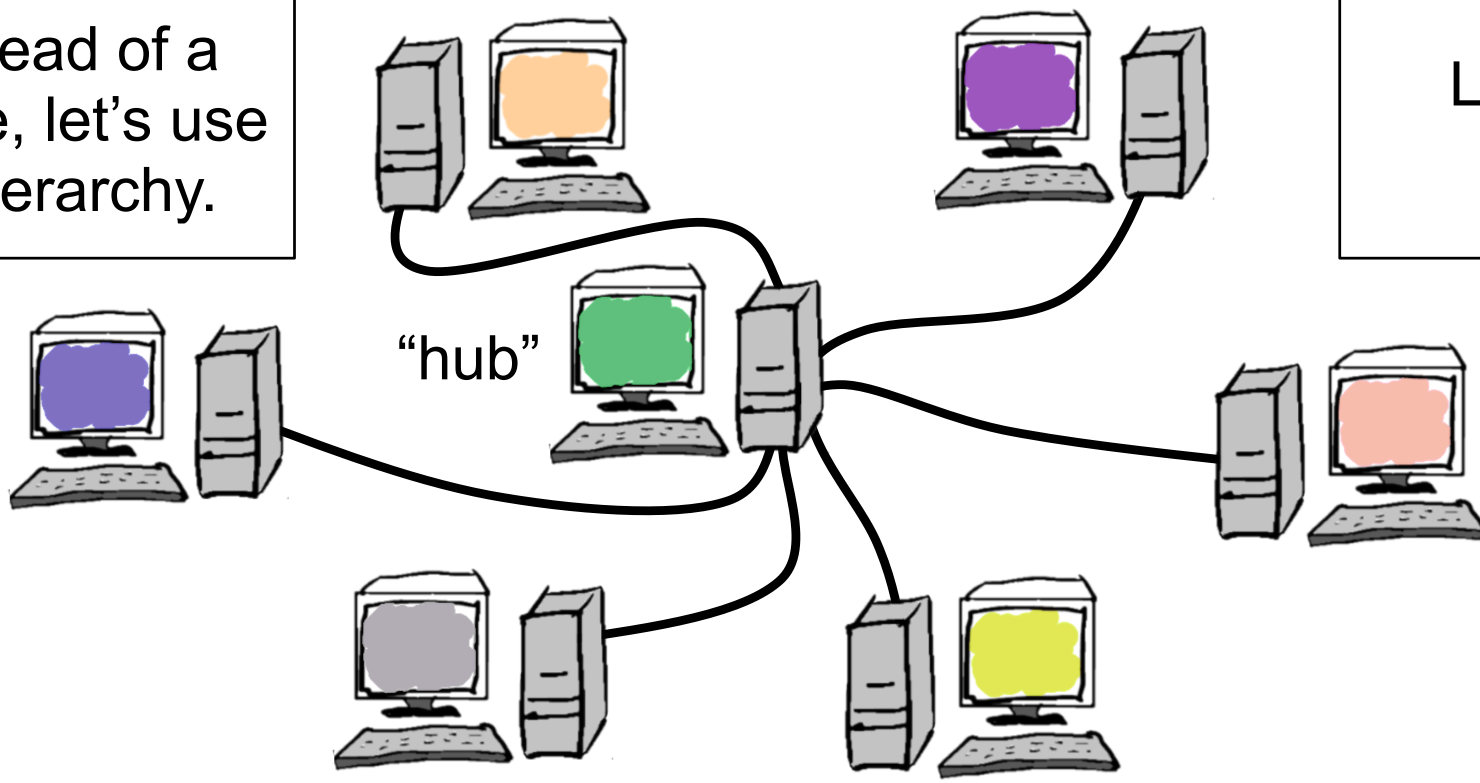
Can you think of an example of hierarchy in connecting different entities?

The Network as a Hierarchy

One Level of Hierarchy: The Star Topology

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

Let's build a "star".



Star Vs. Shared Network or Clique

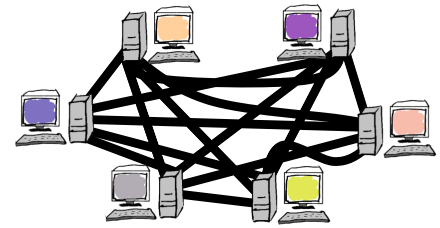
In a star, **all data pass through the hub**.

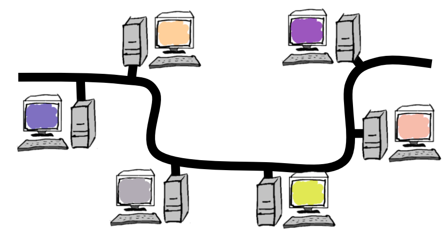
Pros:

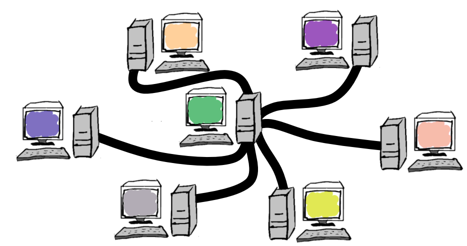
- Fewer wires and interfaces than a clique
- No sharing (of the ether) required.

Cons:

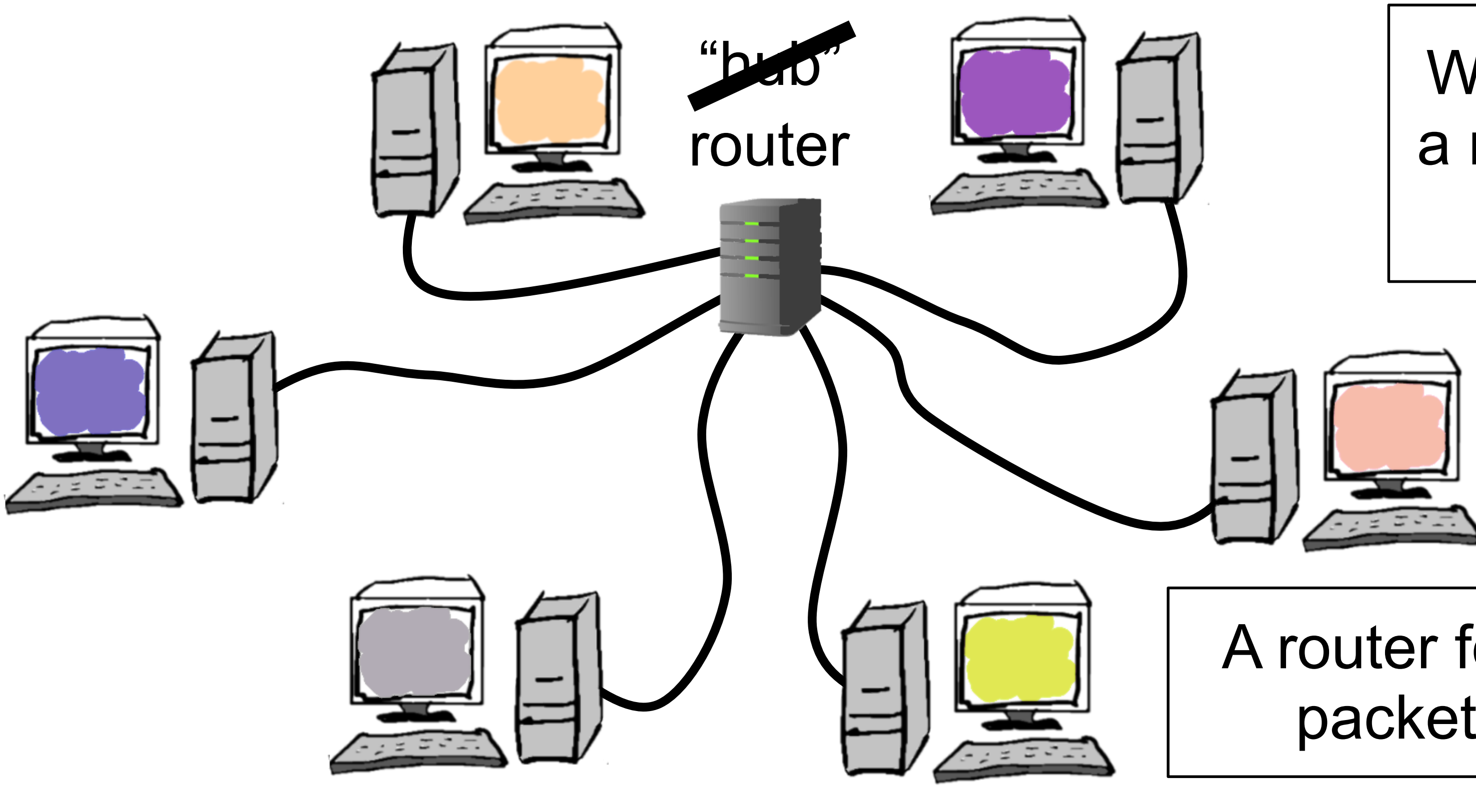
- Paths can be a little slower than direct connection in a clique
(longer, and require processing by hub)
- Hub may become a bottleneck







The “Hub” in a Computer Network is a Router



We don’t need a monitor nor a keyboard.

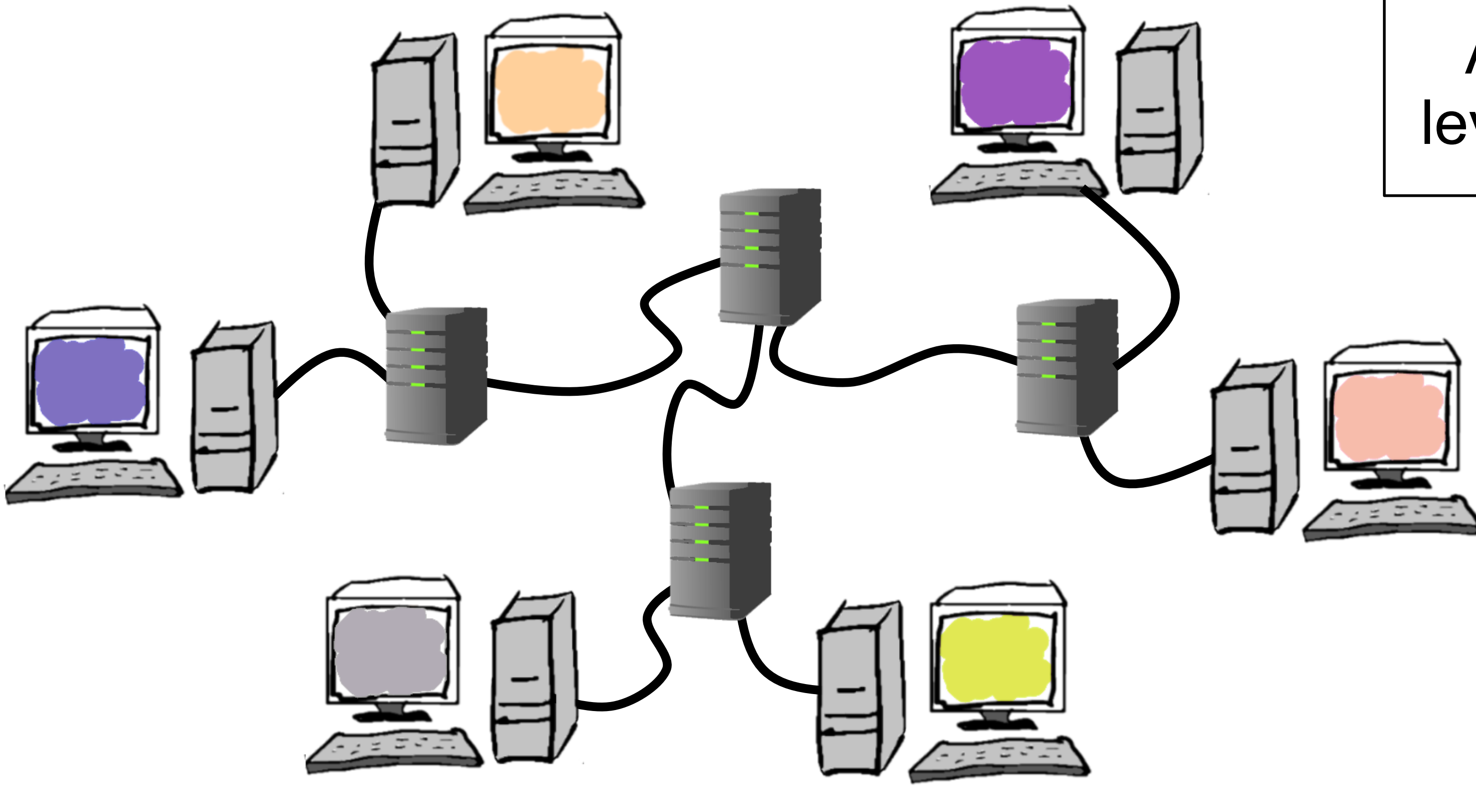
A router forwards data packets (routes).

Hierarchies Can be Organized Hierarchically!

Why stop at one level?

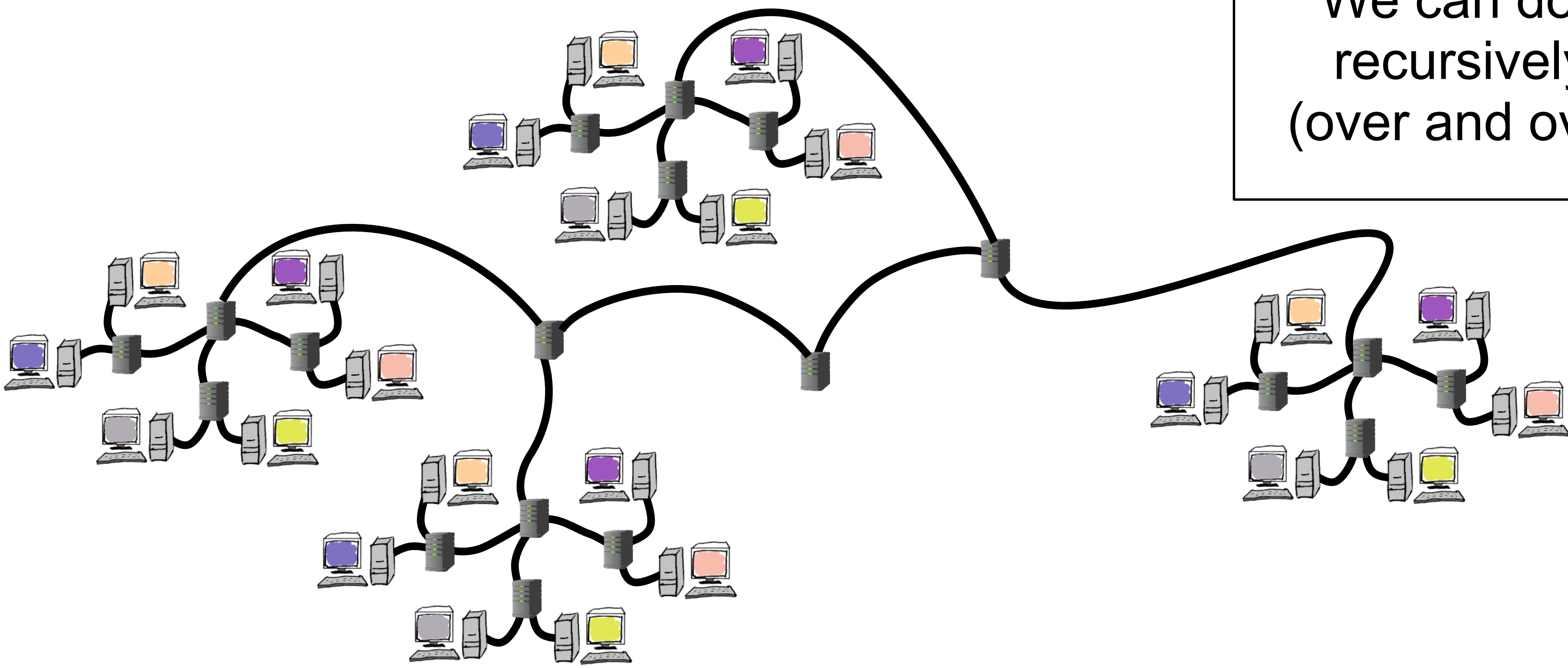
We can **use several levels** of hierarchy.

More Levels of Hierarchy are Possible



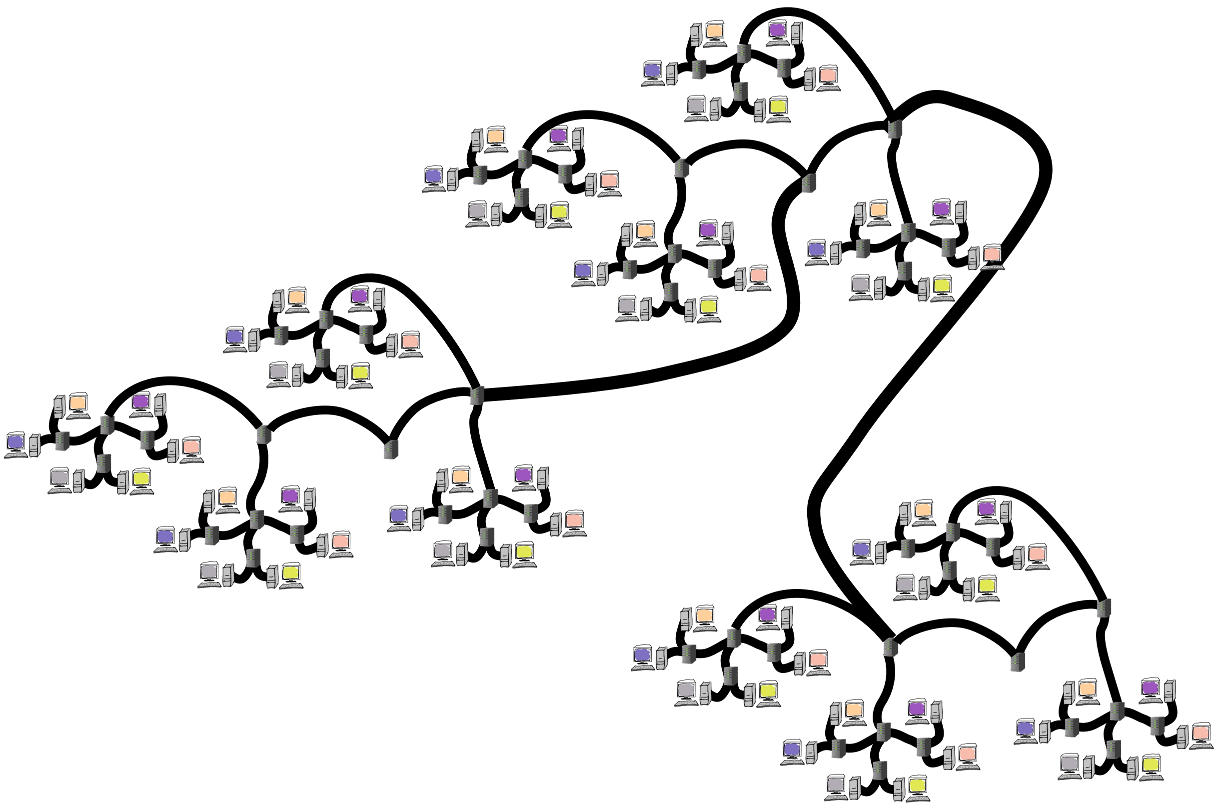
Add a second level of hierarchy

We Can Keep Adding Layers of Hierarchy



We can do it recursively! (over and over)

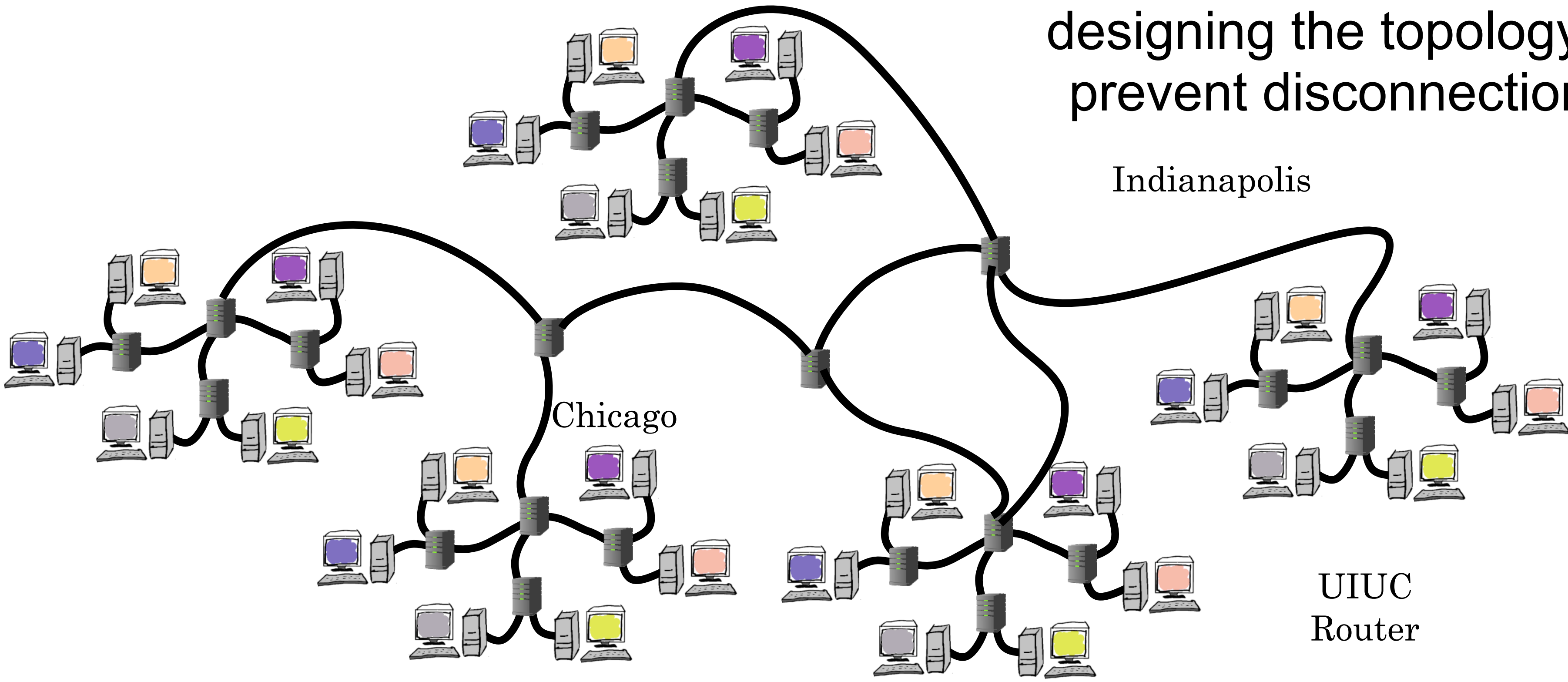
Deep Hierarchies Enable Networks to Span the Globe



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

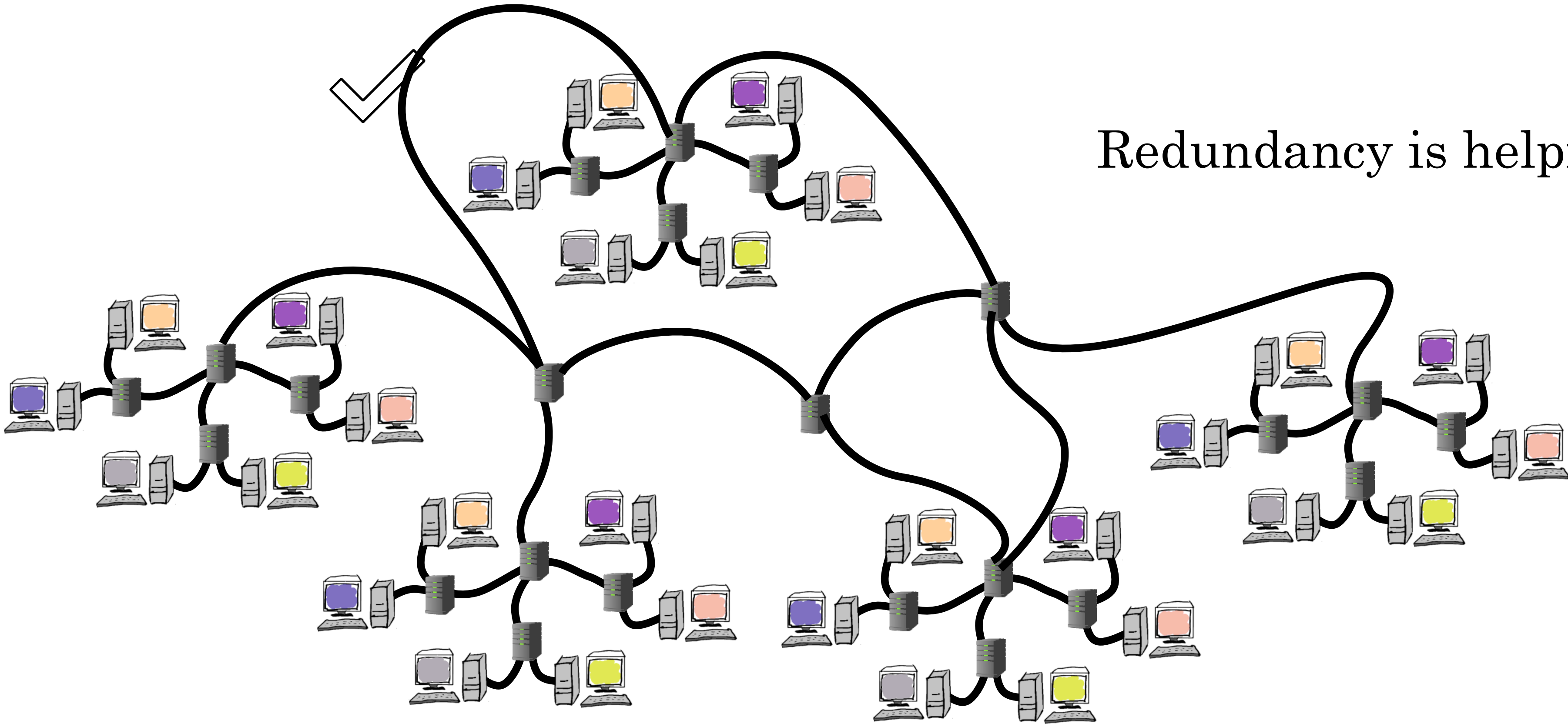
Can UIUC join the Hierarchy?

But pay attention to designing the topology to prevent disconnection!!

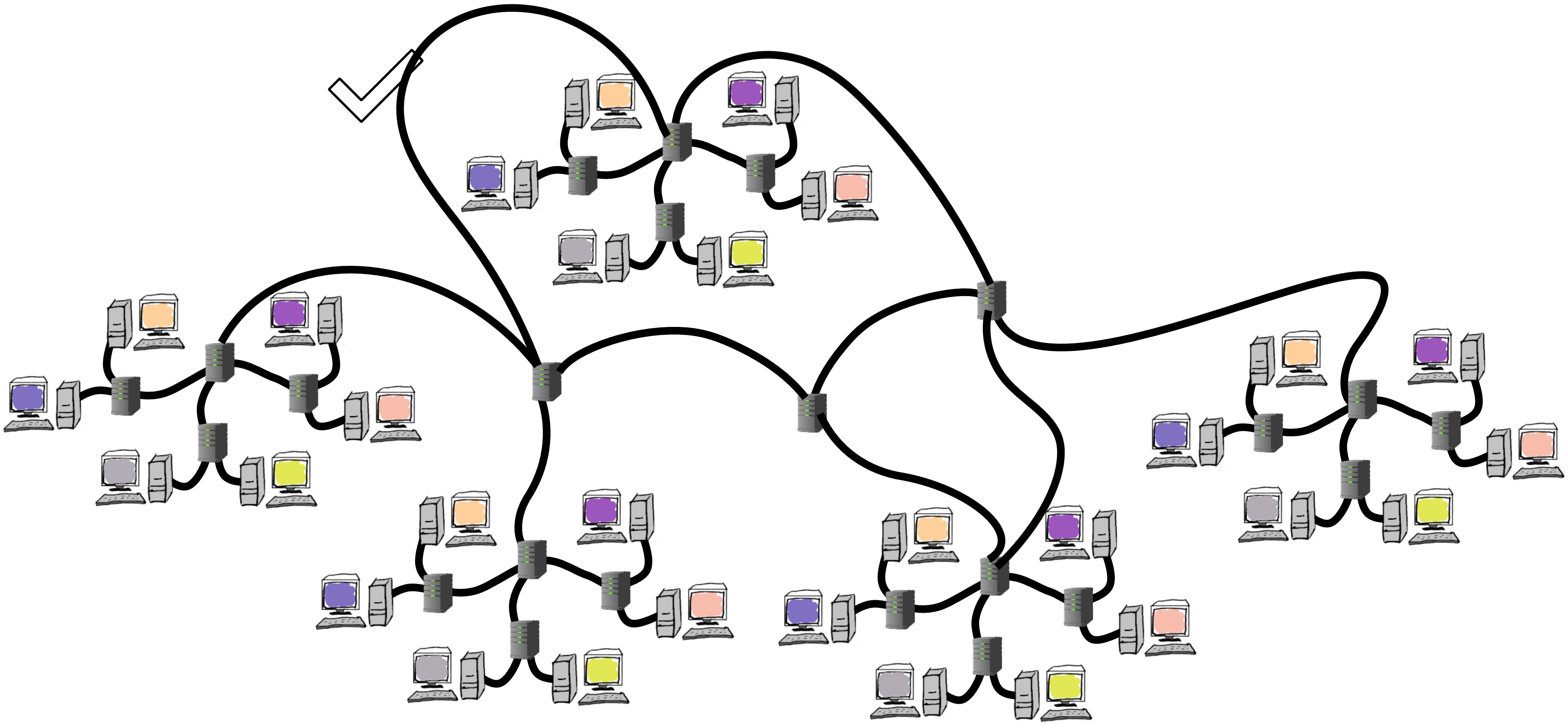


Design Topologies to Minimize the Impact of Failures

Redundancy is helpful



Design Topologies to Minimize the Impact of Failures



Real Failures Can Still be Catastrophic

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

About 18 years ago, a backhoe dug up (and broke) the optical fibers running from our campus to Chicago.

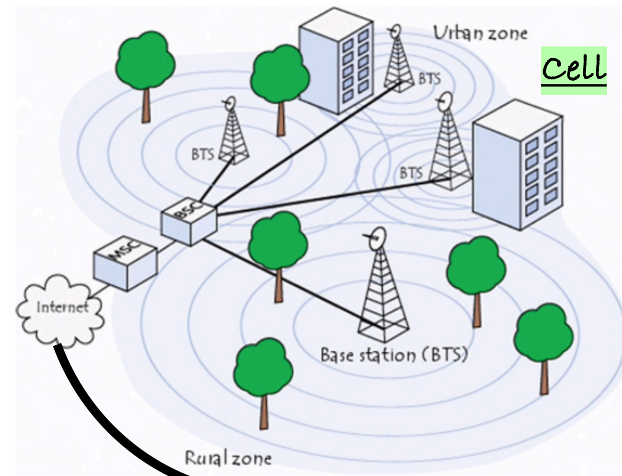
Internet traffic almost instantly shifted to route through Indianapolis.

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

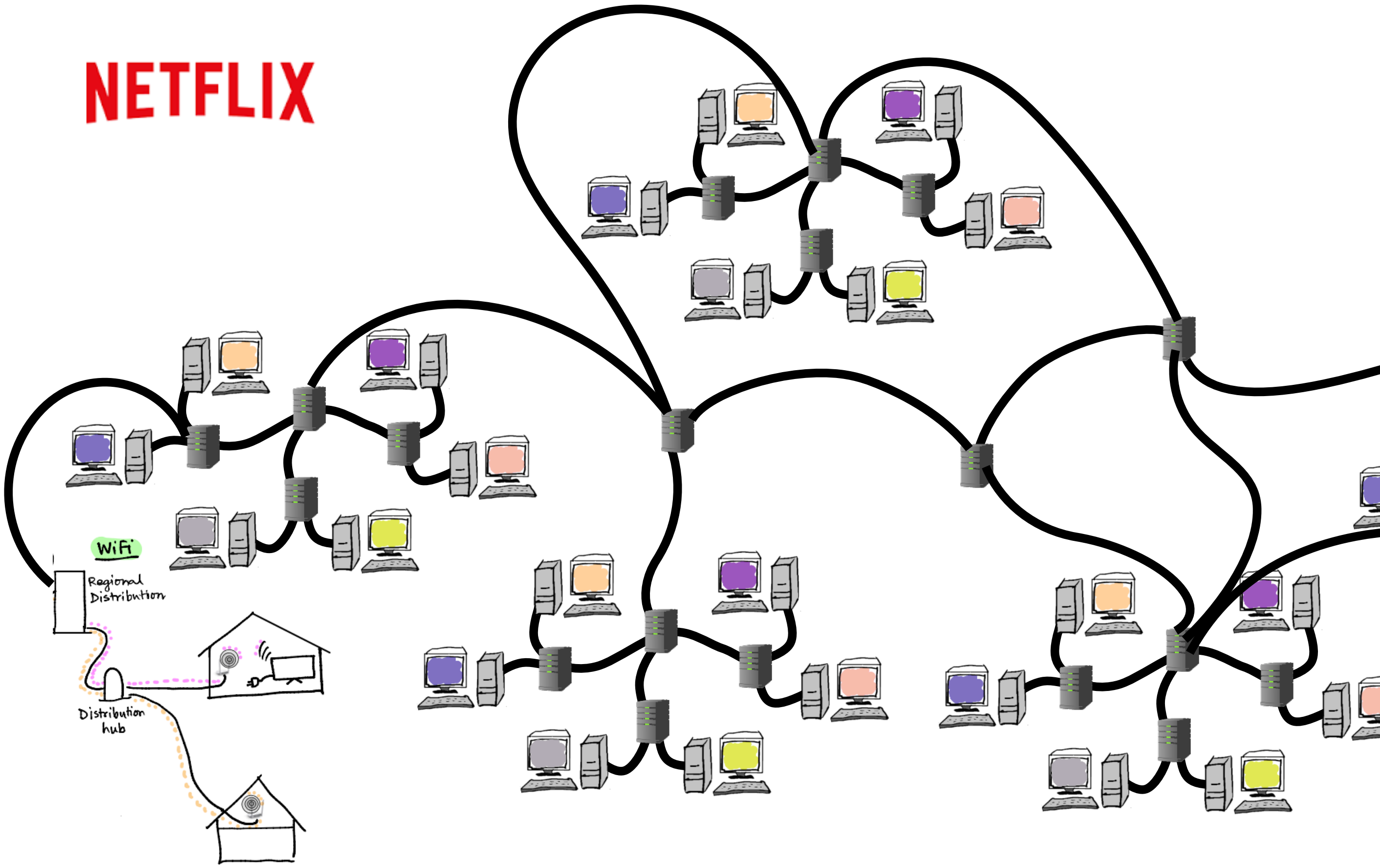
After all, UIUC never sent any traffic that way.

The Internet was down for days at UIUC.

Connect Everyone at the Edge



NETFLIX



Plumbing

Plumbing: the Invisible Infrastructure

Who is doing the plumbing?

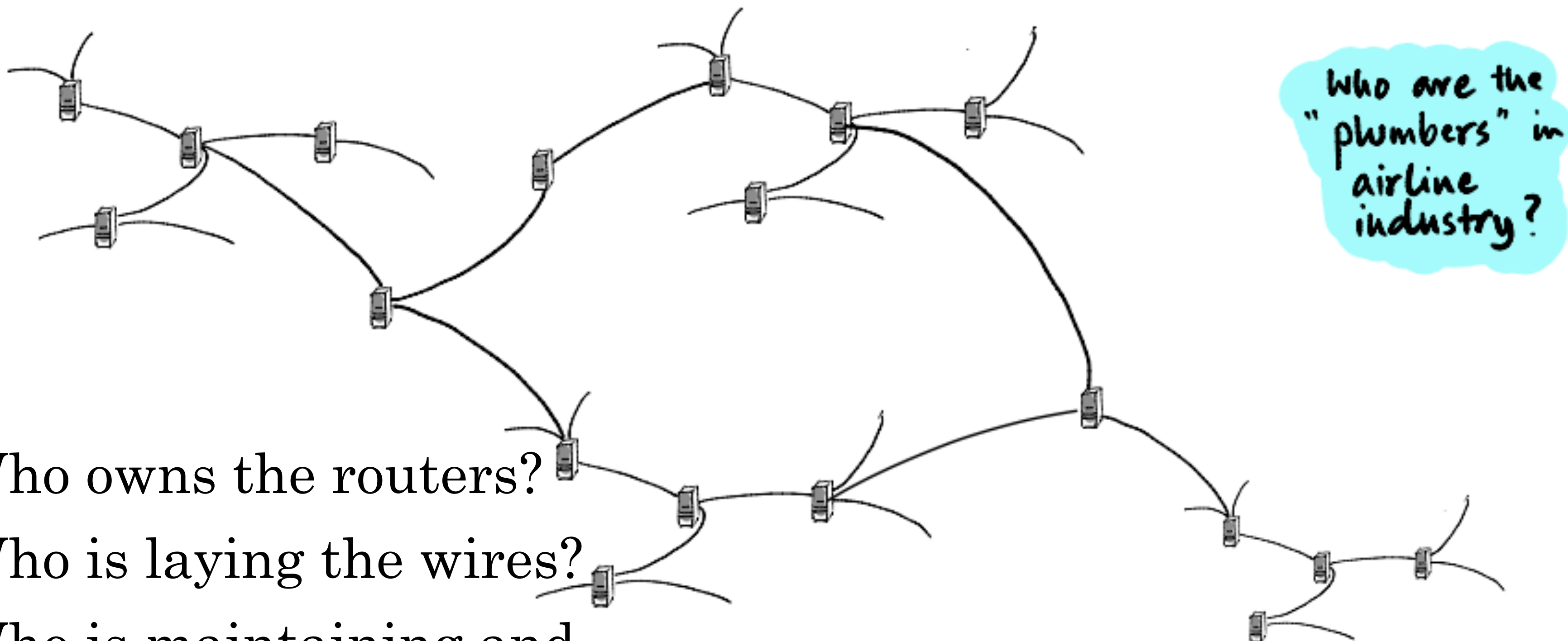
Do you care about Plumbing?
"Absolutely!"

How often do you think about your plumbing?

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

We often talk about infrastructure
that works well as "plumbing."

Plumbing for the Internet



- Who owns the routers?
- Who is laying the wires?
- Who is maintaining and managing the infrastructure?

Tier 1

Tier 2

Tier 3

Tier 1 ISPs (and their Optical Fibers) form the Backbone

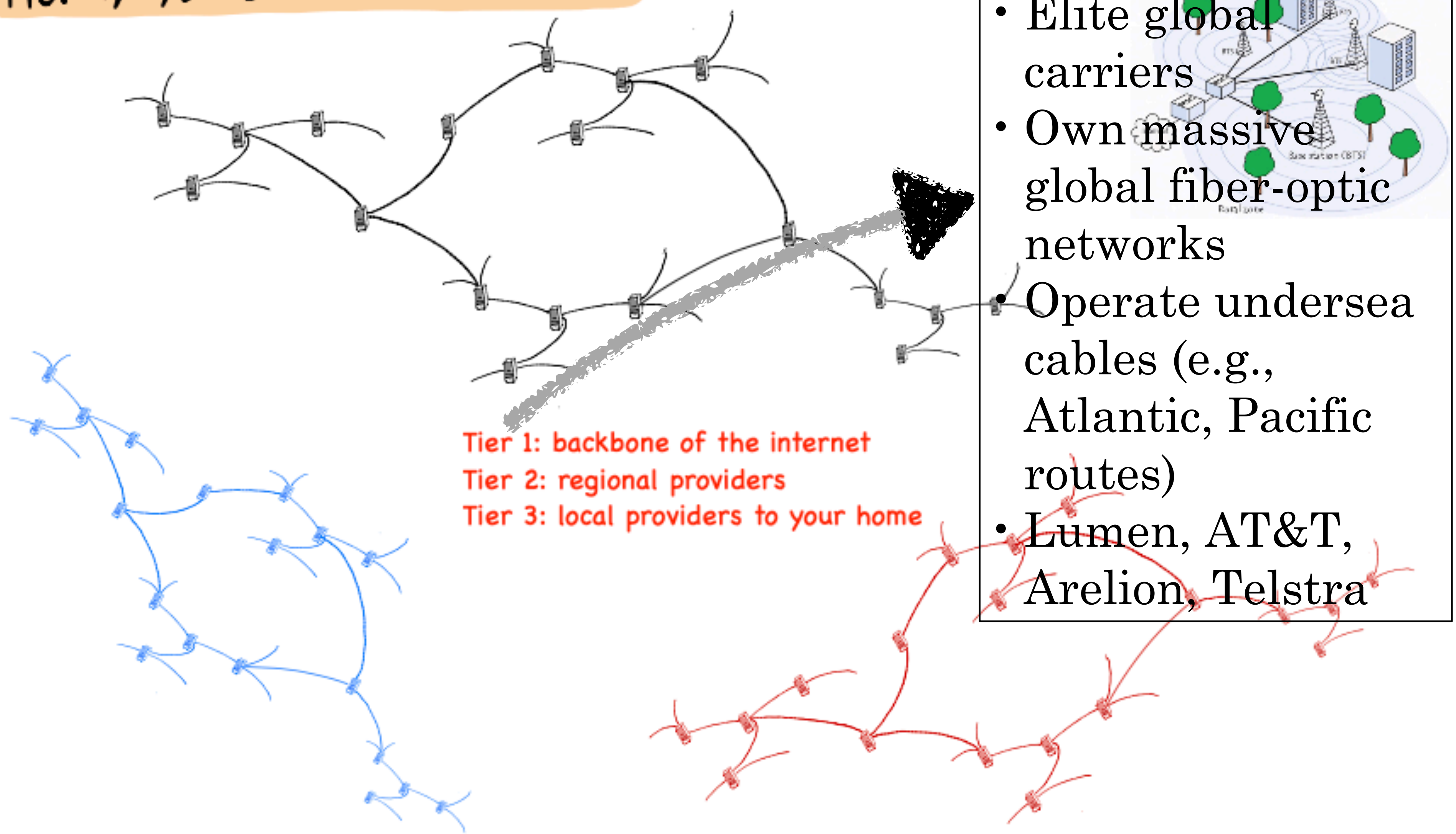
Governments (in the US, for example)
- **own* the right-of-ways** along which
- companies lay bundles of optical fiber.

*Purchased in the 19th century to lay railroads across the continent.

Tier 1 Internet Service Providers (**ISPs**)
- build or lease these fibers
- to **carry traffic**
- **across the Internet**.

These form the backbone of the Internet.

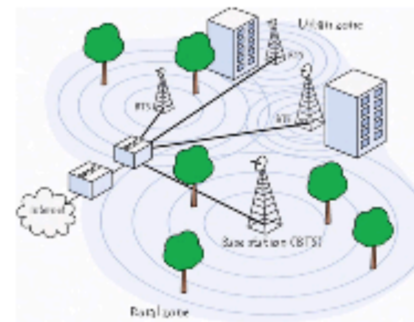
Tier 1,2,3 Service Providers

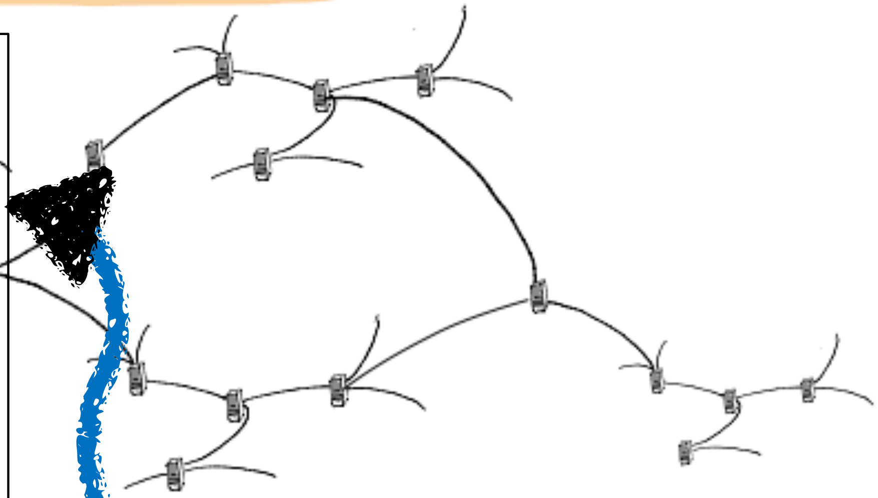


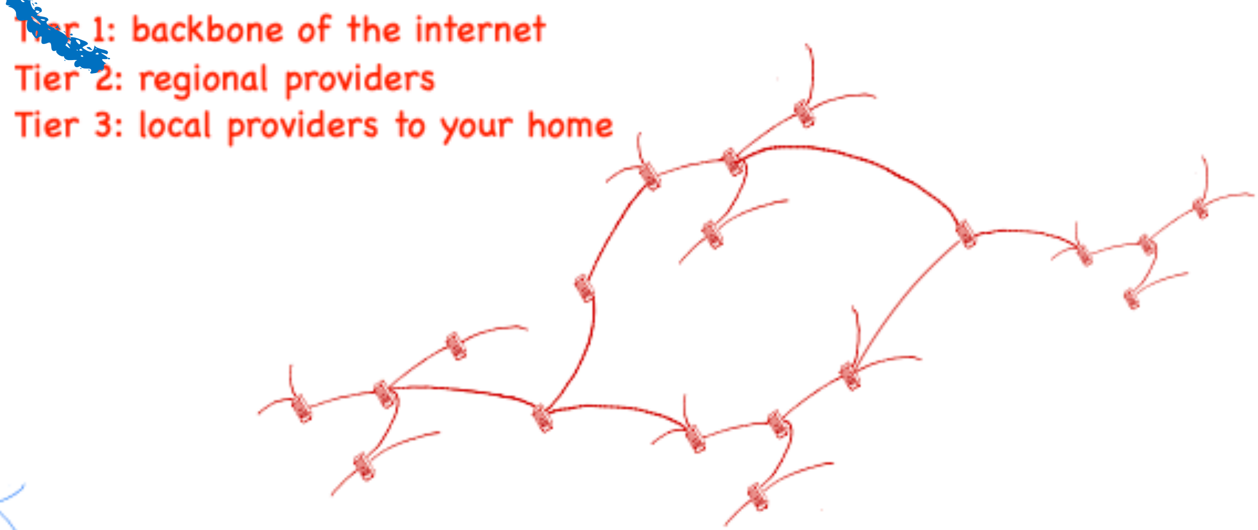
- Elite global carriers
- Own massive global fiber-optic networks
- Operate undersea cables (e.g., Atlantic, Pacific routes)
- Lumen, AT&T, Arelion, Telstra

Tier 1,2,3 Service Providers

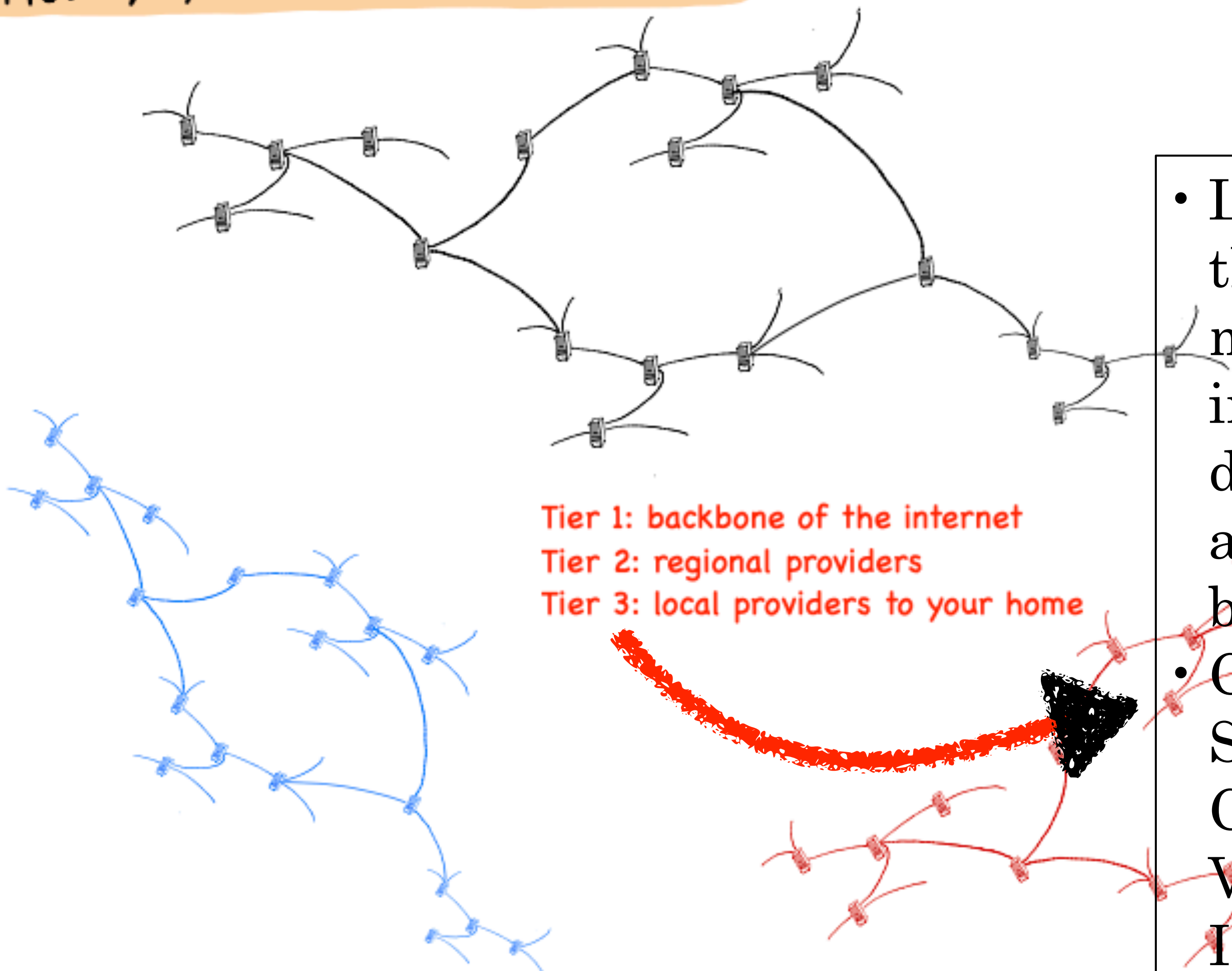
- Operate at a national or regional level.
- Own or lease regional fiber networks and data centers
- Vodafone, British Telecom, Comcast, Spectrum

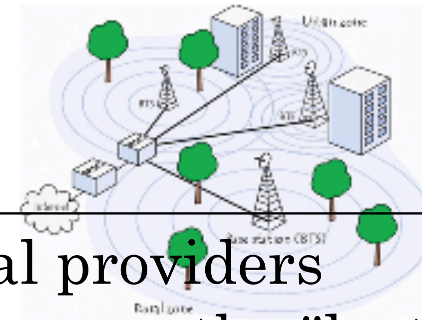






Tier 1,2,3 Service Providers

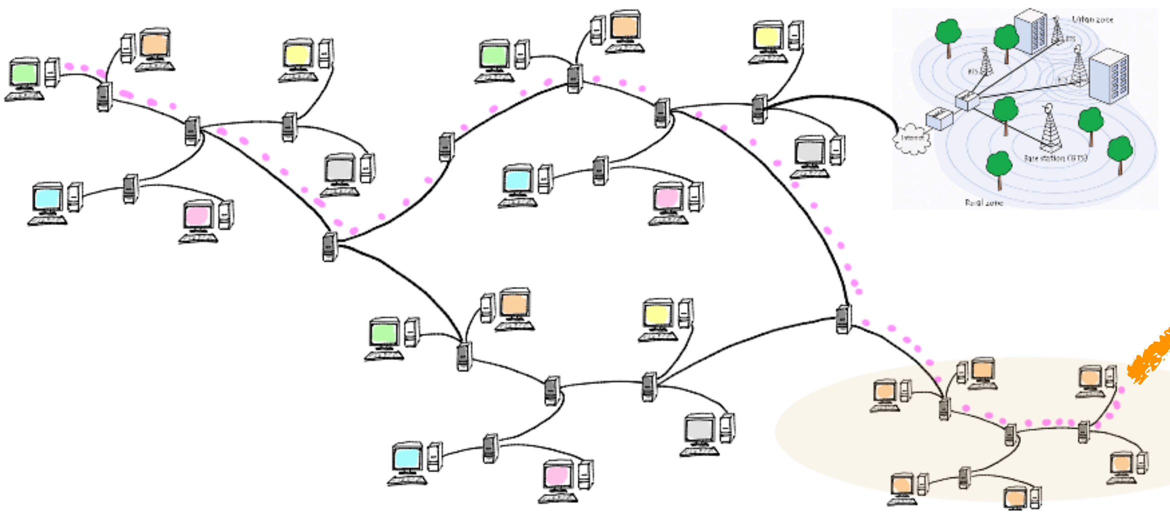




- Local providers that serve the "last mile", i.e. deliver internet access directly to homes and small businesses.
- Comcast, Spectrum (Charter Communications), Verizon Wireless, I3

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**!

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
- **`10000010 01111110 10010111 00010011`**
- (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: Affix an Address and Send it Off!

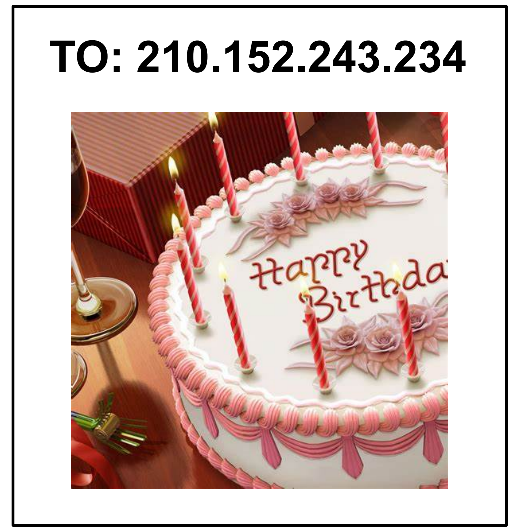
To send a birthday photo

- to your friend in Tokyo, your computer
- **find**s their computer's **IP address** and
- **puts** it **into** a **packet** with the photo, then
- **push**es 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.

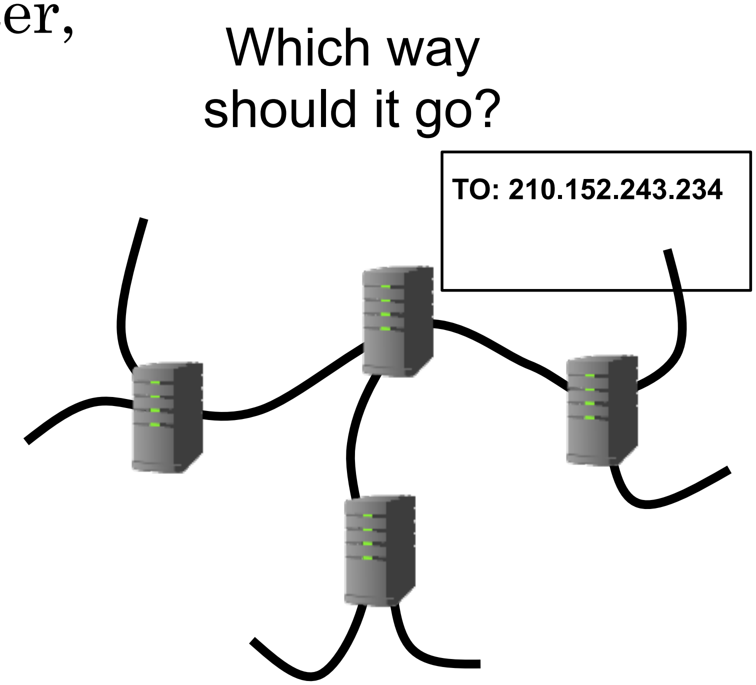


Time Check

How do the Routers know where to forward Data Packets

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).



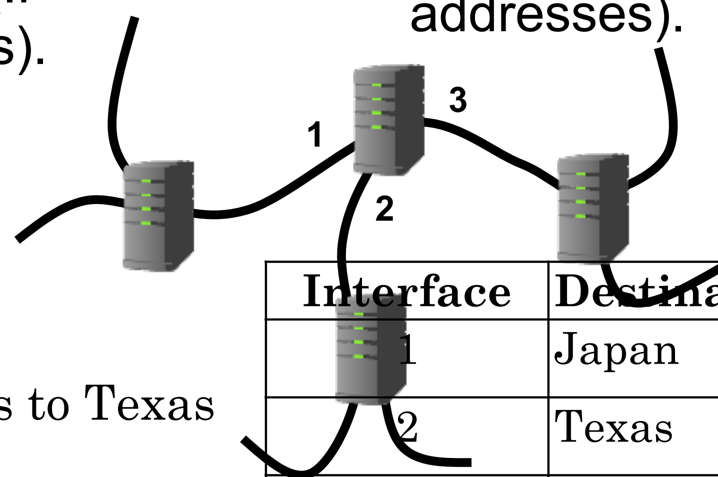
Routers keep updated Routing Tables

Routers periodically

- **advertise IP address ranges that they can reach**
- to their other links,
- as if they are gossiping, who knows whom!!

A **forwarding table maps**

- **IP addresses into**
- **interface numbers**
- (1, 2, or 3, for example).

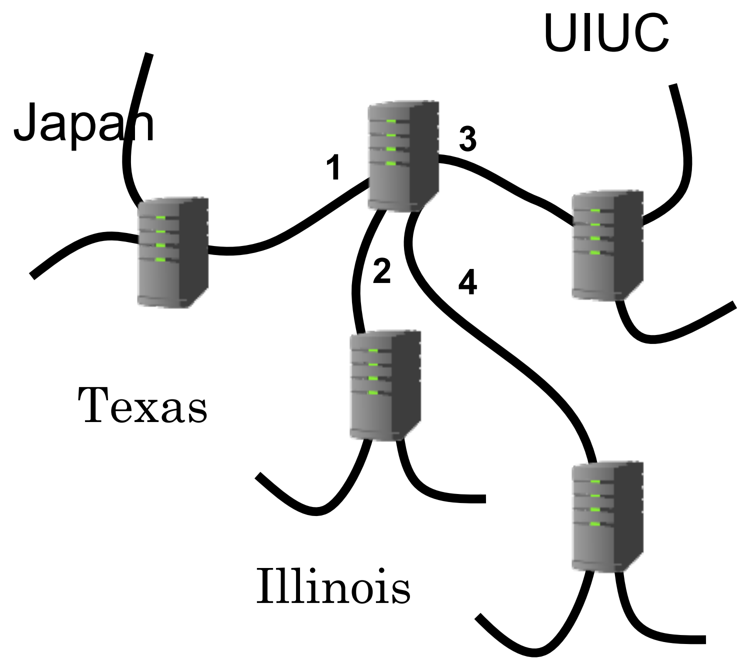


Interface	Destination
1	Japan
2	Texas
3	UIUC

Let’s Route

- A packet arrives for Northwestern University (in Chicago, IL, USA).
- **Which interface?**
- A packet arrives for Tokyo University (in Tokyo, Japan).
- **Which interface?**
- A packet arrives for UIUC.
- **Which interface?**
- Usually, the **more specific answer is chosen**.

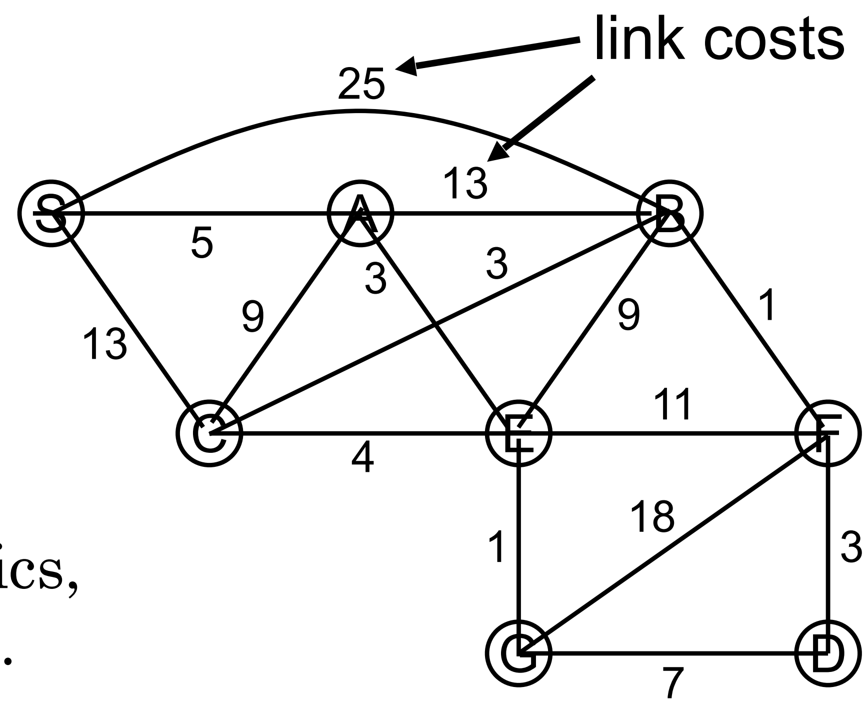
Interface	Destination
1	Japan
2	Texas
3	UIUC
4	Illinois



Network Graph for Routing

How to get from S to D?

Link cost may reflect
- length (delay),
- link capacity,
- congestion (queueing delay),
- any combination of those metrics,
- or just the router's preferences.



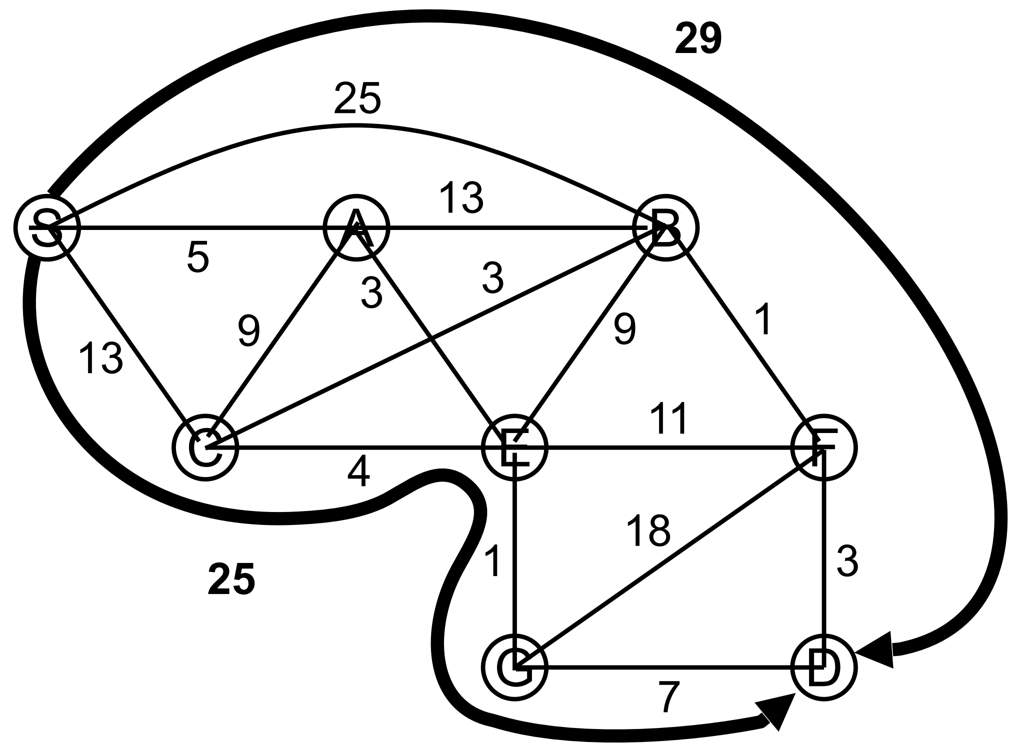
Computing Cost of a Path

How to get from S to D?

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

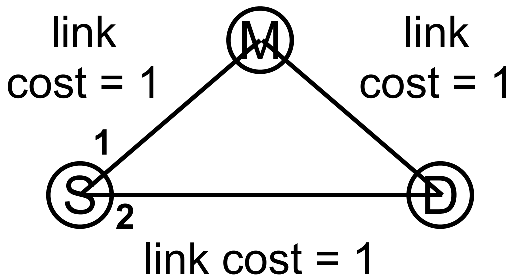
And the **desired path is** the path with the **smallest cost**.

To construct a forwarding table,
- a router must **decide**
- **which path to follow**
- to reach each other node.



Let’s Find Routes Together!

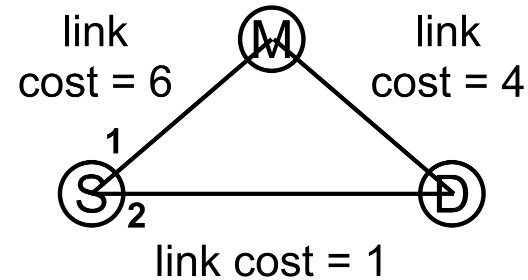
Complete the forwarding table for the node S.



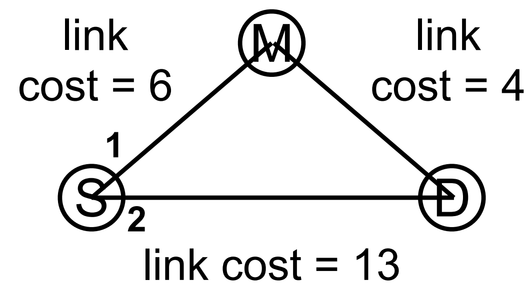
dest	interface
D	**2**
M	**1**

(by “hops”: all link costs are 1)

dest	interface
D	**2**
M	**2**

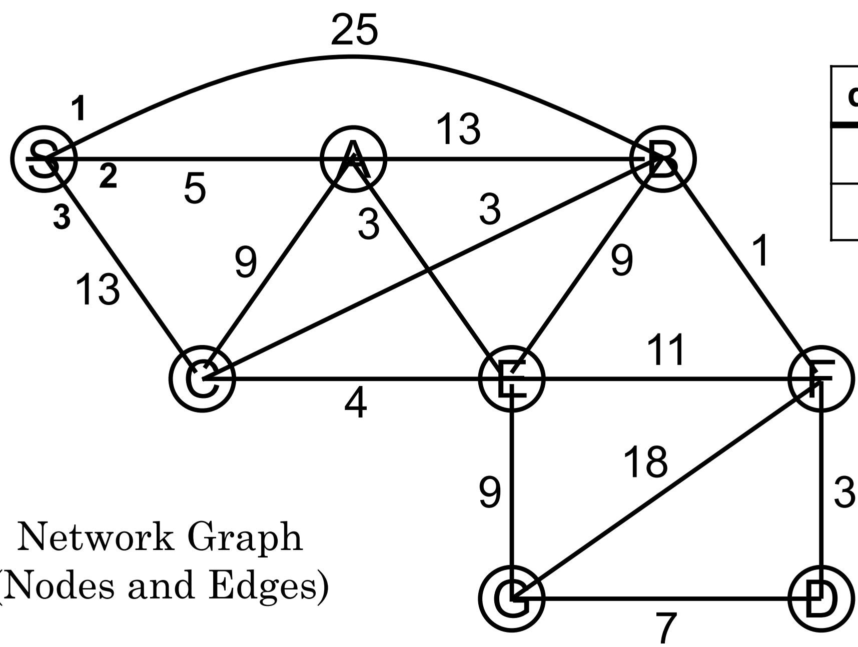


dest	interface
D	**1**
M	**1**



Here’s a challenge …

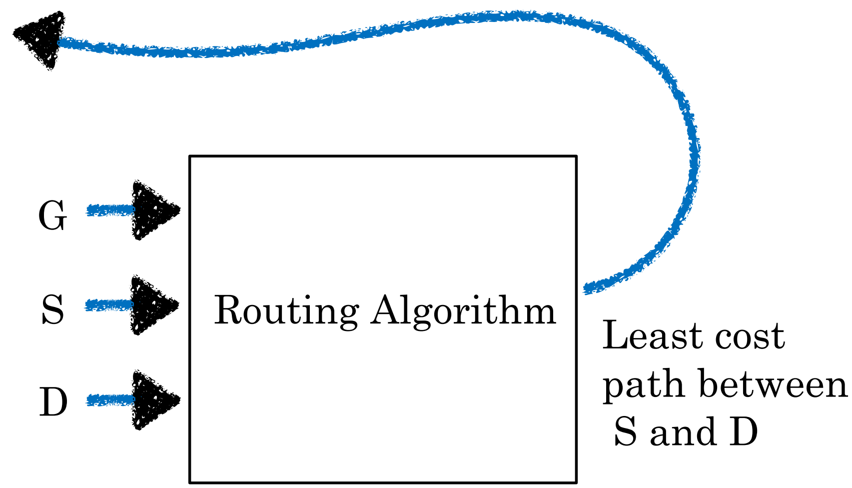
Complete the forwarding table for destination D from the node S.



Network Graph
(Nodes and Edges)

dest	interface
D	?
…	…

The computer will do it for you!!

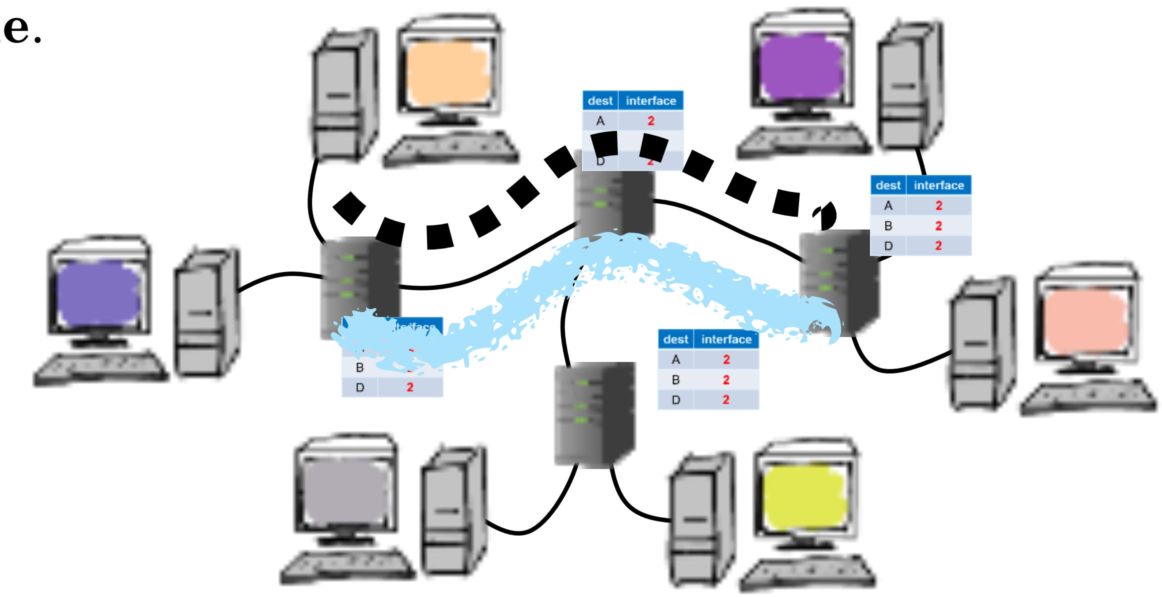


Data and Control Planes

Routers forward **packets**.
- Packets containing data are said to pass **through the data plane**.

Routers exchange **information about routes** available to them.
- These coordination messages travel **through the control plane**.

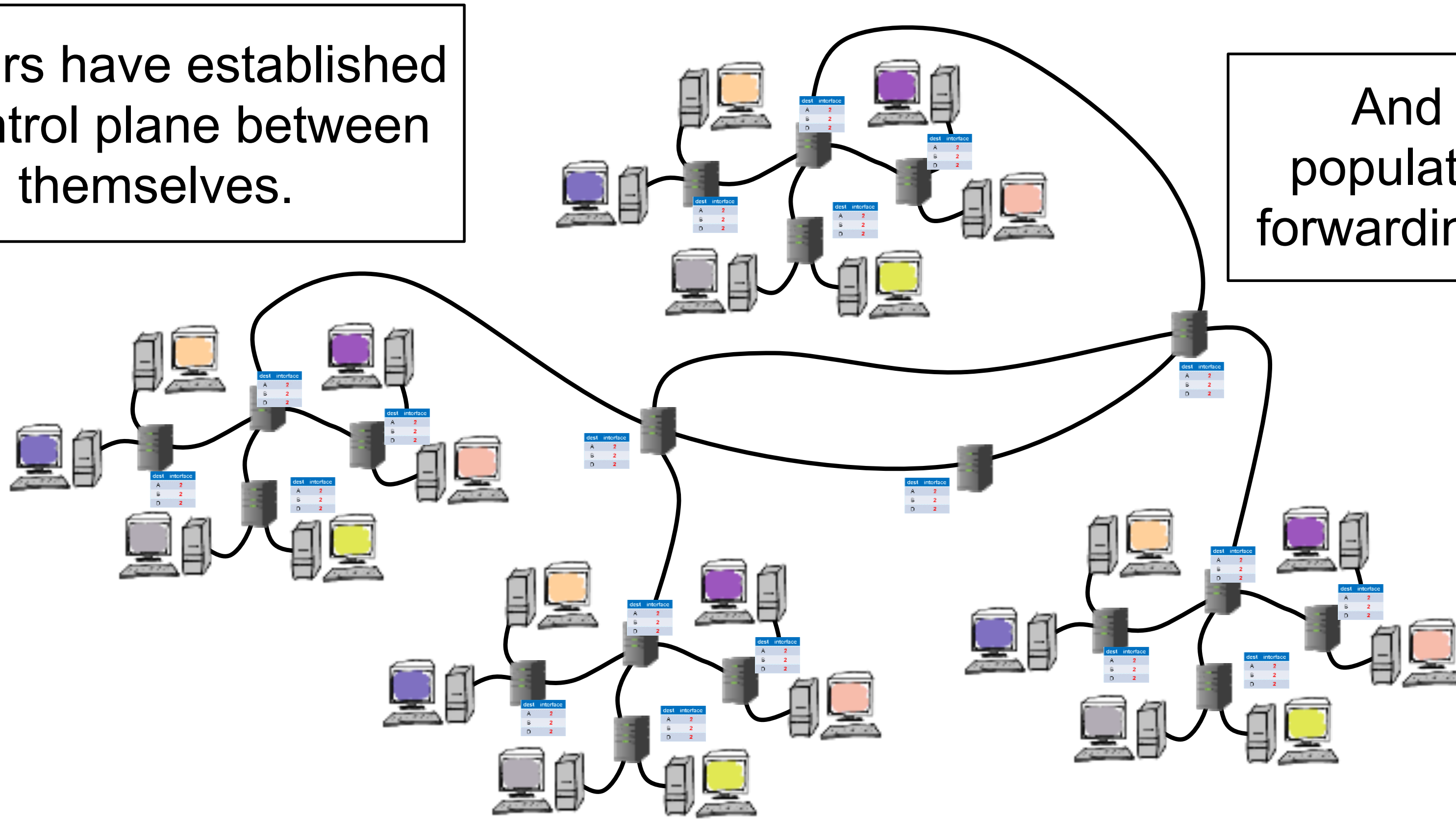
The two planes
- use the same physical network
- but are logically separate.



Internet Plumbing's Ready: Routing and Forwarding

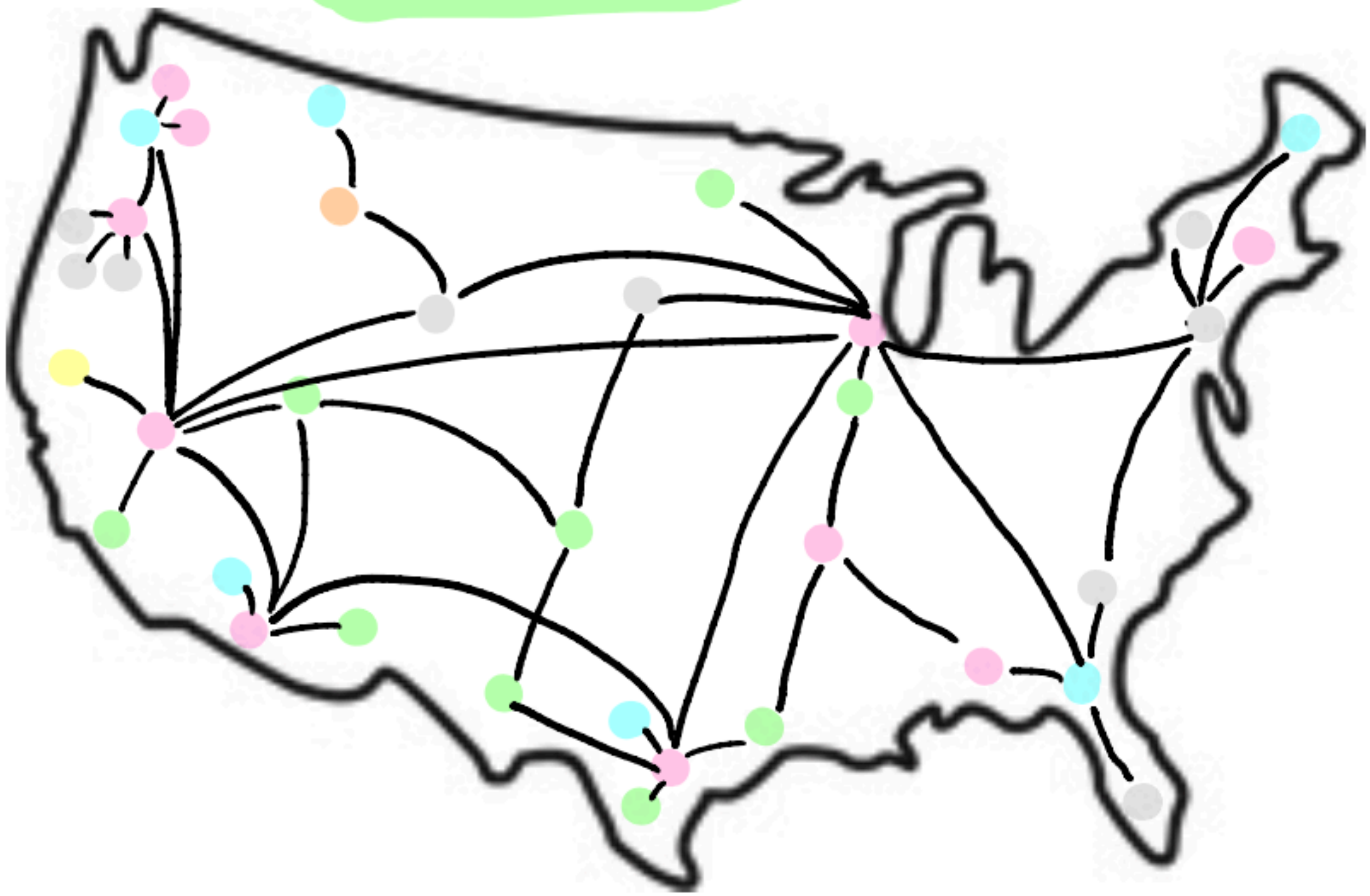
Routers have established a control plane between themselves.

And have populated their forwarding tables.



The airports are ready, and flights can link them

Now what?



Terminology You Should Know from These Slides

- design tradeoffs
- network topology
- clique topology
- network interface
- shared network
- Ethernet
- hierarchy
- star topology
- router
- Internet Service Providers (ISPs);
- Tier 1,2,3
- Internet backbone
- IP address
- forwarding
- Routing table
- Routing algorithm
- Route advertisements
- Routing (building routing table)

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 design choice affects tolerance to failures
- each computer has an IP address
- how a router uses its forwarding table
- routers forward packets in data plane and exchange routing information in control plane
- how to find shortest paths in small graphs

