Internet of Things

Module 1: Introduction and Course Overview

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Background:
How the Internet Works

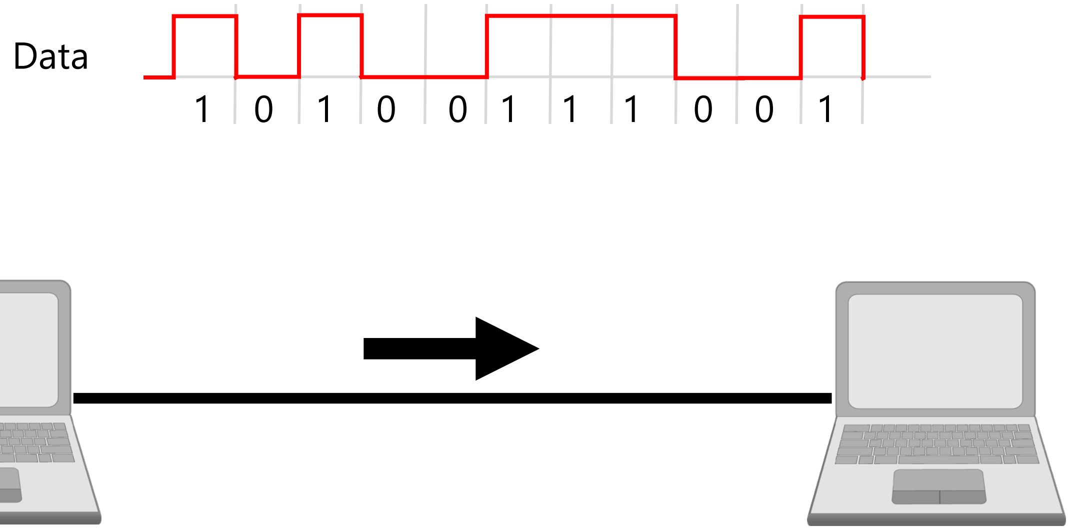
Background: How the Internet Works

1. Internet Architecture
   - How is the Internet built?

2. Networking Routing
   - How does the Internet figure out paths to destinations?

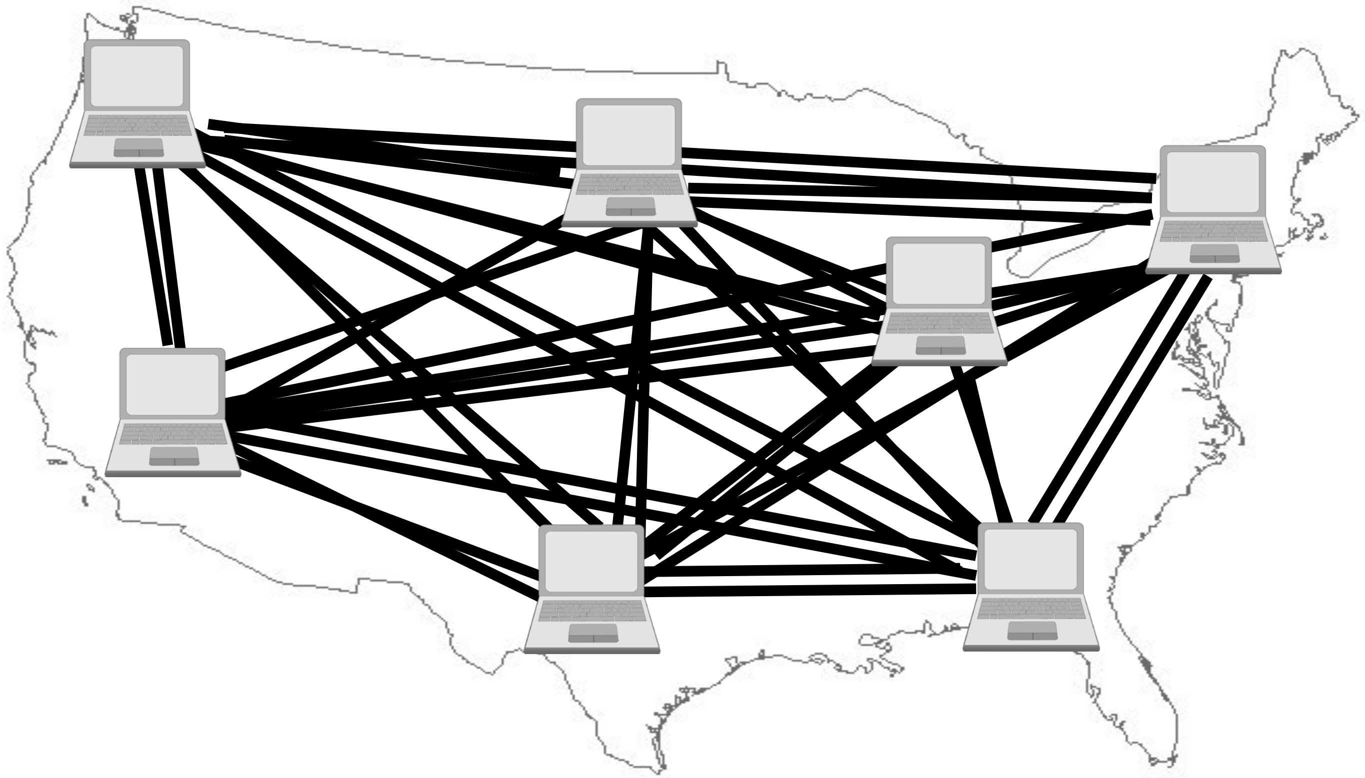
3. Network Devices
   - What does the inside of a router look like?

How Can Two Hosts Communicate?



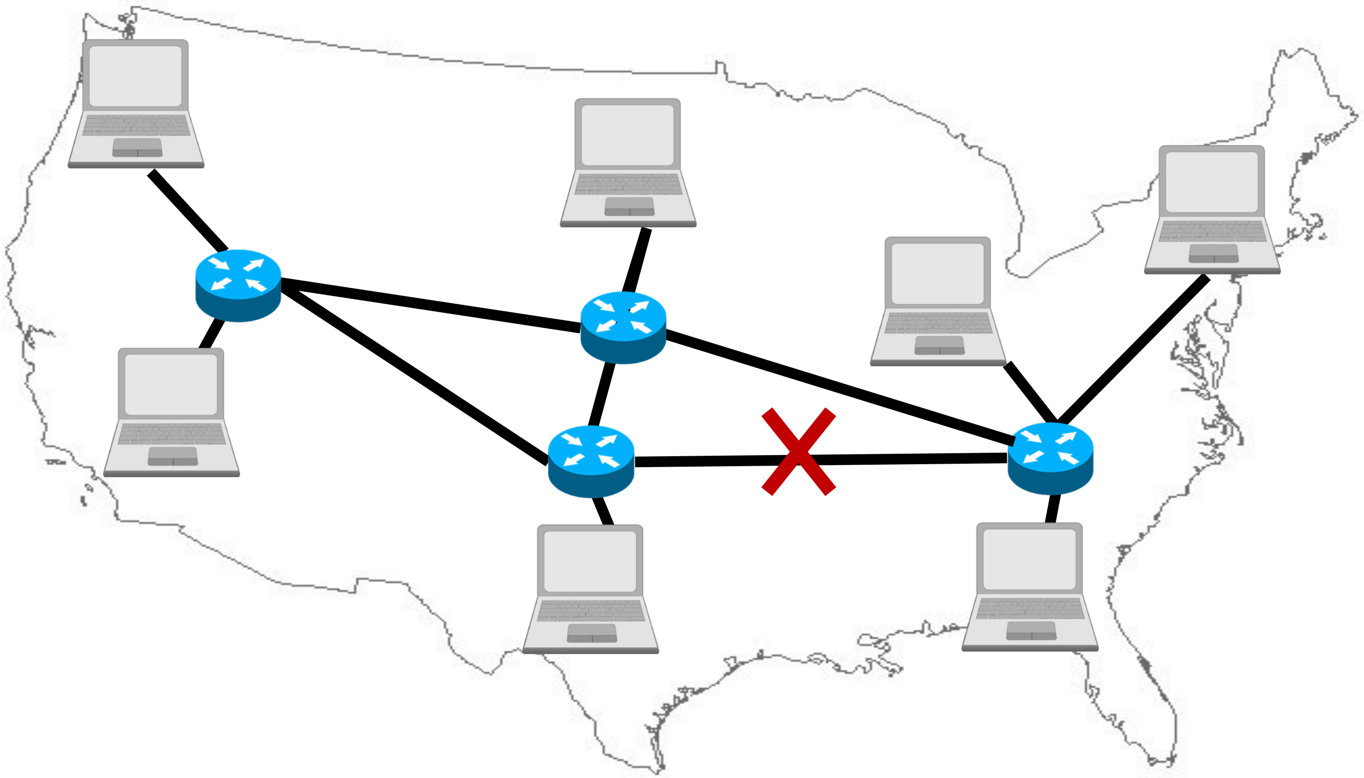
- Encode information on modulated “Carrier signal”
  - Phase, frequency, and amplitude modulation, and combinations thereof
  - Ethernet: self-clocking Manchester coding ensures one transition per clock
  - Technologies: copper, optical, wireless

How Can Many Hosts Communicate?



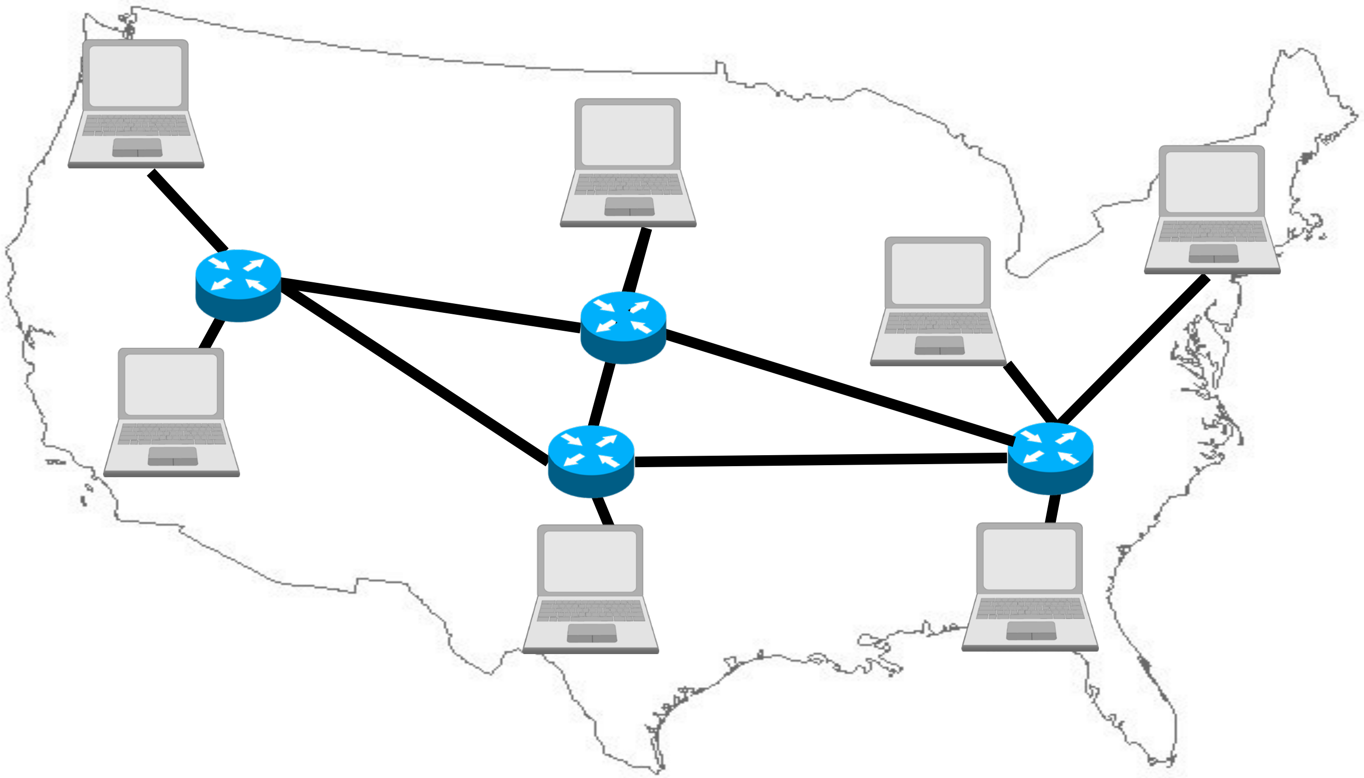
- Naïve approach: full mesh
- Problem: not very scalable
  - >25B devices connected in 2019

How Can Many Hosts Communicate?



- Better approach: Multiplex traffic with routers
- Goals: make network robust to failures and attack, maintain spare capacity, reduce operational costs
  - New challenges: What topology to use? How to find paths? How to identify destinations?

How Can Many Hosts Communicate?



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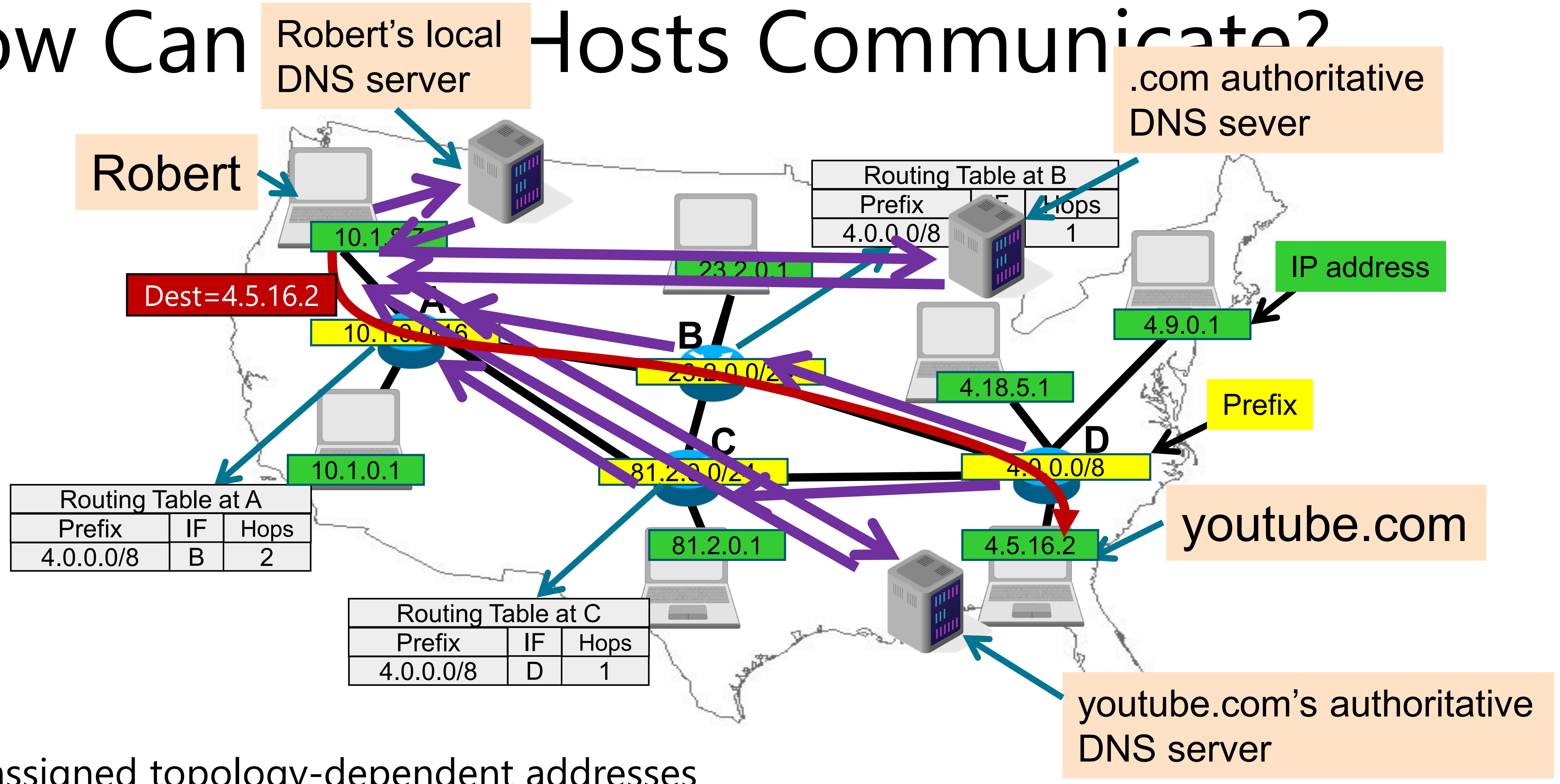
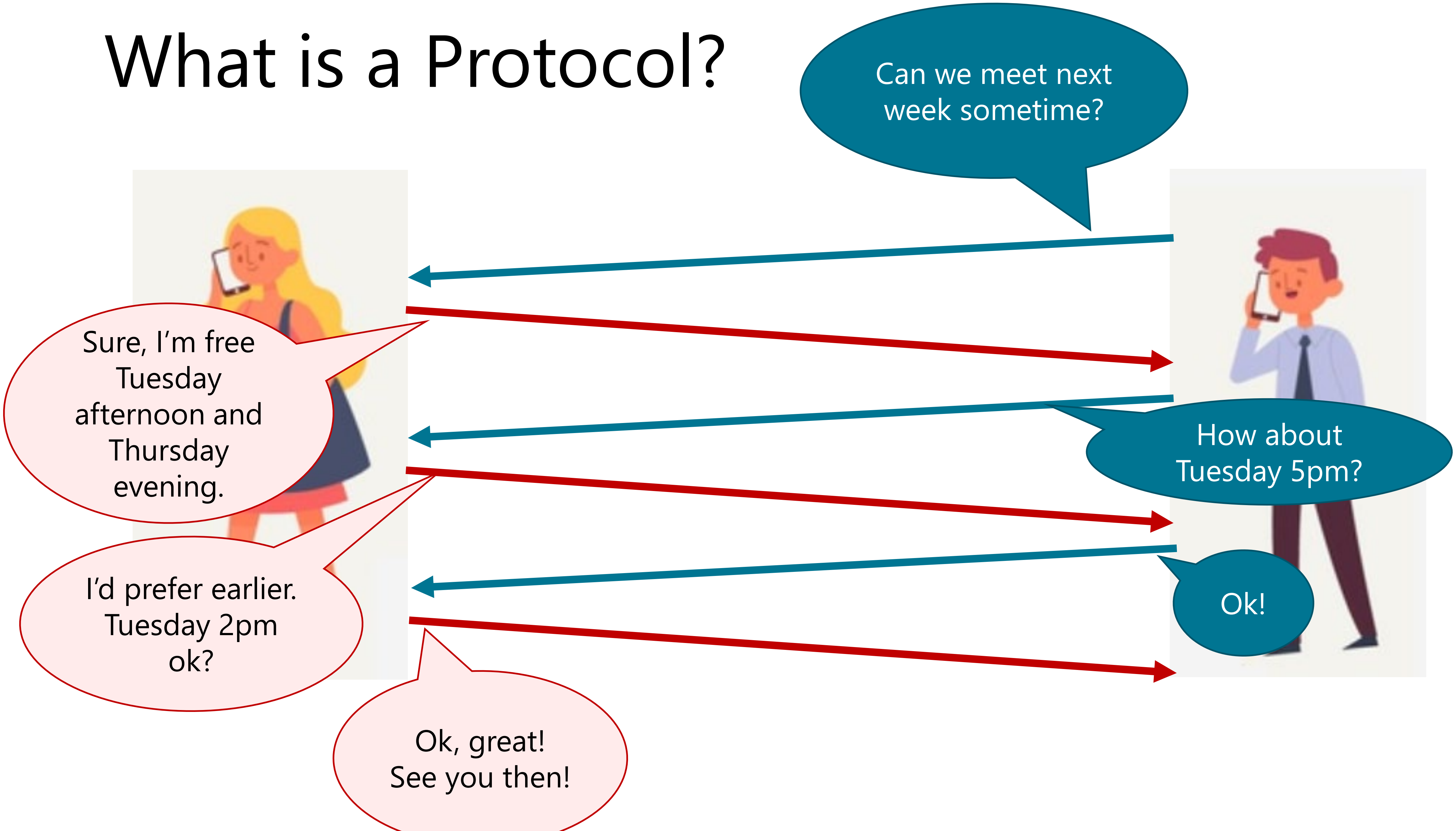


- Hosts assigned topology-dependent addresses
- Routers advertise address blocks ("prefixes")
- Routers compute "shortest" paths to prefixes
- Map IP addresses to names with DNS

What is a Protocol?



What is a Protocol?

- Sequence of communications used to conduct some activity in a distributed system
- Protocols are widely used in networks
  - Figure out how fast to send data, discover paths to destinations, replicate data, encode data into transmittable patterns, etc.
- Protocols often organized into "suites" or "stacks"
  - Handle collection of activities associated with particular environment
  - Examples: TCP/IP (Internet), Infiniband (Data Center), Bluetooth (IoT)

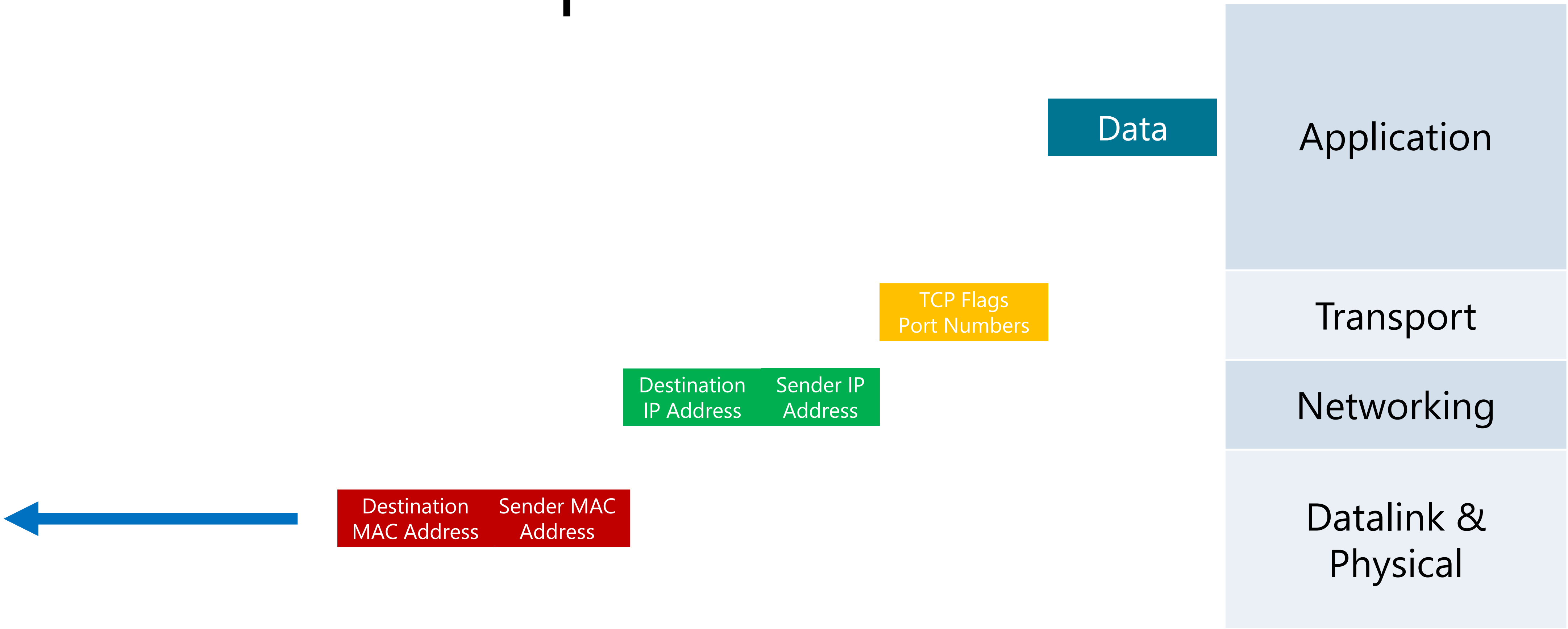
Networks Have Protocols To….

Compute paths through networks	Routing protocols
Figure out how fast to send data	Transport protocols
Encrypting messages so others can't read them	Encryption protocols
Figure out who has an address	Address resolution protocols
Figure out what kinds of things the network can do	Service discovery protocols

The TCP/IP Protocol Stack

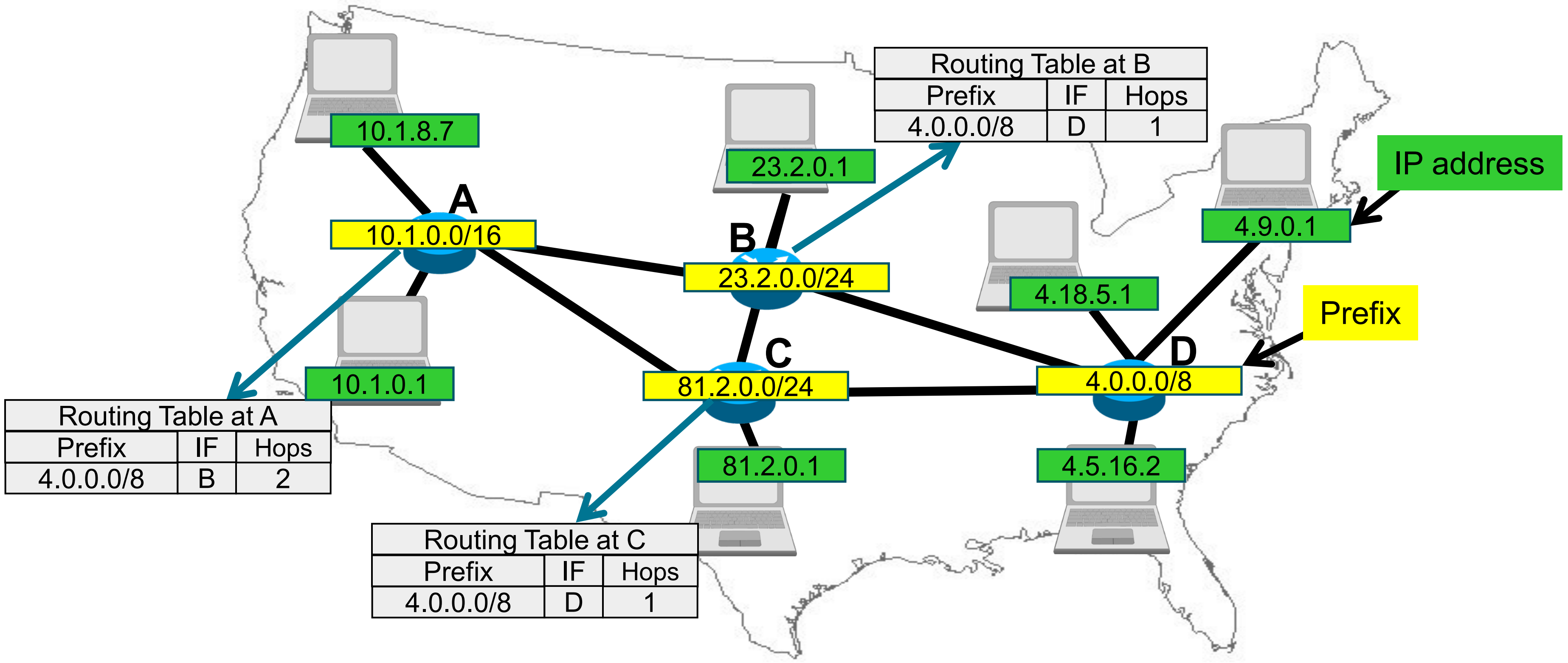
	OSI Model (1984, International Standards Organization)	TCP/IP Model (1973-1989, Cerf/Kahn/DARPA)	Data Protocols	Control Protocols
Layer 7	Application	Application	IMAP, HTTP, H.323, RDP, SSH, BitTorrent, Bitcoin JSON/XML	
Layer 6	Presentation			
Layer 5	Session			
Layer 4	Transport	Transport	TCP, UDP, QUIC, SCTP	
Layer 3	Networking	Networking	IPv4, IPv6	BGP, OSPF, IS-IS BFD, ICMP
Layer 2	Datalink	Datalink & Physical	Ethernet, Wireless Ethernet (WiFi, 802.11)	ARP, DHCP
Layer 1	Physical			

Protocol Encapsulation



- Each layer of protocol stack encapsulates data passed to it
- Each forwarding layer inspects data only at that encapsulation layer
  - Switching only looks at Ethernet header, Routing only looks at IP header, etc.
  - Terminology: “Layer-3 switch”, “Layer-4 load balancer”, “Layer-7 load balancer”

How Can Many Hosts Communicate?



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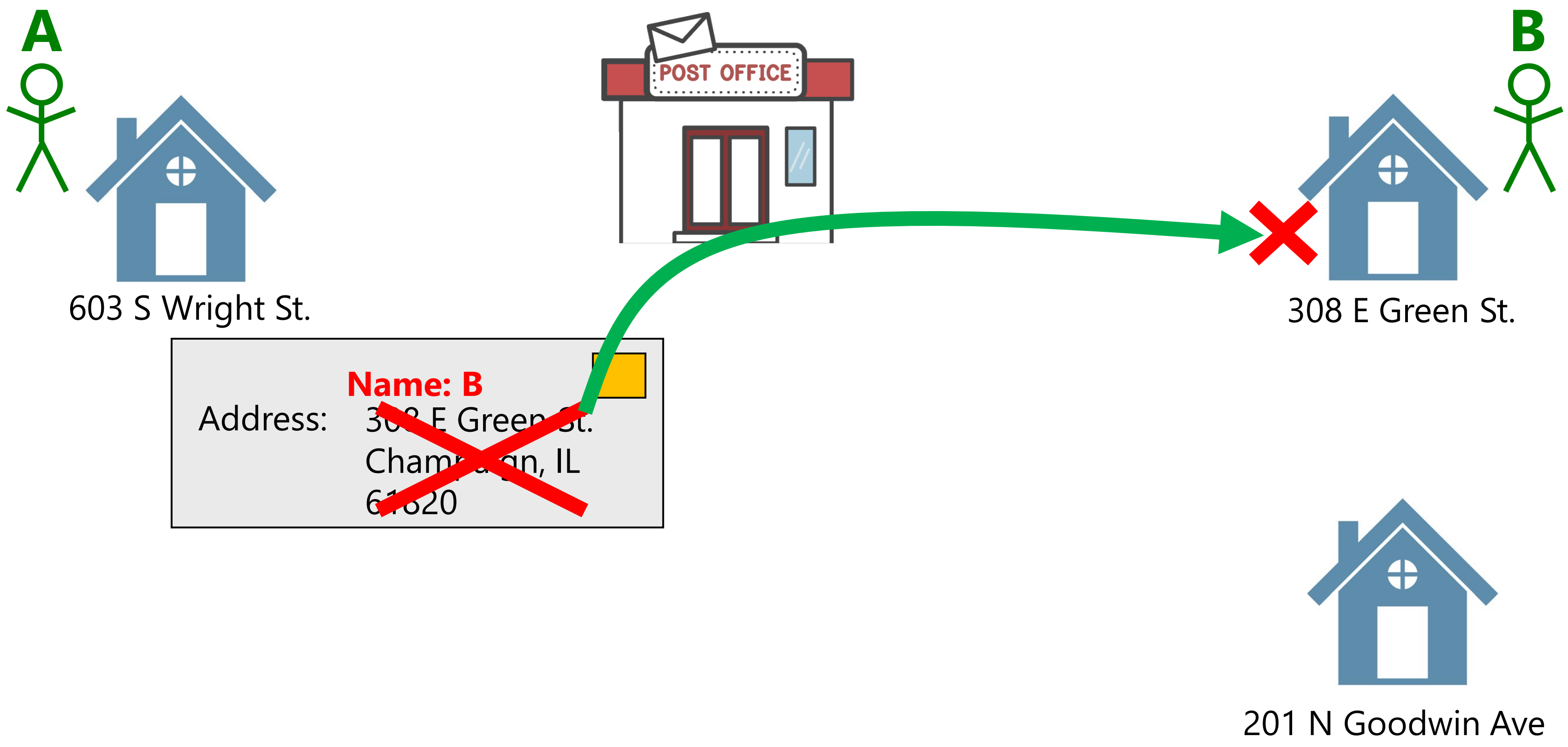
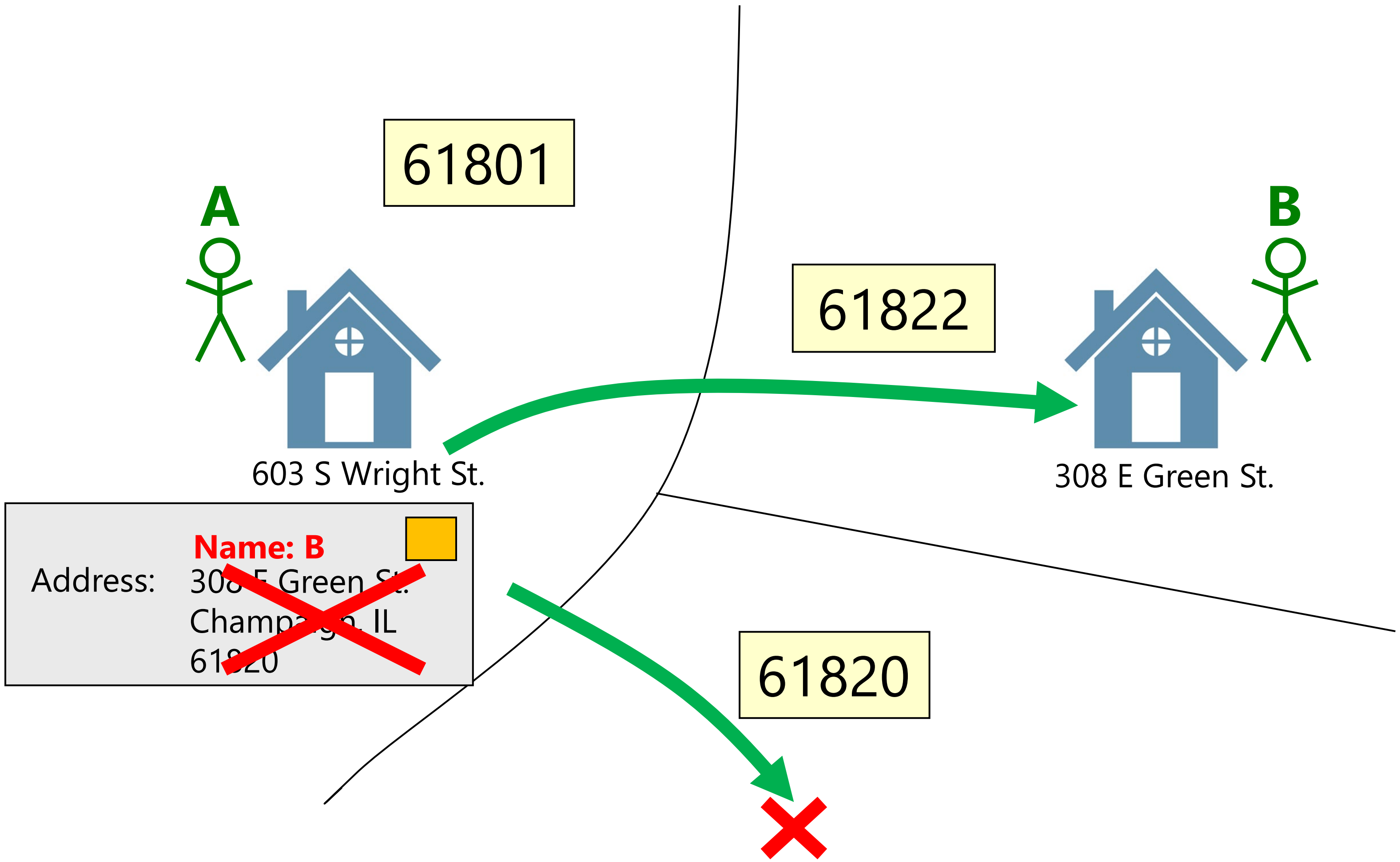
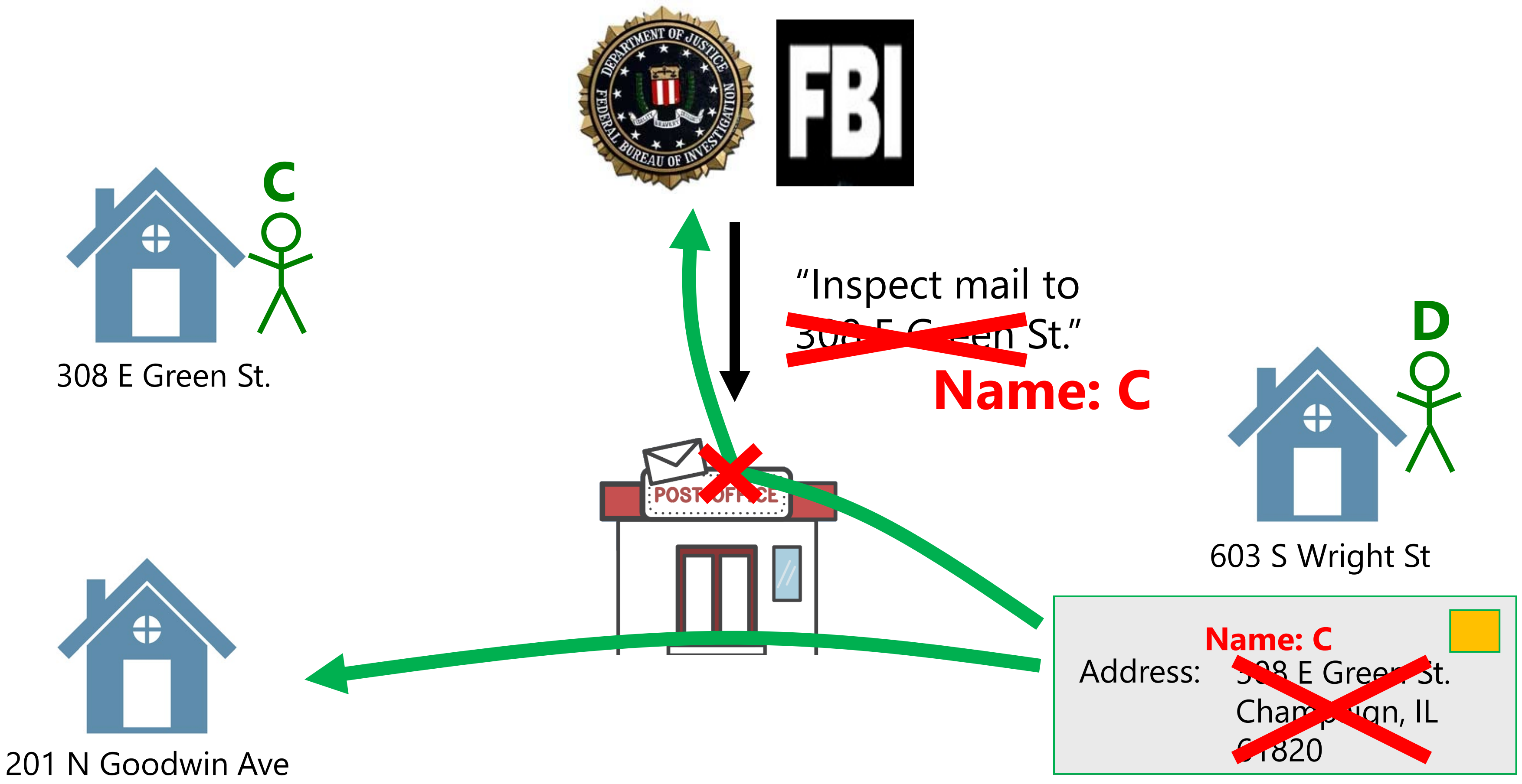
Scenario: Sending a Letter



Scenario: Address Allocation



Scenario: Access Control



Internet Addressing:
Different Layers Use Different Addresses

Application	**URLs** (e.g., http://www.cs.Illinois.edu/index.html) • Identifies "resources" – files, content **Domain names** (e.g., illinois.edu) • Identifies groups of computers under single administrative control
Transport	**Port numbers** (e.g., 143 for IMAP, 22 for SSH) • Identifies application running on a computer
Networking	**IP Addresses** (e.g., 18.220.149.166) • Identifies location where a computer's interface attaches to the Internet
Datalink & Physical	**MAC Addresses** (e.g., 9C-EF-D5-FE-27-72) • Identifies specific computer interface

→ *All these addresses are used for end-to-end communication*

Internet Addressing: MAC Address vs IP Address

MAC Address	IP Address
Datalink layer	Network layer
Flat (location-independent) identifier Like a social security number Usually hard-coded, **requires no configuration**	Hierarchically-assigned, **location-dependent** identifier Like a postal address **Needs to be manually configured**, assigned by DHCP
Portable; can stay the same as the host moves	Not portable; must be changed if host changes networks
Used to get packet to destination on same LAN	Used to get packet to destination IP subnet
Example: 9C-EF-D5-FE-27-72	Example: 18.220.149.166

Can We Use TCP/IP for IoT?

Yes

But, IoT introduces additional challenges:

- Very tight power/compute constraints
- Need to work closely with wireless
- Need to address applications, not just interfaces

Also, creating new protocols can help lock-in and market control

- Bad for innovation but good for security

Common IoT Protocols

zigbee

Bluetooth®

Bluetooth® LOW ENERGY (4.0) / SMART

6LoWPAN

THREAD

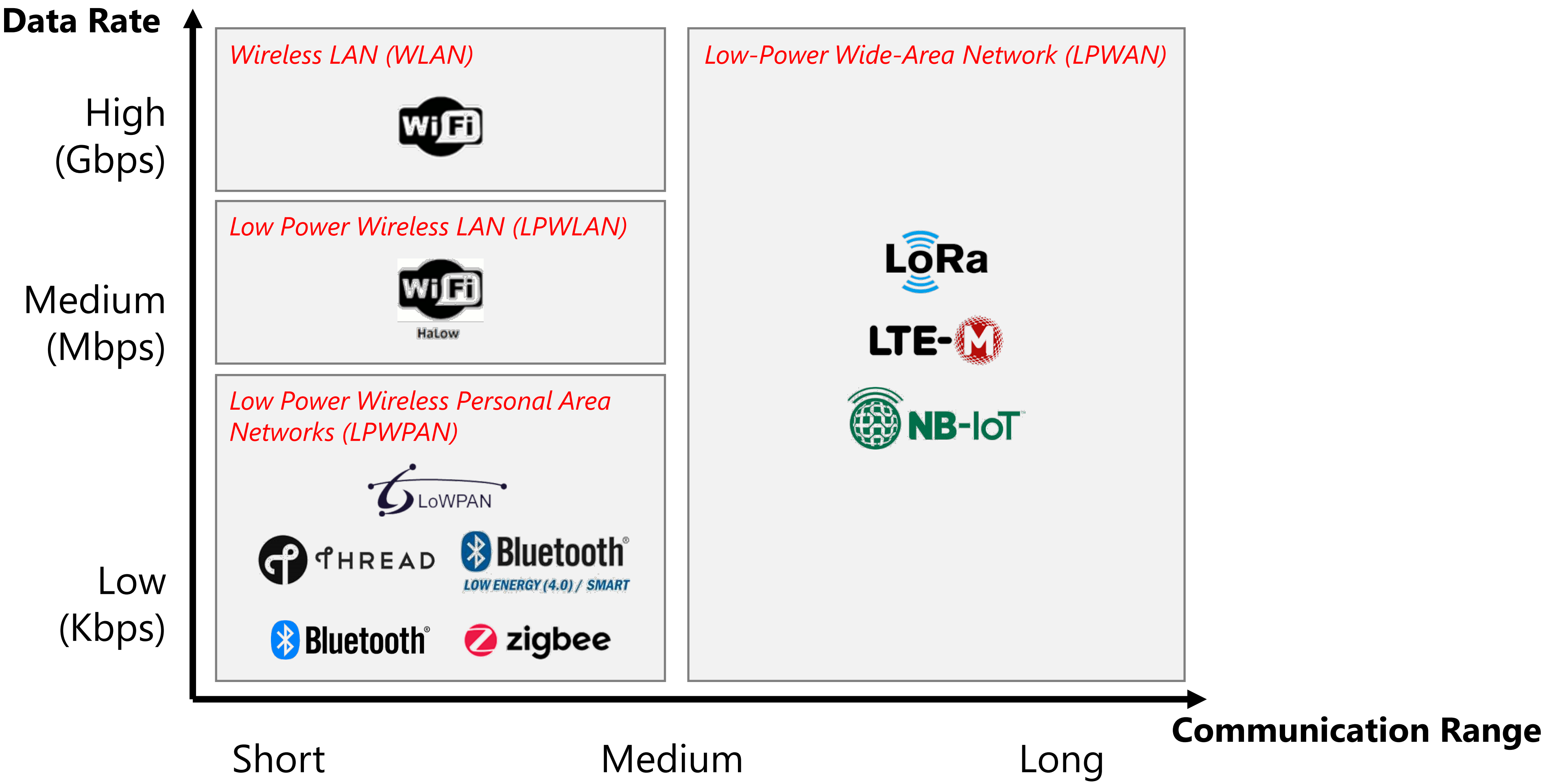
WiFi HaLow

NB-IoT™

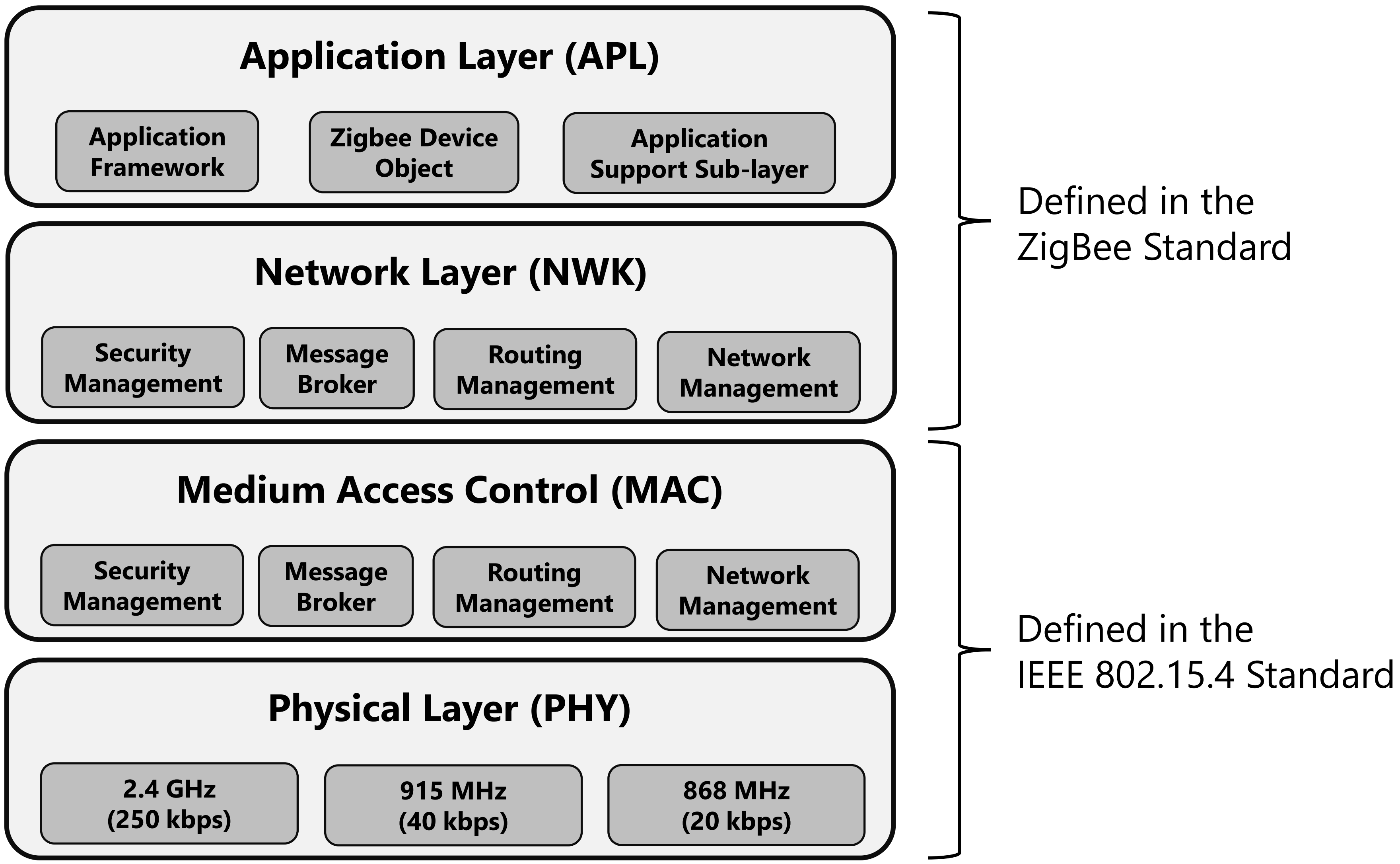
LoRa

LTE-M

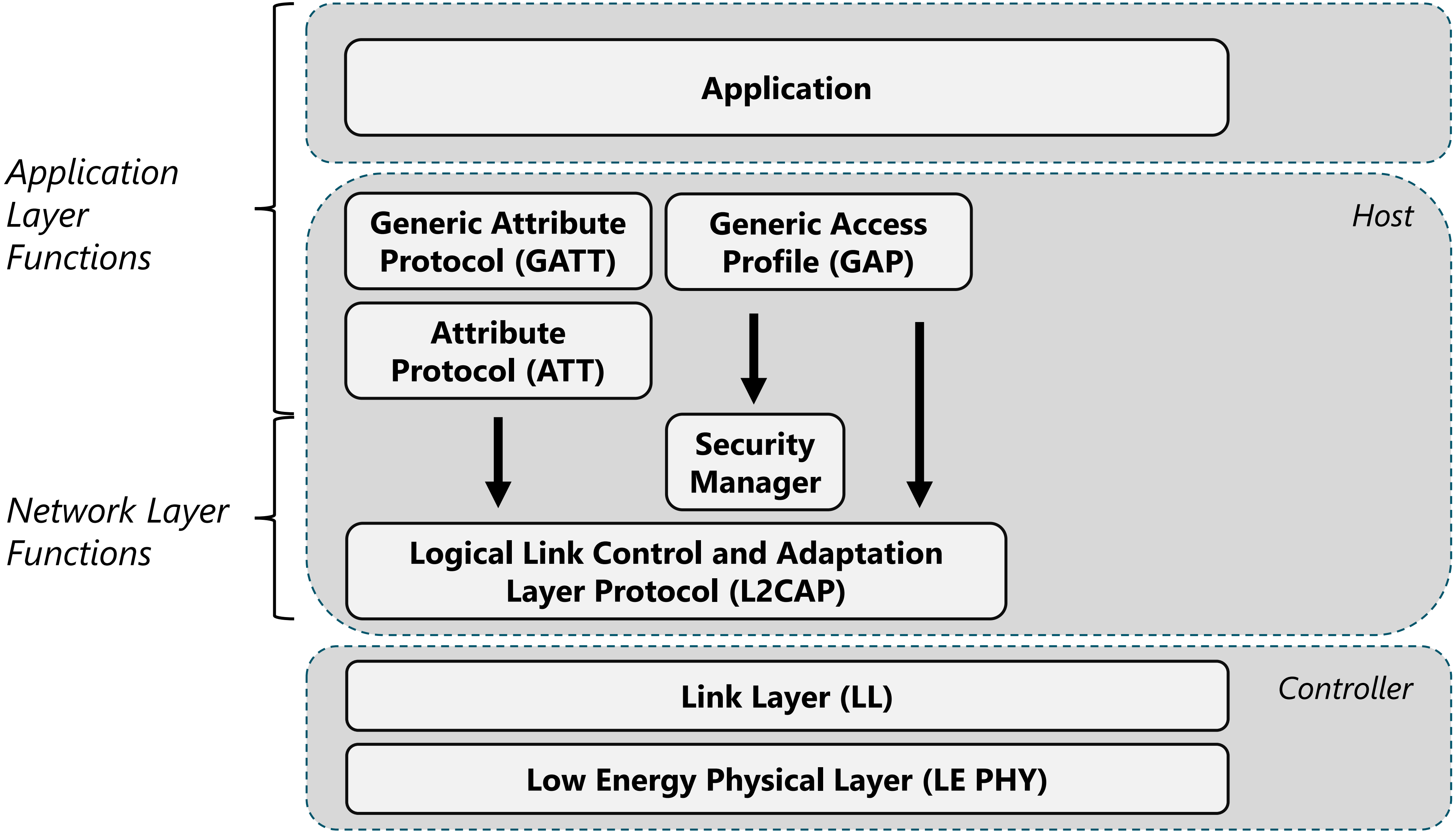
Different IoT Protocols for Different Environments



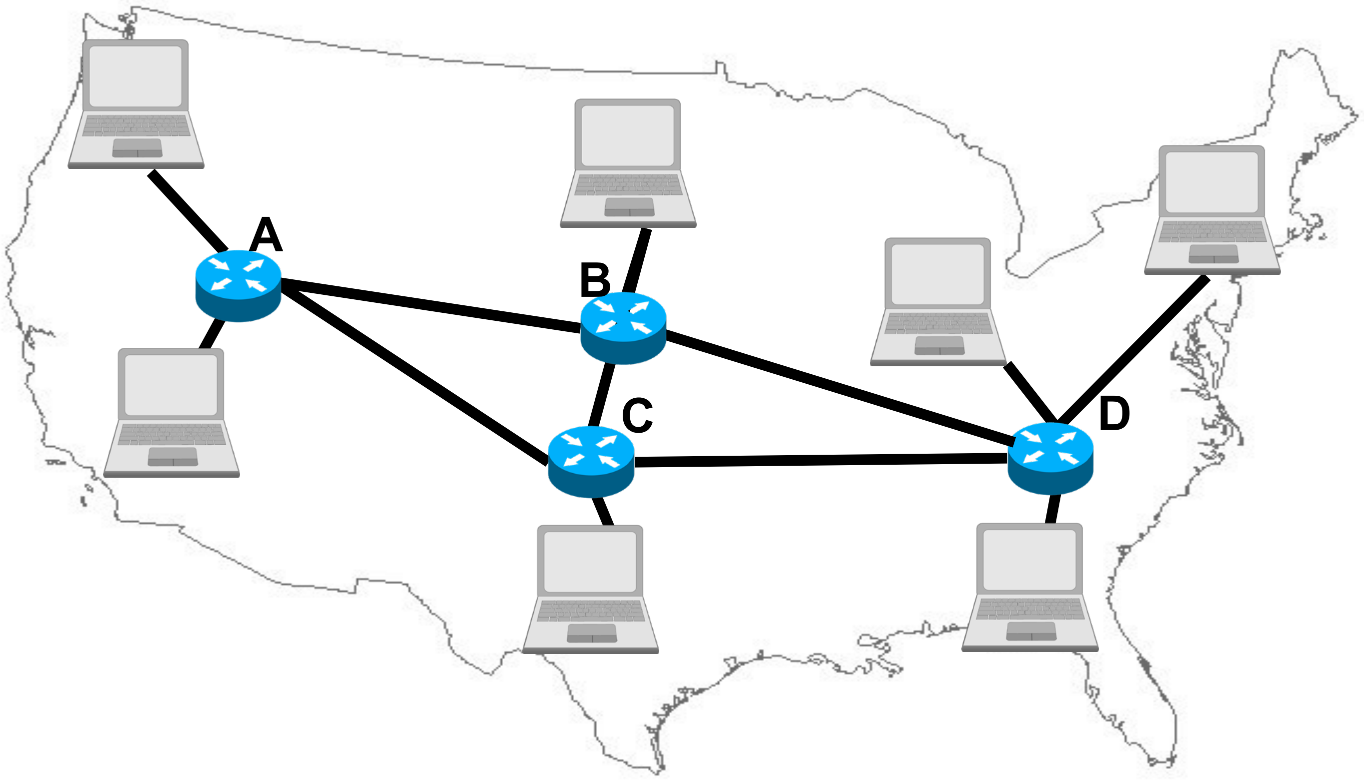
Zigbee Protocol Stack



Bluetooth Low Energy Protocol Stack



Is the Internet Just One Network?

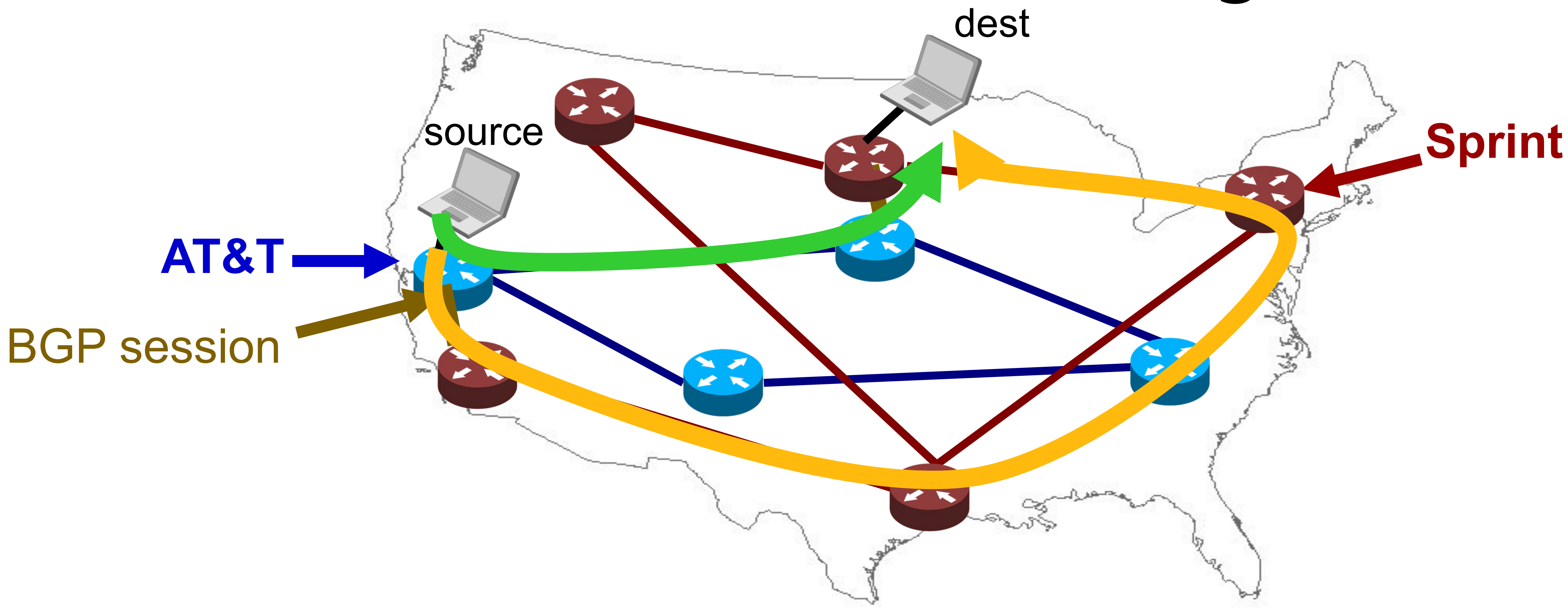


How Does Internet Routing Work?

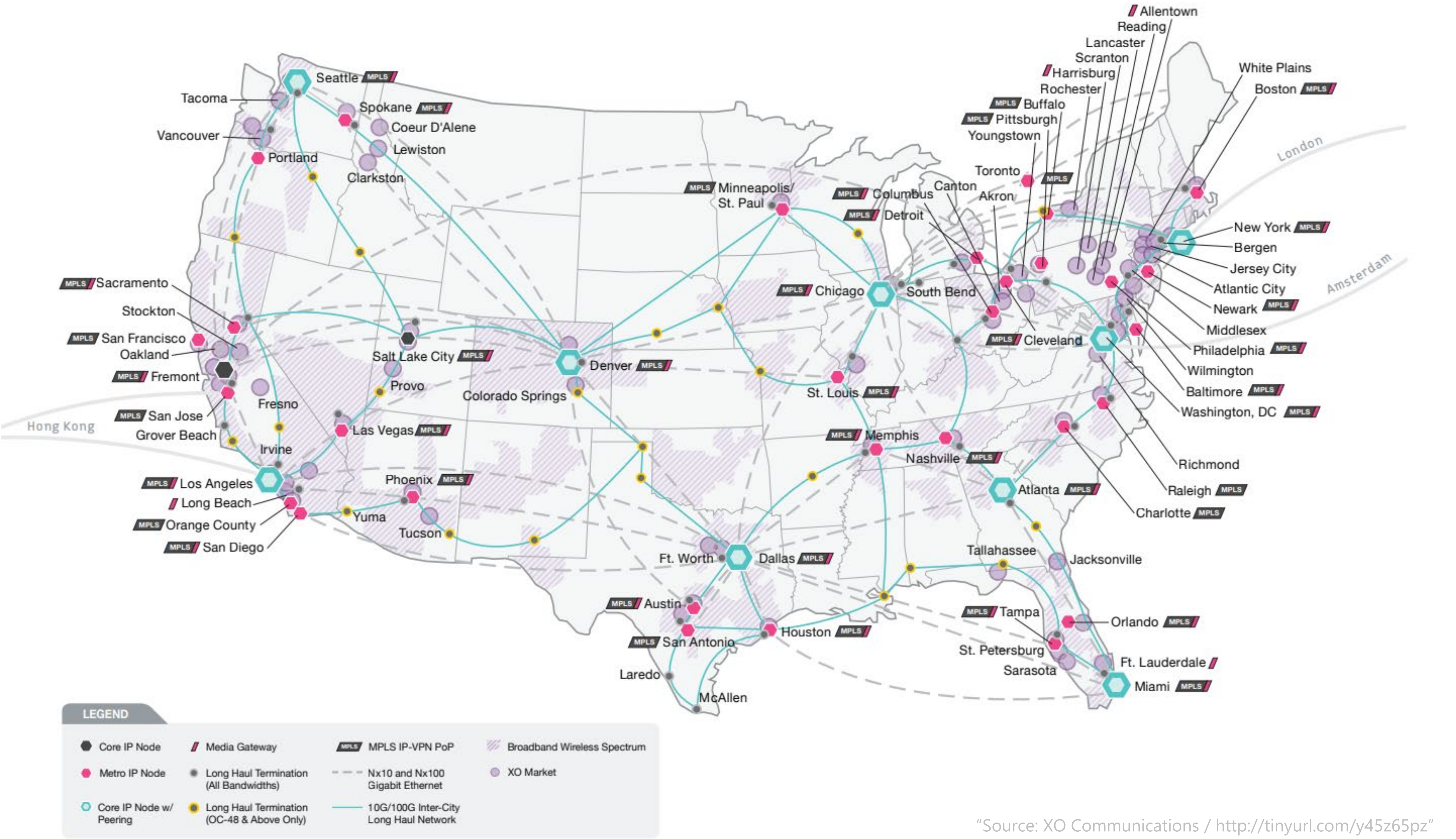
Internet routing works on two levels:

- Each AS runs an intra-domain routing protocol internally
  - Establishes routes to internal prefixes and between routers
  - Example protocols: OSPF, IS-IS
- Each AS runs an inter-domain routing protocol on links to neighboring ASes
  - Establishes routes to external destinations
  - Border Gateway Protocol (BGP)

Intra- vs. Inter-domain Routing

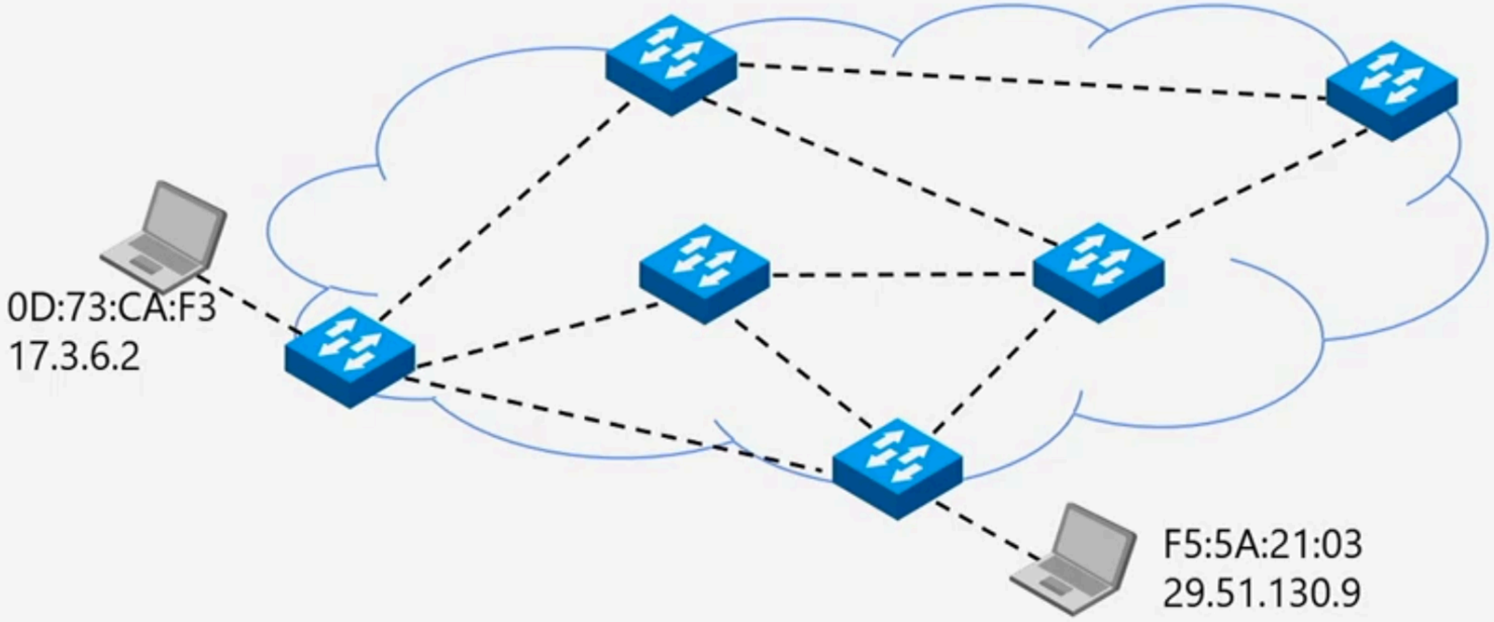


- Run “Interior Gateway Protocol” (IGP) within ISPs
  - OSPF, IS-IS, RIP
- Use “Border Gateway Protocol” (BGP) to connect ISPs
  - To reduce costs, peer at exchange points (AMS-IX, MAE-EAST)



"Source: XO Communications / http://tinyurl.com/y45z65pz"

L2 Switching vs L3 Routing: Routing Proactively Builds State



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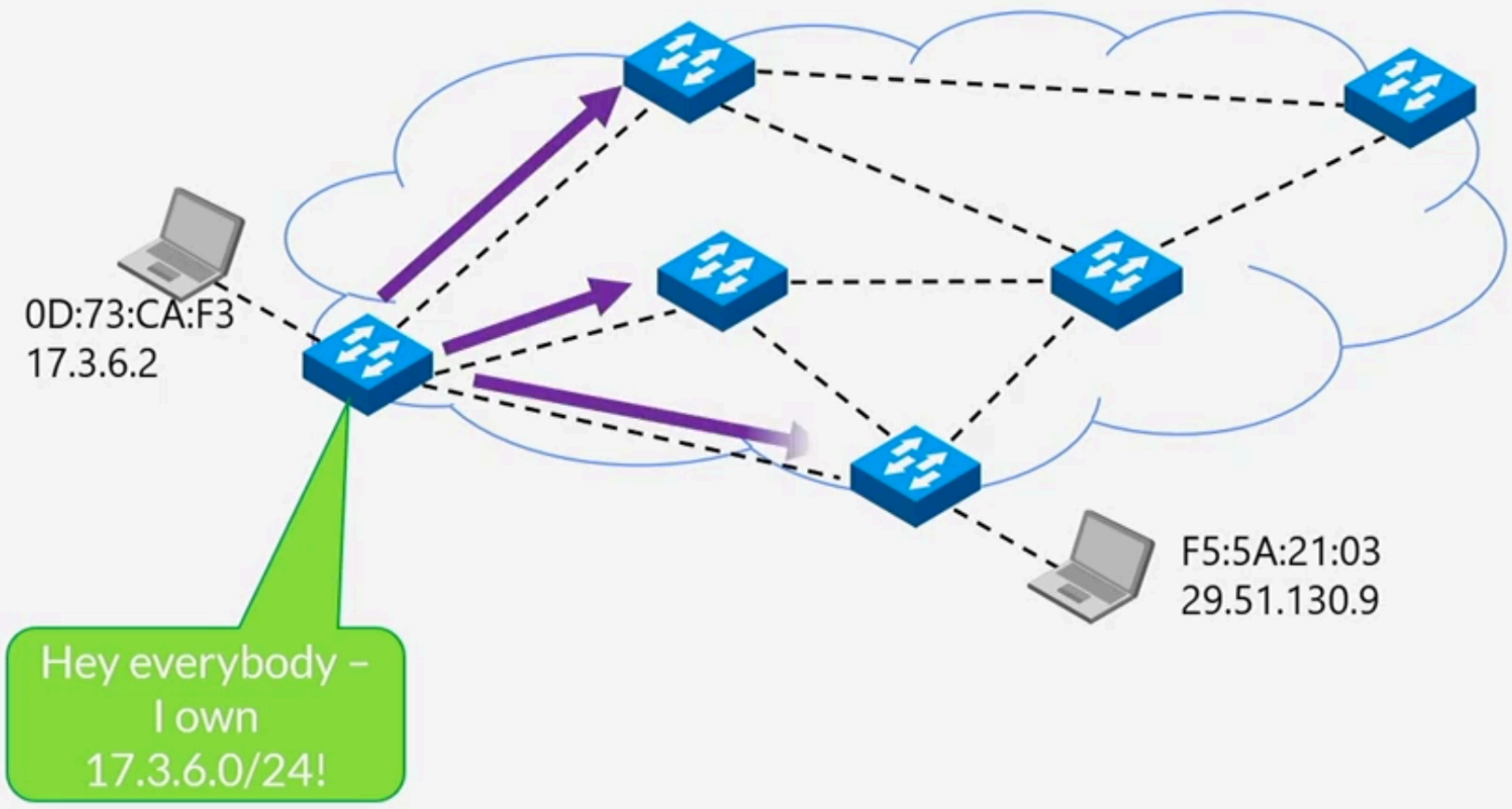
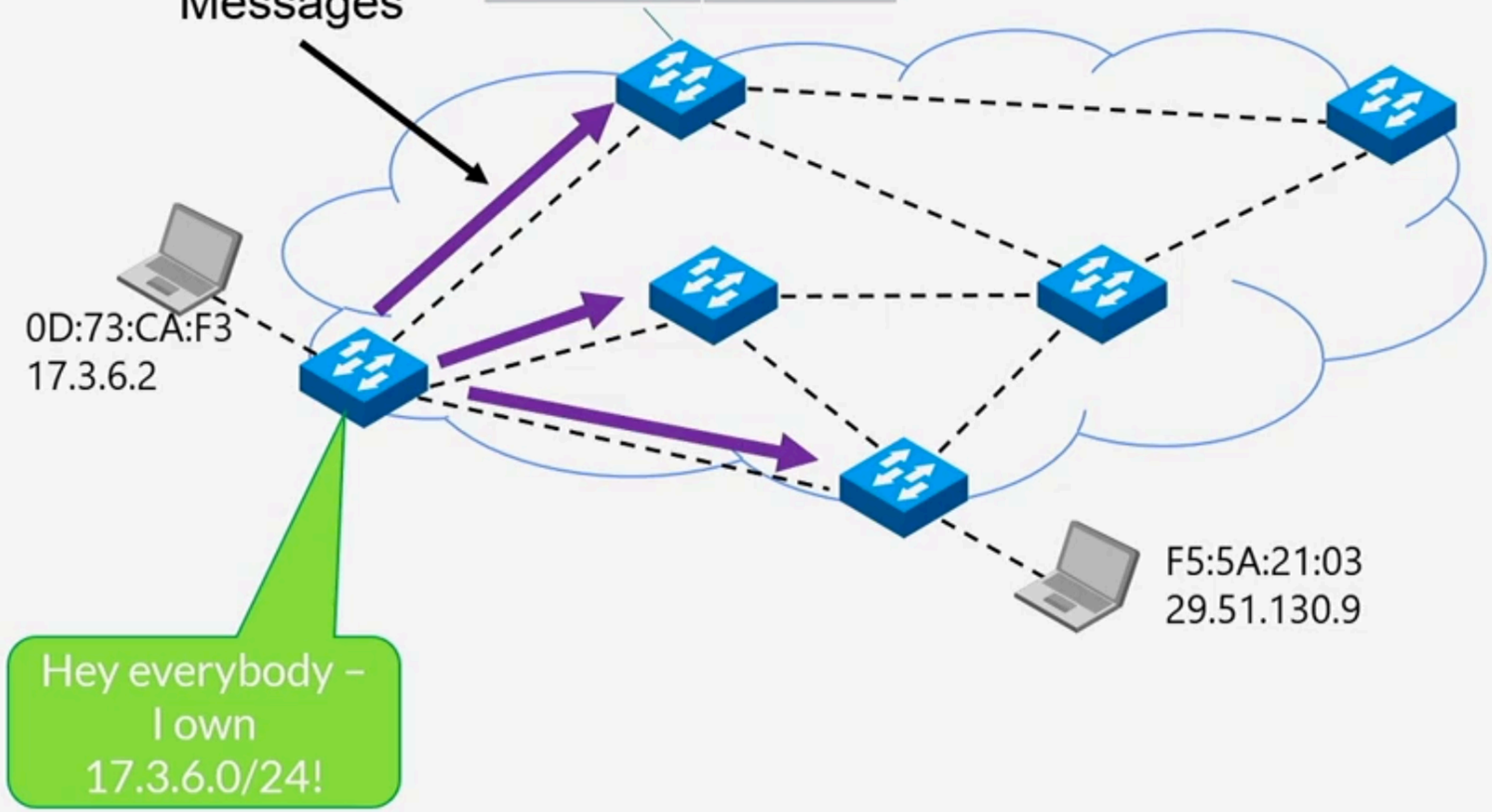


L2 Switching vs L3 Routing: Routing Proactively Builds State

Dest	Nexthop
17.0.0.0/24	fe3/0



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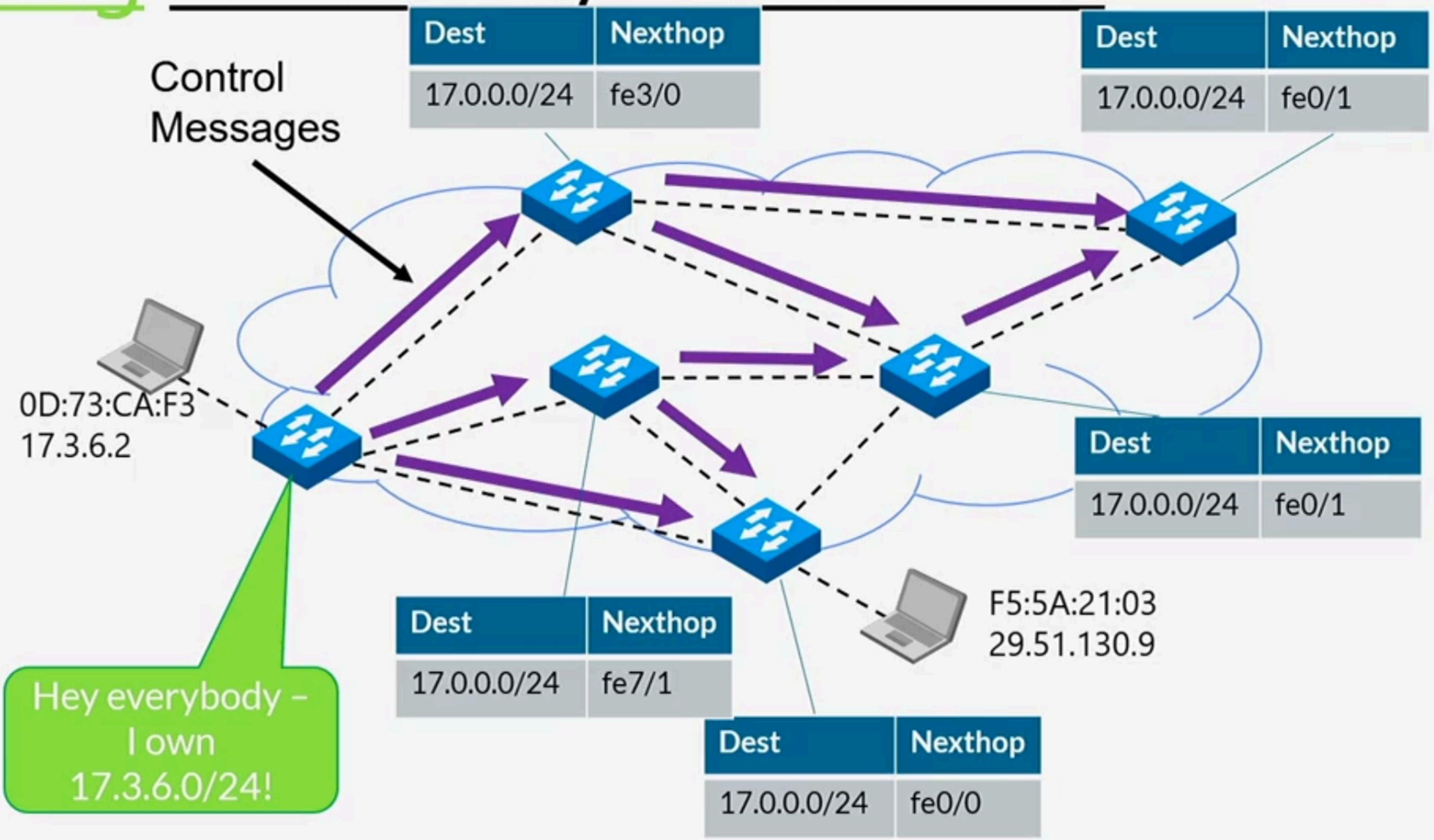

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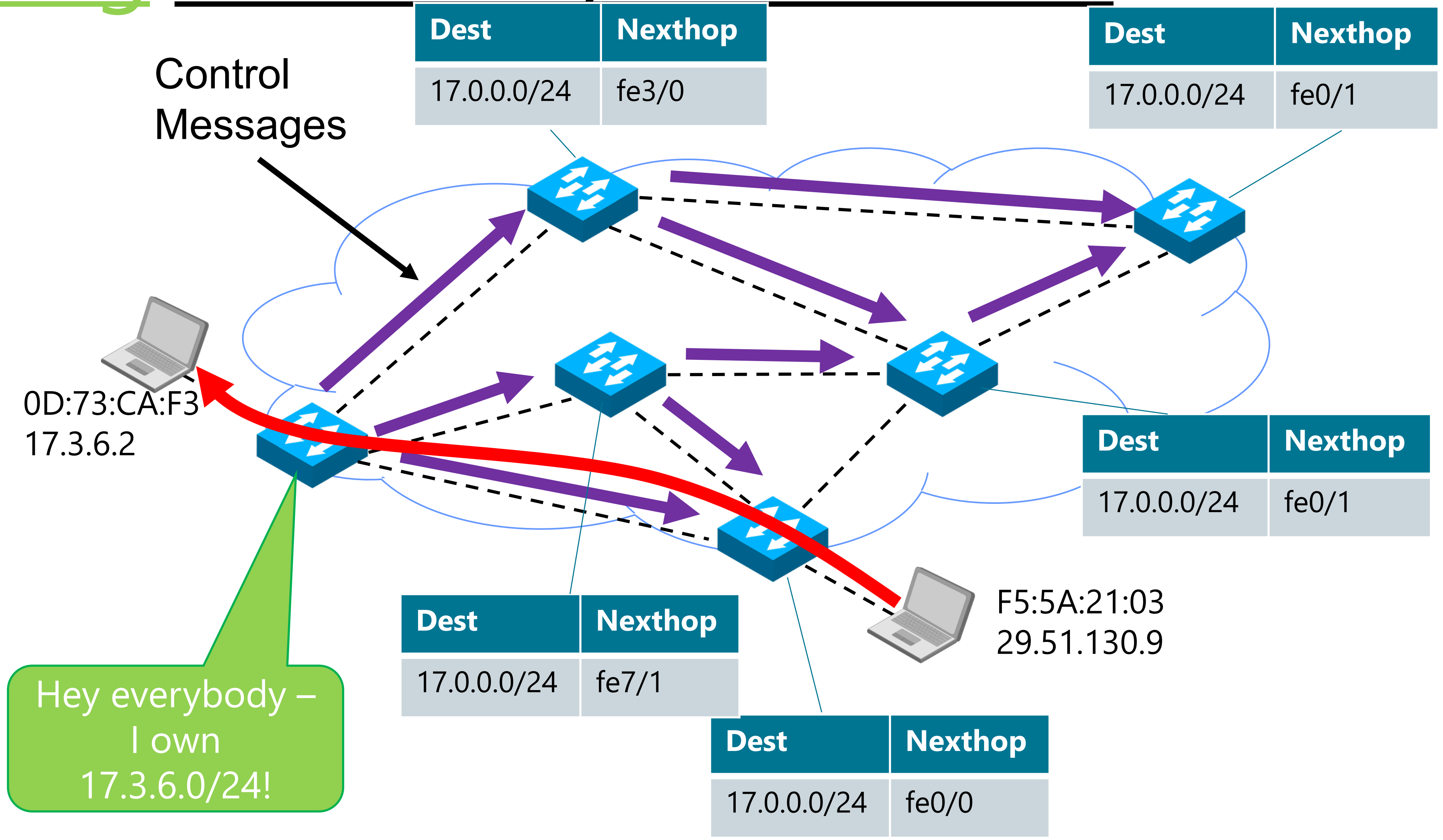
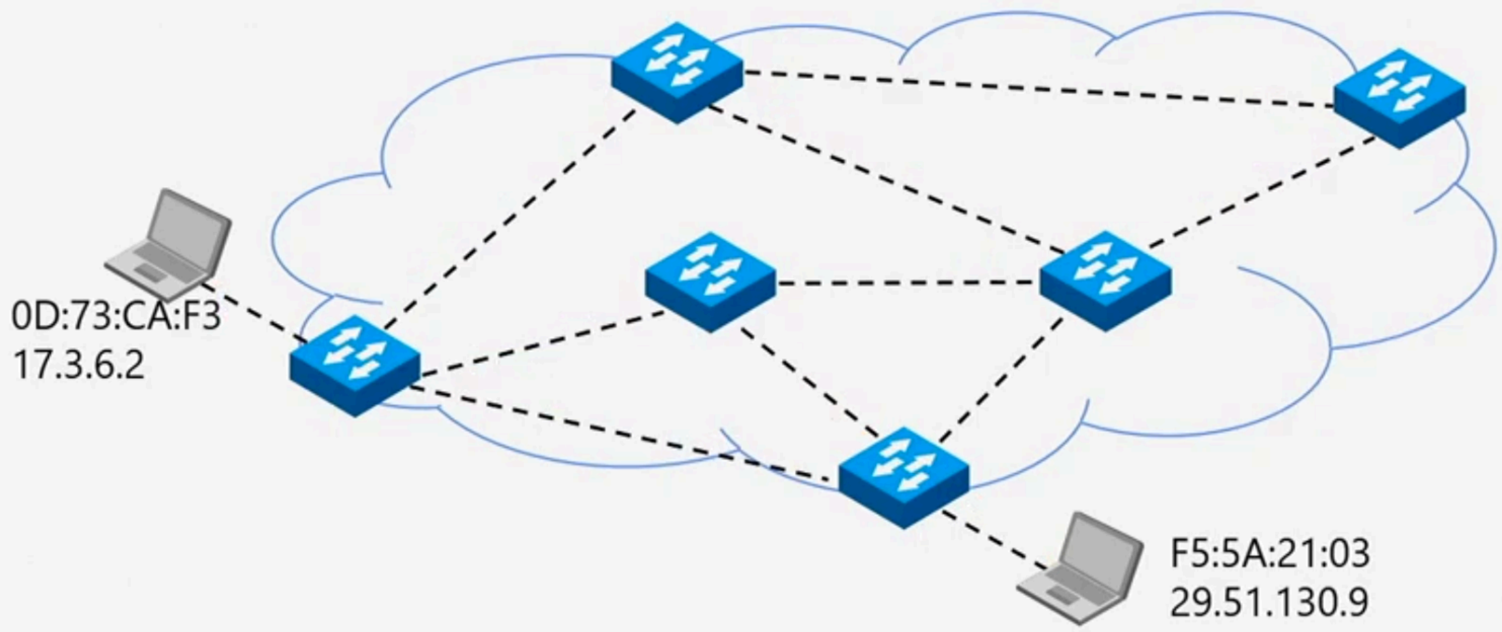


L2 Switching vs L3 Routing: Switching Relies on Broadcast



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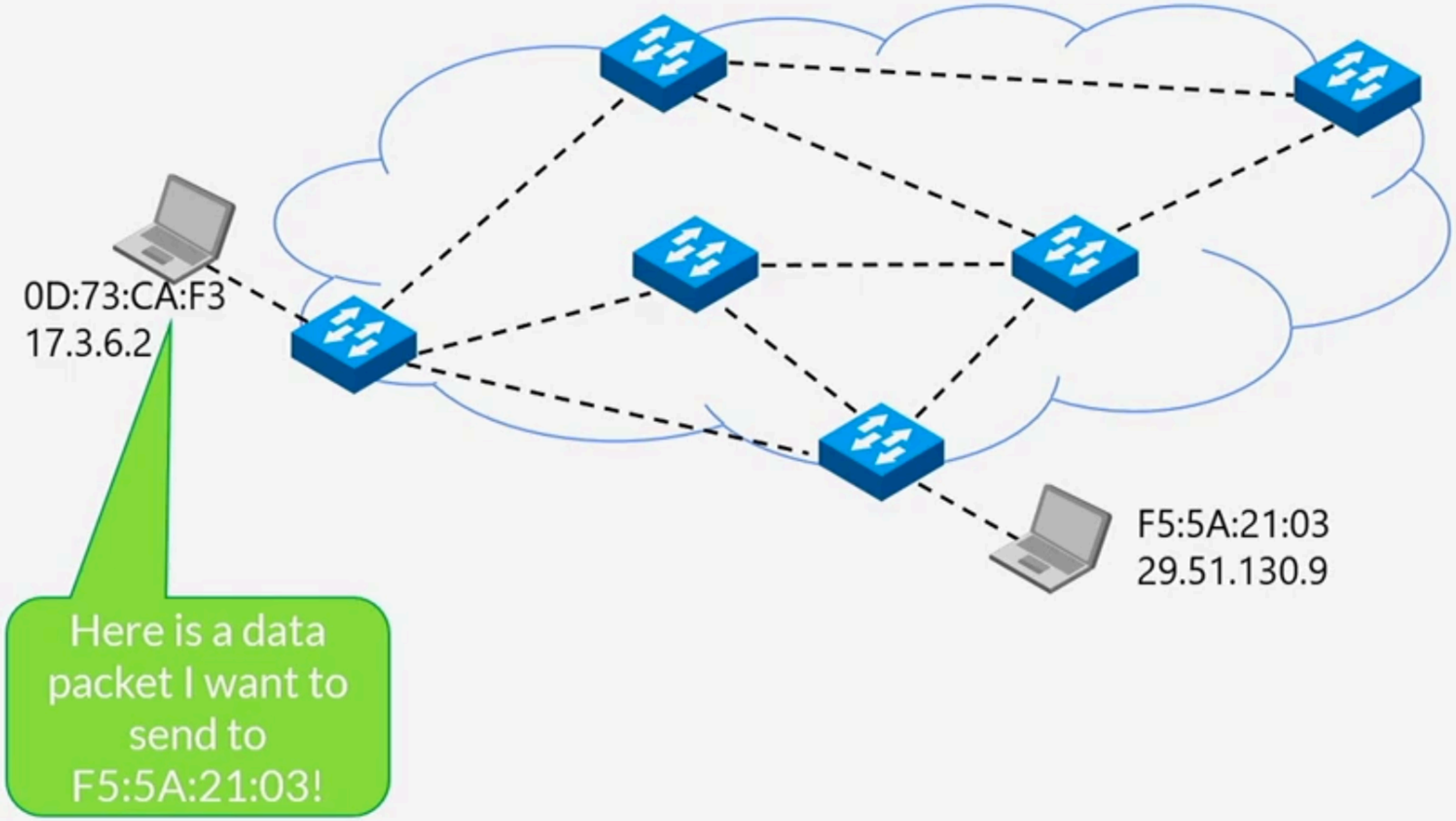

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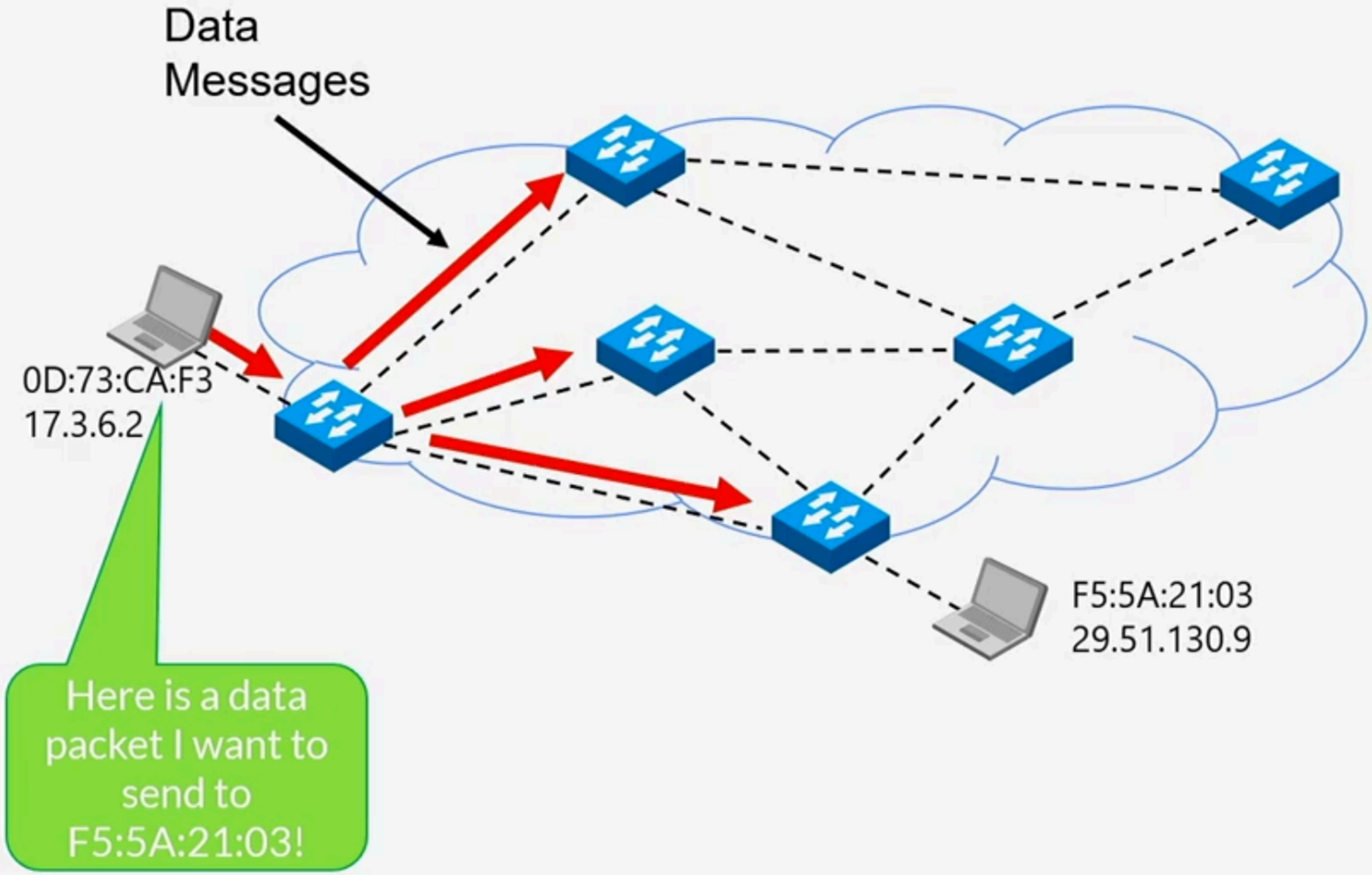

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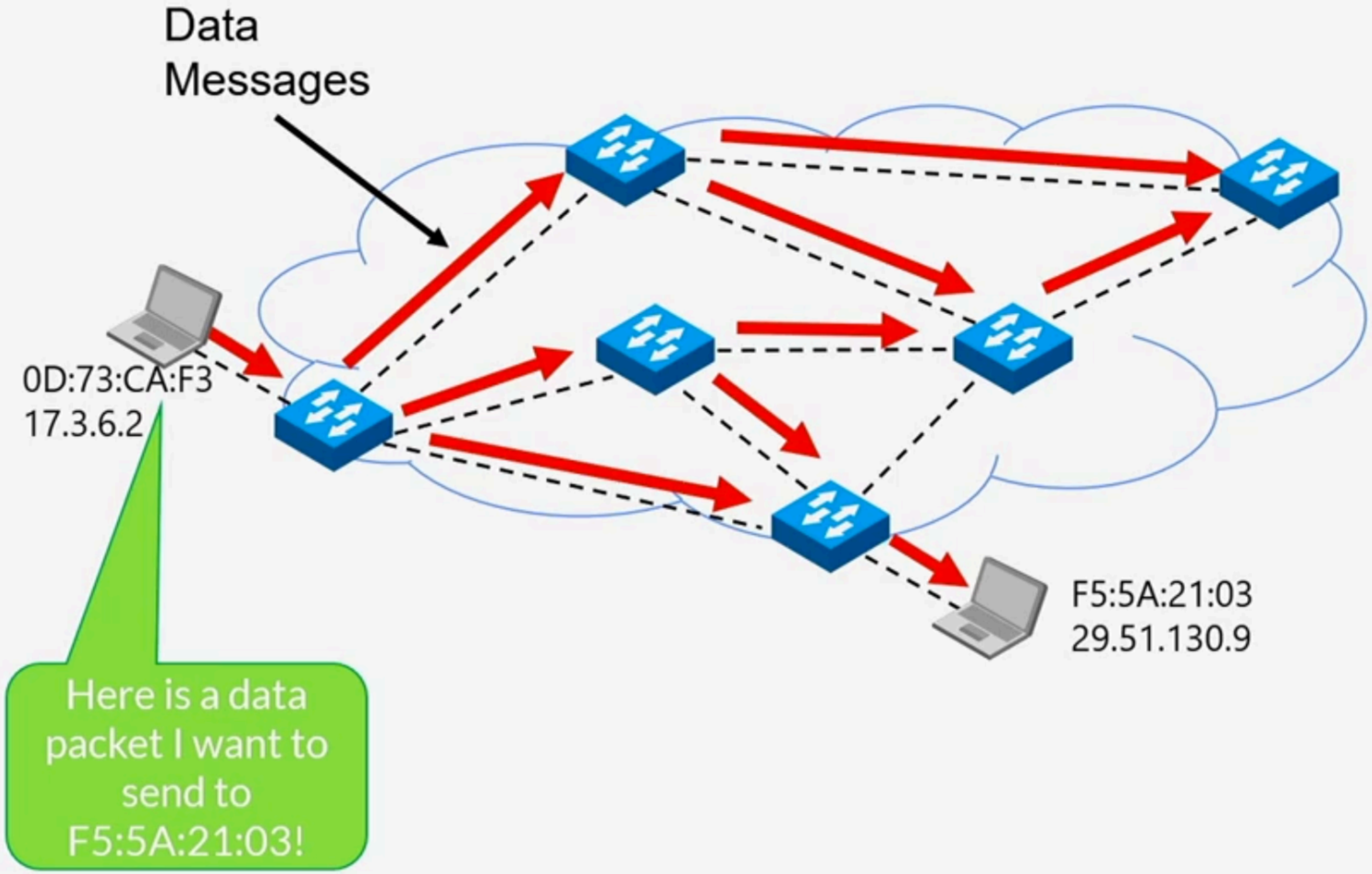

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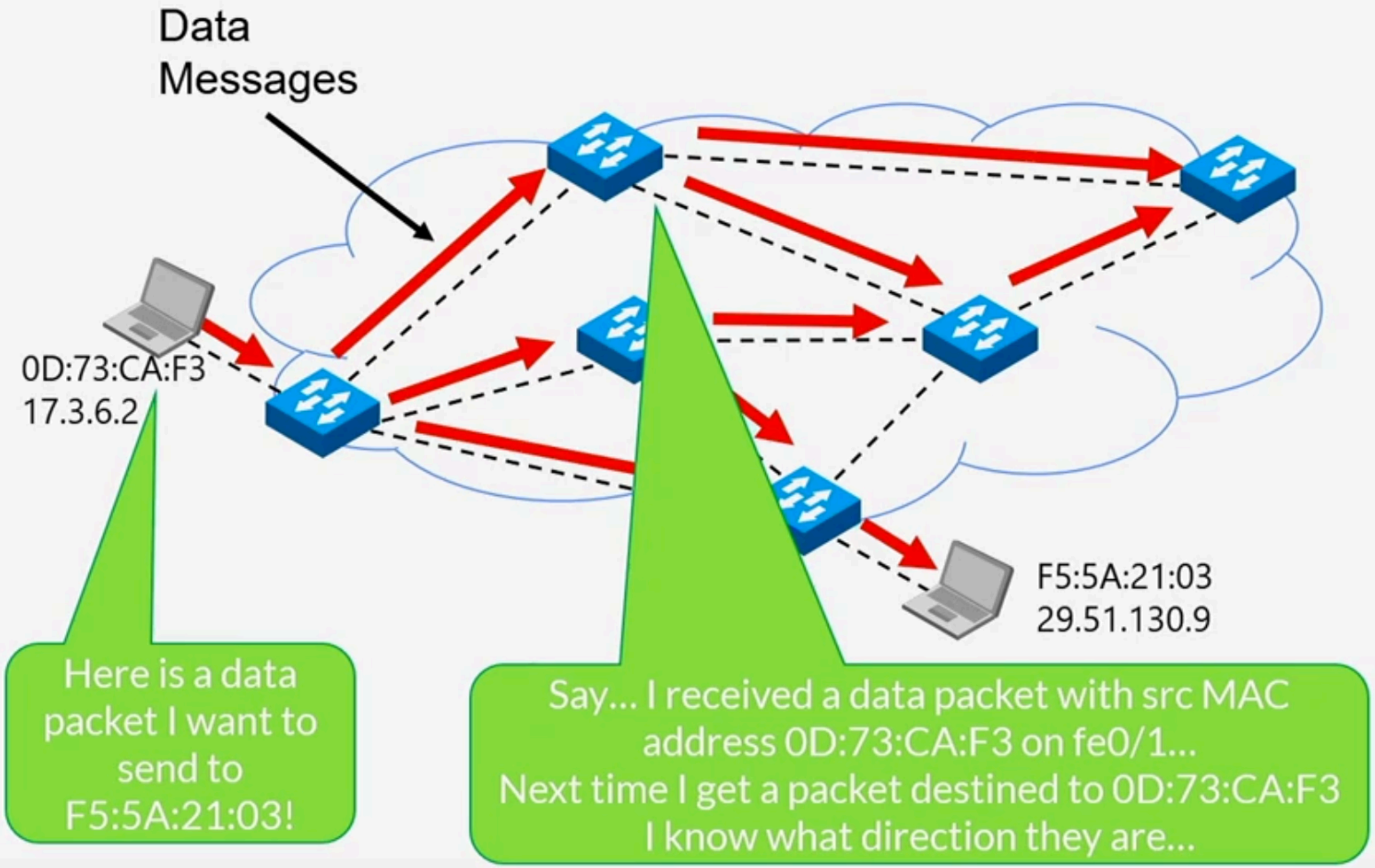
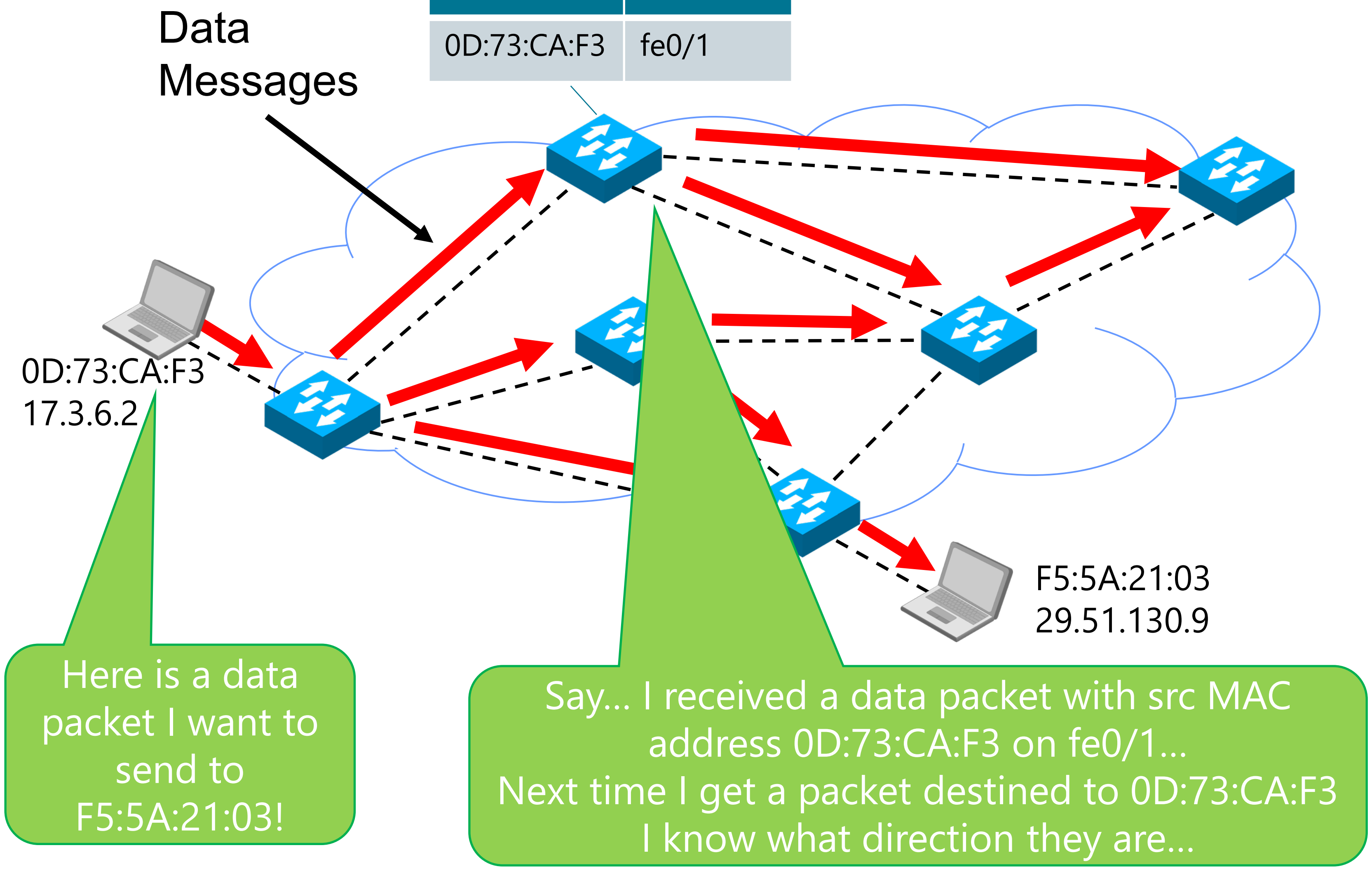


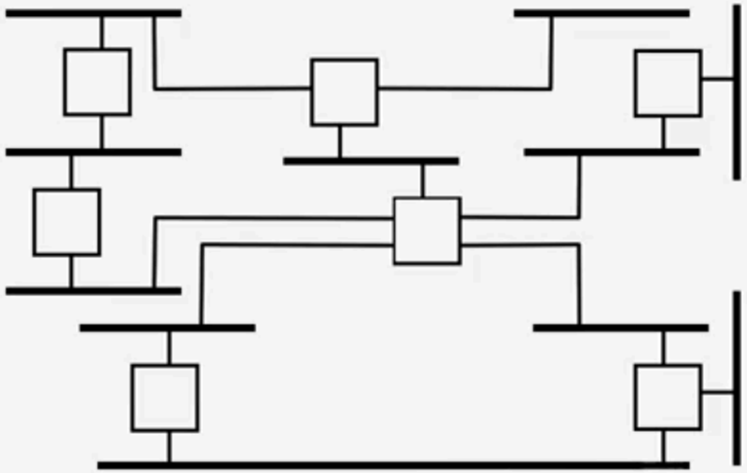
L2 Switching vs L3 Routing: Switching Relies on Broadcast

Dest	Nexthop
0D:73:CA:F3	fe0/1



Virtualizing Ethernet with VLANs

- Divide up hosts into logical groups called **VLANs**
  - Like virtual machines, but for LANs (creates "virtual networks")
  - VLANs isolate traffic at layer 2
- Each VLAN corresponds to IP subnet, single broadcast domain
- Ethernet packet headers have VLAN tag
- Bridges forward packet only on subnets on corresponding VLAN



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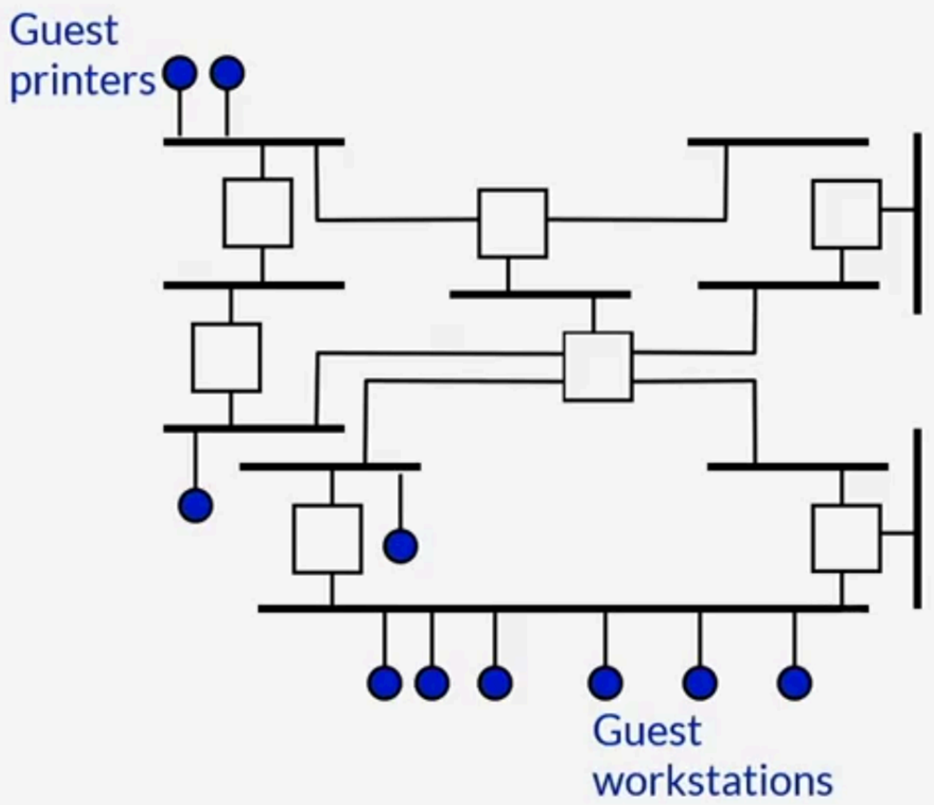

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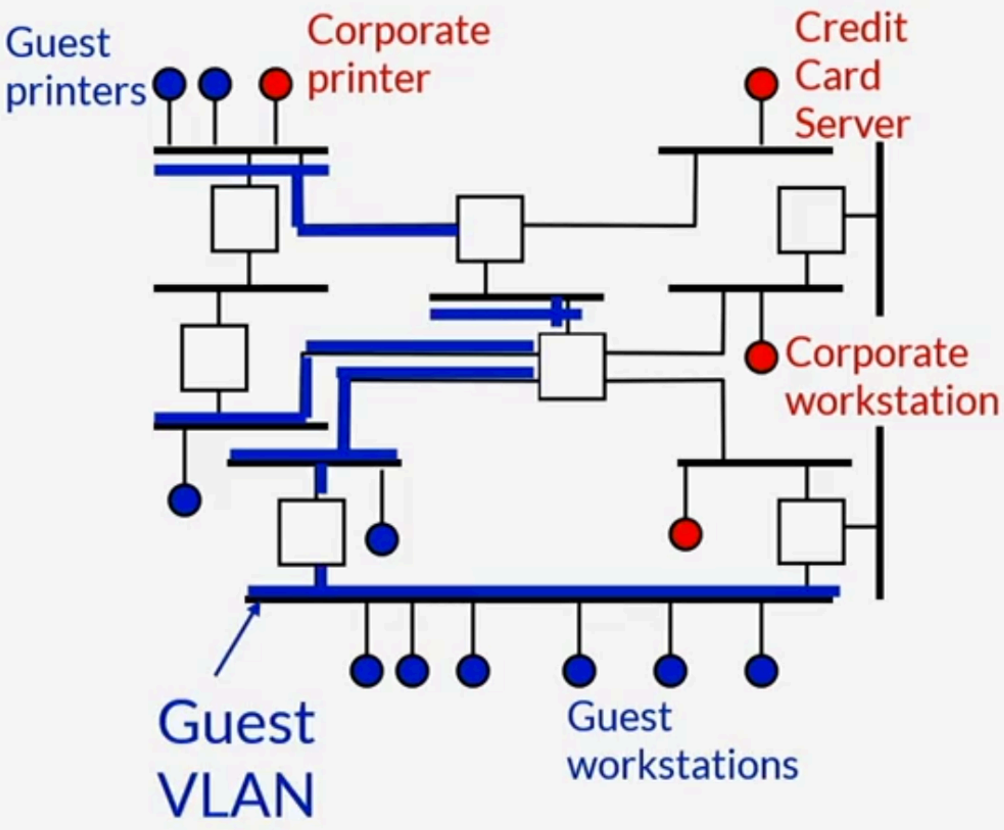

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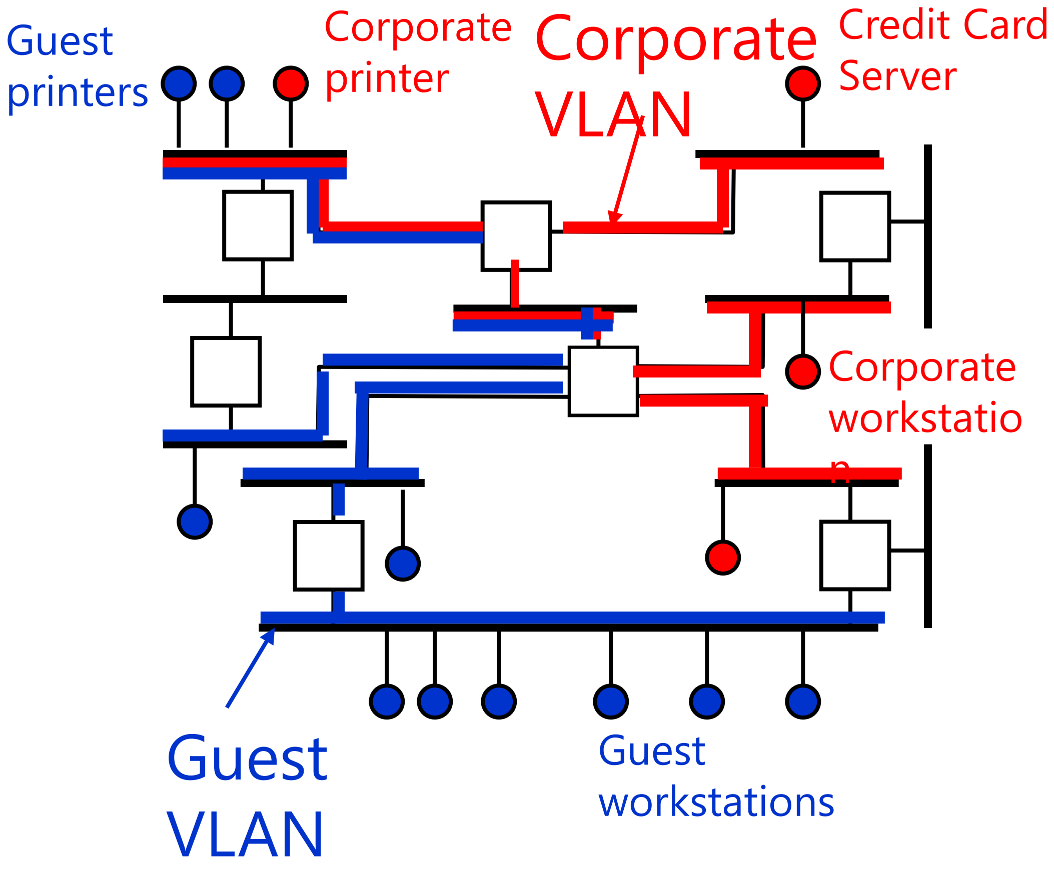
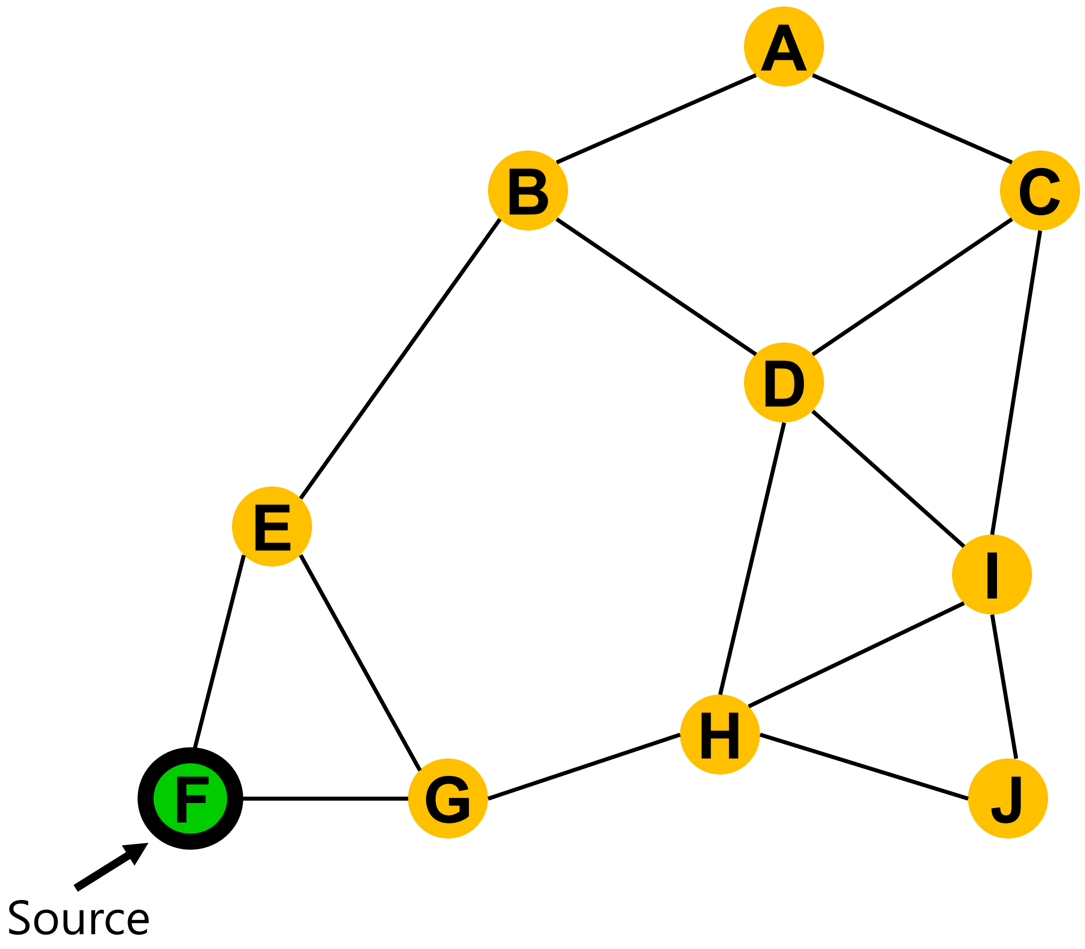
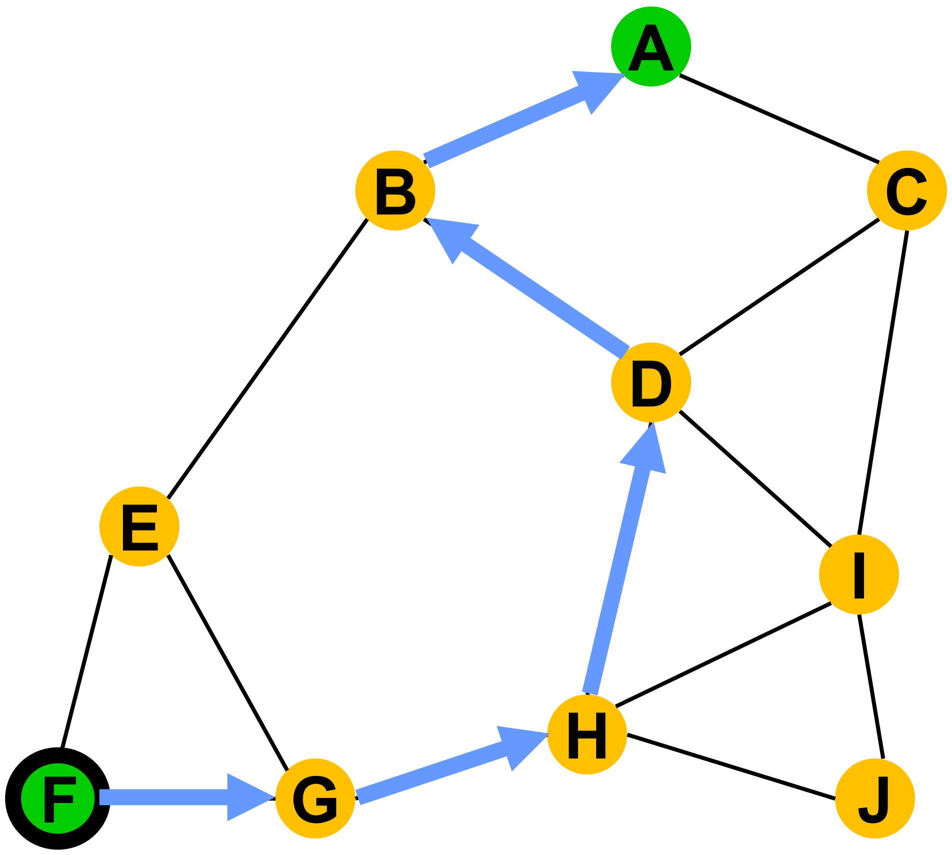


Delivery Models



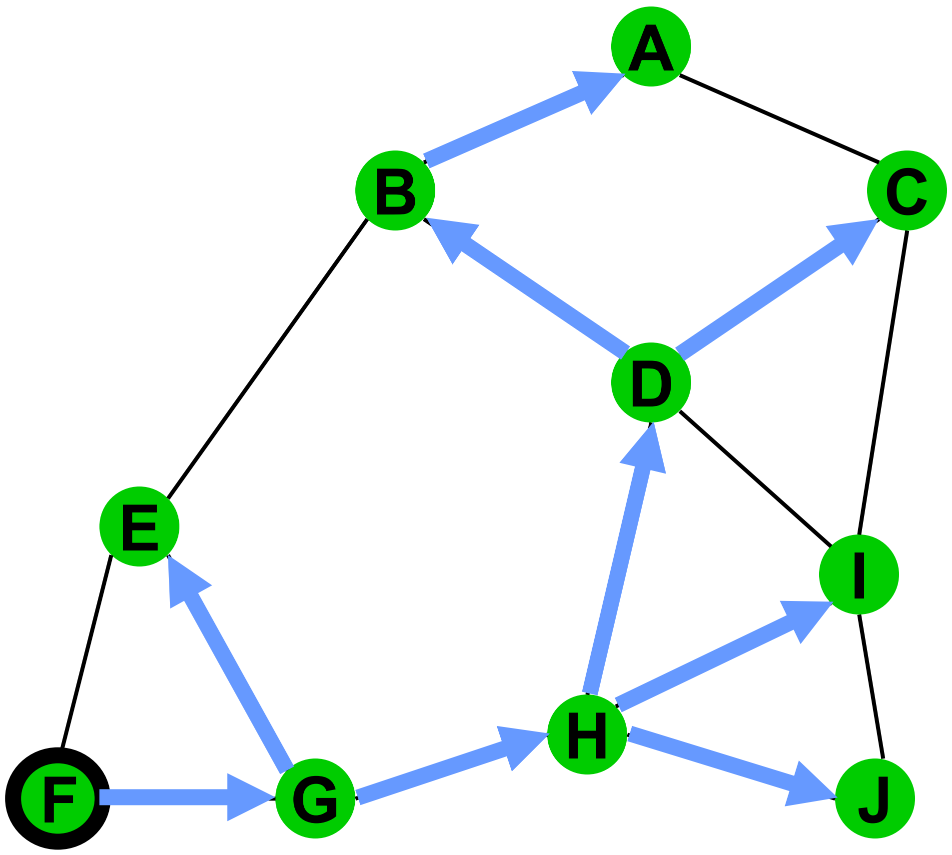
- Unicast
- Broadcast
- Multicast
- Anycast

Delivery Models



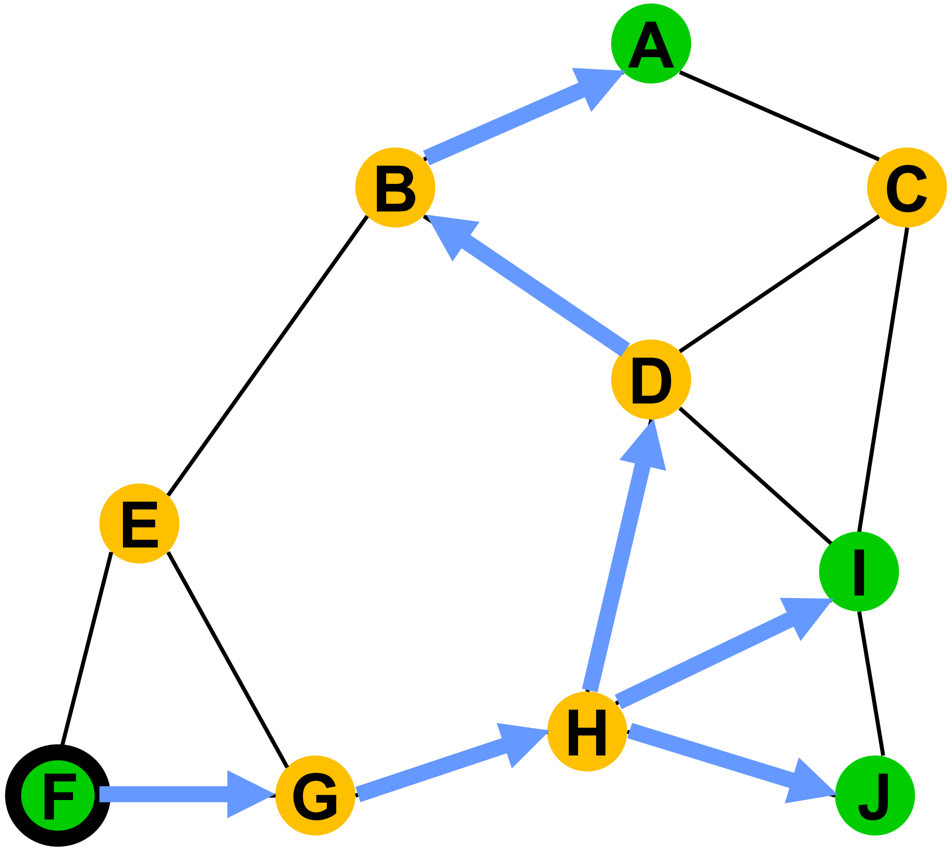
- **Unicast**
  - One source, one destination
  - Widely used (web, cloud, streaming; many protocols)

Delivery Models



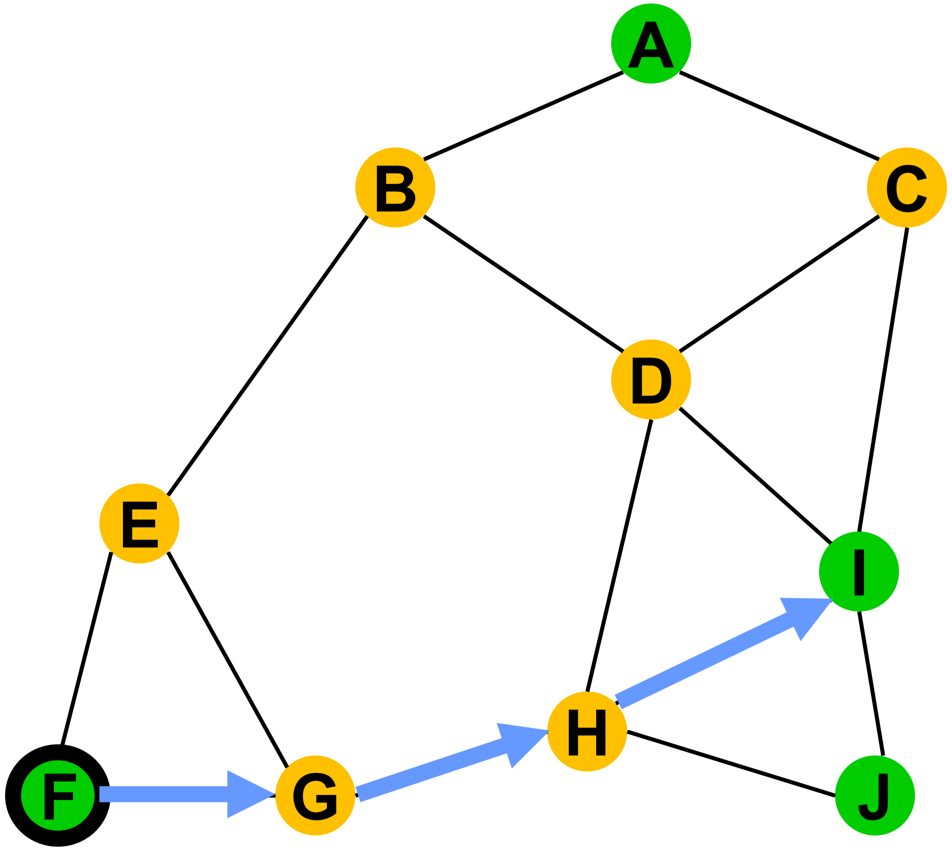
- **Broadcast**
  - One source, all destinations
  - Used to disseminate control information, perform service discovery

Delivery Models



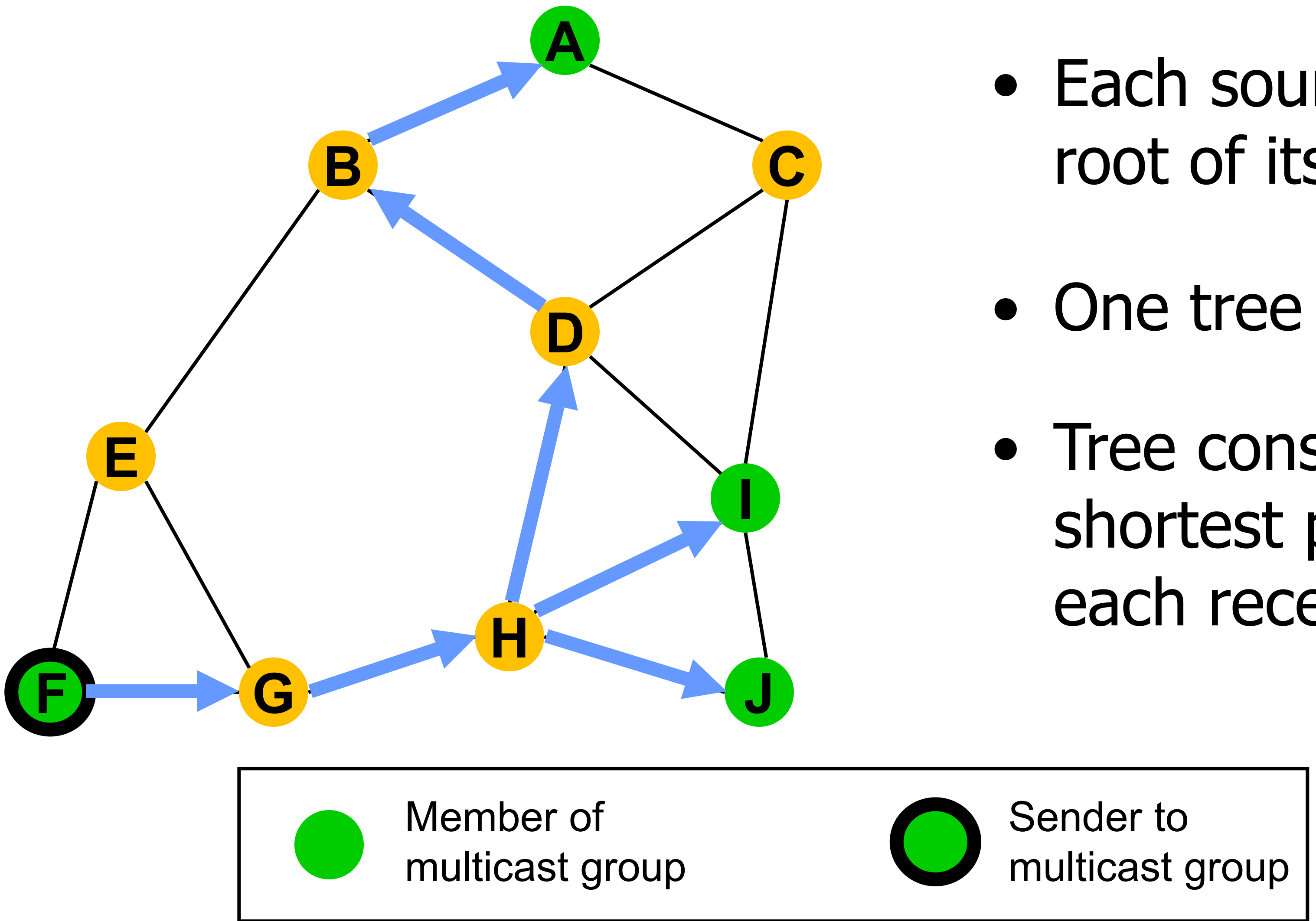
- **Multicast**
  - One source, several (prespecified) destinations
  - Used within some ISP infrastructures for content delivery, overlay networks

Delivery Models



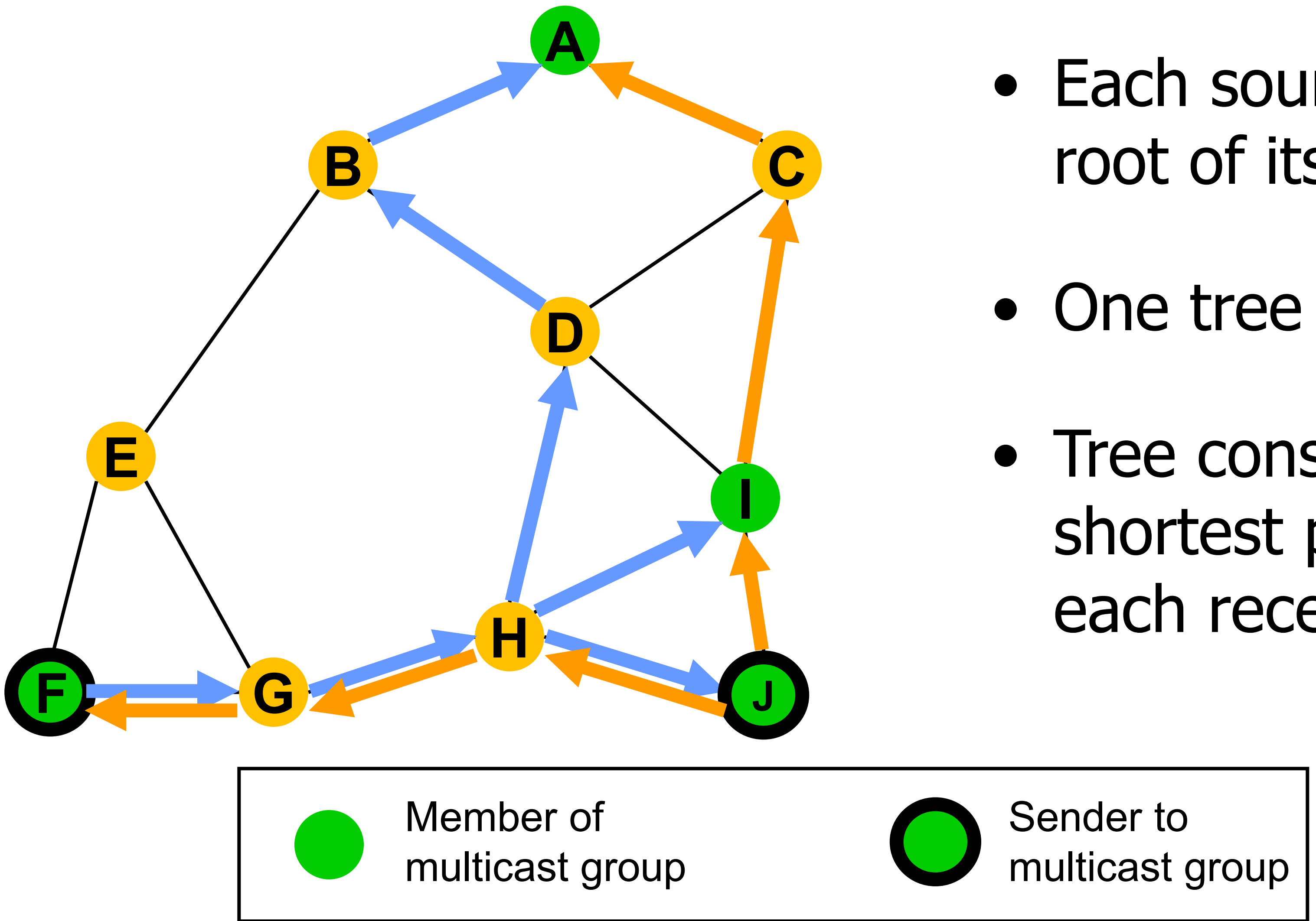
- **Anycast**
  - One source, route to "best" destination
  - Used in DNS, content distribution, service selection

Multicast: Source-Specific Trees



- Each source is the root of its own tree
- One tree per source
- Tree consists of shortest paths to each receiver

Multicast: Source-Specific Trees



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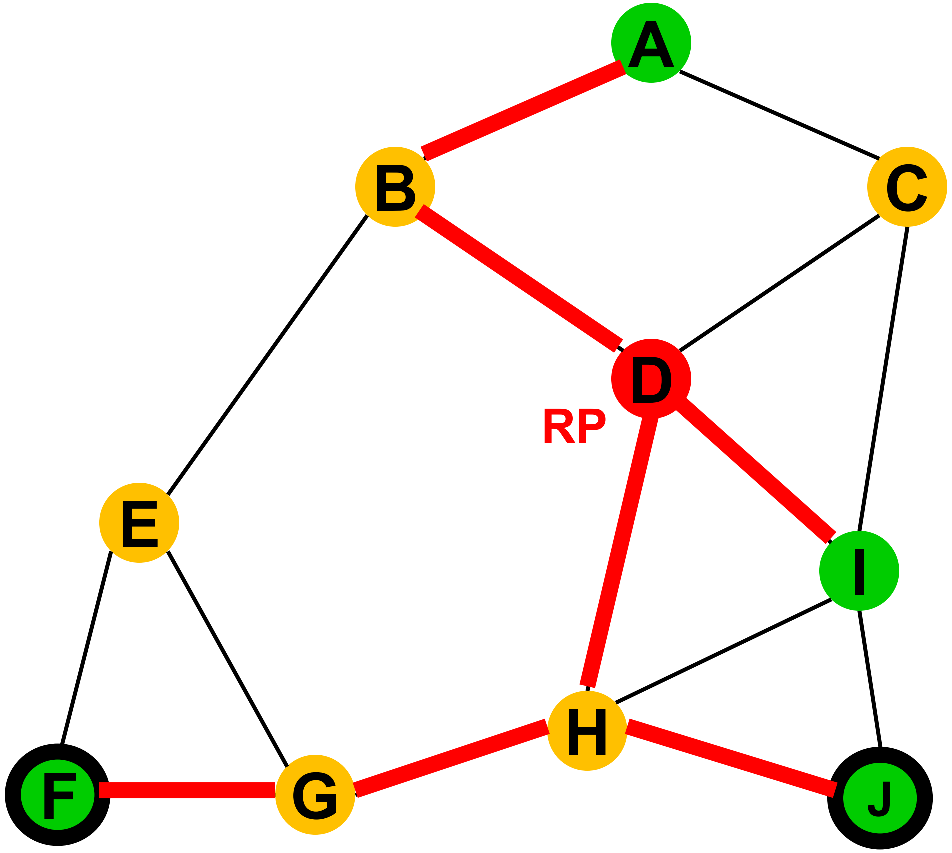
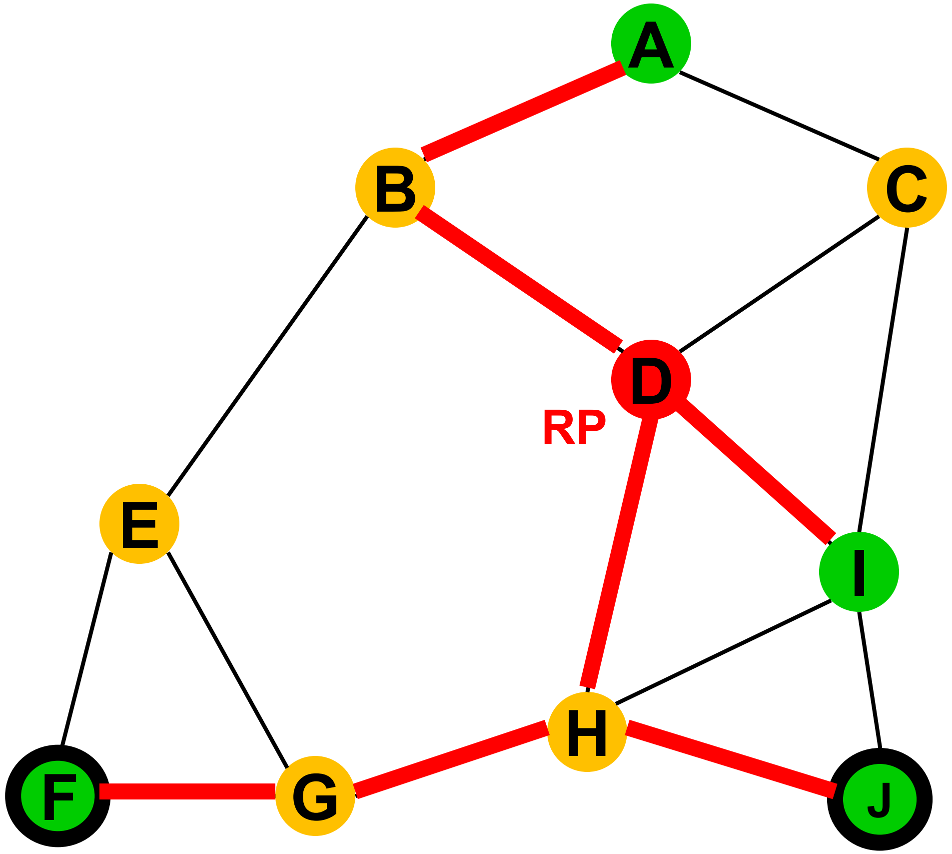
Multicast: Shared Tree



- One tree used by all members of a group
- Rooted at "rendezvous point" (RP)
- Less state to maintain, but hard to pick a tree that's "good" for everybody

Multicast: Shared Tree



- Ideally, find a "Steiner tree" minimum-weighted tree connecting **only** the multicast members
  - Unfortunately, this is NP-hard
- Instead, use heuristics
  - E.g., find a minimum spanning tree (much easier)

Example Applications

- So many applications, scenarios, use cases for IoT
  - Seems hard to digest it all

- But beneath it all are commonalities
  - Common architectures, protocols, designs

- This lecture: some walkthroughs to give you a taste
  - Example applications and solutions for IoT

Environmental Monitoring

- Earth is very important to humans
  - Air we breathe, food we eat, comes from earth
  - 90% of human diseases (and medicines) come from wildlife
- Important we understand environment
  - Global warming reducing arable land, honeybees disappearing, pollution kills millions of people

Environmental Monitoring: Wildlife

- Earth is facing its 6th major extinction event
  - 10,000 species go extinct every year
  - # species halved in last 40 years
  - Comparable to "Snowball Earth" and the asteroid that wiped out the dinosaurs
- Threats: Escalating poaching, human encroachment, climate change, disease
- Understanding the problem can help us solve it

Environmental Monitoring: Wildlife

- Animal monitoring an essential part of almost all conservation efforts
  - If they are ill, injured, caught in a trap, we can find and help them
  - Big changes in migration patterns, population density
  - Elephants, Whales, Tigers, Macaws, etc. on the verge of extinction

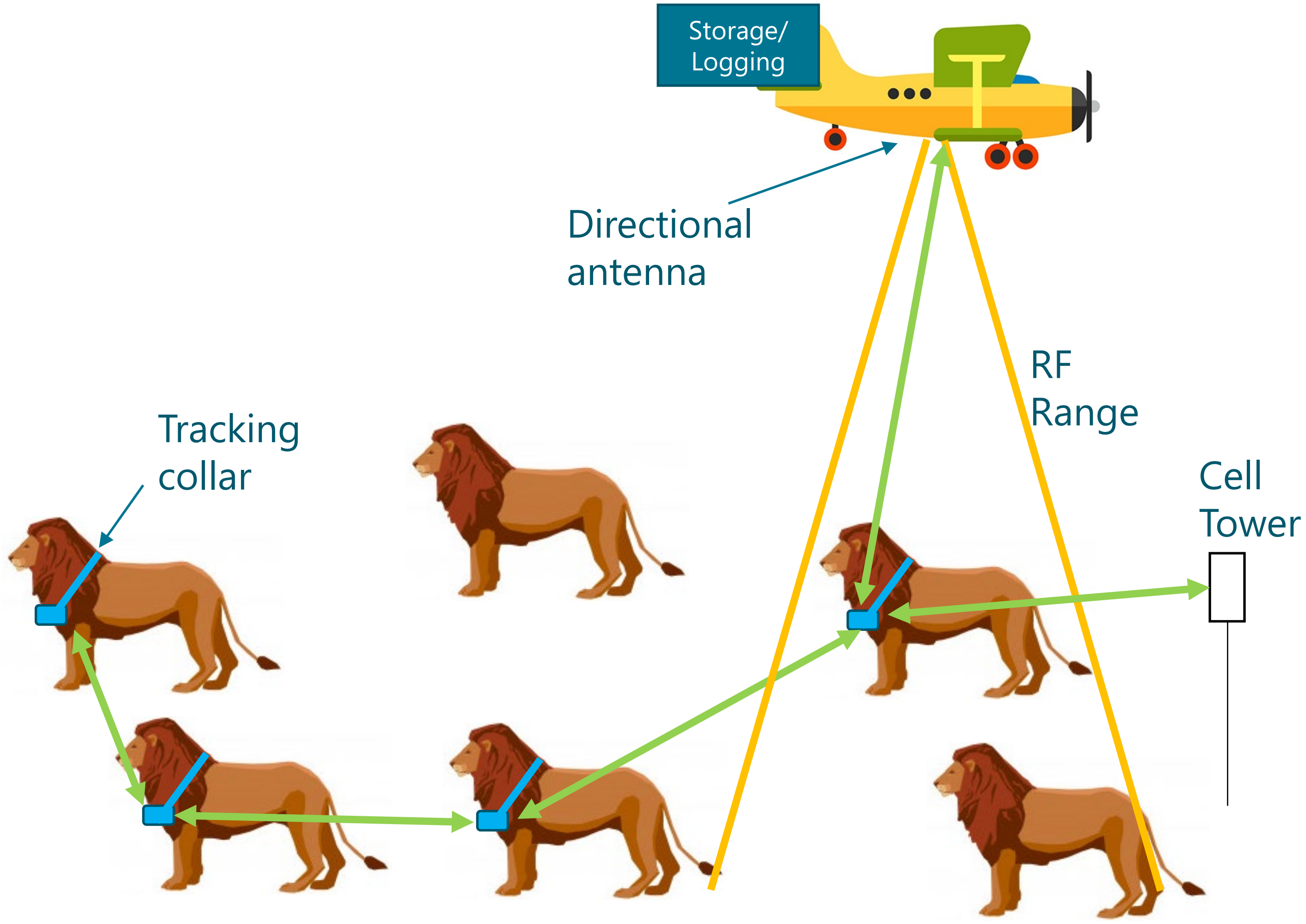
- IoT: Check up on animals continually, rather than once a day or by spotting
  - Enables studies of new dynamics: “interactions” and social habits, movement patterns; rapid response to poaching events

Environmental Monitoring: Wildlife: How it’s Done

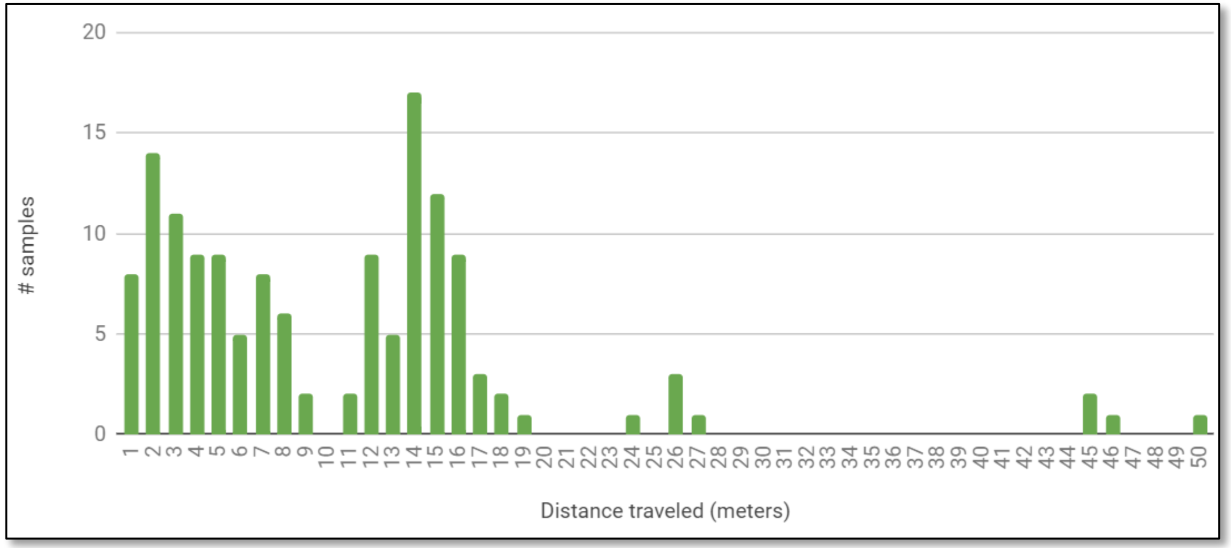
- Animal outfitted with collar containing sensor array, storage, and networking
  - GPS sensor, accelerometer/gyroscope/magnetometer, biometric sensors, flash memory, wireless transceivers, and CPU
  - Considerations: Weight limit (e.g., 3-5 pounds), lifetime (e.g., 1 year with no human intervention)

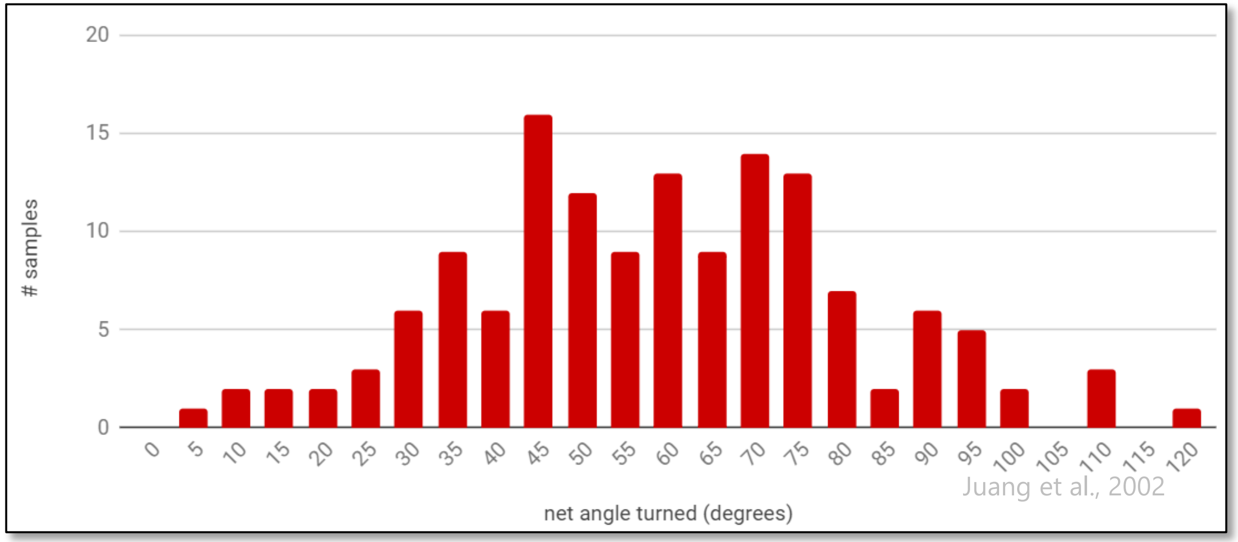
Wildlife Tracking Architecture

- No pervasive infrastructure such as antenna towers
  - Plane flyovers – listen for pings from collars
  - Peer-peer communication to replicate info across collars
    - E.g., use gossip opportunistically during encounters



Environmental Monitoring: Wildlife: Sample Findings (Zebra Monitoring)



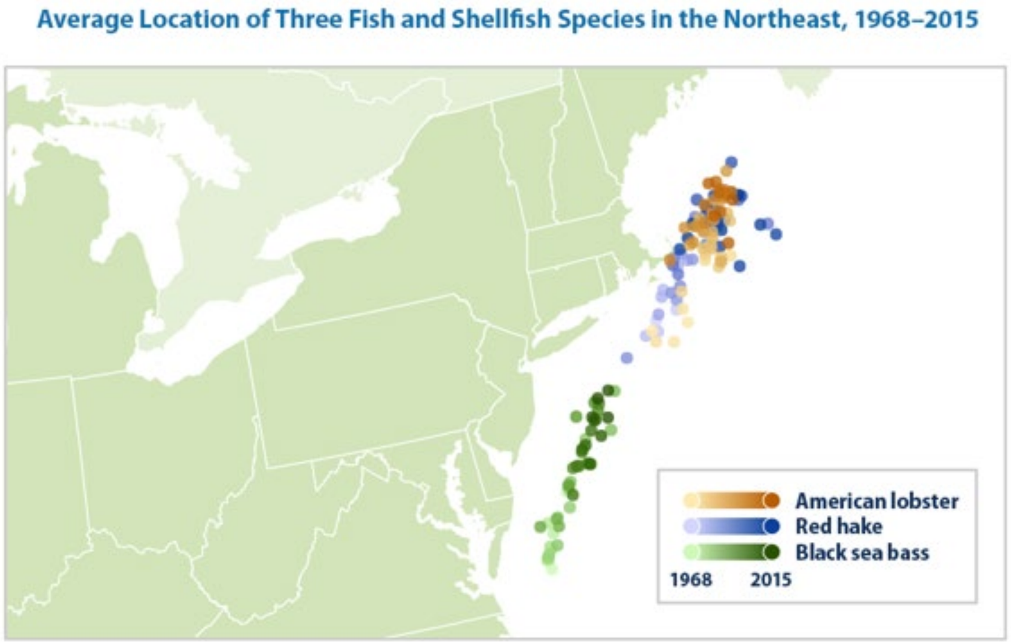


- Movement patterns: grazing, graze-walking, occasionally fast-moving
- Zebras tend not to sleep deeply
- Seek out water about once a day, drink relatively quickly

Other Kinds of Environmental Monitoring

- Forestry monitoring
  - Illegal logging, land-use/species changes, health, fire prediction
  - Study physical characteristics: tree height, diameter at base, stem density, canopy/foliage density, discolorations, water content
  - Challenges: no fixed infrastructure, large multipath effects (long-wave, relays, satellite)

Other Kinds of Environmental Monitoring



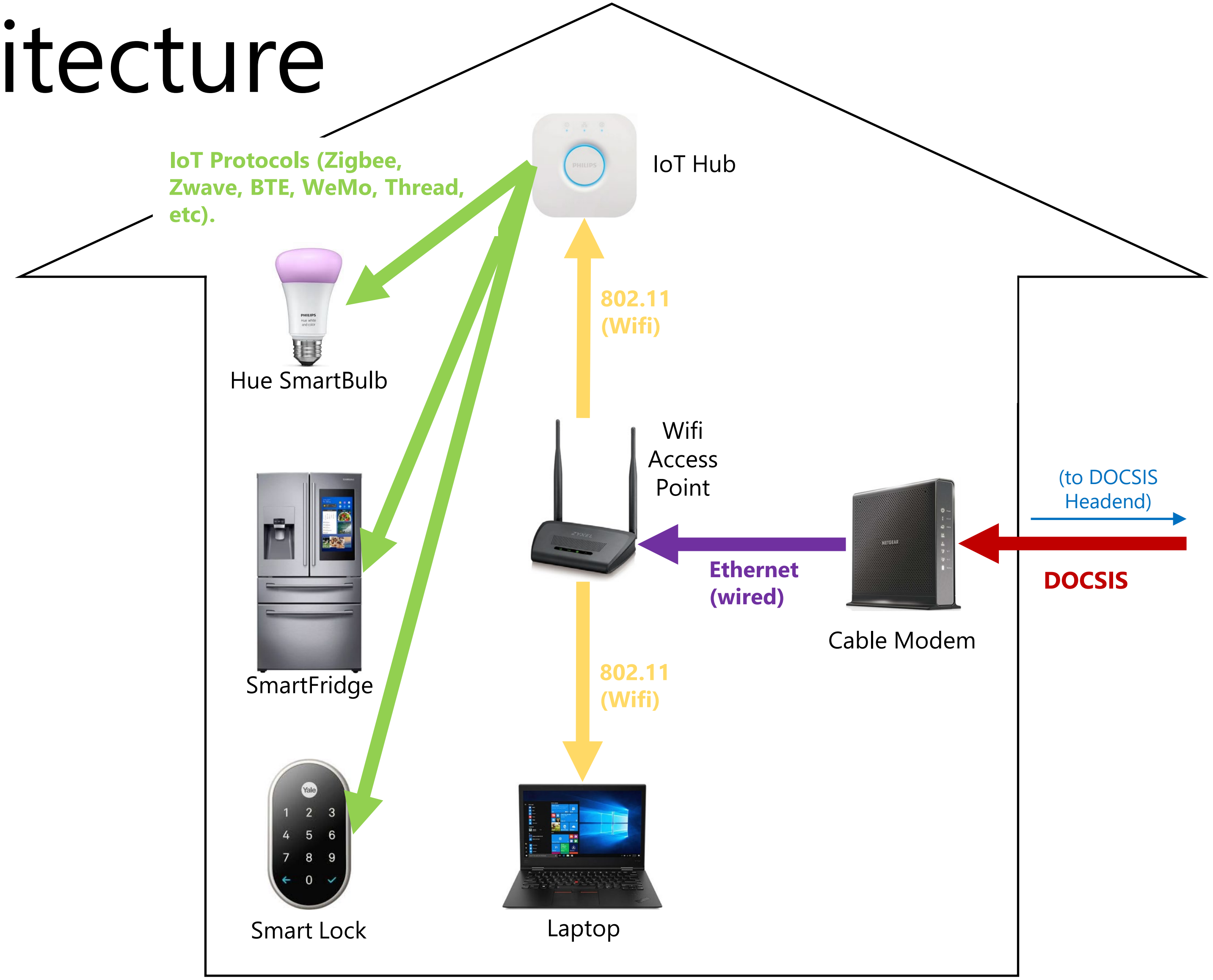
- Marine Animal monitoring
  - Sea turtles, coral reefs, mercury exposure in fish
  - Migration patterns, pollution exposure, breeding/nesting patterns
  - Challenges: underwater communication (sonar/long-wave)

Smart Homes

- Controls lighting, climate, entertainment systems, and appliances
  - Wireless speakers, thermostats, home security systems, domestic robots, smoke/CO detectors, energy brokers, lighting, door locks, refrigerators, laundry machines, flood/water detectors
- Example Applications
  - Automating chores: watering lawns,
  - Turning on/off lights as you move between rooms
  - Automatic doorbell based on presence detection
  - Automatically adjusting thermostat based on learned occupancy patterns

Smart Home Architecture

- Controlled devices connected to "gateway/hub"
- Currently, few accepted industry standards
  - Companies hide documentation to prevent independent development
- Poor release/patching practices lead to security issues
  - Estimated 87% of devices vulnerable



Smart Homes: Elderly Care Monitoring

- 65+ years USA population 35M in 2000, expected to double by 2030
  - Poor health conditions; require help in times of need
- Falls are extremely dangerous
  - 1 in 3 adults over 50 dies within 12 months of suffering a hip fracture
- Deteriorating memory can lead to behavior changes and other lifestyle difficulties
  - Forgetting to exercise, eat, report for doctor appointments
  - Difficulty evacuating in emergencies

Smart Homes: Elderly Care Monitoring

Activities of Daily Living monitoring

- Watch occupant, ensure they are following daily routines (eating, drinking, exercise)
- **Wellness Determination:** learn wellness profile of occupant; detect if occupant is ill, suffering behavioral changes, or otherwise in need of help
- **Environmental monitoring:** sufficient food, air quality, temperature
- **Partnership:** question answering, robotic caretakers, robotic pets

Smart Buildings

- Commercial and industrial buildings
- **Common protocols:** BACnet (traditional), Zigbee, Broadband over Power Lines (IEEE 1901), Wifi (IEEE 802.11)

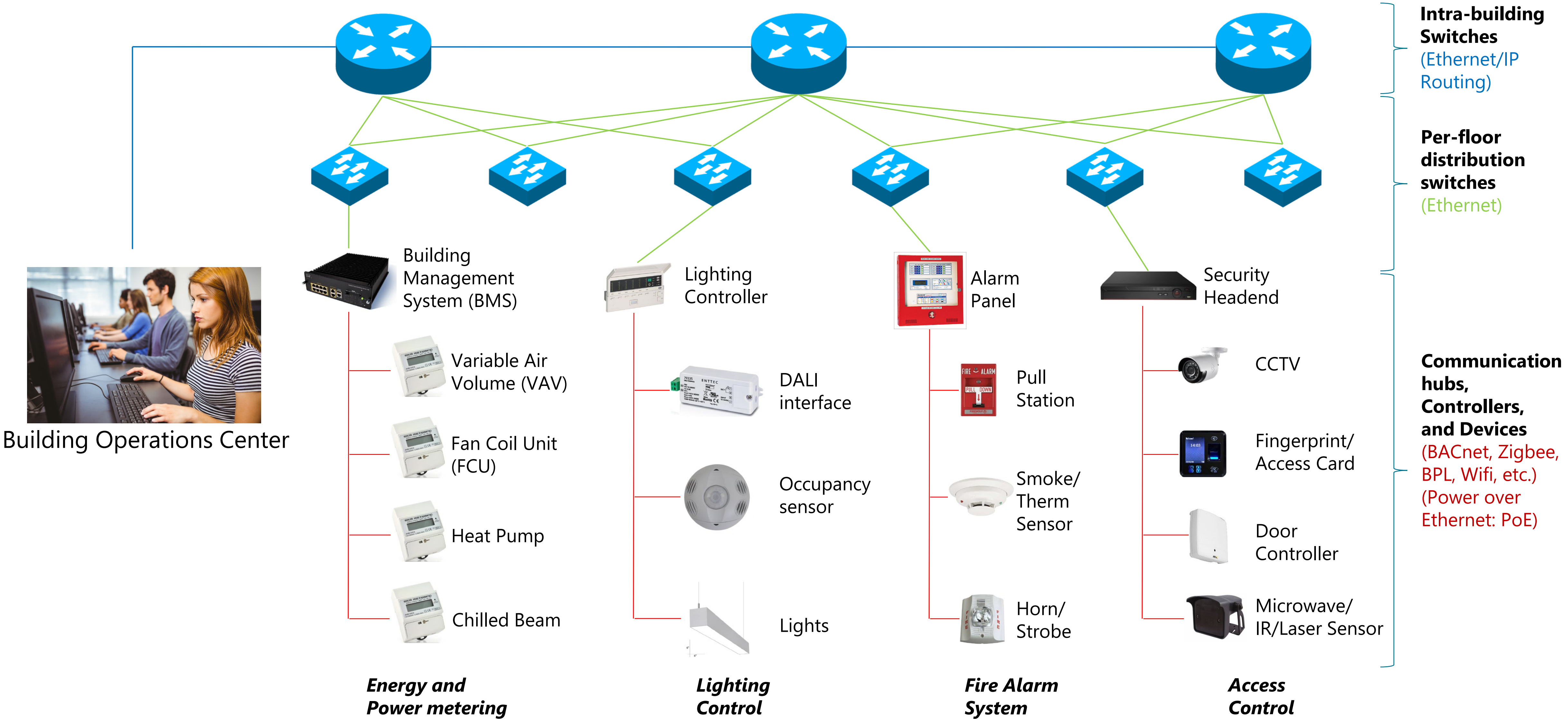
Smart Buildings: Applications

- **Energy management**
  - Manages interplay between internal energy producers/consumers and intelligent purchase of energy from the grid
  - Occupancy detection adjusts lighting and temperature to personalized settings
    - Morning Warmup – bring building to setpoint just in time for occupancy
  - Dim lighting or reduce cooling to respond to grid demand response incentives
  - Networking between smart buildings

Smart Buildings

- **Navigation:** Guide people to destinations via personal assistants, route optimization, improve discretion, balance traffic
- **Security:**
  - Identify people at point of entry (facial recognition, key, etc)
  - Access control to rooms, route people away from sensitive areas
  - Lighting and displays help organize orderly and fast evacuations
  - Pressure, humidity, CO/CO2/refrigerant/biological/chemical sensors – detect if ventilation systems failed or become infected with contaminants
  - Temperature alarms: chilled/hot water supply, supply air, valve indicators, current sensors (slipping fan belts, clogging strainers at pumps, etc)

Smart Building Architecture



Smart City

- Uses sensors and actuators to manage resources and assets more efficiently
  - Power/water/gas supply networks, waste management, police/fire, transportation systems, schools/libraries/hospitals

Smart City Applications: Traffic Control

- Use AI to manage and route pedestrian and car traffic efficiently
- Study: time spent at lights reduced by 40%, travel times reduced by 25%

- Track criminals, detect unsafe/illegal behavior
- Balance traffic flow, detour around hotspots, smooth flow
- Prioritize emergency response, assist evacuations
- Electronic alerts to drivers, road conditions and emergencies

Smart City Applications: Smart Grid

Power Plant

Distribution Grid

Smart Meters

Smart Appliances

- Electrical grid which leverages IoT to improve efficiency and resource management
    - Electronic power conditioning, control of power distribution and usage
- Intelligent appliances in homes “negotiate” with grid
    - Congestion/load pricing
- Prediction of workloads to drive power station ramp-up/provisioning
- Distributed storage (car batteries), distributed generation improve efficiency

Smart City: Network Architecture