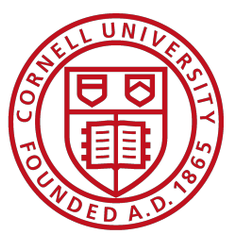
CS4410/11: Operating Systems

CPU Scheduling (Recap)

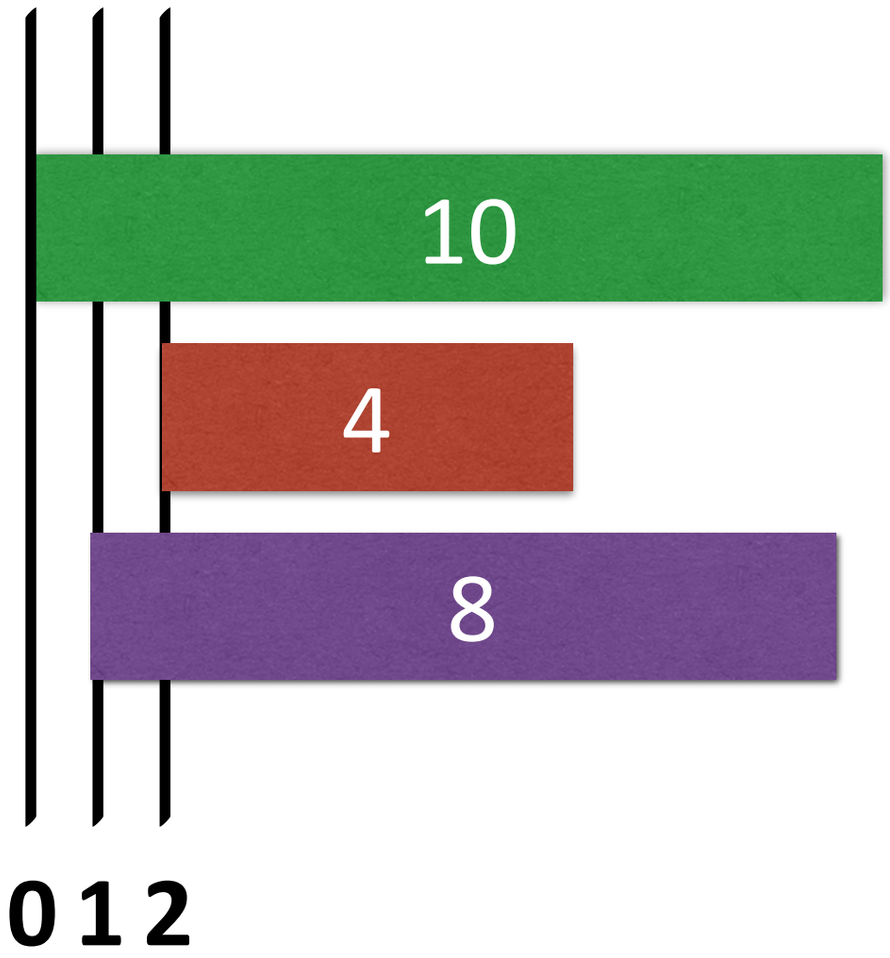
Networking

Rachit Agarwal
Anne Bracy

Slides based on material from Sirer, Rennesse, Rexford (Princeton)



CPU Scheduling — Example



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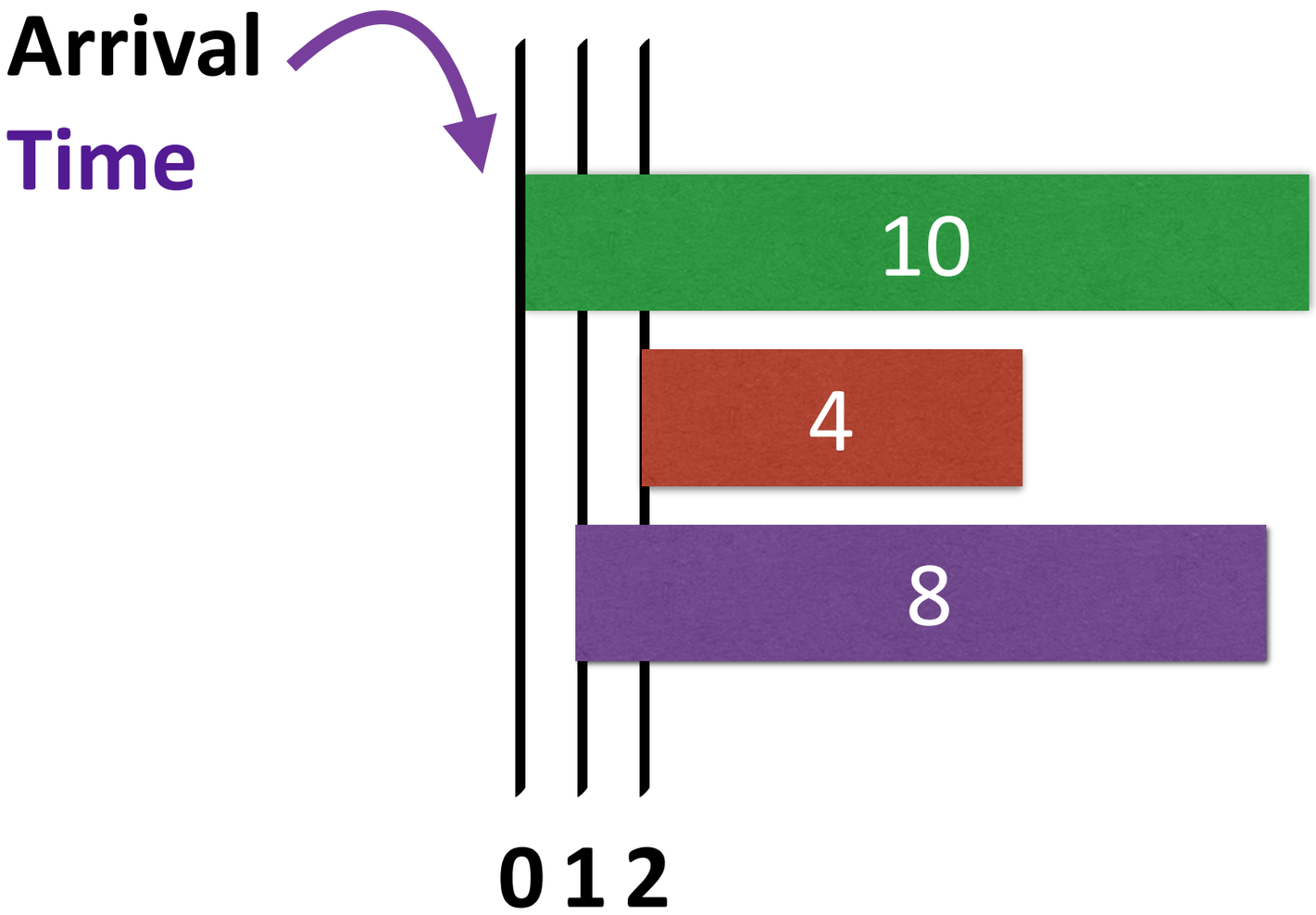

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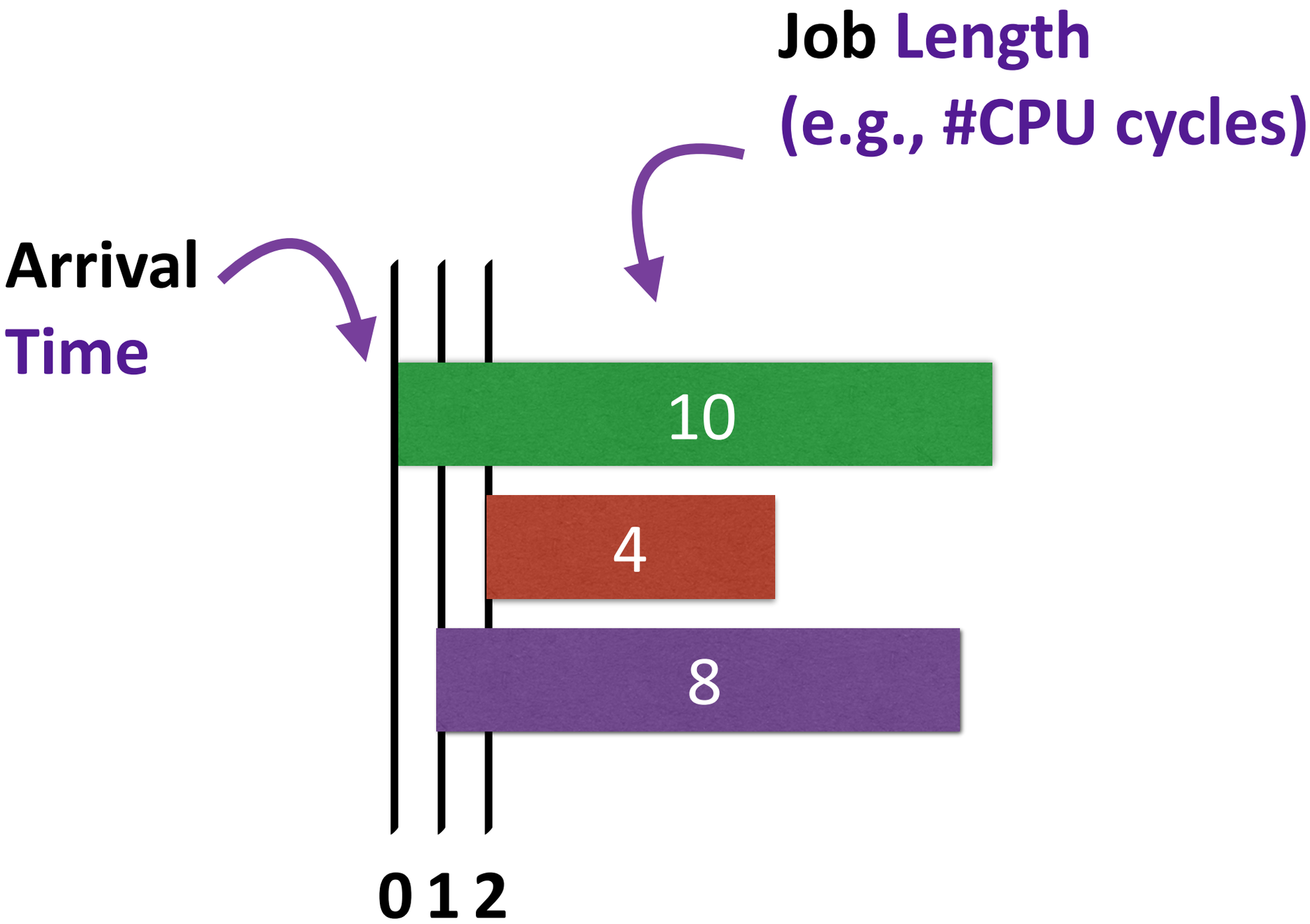
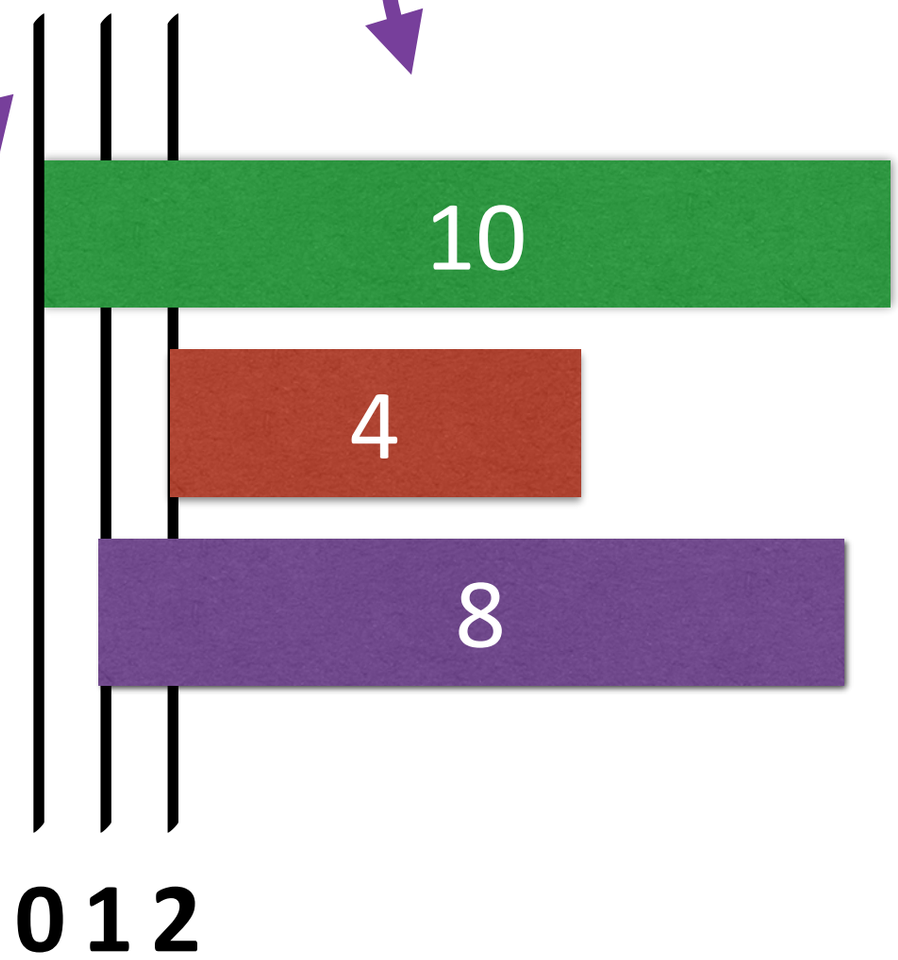


CPU Scheduling — Example

Job Length
(e.g., #CPU cycles)

Arrival Time



- FIFO
- LIFO
- SJF
- SRTF
- RR
- Priority

Networking — What is it about?

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So far: focused on what happens on a “machine”!

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- **Networking**
    - How do machines communicate?

Networking — What is it about?

So far: focused on what happens on a “machine”!

- **Networking**
    - How do machines communicate?
- **Lets start with a simple analogy**
    - How to move stuff from München to Ithaca?

Networking — Key Concepts

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Four “concepts”!

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- **Layering**
    - Abstraction is the key to manage complexity

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    - A name for each computer, protocol, ..

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    - Computers, network devices speaking the same language

Networking — Key Concepts

Four “concepts”!

- **Layering**
    - Abstraction is the key to manage complexity
- **Naming**
    - A name for each computer, protocol, ..
- **Protocols**
    - Computers, network devices speaking the same language
- **Resource Allocation**
    - Share resources (bandwidth, wireless spectrum, paths, …)

Networking — A Stack of Protocol Layers

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Five “layers”!

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- **Modularity**

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Networking — A Stack of Protocol Layers

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- **Interfaces**
    - Hide implementation details

Networking — A Stack of Protocol Layers

Five “layers”!

- **Modularity**
    - Each layer relies on services from layer below
    - Each layer exports services to layer above
- **Interfaces**
    - Hide implementation details
    - Layers can change without disturbing other layers

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Physical layer

Networking — A Stack of Protocol Layers

Five “layers”!

Physical layer

Transfer “signals”

Networking — A Stack of Protocol Layers

Five “layers”!

Link layer

Physical layer

Transfer “signals”

Networking — A Stack of Protocol Layers

Five “layers”!

Link layer	Postman
Physical layer	Transfer “signals”

Networking — A Stack of Protocol Layers

Five “layers”!

Network

Link layer

Physical layer

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Transfer “signals”

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Five “layers”!

Network	Airplane/rail
Link layer	Postman
Physical layer	Transfer “signals”

Networking — A Stack of Protocol Layers

Five “layers”!

Transport	
Network	Airplane/rail
Link layer	Postman
Physical layer	Transfer “signals”

Networking — A Stack of Protocol Layers

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Physical layer	Transfer “signals”

Networking — A Stack of Protocol Layers

Five “layers”!

Application	
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Network	Airplane/rail
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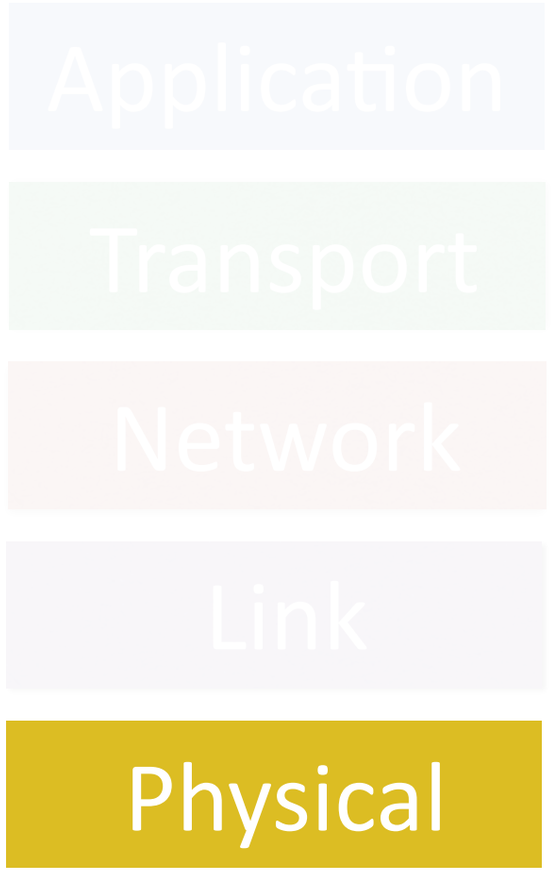
Physical layer	Transfer “signals”

Networking — A Stack of Protocol Layers

Five “layers”!

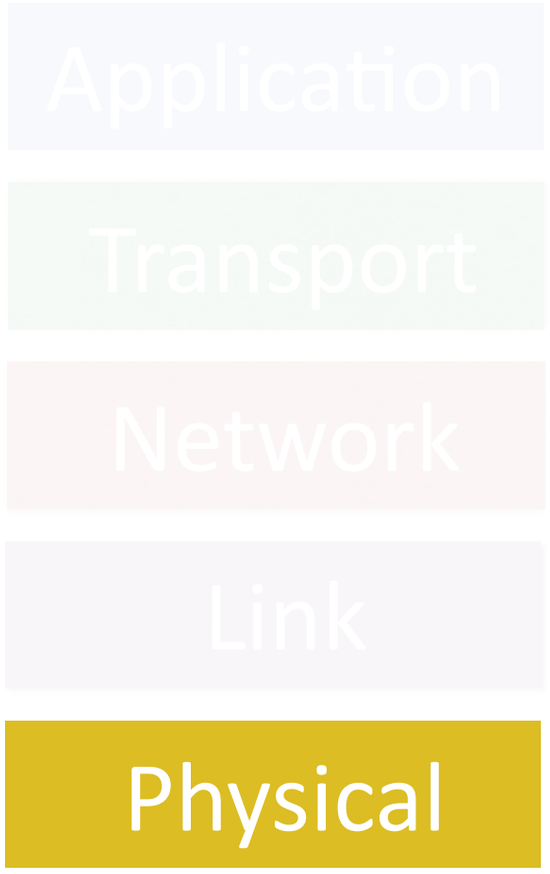
Application	You
Transport	Post office
Network	Airplane/rail
Link layer	Postman
Physical layer	Transfer “signals”

Networking — Physical layer



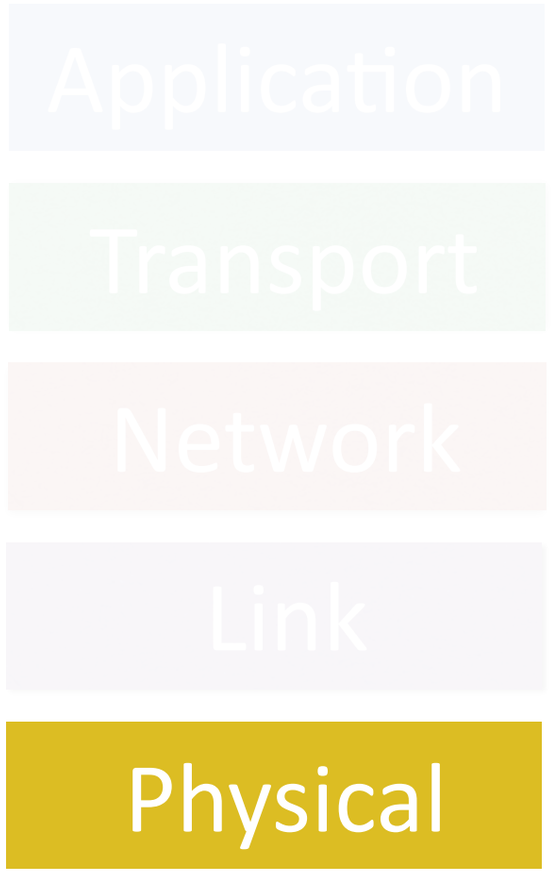
Networking — Physical layer

- **Transfer of bits**



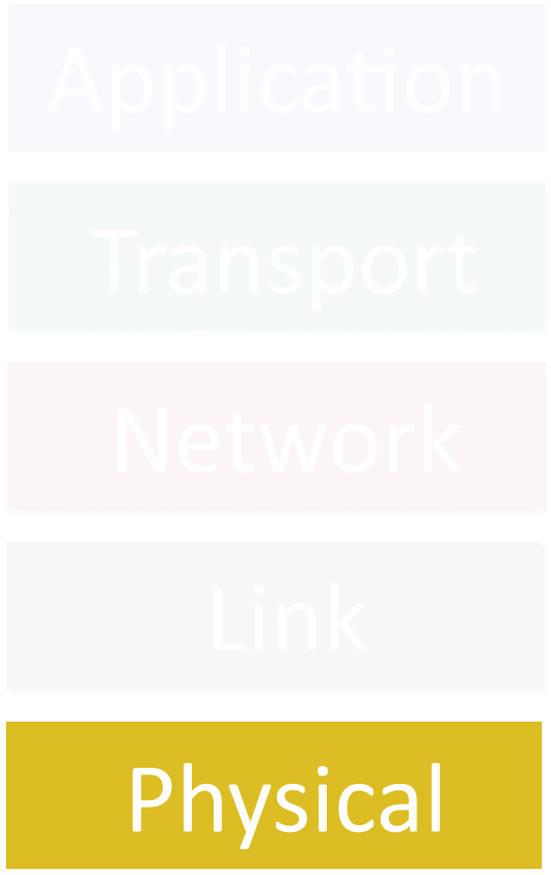
Networking — Physical layer

- **Transfer of bits**
  - 0s and 1s

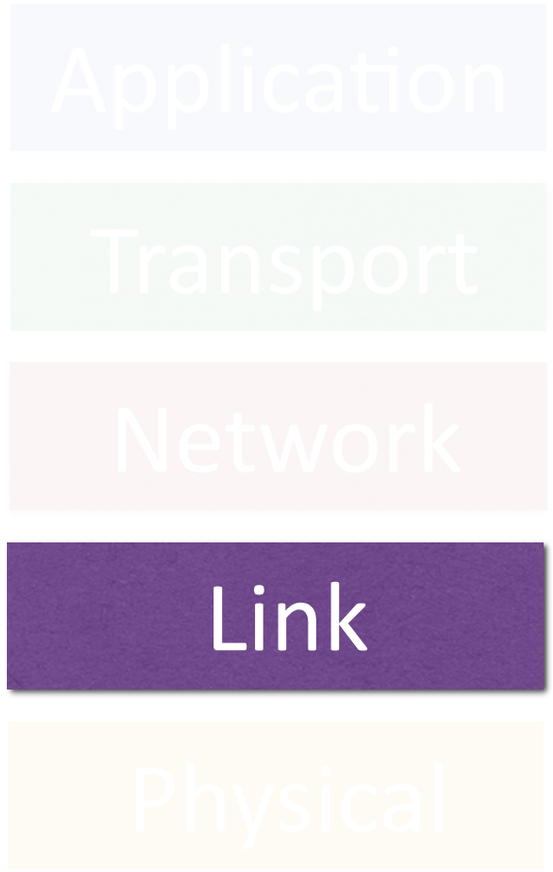


Networking — Physical layer

- **Transfer of bits**
  - 0s and 1s
  - Not concerned with protocols

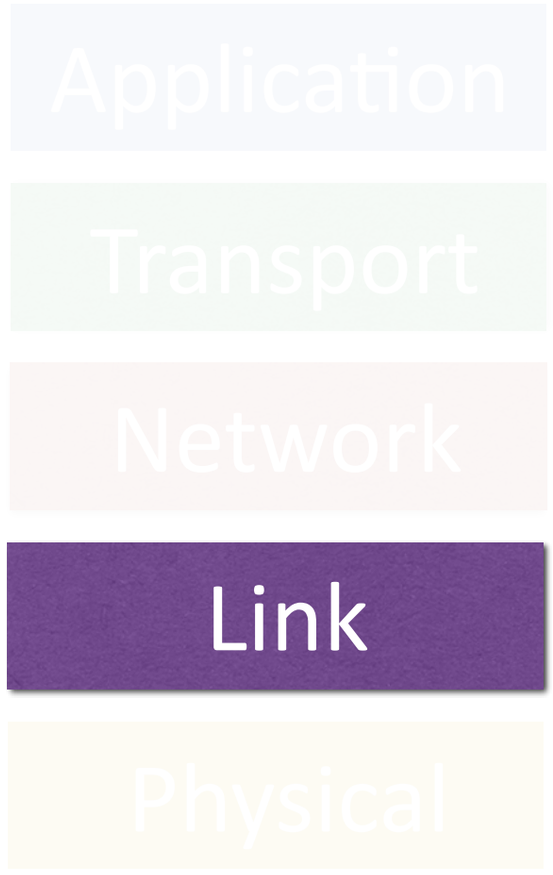


Networking — Link layer



Networking — Link layer

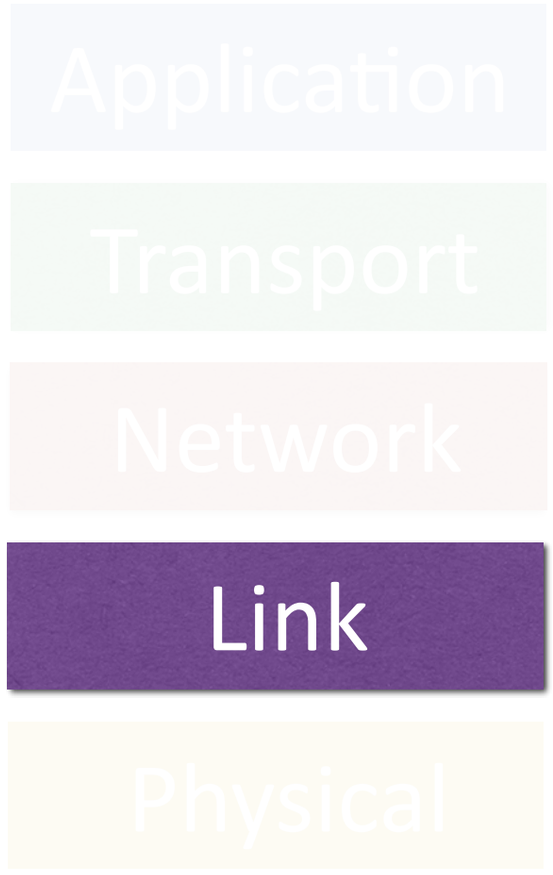
Link = Medium + Adapters



Networking — Link layer

Link = Medium + Adapters

- **Communication Medium**



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- **Network Adapters (e.g., NIC — network interface card)**

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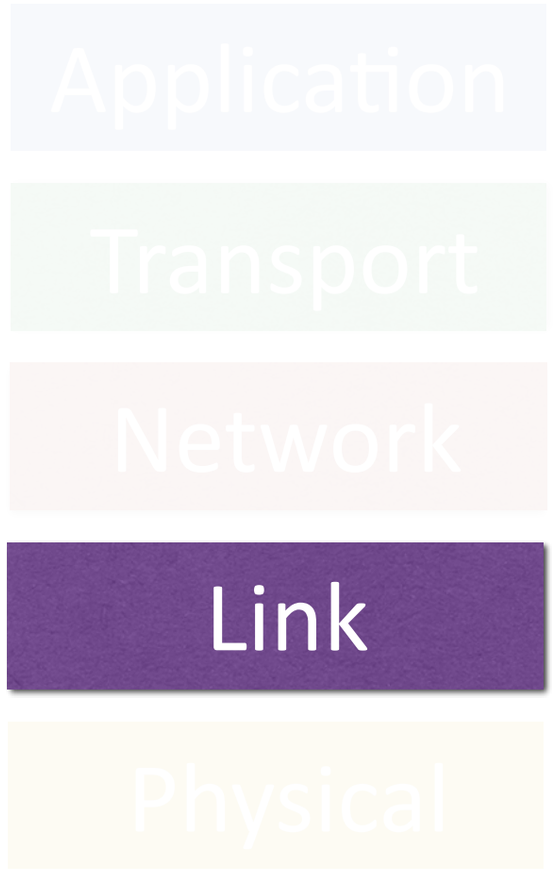
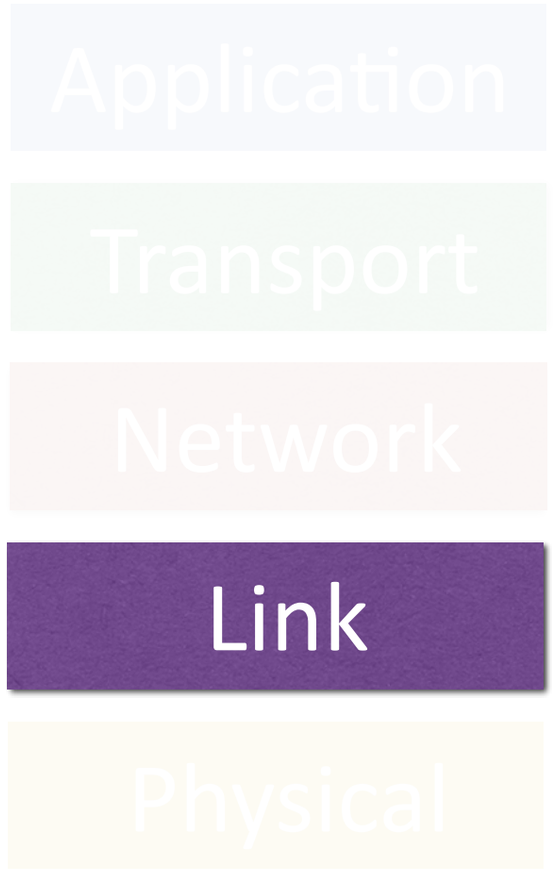


Networking — Link layer

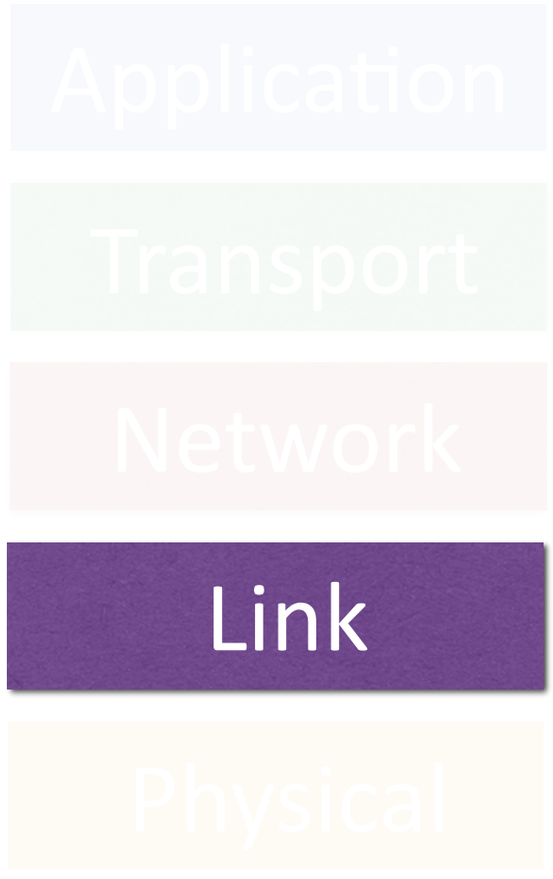
Broadcast links = Shared Medium



Networking — Link layer

Broadcast links = Shared Medium

- Everyone listens to everybody



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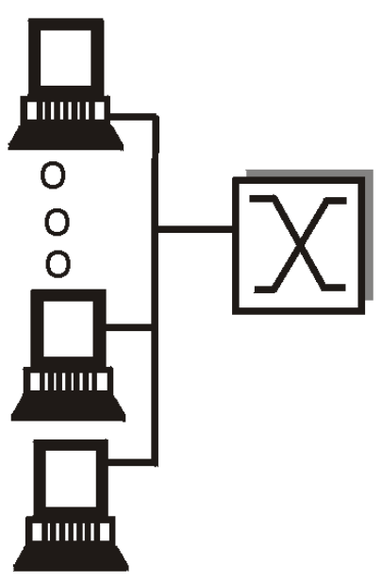
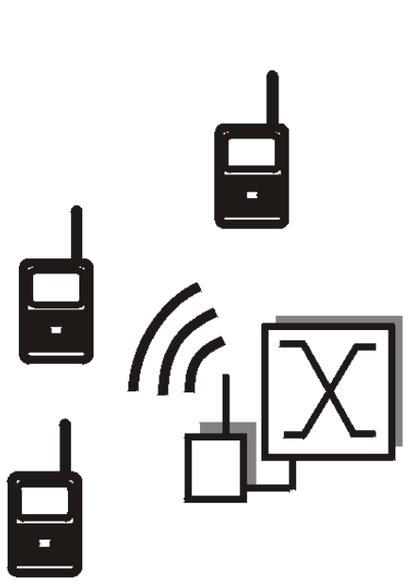


shared wire
(e.g. Ethernet)



shared wireless
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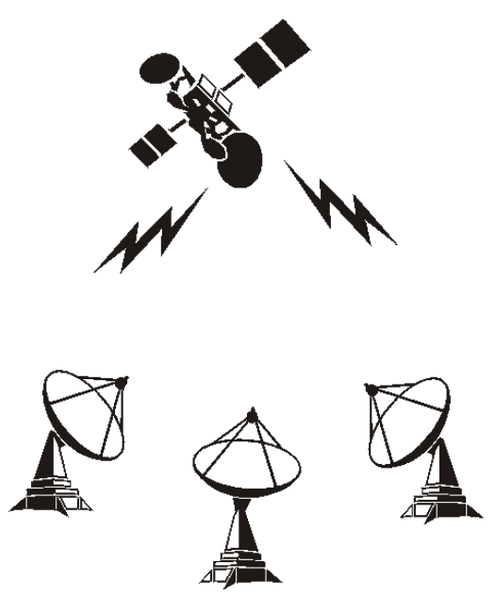

satellite

cocktail party

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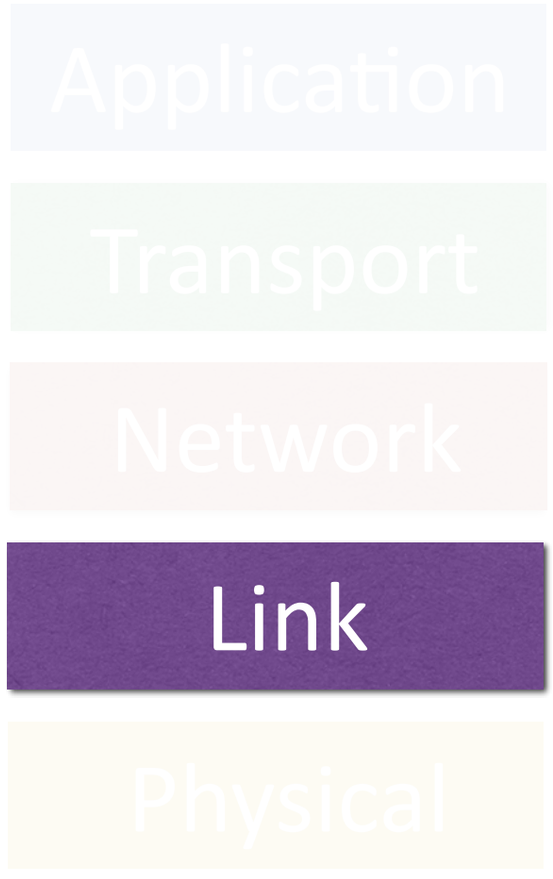

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source

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link-layer “protocol”

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    - Represented as a collection of 0s and 1s

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- **Flow control**
    - When to send/receive frames
    - Depends on the protocol

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Addresses

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  - Special (broadcast) address: FF-FF-FF-FF-FF-FF

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Sharing a medium

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Sharing a medium

- **Ever been to a party?**

Networking — Link layer

Sharing a medium

- **Ever been to a party?**
    - Tried to have an interesting discussion?

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Lets try to come up with a protocol to avoid collisions!

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- **Attempt 1: Time sharing**

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    - Overheads …
    - What if I want to talk to only a few people in the group?
    - What if I want to talk to people in different groups?
    - E.g., one person wants to announce something …

Link layer — Sending/receiving

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Attempt 3: Carrier sense, Collision detection, Random access

Link layer — Sending/receiving

Attempt 3: Carrier sense, Collision detection, Random access

- **Carrier Sense**

Link layer — Sending/receiving

Attempt 3: Carrier sense, Collision detection, Random access

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    - Listen before speaking

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    - Detect simultaneous speaking

Link layer — Sending/receiving

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    - Wait for a random period of time

Link layer — Sending/receiving

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  - …. and don't interrupt
- **Collision detection**
  - Detect simultaneous speaking
  - …. and shut up!
- **Random access**
  - Wait for a random period of time
  - …. before trying to talk again

Link layer — Sending/receiving

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Comparing the three approaches

Link layer — Sending/receiving

Comparing the three approaches

- **Time division**

Link layer — Sending/receiving

Comparing the three approaches

- **Time division**
    - No collisions

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Comparing the three approaches

- **Time division**
    - No collisions
    - Underutilization of resources!
    - What if token is lost?
- **Frequency division**
    - Overheads
- **Random access**
    - Efficient at low load, inefficient at high load (collisions)

Ethernet — Sending/receiving at Link layer

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Ethernet uses CSMA/CD

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Ethernet — Sending/receiving at Link layer

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- **Collision Detection: listen while transmitting**

Ethernet — Sending/receiving at Link layer

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- **Collision Detection: listen while transmitting**
    - No collision: transmission complete

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Ethernet — Sending/receiving at Link layer

Ethernet uses CSMA/CD

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Networking — Link layer (Ethernet)

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Interesting Properties

Networking — Link layer (Ethernet)

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- **Distributed**

Networking — Link layer (Ethernet)

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- **Distributed**
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Networking — Link layer (Ethernet)

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Networking — Link layer (Ethernet)

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Networking — Link layer (Ethernet)

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Networking — Link layer (Ethernet)

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Connection-less, unreliable service

Networking — Link layer (Ethernet)

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Networking — Link layer (Ethernet)

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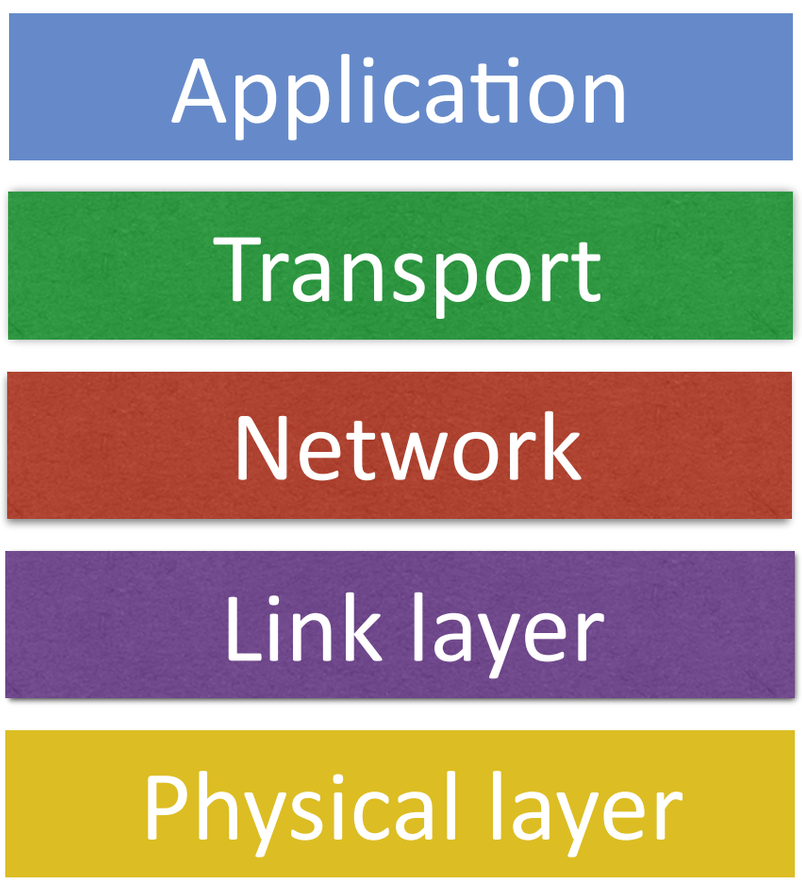
        - I want to listen to what others are talking

Networking — A Stack of Protocol Layers

Five “layers”!



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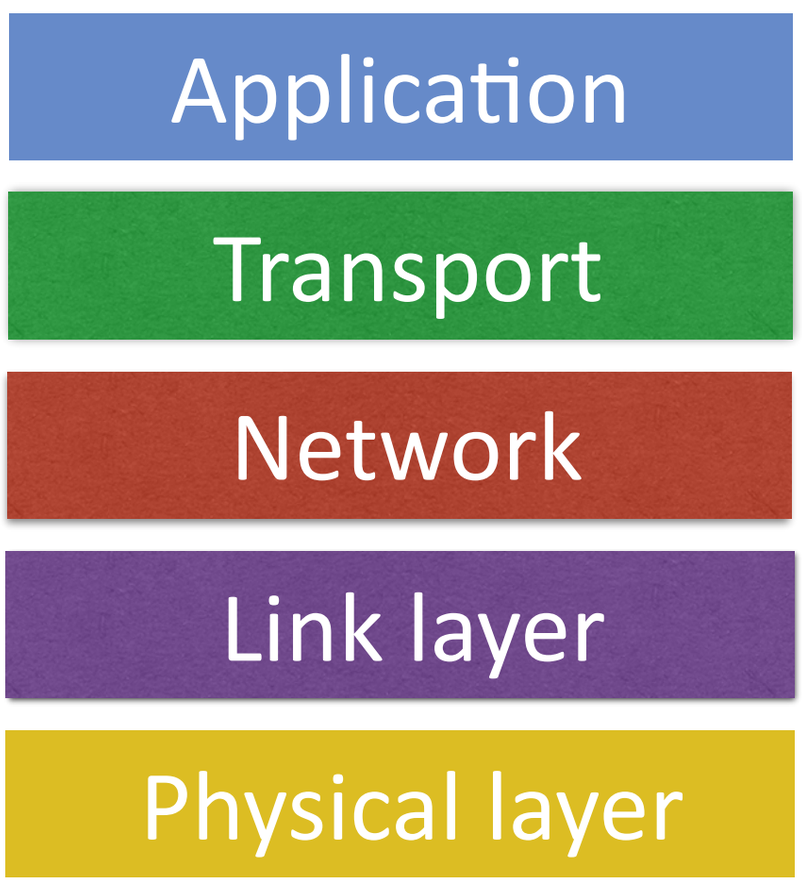

Deliver **signals**

Networking — A Stack of Protocol Layers

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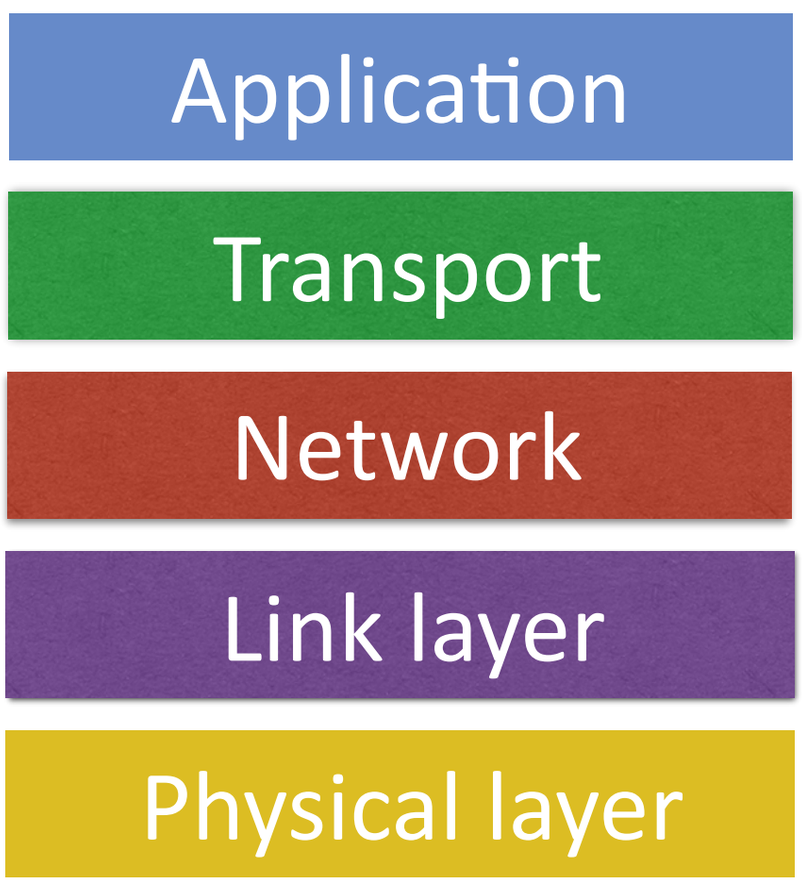

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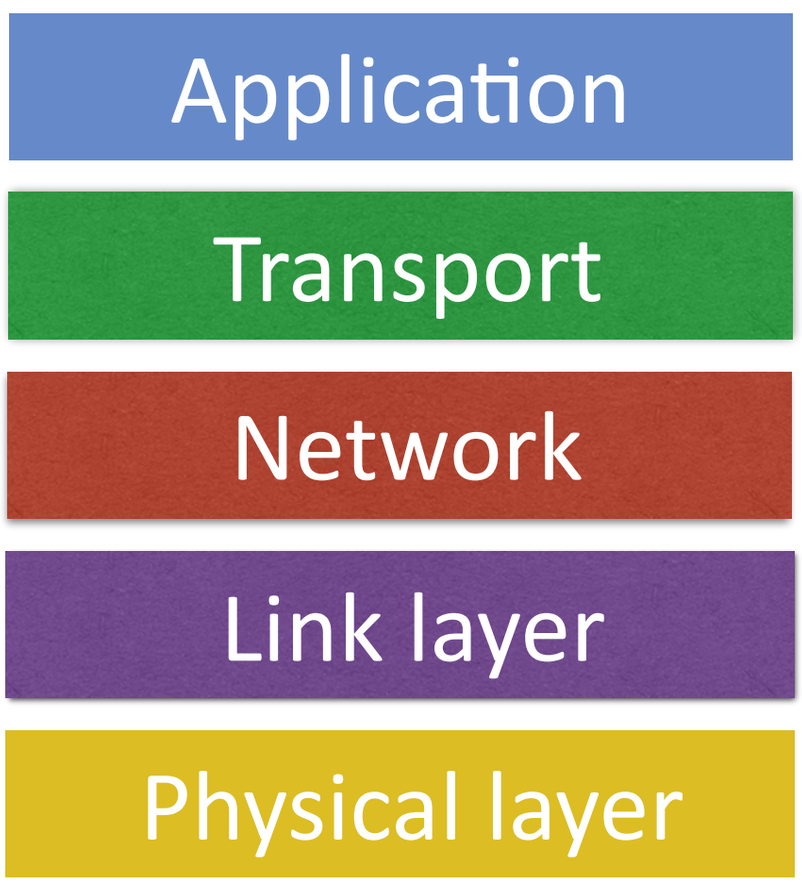

Deliver **globally**

Deliver **locally**

Deliver **signals**

Networking — A Stack of Protocol Layers

Five “layers”!

Application	
Transport	Deliver **(un)reliably**
Network	Deliver **globally**
Link layer	Deliver **locally**
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Networking — A Stack of Protocol Layers

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Networking — Network layer

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Three concepts

Networking — Network layer

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Networking — Network layer

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- **Naming**
    - A way to identify the source/destination

Networking — Network layer

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Networking — Network layer

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Networking — Network layer

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Naming

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Naming

- **Give every computer a unique name**

Networking — Network layer

Naming

- **Give every computer a unique name**
    - Challenges?

Networking — Network layer

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Networking — Network layer

Naming

- **Give every computer a unique name**
    - Challenges?
    - Scalability — why?
    - Assignment — why?

Networking — Network layer

Networking — Network layer

Naming

Networking — Network layer

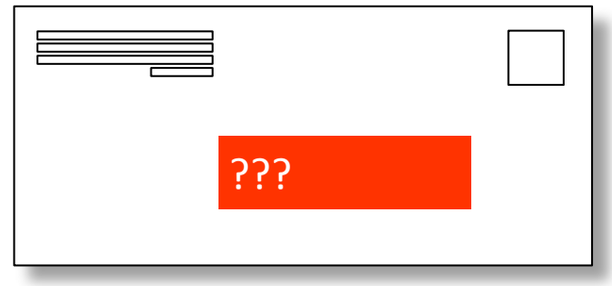
Naming

- **Hierarchical addressing**

Networking — Network layer

Naming

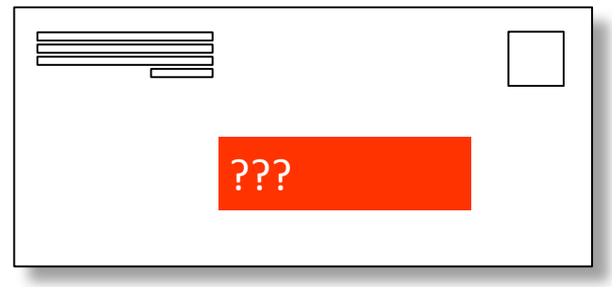
- **Hierarchical addressing**



Networking — Network layer

Naming

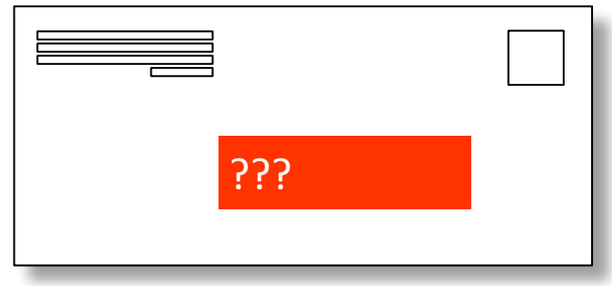
- **Hierarchical addressing**
    - E.g., addresses for houses



Networking — Network layer

Naming

- **Hierarchical addressing**
    - E.g., addresses for houses
    - **Country:** USA



Networking — Network layer

Naming

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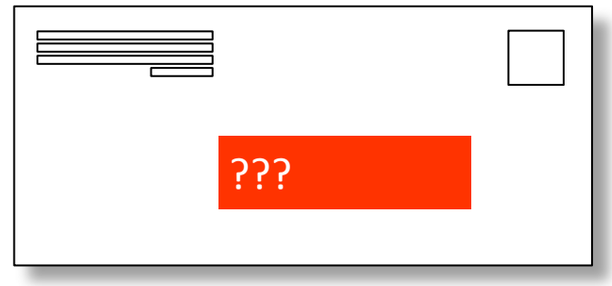

Networking — Network layer

Naming

- **Hierarchical addressing**
    - E.g., addresses for houses
    - **Country:** USA
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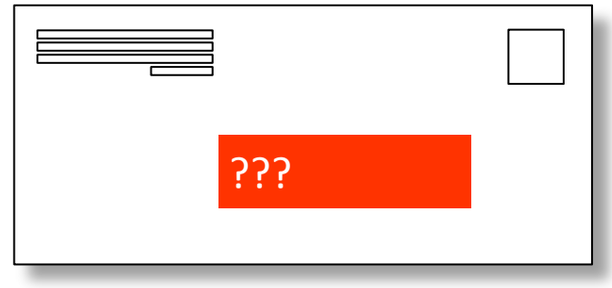

Networking — Network layer

Naming

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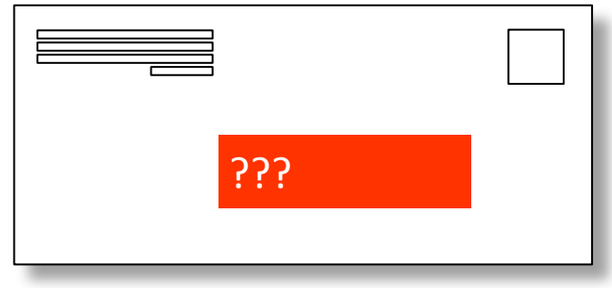

Networking — Network layer

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Hierarchical addressing

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Networking — Network layer

Hierarchical addressing

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Networking — Network layer

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Networking — Network layer

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Networking — Network layer

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IP address: 128.84.139.5

Networking — Network layer

Networking — Network layer

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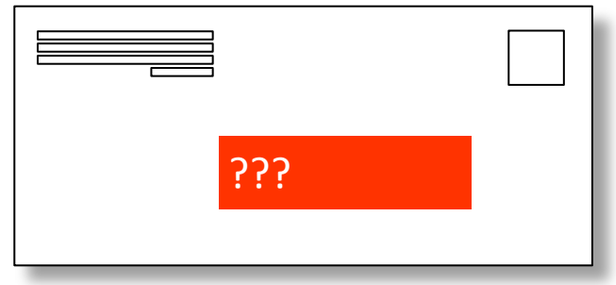

Networking — Network layer

Hierarchical addressing

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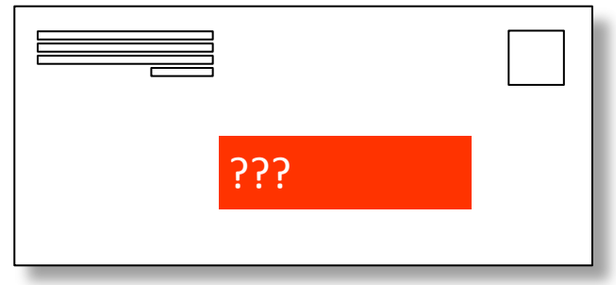

Networking — Network layer

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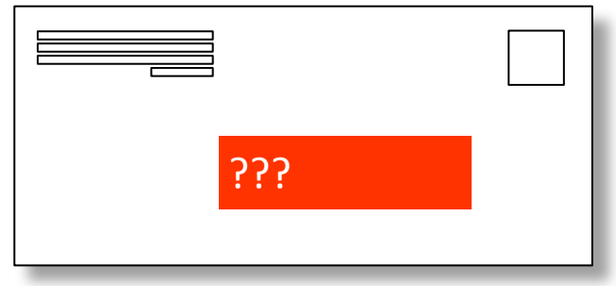

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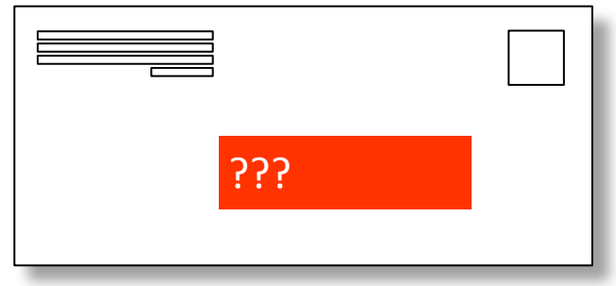

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Networking — Network layer

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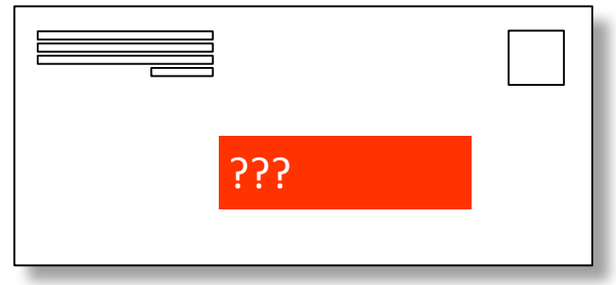

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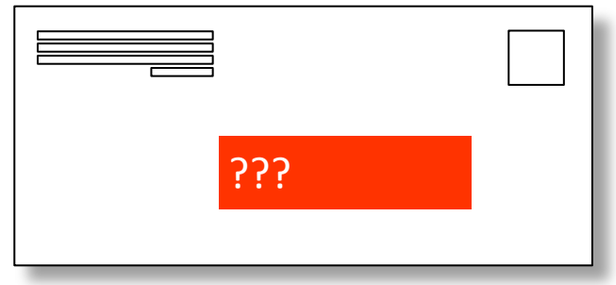
Networking — Network layer

Hierarchical addressing



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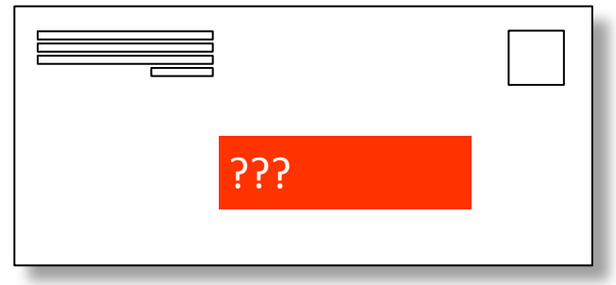
Networking — Network layer

Hierarchical addressing



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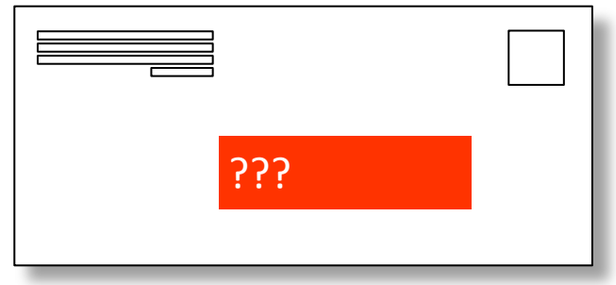
    - **Direction to**: 306 State St.

Networking — Network layer

Hierarchical addressing



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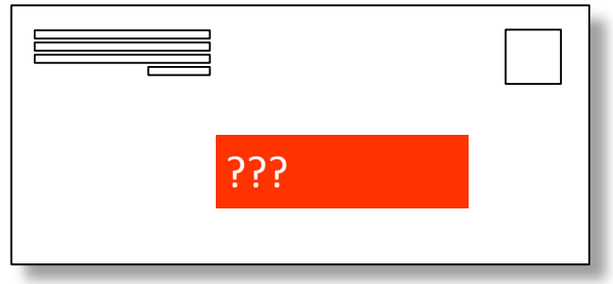
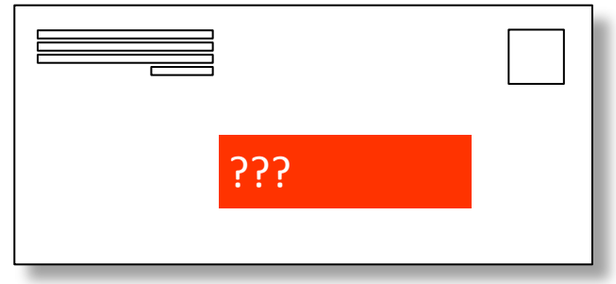
Networking — Network layer



Networking — Network layer

Hierarchical addressing



Networking — Network layer

Hierarchical addressing

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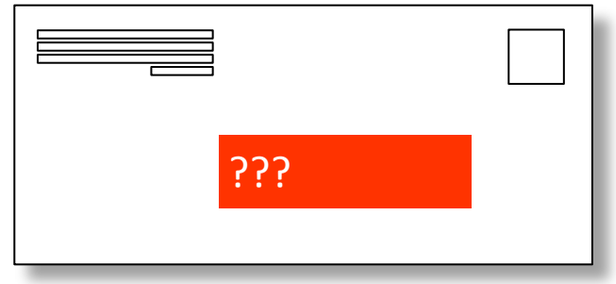

Networking — Network layer

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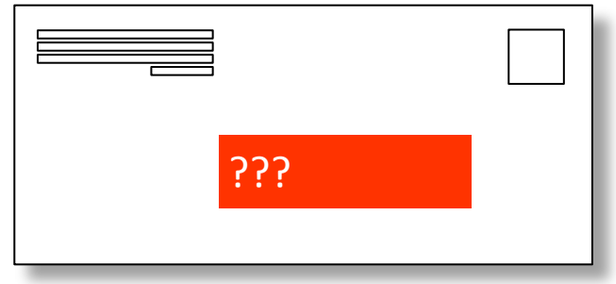

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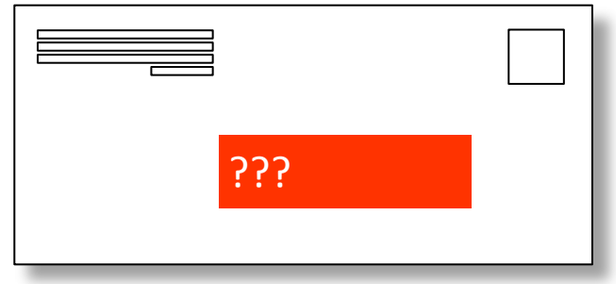
Networking — Network layer

Hierarchical addressing



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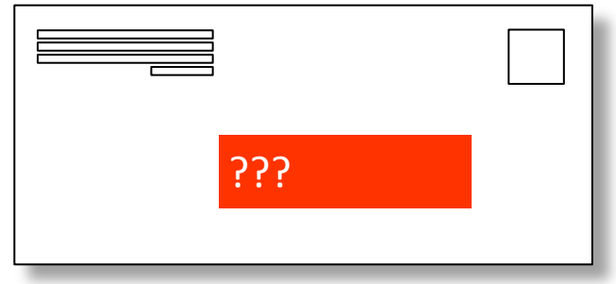

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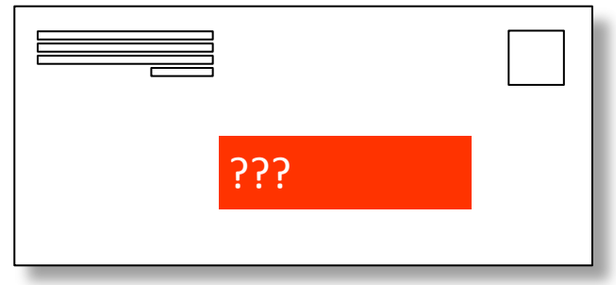
    - **If last local address:** 128.84.139.5

Networking — Network layer

Hierarchical addressing



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Networking — Network layer

Three concepts

- **Naming**
  - A way to identify the source/destination
  - E.g., house address
- **Routing**
  - Finding “how to” move towards the destination
  - E.g., which airplane should the stuff go on
- **Forwarding**
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Network layer — Forwarding

Network layer — Forwarding

Lets come up with an approach? Generalize Ethernet ideas?

Network layer — Forwarding

Network layer — Forwarding

Attempt 1: Broadcast

Network layer — Forwarding

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- **Send to everybody**

Network layer — Forwarding

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Network layer — Forwarding

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    - Oh, well, simplicity
- **Not-so-goods**
    - Oh, well, everything else
    - Bandwidth overheads

Network layer — Forwarding

Network layer — Forwarding

Attempt 2: Time division Multiplexing

Network layer — Forwarding

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- **Each source-destination pair assigned a time slot**

Network layer — Forwarding

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Network layer — Forwarding

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    - No collisions

Network layer — Forwarding

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- **Goods**
    - No collisions
- **Not-so-goods**

Network layer — Forwarding

Attempt 2: Time division Multiplexing

- **Each source-destination pair assigned a time slot**
    - Can send data only during that slot
- **Goods**
    - No collisions
- **Not-so-goods**
    - Underutilization of resources

Network layer — Forwarding

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
    - Can use only “assigned” resources (e.g., bandwidth)

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
    - Can use only “assigned” resources (e.g., bandwidth)
- **Goods**

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
    - Can use only “assigned” resources (e.g., bandwidth)
- **Goods**
    - Predictable performance

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
    - Can use only “assigned” resources (e.g., bandwidth)
- **Goods**
    - Predictable performance
- **Not-so-goods**

Network layer — Forwarding

Attempt 3: Frequency division Multiplexing

- **Each source-destination pair assigned a subset of resources**
    - Can use only “assigned” resources (e.g., bandwidth)
- **Goods**
    - Predictable performance
- **Not-so-goods**
    - Underutilization of resources

Network layer — Forwarding

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved
- **Source sends data**

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved
- **Source sends data**
    - Transmit data using the reserved resources

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved
- **Source sends data**
    - Transmit data using the reserved resources
- **Source tears down connection**

Network layer — Forwarding

Attempt 2 and 3: Circuit Switching

- **Source establishes connection**
    - Resources along the path are reserved
- **Source sends data**
    - Transmit data using the reserved resources
- **Source tears down connection**
    - Free resources for others to use

Network layer — Forwarding

Network layer — Forwarding

Circuit Switching

Network layer — Forwarding

Circuit Switching

- **Goods:**

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**
    - Resource underutilization

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**
    - Resource underutilization
    - Blocked connections

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**
    - Resource underutilization
    - Blocked connections
    - Connection set up overheads

Network layer — Forwarding

Circuit Switching

- **Goods:**
    - Predictable performance
    - Reliable delivery
    - Simple forwarding mechanism
- **Not-so-goods**
    - Resource underutilization
    - Blocked connections
    - Connection set up overheads
    - Per-connection state in switches (scalability problem)

Network layer — Forwarding

Network layer — Forwarding

Attempt 4: Packet Switching

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**
- **Put destination address in the header of each packet**

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**
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    - Just like shipping stuff

Network layer — Forwarding

Attempt 4: Packet Switching

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- **Each device stores a "look-up table"**

Network layer — Forwarding

Attempt 4: Packet Switching

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    - Whats the next hop towards the destination?

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**
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- **Destination receives the packet(s)**

Network layer — Forwarding

Attempt 4: Packet Switching

- **Divide the message into packets**
- **Put destination address in the header of each packet**
    - Just like shipping stuff
- **Each device stores a "look-up table"**
    - Whats the next hop towards the destination?
- **Destination receives the packet(s)**
    - And reconstructs the message

Network layer — Forwarding

Network layer — Forwarding

Packet Switched forwarding

Network layer — Forwarding

Packet Switched forwarding

- **Hop-by-hop forwarding**

Network layer — Forwarding

Packet Switched forwarding

- **Hop-by-hop forwarding**
- **Each router has a “look-up table” (forwarding information base)**

Network layer — Forwarding

Packet Switched forwarding

- **Hop-by-hop forwarding**
- **Each router has a “look-up table” (forwarding information base)**
    - What should be stored in this table?

Network layer — Forwarding

Packet Switched forwarding

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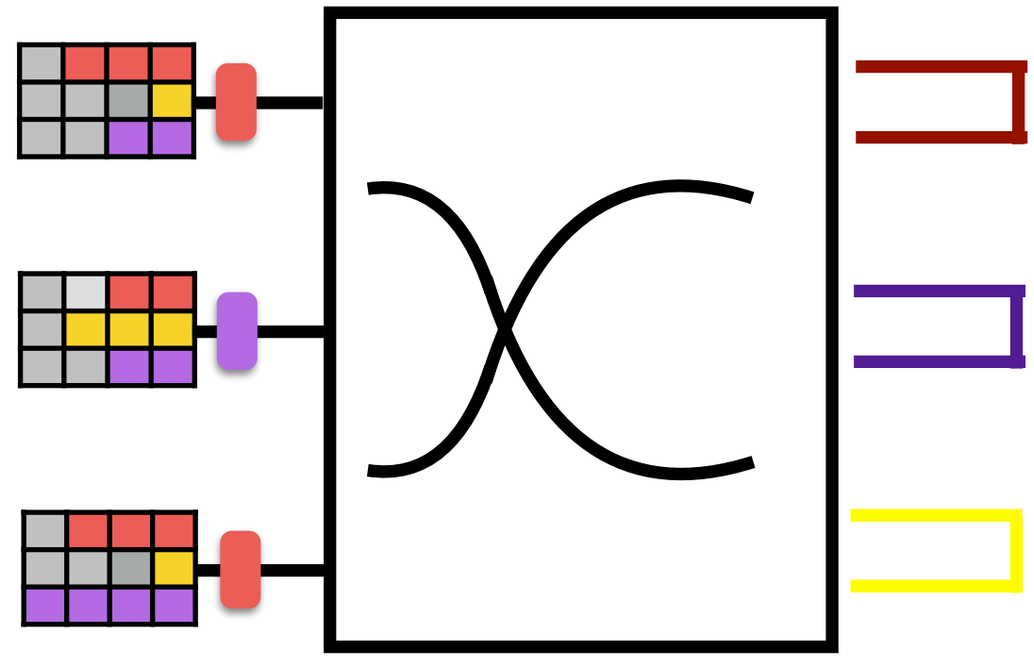
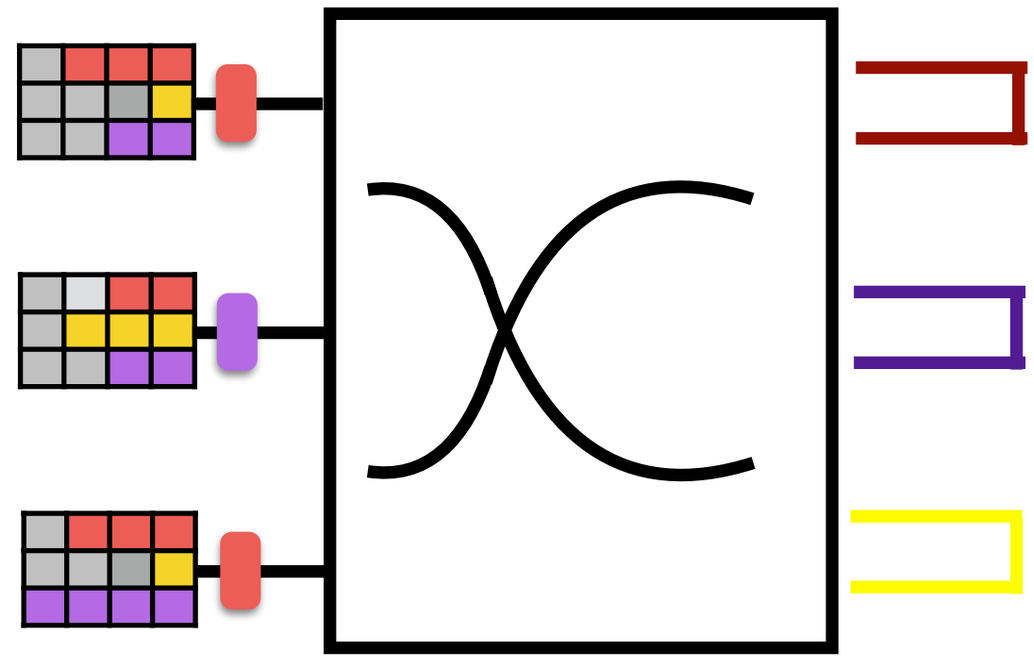
    - What should be stored in this table?



Network layer — Forwarding

Packet Switched forwarding

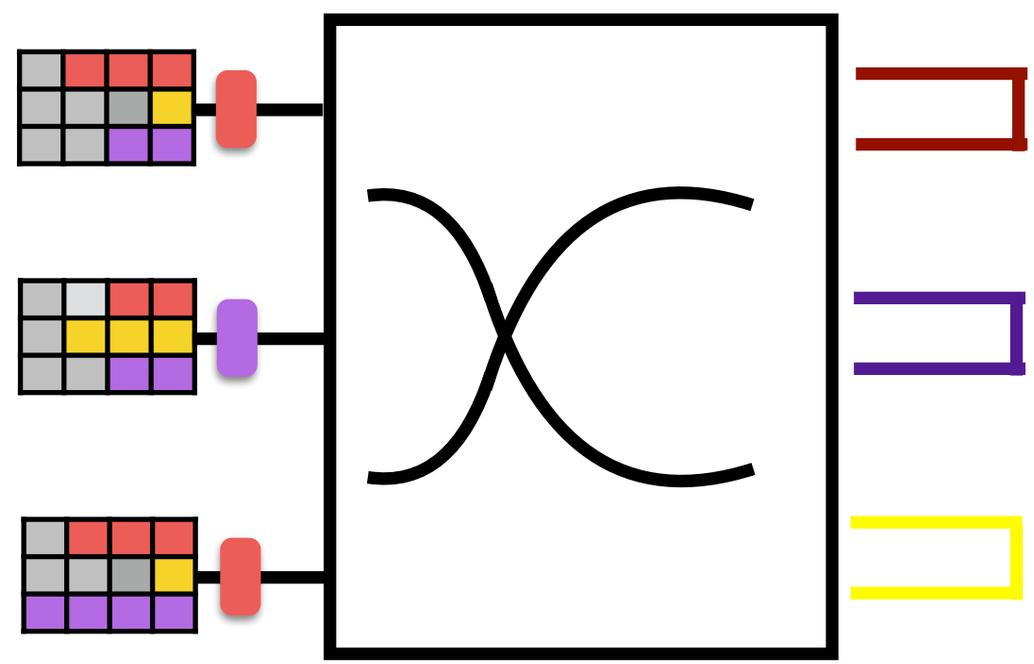
- **Hop-by-hop forwarding**
- **Each router has a "look-up table" (forwarding information base)**
    - What should be stored in this table?
    - Prefix-based forwarding **(longest-prefix matching)**



Network layer — Forwarding

Packet Switched forwarding

- **Hop-by-hop forwarding**
- **Each router has a "look-up table" (forwarding information base)**
    - What should be stored in this table?
    - Prefix-based forwarding **(longest-prefix matching)**
    - Maps **prefixes** to the next-hop



Network layer — Forwarding

Network layer — Forwarding

Packet Switching

Network layer — Forwarding

Packet Switching

- **Goods:**

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
    - No blocked connection problem

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
    - No blocked connection problem
    - No per-connection state

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
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    - No per-connection state
    - No set-up cost

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
    - No blocked connection problem
    - No per-connection state
    - No set-up cost
- **Not-so-goods:**

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
    - No blocked connection problem
    - No per-connection state
    - No set-up cost
- **Not-so-goods:**
    - Packet header overhead

Network layer — Forwarding

Packet Switching

- **Goods:**
    - No resource underutilization
        - A source can send more if others don’t use resources
    - No blocked connection problem
    - No per-connection state
    - No set-up cost
- **Not-so-goods:**
    - Packet header overhead
    - Network failures become a problem