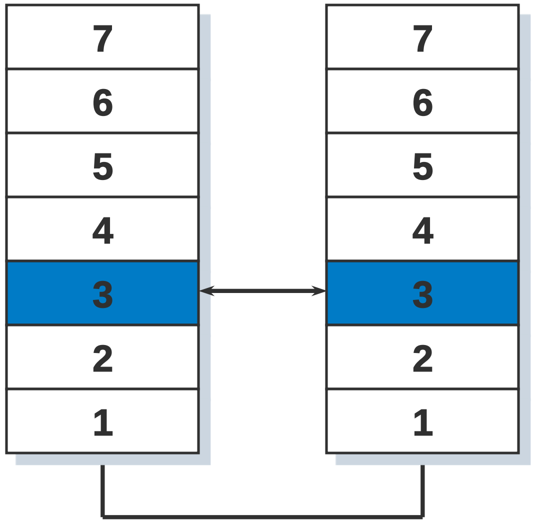
Freie Universität Berlin

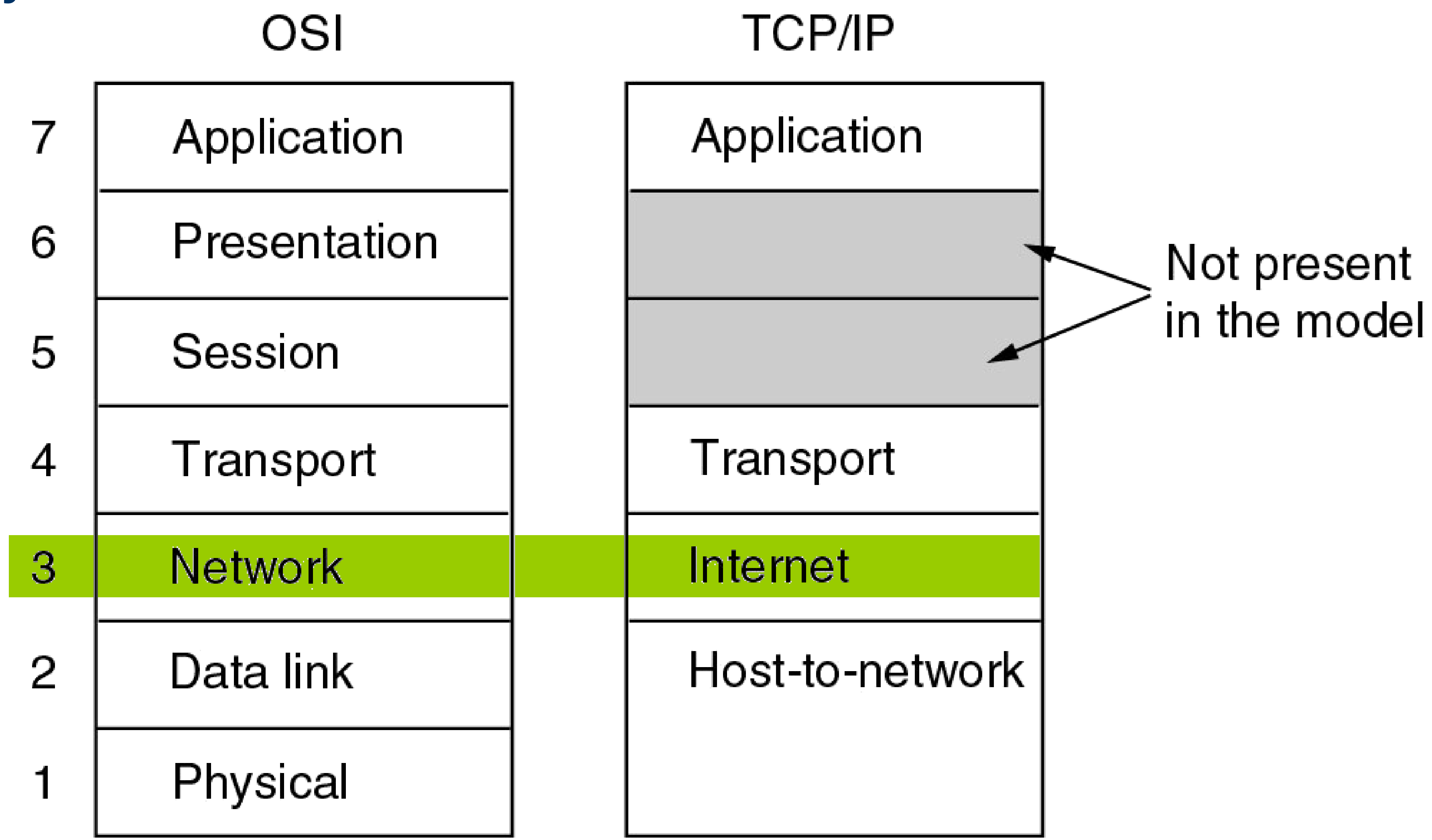
TI III: Operating Systems & Computer Networks
Internetworking



Prof. Dr.-Ing. Jochen Schiller
Computer Systems & Telematics
Freie Universität Berlin, Germany

Content

Network Layer



Reasons for Multiple Networks

Limited number of users/throughput in a single network

Historical reasons:

- Different groups started out individually setting up networks
- Usually heterogeneous

Geographic distribution of different groups over different buildings, campus, …

- Impractical/impossible to use a single network because of distance
  - Most MAC protocols set maximum segment length for medium access, e.g., CSMA/CD
- Long round-trip delay will negatively influence performance

Reliability

- Don’t put all your eggs into one basket
- “Babbling idiot” problem (isolation of errors)

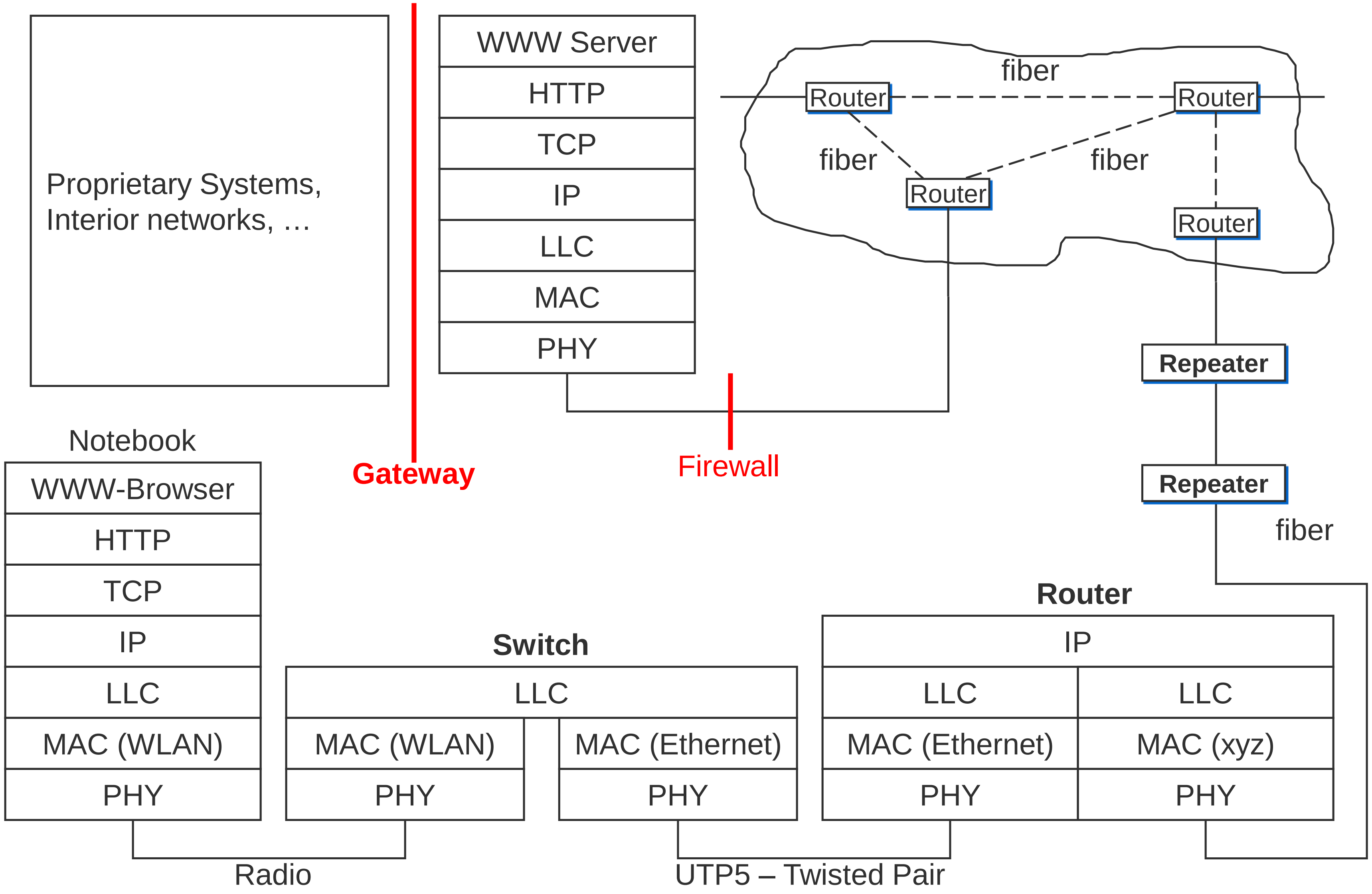
Security

- Contain possible damage caused by promiscuous operation

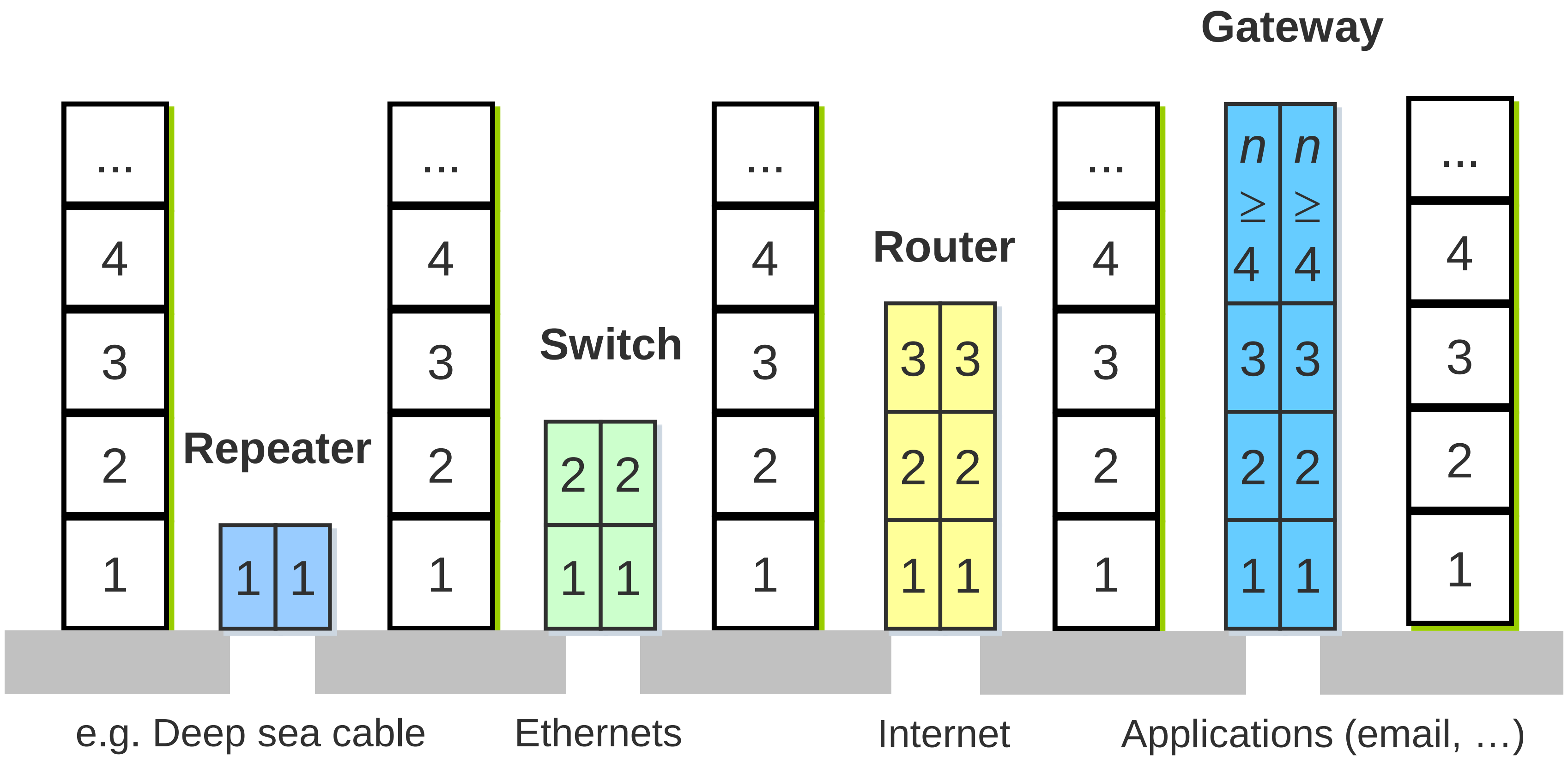
Political / business reasons

- Different authorities, policies, laws, levels of trust, …

Internetworking Units



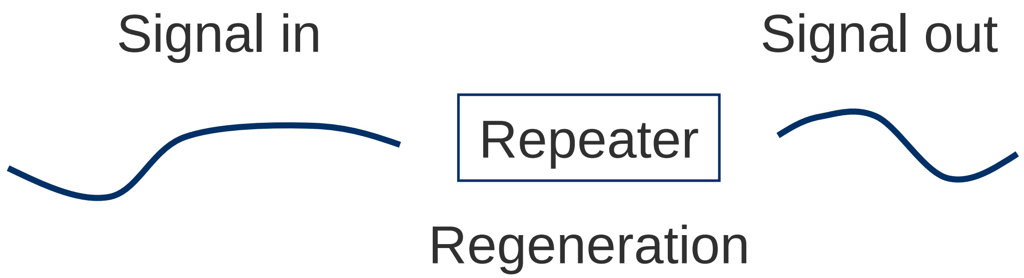
Internetworking Units

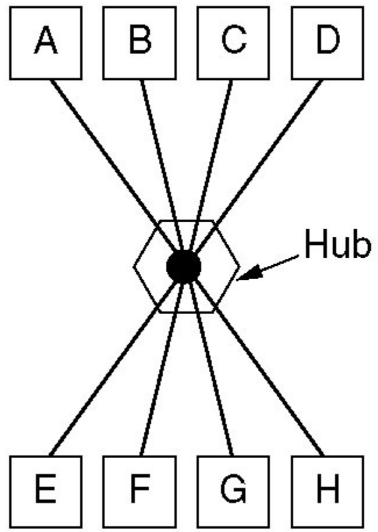


Repeater / Hub

Simplest option: Repeater

- Physical layer device, connected to two or more cables
- Amplifies/regenerates arriving signal, puts on other cables
  - Combats attenuation
  - ➢ Signal encodes data (represented by bits)
    - Can be regenerated
    - Opposed to only amplified (which would also amplify noise)
    - ➢ Analog vs. digital transmission
- Neither understands nor cares about *content (bits)* of packets





Problems of Physical Layer Solutions

Physical layer devices, e.g. repeater or hub, do not solve the more interesting problems

- E.g. no mechanism for handling load, scalability, ...

Some knowledge of data link layer structure is necessary

- Ability to understand/inspect content of packets/frames and do something with that knowledge

➢ Link-layer devices:

- Switch: Interconnect several terminals
- Bridge: Interconnect several networks (of different type)

➢ Nowadays terms sometimes used interchangeably

Switch

Used to connect several terminals or networks

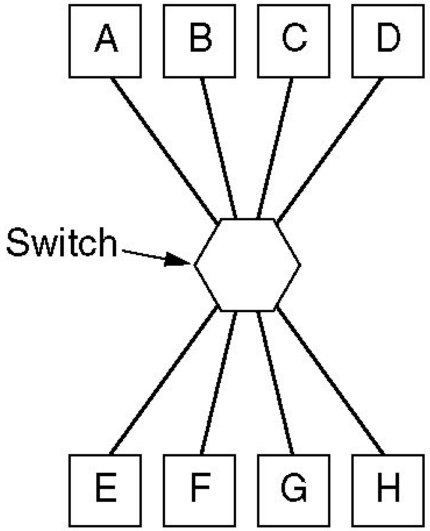
Switch inspects arriving packet's MAC addresses and forwards it *only* on correct cable/port

- Does not bother other terminals
- Requires data buffer and knowledge *on which* port which terminal is connected
  - Mapping function of MAC address to port

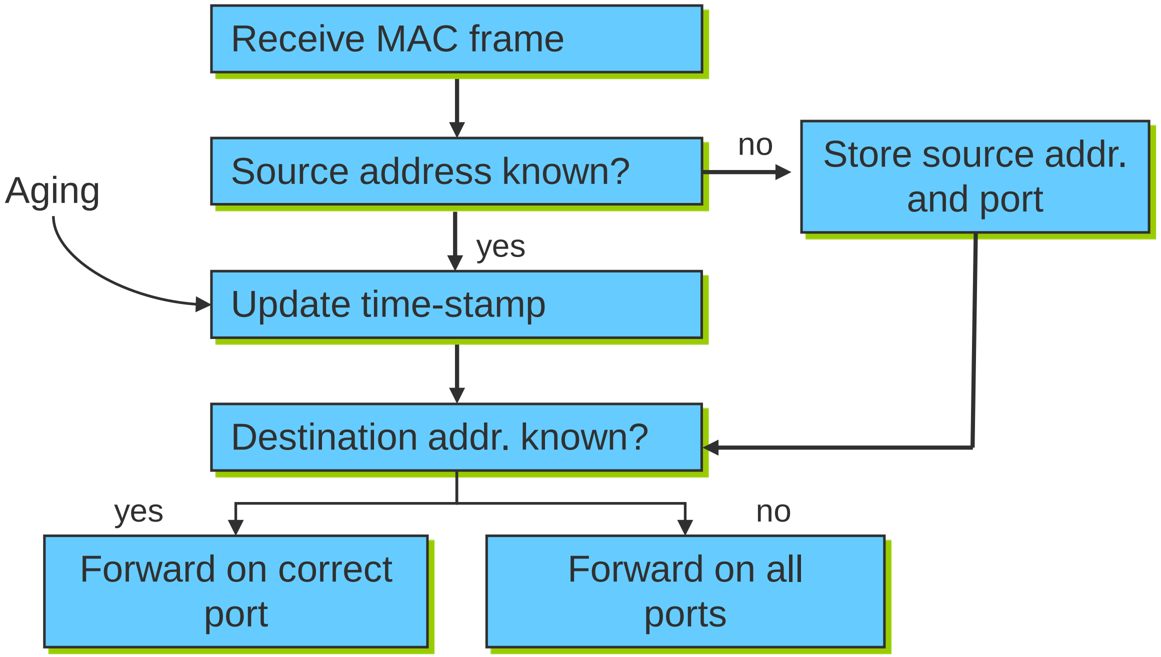
➢ How to obtain knowledge about network topology?

- Observe *from* where packets come to decide how to reach sending terminal

➢ *Backward learning*



Backward Learning – Algorithm

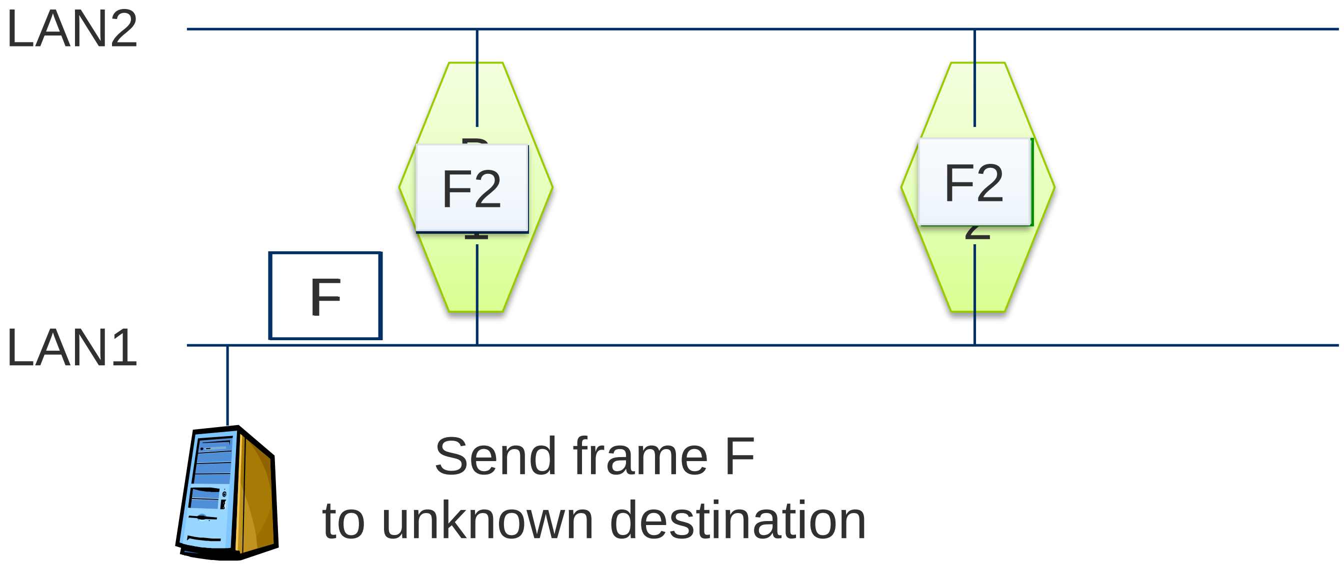


1. Learn address/port mapping from incoming packets
   - Remove expired entries (aging)
2. Forward based on knowledge about destination address
   1. Destination address is known → Forward on correct port
   2. Destination address is unknown → Forward on all ports
      - ➢ Only correct receiver will process frame, others will drop it

Flooding by Bridges – Problems

Backward learning by flooding is simple, but problematic

➢Example: Topology with second switch/bridge for reliability



And so on… How to avoid packet loops?

Create a logical tree on top of physical mesh

- Order bridges by built-in ID, exchange IDs between bridges, only forward packets on port towards lowest bridge ID

➢*Spanning Tree Protocol*

LAN/LAN Interconnection: VLANs

Problem: LANs and switches are geared towards physical proximity of devices

➢ But: LANs should respect *logical* proximity

- Connect devices of working groups together, irrespective *where* they happen to be located

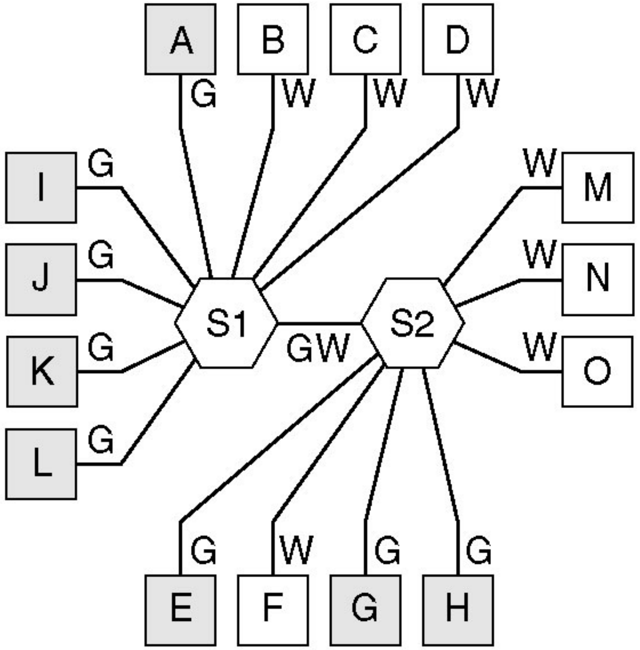
Idea: Put virtual LAN (VLAN) on top of existing physical LAN

Switches (or bridges) need configuration tables which port belongs to which VLAN

- Forward packets to ports of correct VLAN
- **Logical broadcast domain**

VLAN membership of incoming packets determined by port, MAC address or IP address ➔ VLAN mapping

➢ Standard: IEEE 802.1Q



Questions & Tasks

- How far can we (in theory) transmit data?
- What can gateways do compared to the other interworking units?
- Compare switch vs. hub – what are differences / advantages / disadvantages?

Routers

All devices so far either ignored addresses (repeaters, hubs) or worked on MAC-layer addresses (switches, bridges)

For interconnection outside a single LAN or connection of LANs, these simple addresses are insufficient

- Unstructured, “flat” addresses do not scale
  - All forwarding devices would need a list of *all* addresses
- Structured network topologies do not scale
  - World-wide spanning tree is unfeasible

➢ Need more sophisticated addressing structure and devices that operate on it

- Routers and routing
- E.g. based on Internet Protocol (IP) addresses

Example: Route to NASA (redone)

```
Z:\>tracert www.nasa.gov

Tracing route to www.nasa.gov.speedera.net [213.61.6.3]
over a maximum of 30 hops:

  1    <1 ms    <1 ms    <1 ms  router-114.inf.fu-berlin.de [160.45.114.1]
  2    <1 ms    <1 ms    <1 ms  zedat.router.fu-berlin.de [160.45.252.181]
  3     1 ms    <1 ms    <1 ms  ice.spine.fu-berlin.de [130.133.98.2]
  4     1 ms    <1 ms    <1 ms  ar-fuberlin1.g-win.dfn.de [188.1.33.33]
  5     1 ms    <1 ms    <1 ms  cr-berlin1-po5-0.g-win.dfn.de [188.1.20.5]
  6     9 ms     9 ms     9 ms  cr-frankfurt1-po9-2.g-win.dfn.de [188.1.18.185]
  7    10 ms     9 ms     9 ms  ir-frankfurt2-po3-0.g-win.dfn.de [188.1.80.38]
  8    10 ms     9 ms     9 ms  DECIX.fe0-0-guy-smiley.FFM.router.COLT.net
                                                          [80.81.192.61]

  9    10 ms     9 ms     9 ms  ir1.fra.de.colt.net [213.61.46.70]
 10    11 ms    10 ms     9 ms  ge2-2.ar06.fra.DE.COLT-ISC.NET [213.61.63.8]
 11    11 ms    10 ms    10 ms  213.61.4.141
 12    11 ms    10 ms    10 ms  h-213.61.6.3.host.de.colt.net [213.61.6.3]

Trace complete.
```

```
C:\>tracert www.nasa.gov

Tracing route to iznasa.hs.llnwd.net [2a02:3d0:623:a000::8008]
over a maximum of 30 hops:

  1    <1 ms    <1 ms    <1 ms  router-714.imp.fu-berlin.de
                                    [2001:638:80a:105::1]

  2    <1 ms    <1 ms    <1 ms  2001:638:80a:1::1
  3     1 ms     1 ms    <1 ms  2001:638:80a:3::1
  4     *        *        *     Request timed out.
  5    10 ms    10 ms    11 ms  2001:7f8:8::5926:0:1
  6    17 ms    17 ms    17 ms  tge1-4.fr5.dus1.ipv6.llnw.net
                                    [2a02:3d0:622:6c::2]

  7    12 ms    47 ms    12 ms  tge3-4.fr4.fra1.ipv6.llnw.net
                                    [2607:f4e8:1:c6::1]

  8    12 ms    12 ms    12 ms  2a02:3d0:623:6d::2
  9    15 ms    12 ms    12 ms
            https-2a02-3d0-623-a000--8008.fra.ipv6.llnw.net
            [2a02:3d0:623:a000::8008]

Trace complete.
```

Not all addresses can be resolved to names (see DNS)

Some requests are redirected to Content Delivery Networks

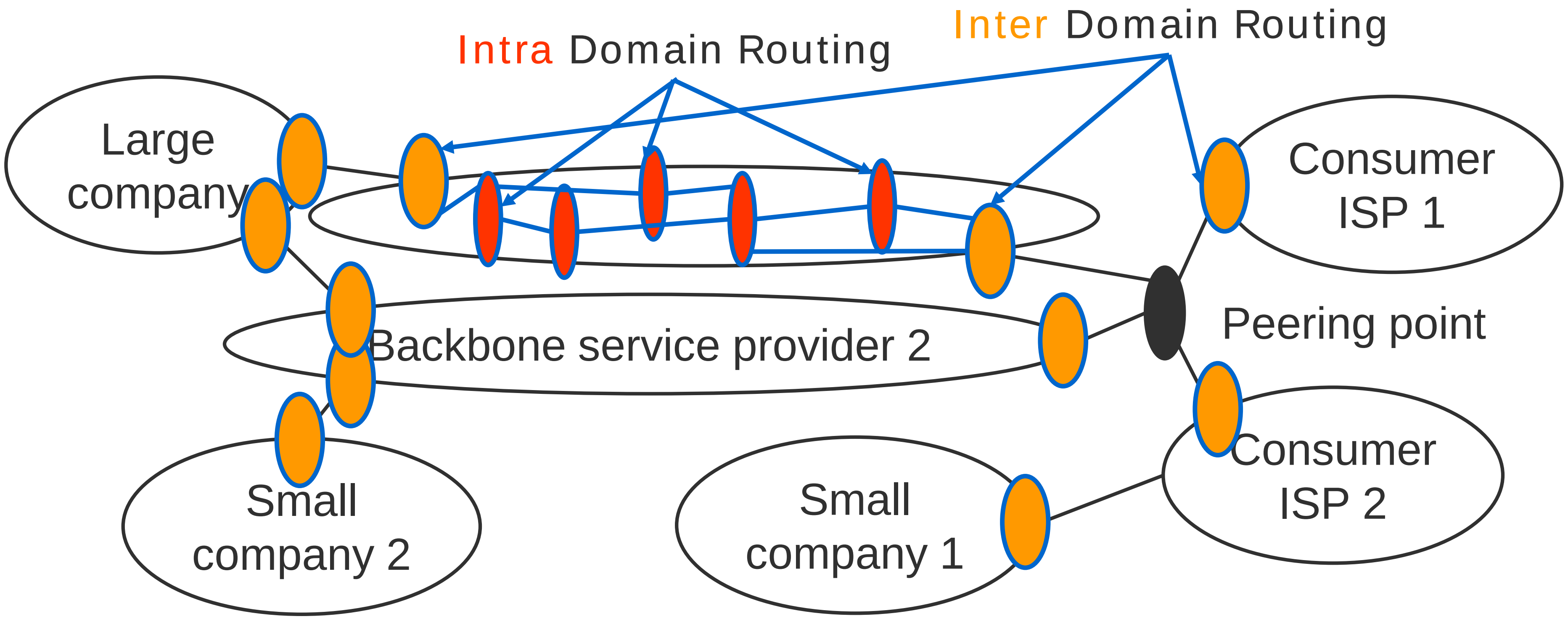
Some nodes simply don't answer…

What happened here?

The Idea of Internet Routing

Routing comprises:

- Updating of routing tables according to routing algorithm
- Exchange of routing information using routing protocol
- Forwarding of data based on routing tables and addresses



Autonomous Systems in the IP World

Large organizations can own multiple networks that are under single administrative control

- ➢Forming *autonomous system* or *routing domain*

Autonomous systems form yet another level of aggregating routing information

- ➢Give raise to *inter-* and *intra-domain routing*

Inter-domain routing is hard

- One organization might not be interested in carrying a competitor's traffic
- Routing metrics of different domains cannot be compared
  - ➢Only *reachability* can be expressed
- Scalability: Currently, inter-domain routers have to know about 200,000 – 400,000 networks

Intra-domain Routing: OSPF

The Internet's most prevalent intra-domain (= interior gateway) routing protocol: *Open Shortest Path First* (OSPF)

Main properties:

- Open, variety of routing distances, dynamic algorithm
- Routing based on traffic type (e.g. real-time traffic uses different paths)
- Load balancing: Also put some packets on the 2nd, 3rd best path
- Hierarchical routing, some security in place, support tunneled routers in transit networks

Essential operation: Compute shortest paths on graph abstraction of autonomous system

➢ Link state algorithm

Basic Ideas of Link State Routing

Distributed, adaptive routing

Algorithm:

1. Discovery of new neighbors
   - HELLO packet
2. Measurement of delay / cost to all neighbors
   - ECHO packet measures round trip time
3. Creation of link state packets containing all learned data
   - Sender and list of neighbors (including delay, age, ...)
   - Periodic or event triggered update (e.g. upon detecting new neighbors, line failure, ...)
4. Flooding of packet to all neighbors
   - Flooding, but with enhancements: Duplicate removal, deletion of old packets, ...
5. Shortest path calculation to all other routers (e.g. Dijkstra)
   - Computing intensive, optimizations exist

Inter-domain Routing: BGPv4

Routing between domains: *Border Gateway Protocols* (BGP)

BGP's perspective: Only autonomous systems and their connections

- Routing complicated by politics, e.g. only route packets for paying customers, …
- Legal constraints, e.g. traffic originating and ending in Canada must not leave Canada while in transit

Basic operation: Distance vector protocol

- Propagate information about reachable networks and distances one hop at a time
  - Each router learns only next step to destination
- Optimizations in BGP:
  - Not only keep track of cost via a given neighbor, but store entire paths to destination ASs
    - -> Path vector protocol
  - More robust, solves problems like count to infinity, i.e. can handle disconnected networks efficiently

Conclusion: Interconnections

Single LANs are insufficient to provide communication for all but the simplest installations

Interconnection of LANs necessary

- Interconnect on purely physical layer: Repeater, hub
- Interconnect on data link layer: Bridges, switches
- Interconnect on network layer: Router
- Interconnect on higher layer: Gateway

Problems:

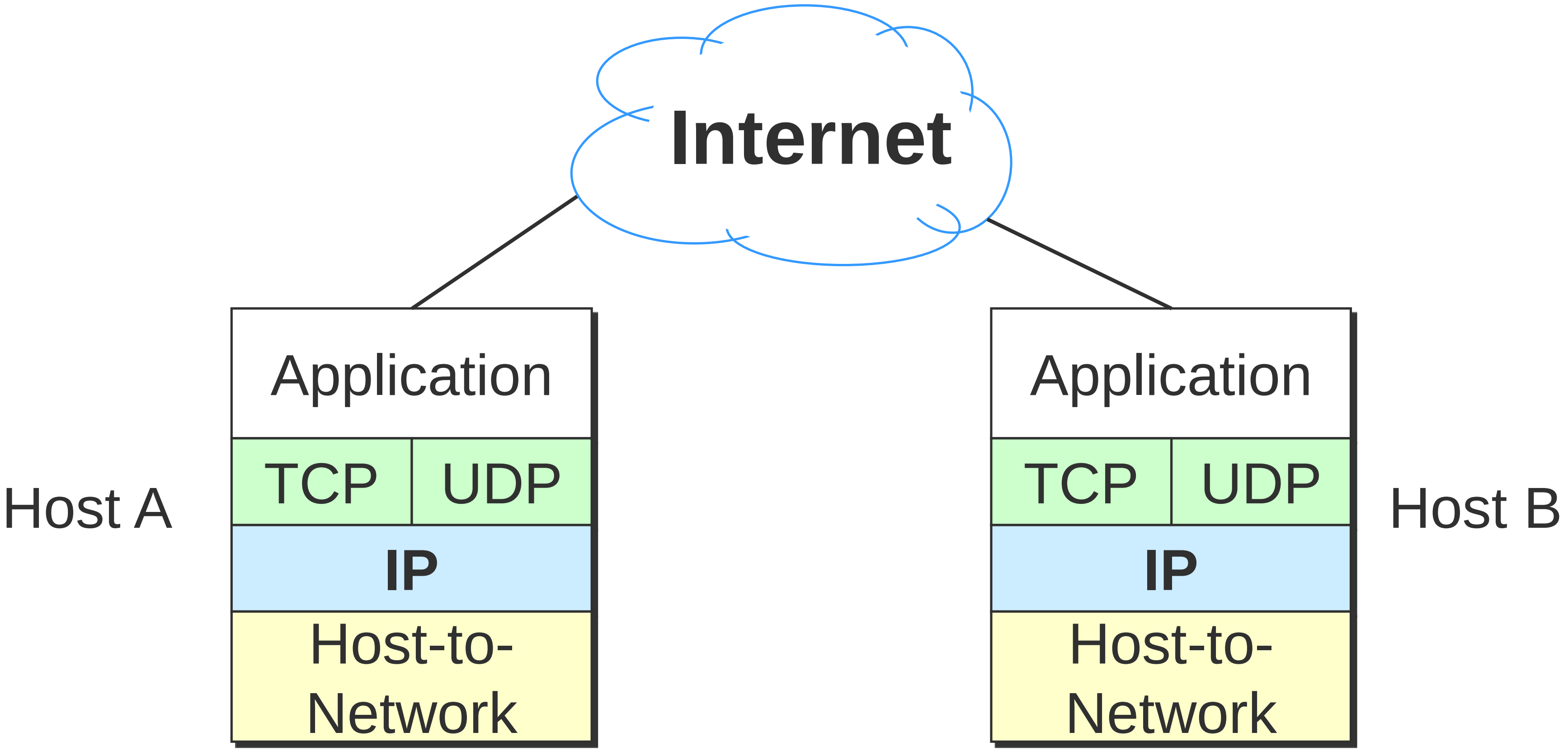
- Redundant bridges can cause traffic floods; need spanning tree algorithm
- Simple addresses do not scale; need routers

Questions & Tasks

- We can’t we set-up a large scale network based on layer 2? Why is this possible on layer 3?
- What is the difference between intra- and inter-domain routing? What are typical protocols for it?
- Why does BGP not always give the shortest path?
- Why not using OSPF for world-wide routing?

INTERNET PROTOCOL

Simplified View of Internet protocols



IP and Supporting Protocols

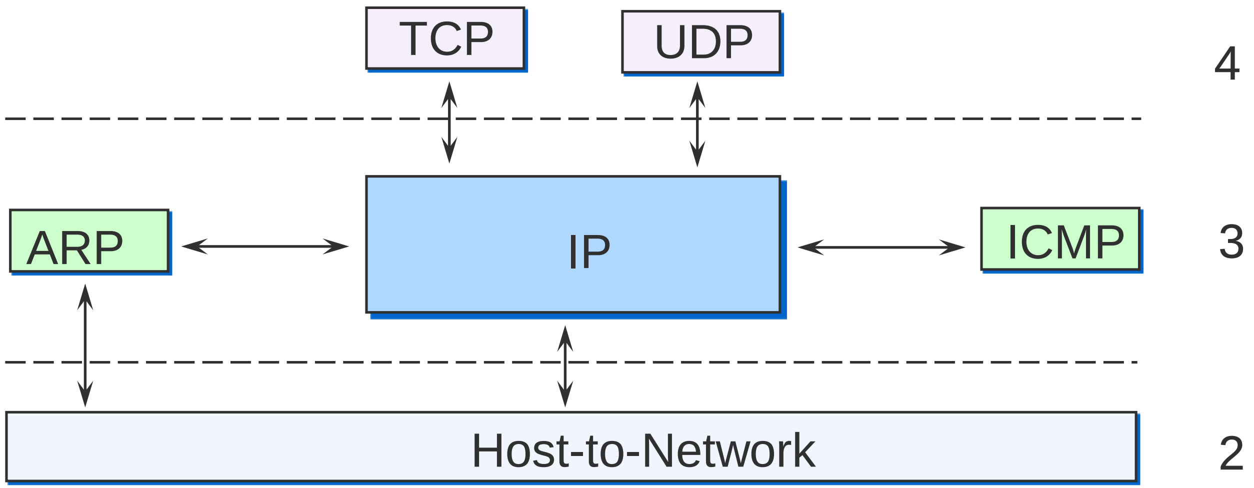
Transport protocols (Layer 4, TCP or UDP) hand over data together with IP address of receiver to Internet Protocol (IP)

IP may need to ask Address Resolution Protocol (ARP) for MAC address (Layer 2)

IP hands over data together with MAC address to Layer 2

IP forwards data to higher layers (TCP or UDP)

Internet Control Message Protocol (ICMP) can signal problems during transmission



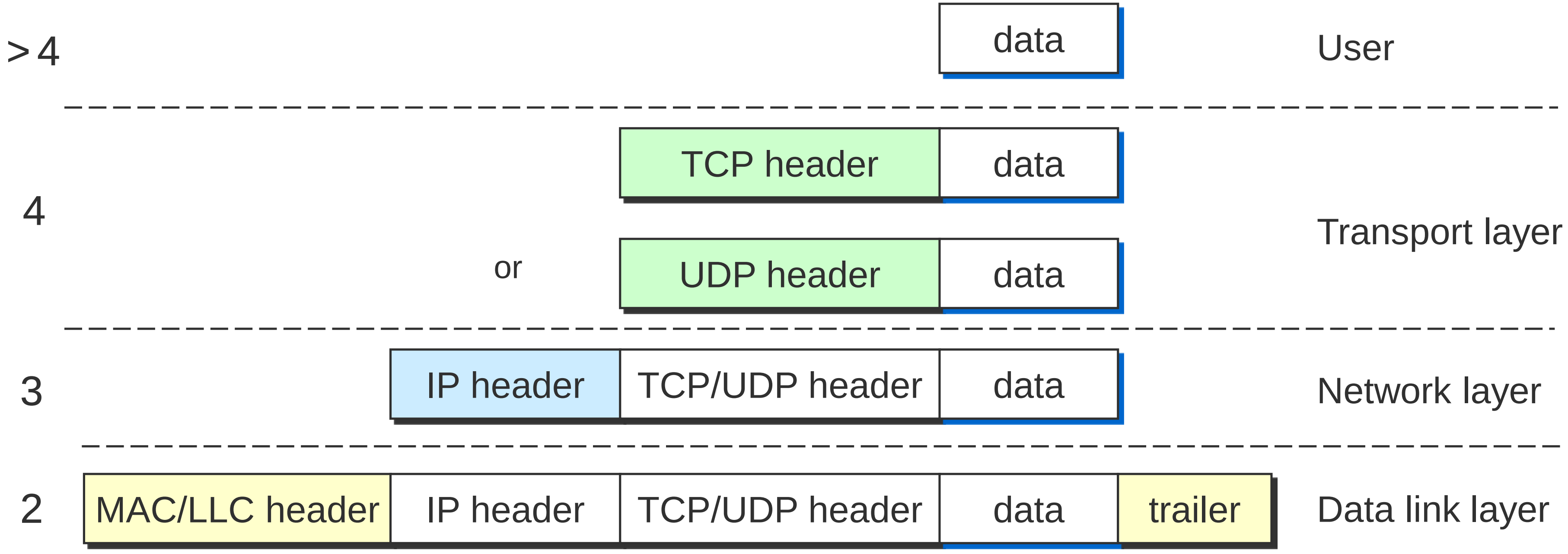
Data Encapsulation / Decapsulation

IP forwards data packets through network to receiver

TCP/UDP add ports (dynamic addresses of processes)

TCP offers reliable data transmission

Packets (PDU, protocol data unit) are encapsulated



Internet Protocol (IP)

History

- Original development with support of US Department of Defense
- Already used back in 1969 in APANET

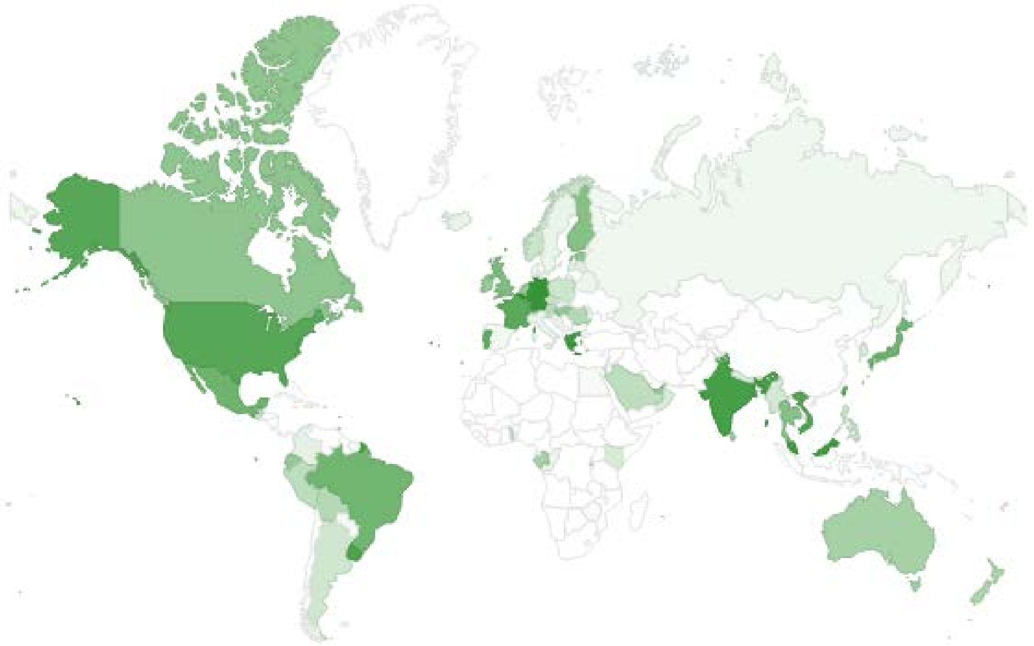
Tasks

- Routing support using structured addresses
- Checking of packet lifetime to avoid routing loops
- Fragmentation and reassembly
- Network diagnostics support

Development

- Today IP (version 4) is still most widely used layer 3 protocol
- Further development started back in the 80s/90s
  - Project IPng (IP next generation) of the IETF (Internet Engineering Task Force)
- Result in mid 90s: IPv6, still not as widely used as expected
- Today widely used, but could be more…
  - E.g., 2020: about 32% access Google via IPv6 (Germany 50%, USA 41%, Sweden 6%)

Per country IPv6 adoption as seen by Google



Source: www.google.com

Properties of IP

Packet oriented

Connectionless (datagram service)

Unreliable transmission

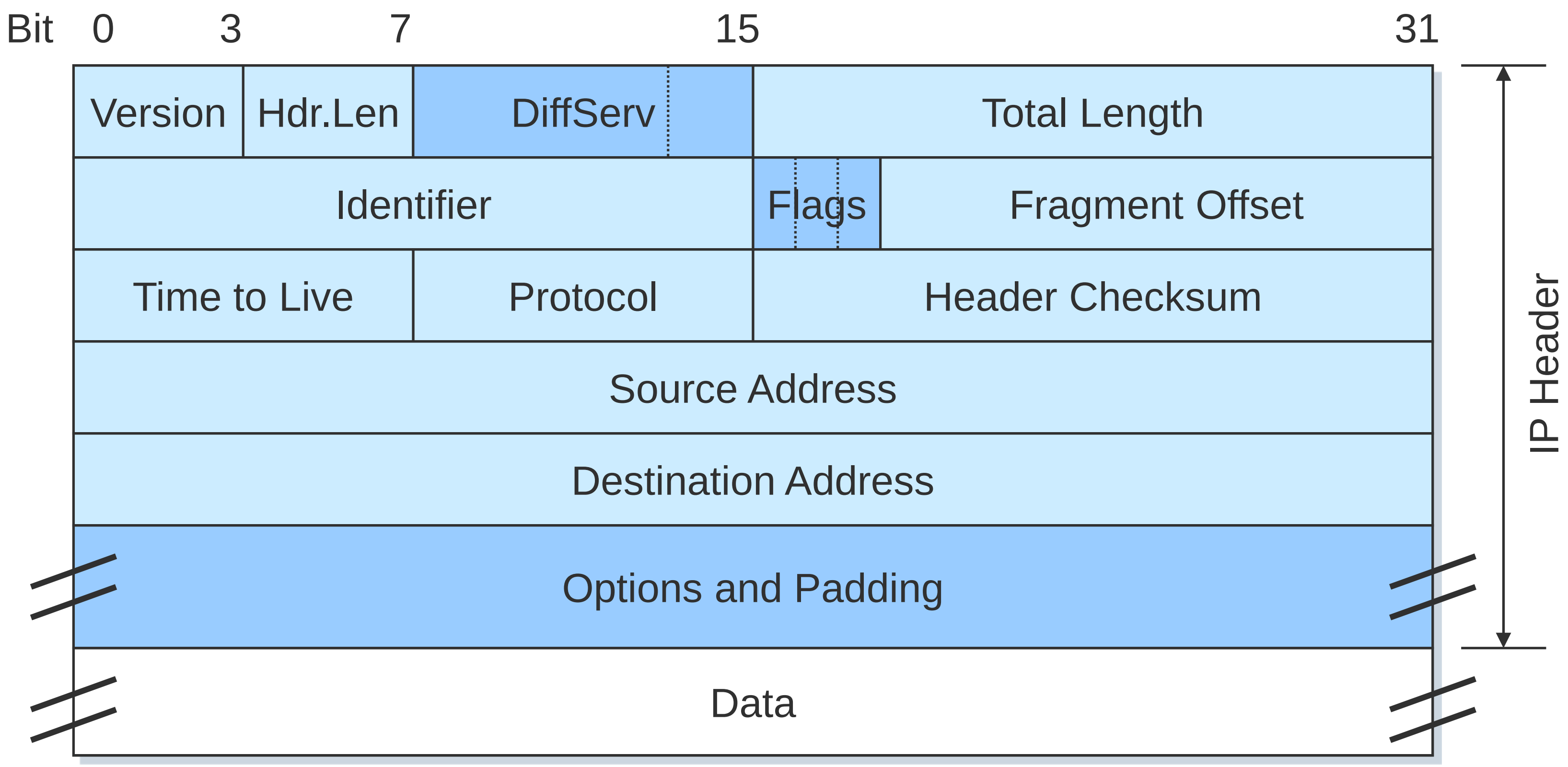
- Datagrams can be lost
- Datagrams can be duplicated
- Datagrams can be reordered
- Datagrams can circle, but solved by Time to Live (TTL) field
- IP cannot handle Layer 2 errors
- At least there is ICMP to signal errors

Routing support via structured addresses

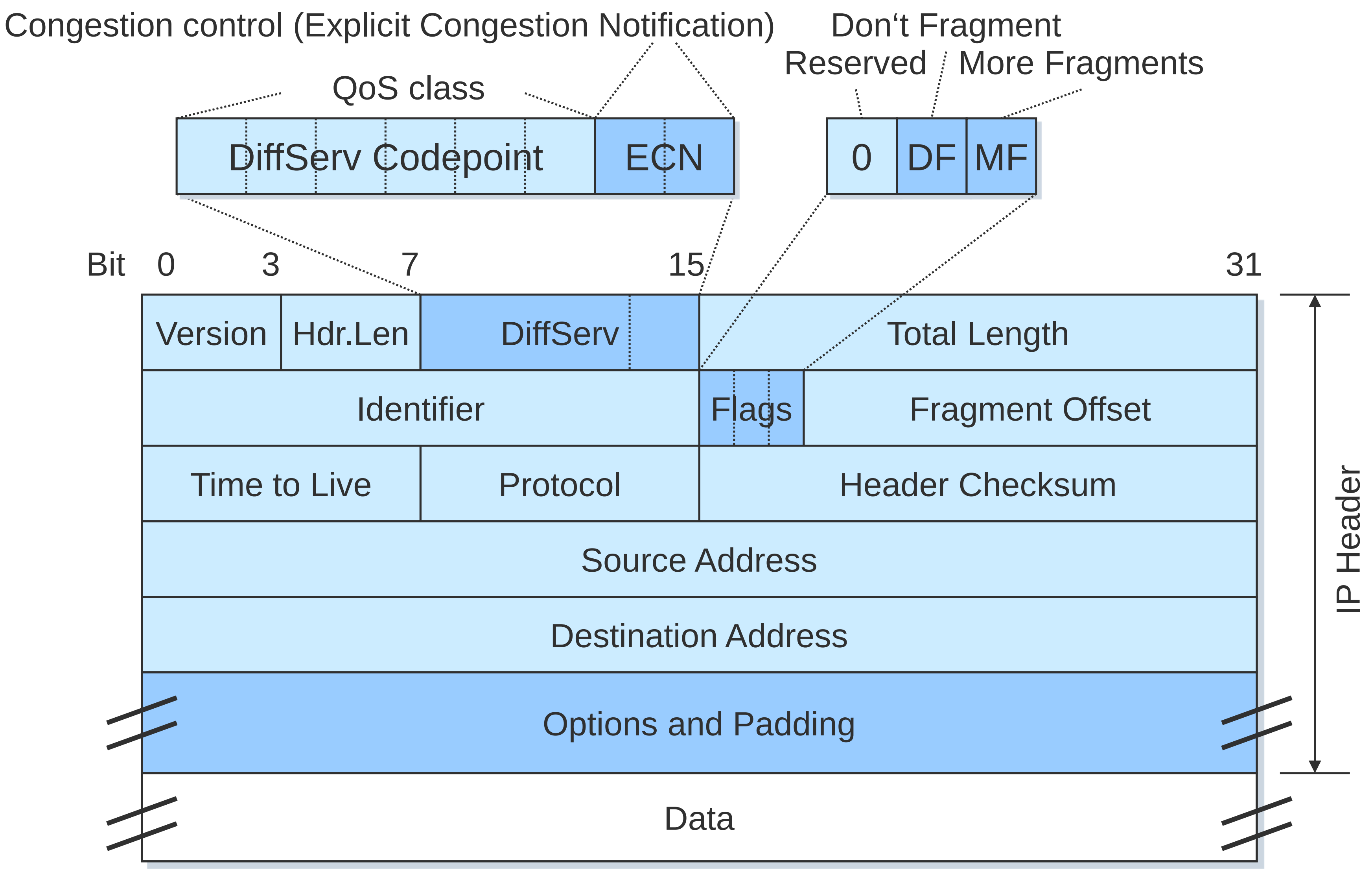
No flow control (yet, first steps taken)

Used in private and public networks

IPv4 Datagram

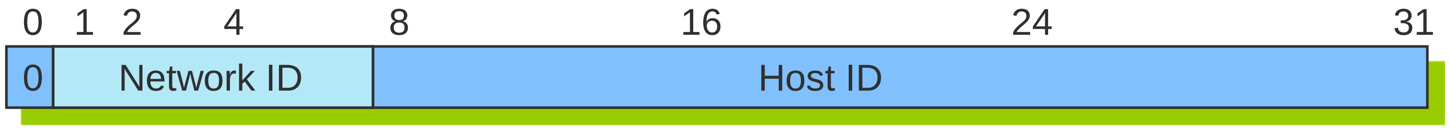


IPv4 Datagram



Structured IP Addresses and Address Classes (Classical View)

1. Class A: 128 networks, 16M hosts



1.0.0.0 – 127.255.255.255

2. Class B: 16k networks, 64k hosts

128.0.0.0 – 191.255.255.255

3. Class C: 2M networks, 256 hosts

192.0.0.0 – 223.255.255.255

4. Class D: group communication (Multicast)

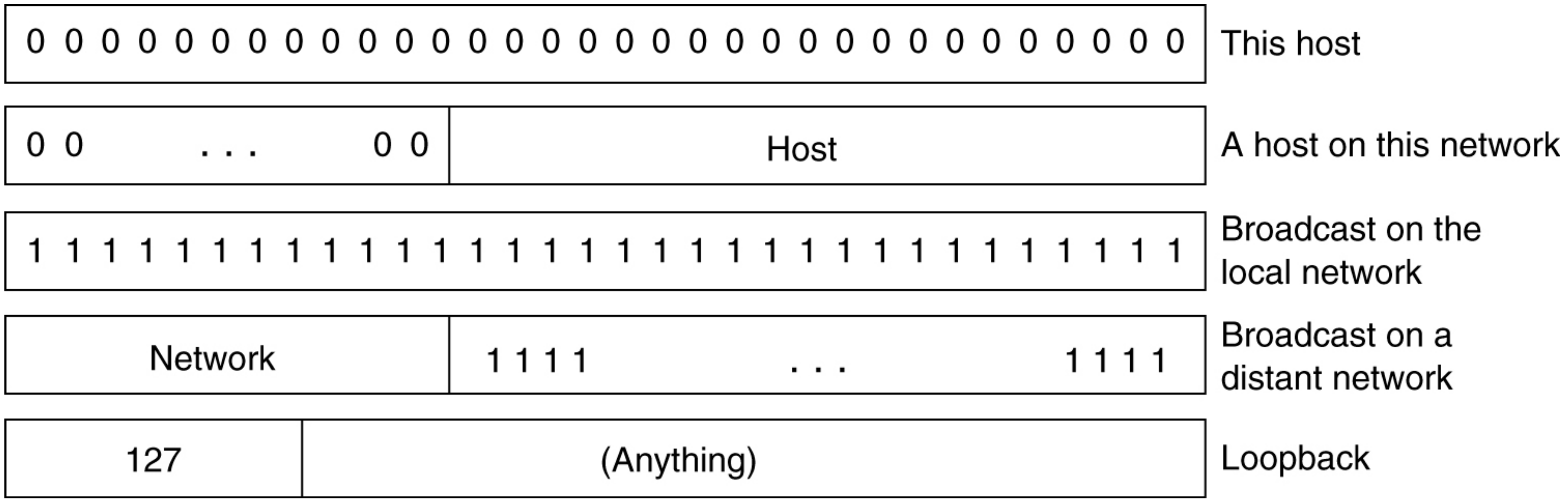
224.0.0.0 – 239.255.255.255

5. Class E: reserved for future use

240.0.0.0 – 255.255.255.255

Special IP Addresses

Some IP addresses are reserved for special uses:



Not all of the network/host combinations are available

- ➢ So-called “private” IP addresses
  - Used for internal networks (addresses not routable)
  - Example: 10.0.0.1, 192.168.0.1

Questions & Tasks

- What service does IP offer?
- Which protocols are needed in addition for what purpose?
- Why does it take that long before everyone uses IPv6? What is needed?
- How to stop circulating packets?
- What is the problem of the classical class-based addressing? (That’s why we have CIDR…)
- What is the purpose of private addresses?

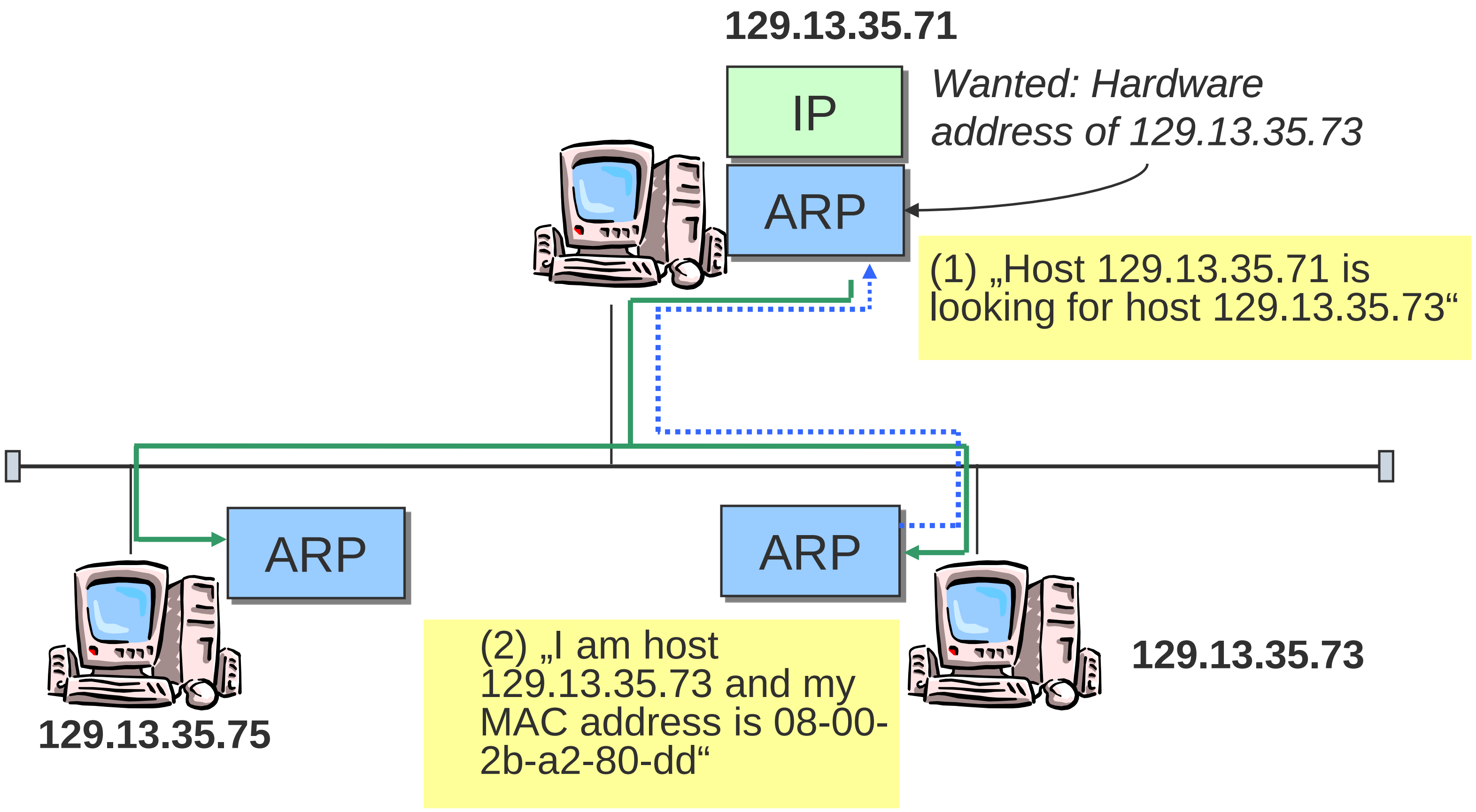
Bridging Addressing Gap: ARP

- What happens once a packet arrives at its destination network / LAN?
  - IP address (which is all that is known about destination) needs to be translated into a MAC address that corresponds to the IP address

Simple solution: Broadcast
- Broadcast on LAN, asking which node has requested IP address
- Node answers with its MAC address
- Router can then forward packet to that MAC address

- *Address Resolution Protocol* (ARP)

Example: ARP



129.13.35.71
IP
ARP
Wanted: Hardware address of 129.13.35.73
(1) „Host 129.13.35.71 is looking for host 129.13.35.73"
ARP
ARP
129.13.35.75
(2) „I am host 129.13.35.73 and my MAC address is 08-00-2b-a2-80-dd"
129.13.35.73

Scalability Problems of IP

Class A and B networks can contain *many* hosts

- Too many for a router to easily deal with
- Additionally, administrative problems in larger networks

➢ Solution: Subnetting, i.e. a network is subdivided into several smaller networks by breaking up the address space

Network classes waste a lot of addresses

- Example: Organization with 2000 hosts requires a class B address, wasting 64K-2K ≈ 62.000 host addresses

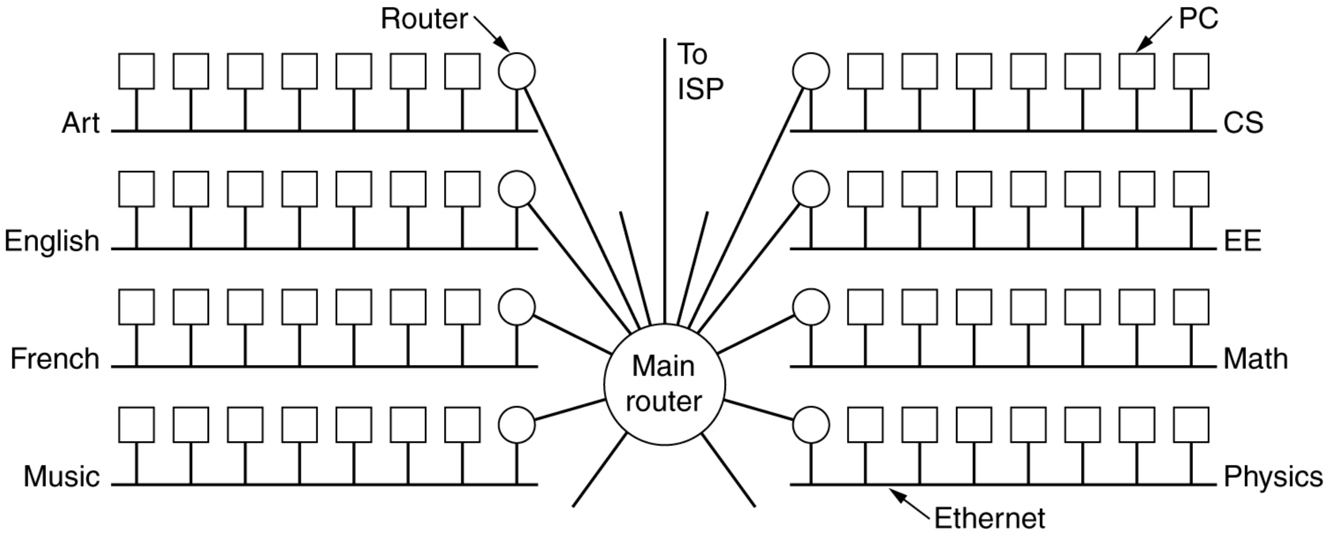
➢ Solution: Classless addressing ➔ Classless Inter Domain Routing (CIDR)

  - Dynamic boundaries between host/network part of IP address
  - Aggregation on routers to reduce size of global routing table

Subnetting

Suppose an organization has one class B address but is organized into several LANs

- Example: University with different departments



Main router should be concerned with whole networks

- Should not be bothered with all the nodes in each departments

Obvious case for hierarchical routing and addressing

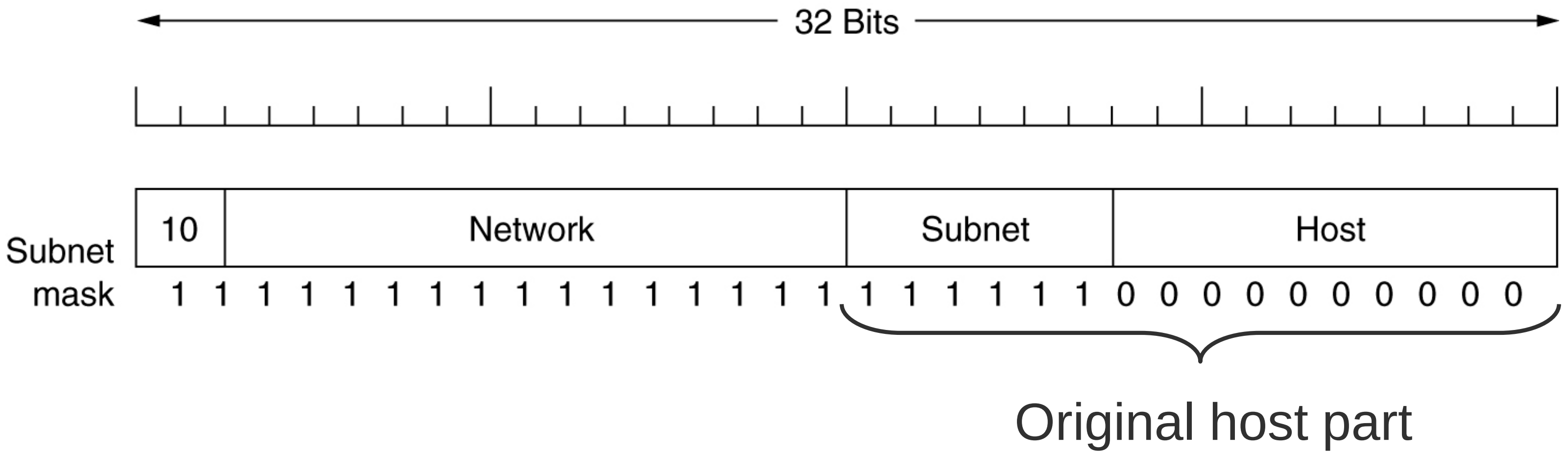
➢ How to put hierarchies into existing IP addresses?

Subnetting – Hierarchies in Addresses

Manipulating class bits to introduce more hierarchy levels is not practical

Idea: Have more hierarchy levels implicitly

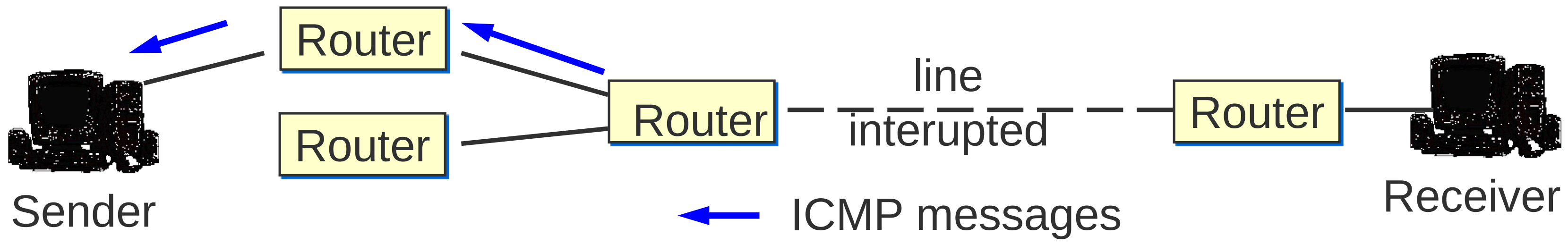
- Introduce a *subnet*, represented by “borrowing” bits from host part of IP address
- Local router has to know where to apply this split
  - Needs a *subnet mask*
- Represented as x.y.u**/#bits** or as bit pattern needed to mask out the host bits



Controling IP: ICMP

IP is responsible for (unreliable) data transfer only

Internet Control Message Protocol (ICMP) is used for error reporting and testing



Examples:

- Destination Unreachable
- Time Exceeded: Time-to-Live field reaches 0
  - Also used when looking up routes using traceroute
- Echo Request / Reply ("ping")
- Timestamp Request / Reply

Conclusion: Internet Protocol

Unreliable datagram transfer

Needs supporting protocols
- ARP for mapping IP to MAC address
- ICMP for error signaling

Classical addressing wastes addresses
- Subnetting, subnet masks
- Classless addressing, CIDR

Version 4 dominant, version 6 coming (since years…)
- **Much** more in Telematics

Content

8. Networked Computer & Internet

9. Host-to-Network

10. Internetworking

11. Transport Layer

12. Applications

13. Network Security

14. Example

Questions & Tasks

- Assume you are in Berlin and want to send an IP-packet to a computer in Tokyo. Which destination MAC-address will the outgoing packet contain? Why? How does the computer know this address?
- How does CIDR help to reduce wasted addresses and routing overhead?
- How can subnetting help? Which part of the address can be “subnetted”?
- What is the role of ICMP?