University of Glasgow

Internet Protocols Laboratory

The Changing Internet

Networked Systems (H)

Lecture 1

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Course Administration

- Aims, Objectives, Learning Outcomes
- Timetable
- Assessment
- Recommended Reading

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Course Coordinator and Materials

- Lecturer and course coordinator
  - Prof Colin Perkins (colin.perkins@glasgow.ac.uk)
  - Office: S101b, Lilybank Gardens

- Course materials on Moodle and https://csperkins.org/teaching/



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Aims and Objectives

- To introduce fundamental concepts and theory of communications
- To provide a solid understanding of the technology that supports modern networked computer systems
- To give students the ability to evaluate and advise industry on the use and deployment of networked systems
- To introduce low-level network programming, and give students practice with systems programming in C

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Intended Learning Outcomes

- By the end of the course, you should be able to:
  - Describe and compare capabilities of various communication technologies and techniques;
  - Know the differences between networks of different scale, and how these affect their design;
  - Understand demands of different applications on quality of service requirements for the underlying communication network;
  - Describe the issues in connecting heterogeneous networks;
  - Describe importance of layering, and the OSI reference model;
  - Demonstrate an understanding of the design and operation of an IP network, such as the Internet, and explain the purpose and function of its various components; and
  - Write simple low-level communication software, showing awareness of good practice for correct and secure programming

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Course Structure

Week	Thursday 11:00-13:00 – Labs	Thursday 16:00-18:00 – Lectures
1		#1: The Changing Internet
2	#1: Introduction to Network Programming in C	#2: Connection Establishment in a Fragmented Network
3	#2: Connection Establishment	#3: Secure Communications
4	#3: Transport Layer Security	#4: Improving Secure Connection Establishment
5	#4: QUIC	#5: Reliability and Data Transfer
6	#5: TCP Behaviour and Congestion Control	#6: Lowering Latency
7		#7: Real-time and Interactive Applications
8	#6: Network Topology	#8: Naming and the Tussle for Control
9		#9: CDNs, Routing, and Future Directions
10		

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Labs

- Lab handouts are available on Moodle
- Timetabled lab sessions are for **support with the lab exercises** and **discussion of related material**
  - **Read the handout and think about the discussion questions** before the scheduled lab
  - Try to complete the exercises, and think of questions you might need to ask, **before** the timetabled lab slot
  - The lab exercises that make use of IPv6 are tested on the Linux servers provided by the School (`stlinux01` - `stlinux08.dcs.gla.ac.uk`). They likely won't work from `eduroam` on campus, and may not work from your home network

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Assessed Exercise

- The assessed exercise is worth 20% of the marks for this course
  - Available on the day of Lecture 5
  - Deadline is the date of Lecture 7 at 4:30pm
- Note well:
  - Following the code of assessment, late submissions of assessed exercises will be accepted for up to 5 working days beyond the due date. Such late submissions will receive a two band penalty for each working day, or part thereof, the submission is late. Submissions that are received more than five working days after the due date will be awarded a band of H. Submissions of assessed exercises that do not follow the instructions given in the handout will be given a two band penalty. **These penalties will be strictly enforced.**
  - If you are ill, or have other extenuating circumstances that may affect your submission, then you may contact the Teaching Office **before the deadline** to request an extension, following the usual procedure.

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Examination

- The final exam is worth 80% of the marks for this course
- Exam format: answer all three questions
  - The aim is to test your understanding of the material, not just to test your memory of all the details – explain **why**, **don't just recite what**
  - The University code of assessment states that excellent performance (Grade A) is likely to be characterised by various factors, including:
    - reasoned arguments developing logical conclusions
    - evidence of wide, relevant reading
    - application of learning to new situations and problem solving
- Past papers are on Moodle and on the website

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Required Reading

- You are expected to read one of the following:
  - Peterson and Davie, **Computer Networks: A Systems Approach**, available for free online at https://book.systemsapproach.org
  - Bonaventure, **Computer Networking: Principles, Protocols and Practice**, available for free online at http://www.computer-networking.info/
  - Kurose and Ross, Computer Networking: A Top-Down Approach, 9th Edition, Pearson, 2025, ISBN 978-0135429334 (£)
  - Tanenbaum, Feamster, and Wetherall, Computer Networks, 6th Edition, Pearson, 2021, ISBN 978-1292374062 (£)
- **You are expected to read-along with the lectures – the lectures introduce the core ideas, while the books and linked papers, RFCs, and blog posts provide detail and context**

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Student Feedback (1/3)

- Feedback on lectured content
  - You are expected to review the slides **before** the timetabled sessions
  - **Active participation** is encouraged – **ask questions** during the lectures
- Feedback on laboratory exercises and coursework
  - Many of lab exercises include discursive elements and open-ended questions for discussion with the lecturer or demonstrators during the lab sessions
  - You are expected to attempt the lab exercises **before** the timetabled labs, and use the lab times to discuss the materials and receive feedback on your understanding

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Student Feedback (2/3)

- Feedback on assessed exercises
  - You will receive your grade along with brief written feedback on your performance for each assessed exercise – this will be available via Moodle
- Feedback on exams
  - Grades will be released after the exam board meetings in June
  - Individual feedback on exam performance is not provided, but summary feedback for the class will be provided on Moodle highlighting common issues

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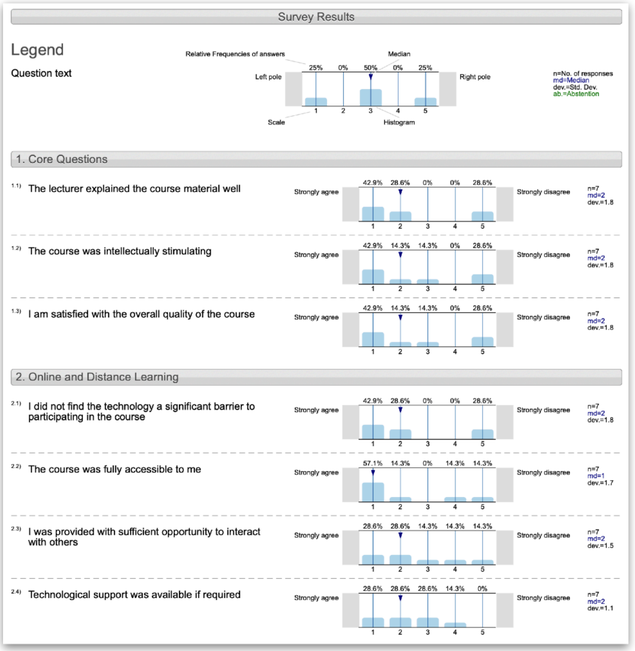
Student Feedback (3/3)

- Only 7 students provided feedback last year
- What was good about the course?
  - “course content was really interesting”; “difficulty of the course was perfect suited to our experience level with networks”; “left the course with a confidence in my networks knowledge and skill set”; “I really enjoyed the detail and the insight of the lecturer as someone experienced in the design of network protocols, with attention as to the philosophical questions of the design of computer networks too”
- How could this course be improved?
  - Some complaints that coursework marking was overly harsh – *the coursework average was a B2, which is typical*
  - Perhaps too much reliance on pre-recorded lectures and in-person discussion – *structure has changed from pre-recorded lectures with an emphasis on discussion to standard lecture format this year*



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Protocols and Layers

- What is a networked system?
- Protocols and Layering

See also: J. Macculey, S. Shenker, and G. Varghese, "**Extracting the Essential Simplicity of the Internet**", Communications of the ACM, Volume 66, Number 2, February 2023. DOI: 10.1145/3547137.
https://www.youtube.com/watch?v=XY6fJVMaawI

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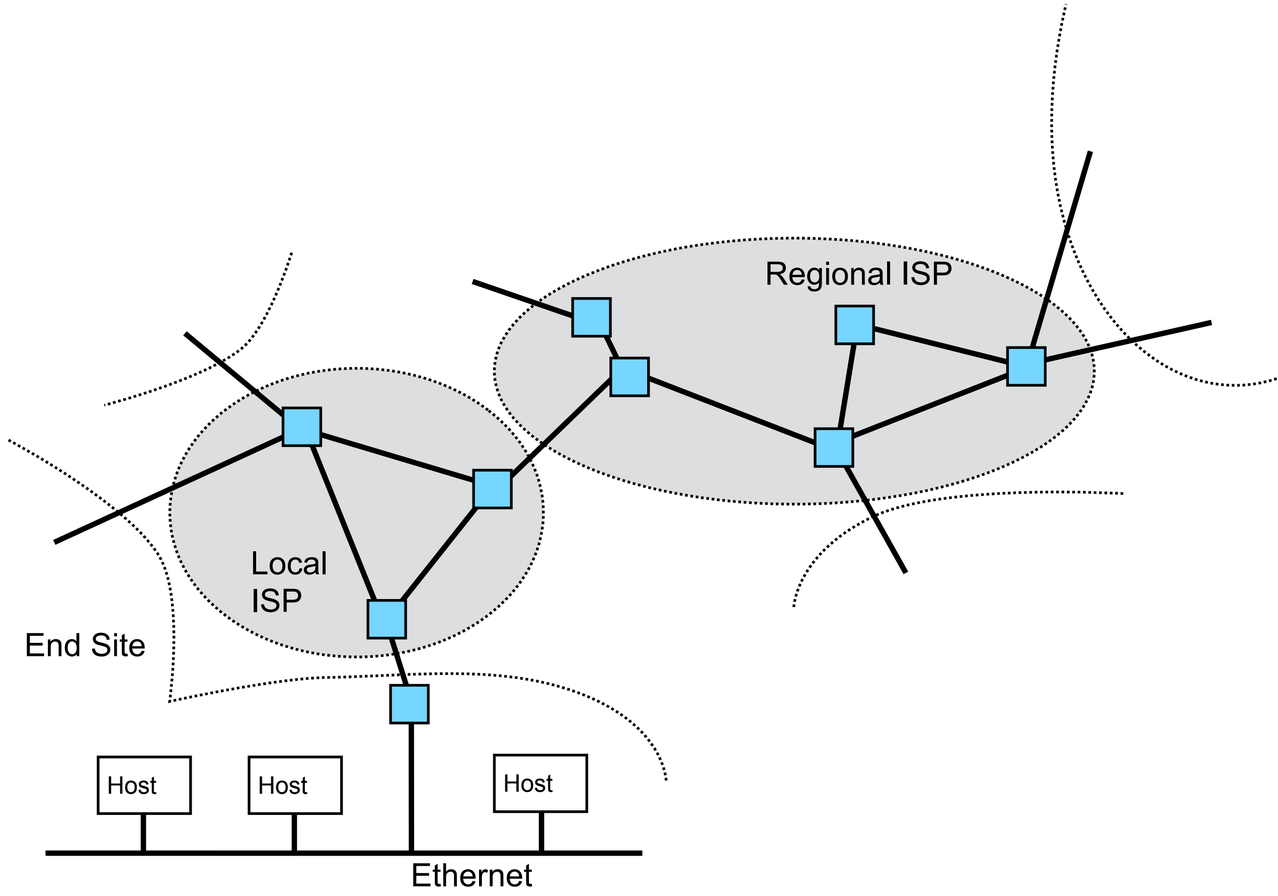
What is a Networked System?

- A cooperating set of autonomous computing devices that exchange data to perform some application goal
  - Communication – how is information exchanged across a single link?
  - Networking – how are links connected to form a wide area network?
  - Internetworking – how do networks interconnect to form **an** internet? How is data delivered across that network?
  - Transport – how do the end-systems ensure that data is delivered reliably?



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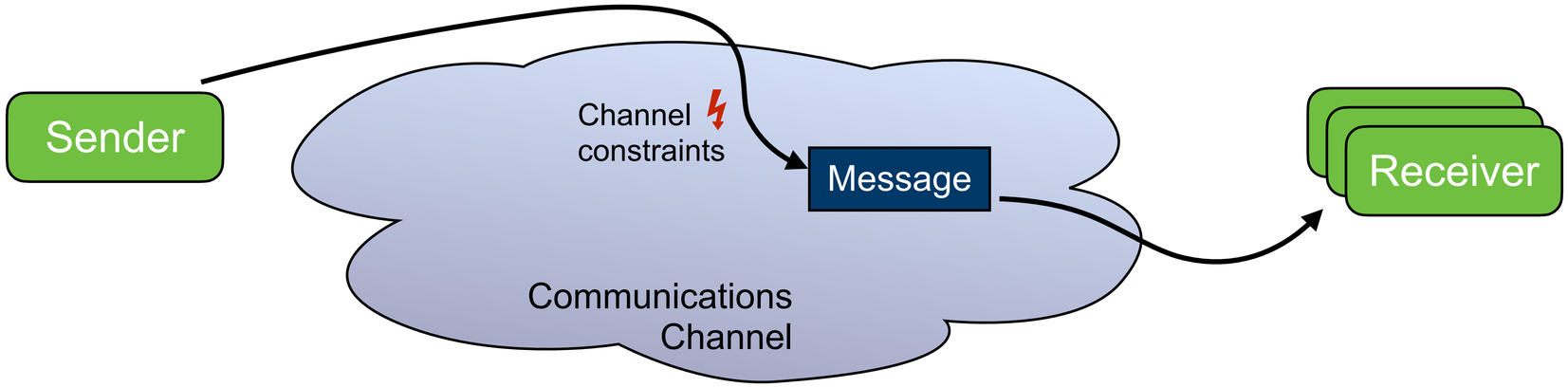
Communication Protocols



- Channel constraints bound communications speed and reliability
- The message syntax, semantics, and communication patterns form a **network protocol** – HTTP, TCP, IP, etc.
- Protocols can be composed and layered to raise level of abstraction

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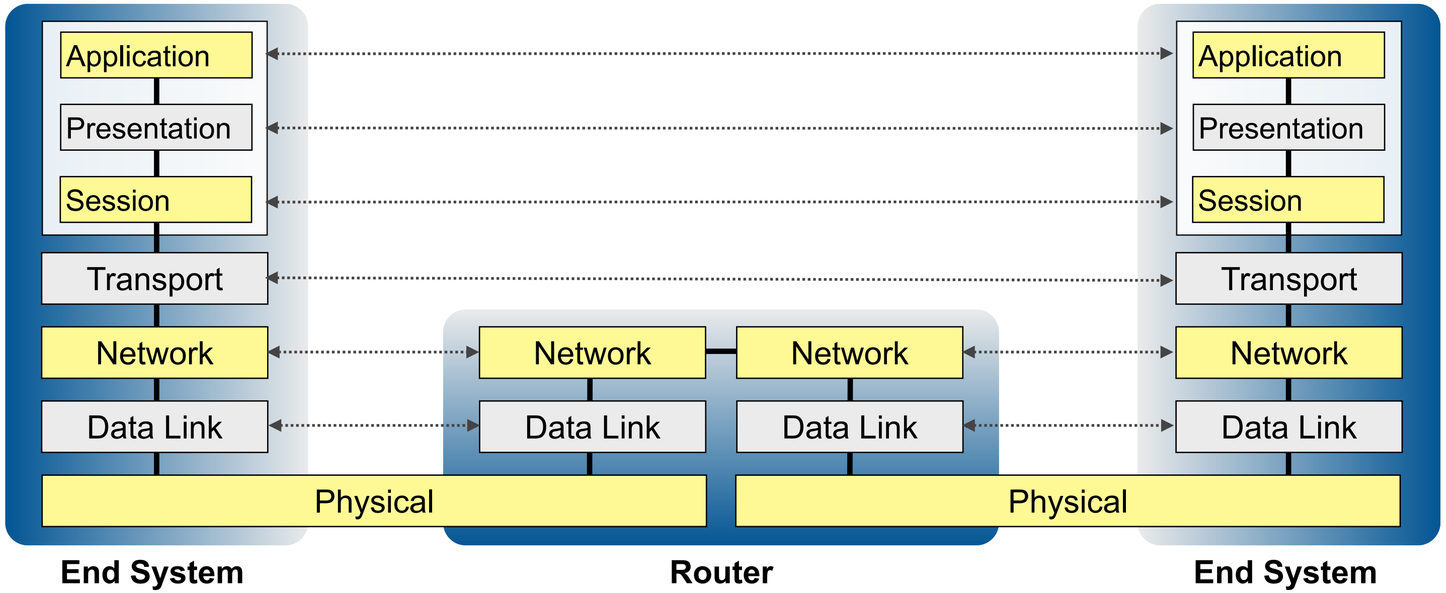
Protocol Layering: The OSI Reference Model



- A standard model for thinking about layered protocol design – but **real networks do not match this model –** they're more complex, and layer violations, sublayers, and tunnels are commonplace

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Physical and Data Link Layers

- Physical link characteristics, modulation and transmission
- Data link layer: framing and addressing, media access control

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The Physical Layer

- Physical layer enables communication via some channel – transmission of raw bitstream
  - What type of cable or wireless link comprises the channel?
  - How to encode bits onto that channel?
    - Baseband encoding
    - Carrier modulation
  - What is the capacity of the channel?

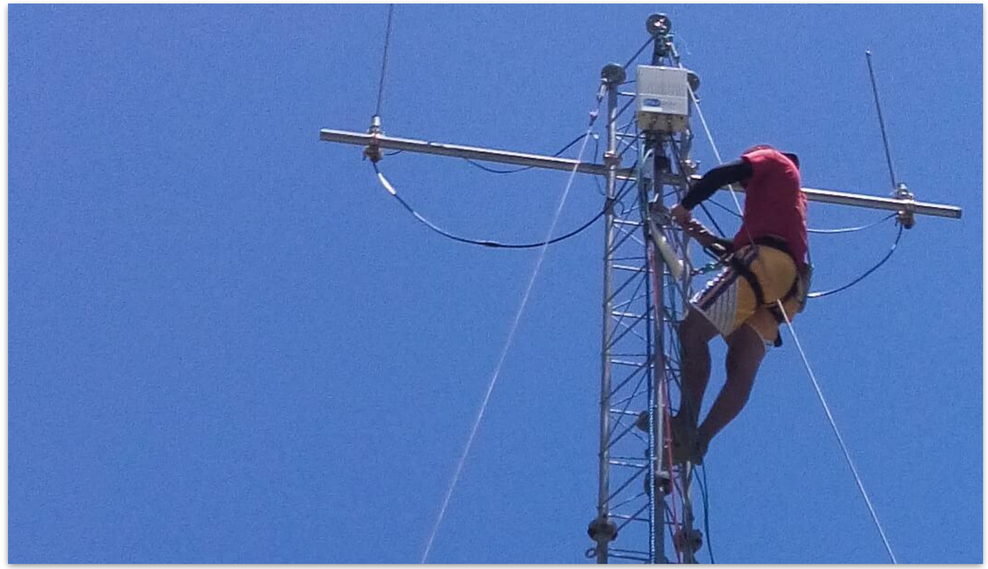

Image: Maria Theresa Perez, “Community Cellular Networks in the Philippines: Experiences from the VBTS project”, Presentation to IRTF GAIA RG, November 2019, https://www.ietf.org/proceedings/106/slides/slides-106-gaia-up-vbts-philippines-00

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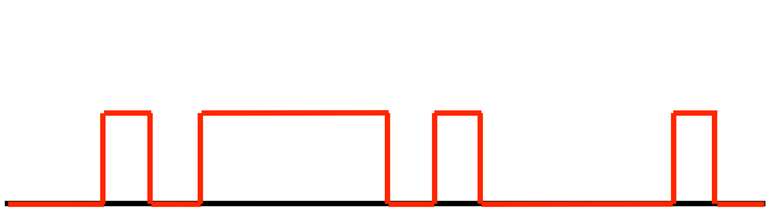
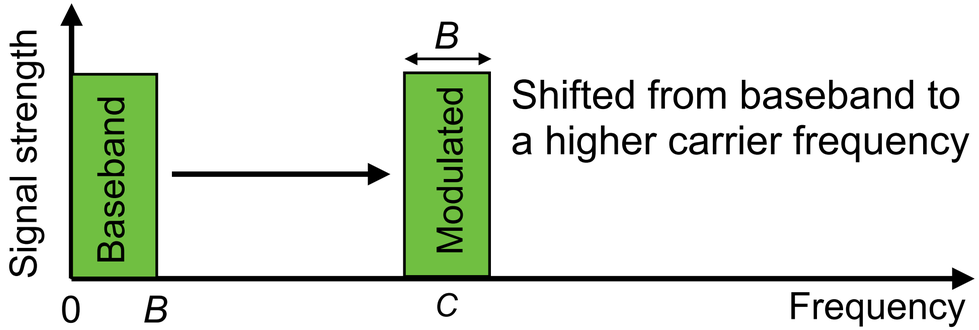
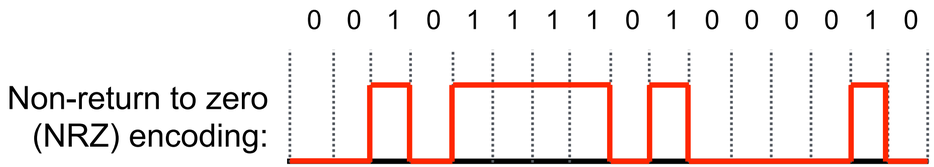
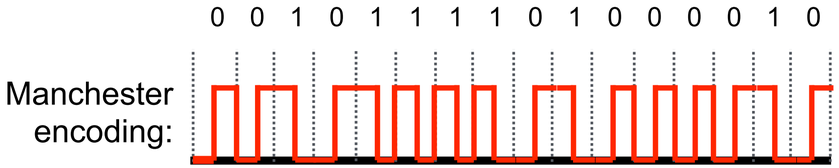
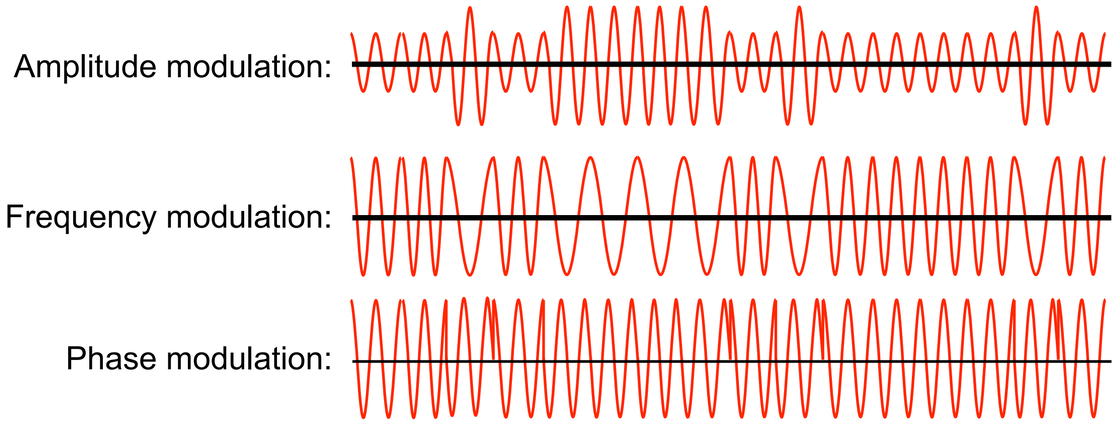
Encoding Data onto the Channel











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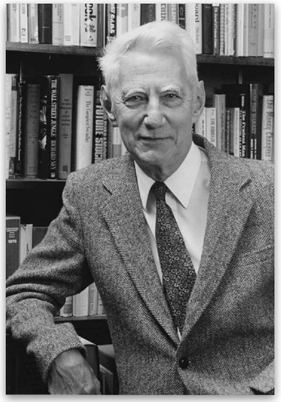
Noise and Channel Capacity

- Real-world network links are imperfect, and subject to **noise**
  - Electrical or radio interference, imperfections in optical fibre
- The Shannon-Hartley theorem predicts the maximum data rate of a channel subject to noise, in bits per second: $R_{max} = B \log_2 (1 + {}^{S}/_{N})$
  - B = bandwidth of the channel (Hz)
  - S = signal strength
  - N = noise strength
  - Assuming Gaussian noise: interference affects all frequencies equally
- Physical limit on maximum transmission rate
  - *B* and *N* depend on properties of the channel
  - *S* depends on transmission power → trade battery life for performance



Source: AT&TT Bell Labs

Claude Shannon
(1916-2001)



Source: Wikipedia

Ralph Hartley
(1888-1970)

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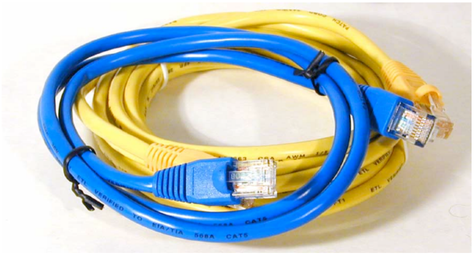
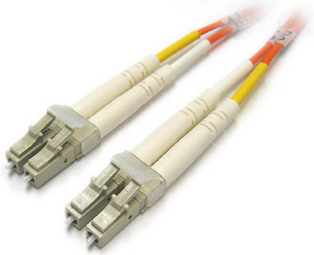
The Data Link Layer

- Physical layer enables communication
- Data link layer provides framing, addressing, media access control
  - Structure the bitstream into meaningful frames of data
  - Detect and correct transmission errors
  - Identify devices
  - Arbitrate access to the channel







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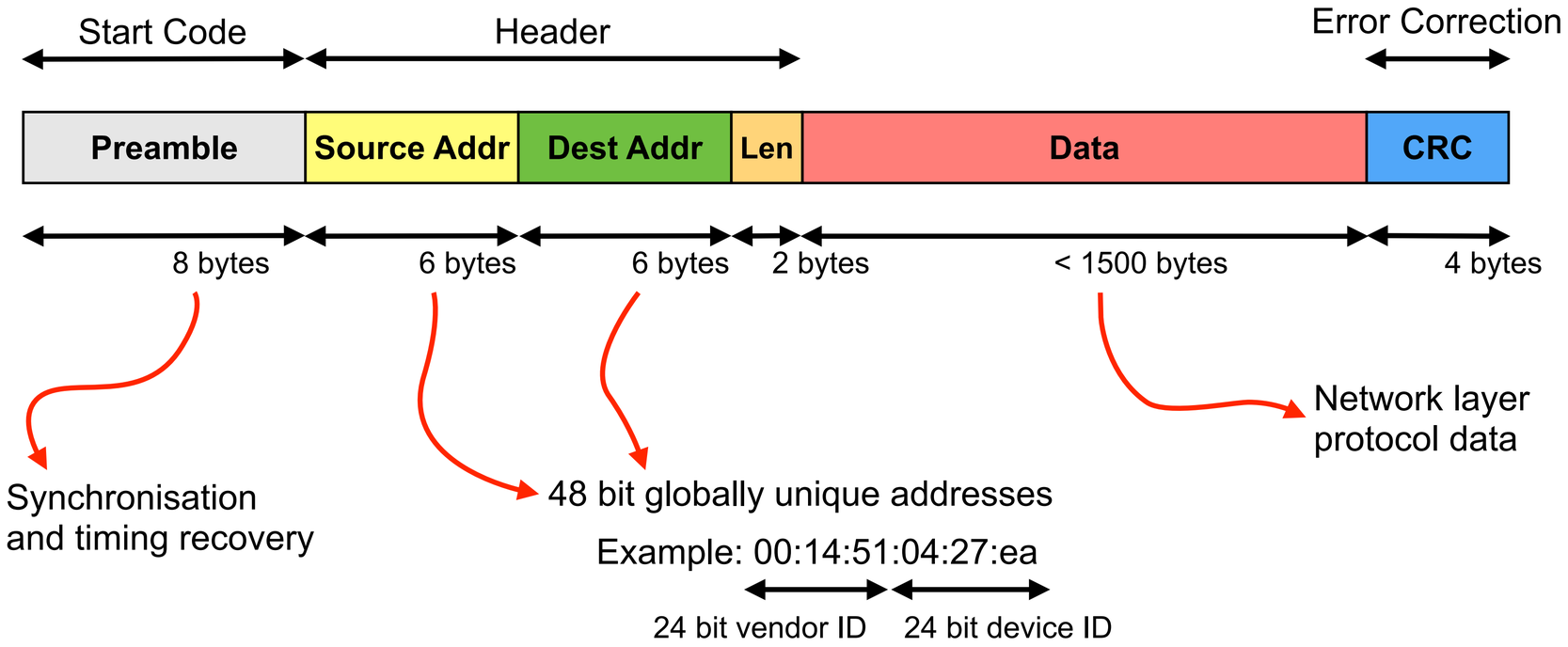
Framing and Addressing



Ethernet/WiFi frame format

Separate the bitstream into meaningful frames of data

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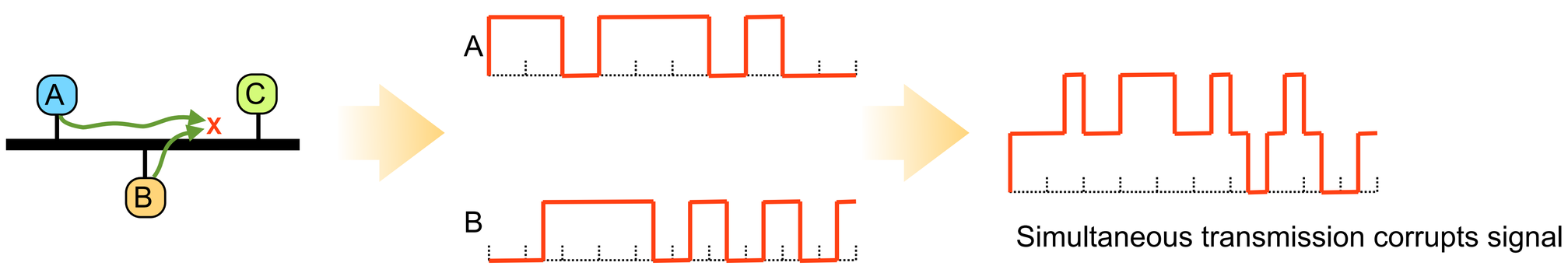
Media Access Control



Control when frames are sent, to avoid collisions

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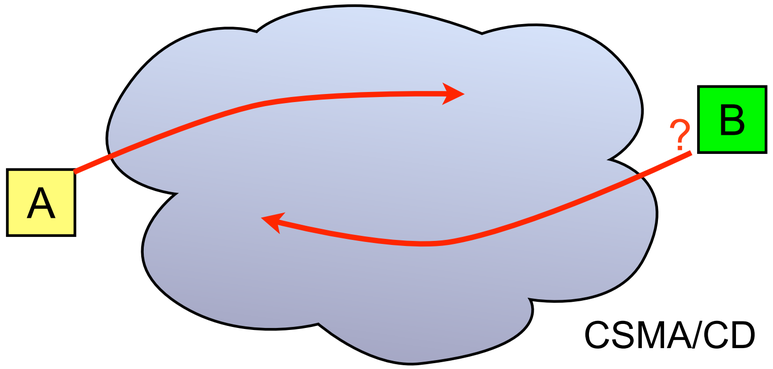
Media Access Control

- When propagation delay low, listen before sending
  - If link is idle, send data immediately
  - If another transmission is active, or if collision occurs, stop sending, wait, then retransmit
    - Wait time should be random – to avoid deterministic repeated collisions; pick a random initial back-off interval of *x* seconds ± 50%
    - Wait time should increase with number of collisions – repeated collisions signal congestion; reduce transmission rate allows network to recover; each repeated collision before success, $x \rightarrow 2x$
- Improves utilisation
  - Active transmissions not disrupted by collisions
  - Only the new sender backs-off if the channel is active
- Examples: Ethernet, Wi-Fi

Why does propagation delay matter?



CSMA/CD

A starts transmitting

B listens, hears no traffic
(message from A hasn't arrived yet)

B starts transmitting

Collision occurs, as messages overlap in transit;
smaller propagation delay → less likely to occur

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The Network Layer and the Internet Protocols

- Network Layer Concepts
  - Addressing
  - Routing
  - Forwarding
- The Internet Protocols: IPv4 and IPv6

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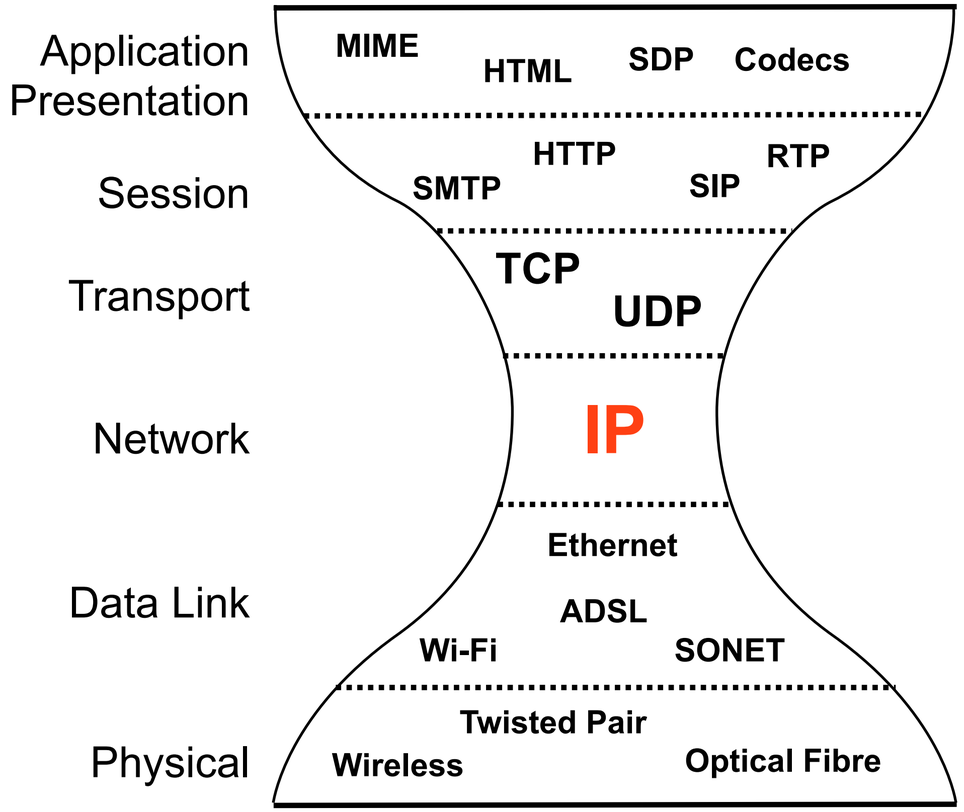
The Network Layer as an Internet Protocol

- Global inter-networking protocol
- Hour glass protocol stack
  - Single standard network layer protocol (IP)
    - Packet switched network, best effort service
    - Uniform network and host addressing
    - Uniform end-to-end connectivity – subject to firewall policy
  - Many transport & application layer protocols
  - Range of link-layer technologies supported
- Decouples end-to-end functionality from per-hop functionality



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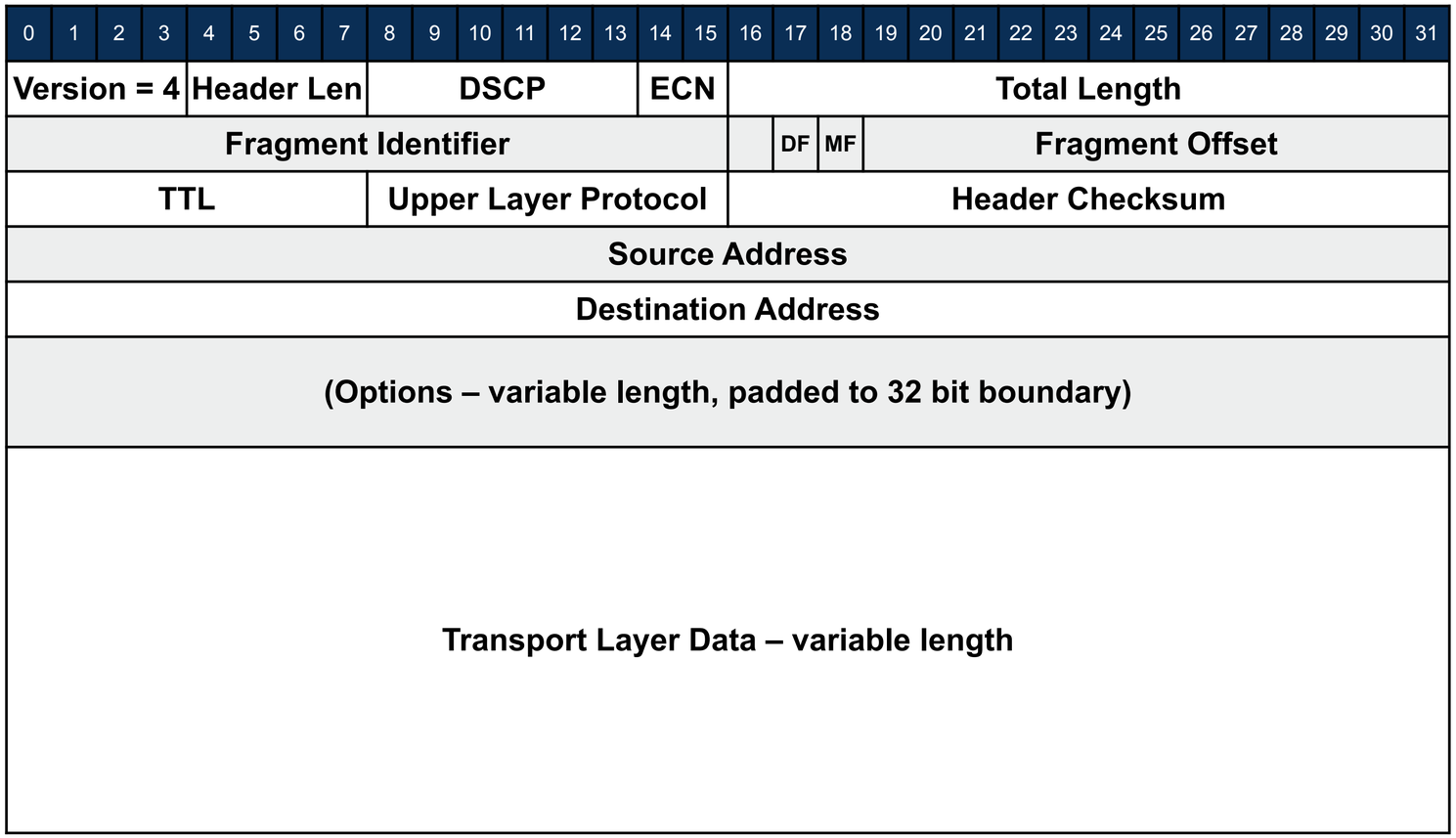
IPv4



- 32 bit addresses insufficient
- Fragmentation difficult at high data rates
- Limited extensibility

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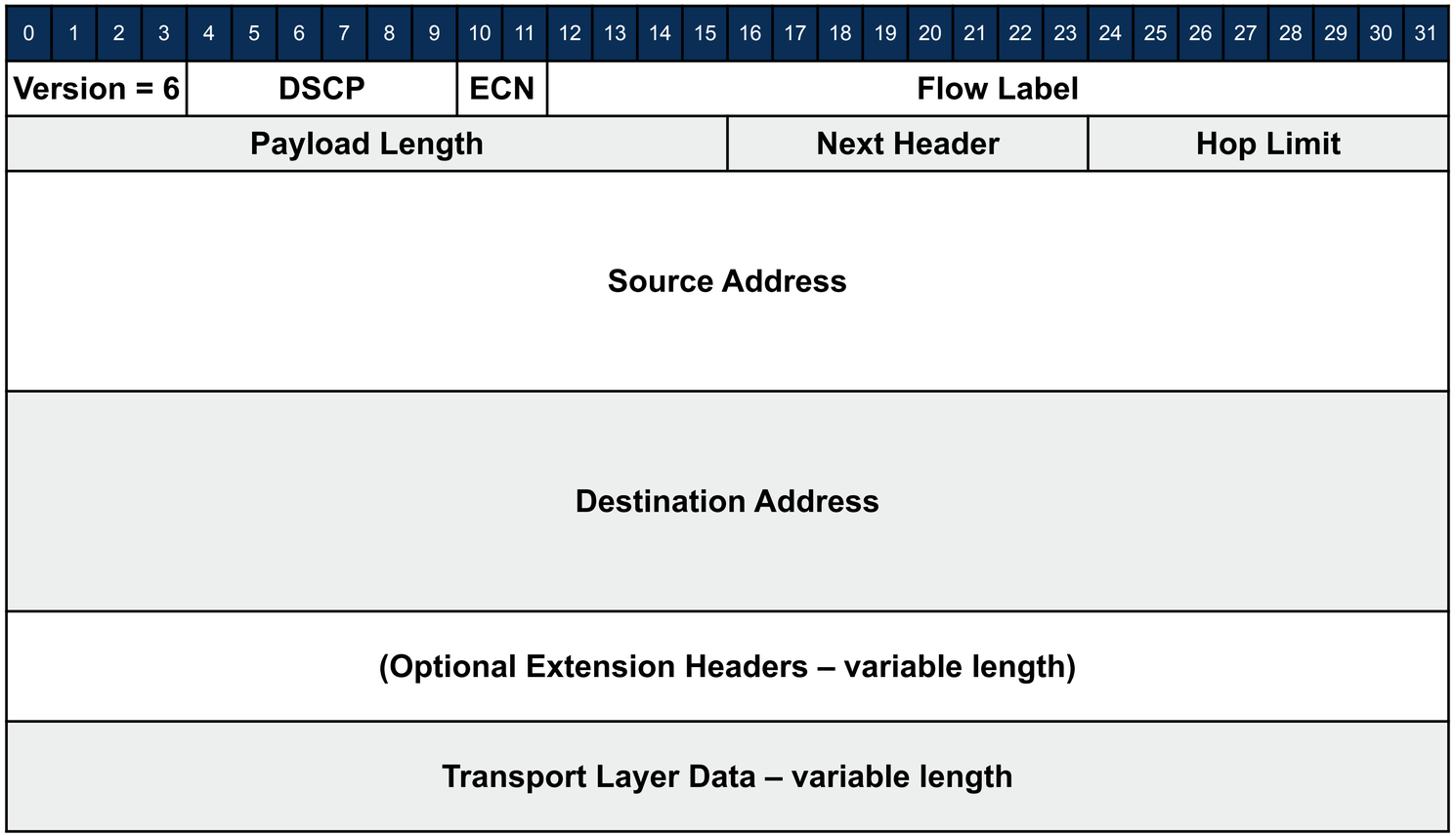
IPv6



- Larger address space
- No in-network fragmentation
- No unnecessary checksum
- Simpler header format

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What About IPv5?

- Experiments with voice over the ARPAnet – the precursor to the Internet – started in the early 1970s
  - Network Voice Protocol: https://datatracker.ietf.org/doc/rfc741/
- This evolved into the Internet Stream Protocol, ST-II, that was assigned IPv5 – an experimental multimedia streaming protocol developed between 1979 and 1995, but never widely deployed
  - ST-II+ specification: https://datatracker.ietf.org/doc/rfc1819/



Danny Cohen, developer of the Network Voice Protocol

Aside: Danny Cohen also wrote “On Holy Wars and a Plea for Peace” (https://www.ietf.org/rfc/ien/ien137.txt) that introduced the terms big- and little-endian for numeric data and message byte order

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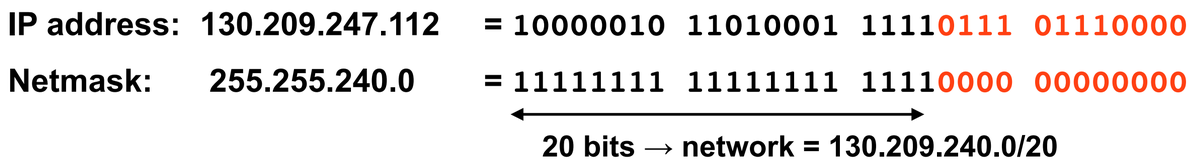
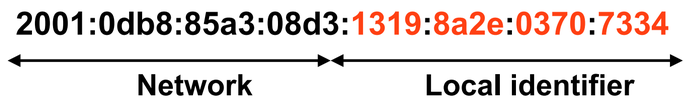
IP Addressing

- IP addresses encode location of network interface
  - If a host has several network interfaces (e.g., Wi-Fi and Ethernet), it has several IP addresses
  - A host can support both IPv4 and IPv6 on each interface
  - A host can have multiple IP addresses of each type assigned to each interface
- DNS names are an application concept – not used by the network

IPv4



IPv6



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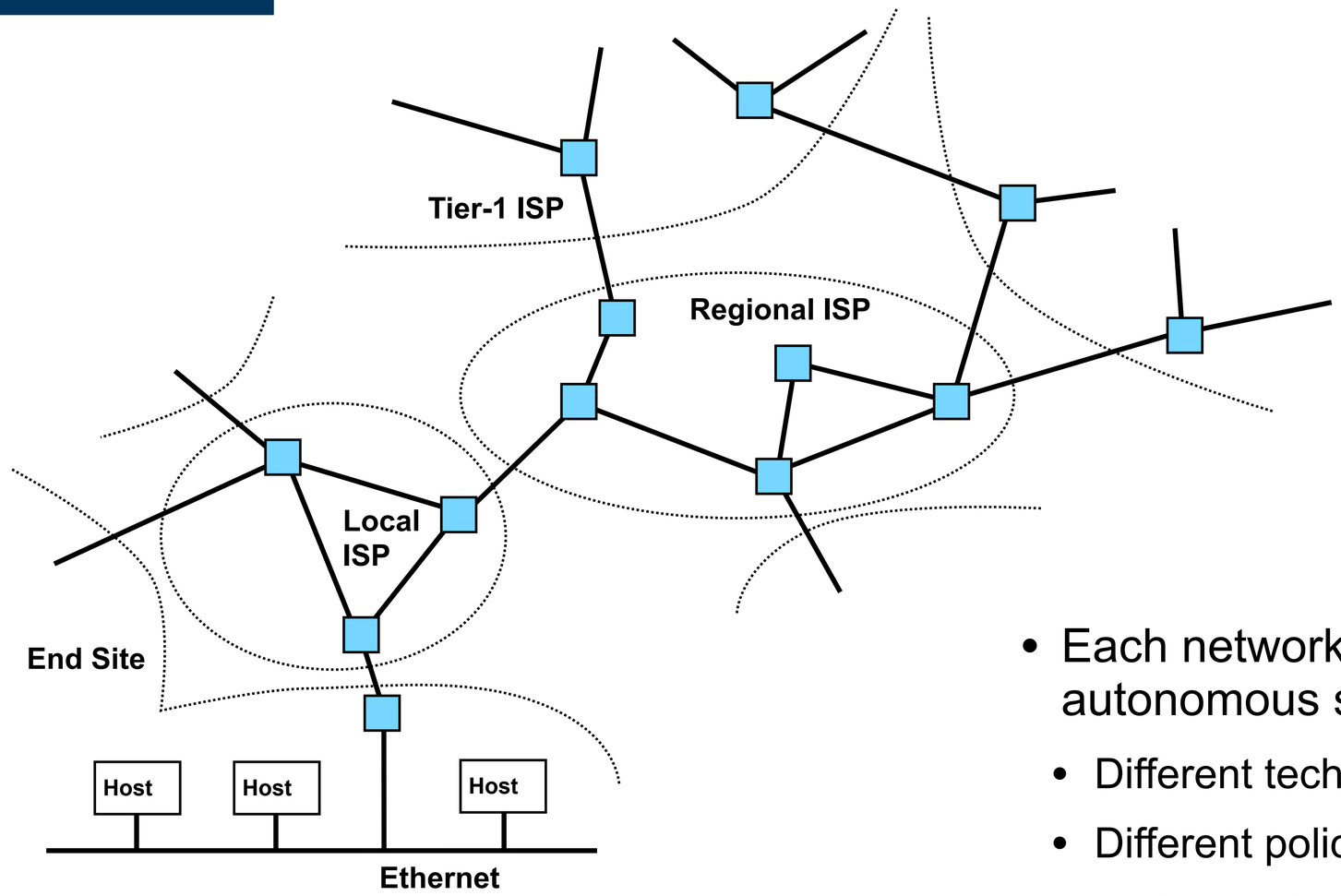
Routing



- Each network administered separately - an autonomous system (AS)
  - Different technologies
  - Different policies
  - Mutual distrust – between AS and its peers; between AS and its customers

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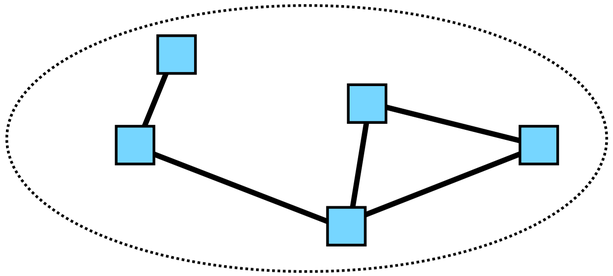
Autonomous Systems and Inter-domain Routing



- Each network administered separately – an autonomous system (AS)
  - Separately administered; different technologies
  - Shortest path routing
  - Distance vector or link state algorithms

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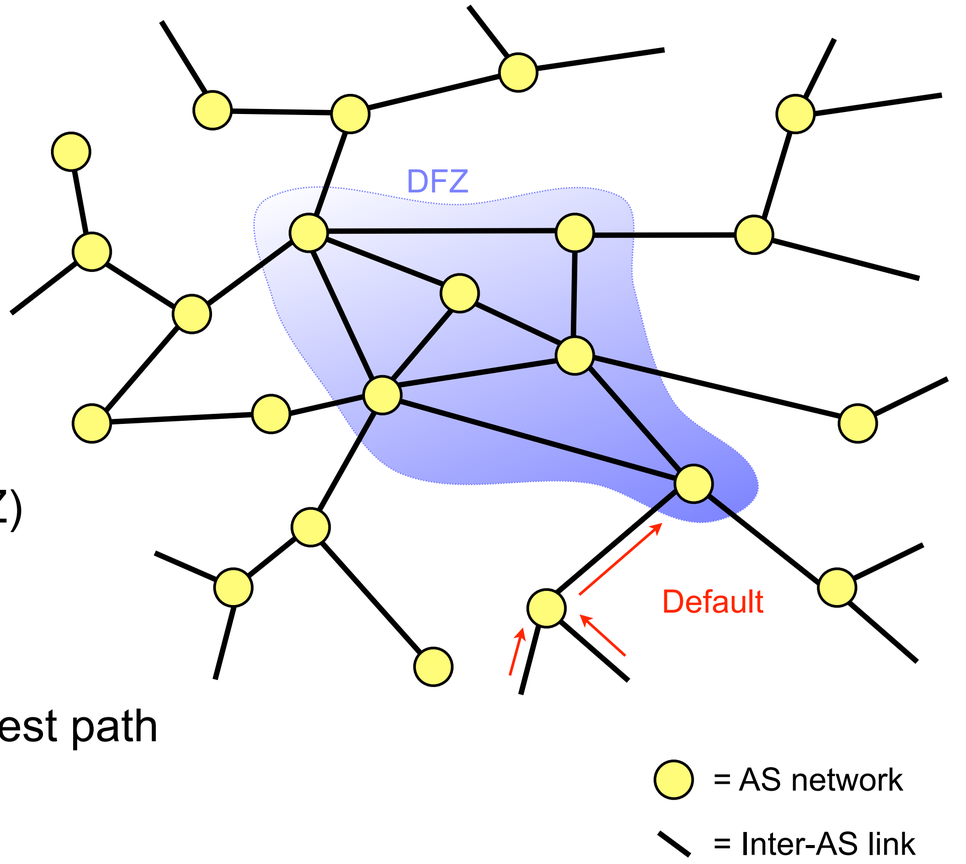
Inter-domain Routing and BGP

- Treats each network as a graph node and routes between ASes
- The AS-level topology:
  - Well connected core; sparse edges
  - Edge networks can use default route to the core
  - Core networks need full routing table: default free zone (DFZ)
- Routing between competitors – no real trust between organisations
  - Policy, politics, and economics are key constraints; not shortest path
  - BGP routing protocol



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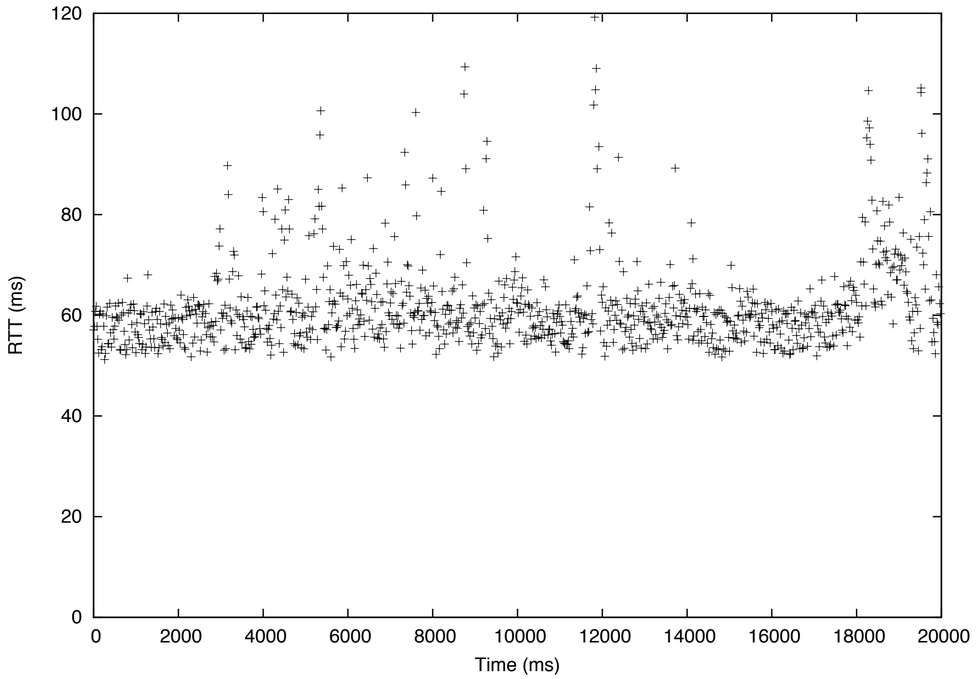
Forwarding



- Best effort, connectionless, packet delivery
  - Just send – no need to setup a connection first
  - Network makes its best effort to deliver packets, but provides no guarantees
  - Time taken to transit the network may vary
  - Packets may be lost, delayed, reordered, duplicated or corrupted
  - The network discards packets it can't deliver
- Easily run over any type of link layer

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The Transport Layer

- Concepts
- UDP
- TCP
- Congestion control

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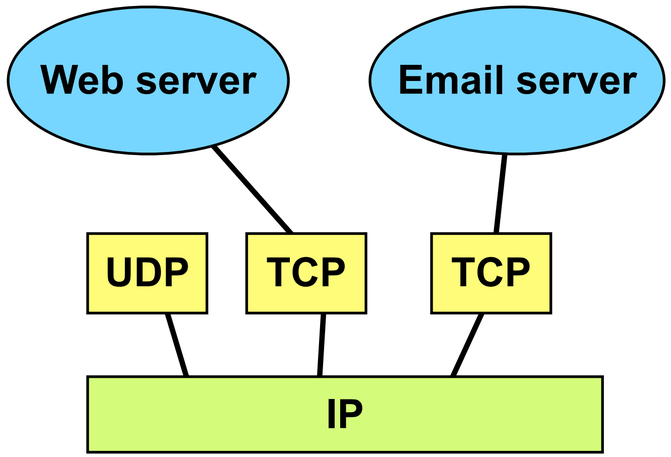
TCP and UDP Transport



- IP network provides best effort service
  - Packets can be lost, duplicated, delayed, or re-ordered
- Transport isolates applications from the network
  - Demultiplexes traffic for different applications
  - Enhances network quality of service to offer appropriate reliability
  - Performs congestion control, adapts to network capacity

- Only two deployable transport protocols in the Internet:
  - **UDP** - user datagram protocol
  - **TCP** - transmission control protocol

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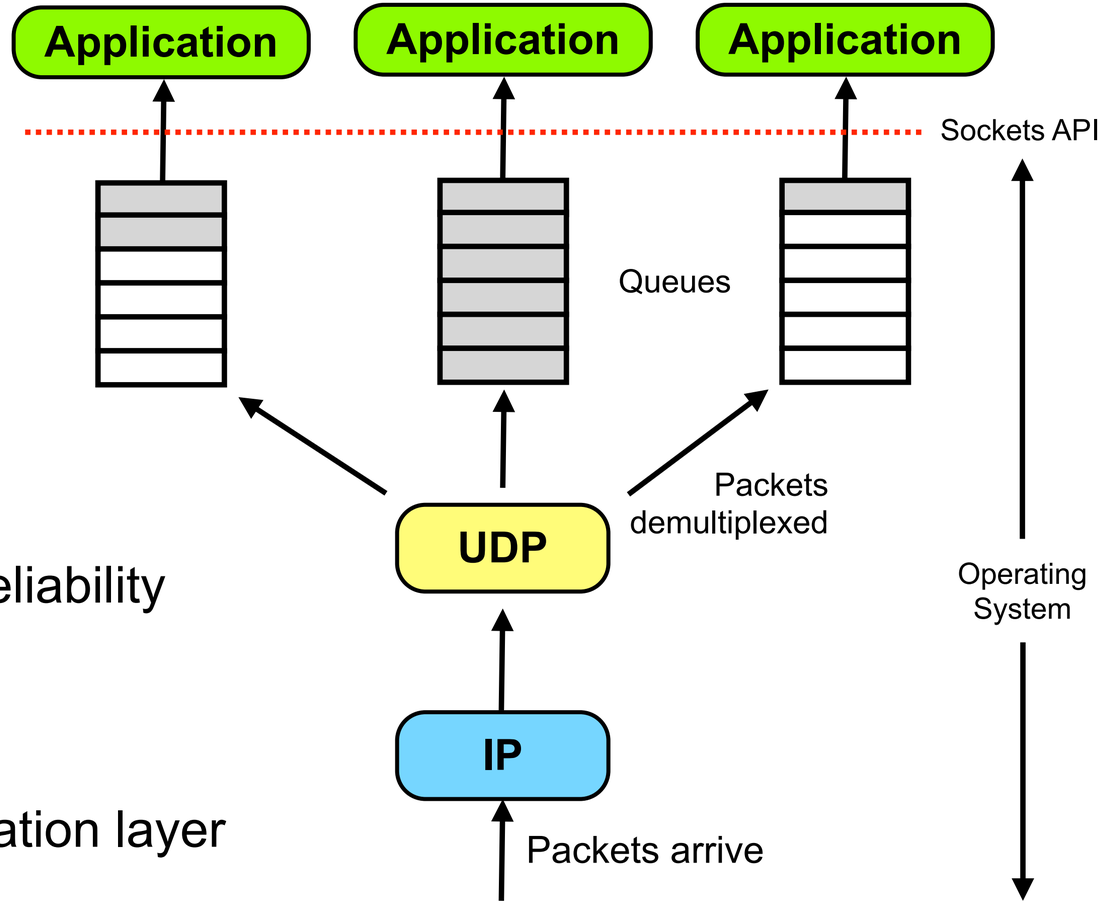
UDP

- Simplest transport protocol
- Exposes raw IP service to applications
  - Connectionless, best effort packet delivery: framed, but unreliable
  - No congestion control
  - Adds 16 bit port number to identify services
- Used by applications preferring timeliness over reliability
  - Voice-over-IP, streaming video, gaming
- Must be able to tolerate some loss of data
- Must be able to adapt to congestion in the application layer



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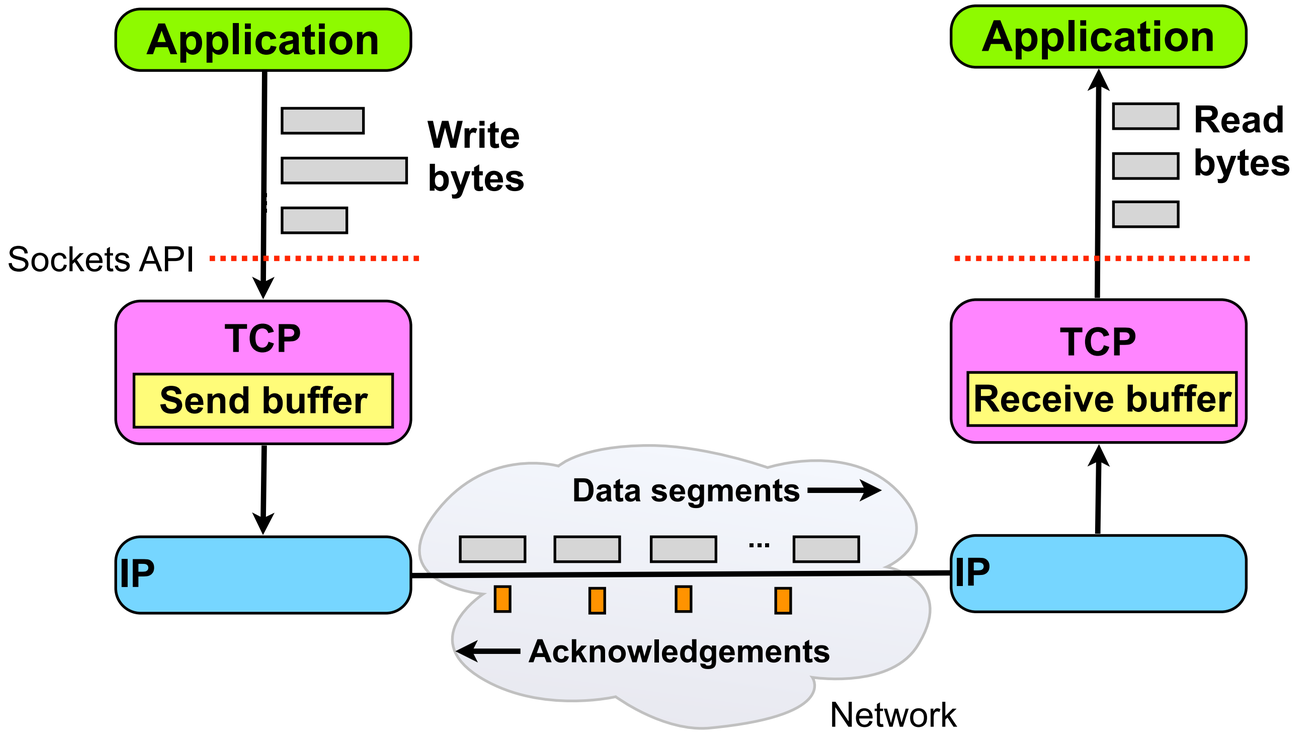
TCP



- Reliable, ordered, byte stream delivery service running over IP
  - Lost packets are retransmitted; ordering is preserved; message boundaries **are not** preserved
  - Adapts sending rate to match network capacity → congestion control
  - Adds port number to identify services
- Used by applications needing reliability → default choice for most applications

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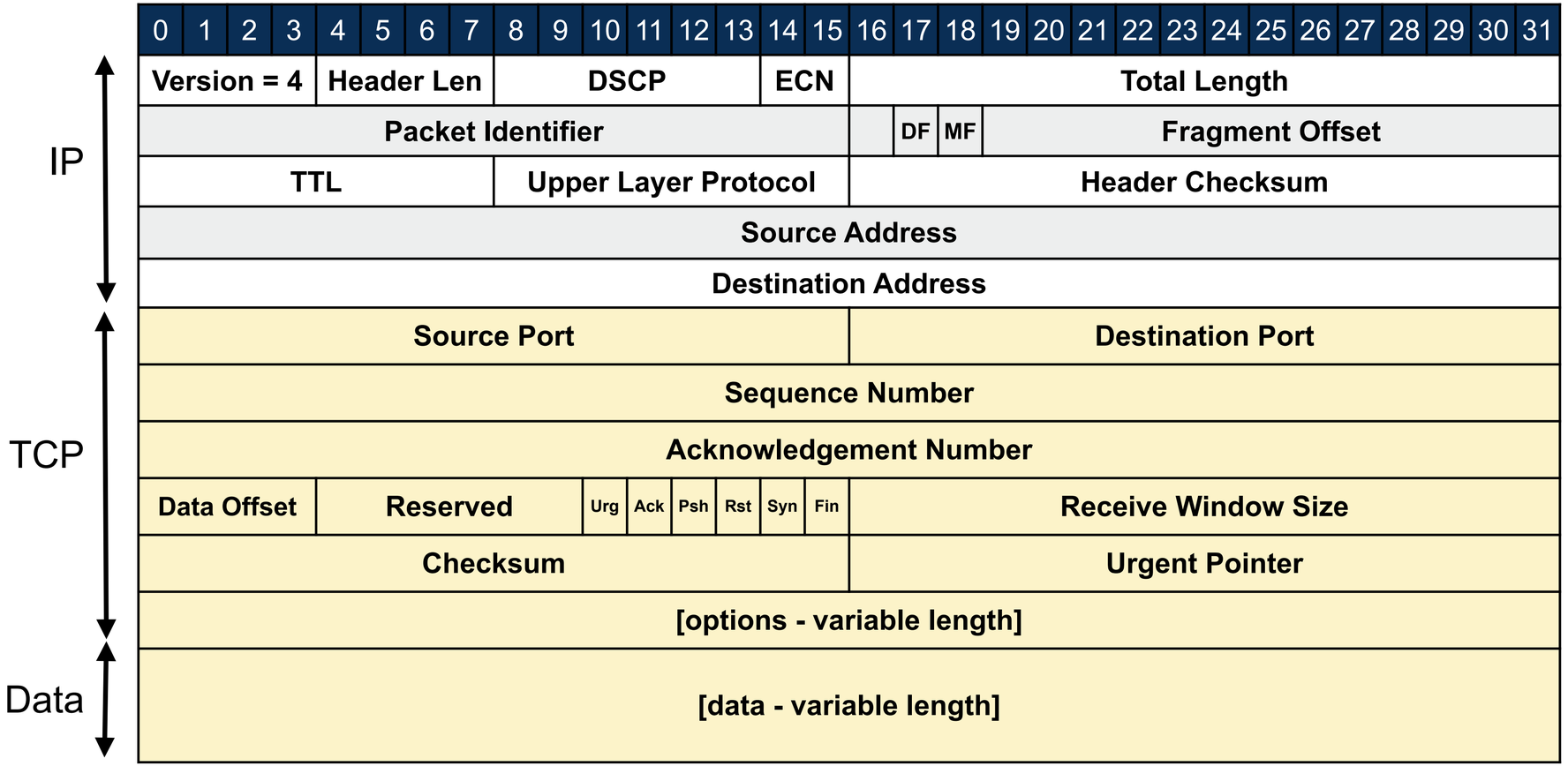
TCP Packet Format



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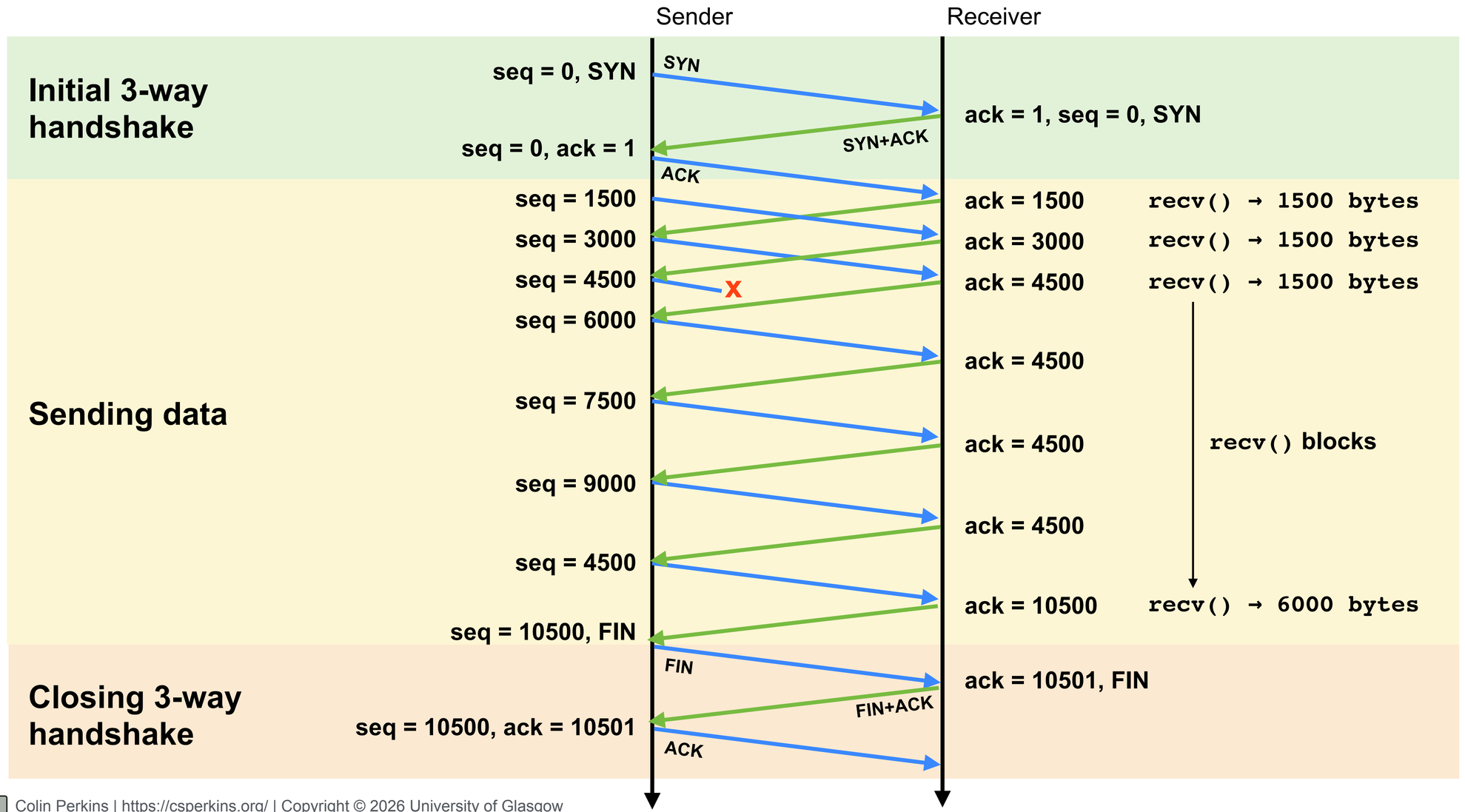
TCP Connection Timeline (Example)



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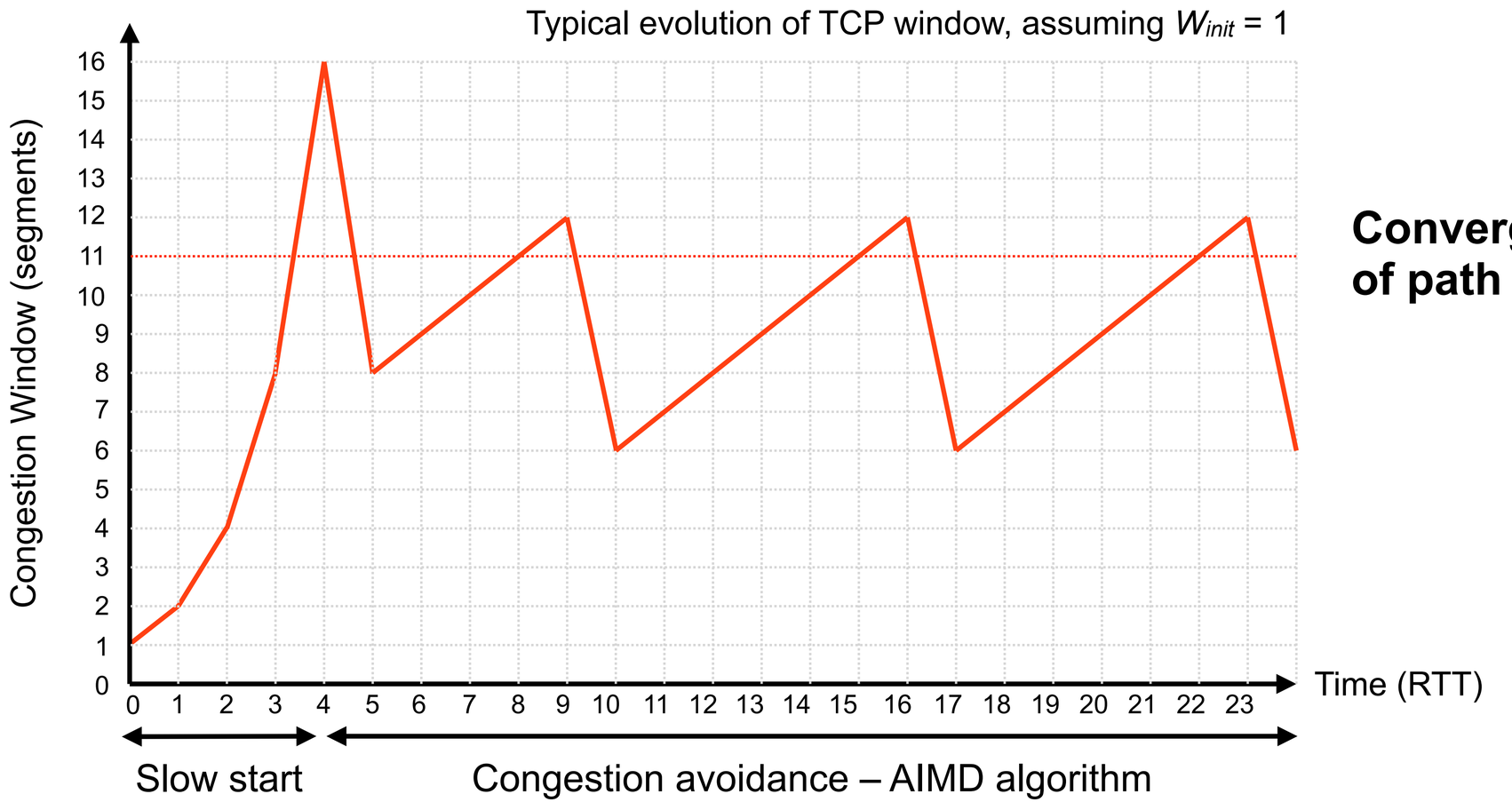
TCP Congestion Control



Converges on fair share of path capacity

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Higher Layer Protocols

- Session Layer
- Presentation Layer
- Application Layer
- The importance of standards

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Higher Layer Protocols

- The OSI reference model defines three layers above the transport:
  - Session layer
  - Presentation layer
  - Application layer
- Internet architecture makes no clear distinction between these layers

- Goal – support application needs:
  - Manage transport layer connections
  - Name and locate application-level resources
  - Negotiate data formats, and perform format conversion if needed
  - Present data in appropriate manner
  - Implement application-level semantics

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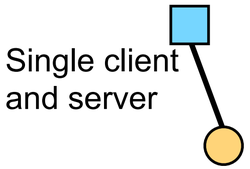
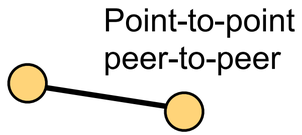
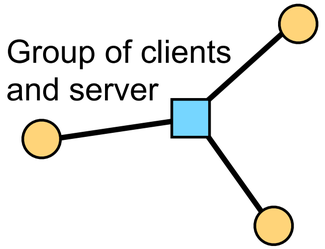
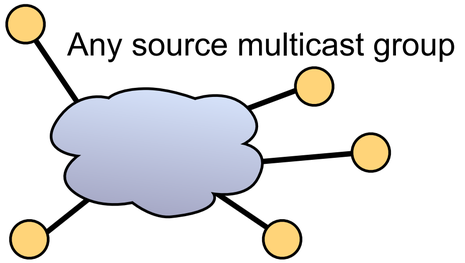
Session Layer: Managing Connections

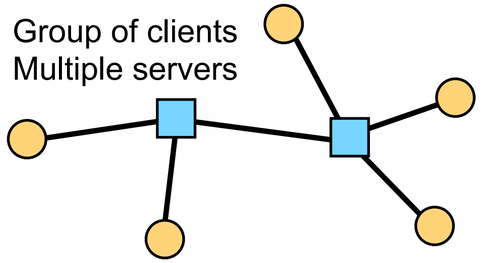
- What connections does the application need?
- How to find participants?
- How to setup connections?
- How does session membership change?
  - Does the group size vary greatly?
  - How rapidly do participants join and leave?
  - Are participants aware of other members?

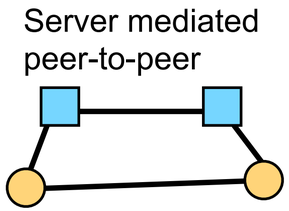


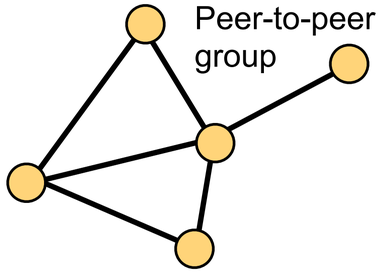


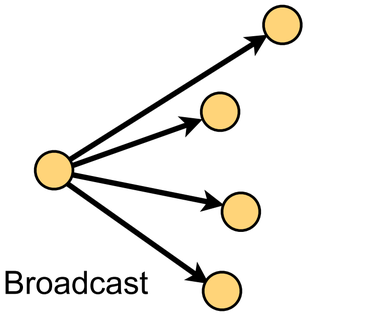












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The Presentation Layer

- Managing the presentation, representation, and conversion of data:
  - Media types and content negotiation
  - Channel encodings
  - Internationalisation, languages, and character sets
- Common services used by many applications

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The Application Layer

- Protocol functions specific to the application logic
  - Deliver email
  - Retrieve a web page
  - Stream video
  - …

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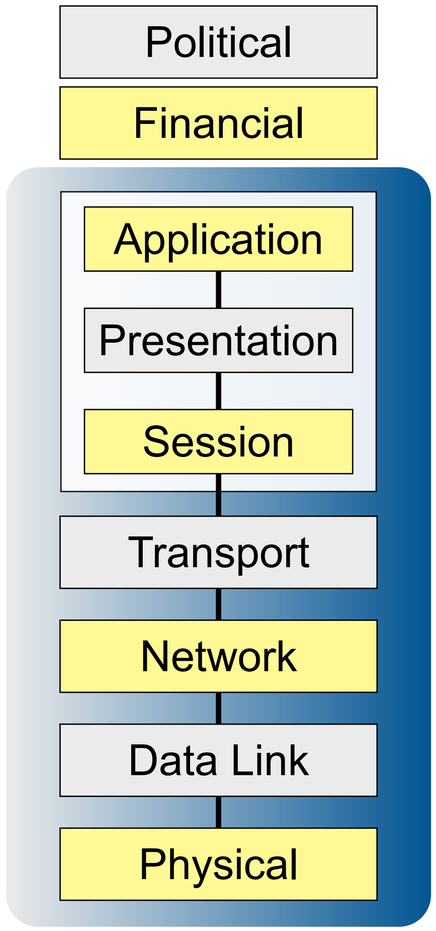
Protocol Standards



End System

- The OSI model is a reasonable way of thinking about network protocols
- But – it misses two key layers:
  - Financial
  - Political
- Successful network protocols support interoperability between different vendors – this interoperability exists because those vendors work to standardise the protocols
- **Rough consensus and running code**

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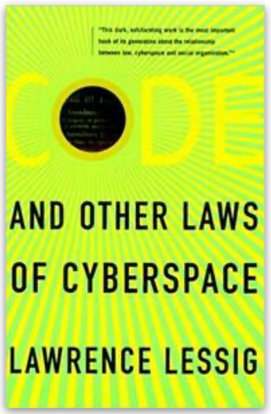
Protocols are political



https://lessig.org/product/code/

The decisions made by protocol designers influences how the Internet can be used

~~Code is law~~

Code influences law

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The Changing Internet

- Exhaustion of IPv4 address space
- Wireless and mobility
- Hypergiants and Centralisation
- Real-time and low-latency
- Overcoming ossification

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The Changing Internet

- The original design of the Internet made certain assumptions:
  - Devices are generally located in a fixed location, and have a small number of network interfaces that are uniquely addressable
  - The network and services are decentralised
  - Best effort service provides sufficient quality
  - The network is trusted
  - Innovation can happen at the edges; the network is dumb
- Reasonable for the 1980s, when the IP architecture was defined, but the network has changed – **how have the protocols and environment changed? How should they change?**

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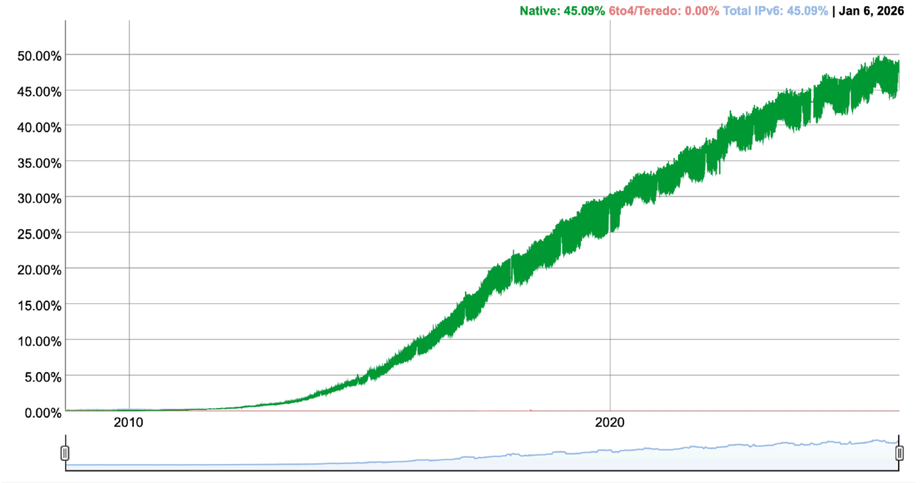
Addressing, Connectivity, and Mobility

- The network is in the middle of a slow transition to IPv6
  - Fraction of users accessing Google over IPv6:
    - France 86%, Germany 77%, India 72%, Malaysia 65%, Greece 65%, Japan 60%, Brazil 57%, US 58%, UK 54%, Canada 43%
    - Worldwide average: 45%
  - **Does your home network support IPv6? What about your mobile provider?**
  - **Does your home network use IPv4 with a NAT or IPv6?**
  - **Does it matter that we've run out of IPv4 addresses?**
- Ubiquitous mobile devices – smartphones – complicate addressing and reachability since IP addresses indicate locations in the network – **why?**



https://www.google.com/intl/en/ipv6/statistics.html

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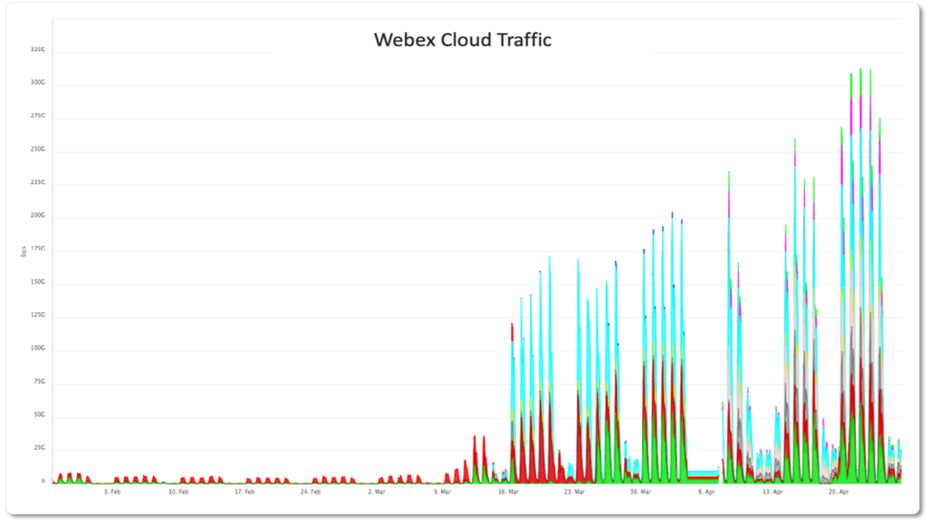
Real-time Applications

- Streaming video is the majority of Internet traffic, and video conferencing providers saw a massive traffic increase due to the pandemic
  - **Have video conferencing apps worked for you?**
  - **What other applications generate real-time traffic?**
  - **What applications will need real-time in future?**
    - AR, VR, holographic conferencing, remote surgery, gaming, …?
  - **Is a best-effort network, such as the Internet, the right approach for real-time traffic?**
    - Do mechanisms to provide guarantees actually help?



Source: Cullen Jennings, Cisco

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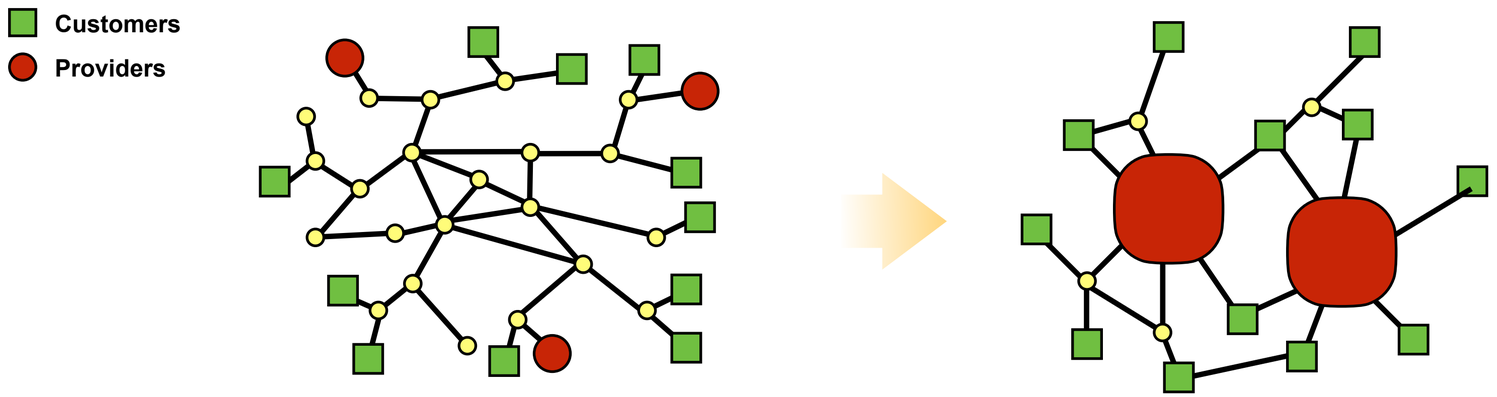
Hypergiants, Centralisation, and Security





Edward Snowden

- Internet topology is flattening and becoming increasingly centralised, with direct connections from “eyeball” networks to massive content providers – Google, Facebook, Amazon, Akamai, …
- **What are the implications for network neutrality, competition, innovation, privacy, freedom of speech, pervasive monitoring, and security?**

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Innovation in the Network

- Can we still change the network protocols?
  - NATs, firewalls, middleboxes → TCP is *hard* to change now
  - Transport encryption, tunnel over UDP → QUIC? Pervasive encryption to defeat pervasive monitoring and surveillance?
  - Protocol ossification is a real concern
  - Is the model smart edges and a dumb network appropriate?
- Can new startups compete with the hypergiants?
  - Several forces pushing towards centralisation – can we evolve the network to counter these?
  - Can we enable a decentralised network?



Is it Still Possible to Extend TCP?

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ABSTRACT

We've known for a while that the Internet has ossified as a result of the race to optimize existing applications or enhance security. NATs, performance-enhancing-proxies, firewalls and traffic normalizers are only a few of the middleboxes that are deployed in the network and look beyond the IP header to do their job. IP itself can't be extended because "IP options are not an option" [10]. Is the same true for TCP?

In this paper we develop a measurement methodology for evaluating middlebox behavior relating to TCP extensions and present the results of measurements conducted from multiple vantage points. The short answer is that we can still extend TCP, but extensions' design is very constrained as it needs to take into account prevalent middlebox behaviors. For instance, absolute sequence numbers cannot be embedded in options, as middleboxes can rewrite ISN and preserve undefined options. Sequence numbering also must be consistent for a TCP connection, because many middleboxes only allow through contiguous flows.

We used these findings to analyze three proposed extensions to TCP. We find that MPTCP is likely to work correctly in the Internet or fallback to regular TCP, TcpCrypt seems ready to be deployed, however it is fragile if resegmentation does happen—for instance with hardware offload. Finally, TCP extended options in its current form is not safe to deploy.

Categories and Subject Descriptors

C.2.2 [**Computer-communication Networks**]: Network Protocols; C.2.6 [**Computer-communication Networks**]: Internetworking

General Terms

Measurement, Design, Experimentation, Standardization

Keywords

Middleboxes, Measurements, TCP, Protocol design

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M. Honda, Y. Nishida, C. Raiciu, A. Greenhalgh, M. Handley, and H. Tokuda, "Is it still possible to extend TCP?" Proc. ACM Internet Measurement Conference, Berlin, Nov. 2011. https://dx.doi.org/10.1145/2068816.2068834

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Can the network evolve to address these challenges?

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