High-performance data networking

CESE4045

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Organization

- TAs: Chenxing Ji Adrian Zapletal
- Prerequisites: Networking basics + programming (Python)
- Mix of:
  - Theory (Slides)
  - Exercises (Reader)
  - Q&A sessions
- Exam (25/01/2024) covers both theory (slides) & exercises (reader)

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Tentative schedule

15/11 Lecture*: Basics
17/11 Q&A: Exercise 1 (starting 09:30)
22/11 Lecture: Software-Defined Networking (SDN)
24/11 Q&A: Exercise 2 (starting 09:30)
29/11 Lecture*: Quality-of-Service (QoS)
01/12 No class
06/12 Q&A: Exercise 3 + Lecture*: Multicast Content Distribution
08/12 Lecture: Network resilience
13/12 Q&A: Exercise 4 + Lecture: P4 (part 1)
15/12 Lecture: P4 (part 2)
20/12 Lecture: Software-defined cellular networks
22/12 Q&A: Exercise 5 (starting 09:30)

* Part of the content and slides from these lectures are from Prof. Piet Van Mieghem and his 2011 book “Data Communications Networking”.

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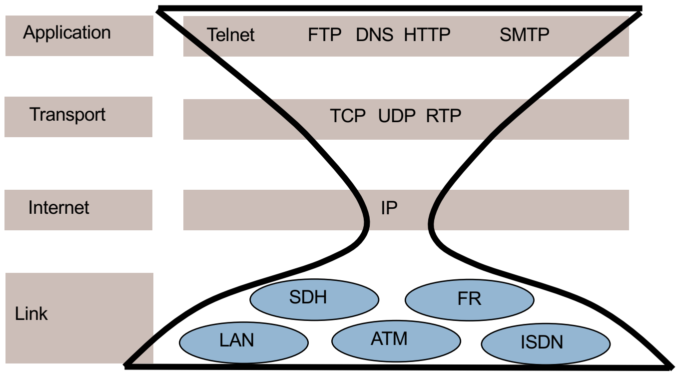
TCP/IP: “Hourglass” design



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Ethernet
Local Area Network - LAN

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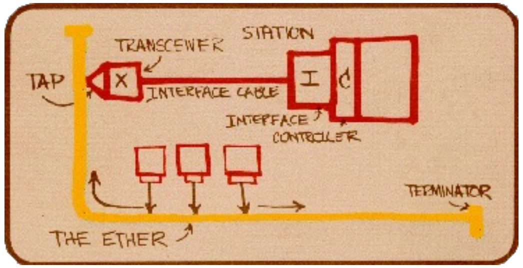
Ethernet



Original drawing by Robert Metcalfe (1976)

Metcalfe's ACM Turing award presentation
https://www.youtube.com/live/QRfRT19N2Rg?si=jeV8SwlJABhxRJOi

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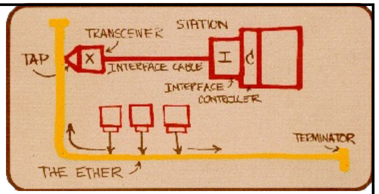
Ethernet



- *Bus (Ether)*: all stations share a single communication channel (distributed access control)
- *Broadcast*:
  - all transceivers receive every transmission
  - host interface filters among packets those intended for the corresponding computer
- *Best-effort delivery*: no notification about packet receipt

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Ethernet Access: CSMA/CD

- Carrier Sense Multiple Access (CSMA)
  - multiple machines can access the Ethernet simultaneously
  - each machine determines whether the “ether” is free by sensing carrier wave propagation
  - each transmission is limited in duration and needs a minimum time between transmissions to prevent monopolization of the network
- Collision Detection (CD)
  - **Collision**: when two electrical waves cross, they become scrambled and meaningless.
  - **Collision detection**: each transceiver monitors the cable while transmitting to search for foreign signal interferences

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Sending Rules

- **Non-persistent CSMA:**
  - Sensing is not continuously but repeated after random time.
  - If no collisions are sensed, the station sends a packet.
- **p-Persistent CSMA**:
  - Continuously sensing, but sending of packet probabilistically: send in current time slot with probability *p* and in another time slot with probability *1-p*

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Binary exponential back-off

After each collision j a station chooses a random time uniformly in [0,2^j-1] timeslots (with a timeslot equal to the worst round-trip time):

IEEE 802.3:

- 1st: 0 or 1 equi-probable
- 2nd: 0 or 1 or 2 or 3
- 3rd: 0 or 1 or 2 or 3 or 4 or 5 or 6 or 7
- Increase until 10th
- Then constant until 16th
- Then failure

- Balances between prevention of collisions and waiting time
- Ethernet is a 1-persistent CSMA/CD scheme with binary exponential back-off

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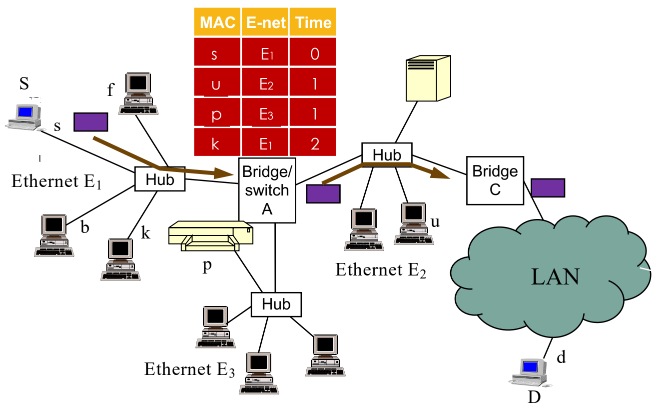
Example of an Ethernet LAN



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Virtual LANs

- A LAN can be subdivided into virtual LANs. VLANs allow to simplify network design and deployment, because VLAN membership can be configured through software.
- IEEE 802.1Q supports virtual LANs (VLANs) on an Ethernet network.
- Ethernet frames get a VLAN tag.
- Frames with different tags may be treated differently by bridges and switches.

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IP

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IP

The Internet Protocol (**IP**) defines an unreliable, connectionless, best-effort delivery mechanism:

- specification of basic unit of transfer (packet)
- IP software handles the routing functionality
- IP includes the rules for unreliable, connectionless, best-effort delivery

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IPv4 packet

0	4	8	16	19	24	31
vers	hlen	ToS	total length (bytes)			
identification			flags	fragment offset		
time to live		protocol	header checksum			
source IP address						
destination IP address						
IP options (if any)					padding	
user data						
...						

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Fragmentation

IP header	data1 600 octets	data2 600 octets	data3 200 octets

fragment1 header	data1	Fragment1:	offset 0
fragment2 header	data2	Fragment2:	offset 600
fragment3 header	data3	Fragment3:	offset 1200

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IPv6

Several major changes over IPv4:

- *extended addressing capability*
  - 128 bits versus 32 bits in IPv4
- *a fixed format to all headers*
  - no option element, no header length field, but extension headers
- *no header checksum*
  - diminish cost of processing, other layers check & correct for errors
- *no hop-by-hop fragmentation*
  - unit of transmission = unit of control: use *path MTU discovery*
- *ICMPv6 and neighbour discovery*
  - support for address resolution and group management integrated into IPv6 (previously separate protocols)
- *easier management*
  - through auto-configuration (SLAAC)
  - longer addresses allow clear structuring of subnets and specific prefixes for different address types (e.g., ff00::/8 for multicast, fe80::/10 for link-local addresses, 2000::/3 for global unicast addresses)

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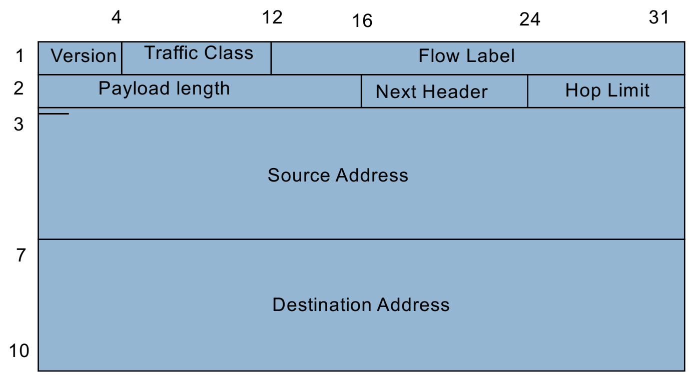
IPv6 Header Format



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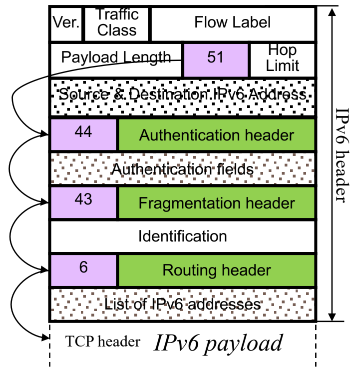
Extension Header



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IPv6 Address Format

- 128 bit, canonically written in hexadecimal
  - `2001:0db8:0004:0a21:dead:beef:0000:1337`
  - Leading 0s can be suppressed and 16 0-bits can be shortened using ::
    (→ `2001:db8:4:a21:dead:beef::1337`)
- For global unicast addresses:
  - First 64 bits: Global Routing Prefix (n bits) + Subnet-ID (64 - n bits)
  - Last 64 bits: Interface-ID
  - Interface-ID often generated using the interface's MAC address

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ICMPv6

- Integrates functions of ICMP (Internet Control Message Protocol), group management (for Multicast), and ARP (Address Resolution Protocol)
- Every IPv6 interface has a link-local address that identifies it and is used for link-local communication (e.g., for Neighbor Discovery)
- Neighbor Discovery: IPv6 nodes can find systems they are physically connected to (other nodes and routers)
  - Routers send periodic Router Advertisements (RAs)
  - Hosts can also solicit RAs by broadcasting a Router Solicitation
  - RAs contain Global Routing Prefix and Subnet-IDs that hosts need for generating global unicast IP addresses
- Duplicate Address Detection automatically resolves address conflicts

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Stateless Address Auto-Configuration (SLAAC)

- Generation of link-local IP address
  - Either generate random Interface-ID (64-bit) or generate it from the hardware MAC address
  - Example MAC address (48 bit, following the IEEE 802 standard): `00:10:4b:4e:52:e4`
  - IPv6 Interface-ID (64 bit): `0210:4bff:fe4e:52e4`
    - Flip 7th bit (identifies whether address is local or universal) and insert `ff:fe` in the middle
  - IPv6 link-local address (128 bit): `fe80::0210:4bff:fe4e:52e4`
    - `fe80::` + Interface-ID
- Ask neighbors whether they own the generated address (Duplicate Address Detection)
  - If duplicate: generate new random Interface-ID
- Generation of global unicast address
  - Global Routing Prefix + Subnet-ID (from RA) + Interface-ID

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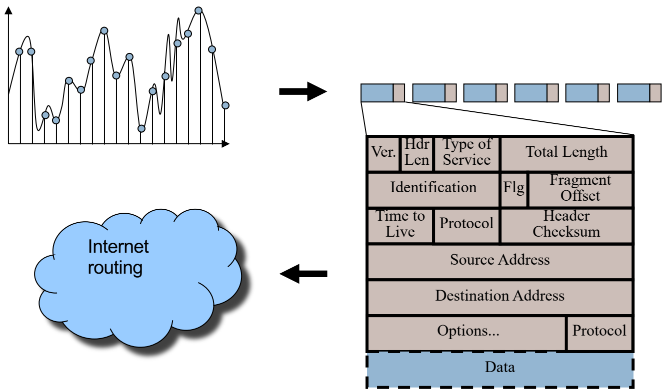
IP packets



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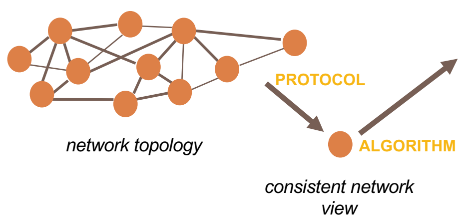
What is Routing?

- Finding one (or more) paths between two (or more) nodes in the network
  - often there is an optimality criterion (e.g. shortest path)
- Basic building blocks:



To	Link	Cost
A	local	0
B	1	1
C	3	1
E	3	6

forwarding table

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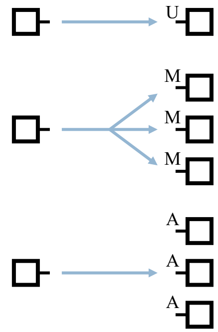
Basic Address Types

unicast:
for one-to-one communication

multicast:
for one/many-to-many communication

anycast:
for one-to-nearest communication



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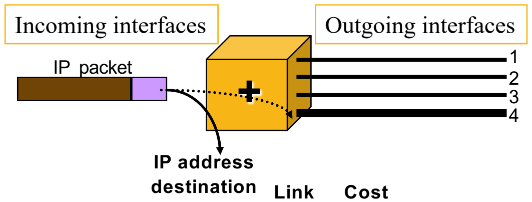
Forwarding



Forwarding TABLE

IP address destination	Link	Cost
IP_1	1	5
IP_2	4	2
IP_3	1	7
...	...	...

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Distributed routing protocol families

- Distance-vector protocols (RIP; Bellman-Ford)
  - exchange list of distances with neighbors
  - maintain list of shortest distances
  - protocol itself constructs forwarding table
  - simple but vulnerable (e.g., count-to-infinity problem)
- Link-state protocols (OSPF; Dijkstra)
  - flood topology information
  - maintain entire map of network
  - local routing algorithm computes forwarding table
  - more robust but more complex

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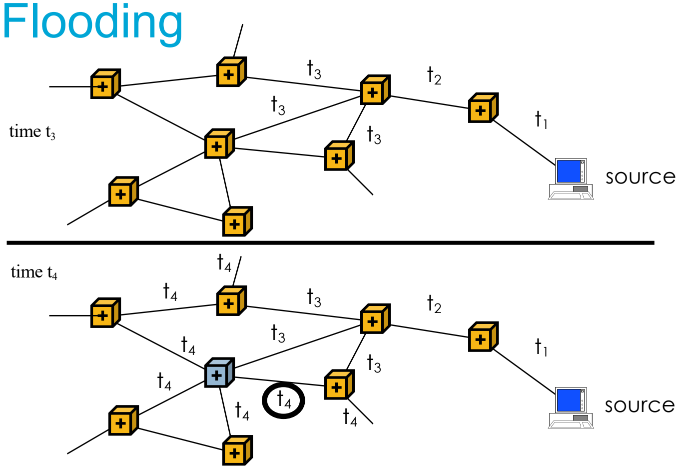
Flooding



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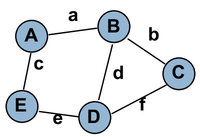
OSPF: Link State Database



From	To	Link	Cost	Num
A	B	a	1	1
A	E	c	5	1
B	A	a	1	1
B	C	b	3	1
B	D	d	3	1
C	B	b	3	1
C	D	f	7	1
D	B	d	3	1
D	C	f	7	1
D	E	e	8	1
E	A	c	5	1
E	D	e	8	1

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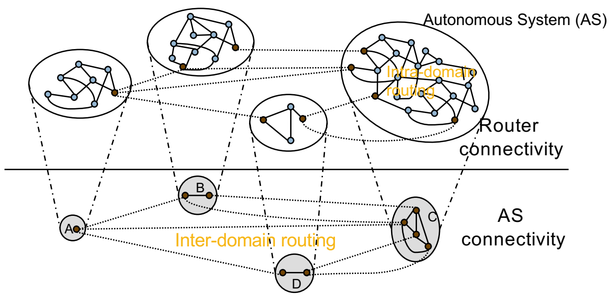
Two-level Routing Hierarchy



- Intra-domain routing (interior gateway protocols): Routing within one AS (e.g., OSPF and IS-IS)
- Inter-domain routing (exterior gateway protocols): Glues together different ASes (e.g., BGP)

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Organization of Internet Routing

- More than 75,000 autonomous routing domains: A domain is a set of routers, links, hosts and local area networks under the same administrative control
- Domain's size: from 1 PC to millions of hosts
- Domains are interconnected in various ways

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Types of domains: Transit

- Transit domains: A transit domain allows external domains to use its own infrastructure to send packets to other domains
- Examples: AT&T, UUNet, Level3, Opentransit, KPN,...

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Types of domains: Stub

- Stub domains:
  A stub domain does not allow external domains to use its infrastructure to send packets to other domains
- A stub is connected to at least one transit domain
- Content stub domains: Google, BBC, ...
- Access stub domains: ISPs providing Internet access via cable, DSL, ...

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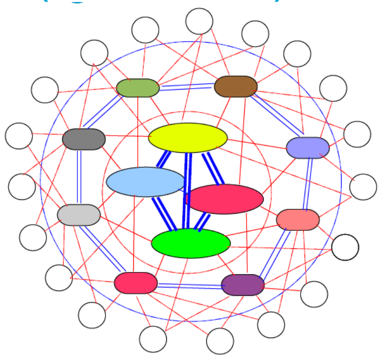
Organization of the Internet (Traditional)



- Tier-1 ISPs
  - About 20 large ISPs
  - Provide transit service
  - E.g., Sprint
- Tier-2 ISPs
  - Regional or National ISPs
  - Customers of T1 ISP(s)
  - Providers of T3 ISP(s)
  - E.g., KPN
- Tier-3 ISPs
  - Smaller ISPs, Corporate Networks, Content providers
  - Customers of T2 or T1 ISPs

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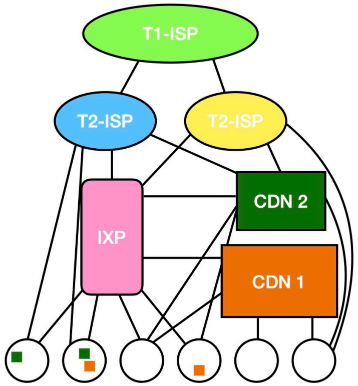
Organization of the Internet (Modern)



- Content Delivery Networks (CDNs)
  - Google, Meta, Netflix, IBM, Akamai, ...
- Direct peering
  - Mostly between ISPs and CDNs
- Points of Presence (PoPs)
  - CDN servers inside ISP networks
- Internet Exchange Points (IXPs)
  - Large interconnect facilities
  - AMS-IX, DE-CIX, ...

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Border Gateway Protocol (BGP)

- Fundamental Internet routing protocol: the heart of the Internet's global connectivity
  - glue between ASs
  - complex protocol
  - only unicast
- Distance vector protocol enhanced with path vectors
  - Path vector contains entire path (list of ASs)
- 'best path': based on policies

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Example BGP Table (RIB)

```
TIME: 08/28/01 15:02:05
TYPE: TABLE_DUMP/INET
VIEW: 0
SEQUENCE: 0
PREFIX: 3.0.0.0/8
FROM: 192.65.184.3 AS513
ORIGINATED: 08/28/01 12:42:08
ORIGIN: IGP
ASPATH: 513 209 701 80
NEXT_HOP: 192.65.184.3
STATUS: 0x1

TIME: 08/28/01 15:02:05
TYPE: TABLE_DUMP/INET
VIEW: 0
SEQUENCE: 1
PREFIX: 3.0.0.0/8
FROM: 64.211.147.146 AS3549
ORIGINATED: 08/28/01 12:41:54
ORIGIN: IGP
ASPATH: 3549 701 80
NEXT_HOP: 64.211.147.146
COMMUNITY: 3549:2256 3549:30840
STATUS: 0x1

TIME: 08/28/01 15:02:05
TYPE: TABLE_DUMP/INET
VIEW: 0
SEQUENCE: 2
PREFIX: 3.0.0.0/8
FROM: 193.148.15.85 AS3257
ORIGINATED: 08/28/01 11:30:59
ORIGIN: IGP
ASPATH: 3257 701 80
NEXT_HOP: 193.148.15.85
STATUS: 0x1
```

main body of entries skipped

```
TIME: 08/28/01 15:02:35
TYPE: TABLE_DUMP/INET
VIEW: 0
SEQUENCE: 38026
PREFIX: 218.67.0.0/17
FROM: 12.127.0.121 AS7018
ORIGINATED: 08/27/01 13:40:42
ORIGIN: INCOMPLETE
ASPATH: 7018 6453 4134
NEXT_HOP: 12.127.0.121
ATOMIC_AGGREGATE
AGGREGATOR: AS4134 202.97.32.22
STATUS: 0x1

TIME: 08/28/01 15:02:35
TYPE: TABLE_DUMP/INET
VIEW: 0
SEQUENCE: 38027
PREFIX: 218.67.0.0/17
FROM: 129.250.0.232 AS2914
ORIGINATED: 08/27/01 13:43:04
ORIGIN: IGP
ASPATH: 2914 6453 4134
NEXT_HOP: 129.250.0.232
MULTI_EXIT_DISC: 0
ATOMIC_AGGREGATE
AGGREGATOR: AS4134 202.97.32.22
COMMUNITY: 2914:420
STATUS: 0x1
```

The syntax is explained in RFC 1771

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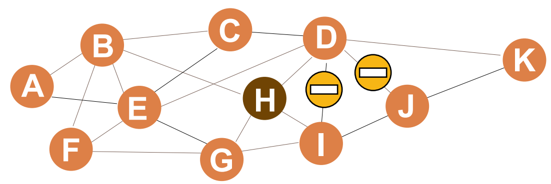
BGP Path Vector Protocol



1. H receives the path vector from its BGP-neighbours about K:
   from B: BHIJK from G: GHDK
   from D: DK from I : IJK
2. H discards the path from B and from G that runs over itself
3. H uses a module with policy information and computes a "distance" for each remaining path from H to K
4. The path corresponding to 'best' distance is stored in H's routing table

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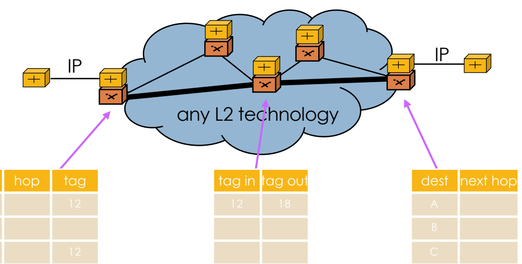
MPLS

Cisco's Tag Switching



Forwarding Information Base (FIB) Tag Information Base (TIB) L3 routing table

TAG BINDING TO
GROUP OF DESTINATIONS

LAYER 2 SWITCHING
NO LAYER 3 FORWARDING

TRADITIONAL
LAYER 3 FORWARDING

Multi Protocol Label Switching (MPLS) concepts

- Forwarding information (label) separate from content of IP header
- Single forwarding paradigm (label swapping) with hierarchy (label stacking) using multiple routing types (L3, L2)
- Flexibility to form forwarding equivalence classes (FEC) related to QoS or VPN
- Traffic engineering (TE): to override IP routing. TE is a powerful mechanism for current ISPs to
  - direct traffic away from congested paths
  - balance traffic across multiple paths
  - offer QoS in case of failures (back-up paths)

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Labels

- Label:
  - short
  - fixed-length
  - local significance
  - exact match for forwarding
- Forwarding equivalency class (FEC):
  - packets that share the same next hop share the same label (locally)
- Needs label distribution mechanism

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Label stacking

- Label stacking allows an indefinite number of labels to be used
- 3 Label operations:
  - Push
  - Pop
  - Swap
- Separates control and forwarding

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MPLS

- Label Distribution Protocol (LDP) or RSVP?
  - LDP can support explicit routing (or QoS or constraint routing)
  - RSVP uses the routing tables of current non-QoS-aware routing protocols
- MPLS use cases
  - traffic engineering
  - scalable IP virtual private networks

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TCP

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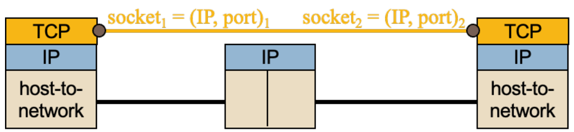
Transmission Control Protocol (TCP)

- Connection-oriented transport protocol
- Reliable transport
  - Positive acknowledgment (ACK) with retransmission
  - Principles of sliding window
- Details:
  - full duplex, ports, connections and endpoints ($socket_1$,$socket_2$)



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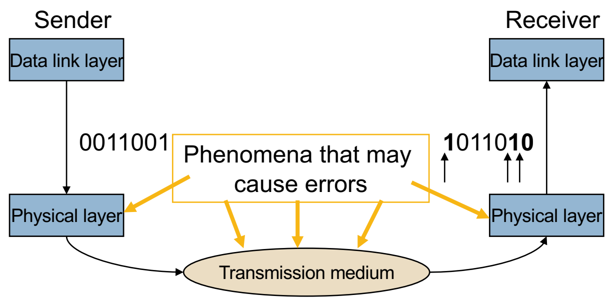
Errors



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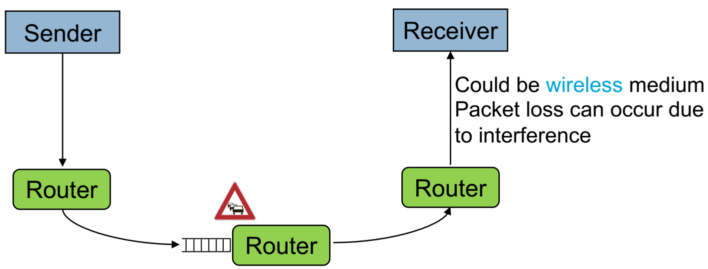
Packet Loss



Congestion: router buffer fills up with packets
If buffer full, router drops packets

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Error Control

Three ways to deal with errors or packet loss after detection:

Retransmission — ARQ/TCP
- infrequent errors
- when time permits

Forward Error Correction — real-time services
- frequent errors
- when time does not permit retransmissions

Discard — UDP
- when strict reliability is not required/too expensive

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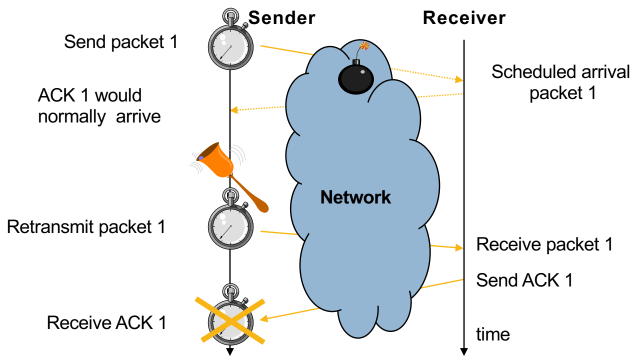
Time-out and Retransmission



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TCP Retransmission Timeout

- Retransmission Timeout (RTO) after
  RTO = min{*rto_min*, *srtt* + 4 * *var*}
  rto_min originally specified as 1s; cur. default in Linux: 200ms
- Smoothed Round-Trip Time *srtt*:
  - At least once every Round-Trip Time (RTT): measure current RTT and store as *r*
    - Don't measure RTT for retransmissions
  - *srtt* = (1 - α) * *srtt* + α * *r*
  - Initial value for *srtt* (when measuring first RTT): *srtt* = *r*
- RTT Variation *var*:
  - *var* = (1 - β) * *var* + β * |*srtt* - *r*|
  - Initial value for *var* (when measuring first RTT): *var* = *r* / 2
- Typically, α = 1/8 and β = 1/4

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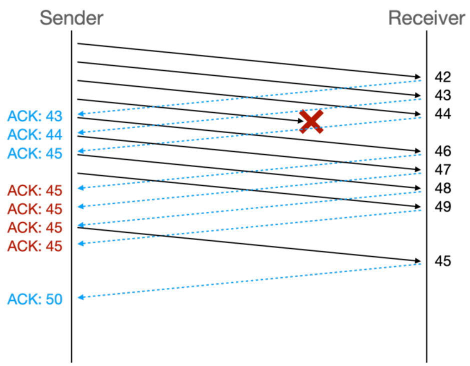
Duplicate Acknowledgments



ACKs acknowledge received data by indicating the sequence number the receiver expects next

If an out-of-order packet arrives, the receiver sends duplicate ACKs

After three duplicate ACKs: sender considers the packet lost and retransmits (Fast Retransmit)

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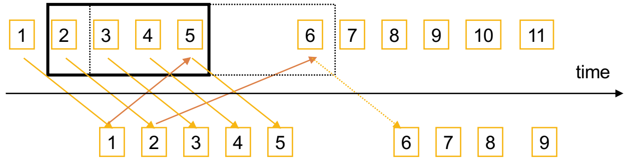
Sliding Window



Tuning sliding window impacts number of packets in network
Packets "inflight" = packets inside the network at a given time

- TCP receive window (*rwnd*): upper limit on packets inflight specified by the receiver to ensure that the receiver is not overwhelmed by incoming packets (flow control)
- TCP congestion window (*cwnd*): upper limit on packets inflight determined by the sender to ensure that the network does not collapse under congestion due to too many packets (congestion control)

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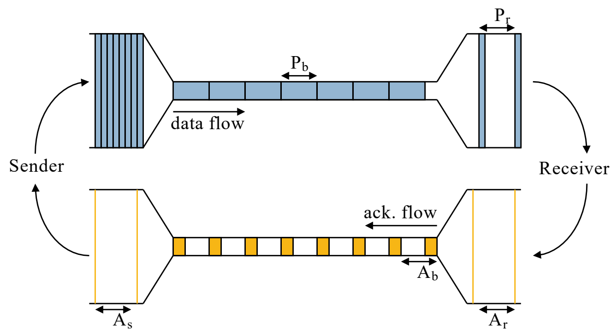
TCP is 'self-clocking'



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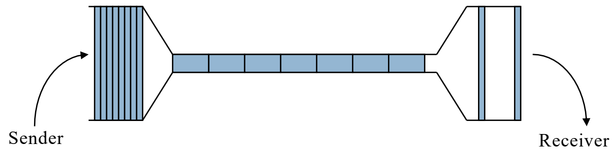
Congestion Control

- Problem: congestion at bottlenecks (typically router buffers)



- Avoid network overload by throttling sending rate on sender side

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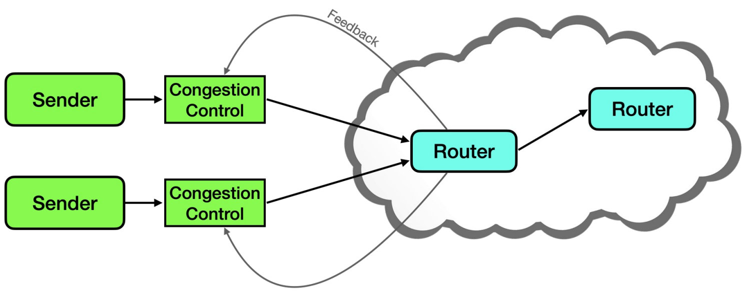
Congestion Control



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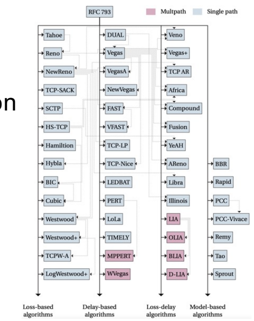
Types of Congestion Control Algorithms (CCAs)

- Loss-based CCAs
  - Use packet loss as congestion signal
  - E.g., Reno, Cubic, …
- Delay-based CCAs
  - Use increasing delay as congestion signal
  - E.g., Vegas, …
- Others
  - Hybrids between loss- and delay-based, model-based, …
  - E.g., BBR, …

- Window-based control
  - Limit inflight using congestion window (cwnd)
- Rate-based control
  - Limit sending rate by pacing packets at a certain rate



An overview of different CCAs ordered by type

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TCP Reno: Overview

- Startup: probe available bandwidth
  - Slow Start: ramp up cwnd exponentially
- Steady state: keep up throughput and react to congestion
  - Congestion Avoidance: Additive Increase, Multiplicative Decrease (AIMD)
  - Raise cwnd linearly (additively)
  - Upon 3 duplicate ACKs:
    - decrease cwnd multiplicatively
    - Fast Retransmit of lost packet
    - Fast Recovery keeps up ACK-clocking
  - Upon RTO: reset to Slow Start

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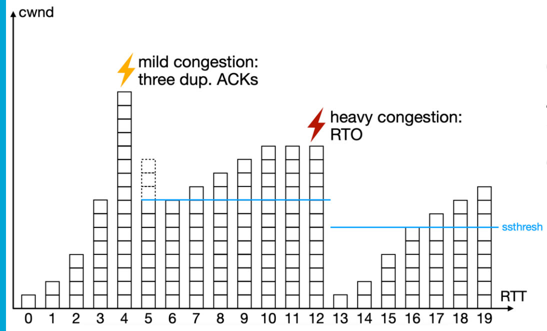
TCP Reno



0 – 4: Slow Start

4: *three dup. ACKs* received
5: Fast Recovery

6 – 10: Congestion Avoidance

10 – 12: no new ACKs arrive
12: *RTO* triggered

11 – 14: Slow Start
15 – 17: Congestion Avoidance

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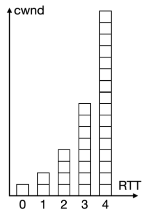
TCP Reno: Slow Start



Initialize *cwnd* = 1; *ssthresh* = ∞
Upon receiving an ACK:
  cwnd = *cwnd* + 1

If *cwnd* > *ssthresh*: switch to Congestion Avoidance
When *ssthresh* is not set, continue Slow Start until packet loss.

Note: nowadays, initial *cwnd* = 10 (typically)

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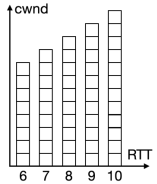
TCP Reno: Congestion Avoidance

Upon receiving an ACK:
    cwnd = *cwnd* + 1/*cwnd*
(Linear, Additive Increase)



Continue Congestion Avoidance until packet loss.

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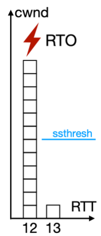
TCP Reno: Packet Loss

Packet loss detected if RTO or three duplicate ACKs received

Upon packet loss:
    ssthresh = max{inflight / 2, 2}
    inflight = number of not yet ACKed packets inside the network

If RTO ("heavy congestion"):
    cwnd = 1
    switch to Slow Start
If three dup. ACKs ("mild congestion"):
    switch to Fast Recovery



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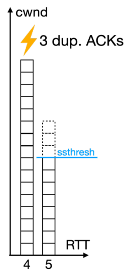
TCP Reno: Fast Recovery

Triggered upon receiving 3 dup. ACKs.

Fast Retransmit: retransmit the lost packet
Set *cwnd* = *ssthresh* + 3 (keep up the ACK clocking by sending three new packets)
(Multiplicative Decrease)

Upon receiving another dup. ACK:
cwnd = *cwnd* + 1 (keep up the ACK clocking)

Upon receiving a new ACK:
cwnd = *ssthresh*
switch to Congestion Avoidance



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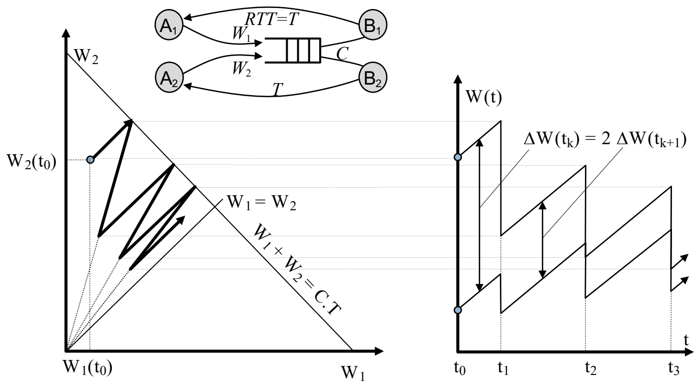
Add. Increase – Mult. Decrease



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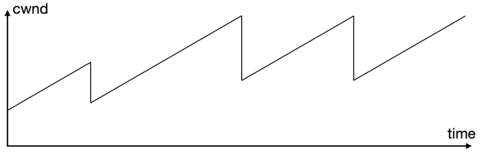
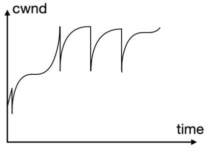
TCP Cubic

- Problem with Reno: linear Add. Increase is too slow in networks with high bandwidth and/or long RTTs



- Cubic: cubic increase function



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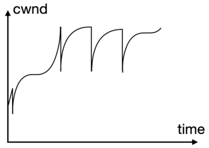
TCP Cubic

- When receiving ACK in Congestion Avoidance: increase *cwnd* according to a monotonic cubic function
  - Reno: linear increase
- Function is based on previous congestion event
  - Inflection point is around where the algorithm estimates congestion to occur again
- Upon 3 dup. ACKs:
  - *ssthresh* = max{0.7 * *cwnd*, 2)
  - *cwnd* = 0.7 * *cwnd*
- Upon RTO:
  - *ssthresh* = 0.7 * *cwnd*
  - *cwnd* = 1, switch to Slow Start
- Currently: Cubic is the default CCA in Linux, Windows, and MacOS and the most commonly used in the Internet



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BBR

- Novel congestion control scheme by Google
- Motivation: problems with loss-based CCAs (e.g., Cubic)
  - When buffers are small: low throughput (high loss, CCA cuts cwnd too often)
  - When buffers are large: high queueing delay (bufferbloat)
- BBR: Bottleneck Bandwidth and Round-trip propagation time
- Idea: adjust behavior based on a model of the network path

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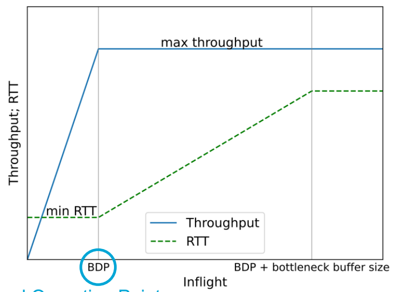
BBR

- Optimal operating point: 1 Bandwidth-Delay Product (BDP) of data is inflight (i.e., inside the network)



Optimal Operating Point

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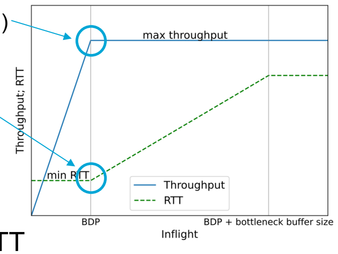
BBR

- Model the network path: measure
  - Bottleneck bandwidth (BtlBw)
  - Round-trip time (RTT)



- Estimated BDP = BtlBw * RTT
- Keep *inflight* around 1 estimated BDP

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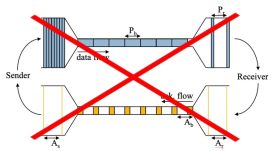
BBR

- Control both cwnd and pacing rate
  - cwnd: cap how much data is allowed inflight
  - pacing rate: control how fast packets are sent
- Both needed: self-clocking through ACKs no longer possible nowadays
  - DOCSIS or WiFi aggregate ACKs and send them out in a burst ("delayed ACKs")



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BBR

- Regularly raise sending rate to probe for bandwidth
- Regularly lower sending rate to obtain samples of the RTT

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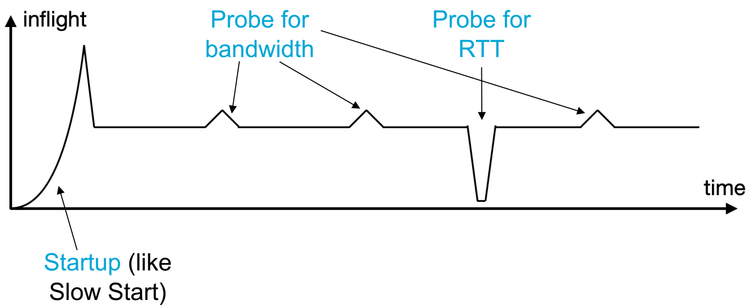
BBR



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BBR

- Deployed in Google's networks
- Now second-most commonly used CCA in the Internet, adoption growing

- Problems: fairness issues, high queueing delay, no reaction to packet loss
  – Now in development: BBRv2, BBRv3

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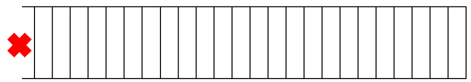
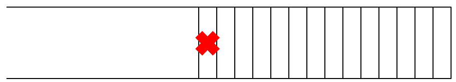
Active Queue Management (AQM)

- Classic buffers ("tail drop"): drop packets when buffer is full
  – High queueing delay
  – Typically drops multiple packets of the same flow



- AQM: drop packets before buffer is full and randomize which packets are dropped
  – Lower queueing delay
  – Fairer



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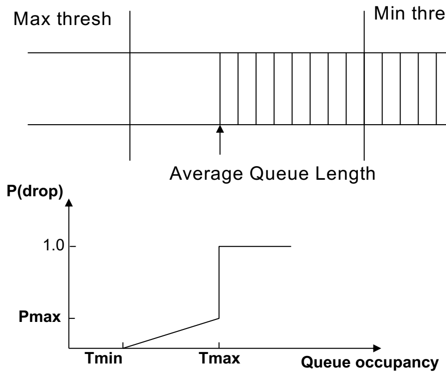
Random Early Detection (RED)



Drop arriving packet with probability *p*
Increase *p* with increasing queue occupancy

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Controlled Delay (CoDel)

- Measure sojourn time of packets in the buffer
- Interval length initially 100 ms
- After each interval: if minimum sojourn time during interval was > 5 ms:
  - Drop a single packet
  - Shorten interval length
    - After n intervals where min. sojourn time was > 5 ms, interval length is 100 - sqrt(n) ms
- Otherwise:
  - Reset interval length to 100 ms

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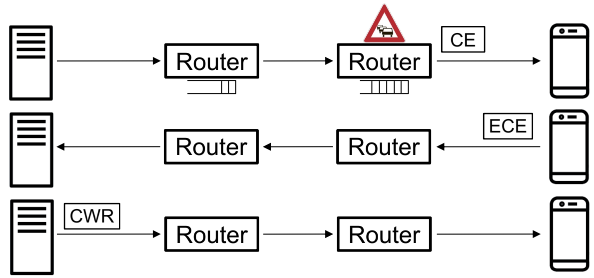
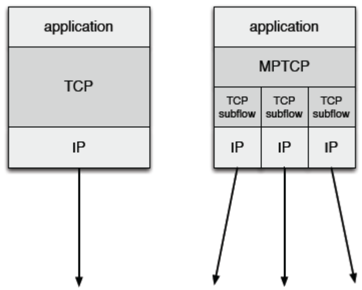
Explicit Congestion Notification (ECN)

- Routers mark packets with explicit congestion notification instead of dropping them
  - Requires AQM
- Sender reacts to ECN-Echo like it would react to packet loss



CE: Congestion Experienced
ECE: ECN-Echo
CWR: Congestion Window Reduced

MPTCP



Traditional versus Multi-Path TCP

QUIC

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Quick UDP Internet Connections (QUIC)

- New transport protocol developed by Google
- Goals
  - Low latency
  - Security
  - Multiplexing without head-of-line blocking
  - Connection migration
  - …
- Utilizes UDP for transport
  - Firewalls or NATs sometimes block traffic that is not TCP or UDP
- But adds TCP-like features such as retransmissions
- Implements congestion control on application layer

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QUIC

	Traditional TCP Stack	QUIC Stack
Application	HTTP/2	HTTP API
Security	TLS	QUIC
Transport	TCP	QUIC / UDP
Network	IP	IP

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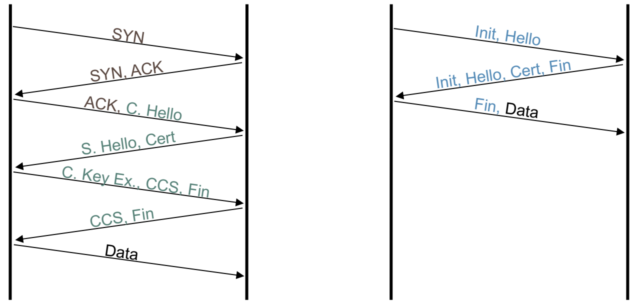
QUIC Handshake



TCP handshake +
TLS handshake +
data transmission

QUIC handshake +
data transmission

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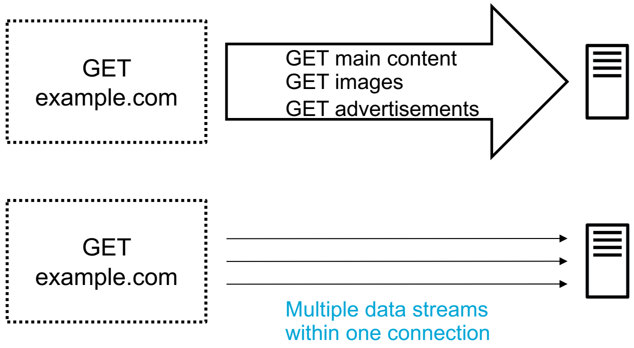
Multiplexing



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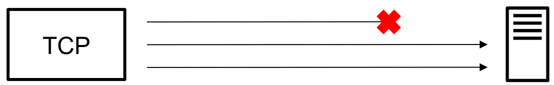
Head-of-Line Blocking



- Error in one stream (e.g. packet loss)
- TCP: blocks all streams until the error is resolved
  - Unnecessary delay!

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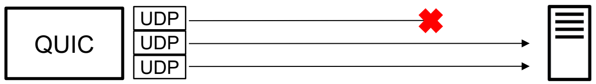
QUIC Multiplexing



- QUIC: Error in one stream (e.g. packet loss) does not affect the other streams

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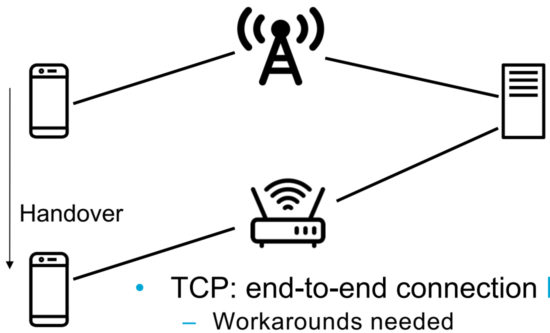
QUIC Connection Migration



- TCP: end-to-end connection breaks
  - Workarounds needed
- QUIC: packets contain connection ID
  - Can reestablish connection fast

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