CS 152
Computer Architecture and Engineering

Lecture 21 – Networks and Routers

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Last Time: NAND Flash

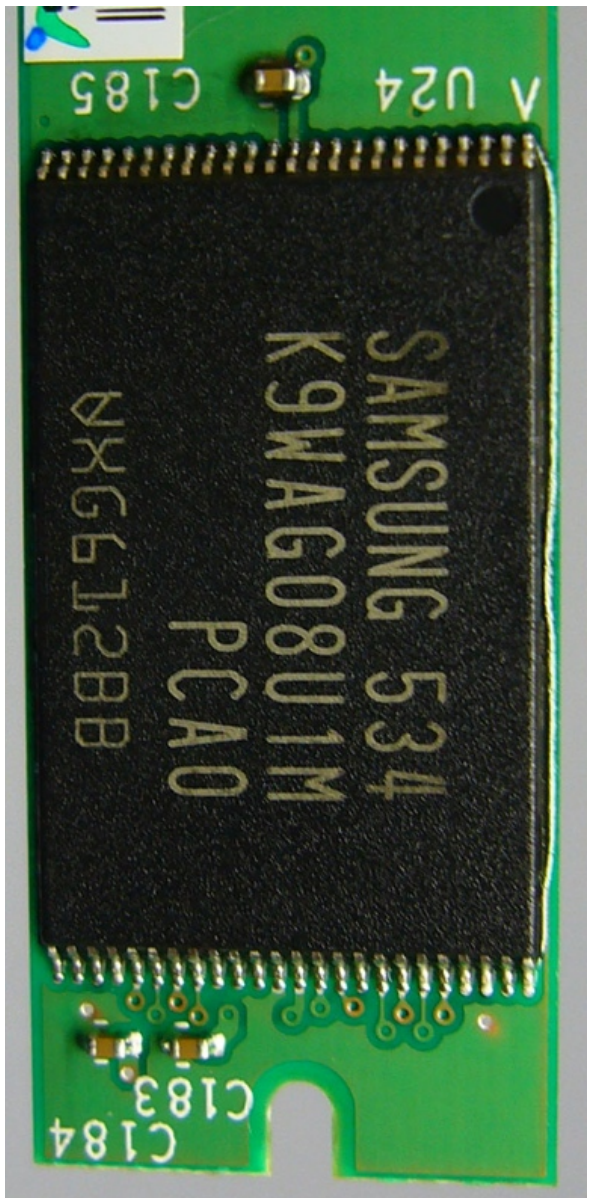
Chip "remembers" for 10 years.

Idea: Disk Replacement

Presents memory to the CPU as a set of pages.

Page format:

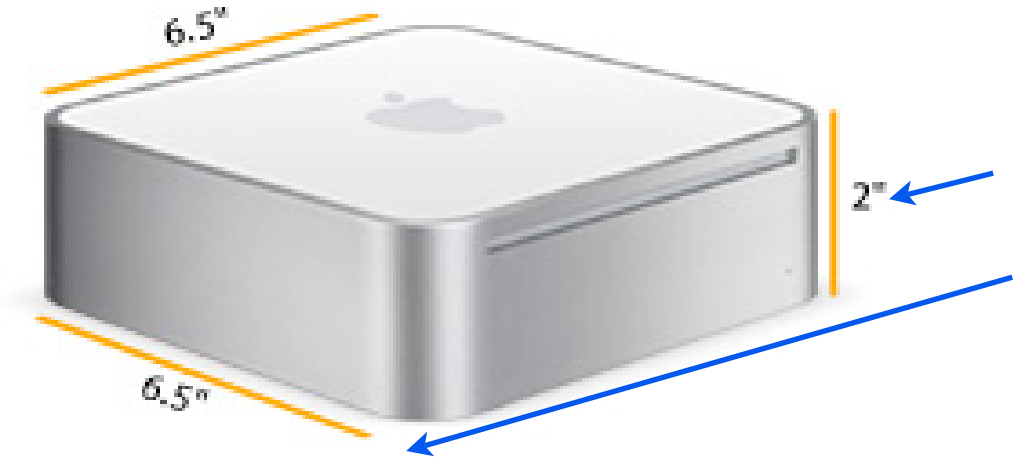
2048 Bytes	+	64 Bytes
(user data)		(meta data)



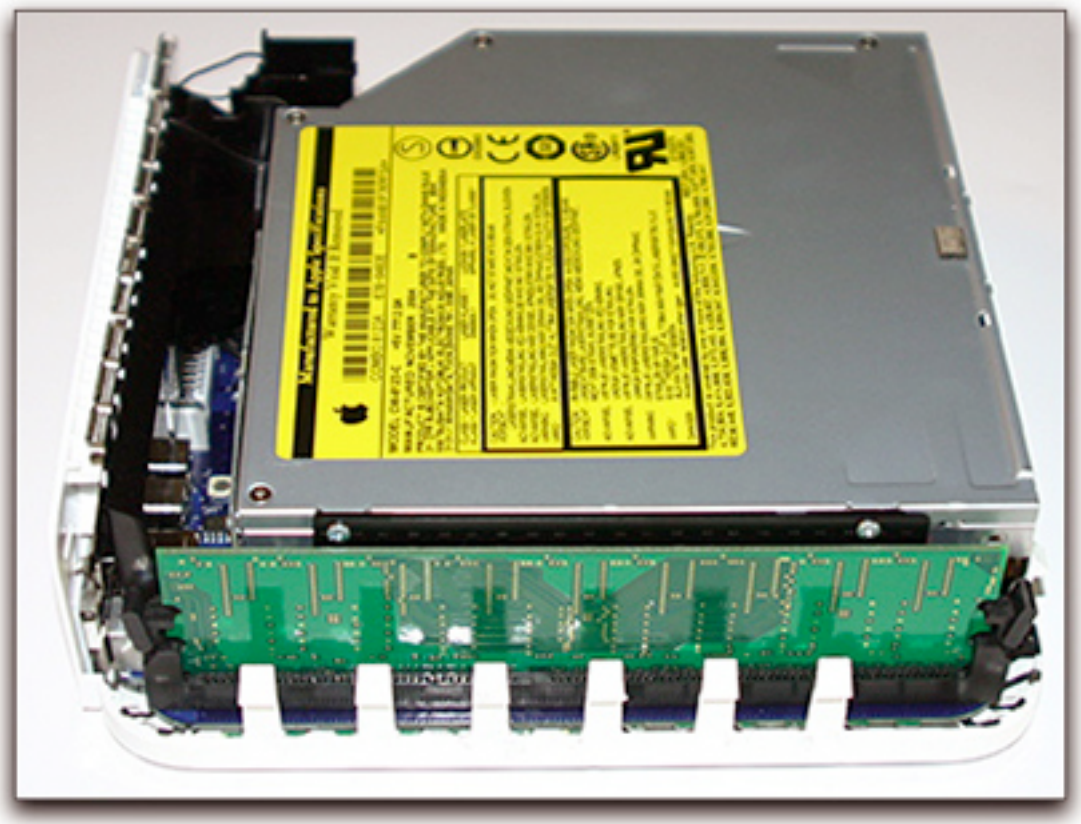
Note: NOR Flash is another flash product, for software code. NOR Flash read interface is just like SRAM.

NAND Flash has better cost/bit than NOR.

Last Time: Making the Mac Mini G4

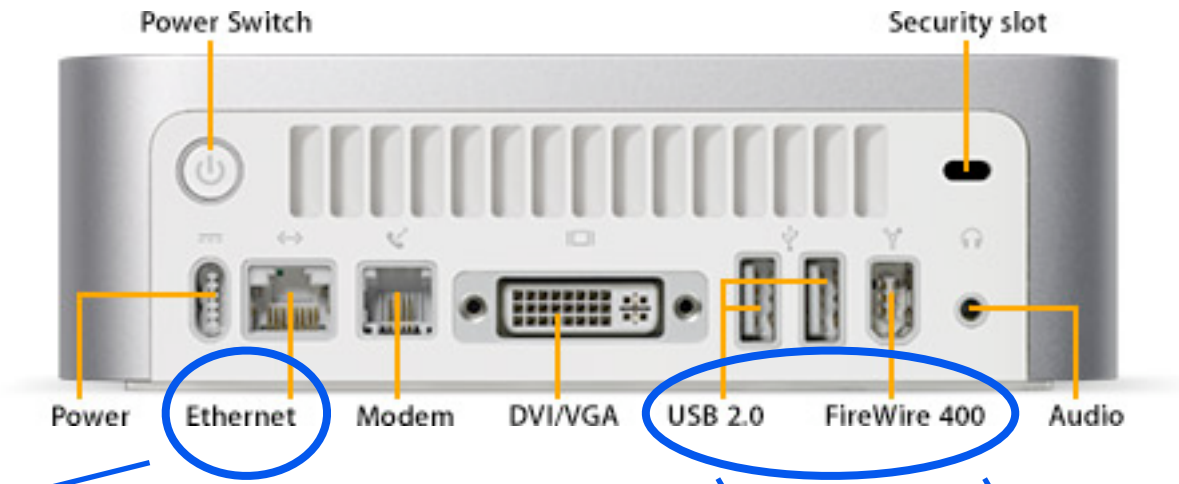


Size fixed by the "form factor" (physical size) of desktop DIMMS. Laptop DRAM is smaller, but too expensive for $499 price.



Why are networks different from buses?

Serial: Data is sent "bit by bit" over one logical wire.



Network. Primary purpose is to connect computers to computers.

USB, FireWire. Primary purpose is to connect devices to a computer.

Today: Networks

- **Link layers:** Using physics to send bits from place to place.
- **Internet:** A network of networks.
- **Routing:** Inside the cloud.

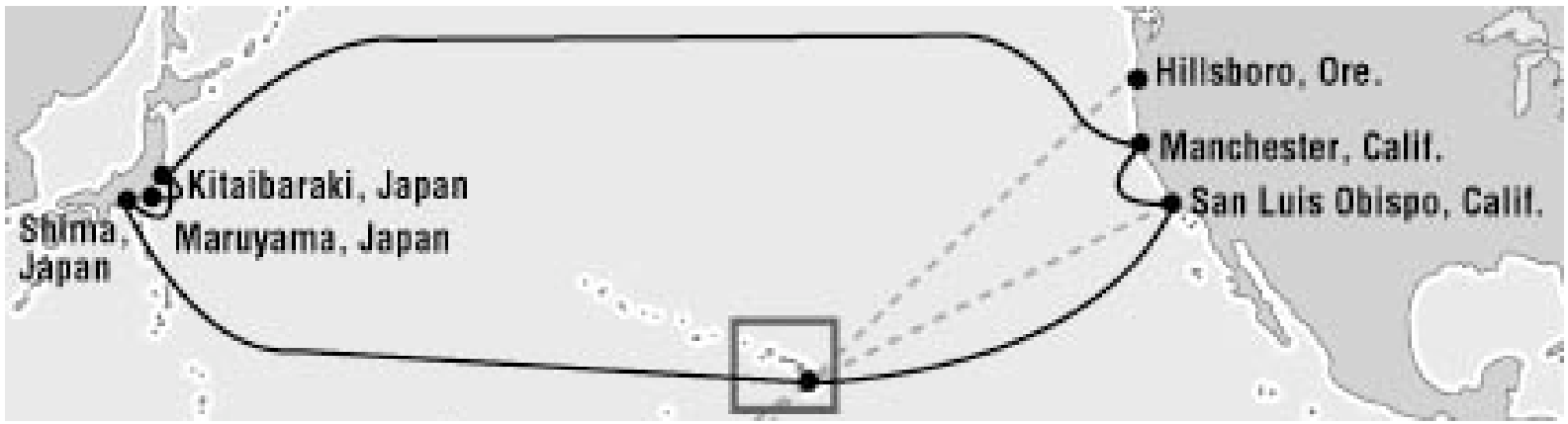
Today: Router Design

- **Router architecture:** What's inside the box?
- **Forwarding engine:** How a router knows the "next hop" for a packet.
- **Switch fabric:** When buses are too slow ... replace it with a switch!

Networking bottom-up: Link two endpoints

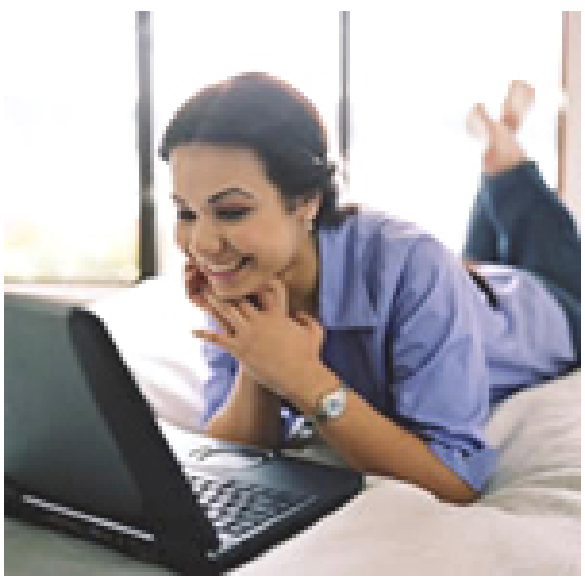
Q1. How far away are the endpoints?

Japan-US undersea cable network



Physical media: optical fiber (photonics)

WiFi wireless from hotel bed to access point.



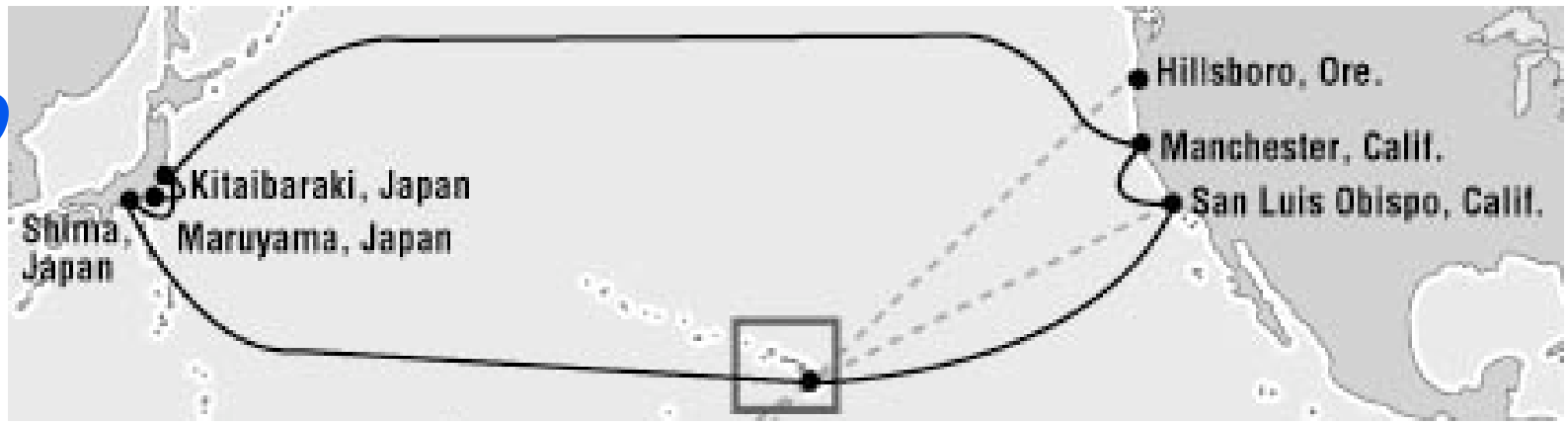
Distance + mobility + bandwidth influences choice of medium.

Physical media: unlicensed radio spectrum

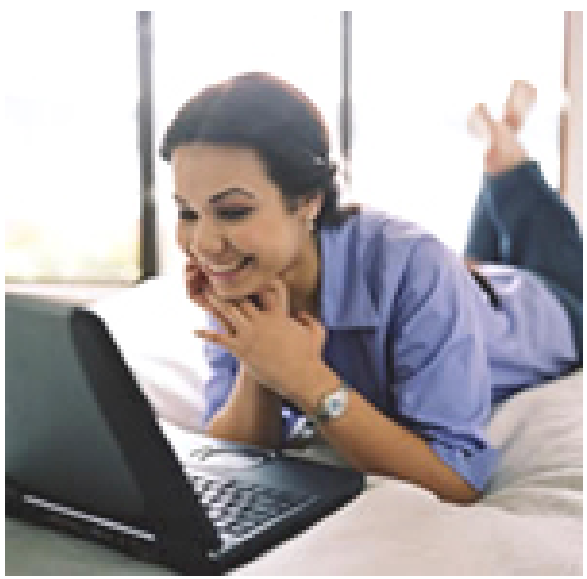
Networking bottom-up: Link two endpoints

Q2. Initial investment cost for the link.

$1B USD. A ship lays cable on ocean floor.



The price of the WiFi laptop card + the base station.



For expensive media, much of the "price" goes to pay off loans.

"Unlicensed radio" -- no fee to the FCC

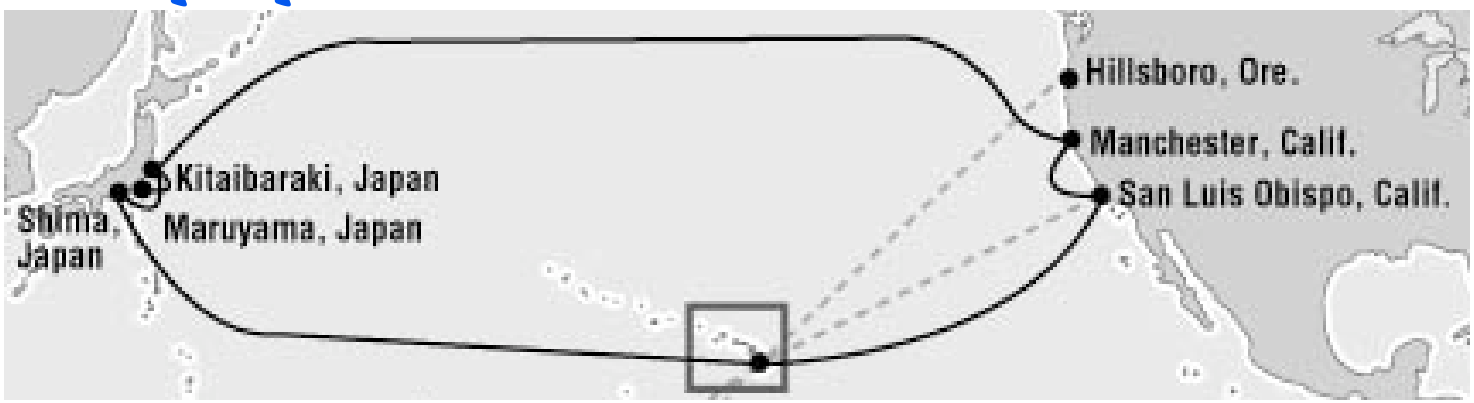
Networking bottom-up: Link two endpoints

Q3. How is the link imperfect?

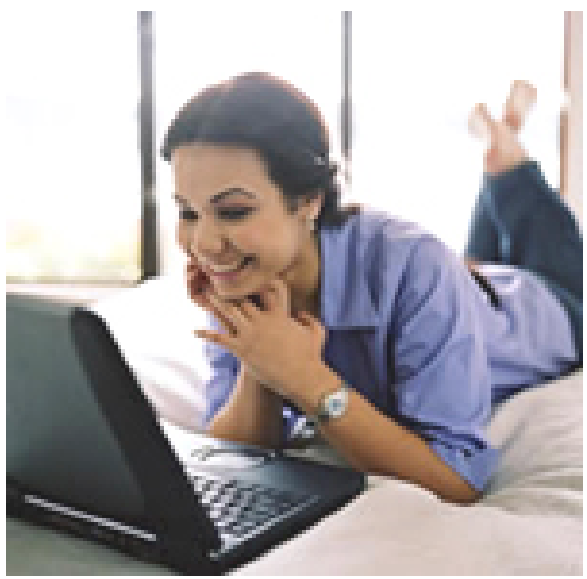
+++ A steady bitstream ("circuit"). No packets to lose.

+++ Only one bit flips per 10,000,000,000,000 sent.

--- Undersea failure is catastrophic



--- Someone walks by and the network stops working - "fading".



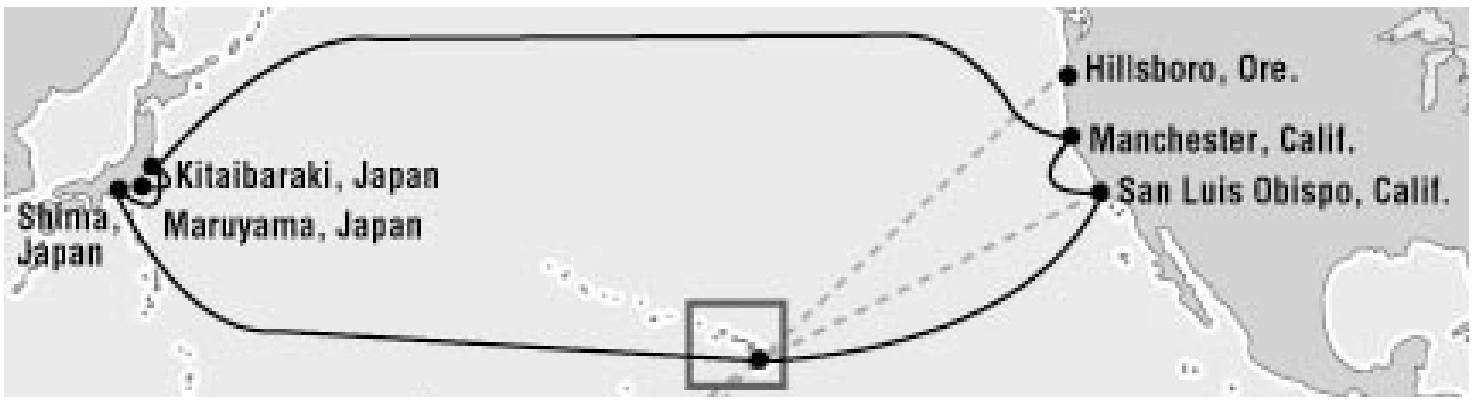
Solution: Short packets spaced in time to escape the fade. If lost, do retransmits.

Networking bottom-up: Link two endpoints

Q4. How does link perform?

BW: 640 Gb/s (CA-JP cable)

Latency: *% ping irt1-ge1-1.tdc.noc.sony.co.jp*
PING irt1-ge1-1.tdc.noc.sony.co.jp (211.125.132.198): 56 data bytes
64 bytes from 211.125.132.198: icmp_seq=0 ttl=242 time=114.571 ms round-trip.



Compare: Light speed in vacuum, SFO-Tokyo, 63ms RT.

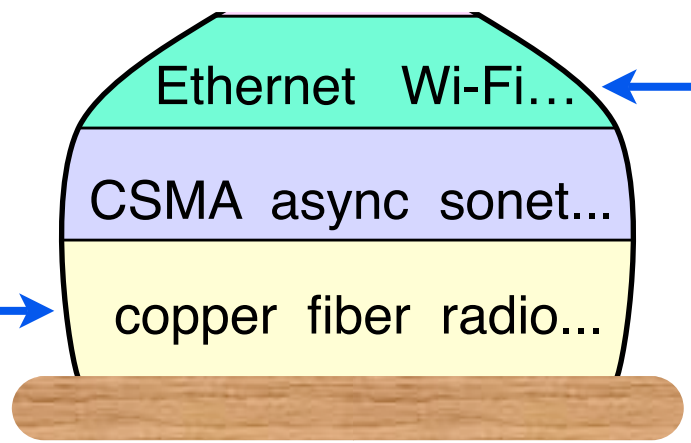
In general, risky to halve the round-trip time for one-way latency: paths are often different each direction.

BW: In theory, 802.11b offers 11 Mb/s. Users are lucky to see 3-5 Mb/s in practice.

Latency: If there is no fading, quite good. I've measured <2 ms RTT on a short hop.

There are dozens of “link networks” ...

Protocol Complexity



Link networks

The undersea cable, the hotel WiFi, and many others ... DSL, Ethernet, ...

Diagram Credit: Steve Deering

Web browsers do not know about link nets

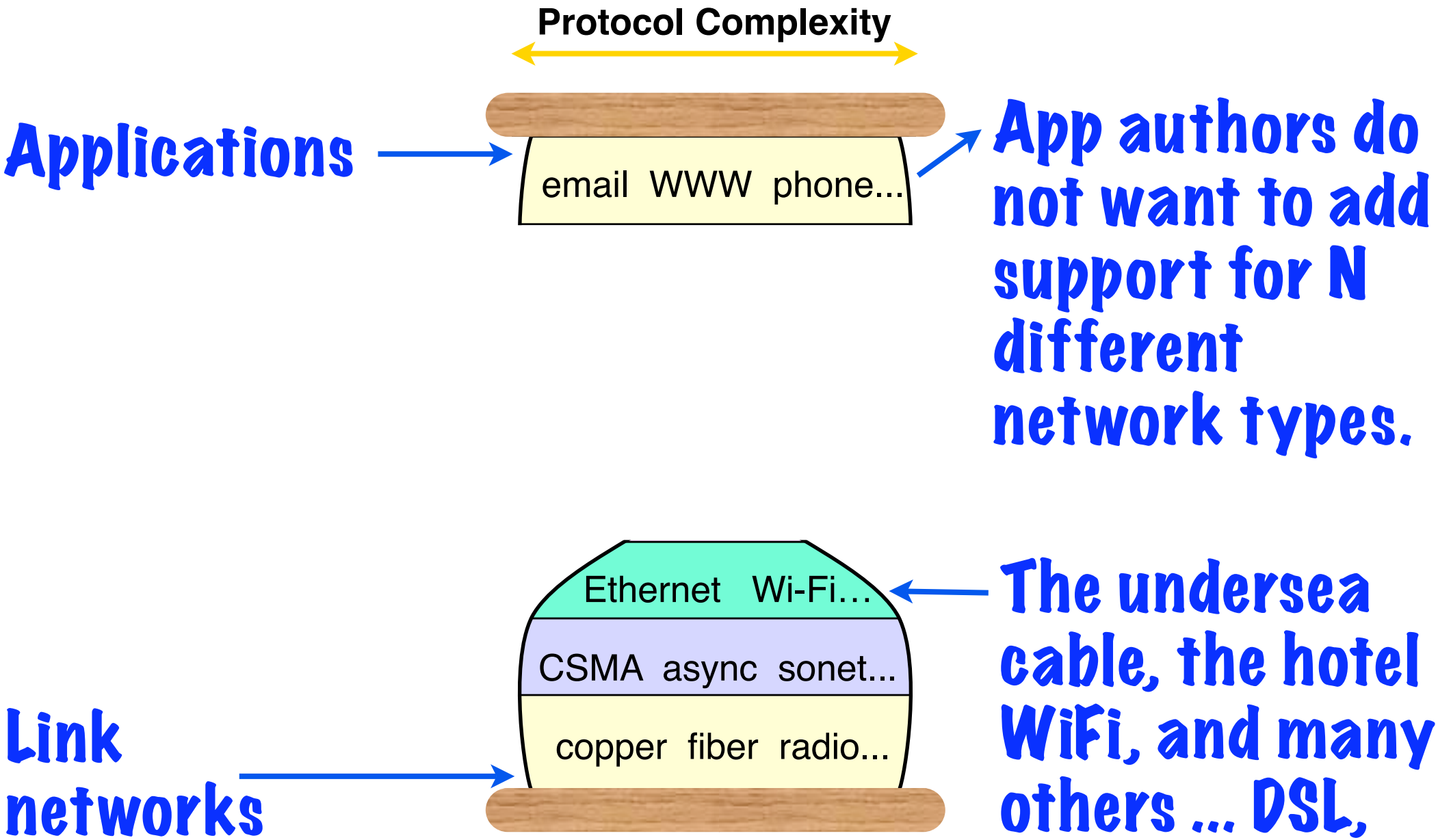
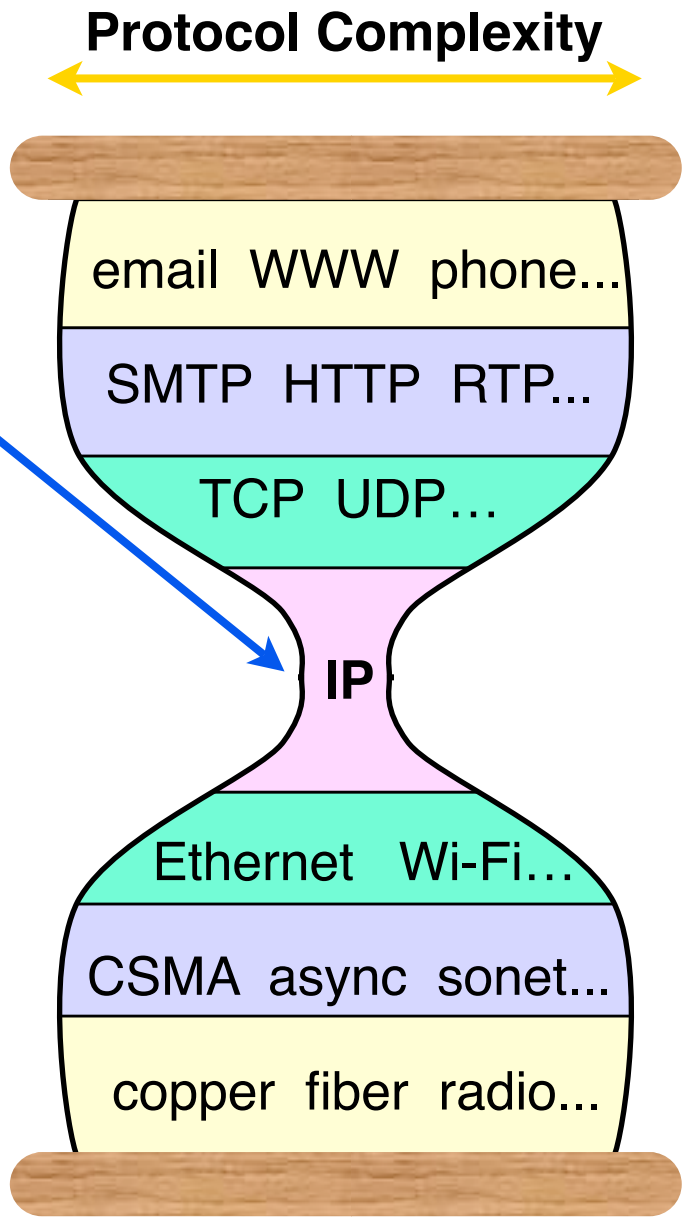


Diagram Credit: Steve Deering

The Internet: A Network of Networks

Internet Protocol (IP): An abstraction for applications to target, and for link networks to support. Very **simple**, very successful.



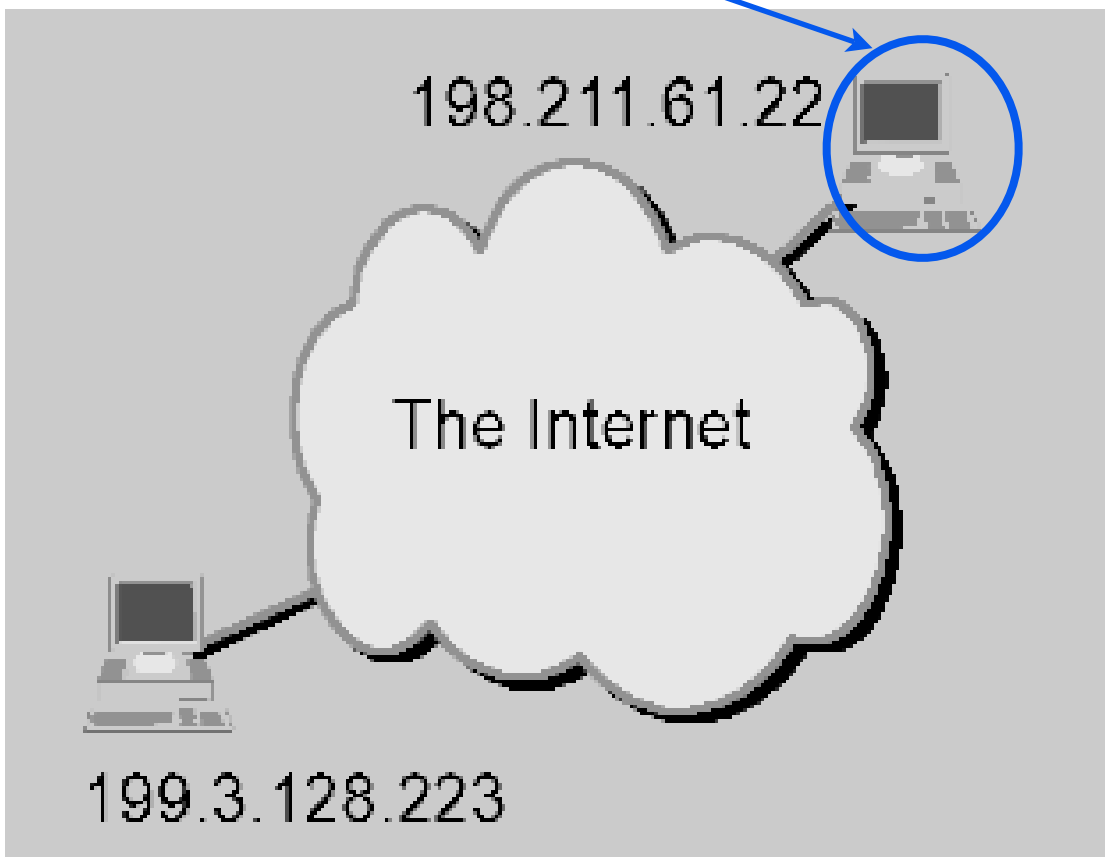
IP presents link network errors/losses in an abstract way (not a link specific way).

Link layer is not expected to be perfect.

Diagram Credit: Steve Deering

The Internet interconnects "hosts" ...

IP4 number for this computer: 198.211.61.22



Every directly connected host has a unique IP number.

Upper limit of 2^32 IP4 numbers (some are reserved for other purposes).

Next-generation IP (IP6) limit: 2^128.

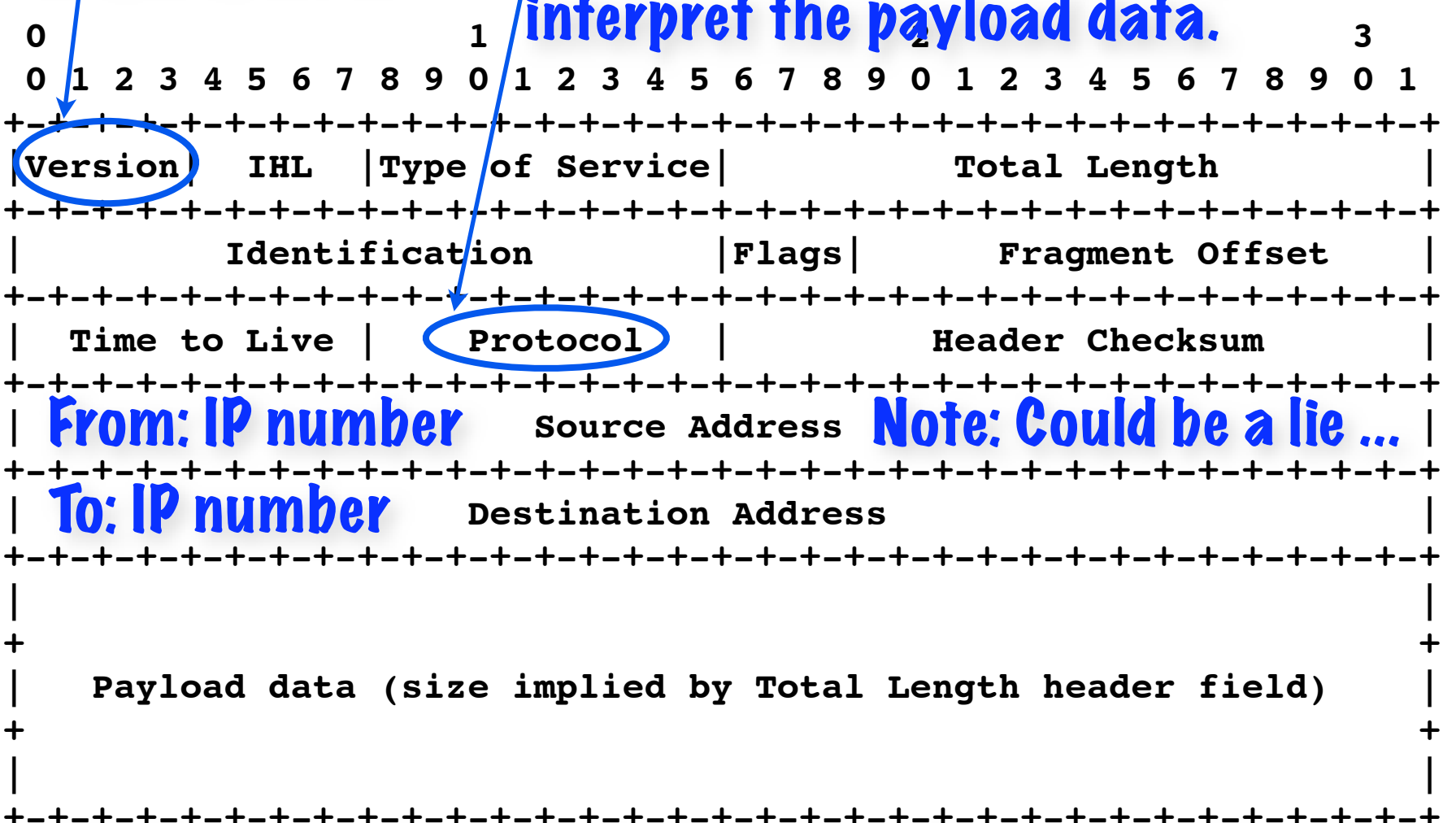
198.211.61.22 ??? A user-friendly form of the 32-bit unsigned value 3335732502, which is:

198*2^24 + 211*2^16 + 61*2^8 + 22

Internet: Sends Packets Between Hosts

IP4, IP6, etc ...

How the destination should interpret the payload data.



Bitfield numbers

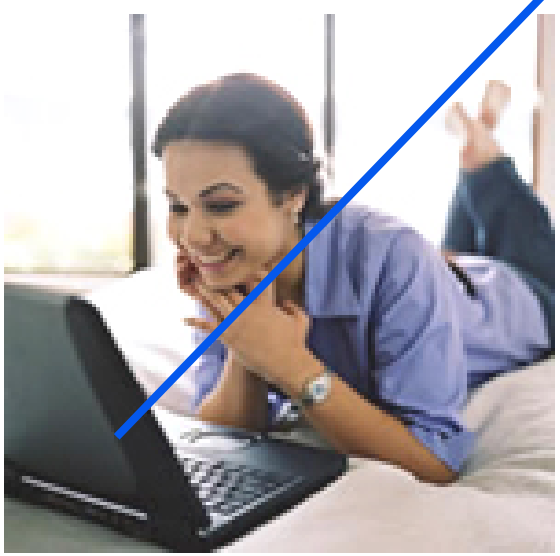
Header

Data

IHL field: # of words in header. The typical header (IHL = 5 words) is shown. Longer headers code add extra fields after the destination address.

Link networks transport IP packets

ISO Layer Names:
- IP packet: "Layer 3"
- WiFi and Cable Modem packets: "Layer 2"
- Radio/cable waveforms: "Layer 1"



801.11b WiFi packet

IP Packet

For this "hop", IP packet sent "inside" of a wireless 802.11b packet.

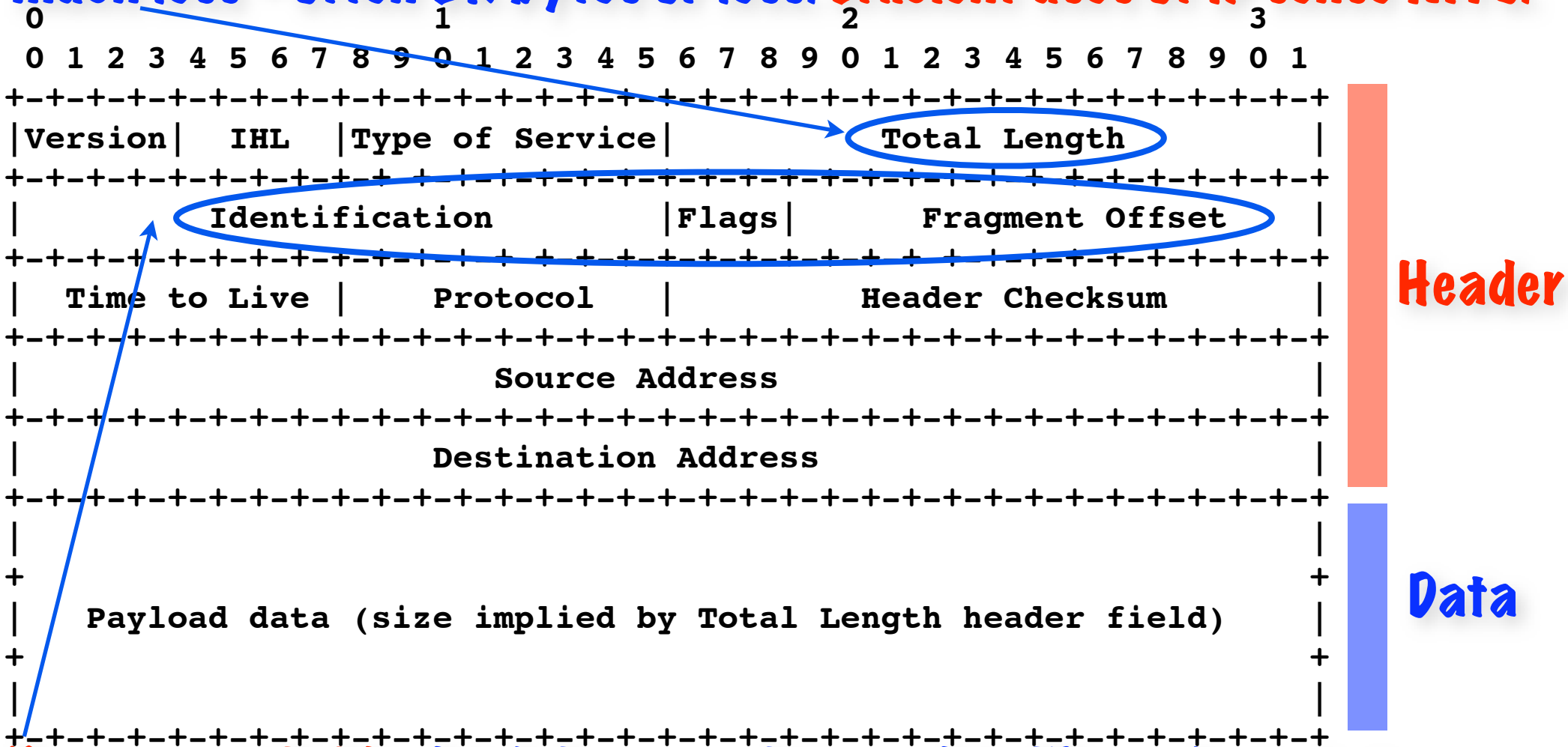
Cable modem packet

IP Packet

For this "hop", IP packet sent "inside" of a cable modem DOCSIS packet.

Link layers "maximum packet size" vary.

Maximum IP packet size 64K bytes. Maximum Transmission Unit (MTU -- generalized "packet size") of link networks may be much less - often 2K bytes or less. Efficient uses of IP sense MTU.



Fragment fields: Link layer splits up big IP packets into many link-layer packets, reassembles IP packet on arrival.

IP abstraction of non-ideal link networks:

- A sent packet may never arrive ("lost")
- If packets sent P1/P2/P3, they may arrive P2/P1/P3 ("out of order").

Best Effort: The link networks, and other parts of the "cloud", do their best to meet the ideal. But, no promises.

- Relative timing of packet stream not necessarily preserved ("late" packets).
- IP payload bits received may not match payload bits sent. IP header protected by checksum (almost always correct).

How do apps deal with this abstraction?

"Computing" apps use the TCP (Transmission Control Protocol).

TCP lets host A send a reliable byte stream to host B. TCP works by retransmitting lost IP packets. Timing is uncertain.

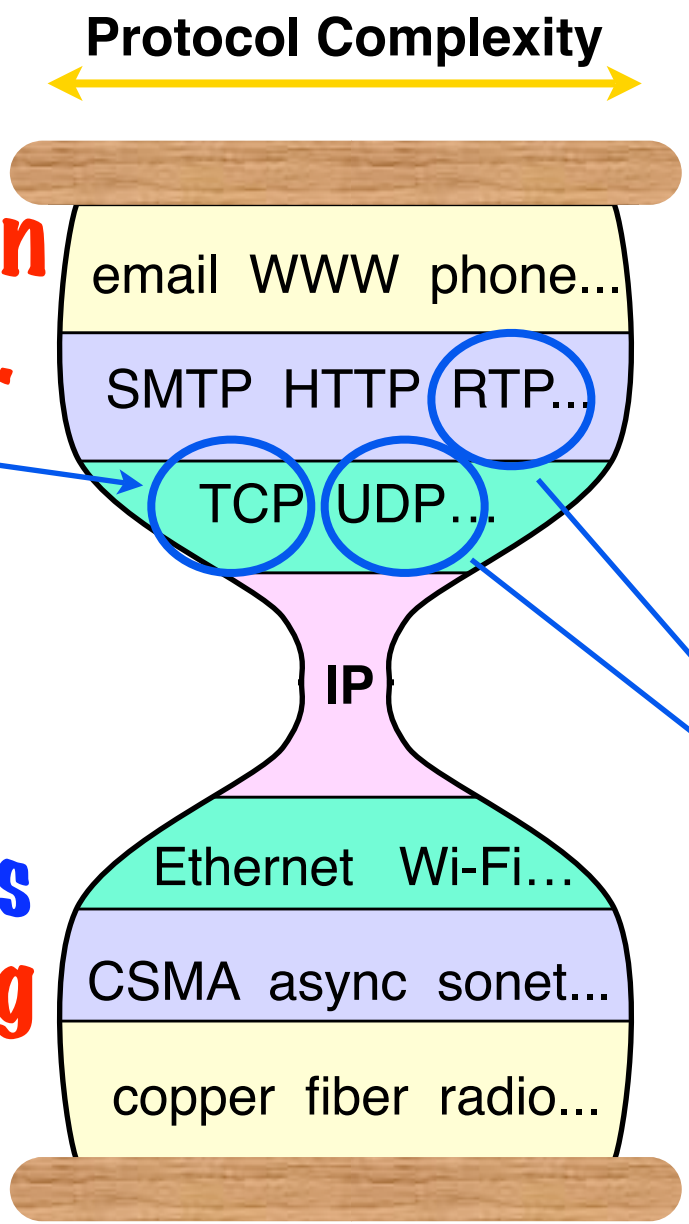


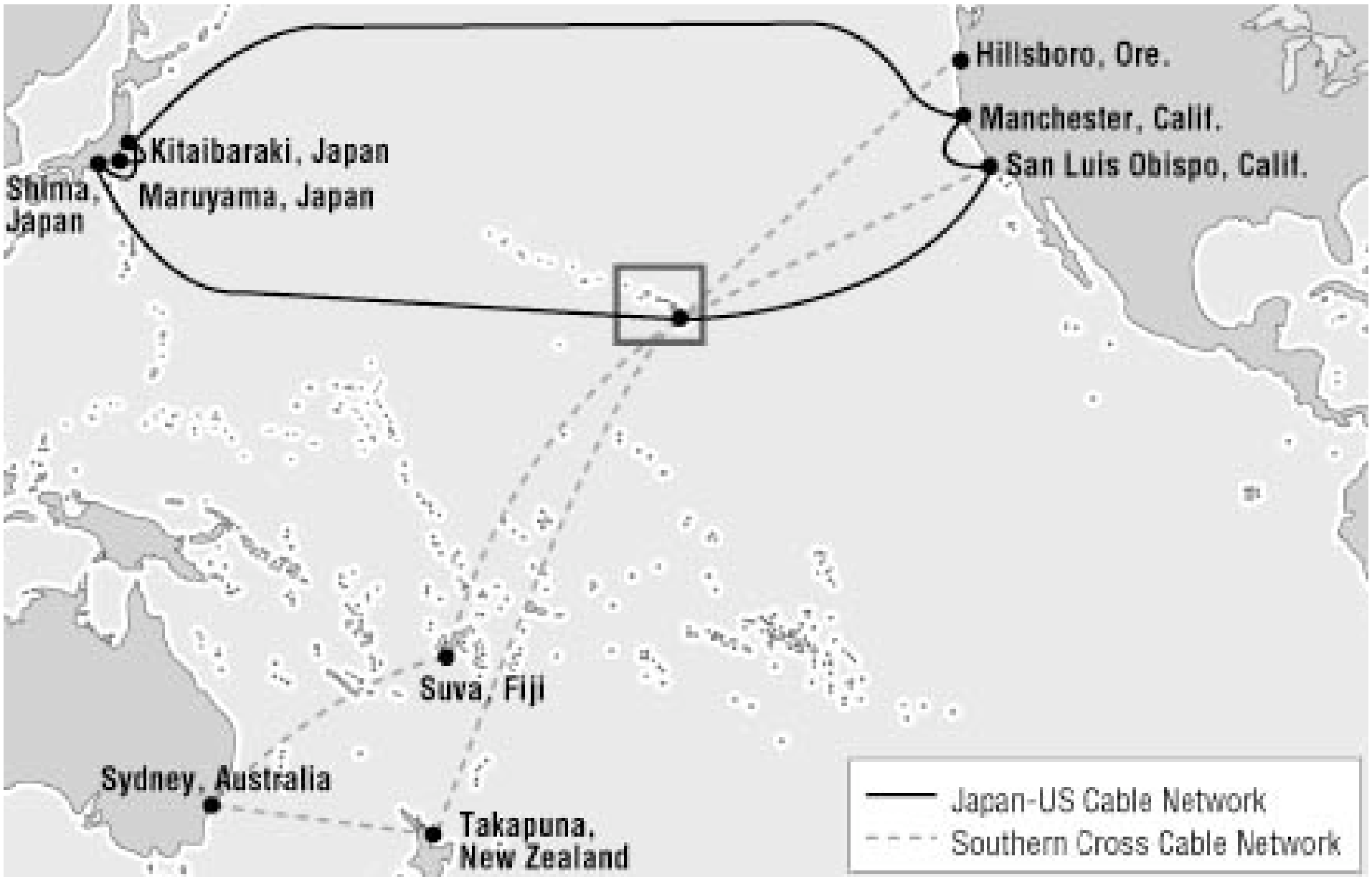
Diagram Credit: Steve Deering

Retransmission is bad for IP telephony: resent packets arrive too late.

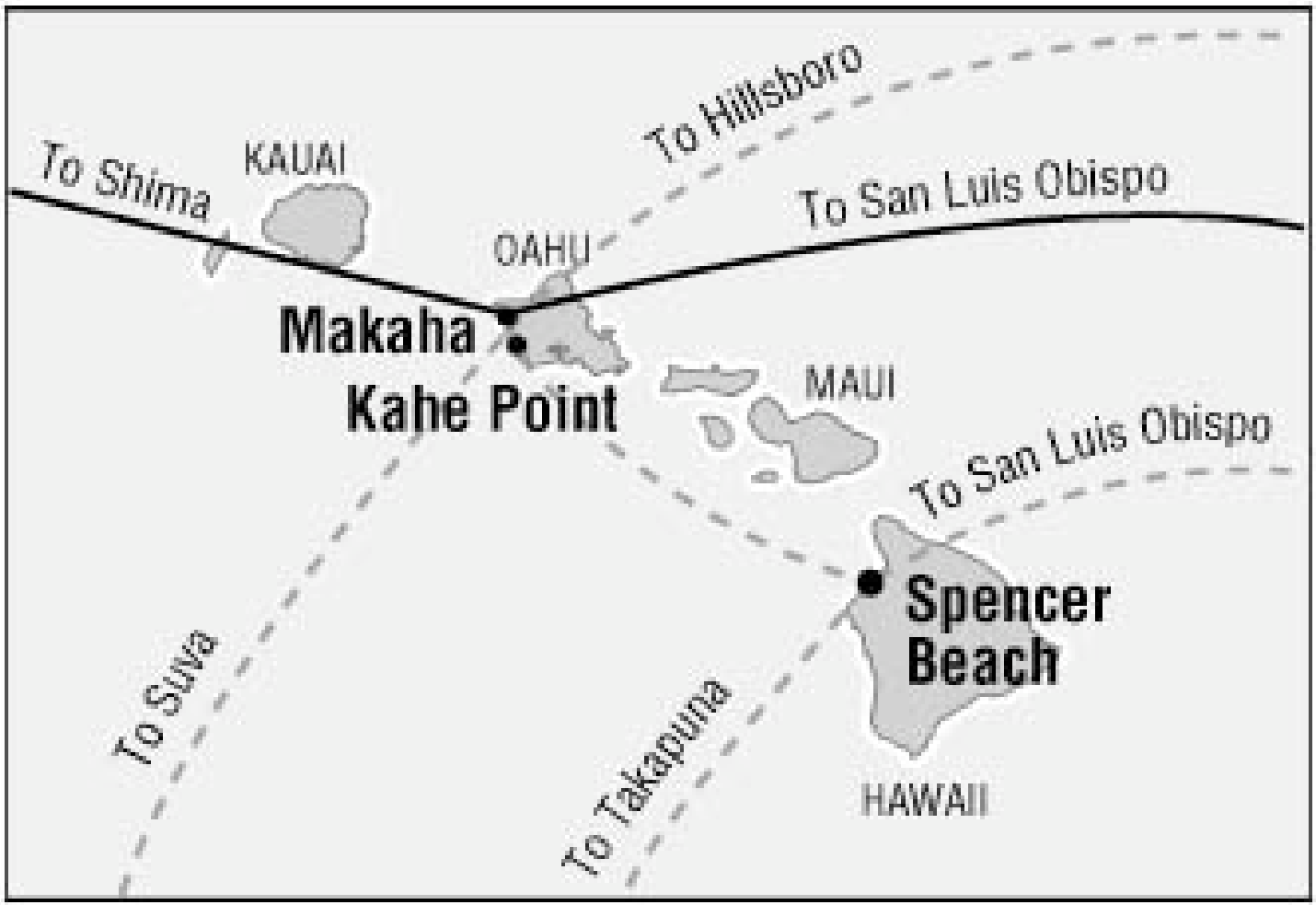
IP telephony uses packets, not TCP. Parity codes, audio tricks used for lost packets.

Routing

Undersea cables meet in Hawaii ...



Routers: Like a hub airport



In Makaha, a router takes each Layer 2 packet off the San Luis Obispo (CA) cable, examines the IP packet destination field, and forwards to Japan cable, Fiji cable, or to Kahe Point (and onto big island cables).

Example: berkeley.edu to sony.co.jp

Passes through 21 routers …

Leaving Cal …

Getting to LA …

Cross Pacific

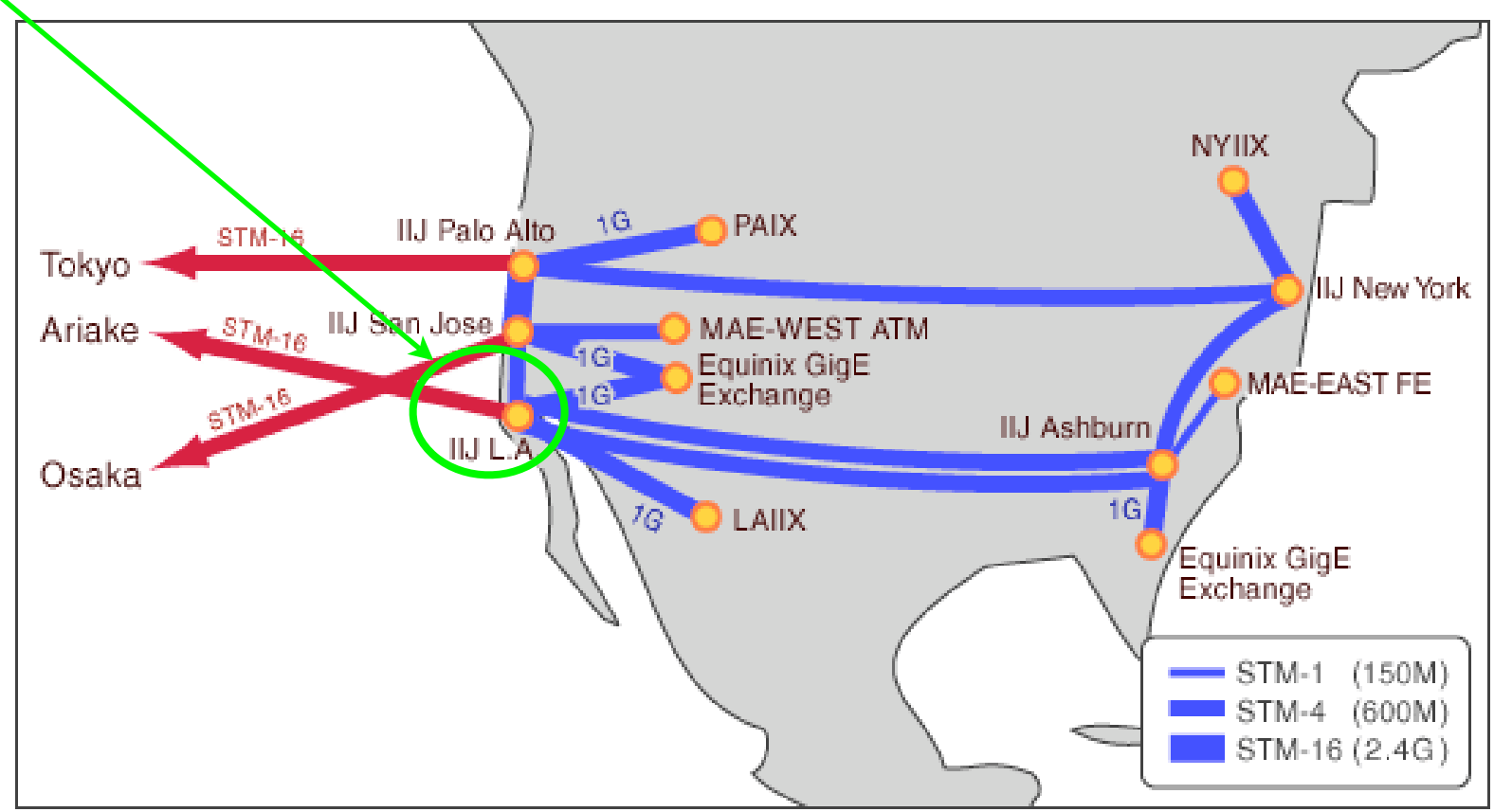
Getting to Sony

```
% traceroute irt1-ge1-1.tdc.noc.sony.co.jp
traceroute to irt1-ge1-1.tdc.noc.sony.co.jp (211.125.132.198), 30 hops max, 40
 1  soda3a-gw.eecs.berkeley.edu (128.32.34.1)  20.581 ms  0.875 ms  1.381 ms
 2  soda-cr-1-1-soda-br-6-2.eecs.berkeley.edu (169.229.59.225)  1.354 ms  3.097
 3  vlan242.inr-202-doecev.berkeley.edu (128.32.255.169)  1.753 ms  1.454 ms  1
 4  ge-1-3-0.inr-001-eva.berkeley.edu (128.32.0.34)  1.746 ms  1.174 ms  2.22 r
 5  svl-dc1--ucb-egm.cenic.net (137.164.23.65)  2.653 ms  2.72 ms  12.031 ms
 6  dc-svl-dc2--svl-dc1-df-iconn-2.cenic.net (137.164.22.209)  2.478 ms  2.451
 7  dc-sol-dc1--svl-dc1-pos.cenic.net (137.164.22.28)  4.509 ms  95.013 ms  7.7
 8  dc-sol-dc2--sol-dc1-df-iconn-1.cenic.net (137.164.22.211)  18.319 ms  4.324
 9  dc-slo-dc1--sol-dc2-pos.cenic.net (137.164.22.26)  19.403 ms  10.077 ms  13
10  dc-slo-dc2--dc1-df-iconn-1.cenic.net (137.164.22.123)  8.049 ms  20.653 ms
11  dc-lax-dc1--slo-dc2-pos.cenic.net (137.164.22.24)  94.579 ms  14.52 ms  21.
12  rtrisi.ultradns.net (198.32.146.38)  25.48 ms  12.432 ms  17.837 ms
13  lax001bb00.iij.net (216.98.96.176)  11.623 ms  25.698 ms  11.382 ms
14  tky002bb01.iij.net (216.98.96.178)  168.082 ms  196.26 ms  121.914 ms
15  tky002bb00.iij.net (202.232.0.149)  144.592 ms  208.622 ms  121.801 ms
16  tky001bb01.iij.net (202.232.0.70)  153.757 ms  110.29 ms  184.985 ms
17  tky001ip30.iij.net (210.130.130.100)  114.234 ms  110.095 ms  169.692 ms
18  210.138.131.198 (210.138.131.198)  113.893 ms  113.665 ms  114.22 ms
19  ert1-ge000.tdc.noc.ssd.ad.jp (211.125.132.69)  114.758 ms  138.327 ms  113.
20  211.125.133.86 (211.125.133.86)  113.956 ms  113.73 ms  113.965 ms
21  irt1-ge1-1.tdc.noc.sony.co.jp (211.125.132.198)  145.247 ms *  136.884 ms
```

Cross ocean in 1 hop - link about 175 ms round-trip

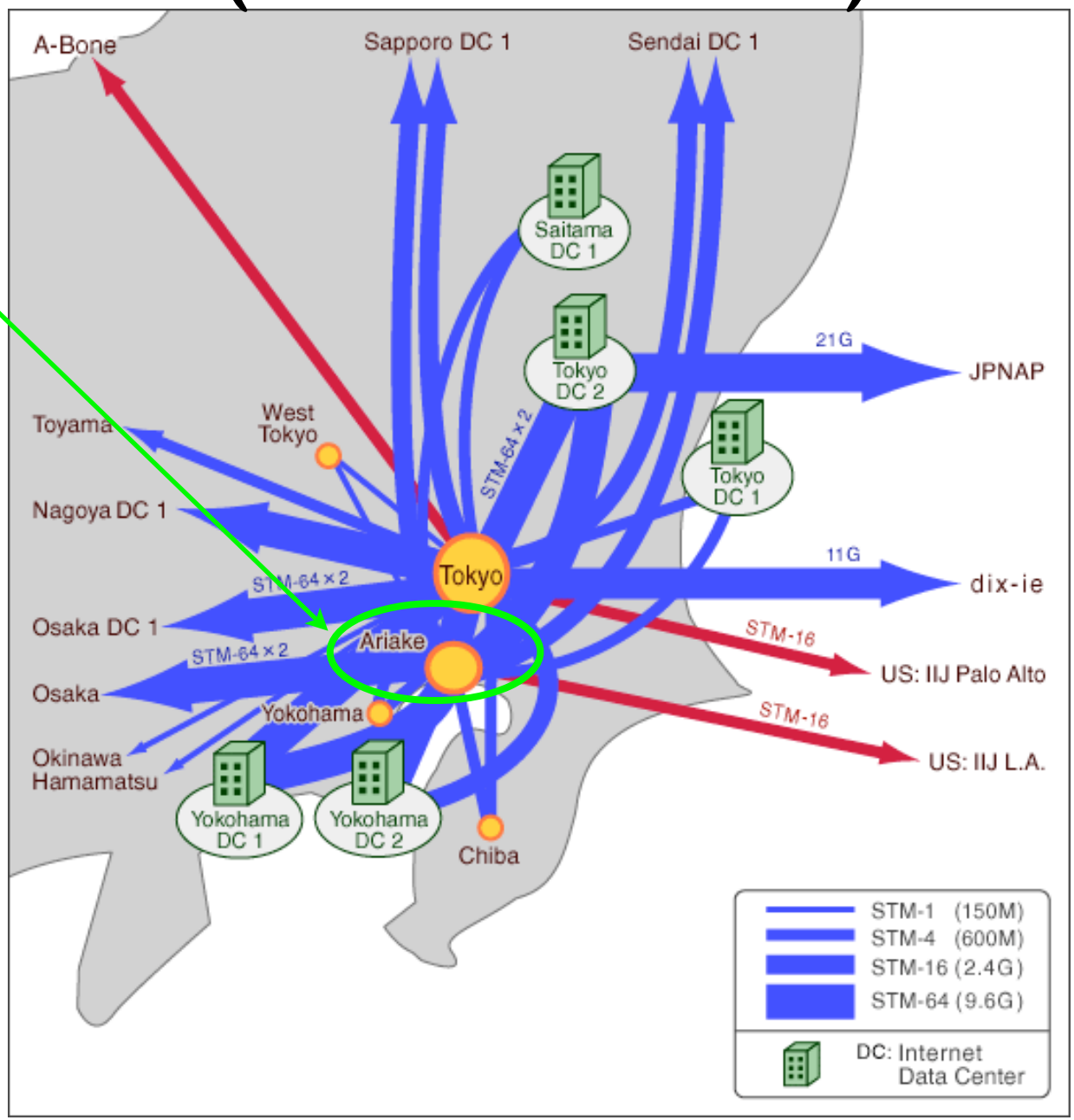
Left on Internet Initiative Japan (IIJ) in LA

```
lax001bb00.iij.net (216.98.96.176)
```



Arrived IIJ in Ariake

```
tky002bb01.iij.net (216.98.96.178)
```



A-to-B packet path may differ from B-to-A

Different paths: Different network properties (latency, bandwidth, etc)

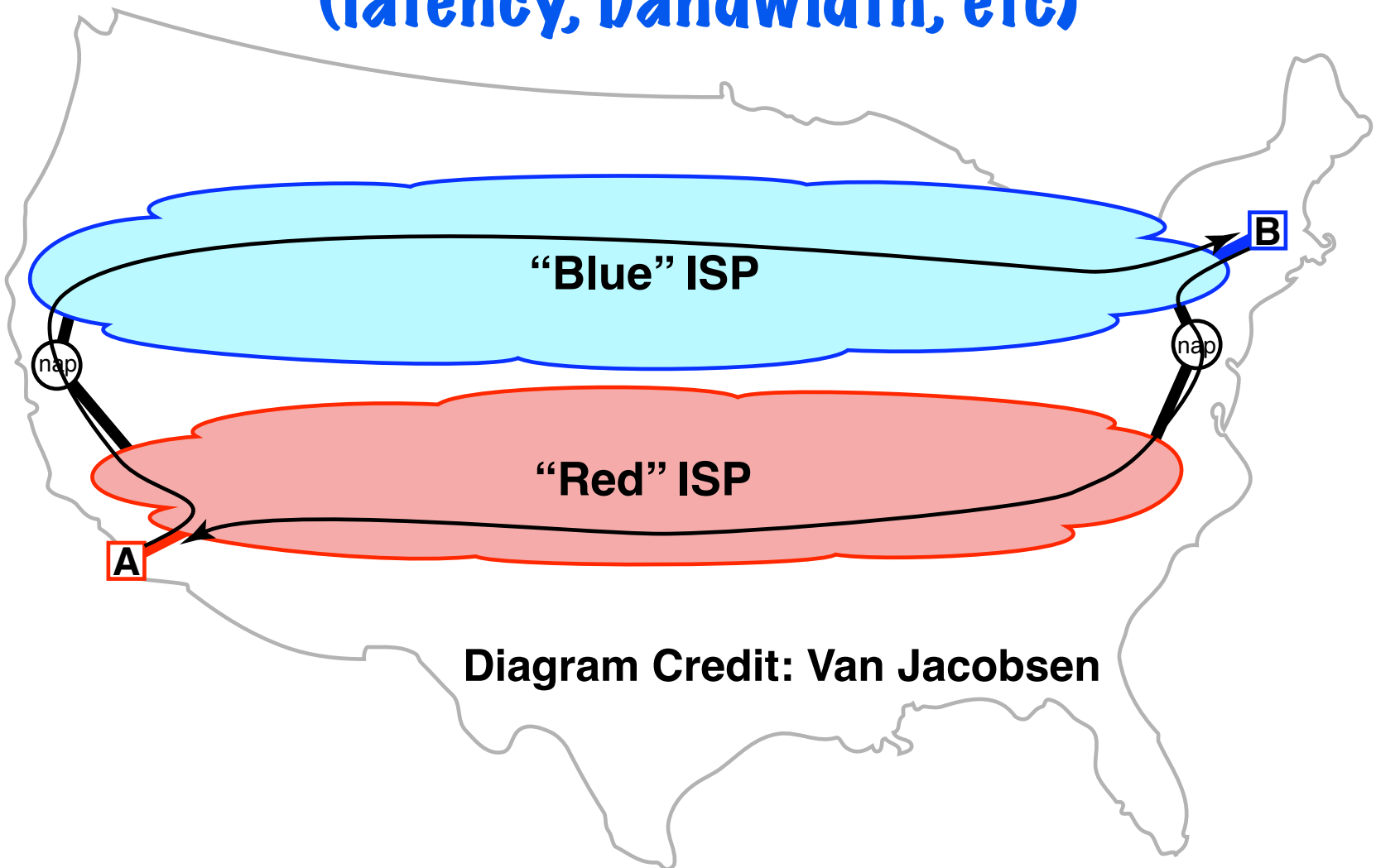


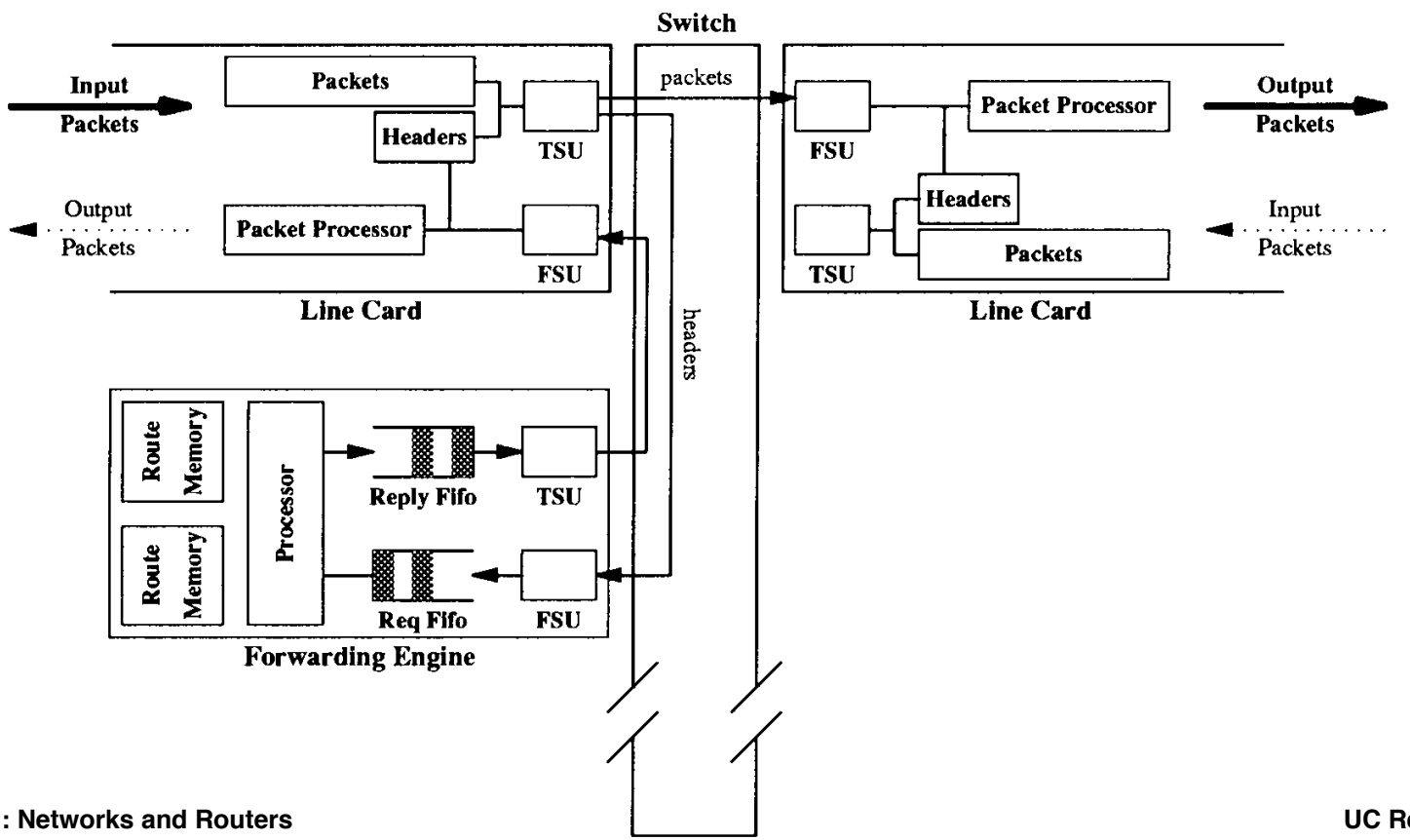
Diagram Credit: Van Jacobsen

Economics: A and B use different network carriers … carriers route data onto their networks ASAP.

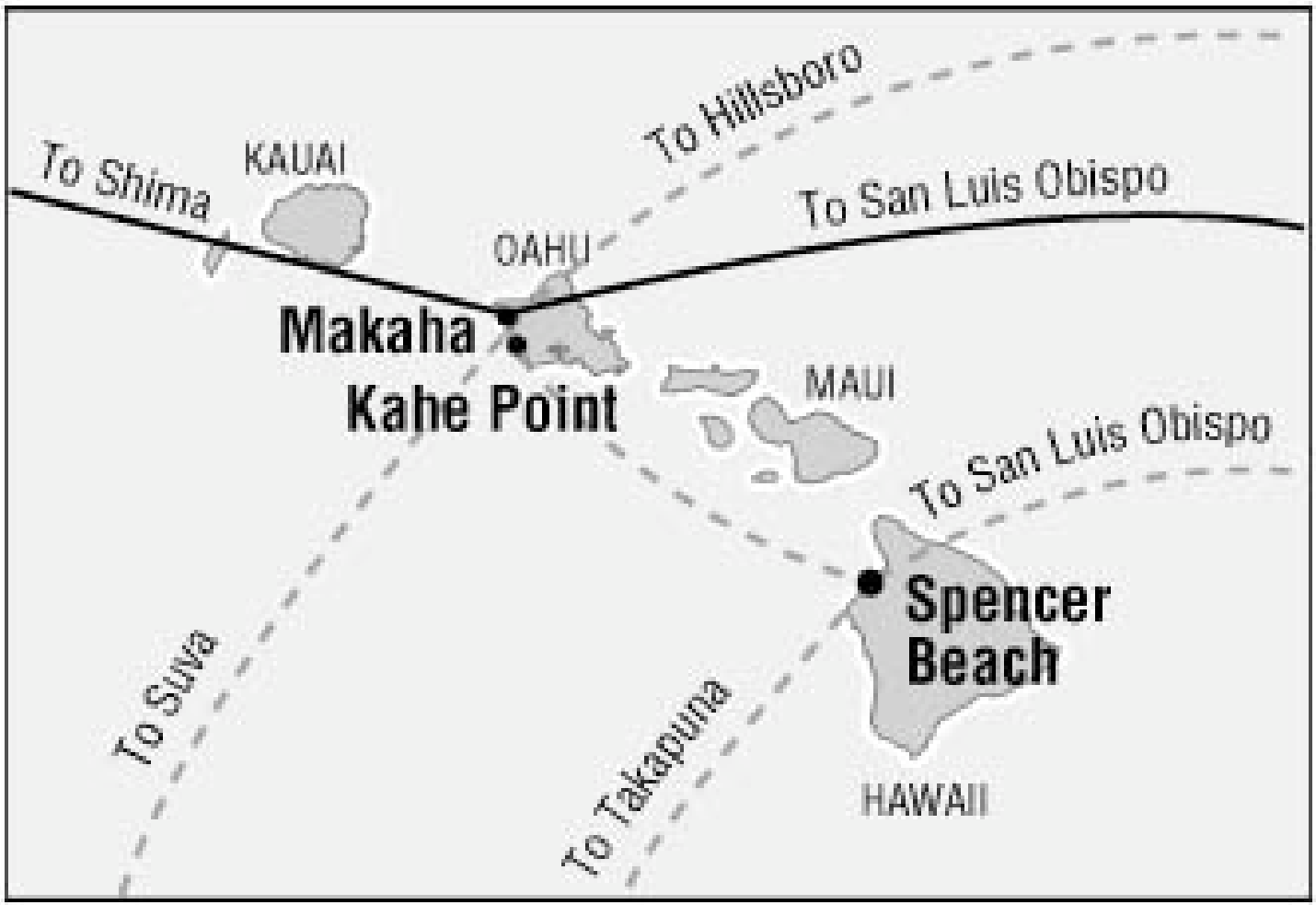
A 50-Gb/s IP Router

Craig Partridge, *Senior Member, IEEE*, Philip P. Carvey, *Member, IEEE*, Ed Burgess, Isidro Castineyra, Tom Clarke, Lise Graham, Michael Hathaway, Phil Herman, Allen King, Steve Kohalmi, Tracy Ma, John Mcallen, Trevor Mendez, Walter C. Milliken, *Member, IEEE*, Ronald Pettyjohn, *Member, IEEE*, John Rokosz, *Member, IEEE*, Joshua Seeger, Michael Sollins, Steve Storch, Benjamin Tober, Gregory D. Troxel, David Waitzman, and Scott Winterble

How to Design a Router



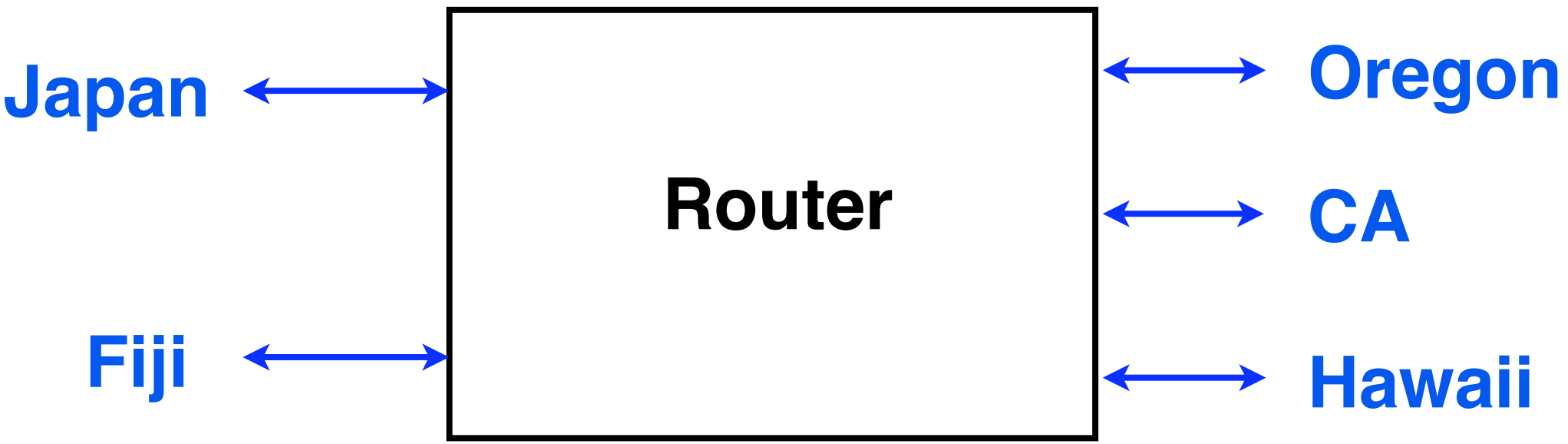
Recall: Routers are like hub airports



In Makaha, a router takes each Layer 2 packet off the San Luis Obispo (CA) cable, examines the IP packet destination field, and forwards to Japan cable, Fiji cable, or to Kahe Point (and onto big island cables).

The Oahu router ...

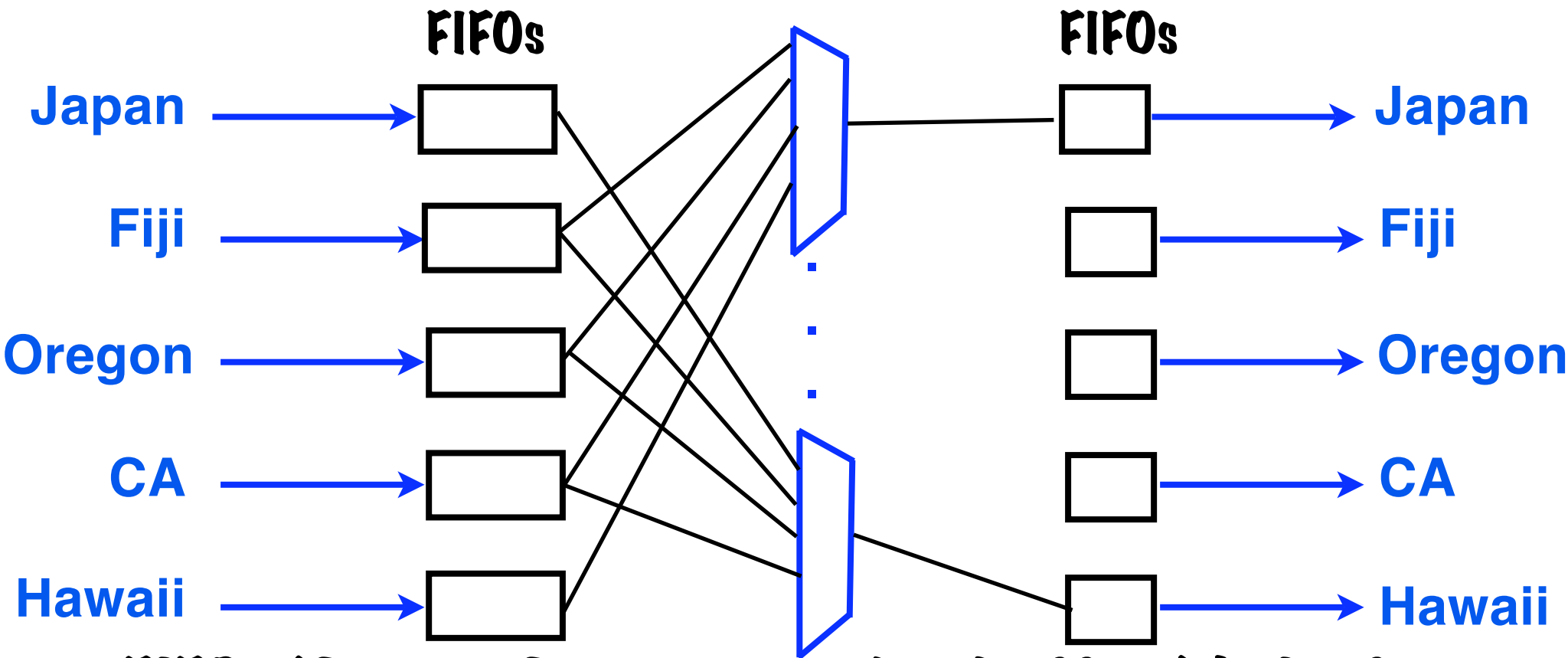
Assume each "line" is 160 Gbits/sec each way.



IP packets are forwarded from each inbound Layer 2 line to one of the four outbound Layer 2 lines, based on the destination IP number in the IP packet.

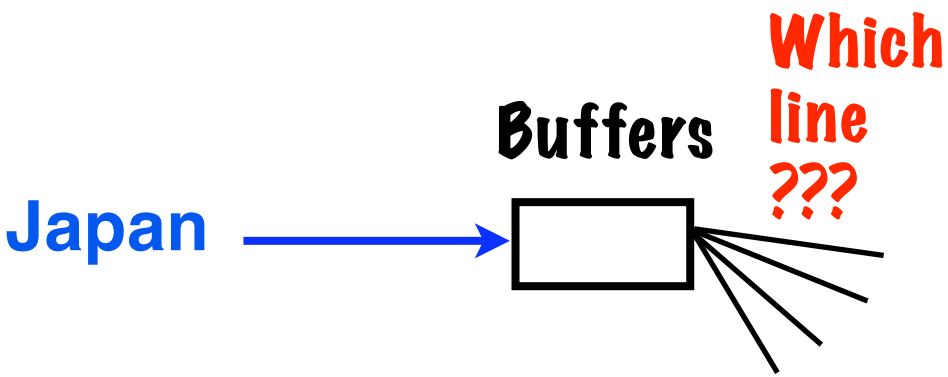
Challenge 1: Switching bandwidth

At line rate: 5*160 Gb/s = 100 GB/s switch!
Latency not an issue ... wide, slow bus OK.



FIFOs (first-in first-out packet buffers) help if an output is sent more bits than it can transmit. If buffers "overflow", packets are discarded.

Challenge 2: Packet forwarding speed



For each packet delivered by each inbound line, the router must decide which outbound line to forward it to. Also, update IP header.

Line rate: 160 Gb/s

Average packet size: 400 bits

Packets per second per line: 400 Million

Packets per second (5 lines): 2 Billion

Thankfully, this is trivial to parallelize ...

Challenge 3: Obeying the routing "ISA"

Network Working Group
Request for Comments: 1812
Obsoletes: 1716, 1009
Category: Standards Track

F. Baker, Editor
Cisco Systems
June 1995

Requirements for IP Version 4 Routers

Internet Engineering Task Force (IETF) "Request for Comments" (RFC) memos act as the "Instruction Set Architecture" for routers.

RFC 1812 (above) is 175 pages, and has 100 references which also define rules …

The MGR Router: A case study ...

A 50-Gb/s IP Router

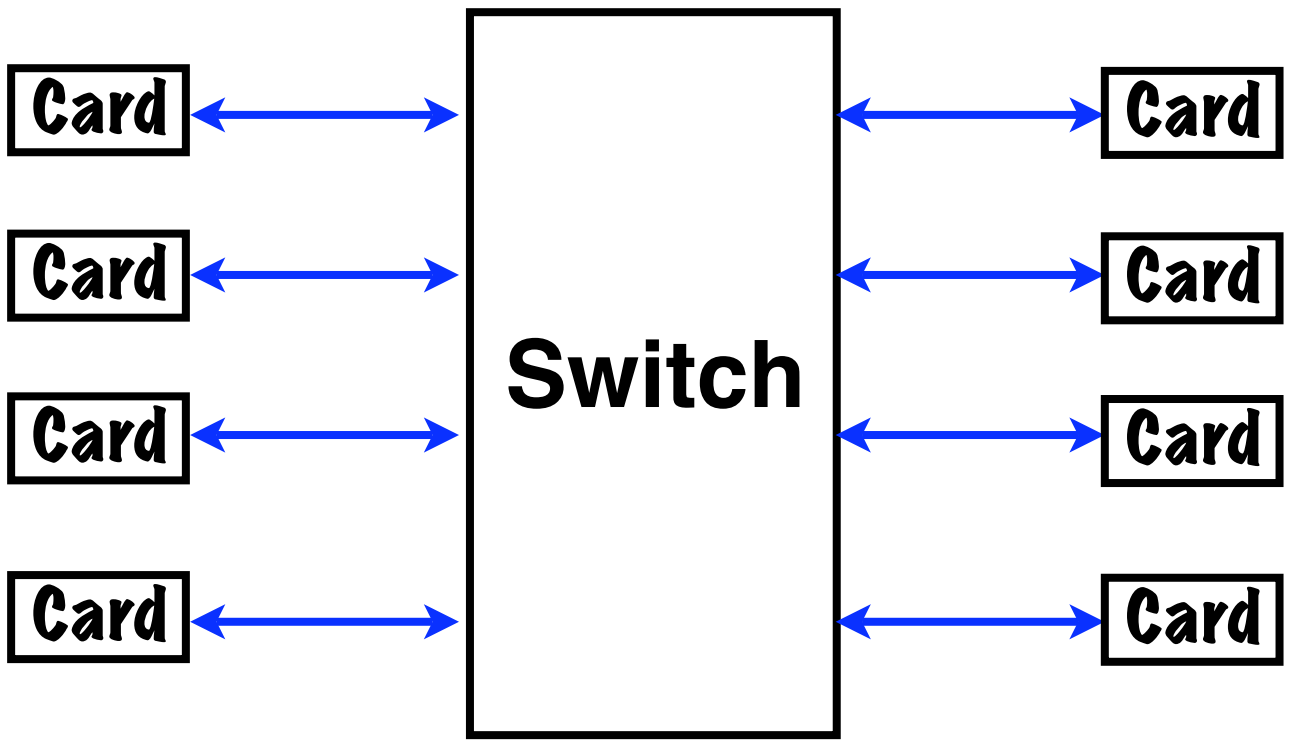
Craig Partridge, *Senior Member, IEEE*, Philip P. Carvey, *Member, IEEE*, Ed Burgess, Isidro Castineyra, Tom Clarke, Lise Graham, Michael Hathaway, Phil Herman, Allen King, Steve Kohalmi, Tracy Ma, John Mcallen, Trevor Mendez, Walter C. Milliken, *Member, IEEE*, Ronald Pettyjohn, *Member, IEEE*, John Rokosz, *Member, IEEE*, Joshua Seeger, Michael Sollins, Steve Storch, Benjamin Tober, Gregory D. Troxel, David Waitzman, and Scott Winterble

The "MGR" Router was a research project in late 1990's. Kept up with "line rate" of the fastest links of its day (OC-48c, 24 Gb/s optical).

Architectural approach is still valid today ...

MGR top-level architecture

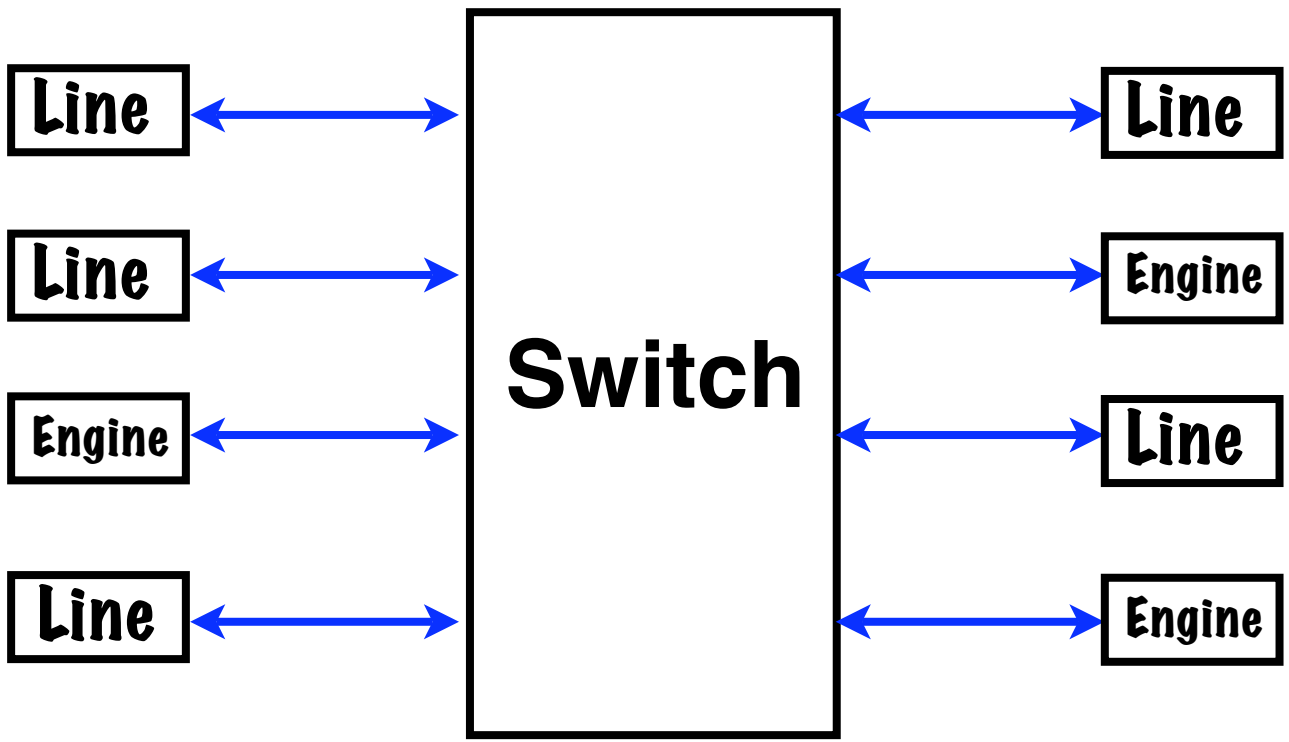
A 50 Gb/s switch is the centerpiece of the design. Cards plug into the switch.



In best case, on each switch "epoch" (transaction), each card can send and receive 1024 bits to/from one other card.

MGR cards come in two flavors ....

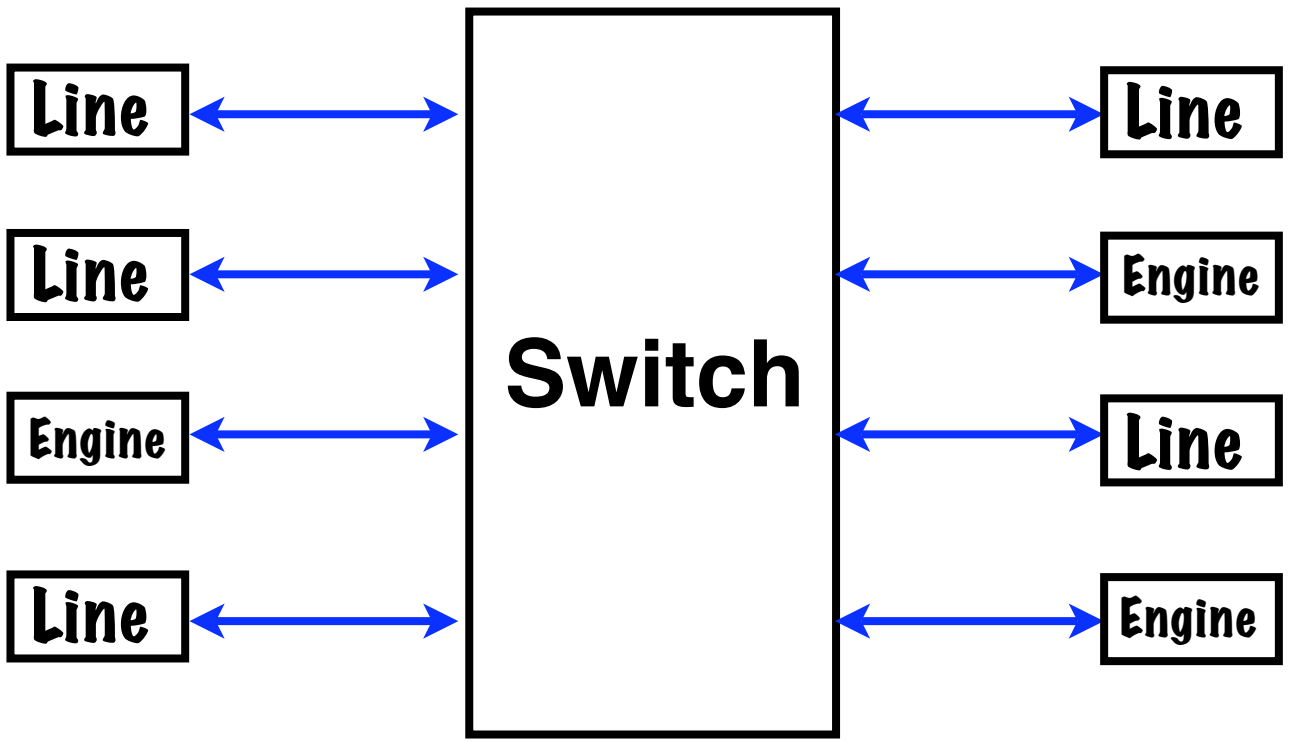
Line card: A card that connects to Layer 2 line. Different version of card for each Layer 2 type.



Forwarding engine: Receives IP headers over the switch from line cards, and returns forwarding directions and modified headers to line card.

A control processor for housekeeping

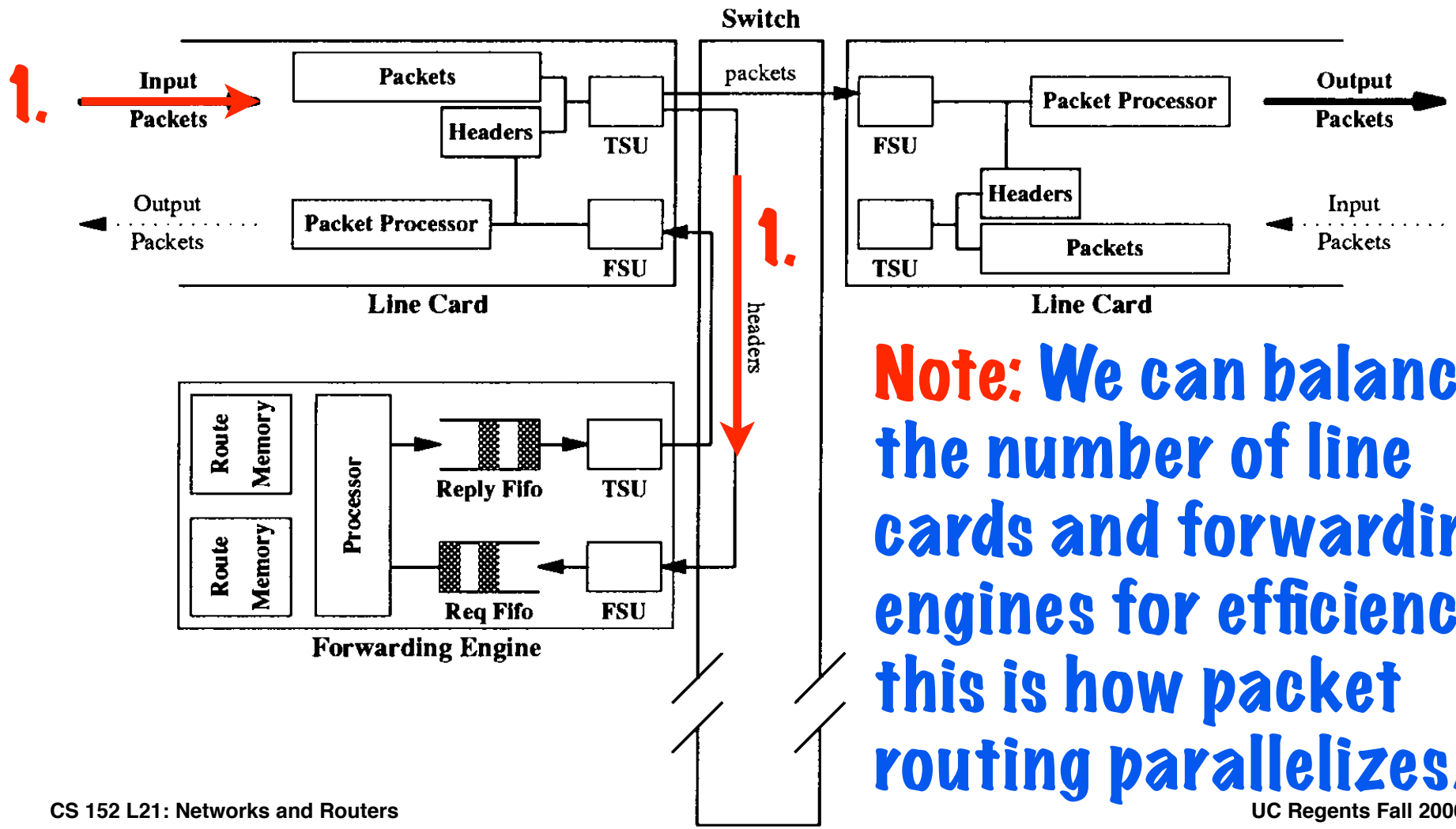
Forwarding engine handles fast path: the "common case" of unicast packets w/o options. Unusual packets are sent to the control processor.



Control processor

The life of a packet in a router ...

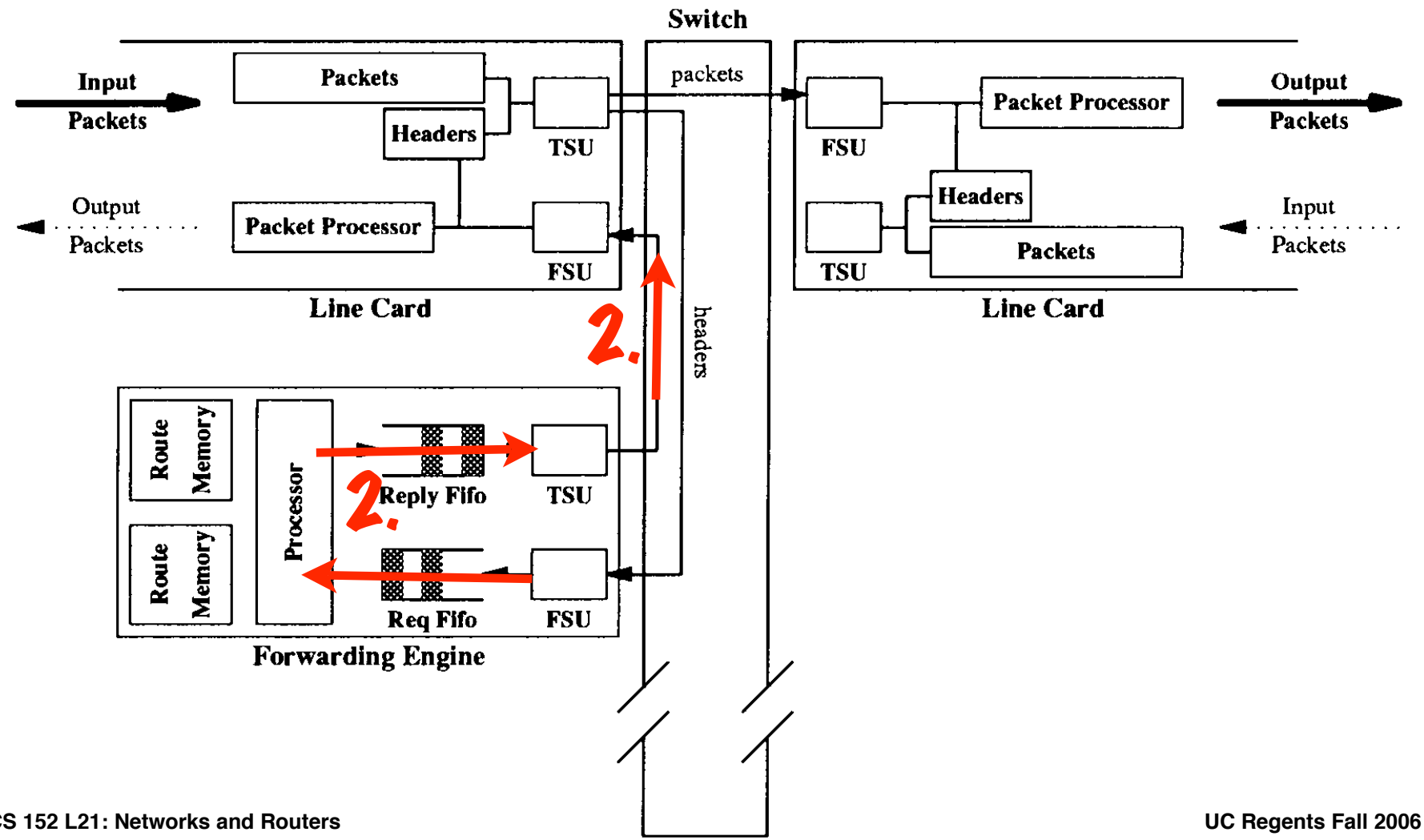
1. Packet arrives in line card. Line card sends the packet header to a forwarding engine for processing.



Note: We can balance the number of line cards and forwarding engines for efficiency: this is how packet routing parallelizes.

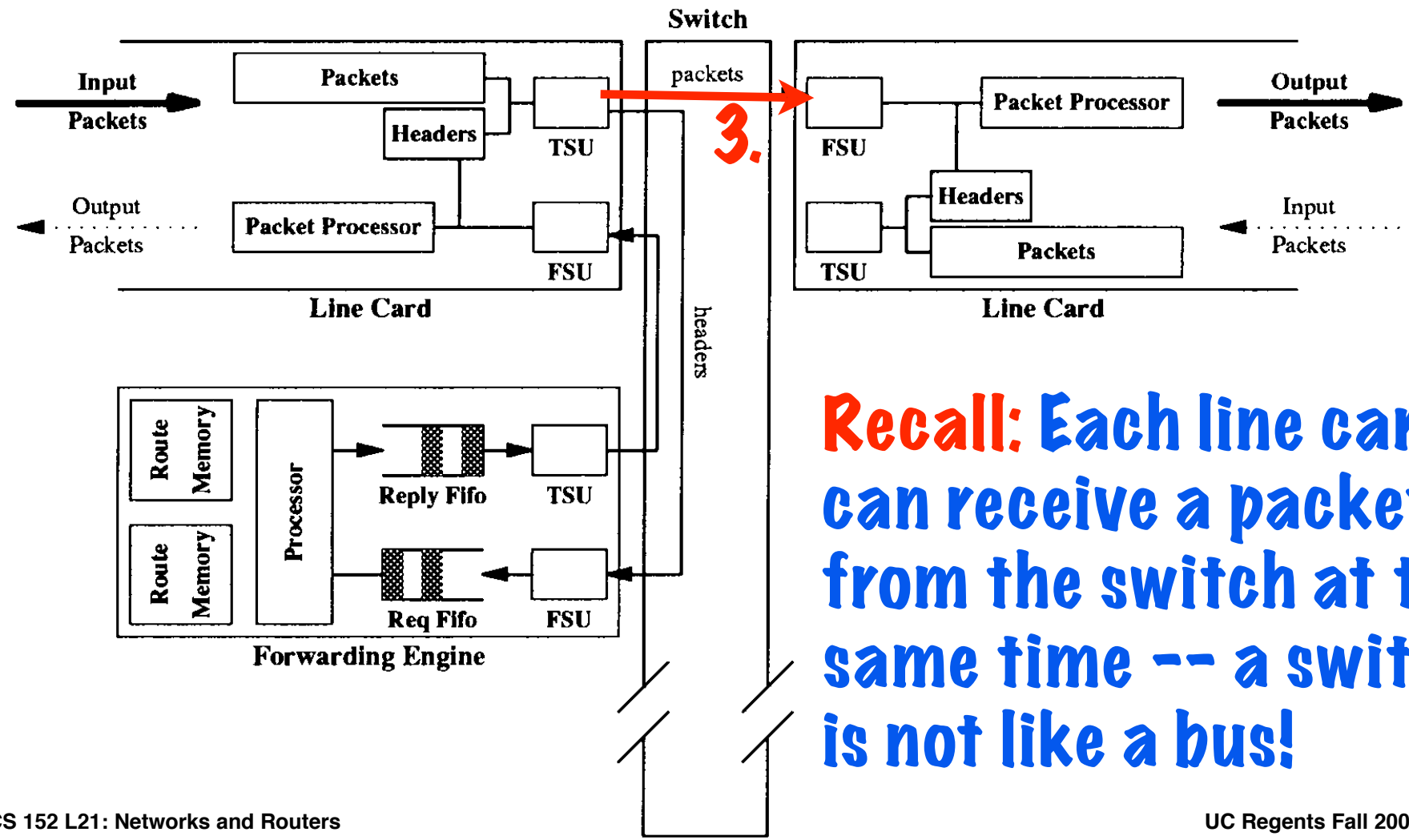
The life of a packet in a router ...

2. Forwarding engine determines the next hop for the packet, and returns next-hop data to the line card, together with an updated header.



The life of a packet in a router ...

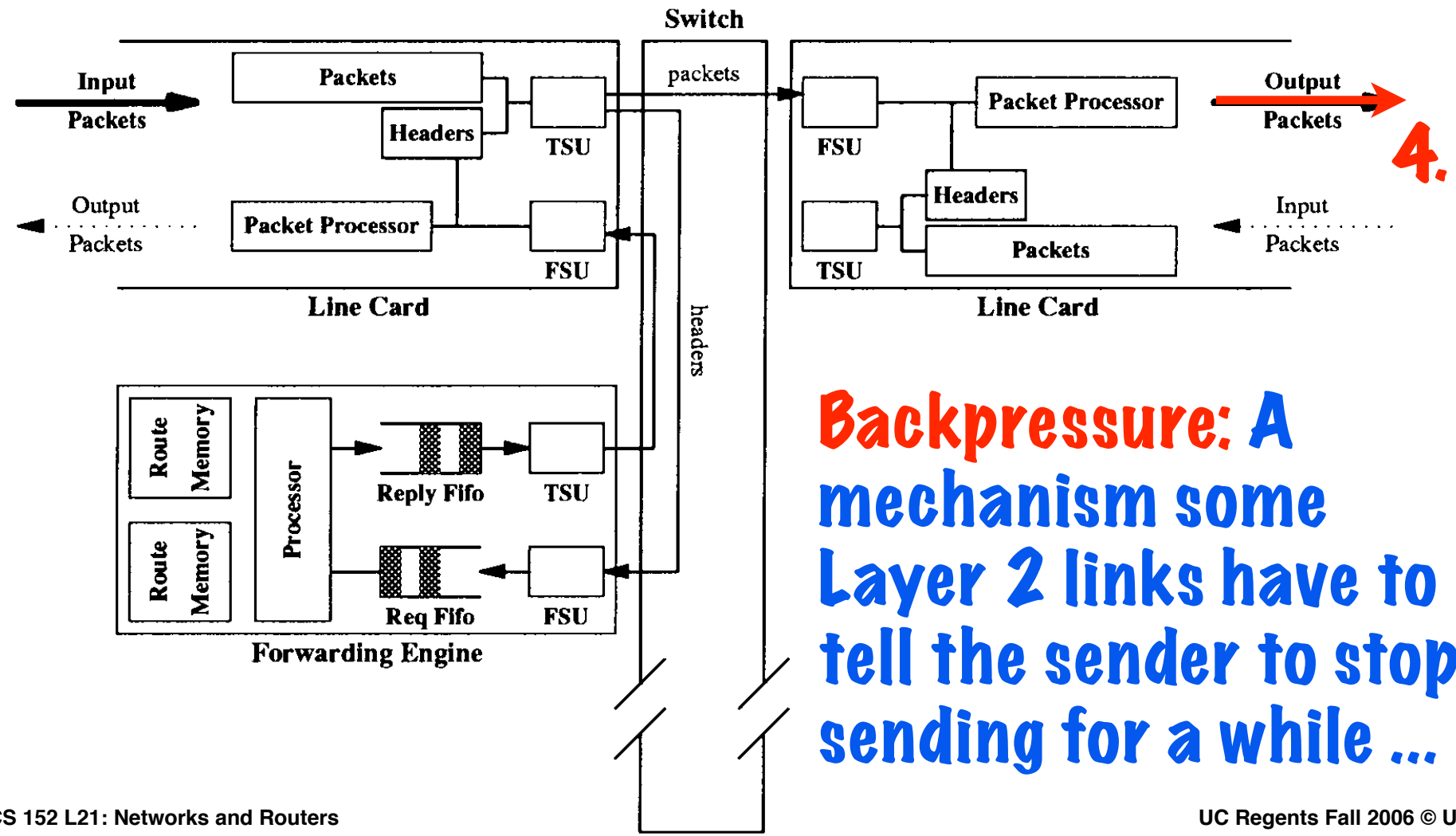
3. Line card uses forwarding information, and sends the packet to another line card via the switch.



Recall: Each line card can receive a packet from the switch at the same time -- a switch is not like a bus!

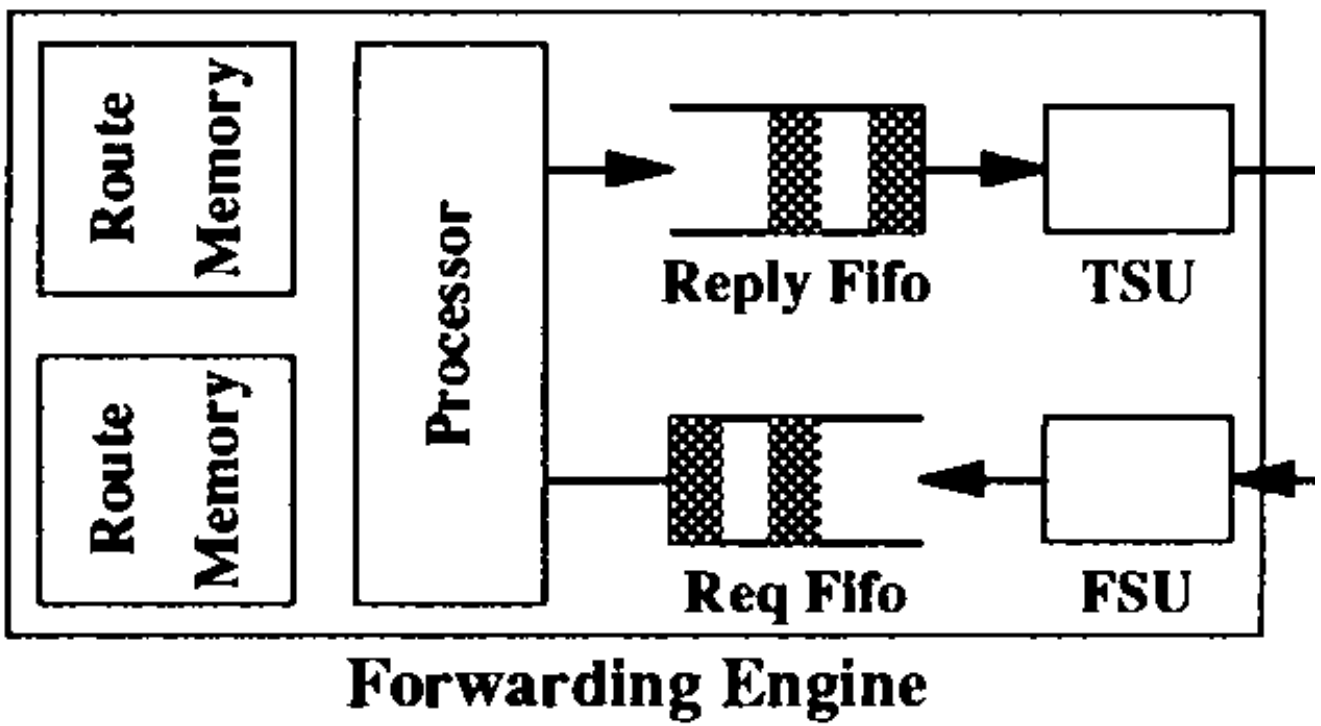
The life of a packet in a router ...

4. Outbound line card sends packet on its way ...

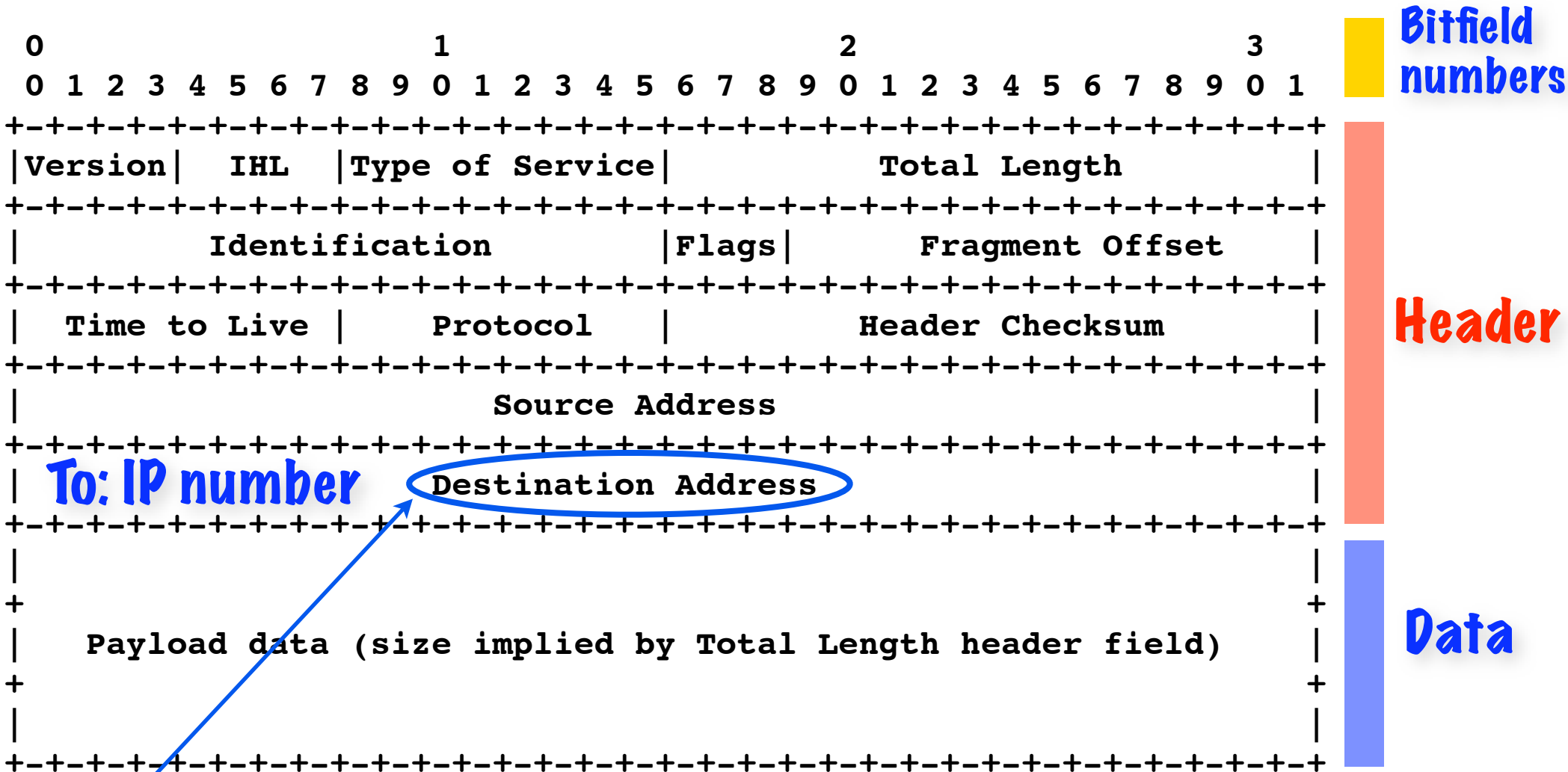


Backpressure: A mechanism some Layer 2 links have to tell the sender to stop sending for a while ...

Packet Forwarding



Forwarding engine computes "next-hop"

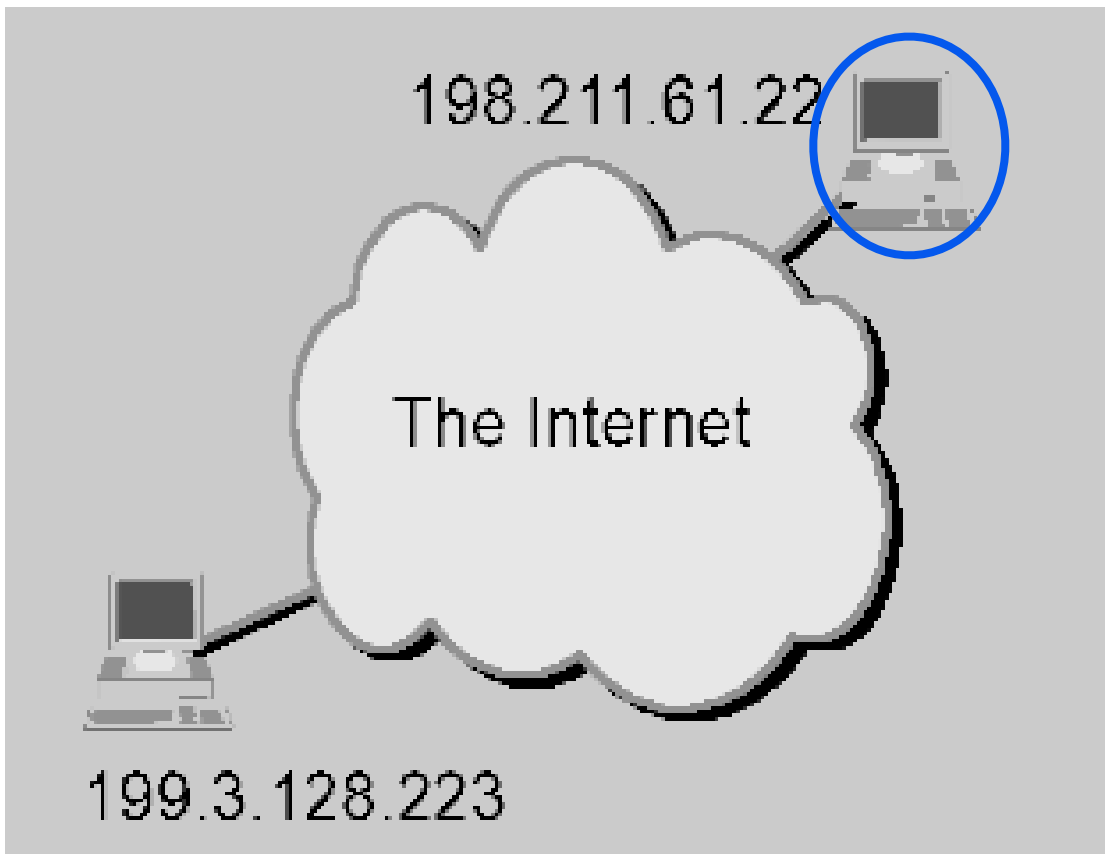


Forwarding engine looks at the destination address, and decides which outbound line card will get the packet closest to its destination. How?

Recall: Internet IP numbers ...

IP4 number for this computer: 198.211.61.22

198.211.61.22 == 3335732502 (32-bit unsigned)



Every directly connected host has a unique IP number.

Upper limit of 2^32 IP4 numbers (some are reserved for other purposes).

BGP: A Border Gateway Protocol

Routers use BGP to exchange routing tables. Tables code if it is possible to reach an IP number from the router, and if so, how "desirable" it is to take that route.

Network Working Group — Y. Rekhter
Request for Comments: 1771 — T.J. Watson Research Center, IBM Corp.
Obsoletes: 1654 — T. Li
Category: Standards Track — cisco Systems
Editors
March 1995

A Border Gateway Protocol 4 (BGP-4)

Routers use BGP tables to construct a "next-hop" table. Conceptually, forwarding is a table lookup: IP number as index, table holds outbound line card.

A table with 4 billion entries ???

Tables do not code every host ...

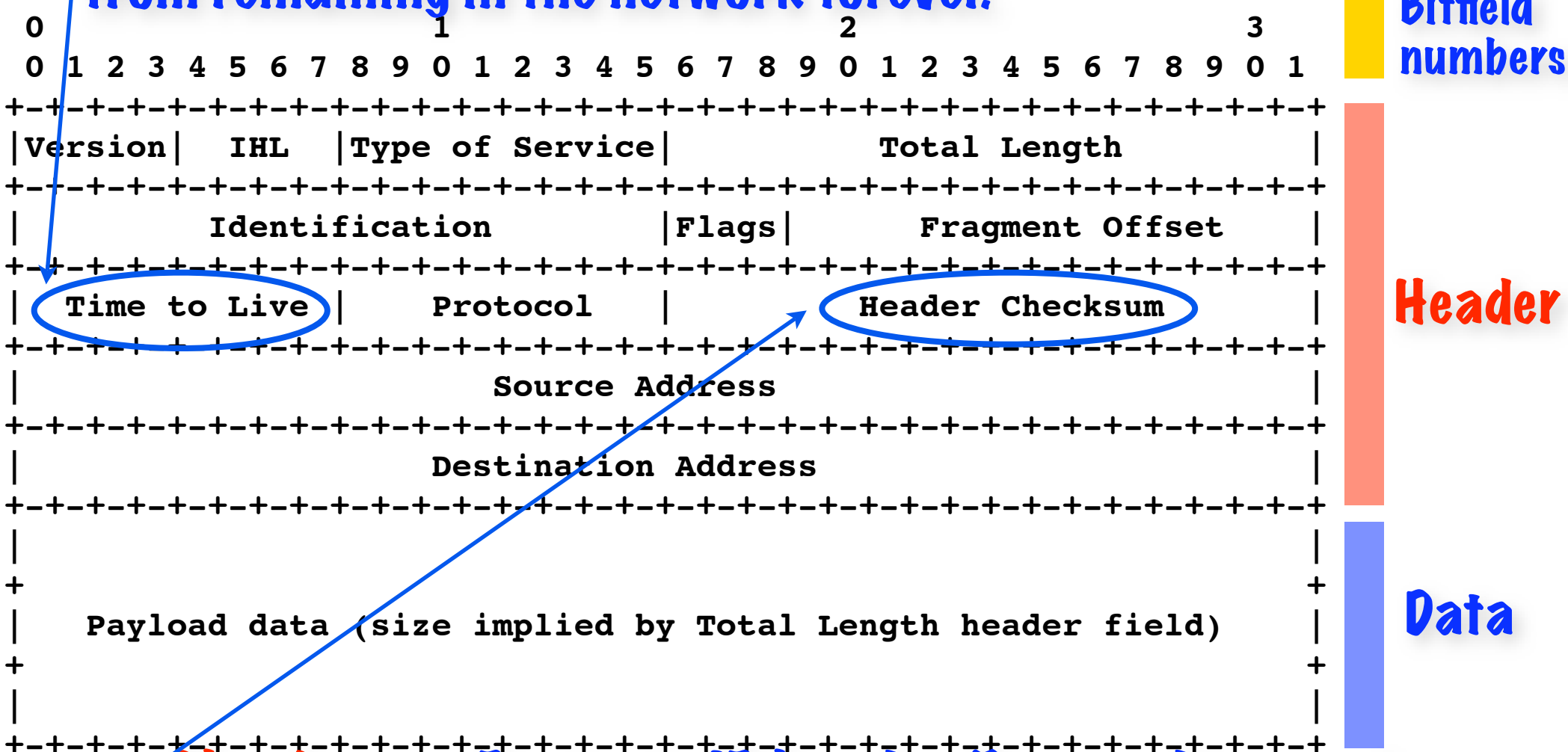
Routers route to a "network", not a "host". /xx means the top xx bits of the 32-bit address identify a single network.

Network	IP Address Range		Comment
	From:	To:	
128.32.0.0/16	128.32.0.0	128.32.255.255	UCB Local Area Networks *
136.152.0.0/16	136.152.0.0	136.152.255.255	UCB Local Area Networks and Home IP Service #
169.229.0.0/16	169.229.0.0	169.229.255.255	UCB Local Area Networks
131.243.52.0/24	131.243.52.0	131.243.52.255	UCB Melvin Calvin Lab. building
192.101.42.0/24	192.101.42.0	192.101.42.255	UCB Local Area Networks
199.133.139.0/24	199.133.139.0	199.133.139.255	USDA/UCB Joint Local Area Network

Thus, all of UCB only needs 6 routing table entries.
Today, Internet routing table has about 100,000 entries.

Forwarding engine: Also updates header

Time to live. Sender sets to a high value. Each router decrements it by one, discards if 0. Prevents a packet from remaining in the network forever.

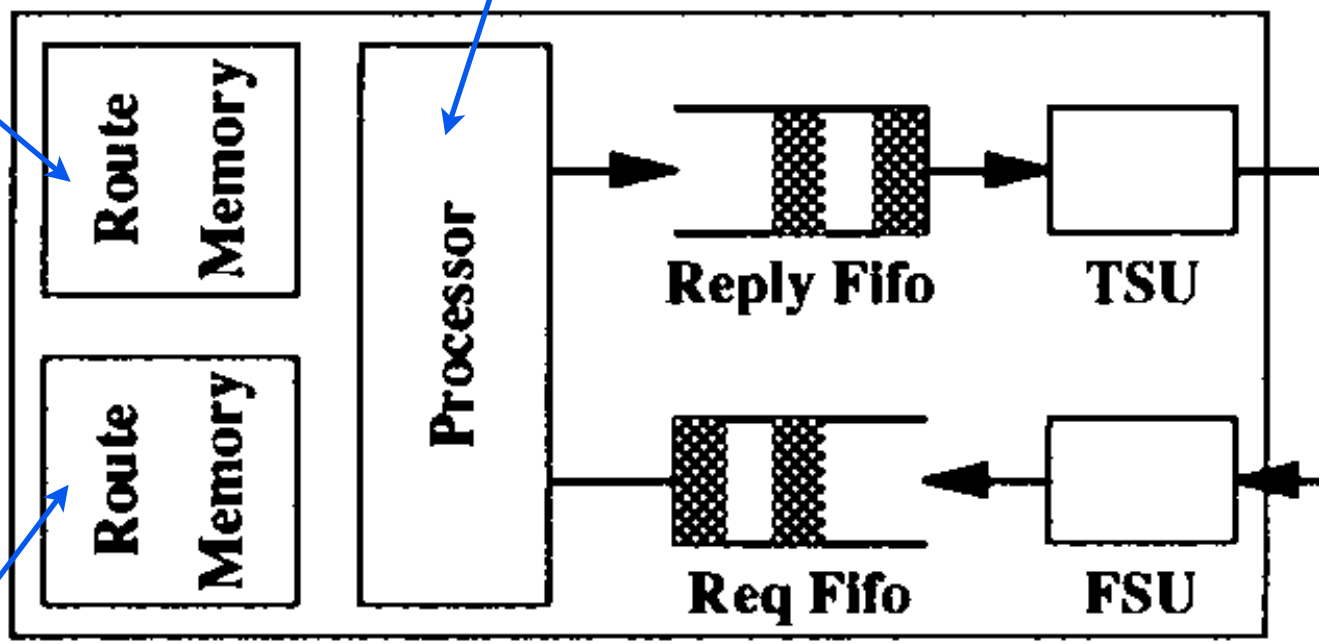


Checksum. Protects IP header. Forwarding engine updates it to reflect the new Time to Live value.

MGR forwarding engine: a RISC CPU

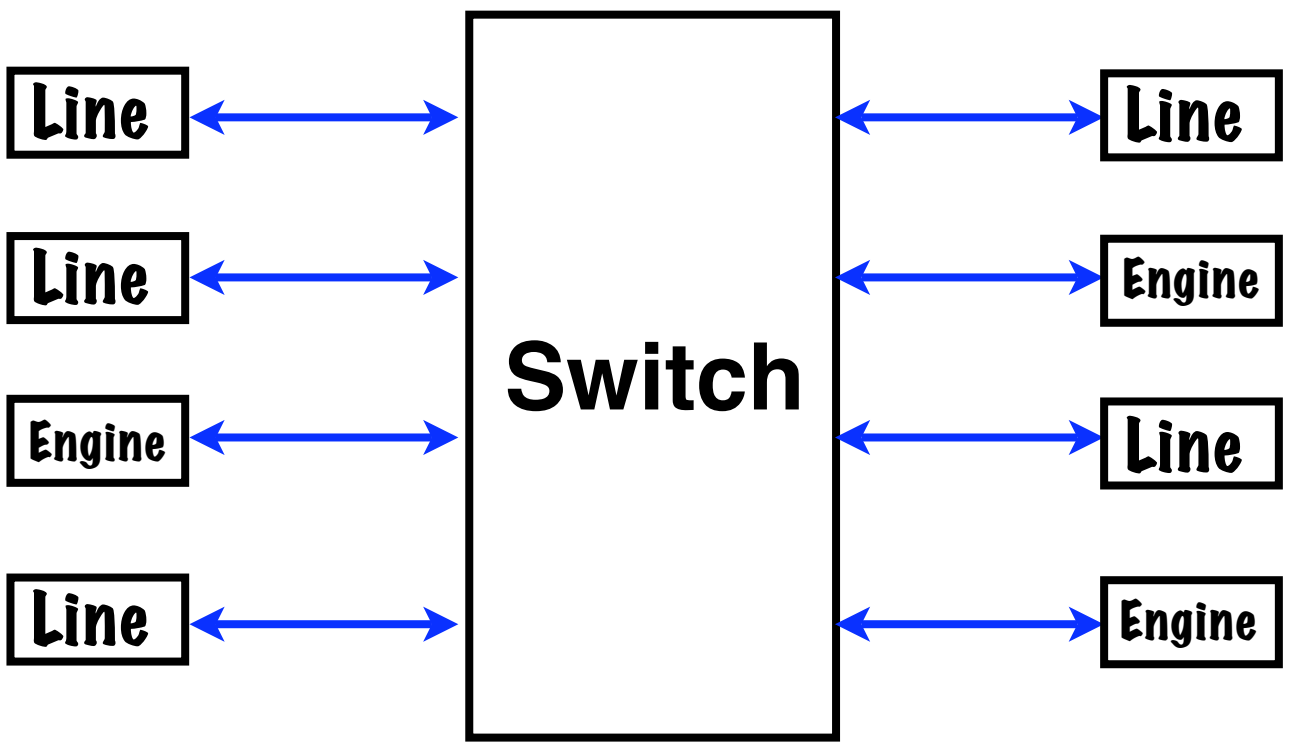
Off-chip memory in two 8MB banks: one holds the current routing table, the other is being written by the router's control processor with an updated routing table. Why??? So that the router can switch to a new table without packet loss.

85 instructions in "fast path", executes in about 42 cycles. Fits in 8KB I-cache

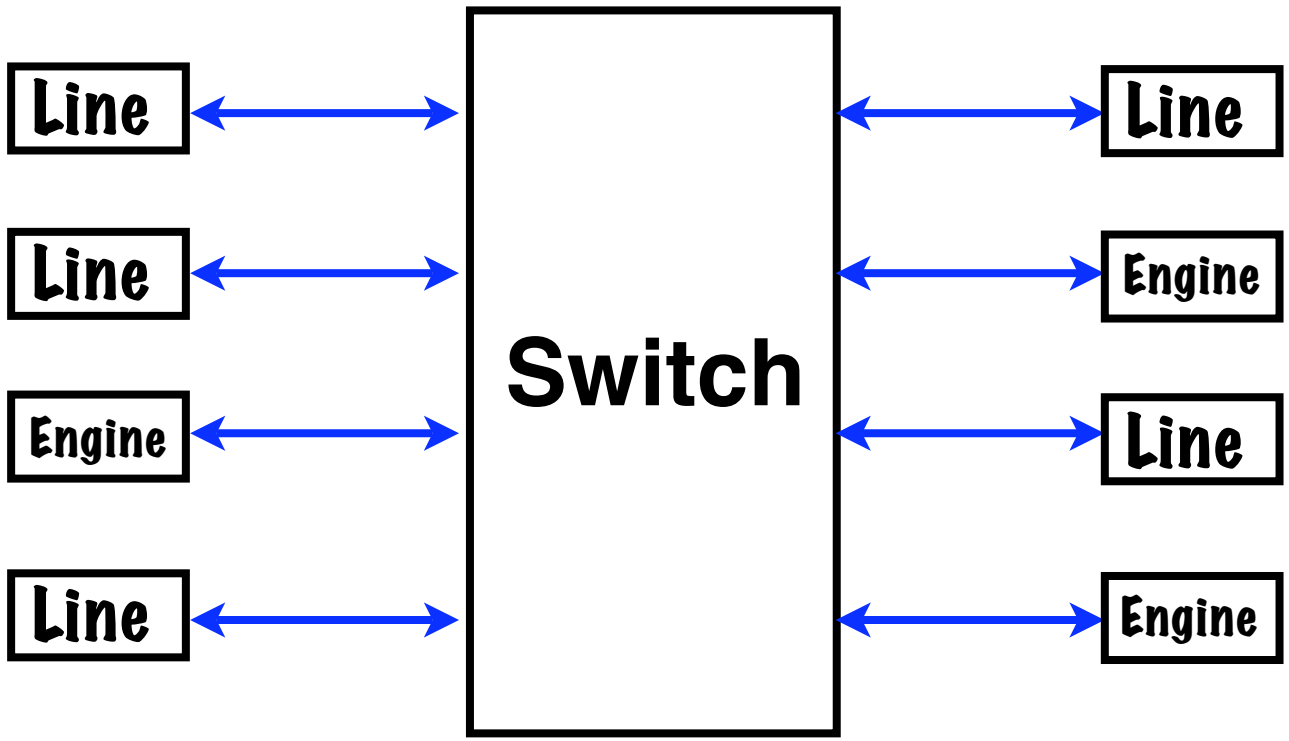


Performance: 9.8 million packet forwards per second. To handle more packets, add forwarding engines. Or use a special-purpose CPU.

Switch Architecture



What if two inputs want the same output?



A pipelined arbitration system decides how to connect up the switch. The connections for the transfer at epoch N are computed in epochs N-3, N-2 and N-1, using dedicated switch allocation wires.

A complete switch transfer (4 epochs)

- **Epoch 1:** All input ports (that are ready to send data) request an output port.
- **Epoch 2:** Allocation algorithm decides which inputs get to write.
- **Epoch 3:** Allocation system informs the winning inputs and outputs.
- **Epoch 4:** Actual data transfer takes place.

Allocation is pipelined: a data transfer happens on every cycle, as does the three allocation stages, for different sets of requests.

Epoch 3: The Allocation Problem

Output Ports (A, B, C, D)

Input Ports (A, B, C, D)

	A	B	C	D
A	0	0	1	0
B	1	0	0	1
C	0	1	0	0
D	1	0	1	0

A 1 codes that an input has a packet ready to send to an output. Note an input may have several packets ready.

Allocator returns a matrix with one 1 in each row and column to set switches. Algorithm should be "fair", so no port always loses ... should also "scale" to run large matrices fast.

	A	B	C	D
A	0	0	1	0
B	0	0	0	1
C	0	1	0	0
D	1	0	0	0

"Best-effort" and Routers

Network Working Group
Request for Comments: 1812
Obsoletes: 1716, 1009
Category: Standards Track

F. Baker, Editor
Cisco Systems
June 1995

Requirements for IP Version 4 Routers

Recall: The IP "non-ideal" abstraction

- A sent packet may never arrive ("lost")

Router drops packets if too much traffic destined for one port, or if Time to Live hits 0, or checksum failure.

- If packets sent P1/P2/P3, they may arrive P2/P1/P3 ("out of order").
- Relative timing of packet stream not necessarily preserved ("late" packets).

This happens when the packet's header forces the forwarding processor out of the "fast path", etc.

- IP payload bits received may not match payload bits sent.

Usually happens "on the wire", not in router.

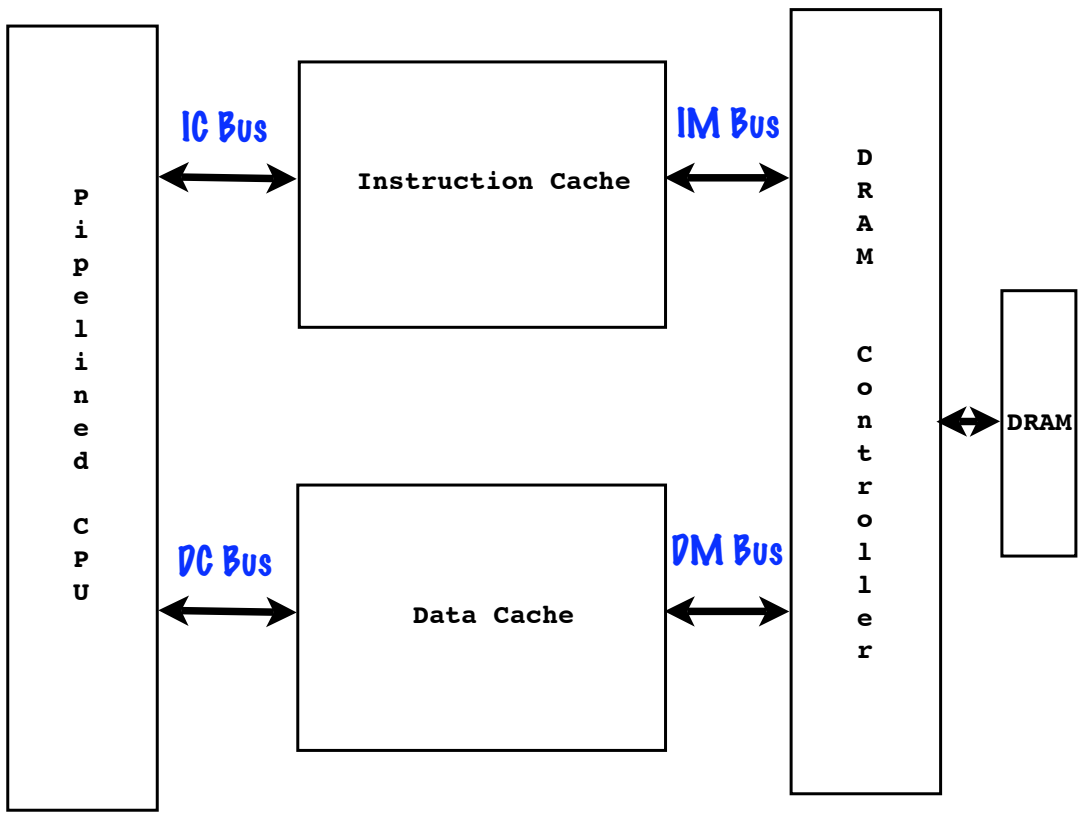
Conclusions: Router Design

- **Router architecture:** The "ISA" for routing was written with failure in mind -- unlike CPUs.
- **Forwarding engine:** The computational bottleneck, many startups target silicon to improve it.
- **Switch fabric:** Switch fabrics have high latency, but that's OK: routing is more about bandwidth than latency.

Reminder: No Checkoff this Friday!

F 11/17				Final Project: Final Checkoff, 12-2PM or 3-5PM, 125 Cory

Final checkoff the following Friday …



TAs will provide "secret" MIPS machine code tests.

Bonus points if these tests run by end of section. If not, TAs give you test code to use over weekend

Final report due following Monday, 11:59 PM