CS162: Operating Systems and Systems Programming

Lecture 20: Networking: TCP/IP (finish), RPC (start?)

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Charles Reiss

https://cs162.eecs.berkeley.edu/

Recall: Sockets

Abstraction of network I/O interface

- **Bidirectional** communication channel
- Uses **file** interface once established
  - read, write, close

Server setup:

- socket(), bind(), listen(), accept()
- read, write, close from socket returned by accept

Client setup:

- socket(), connect()
- then read, write, close

getaddrinfo() to resolve names, addresses for bind() and connect()

Recall: Layering

Complex services from simpler ones

TCP/IP networking layers:

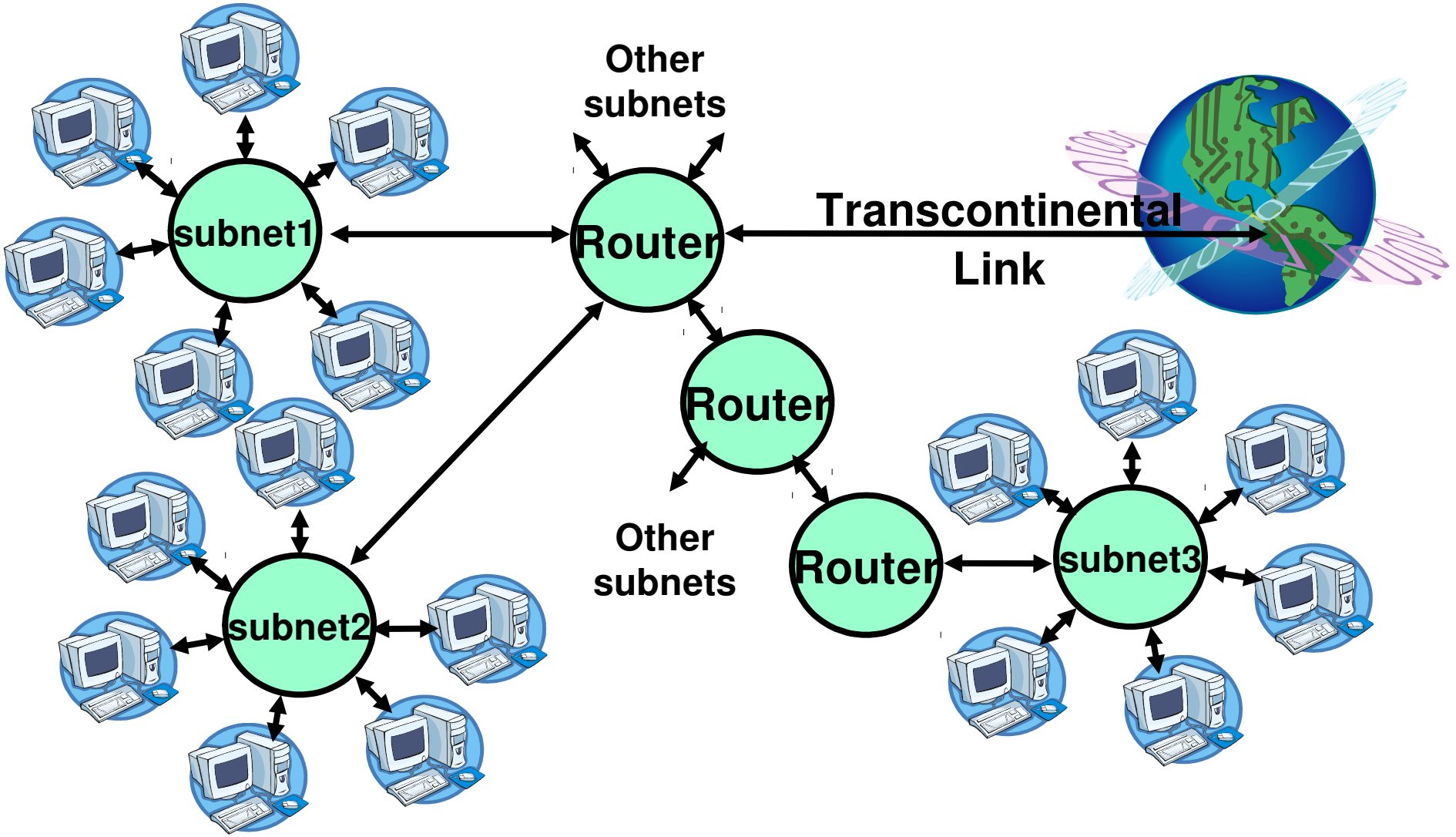
- Physical + Link (Wireless, Ethernet, ...)
  - Unreliable, local exchange of limited-sized **frames**
- **Network (IP) – routing between networks**
  - Unreliable, global exchange of limited-sized **packets**
- Transport (TCP, UDP) – routing
  - Reliablity, streams of bytes instead of packets, …
- Application – everything on top of sockets

Recall: Glue: Adding Functionality

Physical Reality: Frames	Abstraction: Stream
Limited Size	Arbitrary Size
Unordered (sometimes)	Ordered
Unreliable	Reliable
Machine-to-machine	Process-to-process
Only on local area net	Routed anywhere
Asynchronous	Synchronous

Recall:
Hierarchical Networking: The Internet

Hierarchy of networks – scales to millions of host



Recall: Routing (2)

Internet routing mechanism: routing tables

- Each router does table lookup to decide which link to use to get packet closer to destination
- Don't need 4 billion entries (or 2^128 for IPv6) in table: routing is by subnet

Routing table contains:

- Destination address range: output link closer to destination
- Default entry

Names versus Addresses

Names are

- meaningful
- memorable
- don't change if the resource moves

Addresses

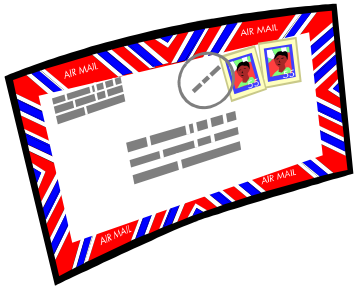
- explain how to access a resource
- change if the resource moves

Example:

- int foo; ← variable in C
- 'foo' is the name, address is a pointer to some place on the stack...

Naming in the Internet

Name = **Address**



You probably want to use human-readable names:

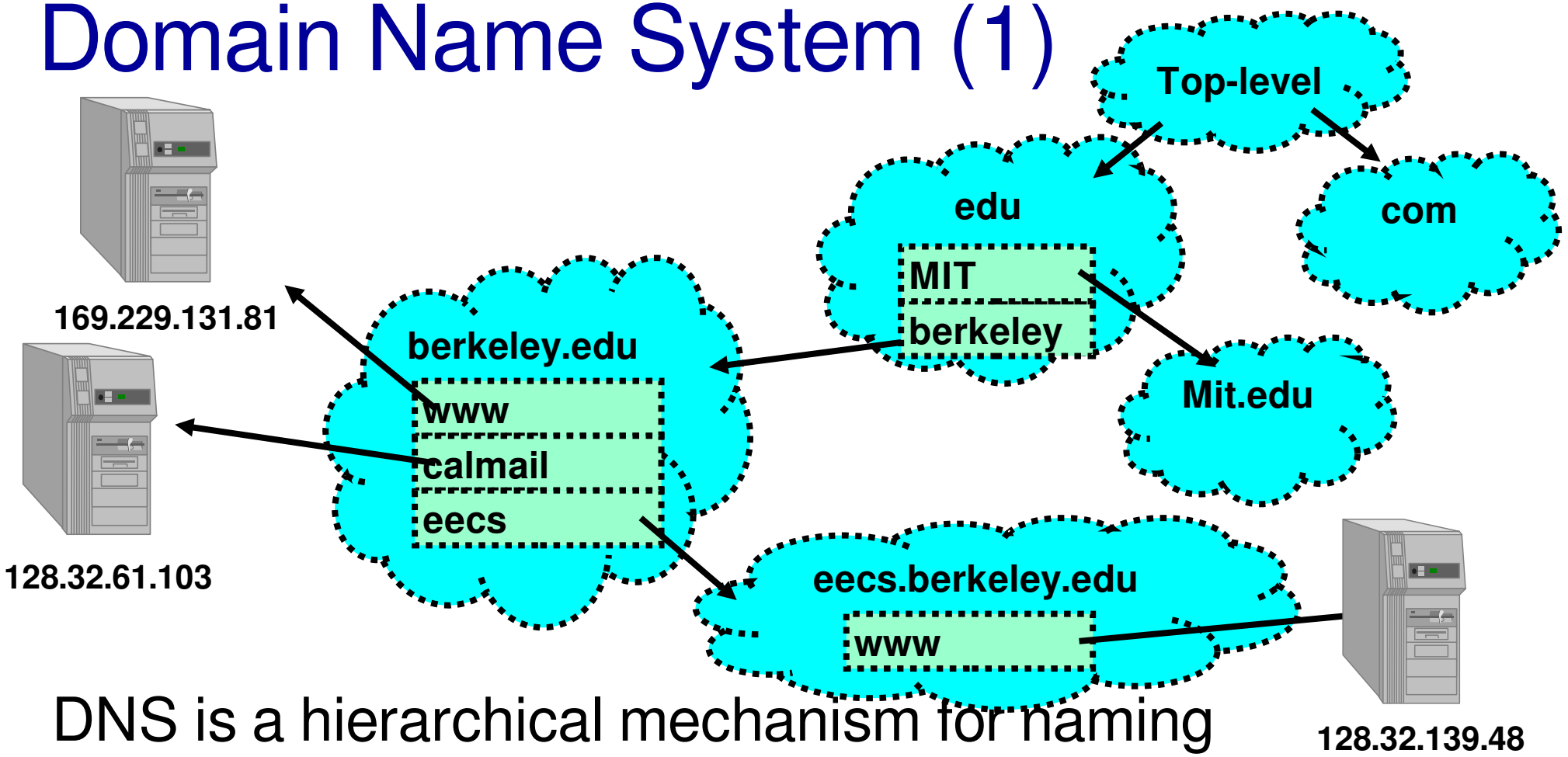
- www.google.com
- www.berkeley.edu

Network wants an IP address:

- that's what's in routing tables
- allows routing tables to take advantage of hierarchy

Mapping is done by the ***Domain Name System***

Domain Name System (1)



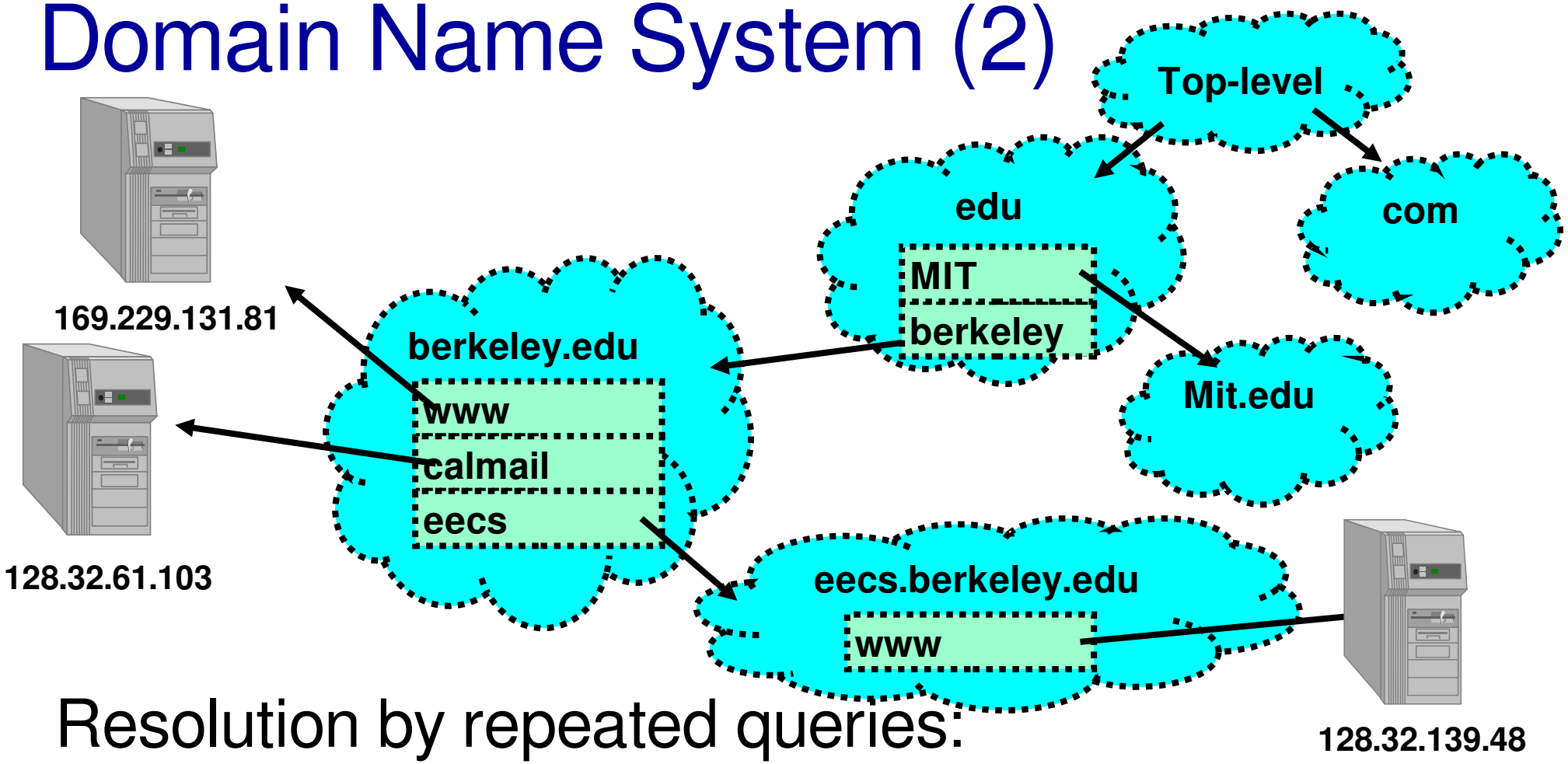
DNS is a hierarchical mechanism for naming

- Name divided into "labels", right to left: www.eecs.berkeley.edu

Each domain owned by a particular organization

- Top level handled by ICANN
- Subsequent levels owned by organizations

Domain Name System (2)



Resolution by repeated queries:

- One server for each "domain" (<root>, edu, berkeley.edu)
- Plus backups: redundancy (available, not gaurenteed consistent)

Domain Name System (3)

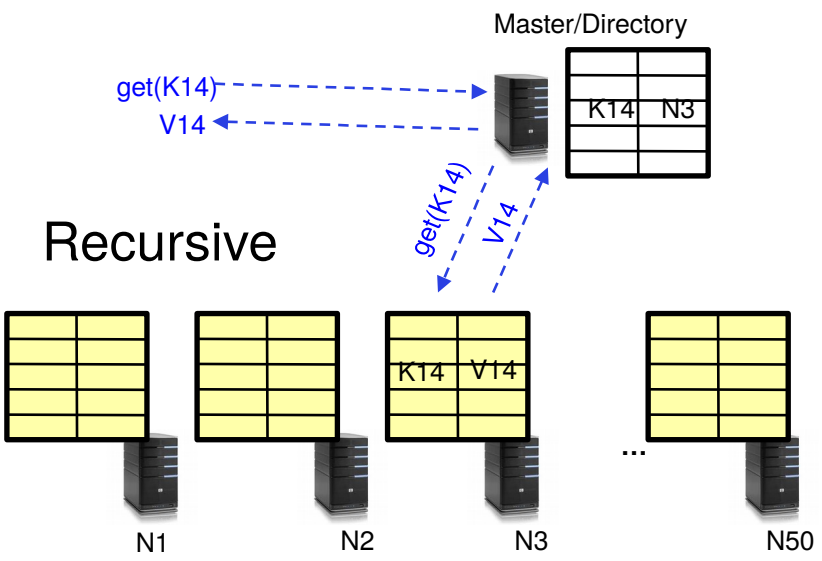
How do you find the root server?

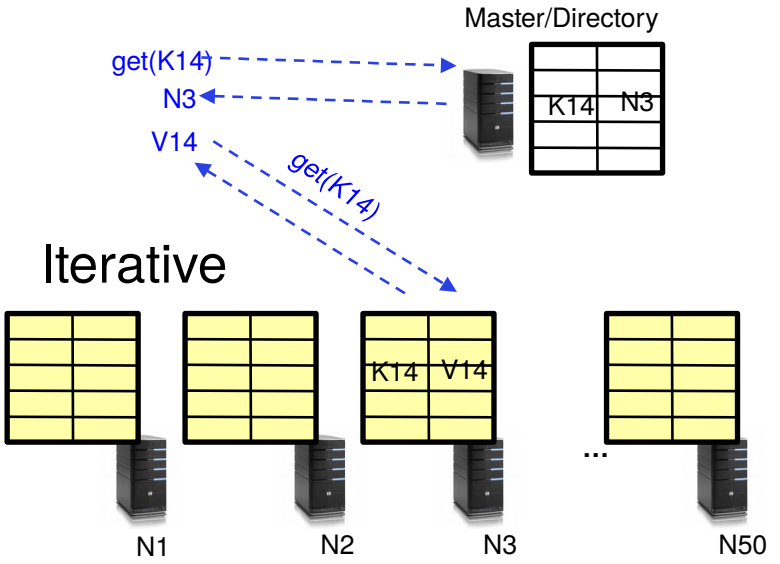
Hardcoded list of root servers and backups (updated rarely)

... or use your ISP's server (makes repeated queries on your behalf)

- *called **a recursive resolver***

Recall: Iterative vs. Recursive Query

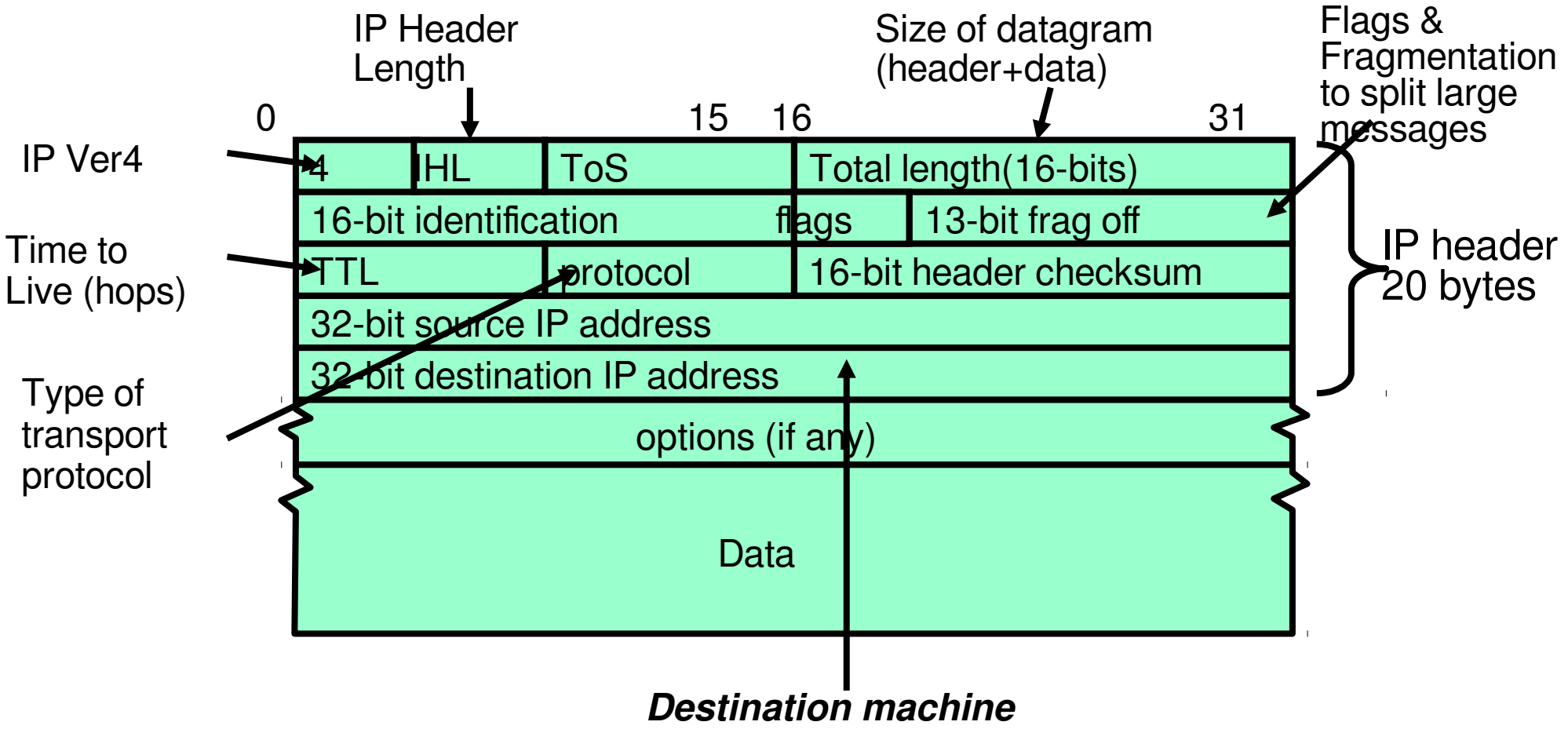




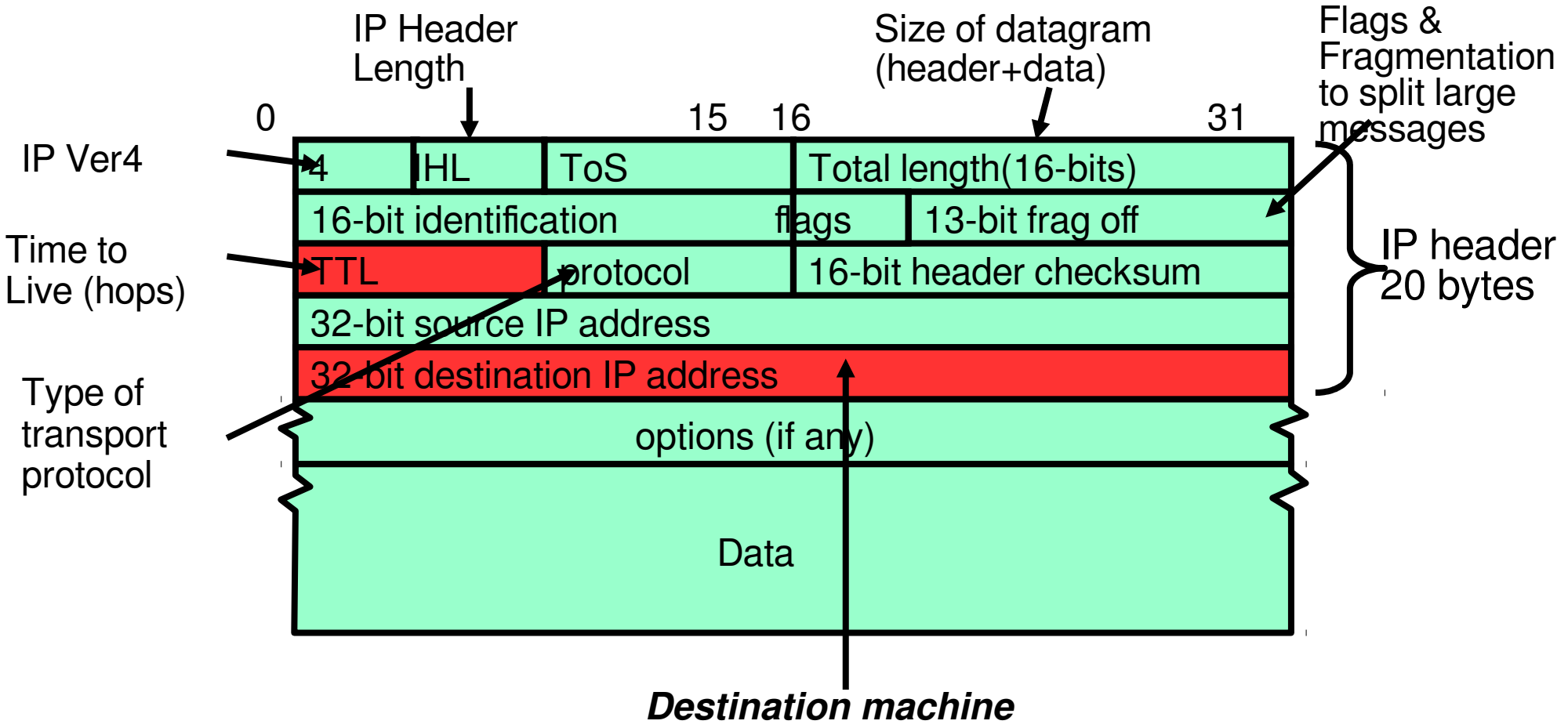
Recursive Query: Directory delegates

Iterative Query: Client delegates

IPv4 Packet Format



IPv4 Packet Format: What the router cares about



Internet Protocol Features

Routing – IP packet goes anywhere

- Just need the IP address

Fragmentation – split big messages into smaller

- Still message size limit (64K)
- Reassemble at destination
- Hides differences in physical layers

Multiple protocols on top:

- 1 byte to specify protocol:
  - ICMP (1), ***TCP*** (6), UDP (17), IPSec (50, 51), …
- Registry of protocol numbers

Internet Protocol Non-Features

Unreliable delivery

- IP packets are not guaranteed
- May be lost by underlying physical layer (radio noise?)
- May be dropped if, e.g., router out of resources

Out-of-order/duplicate delivery

- Tolerance to physical layer retrying packets
- Tolerance to multiple paths

Layering

Complex services from simpler ones

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Ordered Messages: Problem

Want to divide message into packets, e.g.

- "GET /static/hw/hw1.pdf HTTP/1.0" into
- "GET /static" and "/hw/hw1.pdf HTTP/1.0"

Why? Not can't always fit request in one packet (IP: 64K limit – think of uploading a file)

IP might reorder these packets:

- "/hw/hw1.pdf HTTP/1.0", then
- "GET /static"

Ordered Message: Solution

Ordered messages on top of unordered ones:

- Assign sequence numbers to packets: 0,1,2,3,4....
- If packets arrive out of order, hold and put back in order before delivering to user (through socket interface)
- For instance, hold onto #3 until #2 arrives, etc.

Tricky case: packets from "old" connections

Reliable Message Delivery: Problem

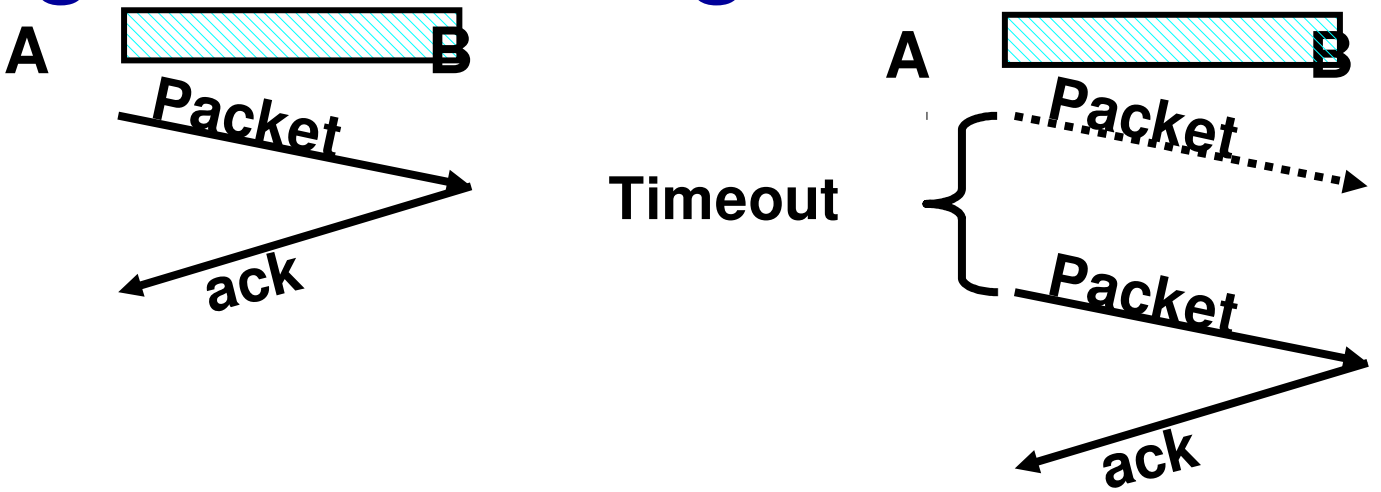
All physical networks can garble and/or drop packets

- Physical hardware problems (bad wire, bad signal)
- Therefore, IP can garble/drop packets (doesn't fix this)

Building reliable message delivery

- Confirm that packets arrive **exactly once**
- Confirm that packets aren't garbled

Using Acknowledgements



Checksum: detect garbled packets

Receiver send packet to acknowledge when packet received and ungarbled:

- No acknowledgement? **Resend** after timeout

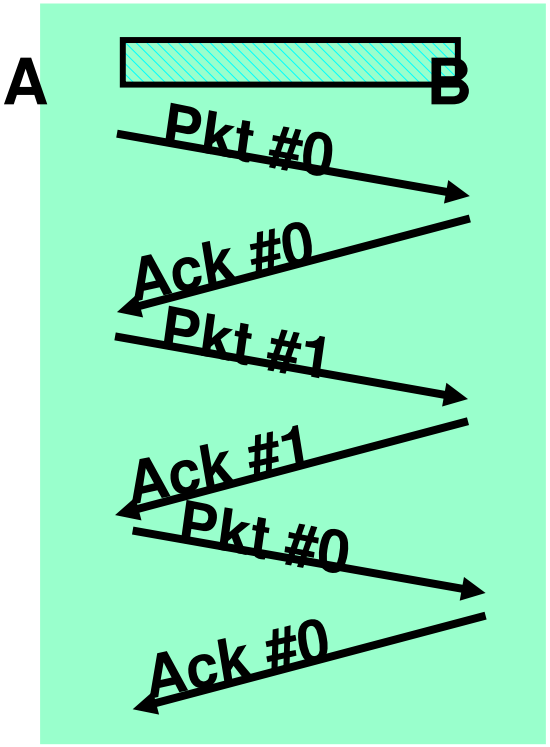
What if ack dropped?

- Packet is resent (wasteful), second chance to acknowledge it.

What about duplicates?

Recall: Sequence number

Simplest version: 1 bit (0/1):



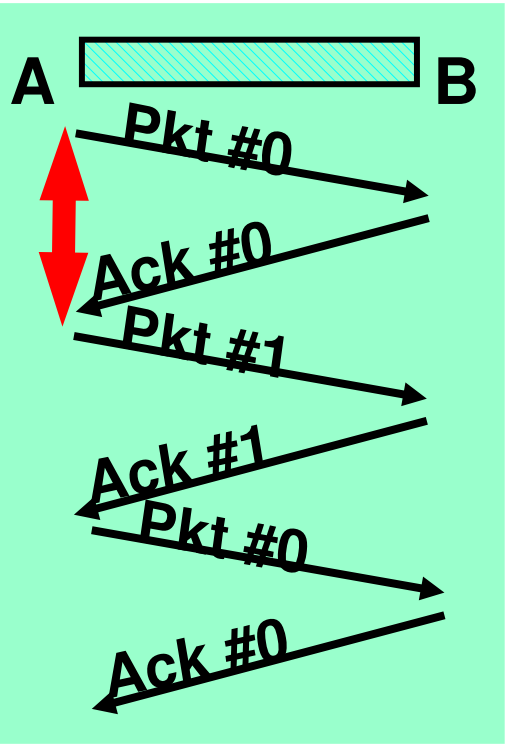
Problem: What if packet delayed too much?

Waiting for Acks: Performance

Time from Soda to google.com and back: **8 ms**

Maximum packet size: ~1500 bytes

1500 bytes / 8 ms = ***188 KByte/s***



Window-based acknowledgements (1)

Windowing protocol (not quite TCP)

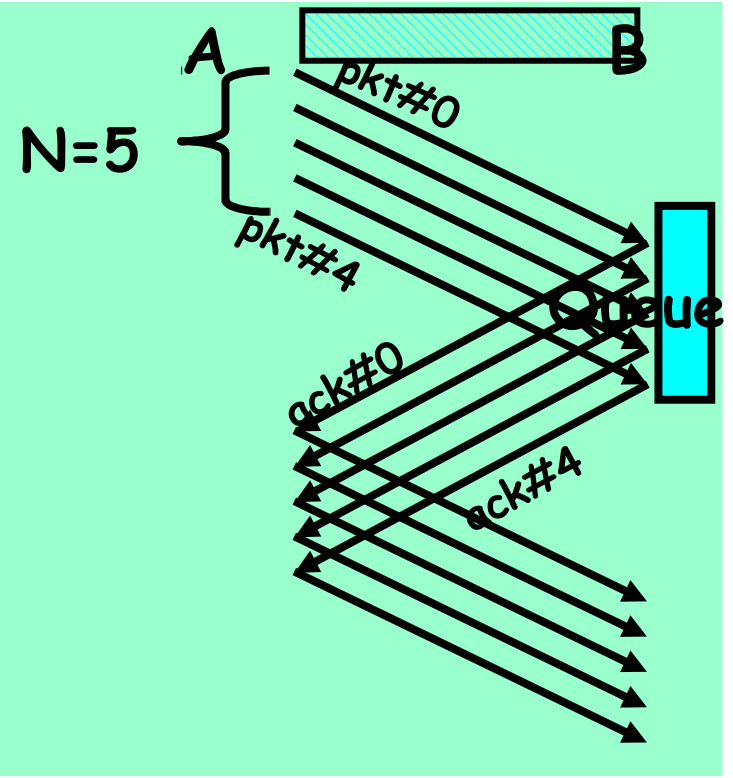
Send up to N packets without ack

- Allows pipelining of packets
- N limits **queue size**

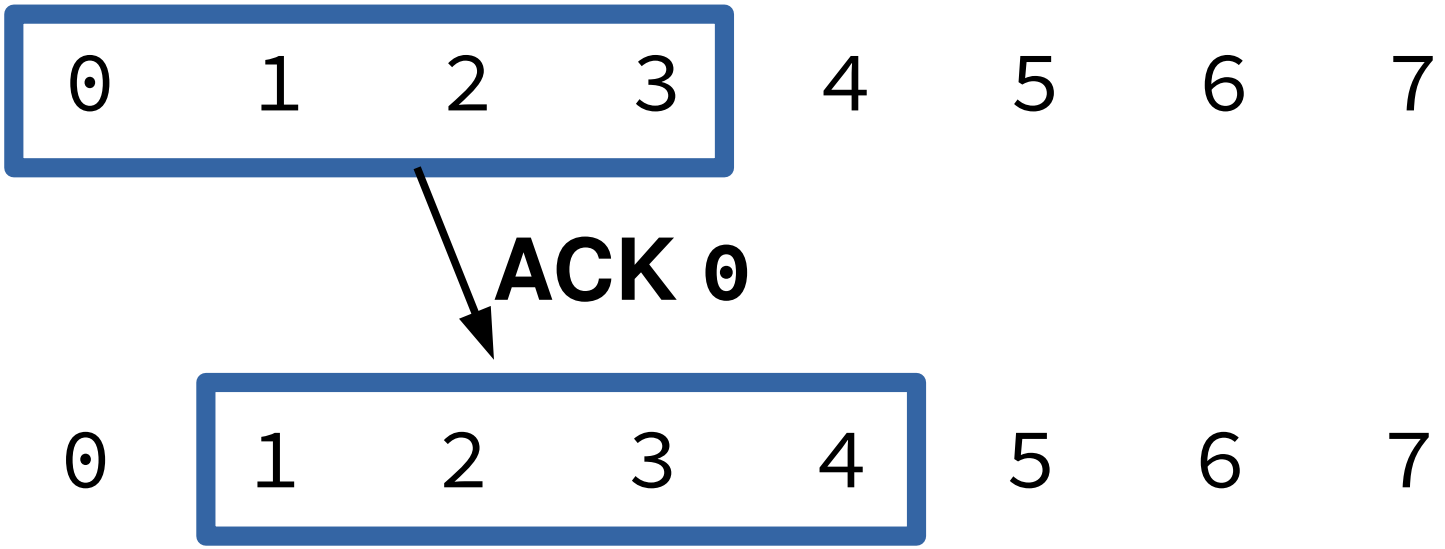
Both source and destination need to store N packets (why?)

Each packet has sequence number

- Ack says "**received all packets up to sequence number X**"
- Advances window



Sliding Window



Window represents packets:

- That might need to be retransmitted (dropped/garbled)
- That receiver needs space to buffer (ordering)

Window-based acknowledgements (2)

Packet lost?

- Resent by timeout, again

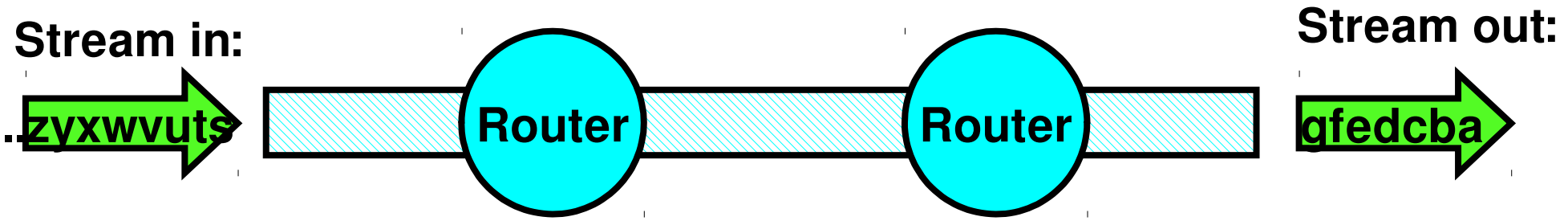
Acknowledgement lost?

- Packet resent, causing ack to be resent (again)
- If we're lucky acknowledged together with later packet instead

Discard out of order packets?

- If no, need some way to indicate "holes"

Transmission Control Protocol (TCP)



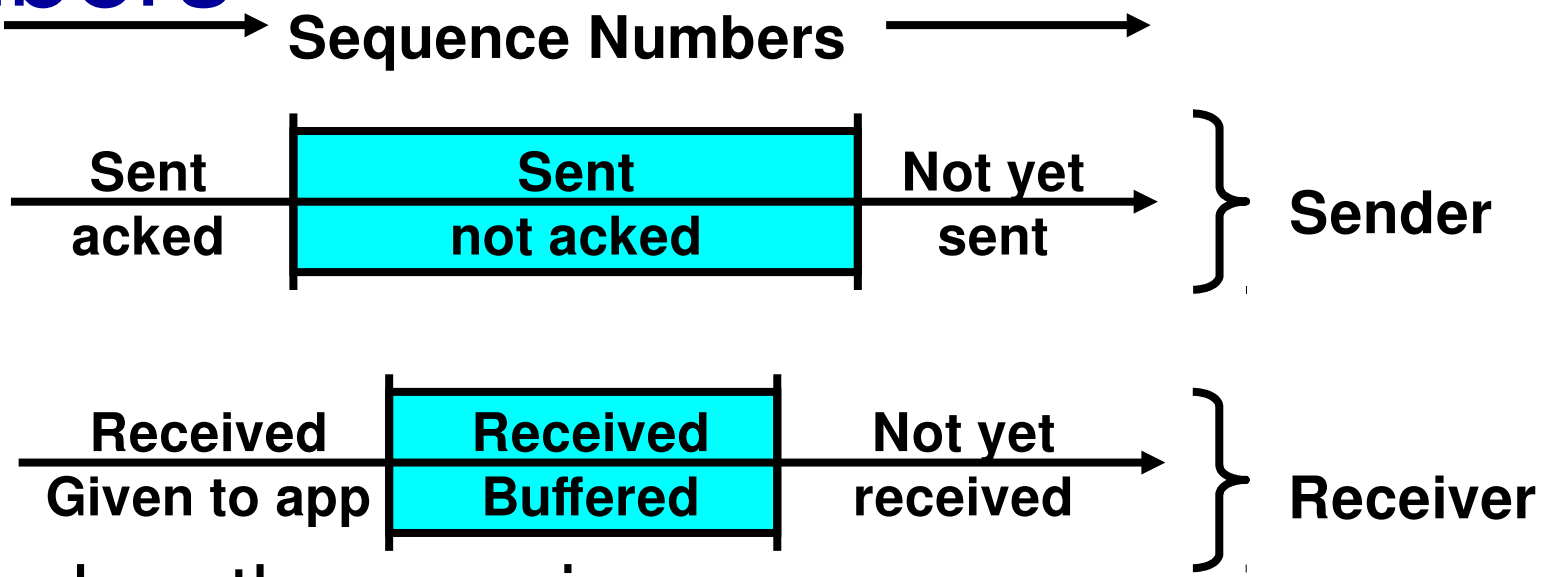
Transmission Control Protocol (TCP)

- **Reliable byte stream** between two processes on different machines over Internet (read, write)
- Bi-directional (two streams for every connection)

TCP Details

- Fragments byte stream into packets, hands packets to IP
- Window-based acknowledgement protocol
- Automatically retransmits lost packets
- Adjusts rate of transmission to avoid *congestion*
  - Mechanism: ***Window size***

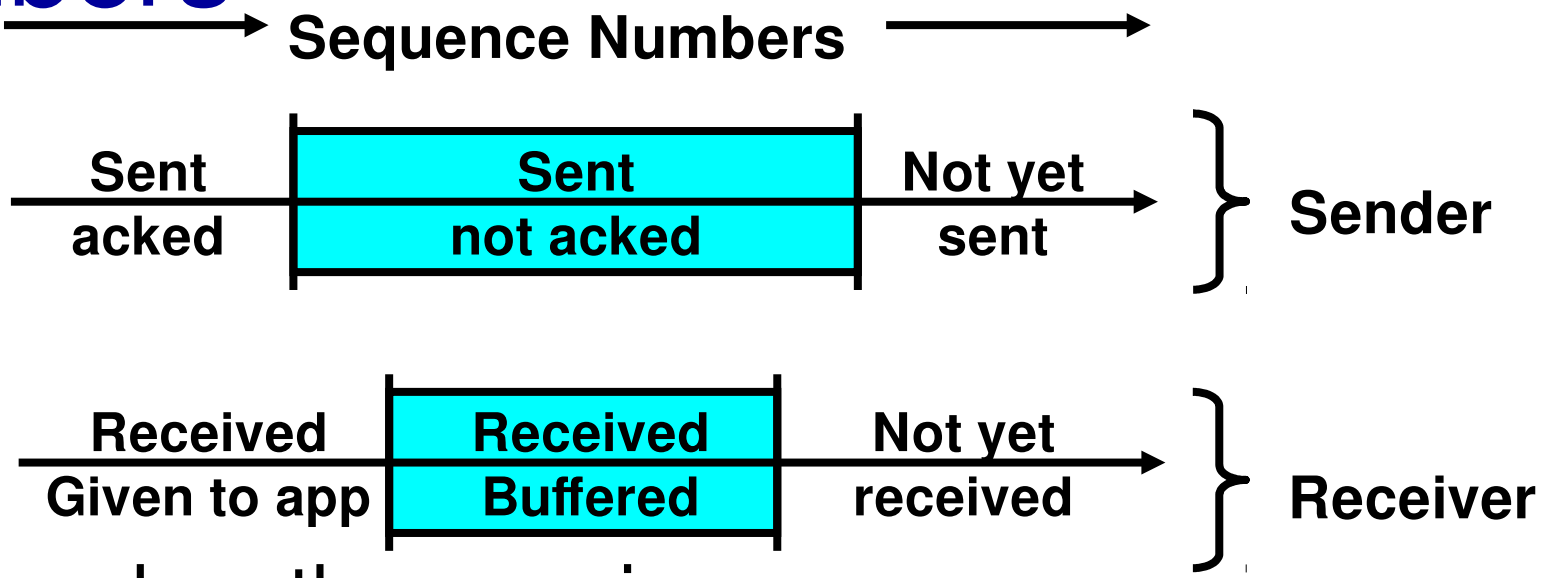
TCP Windows and Sequence Numbers



Sender has three regions:

- sent and ack'ed
- sent and not ack'ed
- not yet sent

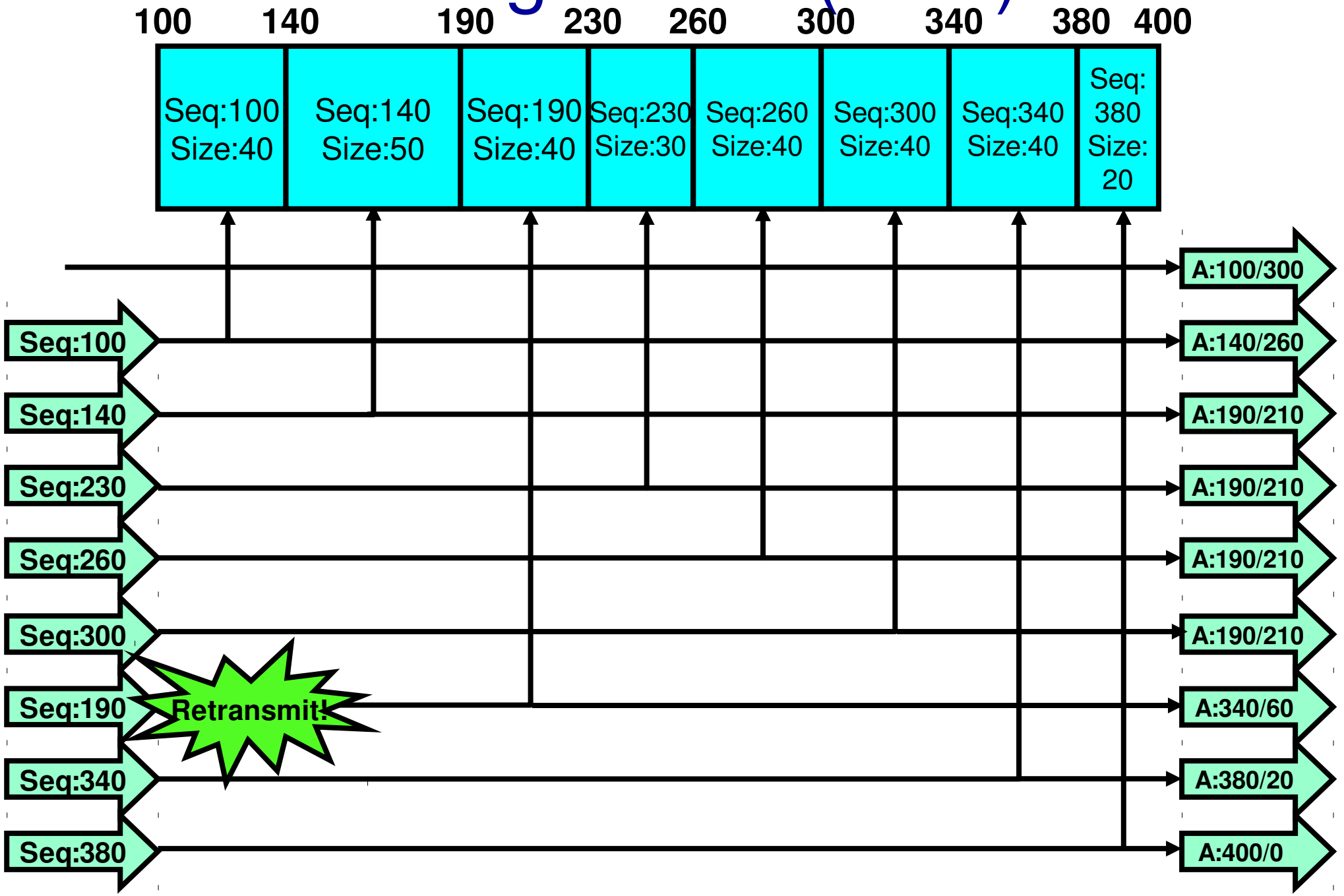
TCP Windows and Sequence Numbers



Receiver has three regions:

- received and ack'ed (given to application)
- received and buffered
- not yet received (or discarded because out of order)

Window-Based Acknowledgements (TCP)



Selective Acknowledgement Option (SACK)

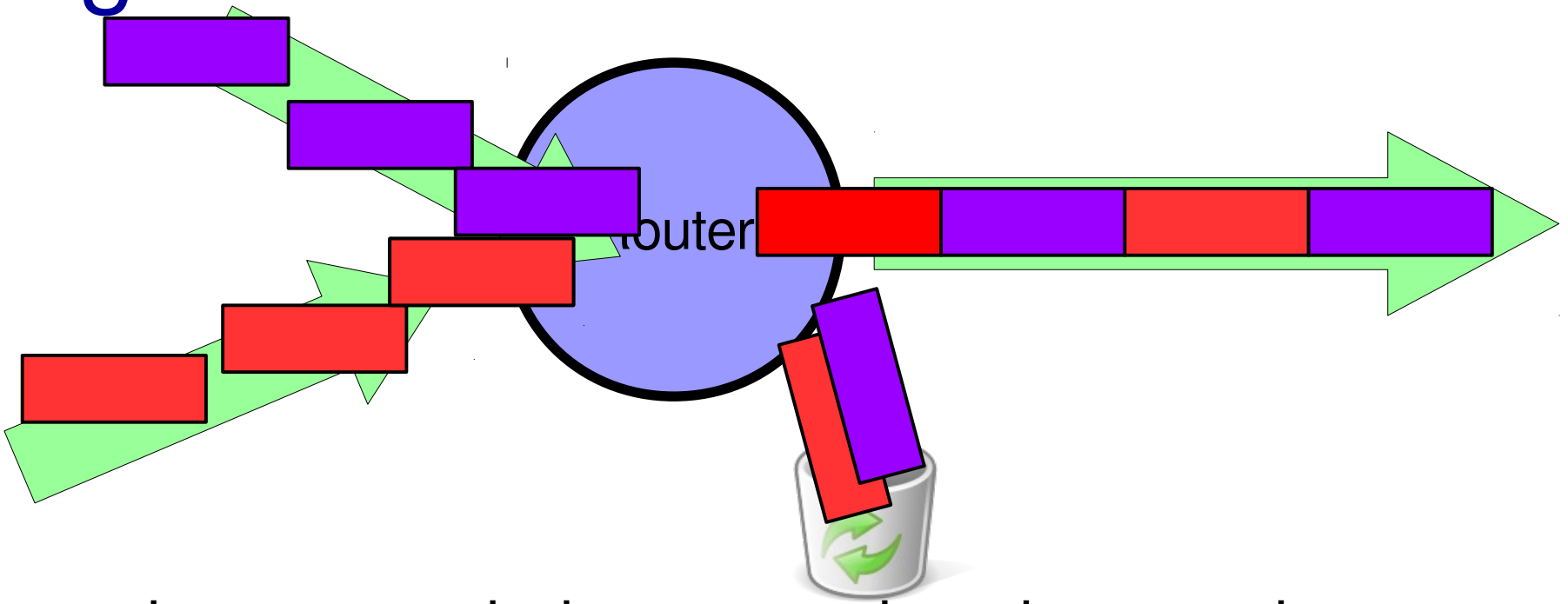
Vanilla TCP Acknowledgement

- Every message encodes Sequence number and Ack
- Can include data for forward stream and/or ack for reverse stream

Selective Acknowledgement

- Acknowledgement information includes not just one number, but rather ranges of received packets
- TCP **Option** (extension) – often not used
- Turns out extending TCP is hard (compatibility problems)

Congestion



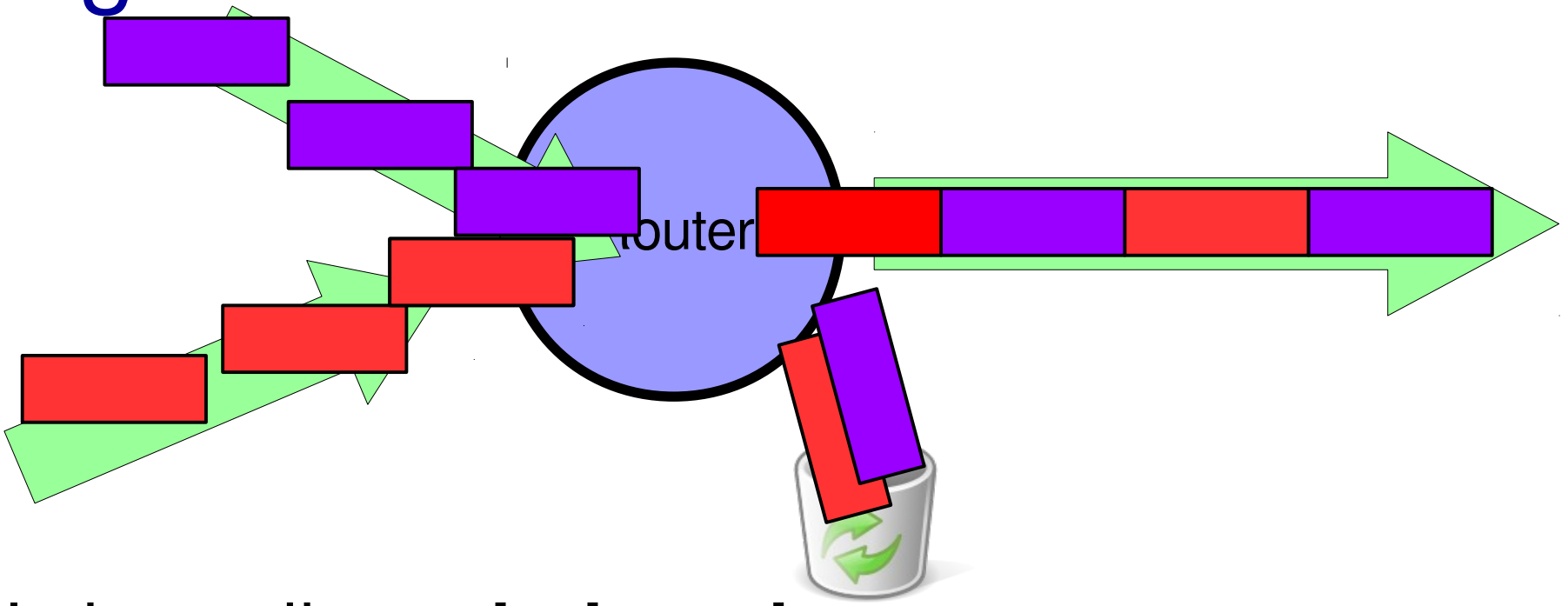
Congestion: too much data somewhere in network

IP's solution: ***drop*** packets

Bad for TCP

- Lots of retransmission – wasted work
- Lots of waiting for timeouts – underutilized connection

Congestion Avoidance

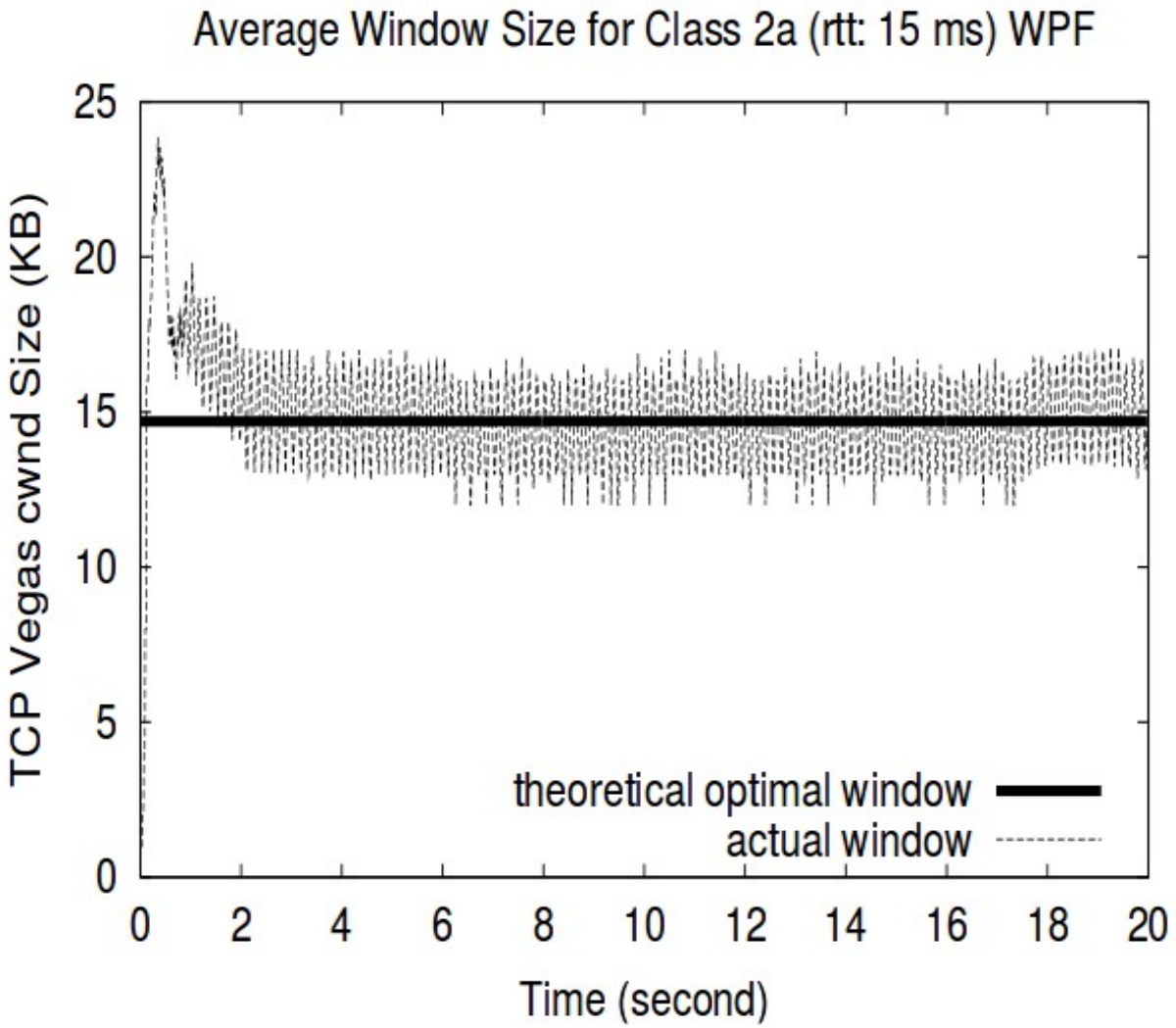


Solution: adjust **window size**

AIMD – Additive Increase, Multiplicative Decrease

- When packet dropped (missed ack) → decrease rapidly
- When packet successfully ack'd, increase slowly

Congestion Avoidance: Changing Window



From Low, Peterson, and Wang, "Understanding vegas: Duality Model", J. ACM, March 2002.

Implementing Congestion Avoidance

Need to track window size

Need to keep buffer of unacknowledged packets

Need to keep buffer of received but unread packets

Need to resend packets when timer expires (one for each connection?)

Need to acknowledge packets and adjust window size

Who does this? On Linux – the kernel

Summary: Network Layering

Link layer (local network):

- **Broadcast** or **Point-to-Point**
- Send *frames* addressed to neighboring machines
- Ethernet, Wi-Fi

Network layer (connecting network):

- ***Forwarding*** between local networks
- Send *packets* addressed to machines anywhere
- IP

Transport layer (Making streams):

- Turn sequence of packets into **reliable stream**
- TCP

Summary: Names and Addresses

DNS name: human readable

- Mapped to IP *address*
- Distributed database

IP address:

- 32-bit (IPv4) or 128-bit (IPv6) number
- Looked up in routing tables to decide where to send packets

Port number:

- 16-bit number
- Used to identify service on particular machine

Logistics

HW2 due today (midnight)

Project 2 Checkpoint 2 due Monday

Break

Implementing Congestion Avoidance

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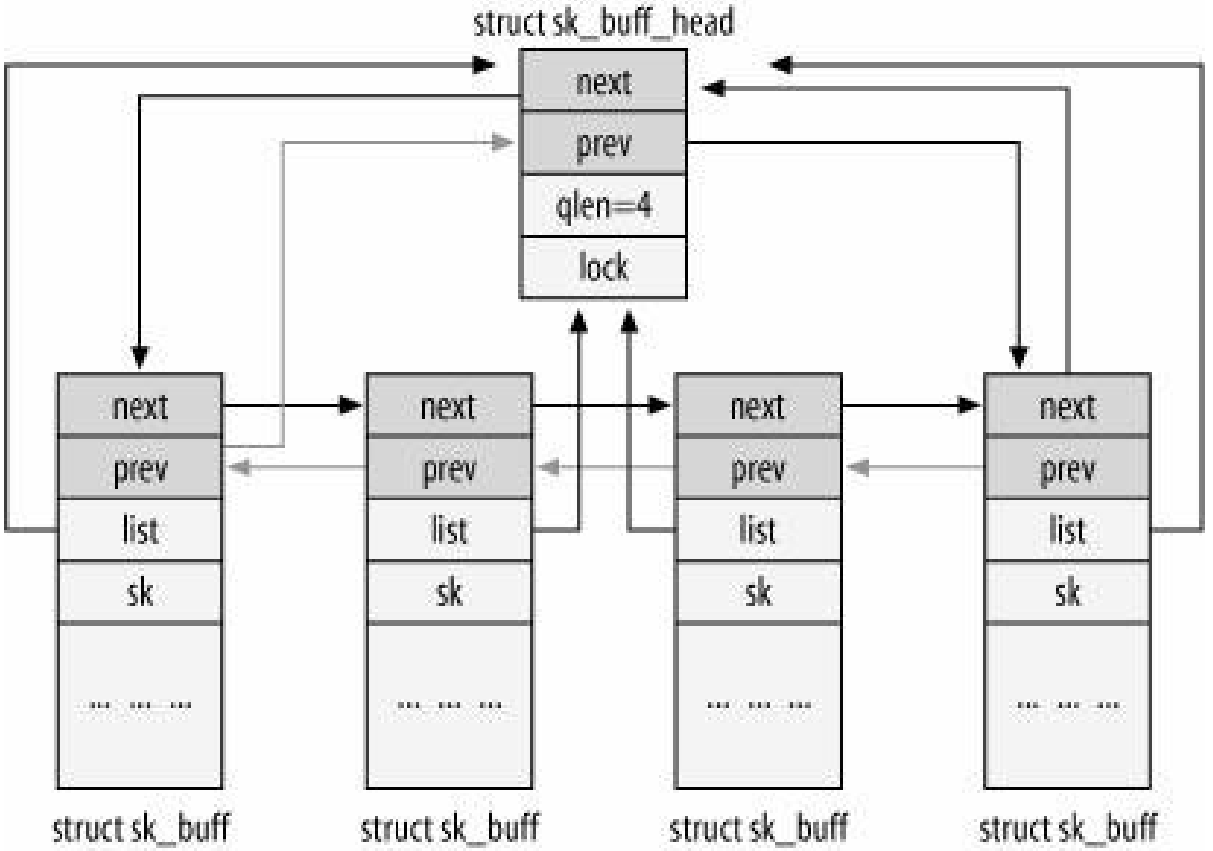
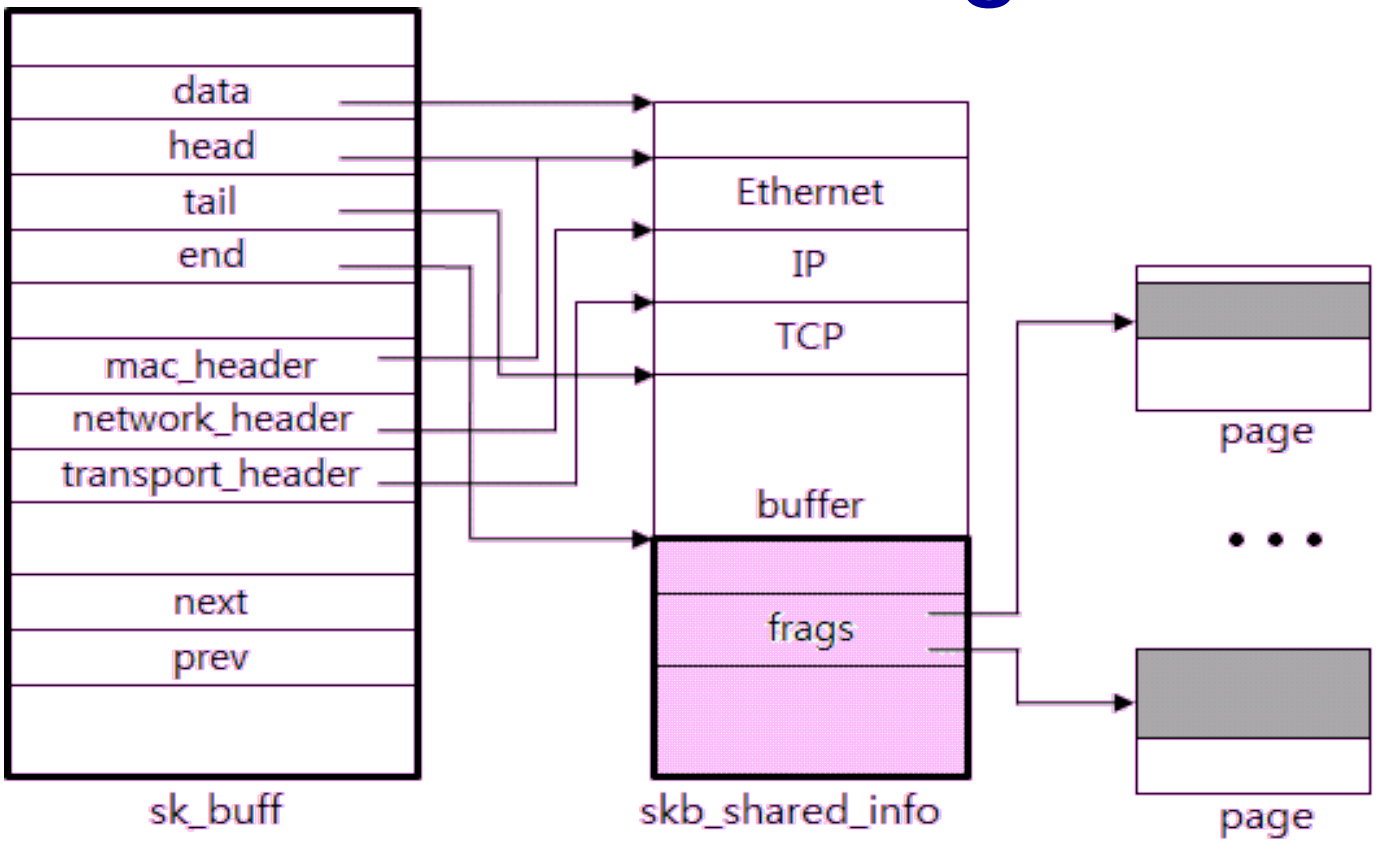
Linux Details: sk_buff structure



Socket **Buffers**: sk_buff structure

- The I/O buffers of sockets are lists of sk_buff
- Packet is linked list of sk_buff structures

sk_buff: Headers and Fragments

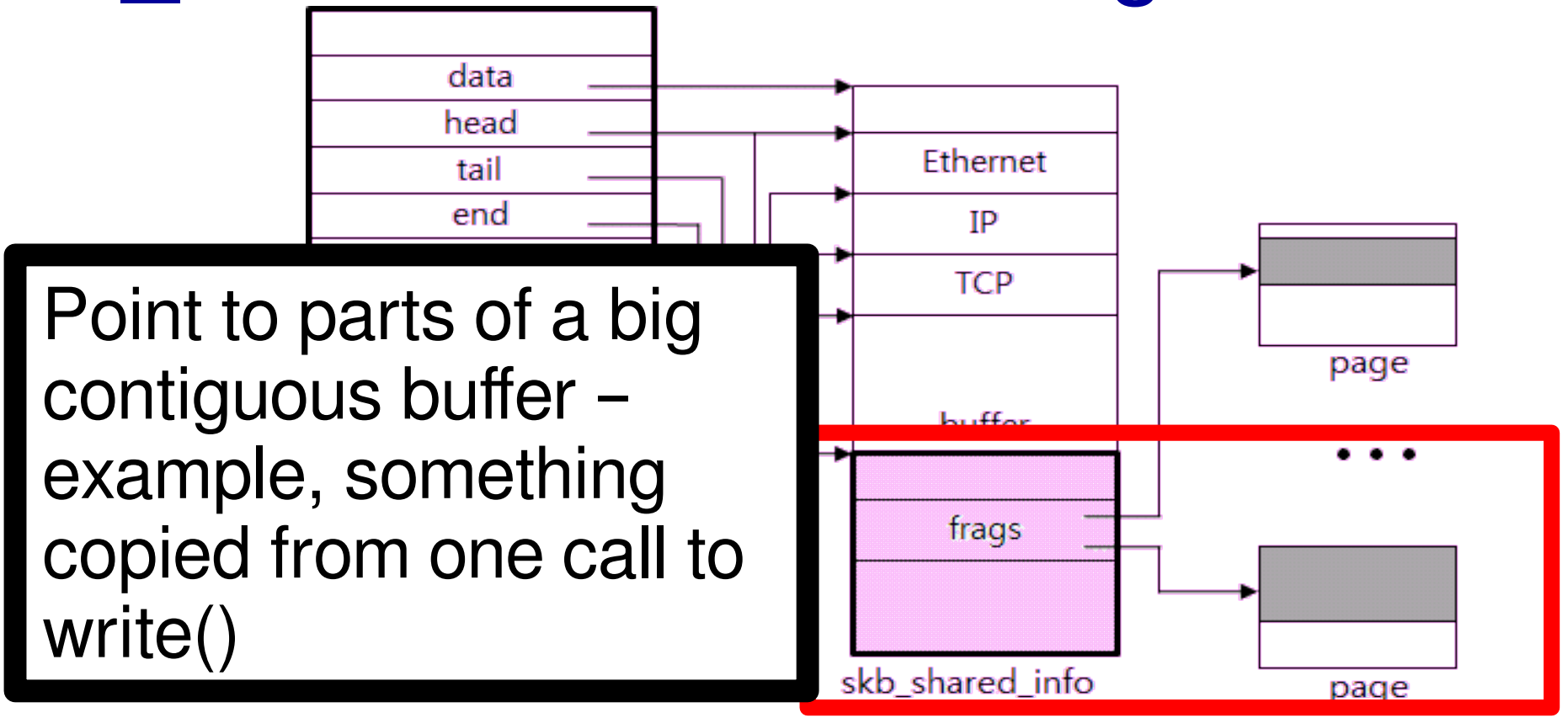


The “linear region”: Space from skb->data to skb->end

- Convenience: header pointers point to parts of packet

And the fragments (in skb_shared_info) – pointers to seperate pages

sk_buff: Headers and Fragments



Point to parts of a big contiguous buffer – example, something copied from one call to write()

The "linear region": Space from skb->data to skb->end

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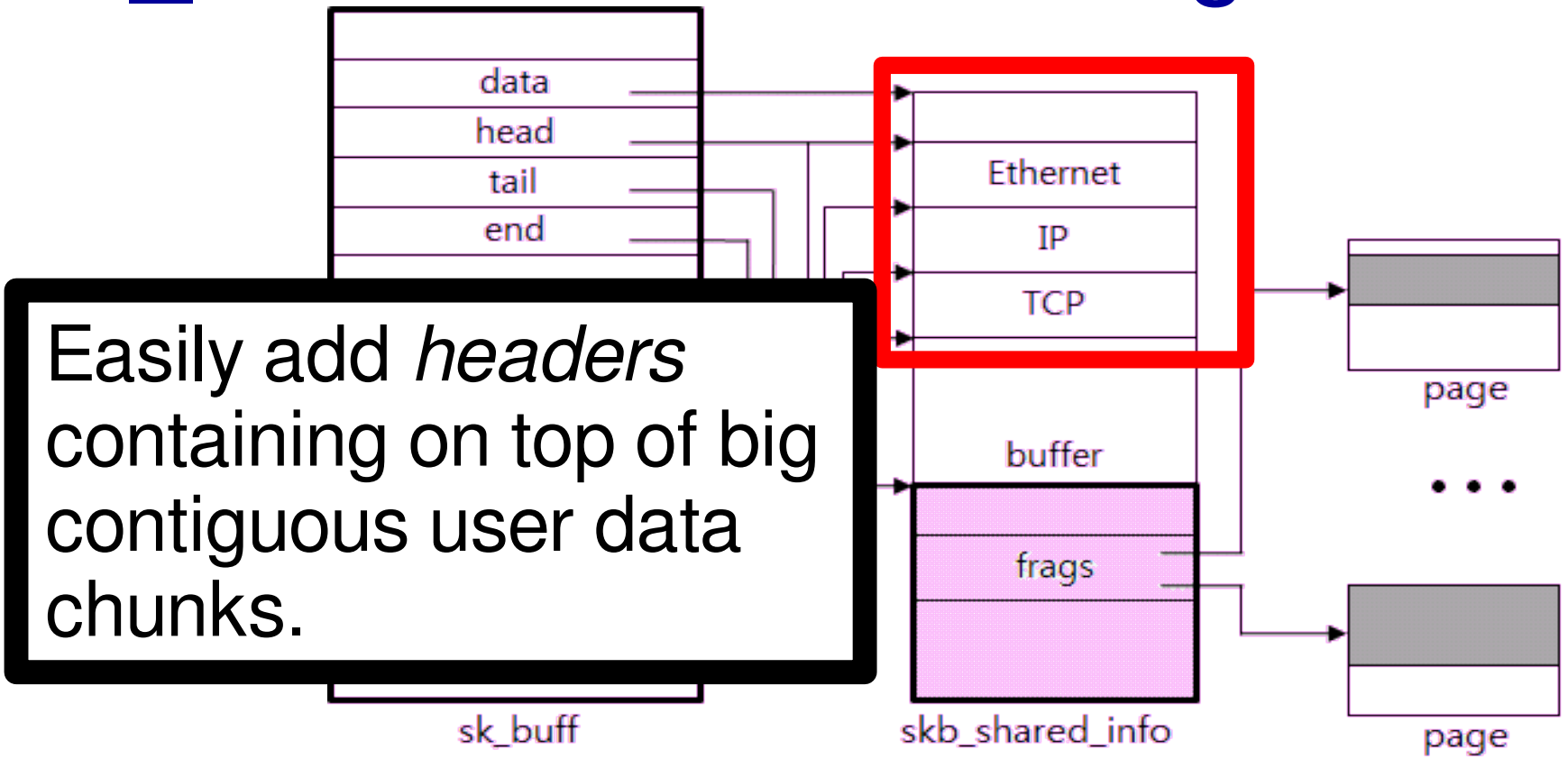
sk_buff: Headers and Fragments



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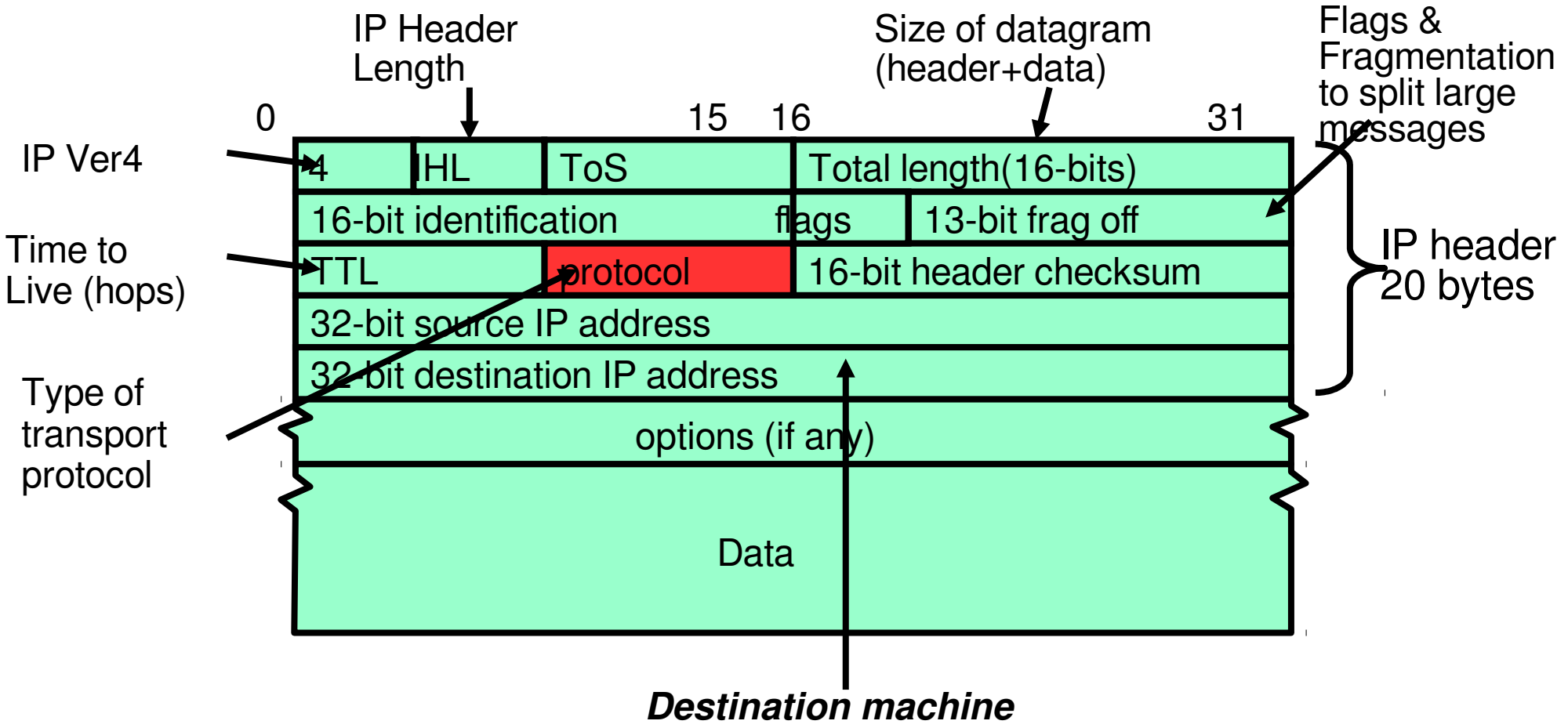
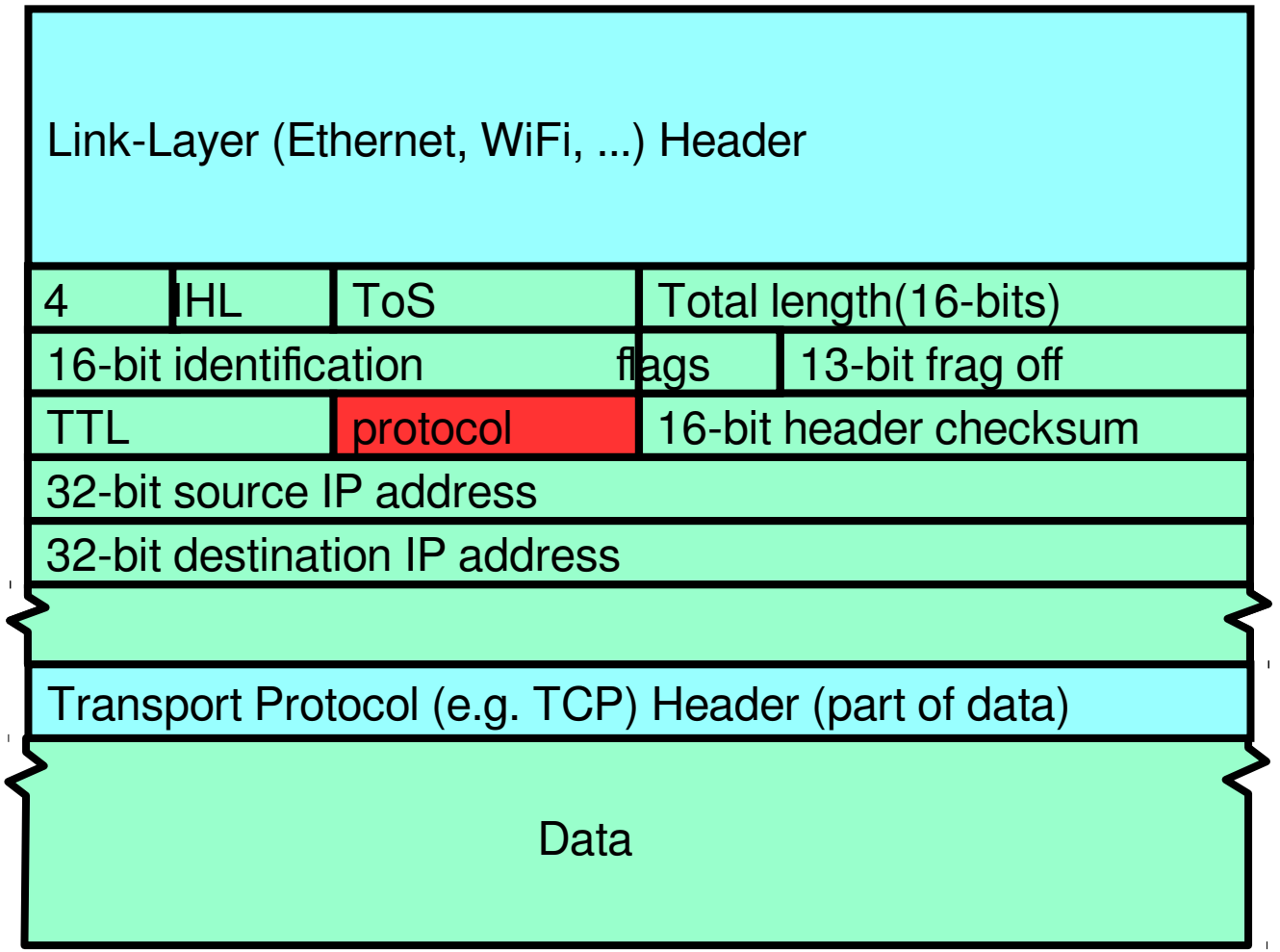
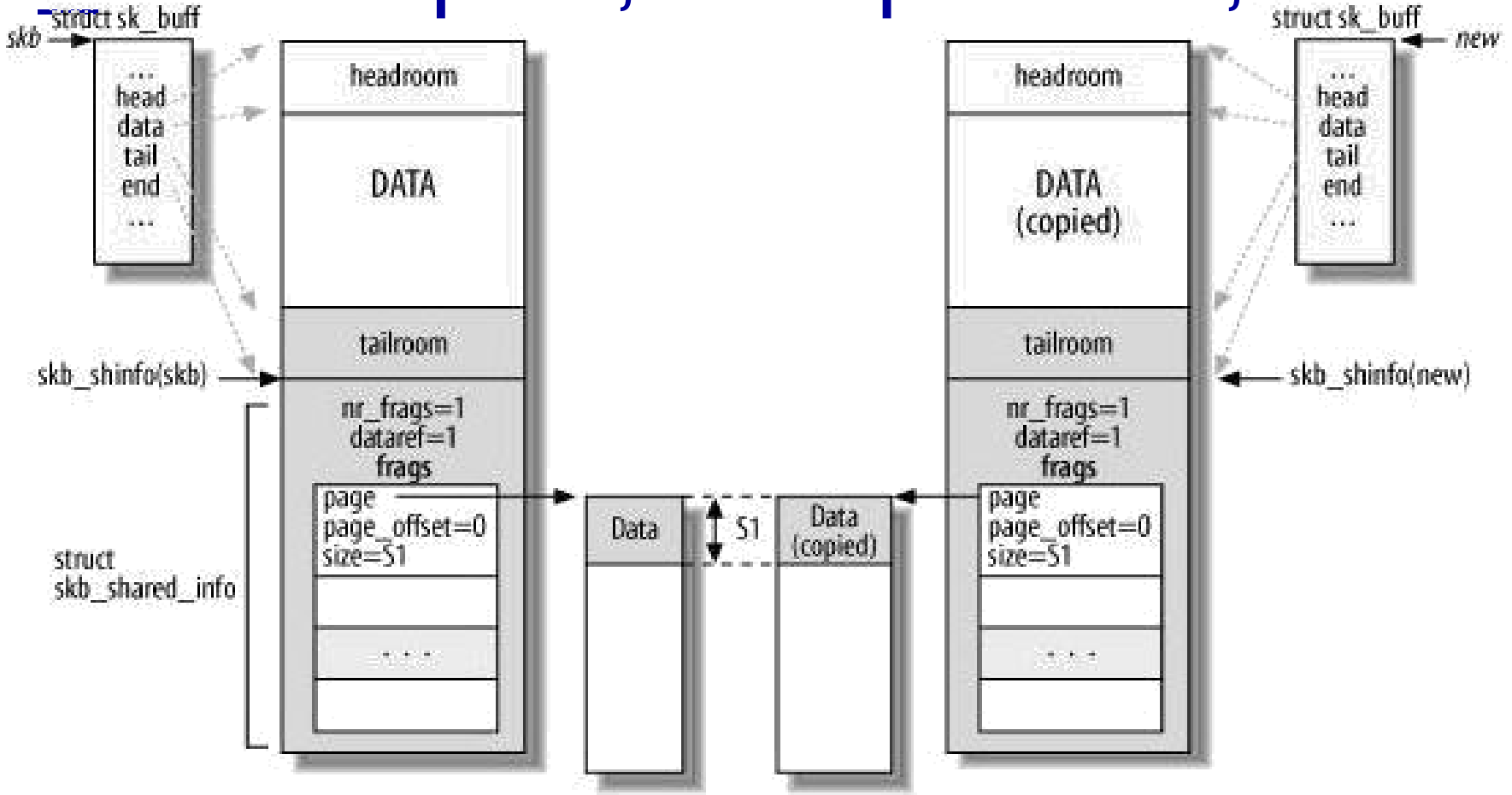
Recall: IPv4 Packet Format



IPv4 Packet in Context



sk_buff: Copies, manipulation, etc



Lots of sk_buff manipulation functions for:

- removing and adding headers, merging data, pulling it up into linear region
- Copying/cloning sk_buff structures

Implementing Congestion Avoidance

Need to track window size

Need to keep buffer of unacknowledged packets

Need to keep buffer of received but unread packets

Need to resend packets when timer expires (one for each connection?)

Need to acknowledge packets and adjust window size

Who does this? On Linux – the kernel

Linux Internal Timer API

```
struct timer_list {
  unsigned long expires;
  void (*function)(unsigned long);
  unsigned long data;
  // ...
};
struct timer_list timer;
timer.expires = …; timer.function = timer_expired; ...
setup_timer(&timer);
```

function(data) called at time=expires

- by **timer interrupt**

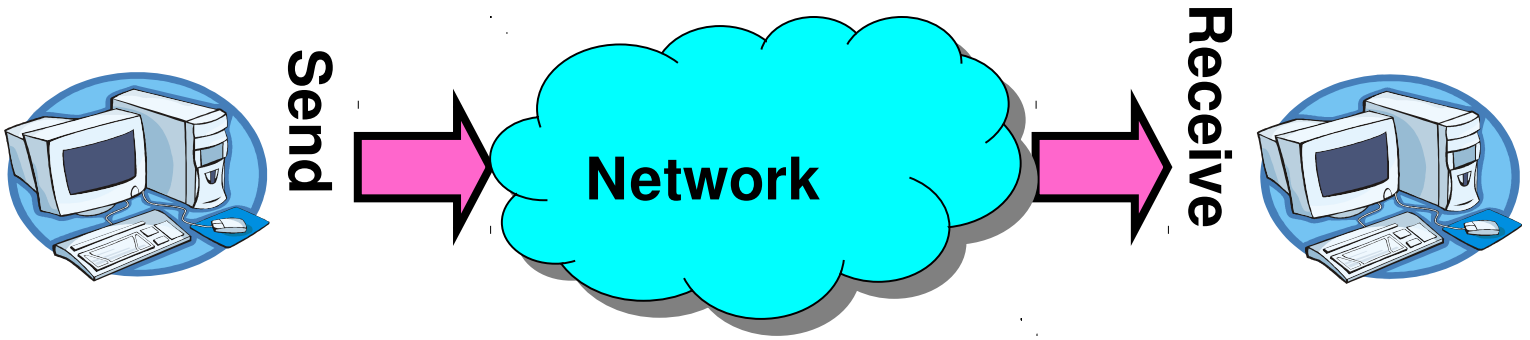
Also APIs to remove, change timers if, e.g.,

- ACK received before timeout
- User closes socket

Recall: The Mailbox Abstraction (2)

Interface:

- Mailbox (mbox): temporary holding area for messages
  - Includes both destination location and queue
- Send(message,mbox)
  - Send message to remote mailbox identified by mbox
- Receive(buffer,mbox)
  - Wait until mbox has message, copy into buffer, and return
  - If threads sleeping on this mbox, wake up one of them



Mailboxes on TCP (1)

Want ***messages***, have **stream**

Need to separate messages

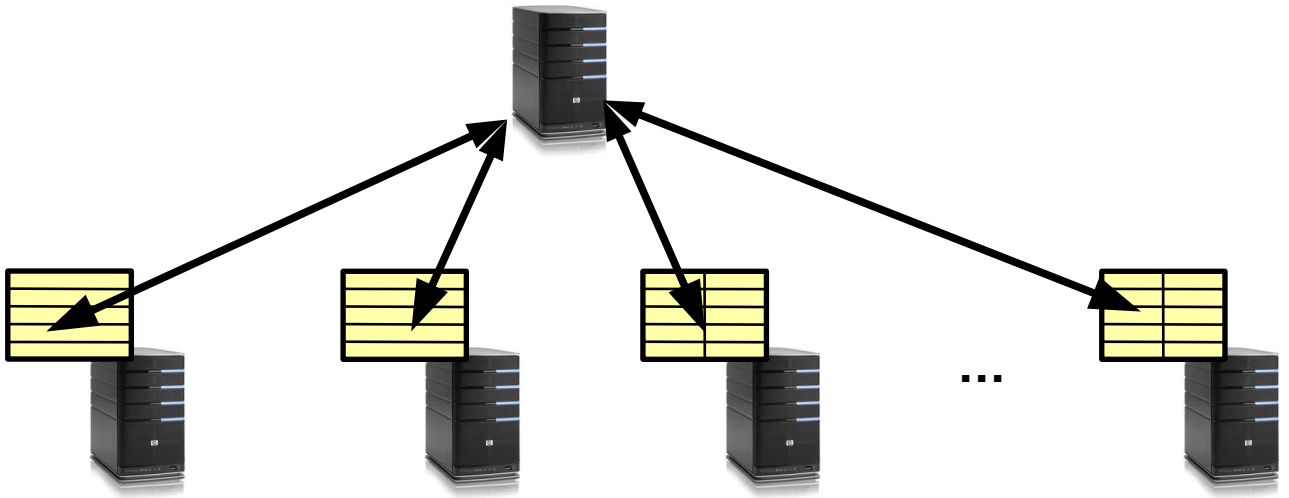
Same idea as storing multiple things in a file

Example: newline after each message

Example: size before each message

Mailboxes on TCP (2)

Want to send to many mailboxes



Solution: one connection for each destination

Reading from multiple sockets at once?

- Multiple threads + local synchronization
- select()/poll() – POSIX interface to wait for multiple files to have data

Remote Procedure Calls

Idea: make communication look like function calls

Wrapper library like for system calls

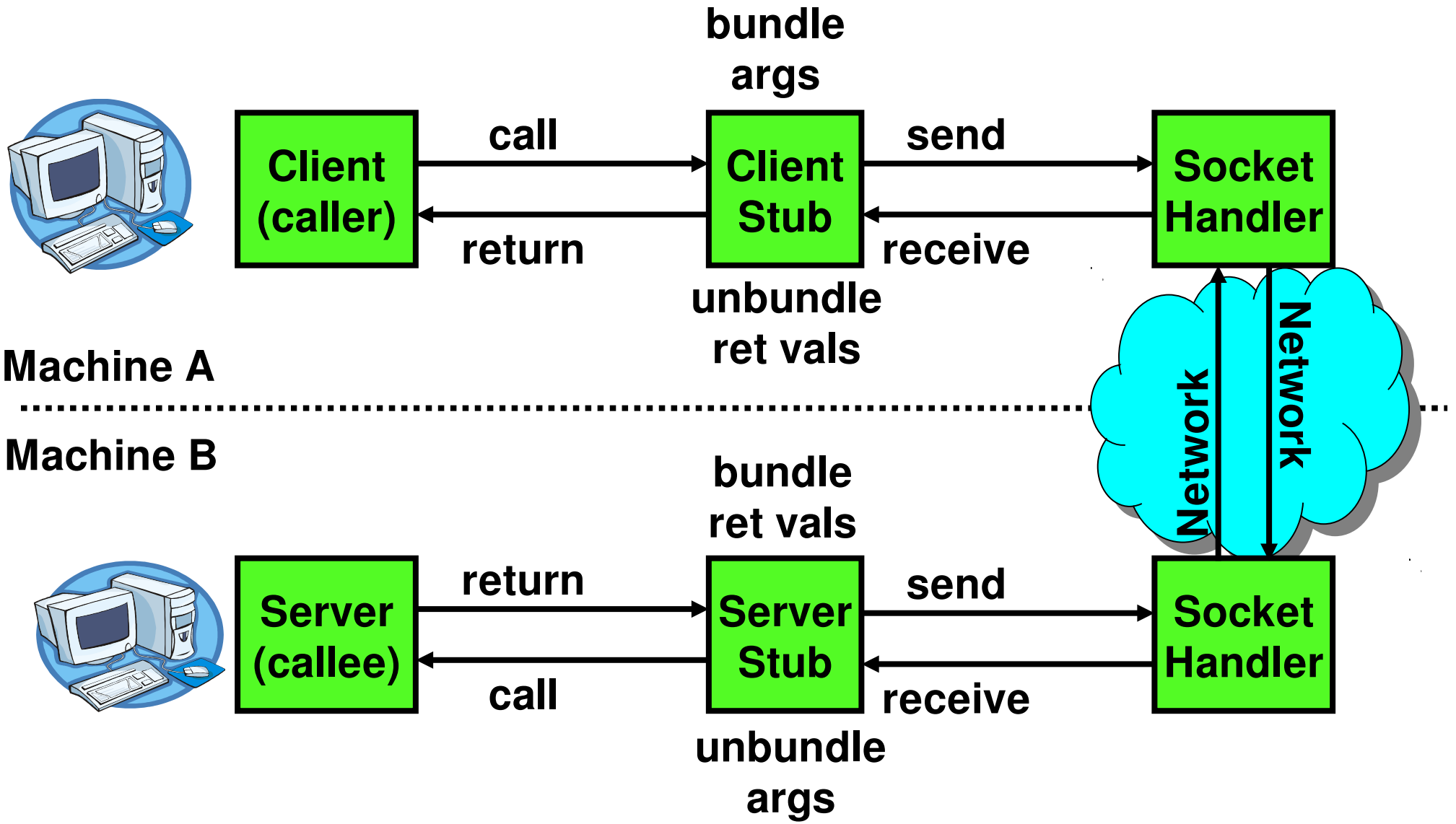
- Called ***stubs***

Also wrappers at the receiving end

- Read messages from socket, make function calls

Look "like" local function calls

RPC Information Flow



RPC (Pseudo)code

Client

```
#include <myprotocol.stubs.h> /* generated by tool */
RPCContext ctx = myprotocol_ConnectToServer(hostname, port);
…
result = myprotocol_mkdir(ctx, "/directory/name");
…
```

Server

```
#include <myprotocol.stubs.h>
main() {
  myprotocol_SetupRPCServer(port);
}
int real_myprotocol_mkdir(RPCContext ctx, char *name)
{
   …
}
```

RPC Details

Setup: Need to specify remote machine somehow

- Example: host:port

Need to ***marshall*** arguments over the network:

- Sometimes also called ***serialization***
- Done by stub

Typically code generated from **file specifying protocol**

- Called **Interface Definition Language (IDL)**
- Generates stubs
- ... including marshalling/demarshalling code

Interface Definition Language

Pseudocode:

```
protocol myprotocol {
   1: int32 mkdir(string name);
   2: int32 rmdir(string name);
}
```

Marshalling example: `mkdir("/directory/name")`

`returning 0`

Client sends: `\001/directory/name\0`

Server sends: `\0\0\0\0`

Marshalling Details

Marshalling with different architectures

- Remember endianness?
- Need to choose a consistent format
- Option: Native format, mark

Marshalling with pointers

- Need to chase pointers
- Something like a graph? Doubly linked list? Gets complicated.

RPC Naming

One option: Well known ports

Another: "Dynamic binding"

- well-known service gives readable names
- NFS (Network File Server) uses this
- just specify the server name and RPC service
- allows multiple services on the same port

RPC: Really Like a Function Call? (1)

What if something fails?

```
result = myprotocol_mkdir(ctx, "/directory/name");
```

What should result be?

Did the server make the directory?

RPC: Really Like a Function Call (2)

RPC for high-level POSIX IO?

```
RemoteFile* rfh = remoteio_open(ctx, "foo.txt");
remoteio_puts(ctx, rfh, "Text.\n");
remoteio_close(ctx, rfh);
```

What happens ***if client fails***? Will the file be left open forever?

Note: not a problem for normal applications – the process dies, its files are closed.

RPC: Really Like a Function Call? (3)

```
for (big list of directories) {
  myprotocol_mkdir(ctx, current-name);
}
```

Local procedure call: ~1 ns

Local system call: ~100 ns

Network part ***only*** of remote procedure call:

- with typical ***local*** network: >400 000 ns
- with ***exceptionally fast*** local network: 2 600 ns

RPC Locally

Doesn't need to be used between different machines – maybe just different address spaces

Gives **location transparency**

- Move service whereever convenient
- Easier to treat one machine as a big machine

Much faster implementations available locally

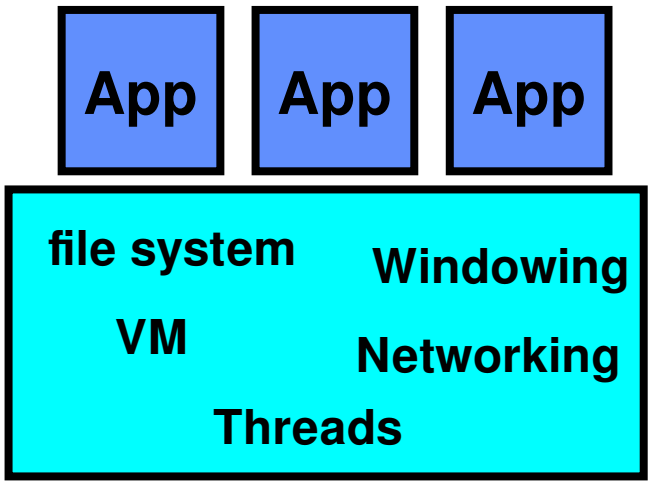
- **Shared memory**

Interlude: Microkernels (1)

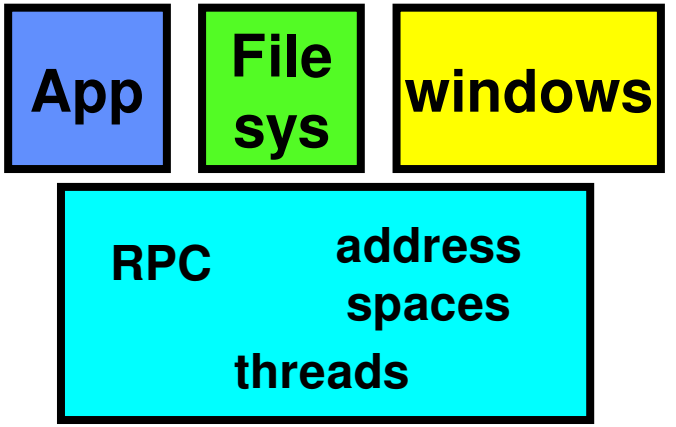
Split OS into **separate processes**

- Example: Filesystem, Network driver is external process

Use RPC to these components instead of system calls



Monolithic Structure

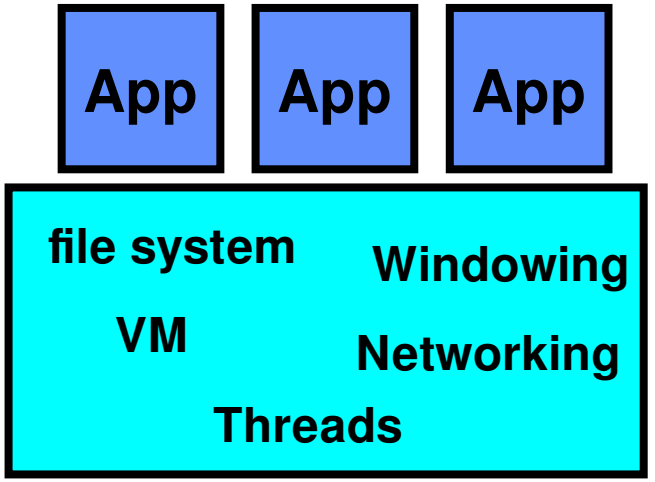


Microkernel Structure

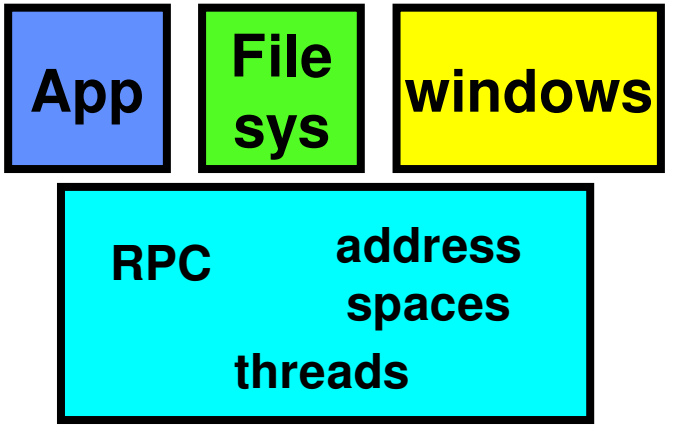
Interlude: Microkernels (2)

Microkernel provides **only services it "needs" to**:

- communication
- address space management
- thread scheduling
- almost-direct access to devices for service processes



Monolithic Structure



Microkernel Structure

Interlude: Why Microkernels?

Pro

- **Failure isolation**
- Easier to update/replace parts
- Easier to distribute – way to build OS that runs "across many machines"

Con

- More communication overhead/context switches
- Maybe harder to program?

Recall: What is an operating system?

Always:

- ***Memory management***
- I/O management
- ***CPU scheduling***
- ***Communication?***

Core OS service – not provided by kernel in "true" microkernel design

Sometimes:

- Filesystems
- ? Multimedia support
- ? User interface
- ? Internet browser

Microkernels in the Wild

Does anyone use a microkernel?

- Yes. Some embedded-targetted systems (Symbian, QNX, (se)L4)
- Some less "pure" microkernel than others (maybe some device drivers not separate services)

Many OSs provide *some services* like a microkernel

- OS X, Linux: Windowing (graphics + user inputs)

Some OSs started with microkernels

- Windows NT/XP/2000+/7/8: originally microkernel design (changed for performance?)
- OS X: hybrid of Mach microkernel and FreeBSD monolithic kernel

Distributed Operating Systems

Microkernel design lets OS be placed across a set of machines – just implement RPC, applications don't need to know

Questions:

- What about machine failures?
- What about the slowness of intermachine calls?
- What about sharing memory between machines?
- What about moving processes to/starting processes on remote machines?

Distributed Operating Systems

Microkernel design lets OS be placed across a set of machines – just implement RPC, applications don't need to know

Questions:

- Wh
- What about the slowness of intermachine calls?
- ***What about sharing memory between machines?***
- ***What about moving processes to/starting processes on remote machines?***

Good solutions to these problems – out of scope for this course

Distributed Operating Systems

Microkernel design lets OS be placed across a set of machines – just implement RPC, applications don't need to know

Questions:

- ***What about machine failures?***
- ***What about the slowness of intermachine calls?***
- Wha
- Wha
  remo

s on

Can live with these problems, but ... not great.

More recently: fault-tolerant designs, application awareness of locality

Summary: Networks

Network: physical connection that allows two computers to communicate

- Packet: sequence of bits carried over the network

Broadcast Network: Shared Communication Medium

- Transmitted packets sent to all receivers
- Arbitration: act of negotiating use of shared medium
  - Ethernet: Carrier Sense, Multiple Access, Collision Detect

Point-to-point network: a network in which every physical wire is connected to only two computers

- Switch: a bridge that transforms a shared-bus (broadcast) configuration into a point-to-point network.

Summary: Example Protocols

Protocol: Agreement between two parties as to how information is to be transmitted

Internet Protocol (IP)

- Used to route messages through routes across globe
- 32-bit addresses, 16-bit ports

DNS: System for mapping from names to IP addresses

- Hierarchical mapping from authoritative domains

Remote Procedure Call (RPC): Call procedure on remote machine

- Provides same interface as procedure
- Automatic packing and unpacking of arguments without user programming (in stub)