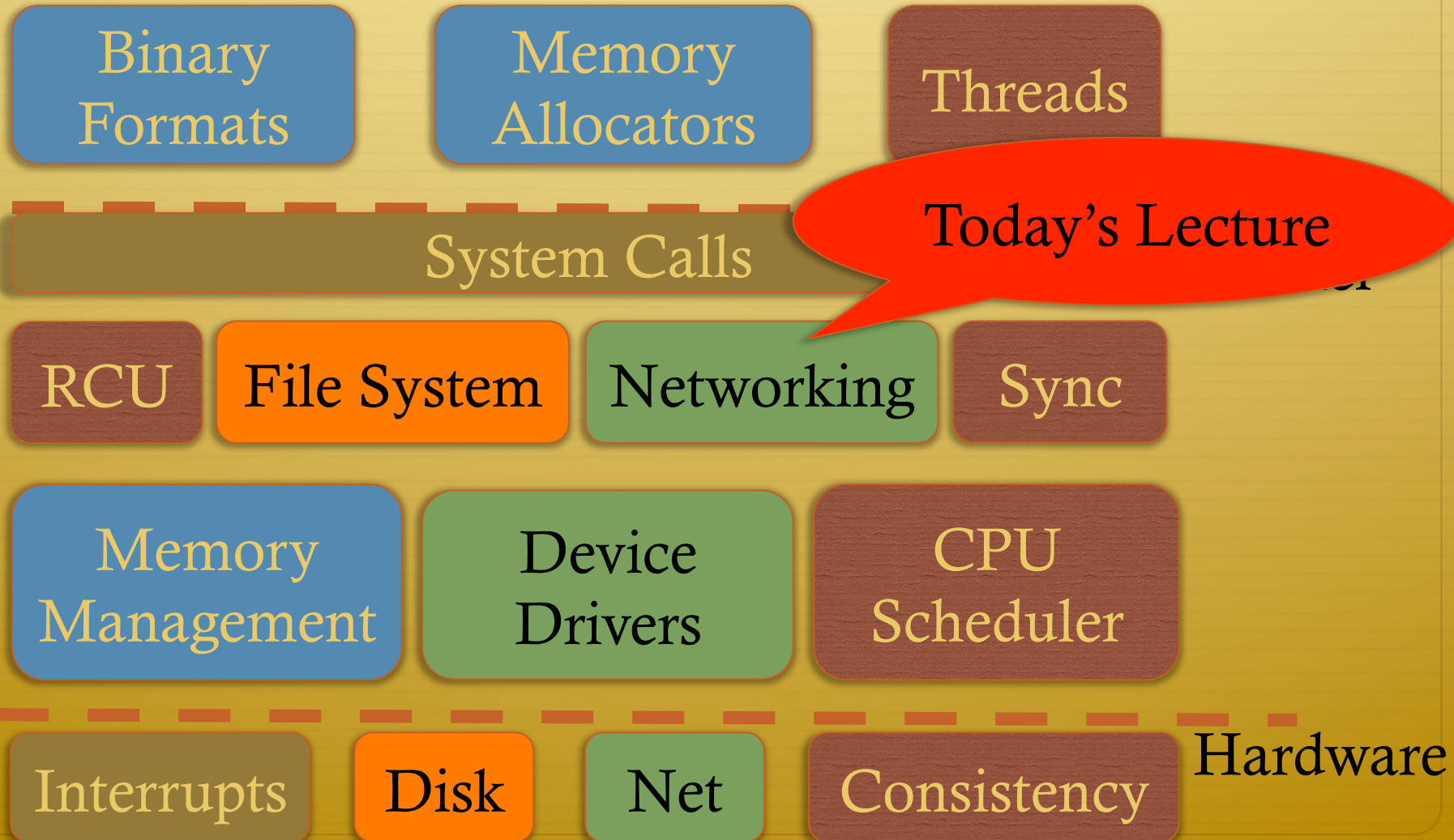


Logical Diagram



Networking (2 parts)



✦ Goals:

- ✦ Review networking basics
- ✦ Discuss APIs
- ✦ Trace how a packet gets from the network device to the application (and back)
- ✦ Understand Receive livelock and NAPI

4 to 7 layer diagram

(from Understanding Linux Network Internals)

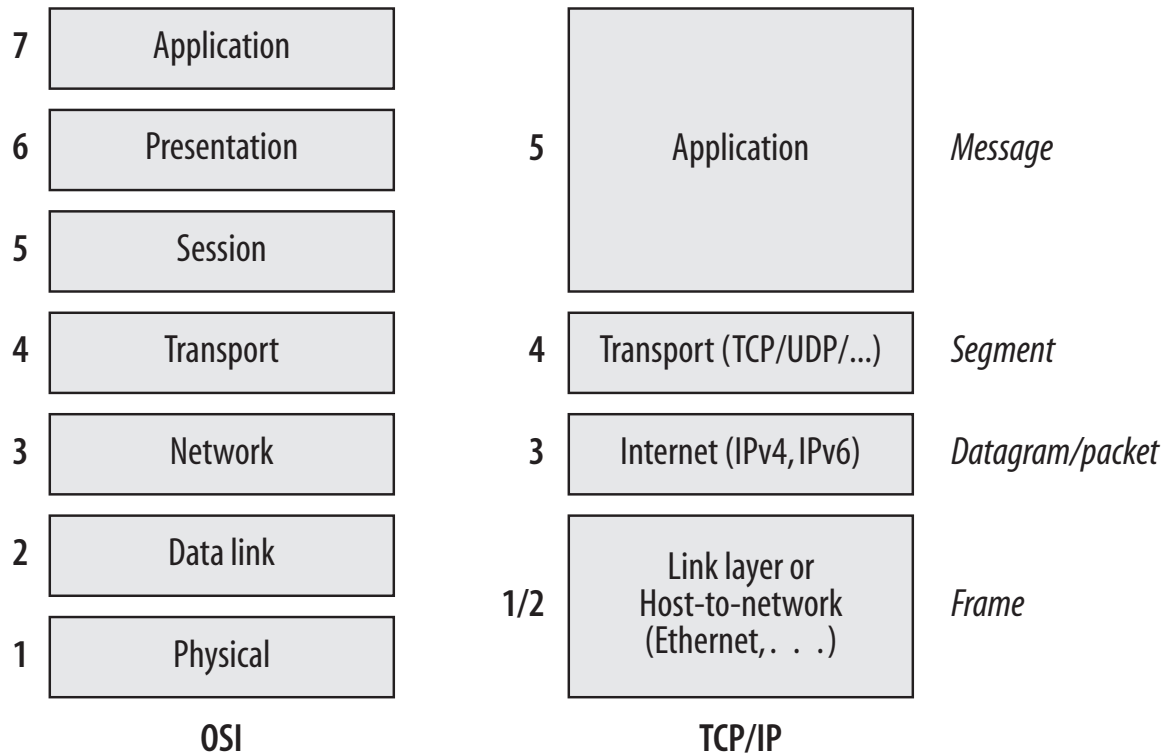


Figure 13-1. OSI and TCP/IP models

Nomenclature



- ✦ Frame: hardware
- ✦ Packet: IP
- ✦ Segment: TCP/UDP
- ✦ Message: Application

TCP/IP Reality



- ✦ The OSI model is great for undergrad courses
- ✦ TCP/IP (or UDP) is what the majority of programs use
 - ✦ Some random things (like networked disks) just use ethernet + some custom protocols

Ethernet

(or 802.2 or 802.3)

- ✦ All slight variations on a theme (3 different standards)
- ✦ Simple packet layout:
 - ✦ Header: Type, source MAC address, destination MAC address, length, (and a few other fields)
 - ✦ Data block (payload)
 - ✦ Checksum
- ✦ Higher-level protocols “nested” inside payload
- ✦ “Unreliable” – no guarantee a packet will be delivered

Ethernet History



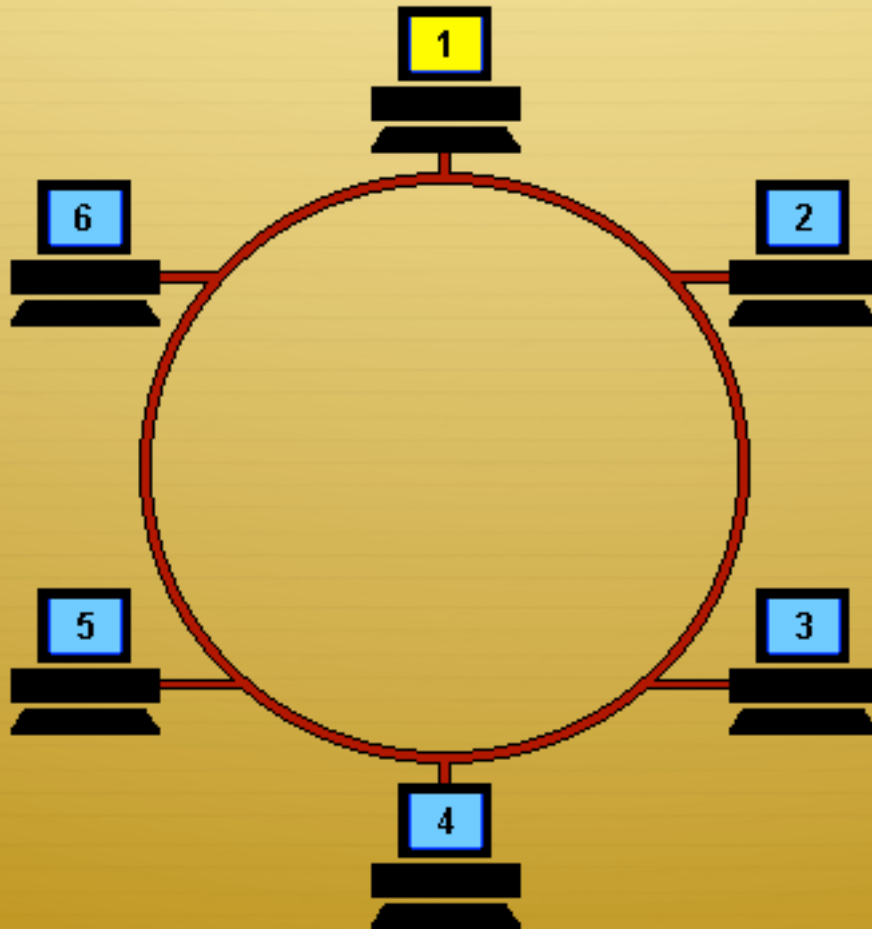
- ✦ Originally designed for a shared wire (e.g., coax cable)
- ✦ Each device listens to all traffic
 - ✦ Hardware filters out traffic intended for other hosts
 - ✦ I.e., different destination MAC address
 - ✦ Can be put in “promiscuous” mode, and record everything (called a network sniffer)
- ✦ Sending: Device hardware automatically detects if another device is sending at same time
 - ✦ Random back-off and retry

Early competition

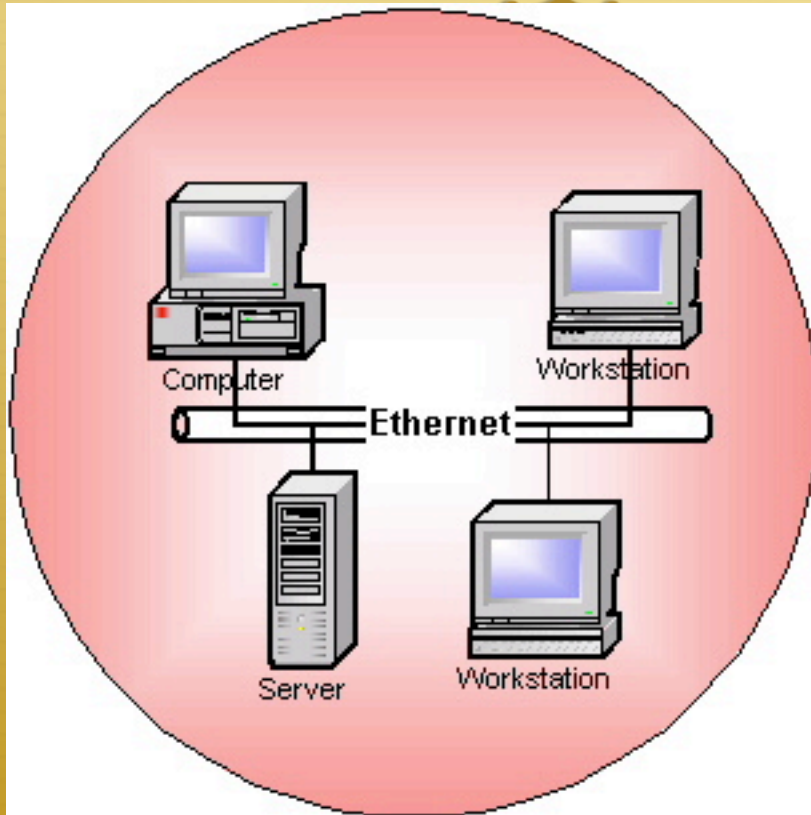


- ✦ Token-ring network: Devices passed a “token” around
 - ✦ Device with the token could send; all others listened
 - ✦ Like the “talking stick” in a kindergarten class
- ✦ Send latencies increased proportionally to the number of hosts on the network
 - ✦ Even if they weren’t sending anything (still have to pass the token)
- ✦ Ethernet has better latency under low contention and better throughput under high

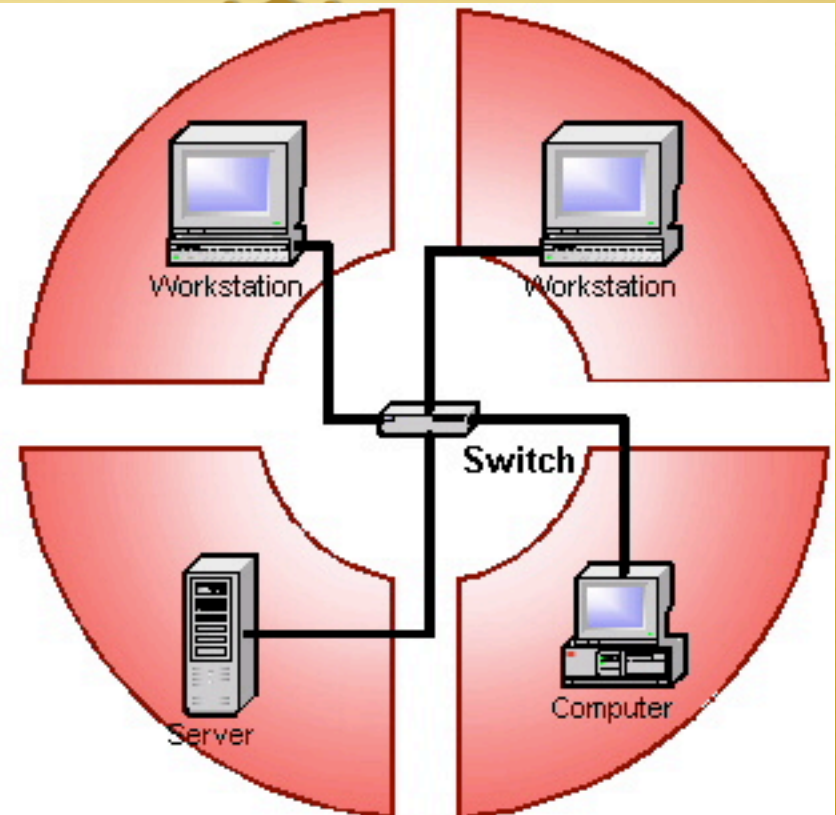
Token ring



Shared vs Switched

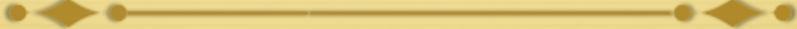


Shared Ethernet: 1 collision domain for multiple nodes. The possibility of collisions. Non-deterministic



Switched Full Duplex Ethernet: 1 collision domain per node. Use of switch. No possibility of collisions. Deterministic.

Switched networks



- ✦ Modern ethernets are switched
- ✦ What is a hub vs. a switch?
 - ✦ Both are a box that links multiple computers together
 - ✦ Hubs broadcast to all plugged-in computers (let computers filter traffic)
 - ✦ Switches track who is plugged in, only send to expected recipient
 - ✦ Makes sniffing harder ☹

Internet Protocol (IP)



- ✦ 2 flavors: Version 4 and 6
 - ✦ Version 4 widely used in practice---today's focus
- ✦ Provides a network-wide unique device address (IP address)
- ✦ This layer is responsible for routing data across multiple ethernet networks on the internet
 - ✦ Ethernet packet specifies its payload is IP
 - ✦ At each router, payload is copied into a new point-to-point ethernet frame and sent along

Transmission Control Protocol (TCP)

- ✦ Higher-level protocol that layers end-to-end reliability, transparent to applications
 - ✦ Lots of packet acknowledgement messages, sequence numbers, automatic retry, etc.
 - ✦ Pretty complicated
- ✦ Applications on a host are assigned a *port* number
 - ✦ A simple integer from 0-64k
 - ✦ Multiplexes many applications on one device
 - ✦ Ports below 1k reserved for privileged applications

User Datagram Protocol (UDP)

- ✦ The simple alternative to TCP
 - ✦ None of the frills (no reliability guarantees)
- ✦ Same port abstraction (1-64k)
 - ✦ But different ports
 - ✦ I.e., TCP port 22 isn't the same port as UDP port 22

Some well-known ports



- ✦ 80 – http
- ✦ 22 – ssh
- ✦ 53 – DNS
- ✦ 25 – SMTP

Example

(from Understanding Linux Network Internals)

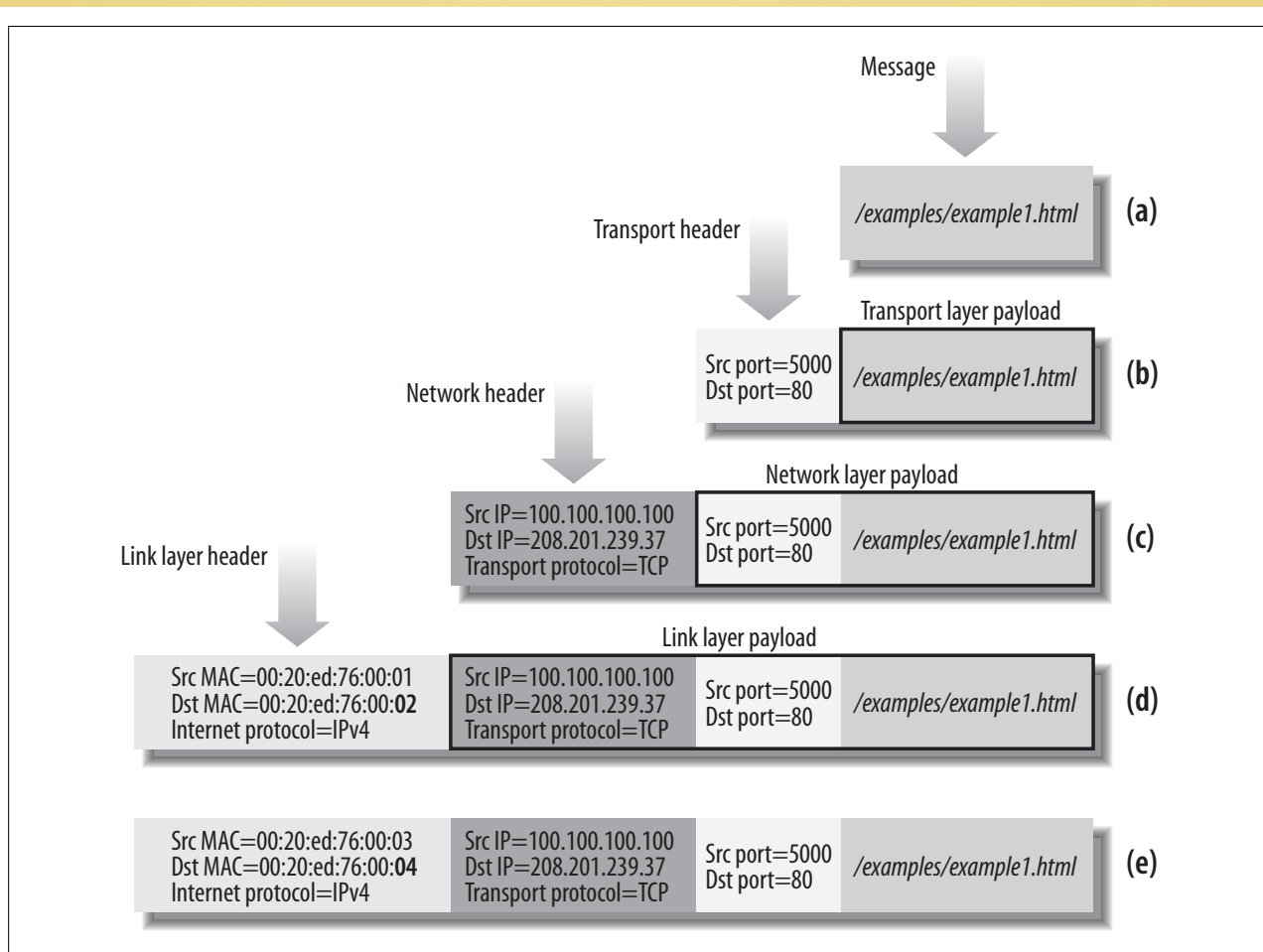


Figure 13-4. Headers compiled by layers: (a...d) on Host X as we travel down the stack; (e) on Router RT1

Networking APIs



- ✦ Programmers rarely create ethernet frames
- ✦ Most applications use the **socket** abstraction
 - ✦ Stream of messages or bytes between two applications
 - ✦ Applications still specify: protocol (TCP vs. UDP), remote host address
 - ✦ Whether reads should return a stream of bytes or distinct messages
- ✦ While many low-level details are abstracted, programmers must understand basics of low-level protocols

Sockets, cont.



- ✦ One application is the **server**, or **listens** on a pre-determined port for new connections
- ✦ The **client connects** to the server to create a message channel
- ✦ The server **accepts** the connection, and they begin exchanging messages

Creation APIs



- ✦ `int socket(domain, type, protocol)` – create a file handle representing the communication endpoint
 - ✦ Domain is usually `AF_INET` (IP4), many other choices
 - ✦ Type can be `STREAM`, `DGRAM`, `RAW`
 - ✦ Protocol – usually 0
- ✦ `int bind(fd, addr, addrlen)` – bind this socket to a specific port, specified by `addr`
 - ✦ Can be `INADDR_ANY` (don't care what port)

Server APIs



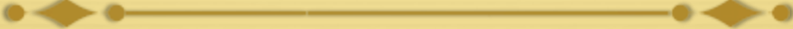
- ✦ `int listen(fd, backlog)` – Indicate you want incoming connections
 - ✦ Backlog is how many pending connections to buffer until dropped
- ✦ `int accept(fd, addr, len, flags)` – Blocks until you get a connection, returns where from in `addr`
 - ✦ Return value is a new file descriptor for child
 - ✦ If you don't like it, just close the new `fd`

Client APIs



- ✦ Both client and server create endpoints using `socket()`
 - ✦ Server uses `bind`, `listen`, `accept`
 - ✦ Client uses `connect(fd, addr, addrlen)` to connect to server
- ✦ Once a connection is established:
 - ✦ Both use `send/recv`
 - ✦ Pretty self-explanatory calls

Client/server toy example



✦ Quick demo ..

✦ Client/server code from

http://www.linuxhowtos.org/C_C++/socket.htm

Linux implementation



- ✦ Sockets implemented in the kernel
 - ✦ So are TCP, UDP and IP
- ✦ Benefits:
 - ✦ Application doesn't need to be scheduled for TCP ACKs, retransmit, etc.
 - ✦ Kernel trusted with correct delivery of packets
- ✦ A single system call (i386):
 - ✦ `sys_socketcall(call, args)`
 - ✦ Has a sub-table of calls, like `bind`, `connect`, etc.

Plumbing



- ✦ Each message is put in a `sk_buff` structure
- ✦ Between socket/application and device, the `sk_buff` is passed through a stack of protocol handlers
 - ✦ These handlers update internal bookkeeping, wrap payload in their headers, etc.
- ✦ At the bottom is the device itself, which sends/receives the packets

sk_buff

(from Understanding Linux Networking Internals)

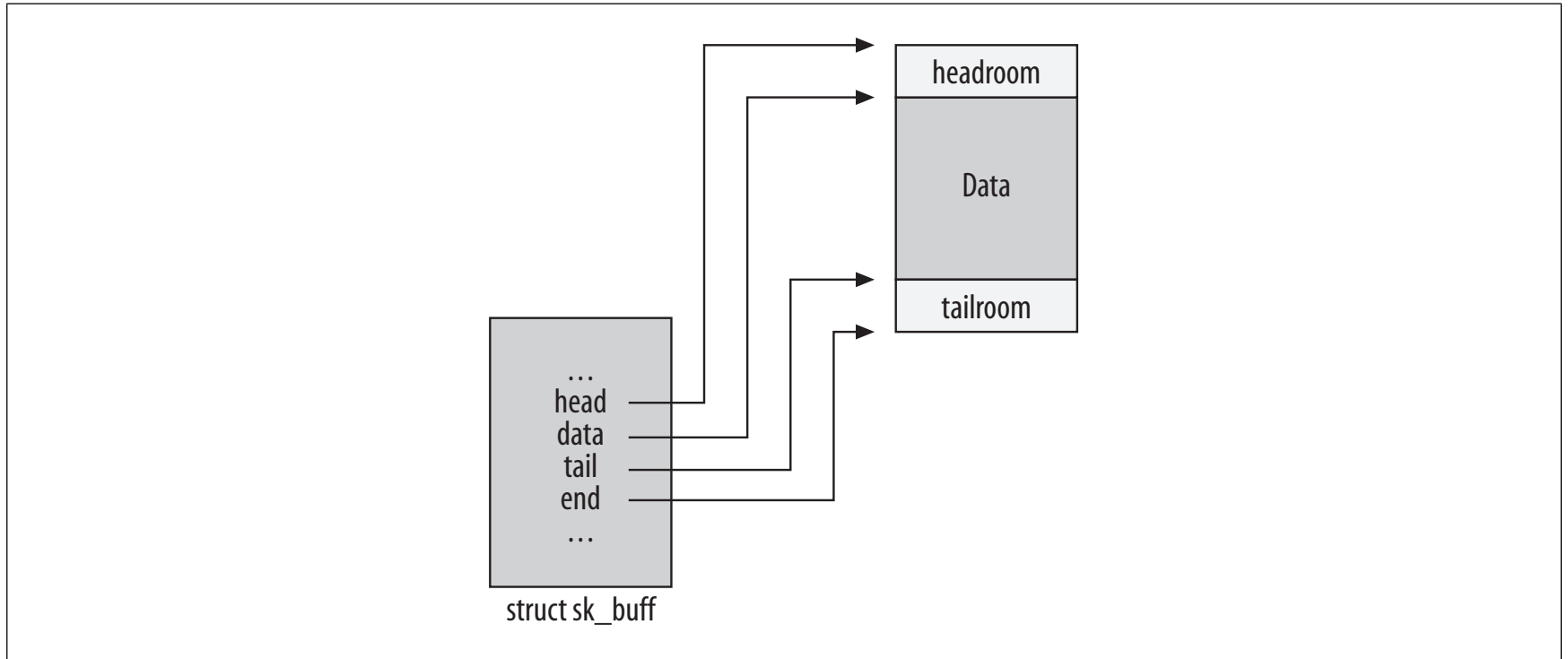
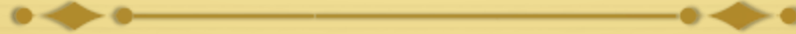


Figure 2-2. head/end versus data/tail pointers

Efficient packet processing



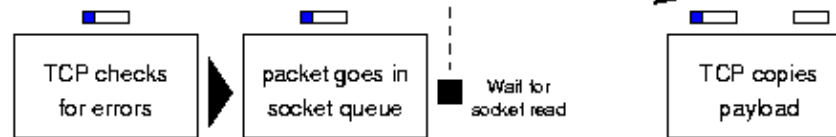
- ✦ Moving pointers is more efficient than removing headers
- ✦ Appending headers is more efficient than re-copy

Walk through how a rcvd packet is processed

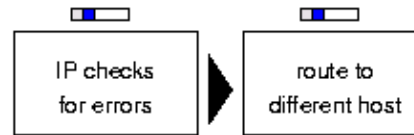
Application



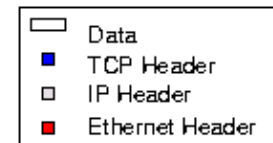
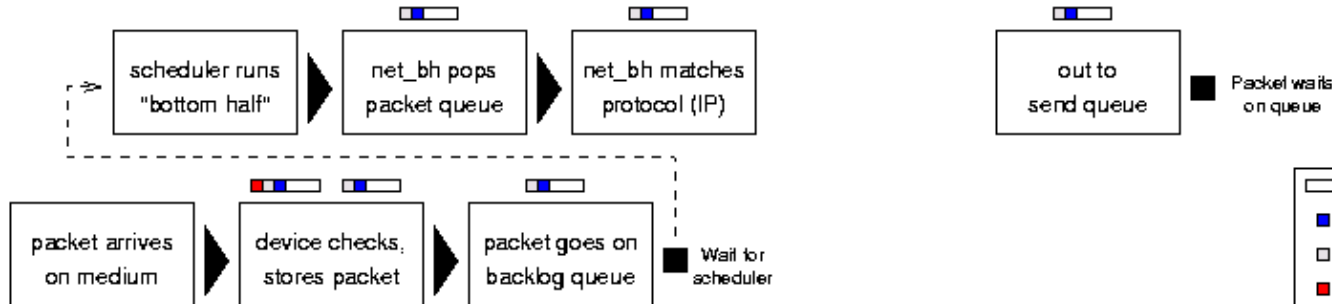
Transport



Internet



Link



Interrupt handler



- ✦ “Top half” responsible to:
 - ✦ Allocate a buffer (`sk_buff`)
 - ✦ Copy received data into the buffer
 - ✦ Initialize a few fields
 - ✦ Call “bottom half” handler
- ✦ In some cases, `sk_buff` can be pre-allocated, and network card can copy data in (DMA) before firing the interrupt
 - ✦ Lab 6 will follow this design

Quick review



- ✦ Why top and bottom halves?
 - ✦ To minimize time in an interrupt handler with other interrupts disabled
 - ✦ Gives kernel more scheduling flexibility
 - ✦ Simplifies service routines (defer complicated operations to a more general processing context)

Digression: Softirqs



- ✦ A hardware IRQ is the hardware interrupt line
 - ✦ Also used for hardware “top half”
- ✦ Soft IRQ is the associated software “interrupt” handler
 - ✦ Or, “bottom half”
- ✦ How are these implemented in Linux?
 - ✦ Two canonical ways: Softirq and Tasklet
 - ✦ More general than just networking

Softirqs



- ✦ Kernel's view: per-CPU work lists
 - ✦ Tuples of <function, data>
- ✦ At the right time, call function(data)
 - ✦ Right time: Return from exceptions/interrupts/sys. calls
 - ✦ Also, each CPU has a kernel thread ksoftirqd_CPU# that processes pending requests
 - ✦ ksoftirqd is nice +19. What does that mean?
 - ✦ Lowest priority – only called when nothing else to do

Softirqs, cont.



- ✦ Device programmer's view:
 - ✦ Only one instance of a softirq function will run on a CPU at a time
 - ✦ Doesn't need to be reentrant
 - ✦ **reentrant** if it can be interrupted in the middle of its execution and then safely called again ("re-entered") before its previous invocations complete execution
 - ✦ If interrupted, won't be called again by interrupt handler
 - ✦ Subsequent calls enqueued!
 - ✦ One instance can run on each CPU concurrently, though
 - ✦ Must use locks

Tasklets



- ✦ For the faint of heart (and faint of locking prowess)
- ✦ Constrained to only run one at a time on any CPU
 - ✦ Useful for poorly synchronized device drivers
 - ✦ Say those that assume a single CPU in the 90's
 - ✦ Downside: If your driver uses tasklets, and you have multiple devices of the same type---the bottom halves of different devices execute serially

Softirq priorities



- ✦ Actually, there are 6 queues per CPU; processed in priority order:
 - ✦ HI_SOFTIRQ (high/first)
 - ✦ TIMER
 - ✦ NET TX
 - ✦ NET RX
 - ✦ SCSI
 - ✦ TASKLET (low/last)

Observation 1



- ✦ Devices can decide whether their bottom half is higher or lower priority than network traffic (HI or TASKLET)
 - ✦ Example: Video capture device may want to run its bottom half at HI, to ensure quality of service
 - ✦ Example: Printer may not care

Observation 2



- ✦ Transmit traffic prioritized above receive. Why?
 - ✦ The ability to send packets may stem the tide of incoming packets
 - ✦ Obviously eliminates retransmit requests based on timeout
 - ✦ Can also send “back-off” messages

Receive bottom half



- ✦ For each pending `sk_buff`:
 - ✦ Pass a copy to any taps (sniffers)
 - ✦ Do any MAC-layer processing, like bridging
 - ✦ Pass a copy to the appropriate protocol handler (e.g., IP)
 - ✦ Recur on protocol handler until you get to a port
 - ✦ Perform some handling transparently (filtering, ACK, retry)
 - ✦ If good, deliver to associated socket
 - ✦ If bad, drop

Socket delivery



- ✦ Once the bottom half/protocol handler moves a payload into a socket:
 - ✦ Check and see if the task is blocked on input for this socket
 - ✦ If so, wake it up
- ✦ Read/recv system calls copy data into application

Socket sending



- ✦ Send/write system calls copy data into socket
 - ✦ Allocate `sk_buff` for data
 - ✦ Be sure to leave plenty of head and tail room!
- ✦ System call does protocol handling during application's timeslice
 - ✦ Note that receive handling done during `ksoftirqd` timeslice
- ✦ Last protocol handler enqueues a `softirq` to transmit

Transmission



- ✦ Softirq can go ahead and invoke low-level driver to do a send
- ✦ Interrupt usually signals completion
 - ✦ Interrupt handler just frees the sk_buff

Switching gears



- ✦ We've seen the path network data takes through the kernel in some detail
- ✦ Now, let's talk about how network drivers handle heavy loads

Our cup runneth over



- ✦ Suppose an interrupt fires every time a packet comes in
 - ✦ This takes N ms to process the interrupt
- ✦ What happens when packets arrive at a frequency approaching or exceeding N ?
 - ✦ You spend all of your time handling interrupts!
- ✦ Will the bottom halves for any of these packets get executed?
 - ✦ No. They are lower-priority than new packets

Receive livelock



- ✦ The condition that the system never makes progress because it spends all of its time starting to process new packets
- ✦ Real problem: Hard to prioritize other work over interrupts
- ✦ Principle: Better to process one packet to completion than to run just the top half on a million

Receive livelock in practice

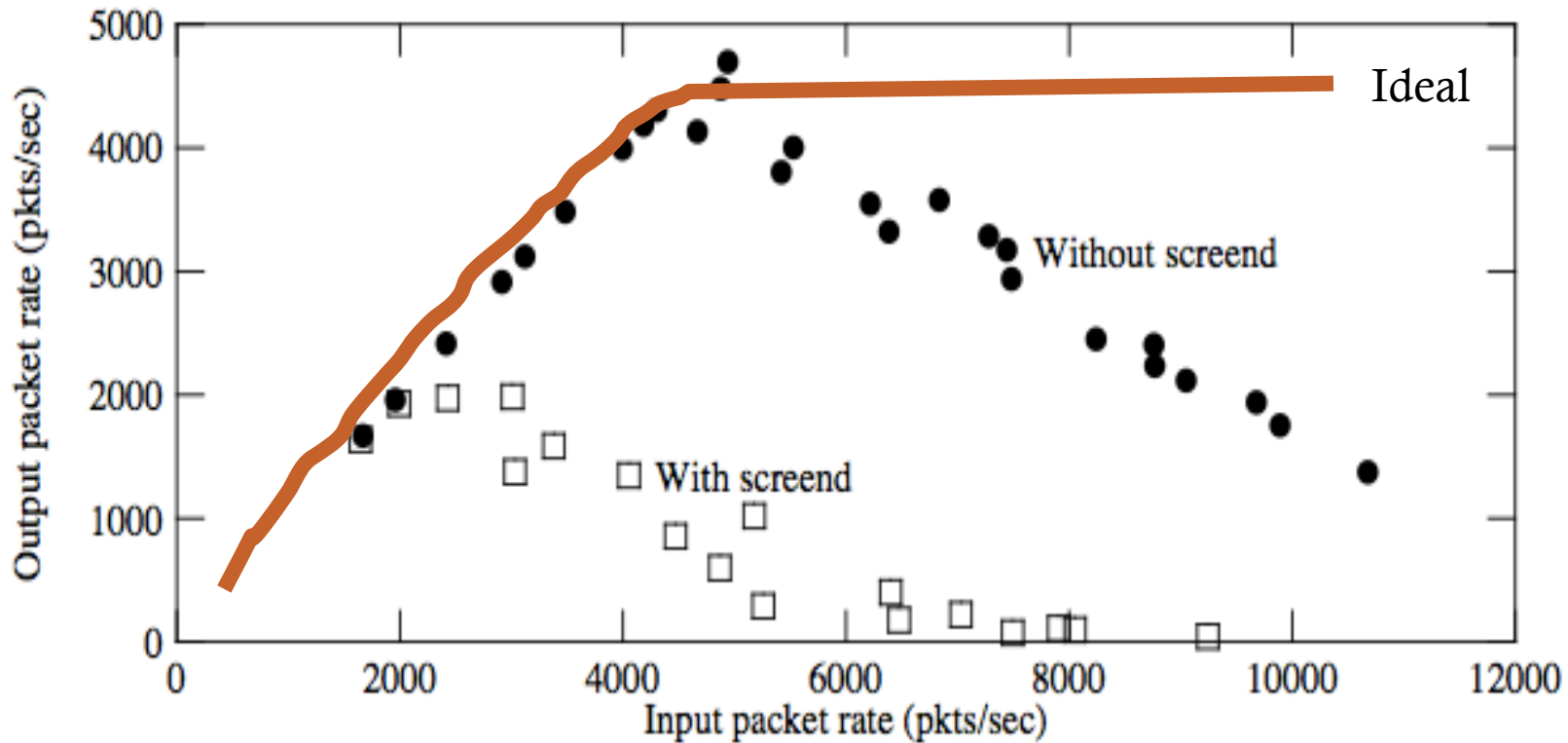


Fig. 2. Forwarding performance of unmodified kernel.

Shedding load



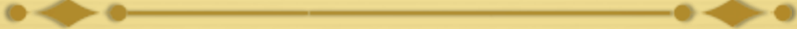
- ✦ If you can't process all incoming packets, you must drop some
- ✦ Principle: If you are going to drop some packets, better do it early!
- ✦ If you quit taking packets off of the network card, the network card will drop packets once its buffers get full

Idea



- ✦ Under heavy load, disable the network card's interrupts
- ✦ Use polling instead
 - ✦ Ask if there is more work once you've done the first batch
- ✦ This allows a packet to make it all the way through all of the bottom half processing, the application, and get a response back out
- ✦ Ensuring some progress! Yay!

Why not poll all the time?



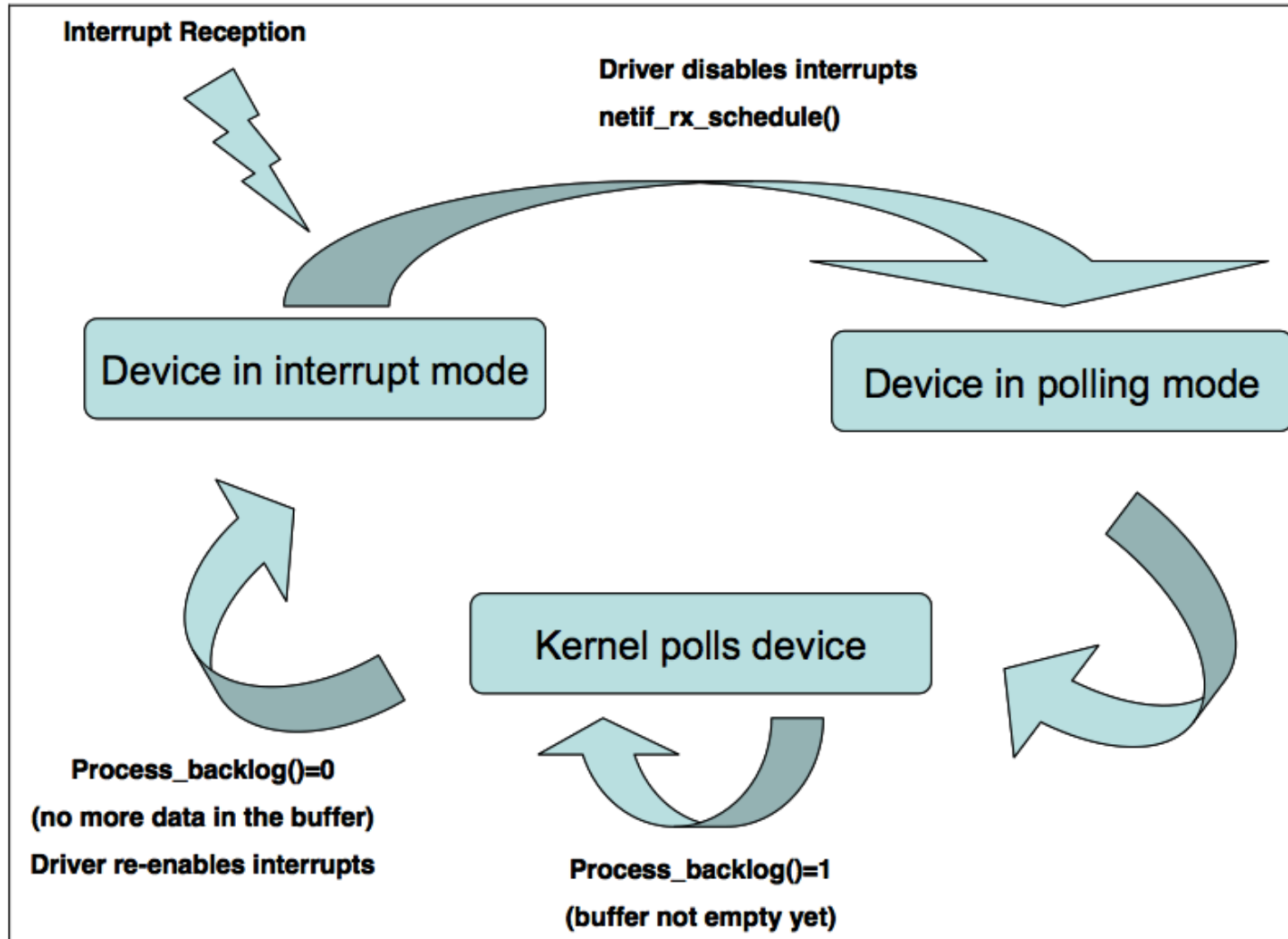
- ✦ If polling is so great, why even bother with interrupts?
- ✦ Latency: When incoming traffic is rare, we want high-priority, latency-sensitive applications to get their data ASAP

General insight

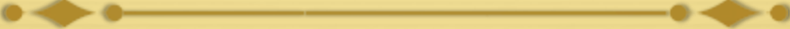


- ✦ If the expected input rate is low, interrupts are better
- ✦ When the expected input rate gets above a certain threshold, polling is better
- ✦ Just need to figure out a way to dynamically switch between the two methods...

Pictorially..



Why haven't we seen this before?



- ✦ Why don't disks have this problem?
- ✦ Inherently rate limited
- ✦ If the CPU is bogged down processing previous disk requests, it can't issue more
- ✦ An external CPU can generate all sorts of network inputs

Linux NAPI



- ✦ Or New API. Seriously.
- ✦ Every driver provides a `poll()` method that does the low-level receive
 - ✦ Called in first step of `softirq` RX function
- ✦ Top half just schedules `poll()` to do the receive as `softirq`
 - ✦ Can disable the interrupt under heavy loads; use timer interrupt to schedule a poll
 - ✦ Bonus: Some rare NICs have a timer; can fire an interrupt periodically, only if something to say!

NAPI



- ✦ Gives kernel control to throttle network input
- ✦ Slow adoption – means some measure of driver rewriting
- ✦ Backwards compatibility solution:
 - ✦ Old top half still creates sk_buffs and puts them in a queue
 - ✦ Queue assigned to a fake “backlog” device
 - ✦ Backlog poll device is scheduled by NAPI softirq
 - ✦ Interrupts can still be disabled

NAPI Summary



- ✦ Too much input is a real problem
- ✦ NAPI lets kernel throttle interrupts until current packets processed
- ✦ Softirq priorities let some devices run their bottom halves before net TX/RX
 - ✦ Net TX handled before RX

General summary



- ✦ Networking basics and APIs
- ✦ Idea of plumbing from socket to driver
 - ✦ Through protocol handlers and softirq poll methods
- ✦ NAPI and input throttling