CSE 506: Operating Systems

Networking & NFS
4 to 7 layer diagram

Figure 13-1. OSI and TCP/IP models
TCP/IP Reality

- The OSI model is great for undergrad courses
- TCP/IP (or UDP) is what the majority of world uses
Ethernet (or 802.2 or 802.3)

- LAN (Local Area Network) connection
- Simple packet layout:
  - Header
    - type
    - source MAC address
    - destination MAC address
    - length (up to 1500 bytes regular, up to 9000 bytes “jumbo”)
    - ...
  - Data block (payload)
  - Checksum
- Higher-level protocols “nested” inside payload
- “Unreliable” – no guarantee packet will be delivered
Ethernet Details

• 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
    • Accept everything, even if destination MAC is not own

• If multiple devices talk at the same time
  – Hardware automatically retries after a random delay
**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 point-to-point and switched
- What is a hub vs. a switch?
  - Both are boxes that link multiple computers together
  - Hubs broadcast to all plugged-in computers
    - Let NICs figure out what to pass to host
      - Promiscuous mode sees everyone’s 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
  – Version 6 should be used in practice – but isn’t
    • Public IPv4 address space is practically exhausted (see arin.net)

• Provides a network-wide unique address (IP address)
  – Along with netmask
  – Netmask determines if IP is on local LAN or not

• If destination not on local LAN
  – Packet sent to LAN’s gateway
  – At each gateway, payload sent to next hop
Address Resolution Protocol (ARP)

- IPs are logical (set in OS with `ifconfig` or `ipconfig`)
- OS needs to know where (physically) to send packet
  - And switch needs to know which port to send it to
- Each NIC has a MAC (Media Access Control) address
  - “physical” address of the NIC
- OS needs to translate IP to MAC to send
  - Broadcast “who has 10.22.17.20?” on the LAN
  - Whoever responds is the physical location
    - Machines can cheat (spoof) addresses by responding
  - ARP responses cached to avoid lookup for each packet
User Datagram Protocol (UDP)

• Simple protocol for communication
  – Send packet, receive packet
  – No association between packets in underlying protocol
    • Application is responsible for dealing with...
      – Packet ordering
      – Lost packets
      – Corruption of content
      – Flow control
      – Congestion

• Applications on a host are assigned a port number
  – A simple integer
  – Multiplexes many applications on one device
  – Ports below 1k reserved for privileged applications
Transmission Control Protocol (TCP)

- Higher-level protocol layers end-to-end reliability
  - Transparent to applications
  - Lots of features
    - packet acks, sequence numbers, automatic retry, etc.
    - Pretty complicated

- Same port abstraction (1-64k)
  - But different ports
  - i.e., TCP port 22 isn’t the same port as UDP port 22
Networking APIs

• Programmers rarely create Ethernet frames
• Most applications use the socket abstraction
  – Stream of messages or bytes between two applications
  – Applications specify protocol (TCP or UDP), remote IP
• `bind() / listen()`: waits for incoming connection
• `connect() / accept()`: connect to remote end
• `send() / recv()`: send and receive data
  – All headers are added/stripped by OS
Linux implementation

• Sockets implemented in the kernel
  – So are TCP, UDP, and IP

• Benefits:
  – Application not involved in TCP ACKs, retransmit, etc.
    • If TCP is implemented in library, app wakes up for timers
  – Kernel trusted with correct delivery of packets

• A single system call:
  – sys_socketcall(call, args)
    • Has a sub-table of calls, like bind, connect, etc.
Linux Plumbing

• Each message is put in a `sk_buff` structure
  – Passed through a stack of protocol handlers
  – Handlers update bookkeeping, wrap headers, etc.

• At the bottom is the device itself (e.g., NIC driver)
  – Sends/receives packets on the wire
sk_buff

struct sk_buff

- head
- data
- tail
- end

Data

headroom
tailroom
Efficient packet processing

• Moving pointers is better than removing headers
• Appending headers is more efficient than re-copy
Received Packet Processing

Application
- application reads from socket
- socket reads from queue
- Wait for data (if necessary)
- socket asks for payload
- application gets data, continues

Transport
- TCP checks for errors
- packet goes in socket queue
- Wait for socket read
- TCP copies payload

Internet
- IP checks for errors
- route to different host
- (See IP Forwarding)

Link
- scheduler runs "bottom half"
- net_bh pops packet queue
- net_bh matches protocol (IP)
- out to send queue
- Packet waits on queue
- packet arrives on medium
- device checks, stores packet
- packet goes on backlog queue
- Wait for scheduler

Source = http://www.cs.unh.edu/cnrg/people/gherrin/linux-net.html#tth_sEc6.2
Interrupt Handler

• “Top half” responsible to:
  – Allocate/get a buffer \((\text{sk\_buff})\)
  – Copy received data into the buffer
  – Initialize a few fields
  – Call “bottom half” handler

• In reality:
  – Systems allocate ring of \(\text{sk\_buffs}\) and give to NIC
  – Just “take” the buff from the ring
    • No need to allocate (was done before)
    • No need to copy data into it (DMA already did it)
SoftIRQs

• A hardware IRQ is the hardware interrupt line
  – Use to trigger the “top half” handler from IDT

• SoftIRQ is the big/complicated software 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 \(<\text{function, data}>\)
- At the right time, call \texttt{function(data)}
  - Right time: Return from exceptions/interrupts/sys. calls
  - Each CPU also has a kernel thread ksoftirqd\_CPU#
    - Processes pending requests
    - In case softirq can’t handle them quickly enough
SoftIRQs

• Device programmer’s view:
  – Only one instance of SoftIRQ will run on a CPU at a time
    • Doesn’t need to be reentrant
      – If interrupted by HW interrupt, will not be called again
        » Guaranteed that invocation will be finished before start of next
  – One instance can run on each CPU concurrently
    • Must use spinlocks to avoid conflicting on data structures
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
    • Those that assume a single CPU in the 90’s
  – Downside: All bottom halves are serialized
    • Regardless of how many cores you have
    • Even if processing for different devices of the same type
      – e.g., multiple disks using the same driver
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 number
      – Perform some handling transparently (filtering, ACK, retry)
    • If good, deliver to associated socket
    • If bad, drop
Socket delivery

• Once bottom half moves payload into a socket:
  – Check to see if task is blocked on input for this socket
    • If yes, wake it up corresponding process

• 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 handles protocol in application’s timeslice
  – Receive handling not counted toward app
• Last protocol handler enqueues packet for transmit
Receive livelock

• Condition when system never makes progress
  – Spends all time starting to process new packets
• Hard to prioritize other work over interrupts
• Better 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.

Source: Mogul & Ramakrishnan, ToCS 96
Shedding load

• If can’t process all incoming packets
  – Must drop some

• If going to drop some packets, better do it early!
  – Stop taking packets off of the network card
    • NIC will drop packets once its buffers get full on its own
Polling Instead of Interrupts

• Under heavy load, disable NIC interrupts
• Use polling instead
  – Ask if there is more work once you’ve done the first batch
• Allows packet go through bottom half processing
  – And the application, and then get a response back out
  – Ensures some progress
Why not poll all the time?

• If polling is so great, why bother with interrupts?
• Latency
  – If incoming traffic is rare, want high-priority
    • Latency-sensitive applications get their data ASAP
    • Ex.: annoying to wait at ssh prompt after hitting a key
General Insight on Polling

• If the expected input rate is low
  – Interrupts are better

• When expected input rate is above threshold
  – Polling is better

• Need way to dynamically switch between methods
Interrupt Reception

Driver disables interrupts
netif_rx_schedule()

Device in interrupt mode

Device in polling mode

Kernel polls device

Process_backlog()=0
(no more data in the buffer)
Driver re-enables interrupts

Process_backlog()=1
(buffer not empty yet)
Why is this only relevant to networks?

• Why don’t disks have this problem?
  – Inherently rate limited

• If CPU is too busy processing previous disk requests
  – It can’t issue more

• External CPU can generate all sorts of network inputs
Linux NAPI

• “New API”

• Drivers provides `poll()` for low-level receive
  – Called in first step of softirq RX function

• Top half schedules `poll()` to do receive as softirq
  – Can disable the interrupt under heavy loads
    • Use timer interrupt to schedule a poll
  – Bonus: Some NICs have a built-in timer
    • Can fire an interrupt periodically, only if something to say!

• Gives kernel control to throttle network input
Linux NAPI and Legacy Drivers

• Slow adoption – drivers need to be rewritten
• Backwards compatibility solution:
  – Old top half 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 on NIC
NFS

CLIENT
- System Calls
  - VNODE/VFS
    - PC Filesystem
      - Floppy
    - 4.2 Filesystem
      - Disk
    - NFS Filesystem
      - RPC / XDR

SERVER
- System Calls
  - VNODE/VFS
    - Server Routines
      - RPC / XDR

Network
Intuition

• Instead of translating VFS requests into disk accesses
  – Translate them into remote procedure calls to server
• Easy, right?
Challenges

- Server can crash or be disconnected
- Client can crash or be disconnected
- How to coordinate multiple clients on same file?
- Security
Disconnection

- Machine can crash between writes to the hard drive
  - Client can crash between writes to the server
- Server must recover if client fails between requests
  - Simple protocols (e.g., send block updates) won’t work
    - Client disconnects after marking block in use, before referencing it
  - When is it safe to reclaim the block?
    - What if, 3 months later, the client tries to use the block?
Stateful protocols

- Stateful protocols persist state across requests
  - Like the example on previous slide
- Server Challenges:
  - Knowing when a connection has failed (timeout)
  - Tracking state that needs to be cleaned up on a failure
- Client Challenges:
  - If server thinks we failed (timeout)
    - Must recreate server state to make progress
Stateless protocol

• The (potentially) simpler alternative:
  – All necessary state is sent with a single request
  – Server implementation much simpler!

• Downside:
  – May introduce more complicated messages
    • And more messages in general
NFS is stateless

• Every request sends all needed info
  – User credentials (for security checking)
  – File identifier and offset

• Each request matches VFS operation
  – e.g., write, delete, stat
Challenge: Lost request?

• Request sent to NFS server, no response received
  – Did the message get lost in the network (UDP)?
  – Did the server die?
  – Is the server slow?
    • Don’t want to do things twice
      – Bad idea: write data at the end of a file twice

• Idea: Make all requests idempotent
  – Requests have same effect when executed multiple times
    • Ex: write() has an explicit offset, same effect if done 2x
Challenge: Inode reuse

- Process A opens file ‘foo’
  - Maps to inode 30
- Process B unlinks file ‘foo’
  - On local system, OS holds reference to the inode
    - Blocks belonging to file ‘foo’ not reused
  - NFS is stateless, server doesn’t know about open handle
    - The file can be deleted and the inode reused
    - Next request for inode 30 will go to the wrong file
- Idea: Generation numbers
  - If inode in NFS is recycled, generation number is incremented
  - Client requests include an inode + generation number
    - Enables detecting attempts to access an old inode
Challenge: Security

• Local UID/GID passed as part of the call
  – UIDs must match across systems
  – Yellow pages (yp) service; evolved to NIS
  – Replaced with LDAP or Active Directory

• Root squashing: “root” (UID 0) mapped to “nobody”
  – Ineffective security
    • Can send any UID in the NFS packet
    • With root access on NFS client, “su” to another user to get UID
Challenge: File locking

• Must have way to change file without interference
  – Get a server-side lock
    • What happens if the client dies?
    • Lots of options (timeouts, etc), mostly bad
  – Punted to a separate, optional locking service
    • With ugly hacks and timeouts
Challenge: Removal of open files

• Unix allows accessing deleted files if still open
  – Reference in in-memory inode prevents cleanup
    • Applications expect this behavior
      – How to deal with it with NFS?

• On client, check if file is open before removing it
  – If yes, rename file instead of deleting it
    • .nfs* files in modern NFS
  – When file is closed, delete temp file
    • If client crashes, garbage file is left over 😞
Challenge: Time synchronization

- Each CPU’s clock ticks at slightly different rates
  - These clocks can drift over time
- Tools like ‘make’ use timestamps
  - Clock drift can cause programs to misbehave
    make[2]: warning: Clock skew detected. Your build may be incomplete.
- Systems using NFS must have clocks synchronized
  - Usually with external protocol like NTP
    - Synchronization depends on unknown communication delay
      - Very complex protocol
      - Works pretty well in practice
Challenge: Caches and Consistency

- Clients A and B have file in their cache
- Client A writes to the file
  - Data stays in A’s cache
  - Eventually flushed to the server
- Client B reads the file
  - Does B see the old contents or the new file contents?
    - Who tells B that the cache is stale?
      - Server can tell
        » But only after A actually wrote/flushed the data
Consistency/Performance Tradeoff

• Performance: cache always, write when convenient
  – Other clients can see old data, or make conflicting updates

• Consistency: write everything immediately
  – And tell everyone who may have it cached
  – Much more network traffic, lower performance
  – Common case: accessing an unshared file
Close-to-Open Consistency

• NFS Model: Flush all writes on a close
• When opening file, get latest version on the server
  – Copy entire file from server into local cache
  – Odd behavior when multiple clients use the same file
    • Probably a reasonable compromise
  – What if the file is really big?
    • How big is “really big”?
NFS Evolution

• The simple protocol was version 2
• Version 3 (1995):
  – 64-bit file sizes and offsets (large file support)
  – Bundle attributes with other requests to eliminate stat()
  – Other optimizations
  – Still widely used today

• Attempts to address many of the problems of v3
  – Security (eliminate homogeneous UID assumptions)
  – Performance

• Becomes a stateful protocol

• pNFS – extensions for parallel distributed accesses

• Too advanced for its own good
  – Much more complicated than v3
    • Slow adoption
  – Barely being phased in now
    • With hacks that lose some of the features (looks more like v3)