CS162
Operating Systems and Systems Programming
Lecture 22

Networking II

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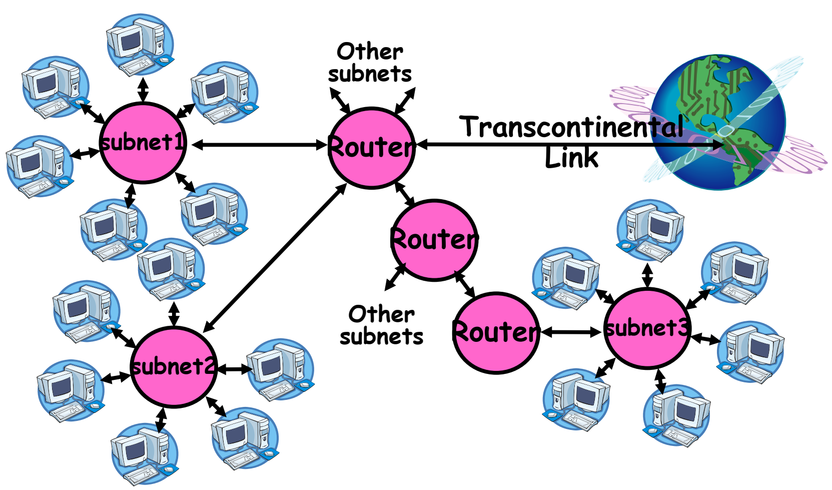
Review: Networking

- 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.
- Internet Protocol (IP): unreliable packet service
  - Used to route messages across globe
  - 32-bit destination addresses
- Routing: the process of forwarding packets hop-by-hop through routers to reach their destination
  - Internet has networks of many different scales
    - » LANs, Autonomous Systems (AS), etc.
  - Different algorithms run at different scales
    - » Border Gateway Protocol (BGP) at large scales
    - » Variants of Distance Vector (DV) protocols at short scales

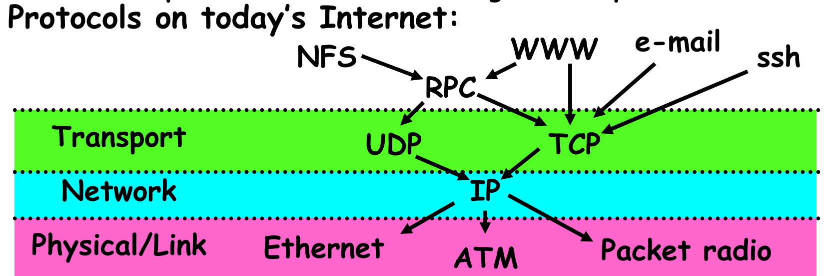
Review: Hierarchical Networking (The Internet)

- How can we build a network with millions of hosts?
  - Hierarchy! Not every host connected to every other one
  - Use a network of Routers to connect subnets together



Review: Network Protocols

- Protocol: Agreement between two parties as to how information is to be transmitted
  - Example: system calls are the protocol between the operating system and application
  - Networking examples: many levels
    - » Physical level: mechanical and electrical network (e.g. how are 0 and 1 represented)
    - » Link level: packet formats/error control (for instance, the CSMA/CD protocol)
    - » Network level: network routing, addressing
    - » Transport Level: reliable message delivery
- Protocols on today's Internet:

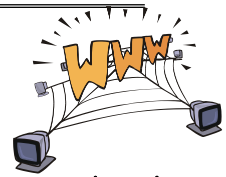


Goals for Today

- Networking
  - Reliable Messaging
    - » TCP windowing and congestion avoidance
  - Two-phase commit

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne

Network Layering



- **Layering:** building complex services from simpler ones
  - Each layer provides services needed for higher layers by utilizing services provided by lower layers
- Our goal in the following is to show how to construct a secure, ordered, arbitrary-sized message service routed to anywhere:

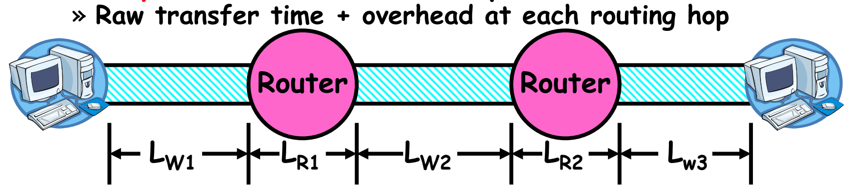
Physical Reality: Packets	Abstraction: Messages
Limited Size	Arbitrary Size
Unordered (sometimes)	Ordered
Unreliable	Reliable
Machine-to-machine	Process-to-process
Only on local area net	Routed anywhere
Asynchronous	Synchronous
Insecure	Secure

Basic Networking Limitations

- The physical/link layer is pretty limited
  - Packets of limited size
    - » Maximum Transfer Unit (MTU): often 200-1500 bytes
  - Packets can get lost or garbled
  - Hardware routing limited to physical link or switch
  - Physical routers crash/links get damaged
    - » Famous Baltimore tunnel fire (July 2001): cut Internet half
- **Datagram:** an independent, self-contained network message whose arrival, arrival time, and content are not guaranteed
- Need resilient routing algorithms to send messages on wide area
  - Multi-hop routing mechanisms
  - Redundant links/Ability to route around failed links
- Handling Arbitrary Sized Messages:
  - Must deal with limited physical packet size
  - Split big message into smaller ones (called fragments)
    - » Must be reassembled at destination
    - » May happen on demand if packet routed through areas of reduced MTU (e.g. TCP)
  - Checksum computed on each fragment or whole message

Performance Considerations

- Before continuing, need some performance metrics
  - **Overhead:** CPU time to put packet on wire
  - **Throughput:** Maximum number of bytes per second
    - » Depends on "wire speed", but also limited by slowest router (routing delay) or by congestion at routers
  - **Latency:** time until first bit of packet arrives at receiver
    - » Raw transfer time + overhead at each routing hop



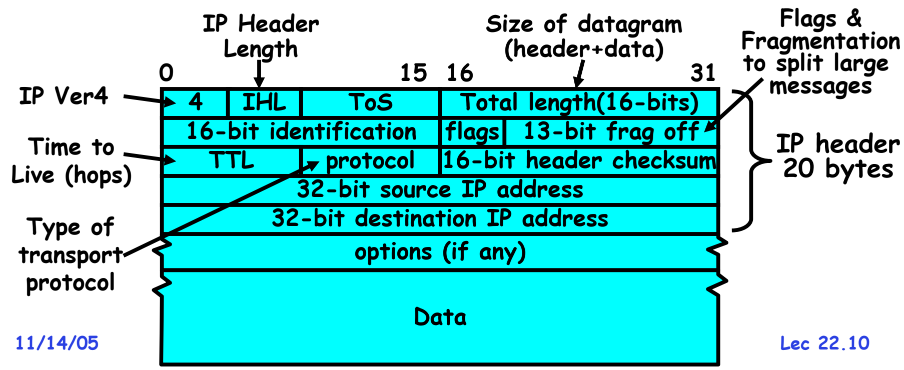
- Contributions to Latency
  - Wire latency: depends on speed of light on wire
    - » about 1.5 ns/foot
  - Router latency: depends on internals of router
    - » Could be < 1 ms (for a good router)
    - » Question: can router handle full wire throughput?

Sample Computations

- E.g.: Ethernet within Soda
  - Latency: speed of light in wire is 1.5ns/foot, which implies latency in building < 1 μs (if no routers in path)
  - Throughput: 10-1000Mb/s
  - Throughput delay: packet doesn't arrive until all bits
    - » So: 4KB/100Mb/s = 0.3 milliseconds (same order as disk!)
- E.g.: ATM within Soda
  - Latency (same as above, assuming no routing)
  - Throughput: 155Mb/s
  - Throughput delay: 4KB/155Mb/s = 200μ
- E.g.: ATM cross-country
  - Latency (assuming no routing):
    - » 3000miles * 5000ft/mile ⇒ 15 milliseconds
  - How many bits could be in transit at same time?
    - » 15ms * 155Mb/s = 290KB
  - In fact, Berkeley→MIT Latency ~ 90ms
    - » Implies 1.7MB in flight if routers have wire-speed throughput
- Requirements for good performance:
  - Local area: minimize overhead/improve bandwidth
  - Wide area: keep pipeline full!

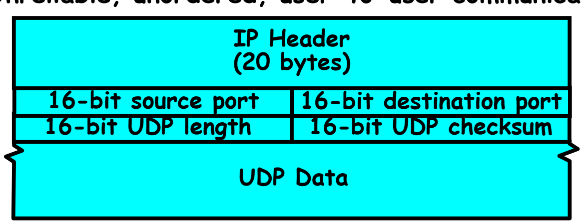
IP Packet Format

- Internet Protocol (IP): Sends packets to arbitrary destination in network
  - Deliver messages unreliably ("best effort") from one machine in Internet to another
  - Since intermediate links may have limited size, must be able to fragment/reassemble packets on demand
  - Includes 256 different "sub-protocols" built on top of IP
    - » Examples: ICMP(1), TCP(6), UDP (17), IPSEC(50,51)
- IP Packet Format:



Process-to-process communication: UDP

- Process to process communication
  - Basic routing gets packets from machine→machine
  - What we really want is routing from process→process
    - » Example: ssh, email, ftp, web browsing
  - Several IP protocols include notion of a "port", which is a 16-bit identifiers used in addition to IP addresses
    - » A communication channel (connection) defined by 4 items: [source address, source port, dest address, dest port]
- UDP: The Unreliable Datagram Protocol
  - UDP layered on top of basic IP (IP Protocol 17)
    - » Unreliable, unordered, user-to-user communication



  - Often used for high-bandwidth video streams
    - » Many uses of UDP considered "anti-social" – none of the "well-behaved" aspects of (say) TCP/IP

Administrivia

- My office hours
  - New office hour: Thursday 2:30-3:30
- Project 4 design document
  - Due Monday November 28th
- MIDTERM II: Wednesday November 30th
  - 5:30-8:30pm, 10 Evans
  - All material from last midterm and up to Monday 11/28
  - Includes virtual memory
- Final Exam
  - December 17th, 12:30 – 3:30, 220 Hearst Gym
- Final Topics: Any suggestions?

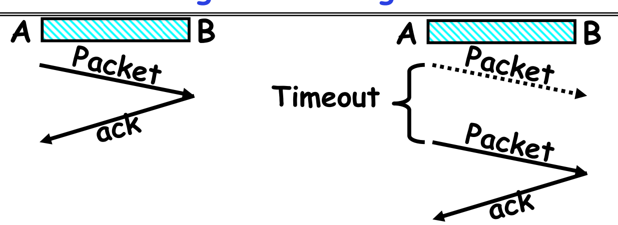
Sequence Numbers

- Ordered Messages
  - Several network services are best constructed by ordered messaging
    - » Ask remote machine to first do x, then do y, etc.
  - Unfortunately, underlying network is packet based:
    - » Packets are routed one at a time through the network
    - » Can take different paths or be delayed individually
  - IP can reorder packets! P_0,P_1 might arrive as P_1,P_0
- Solution requires queuing at destination
  - Need to hold onto packets to undo misordering
  - Total degree of reordering impacts queue size
- Ordered messages on top of unordered ones:
  - Assign sequence numbers to packets
    - » 0,1,2,3,4…..
    - » If packets arrive out of order, reorder before delivering to user application
    - » For instance, hold onto #3 until #2 arrives, etc.
  - Sequence numbers are specific to particular connection
    - » Reordering among connections normally doesn't matter
  - If restart connection, need to make sure use different range of sequence numbers than previously…

Reliable Message Delivery: the Problem

- All physical networks can garble and/or drop packets
  - Physical media: packet not transmitted/received
    - » If transmit close to maximum rate, get more throughput – even if some packets get lost
    - » If transmit at lowest voltage such that error correction just starts correcting errors, get best power/bit
  - Congestion: no place to put incoming packet
    - » Point-to-point network: insufficient queue at switch/router
    - » Broadcast link: two host try to use same link
    - » In any network: insufficient buffer space at destination
    - » Rate mismatch: what if sender send faster than receiver can process?
- Reliable Message Delivery on top of Unreliable Packets
  - Need some way to make sure that packets actually make it to receiver
    - » Every packet received at least once
    - » Every packet received only once
  - Can combine with ordering: every packet received by process at destination once and in order

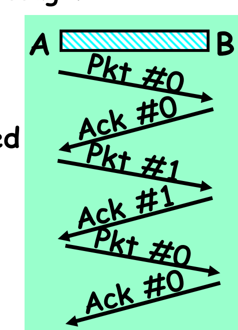
Using Acknowledgements



- How to ensure transmission of packets?
  - Detect garbling at receiver via checksum, discard if bad
  - Receiver acknowledges (by sending "ack") when packet received properly at destination
  - Timeout at sender: if no ack, retransmit
- Some questions:
  - If the sender doesn't get an ack, does that mean the receiver didn't get the original message?
    - » No
  - What it ack gets dropped? Or if message gets delayed?
    - » Sender doesn't get ack, retransmits. Receiver gets message twice, acks each.

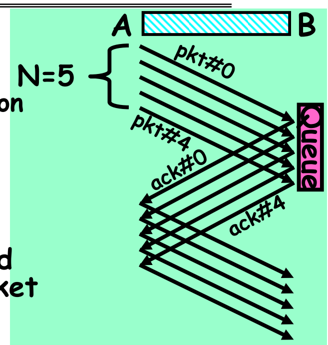
How to deal with message duplication

- Solution: put sequence number in message to identify re-transmitted packets
  - Receiver checks for duplicate #'s; Discard if detected
- Requirements:
  - Sender keeps copy of unack'ed messages
    - » Easy: only need to buffer messages
  - Receiver tracks possible duplicate messages
    - » Hard: when ok to forget about received message?
- Alternating-bit protocol:
  - Send one message at a time; don't send next message until ack received
  - Sender keeps last message; receiver tracks sequence # of last message received
- Pros: simple, small overhead
- Con: Poor performance
  - Wire can hold multiple messages; want to fill up at (wire latency × throughput)
- Con: doesn't work if network can delay or duplicate messages arbitrarily

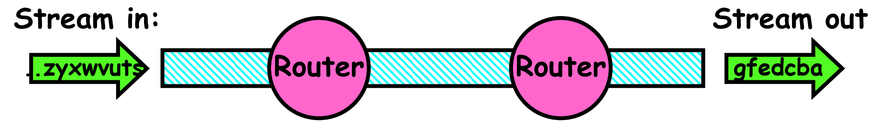


Better messaging: Window-based acknowledgements

- **Window based protocol (TCP):**
  - Send up to N packets without ack
    - » Allows pipelining of packets
    - » Window size (N) < queue at destination
  - Each packet has sequence number
    - » Receiver acknowledges each packet
    - » Ack says "received all packets up to sequence number X"/send more
- Acks serve dual purpose:
  - Reliability: Confirming packet received
  - Flow Control: Receiver ready for packet
    - » Remaining space in queue at receiver can be returned with ACK
- What if packet gets garbled/dropped?
  - Sender will timeout waiting for ack packet
    - » Resend missing packets⇒ Receiver gets packets out of order!
  - Should receiver discard packets that arrive out of order?
    - » Simple, but poor performance
  - Alternative: Keep copy until sender fills in missing pieces?
    - » Reduces # of retransmits, but more complex
- What if ack gets garbled/dropped?
  - Timeout and resend just the un-acknowledged packets

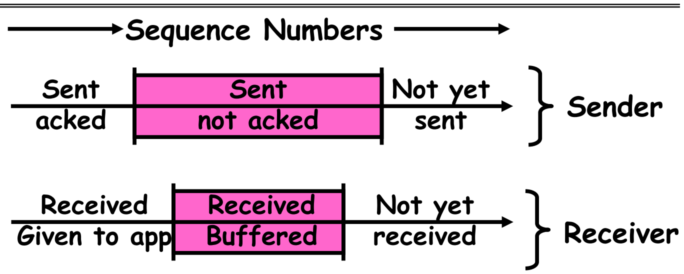


Transmission Control Protocol (TCP)



- Transmission Control Protocol (TCP)
  - TCP (IP Protocol 6) layered on top of IP
  - Reliable byte stream between two processes on different machines over Internet (read, write, flush)
- TCP Details
  - Fragments byte stream into packets, hands packets to IP
    - » IP may also fragment by itself
  - Uses window-based acknowledgement protocol (to minimize state at sender and receiver)
    - » "Window" reflects storage at receiver – sender shouldn't overrun receiver's buffer space
    - » Also, window should reflect speed/capacity of network – sender shouldn't overload network
  - Automatically retransmits lost packets
  - Adjusts rate of transmission to avoid congestion
    - » A "good citizen"

TCP Windows and Sequence Numbers



- Sender has three regions:
  - Sequence regions
    - » sent and ack'ed
    - » Sent and not ack'ed
    - » not yet sent
  - Window (colored region) adjusted by sender
- Receiver has three regions:
  - Sequence regions
    - » received and ack'ed (given to application)
    - » received and buffered
    - » not yet received (or discarded because out of order)

Congestion Avoidance

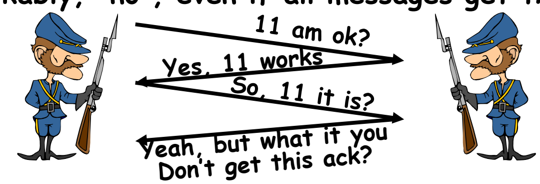
- Congestion
  - How long should timeout be for re-sending messages?
    - » Too long→wastes time if message lost
    - » Too short→retransmit even though ack will arrive shortly
  - Stability problem: more congestion ⇒ ack is delayed ⇒ unnecessary timeout ⇒ more traffic ⇒ more congestion
    - » Closely related to window size at sender: too big means putting too much data into network
- How does the sender's window size get chosen?
  - Must be less than receiver's advertised buffer size
  - Try to match the rate of sending packets with the rate that the slowest link can accommodate
  - Sender uses an adaptive algorithm to decide size of N
    - » Goal: fill network between sender and receiver
    - » Basic technique: slowly increase size of window until acknowledgements start being delayed/lost
- Specifically TCP solution: "slow start"
  - Start sending slowly
  - If no timeout, slowly increase window size (throughput)
  - Timeout ⇒ congestion, so cut window size in half

Sequence-Number Initialization

- How do you choose an initial sequence number?
  - When machine boots, ok to start with sequence #0?
    - » No: could send two messages with same sequence #!
    - » Receiver might end up discarding valid packets, or duplicate ack from original transmission might hide lost packet
  - Also, if it is possible to predict sequence numbers, might be possible for attacker to hijack TCP connection
- Some ways of choosing an initial sequence number:
  - Time to live: each TCP packet has a deadline.
    - » If not delivered in X seconds, then is dropped
    - » Thus, can re-use sequence numbers if wait for all packets in flight to be delivered or to expire
  - Epoch #: uniquely identifies *which* set of sequence numbers are currently being used
    - » Epoch # stored on disk, Put in every message
    - » epoch # incremented on crash and/or when run out of sequence #
  - Pseudo-random increment to previous sequence number
    - » Used by a number of implementations now

General's Paradox

- General's paradox:
  - Constraints of problem:
    - » Two generals, on separate mountains
    - » Can only communicate via messengers
    - » Messengers can be captured
  - Problem: need to coordinate attack
    - » If they attack at different times, they all die
    - » If they attack at same time, they win
  - Named after Custer, who died at Little Big Horn because he arrived a couple of days too early
- Can messages over an unreliable network be used to guarantee two entities do something simultaneously?
  - Remarkably, "no", even if all messages get through



  - No way to be sure last message gets through!

Two-Phase Commit

- Since we can't solve the General's Paradox (i.e. simultaneous action), let's solve a related problem
  - Distributed transaction: Two machines agree to do something, or not do it, atomically
- Two-Phase Commit protocol does this
  - Use a persistent, stable log on each machine to keep track of whether commit has happened
    - » If a machine crashes, when it wakes up it first checks its log to recover state of world at time of crash
  - Prepare Phase:
    - » The global coordinator requests that all participants will promise to commit or rollback the transaction
    - » Participants record promise in log, then acknowledge
    - » If anyone votes to abort, coordinator writes "abort" in its log and tells everyone to abort; each records "abort" in log
  - Commit Phase:
    - » After all participants respond that they are prepared, then the coordinator writes "commit" to its log
    - » Then asks all nodes to commit; they respond with ack
    - » After receive acks, coordinator writes "got commit" to log
  - Log can be used to complete this process such that all machines either commit or don't commit

Two phase commit example

- Simple Example: A≡ATM machine, B≡The Bank
  - Phase 1:
    - » A writes "Begin transaction" to log
      A→B: OK to transfer funds to me?
    - » Not enough funds:
      B→A: transaction aborted; A writes "Abort" to log
    - » Enough funds:
      B: Write new account balance to logg
      B→A: OK, I can commit
  - Phase 2: A can decide for both whether they will commit
    - » A: write new account balance to log
    - » Write "commit" to log
    - » Send message to B that commit occurred; wait for ack
    - » Write "Got Commit" to log
- What if B crashes at beginning?
  - Wakes up, does nothing; A will timeout, abort and retry
- What if A crashes at beginning of phase 2?
  - Wakes up, sees transaction in progress; sends "abort" to B
- What if B crashes at beginning of phase 2?
  - B comes back up, look at log; when A sends it "Commit" message, it will say, oh, ok, commit

Distributed Decision Making Discussion

- Two-Phase Commit: Blocking
  - A Site can get stuck in a situation where it cannot continue until some other site (usually the coordinator) recovers.
  - Example of how this could happen:
    - » Participant site B writes a "prepared to commit" record to its log, sends a "yes" vote to the coordintor (site A) and crashes
    - » Site A crashes
    - » Site B wakes up, check its log, and realizes that it has voted "yes" on the update. It sends a message to site A asking what happened. At this point, B cannot change its mind and decide to abort, because update may have committed
    - » B is blocked until A comes back
  - Blocking is problematic because a blocked site must hold resources (locks on updated items, pagespinned in memory, etc) until it learns fate of update
- Alternative: There are alternatives such as "Three Phase Commit" which don't have this blocking problem

Conclusion

- **Layering:** building complex services from simpler ones
- **Datagram:** an independent, self-contained network message whose arrival, arrival time, and content are not guaranteed
- Performance metrics
  - **Overhead:** CPU time to put packet on wire
  - **Throughput:** Maximum number of bytes per second
  - **Latency:** time until first bit of packet arrives at receiver
- **Arbitrary Sized messages:**
  - Fragment into multiple packets; reassemble at destination
- **Ordered messages:**
  - Use sequence numbers and reorder at destination
- **Reliable messages:**
  - Use Acknowledgements
  - Want a window larger than 1 in order to increase throughput
- **TCP:** Reliable byte stream between two processes on different machines over Internet (read, write, flush)
- **Two-phase commit:** distributed decision making