CS162
Operating Systems and Systems Programming
Lecture 23

Distributed Decision Making (Con't), Networking and TCP/IP

November 18th, 2020

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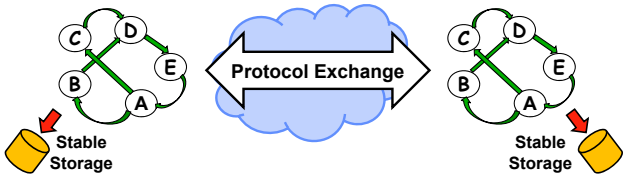
Recall: How do entities communicate? A Protocol!



- A protocol is an agreement on how to communicate, including:
  - Syntax: how a communication is specified & structured
    - » Format, order messages are sent and received
  - Semantics: what a communication means
    - » Actions taken when transmitting, receiving, or when a timer expires
- Described formally by a state machine
  - Often represented as a message transaction diagram
  - Can be a partitioned state machine: two parties synchronizing duplicate sub-state machines between them
  - Stability in the face of failures!

Recall: Distributed Applications

- How do you actually program a distributed application?
  - Need to synchronize multiple threads, running on different machines
    - » No shared memory, so cannot use test&set

  - One Abstraction: send/receive messages
    - » Already atomic: no receiver gets portion of a message and two receivers cannot get same message
- 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

Using Messages: Send/Receive behavior

- When should `send(message,mbox)` return?
  - When receiver gets message? (i.e. ack received)
  - When message is safely buffered on destination?
  - Right away, if message is buffered on source node?
- Actually two questions here:
  - When can the sender be sure that receiver actually received the message?
  - When can sender reuse the memory containing message?
- Mailbox provides 1-way communication from T1→T2
  - T1→buffer→T2
  - Very similar to producer/consumer
    - » Send = V, Receive = P
    - » However, can't tell if sender/receiver is local or not!

Messaging for Producer-Consumer Style

- Using send/receive for producer-consumer style:

```
Producer:
    int msg1[1000];
    while(1) {
        prepare message;
        send(msg1,mbox);
    }
Consumer:
    int buffer[1000];
    while(1) {
        receive(buffer,mbox);
        process message;
    }
```

Send Message

Receive Message

- No need for producer/consumer to keep track of space in mailbox: handled by send/receive
  - This is one of the roles of the window in TCP: window is size of buffer on far end
  - Restricts sender to forward only what will fit in buffer

Messaging for Request/Response communication

- What about two-way communication?
  - Request/Response
    - » Read a file stored on a remote machine
    - » Request a web page from a remote web server
  - Also called: client-server
    - » Client ≡ requester, Server ≡ responder
    - » Server provides "service" (file storage) to the client
- Example: File service

```
Client: (requesting the file)
  char response[1000];

  send("read rutabaga", server_mbox);
  receive(response, client_mbox);

Server: (responding with the file)
  char command[1000], answer[1000];

  receive(command, server_mbox);
  decode command;
  read file into answer;
  send(answer, client_mbox);
```

Request File

Get Response

Receive Request

Send Response

Distributed Consensus Making

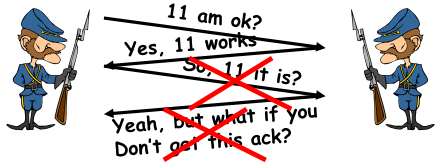
- Consensus problem
  - All nodes propose a value
  - Some nodes might crash and stop responding
  - Eventually, all remaining nodes decide on the same value from set of proposed values
- Distributed Decision Making
  - Choose between "true" and "false"
  - Or Choose between "commit" and "abort"
- Equally important (but often forgotten!): make it durable!
  - How do we make sure that decisions cannot be forgotten?
    - » This is the "D" of "ACID" in a regular database
  - In a global-scale system?
    - » What about erasure coding or massive replication?
    - » Like BlockChain applications!

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

General's Paradox (con't)

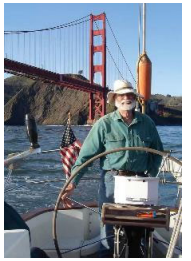
- Can messages over an unreliable network be used to guarantee two entities do something simultaneously?
  - Remarkably, "no", even if all messages get through



  - No way to be sure last message gets through!
  - In real life, use radio for simultaneous (out of band) communication
- So, clearly, we need something other than simultaneity!

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 or more machines agree to do something, or not do it, atomically
  - No constraints on time, just that it will eventually happen!
- Two-Phase Commit protocol: Developed by Turing award winner Jim Gray
  - (first Berkeley CS PhD, 1969)
  - Many important DataBase breakthroughs also from Jim Gray



Jim Gray

Two-Phase Commit Protocol

- Persistent stable log on each machine: 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 used to guarantee that all machines either commit or don't

2PC Algorithm

- One coordinator
- N workers (replicas)
- High level algorithm description:
  - Coordinator asks all workers if they can commit
  - If all workers reply "VOTE-COMMIT", then coordinator broadcasts "GLOBAL-COMMIT"
    Otherwise coordinator broadcasts "GLOBAL-ABORT"
  - Workers obey the GLOBAL messages
- Use a persistent, stable log on each machine to keep track of what you are doing
  - If a machine crashes, when it wakes up it first checks its log to recover state of world at time of crash

Two-Phase Commit: Setup

- One machine *(coordinator)* initiates the protocol
- It asks *every* machine to **vote** on transaction

- Two possible votes:
  - **Commit**
  - **Abort**

- Commit transaction only if unanimous approval

Two-Phase Commit: Preparing

Worker Agrees to Commit

- Machine has **guaranteed** that it will accept transaction
- Must be **recorded in log** so machine will remember this decision if it fails and restarts

Worker Agrees to Abort

- Machine has **guaranteed** that it will **never accept** this transaction
- Must be **recorded in log** so machine will remember this decision if it fails and restarts

Two-Phase Commit: Finishing

Commit Transaction

- Coordinator learns *all machines have agreed to commit*
- Record decision to commit in local log
- Apply transaction, inform voters

Abort Transaction

- Coordinator learns *at least on machine has voted to abort*
- Record decision to abort in local log
- Do not apply transaction, inform voters

Two-Phase Commit: Finishing

Commit Transaction

- Coordinator learns *all machines have agreed to commit*
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Abort Transaction

- Coordinator learns *at least on machine has voted to abort*
- Record decision to abort in local log
- Do not apply transaction, inform voters

Because no machine can take back its decision, exactly one of these will happen

Administrivia

- Midterm 3: Thursday 12/3: 5-7PM as before
  - Material up to Lecture 25
  - Cameras and Zoom screen sharing again as with Midterm 2
  - Review session TBA
- Lecture 26 will be a fun lecture
  - Let me know if there are topics you would like to discuss!

Recall: CS 162 Collaboration Policy

Explaining a concept to someone in another group
Discussing algorithms/testing strategies with other groups
Discussing debugging approaches with other groups
Searching online for generic algorithms (e.g., hash table)

Sharing code or test cases with another group
Copying OR reading another group's code or test cases
Copying OR reading online code or test cases from prior years
Helping someone in another group to debug their code

- We compare all project submissions against prior year submissions and online solutions and will take actions (described on the course overview page) against offenders
- Don't put a friend in a bad position by asking for help that they shouldn't give!

Detailed Algorithm

Coordinator Algorithm

Coordinator sends **VOTE-REQ** to all workers

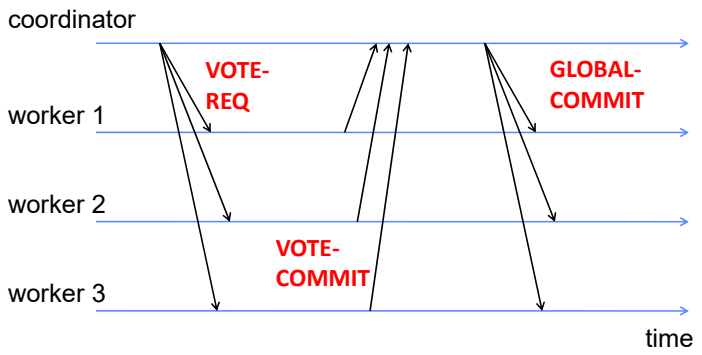
- If receive **VOTE-COMMIT** from all N workers, send **GLOBAL-COMMIT** to all workers
- If don't receive **VOTE-COMMIT** from all N workers, send **GLOBAL-ABORT** to all workers

Worker Algorithm

- Wait for **VOTE-REQ** from coordinator
- If ready, send **VOTE-COMMIT** to coordinator
- If not ready, send **VOTE-ABORT** to coordinator
  - And immediately abort

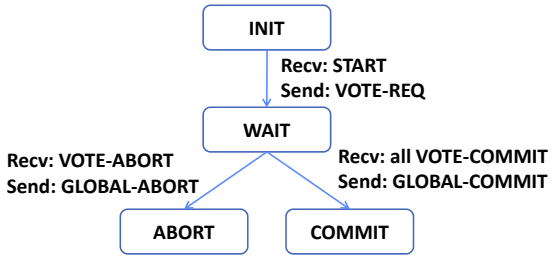
- If receive **GLOBAL-COMMIT** then commit
- If receive **GLOBAL-ABORT** then abort

Failure Free Example Execution

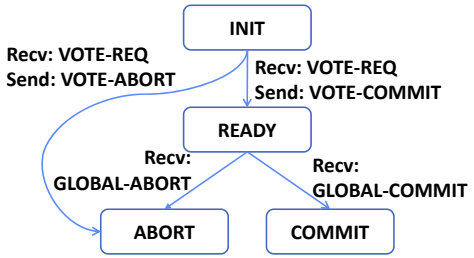


State Machine of Coordinator

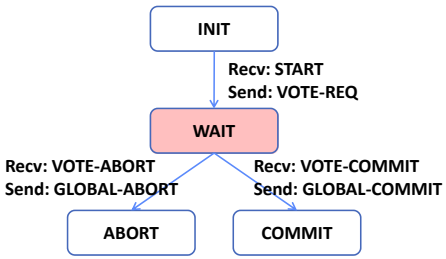
- Coordinator implements simple state machine:



State Machine of Workers

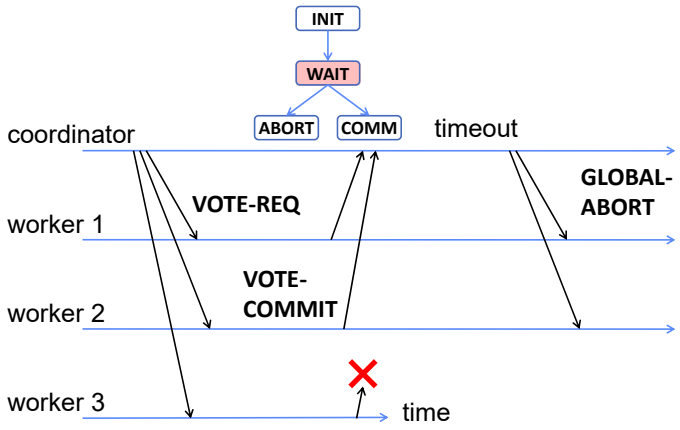


Dealing with Worker Failures

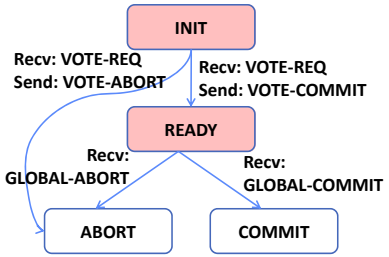


- Failure only affects states in which the coordinator is waiting for messages
- Coordinator only waits for votes in "WAIT" state
- In WAIT, if doesn't receive N votes, it times out and sends GLOBAL-ABORT

Example of Worker Failure

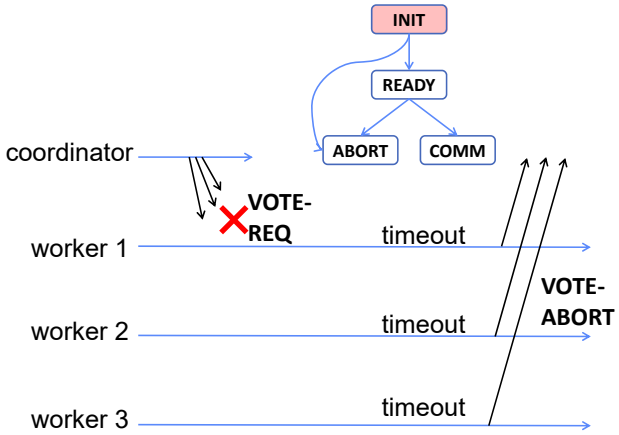


Dealing with Coordinator Failure

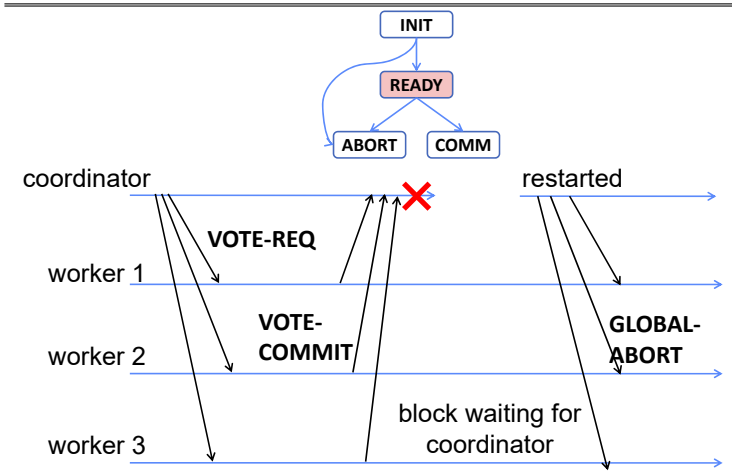


- Worker waits for VOTE-REQ in INIT
  - Worker can time out and abort (coordinator handles it)
- Worker waits for GLOBAL-* message in READY
  - If coordinator fails, workers must **BLOCK** waiting for coordinator to recover and send GLOBAL_* message

Example of Coordinator Failure #1



Example of Coordinator Failure #2

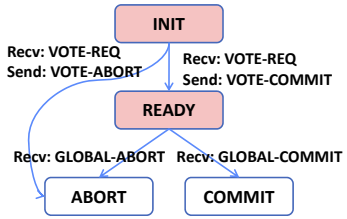


Durability

- All nodes use stable storage to store current state
  - stable storage is non-volatile storage (e.g. backed by disk) that guarantees atomic writes.
  - E.g.: SSD, NVRAM
- Upon recovery, nodes can restore state and resume:
  - Coordinator aborts in INIT, WAIT, or ABORT
  - Coordinator commits in COMMIT
  - Worker aborts in INIT, ABORT
  - Worker commits in COMMIT
  - Worker "asks" Coordinator in READY

Blocking for Coordinator to Recover

- A worker waiting for global decision can ask fellow workers about their state
  - If another worker is in ABORT or COMMIT state then coordinator must have sent GLOBAL-*
    - » Thus, worker can safely abort or commit, respectively
  - If another worker is still in INIT state then both workers can decide to abort
  - If all workers are in ready, need to BLOCK (don't know if coordinator wanted to abort or commit)



Distributed Decision Making Discussion (1/2)

- Why is distributed decision making desirable?
  - Fault Tolerance!
  - A group of machines can come to a decision even if one or more of them fail during the process
    - » Simple failure mode called "failstop" (different modes later)
  - After decision made, result recorded in multiple places
- Why is 2PC not subject to the General's paradox?
  - Because 2PC is about *all nodes eventually coming to the same decision – not necessarily at the same time!*
  - Allowing us to reboot and continue allows time for collecting and collating decisions

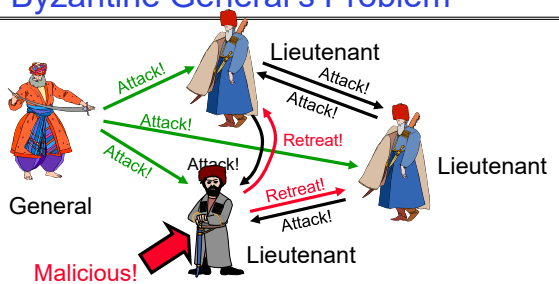
Distributed Decision Making Discussion (2/2)

- Undesirable feature of Two-Phase Commit: Blocking
  - One machine can be stalled until another site recovers:
    - » Site B writes "prepared to commit" record to its log, sends a "yes" vote to the coordinator (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 decide to abort, because update may have committed
    - » B is blocked until A comes back
  - A blocked site holds resources (locks on updated items, pages pinned in memory, etc) until learns fate of update

Alternatives to 2PC

- Three-Phase Commit: One more phase, allows nodes to fail or block and still make progress.
- PAXOS: An alternative used by Google and others that does not have 2PC blocking problem
  - Develop by Leslie Lamport (Turing Award Winner)
  - No fixed leader, can choose new leader on fly, deal with failure
  - Some think this is extremely complex!
- RAFT: PAXOS alternative from John Osterhout (Stanford)
  - Simpler to describe complete protocol
- What happens if one or more of the nodes is malicious?
  - Malicious: attempting to compromise the decision making
  - Use a more hardened decision making process: Byzantine Agreement and Block Chains

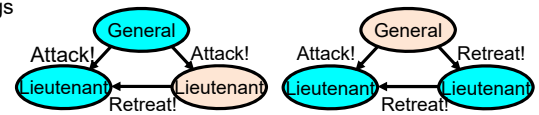
Byzantine General's Problem



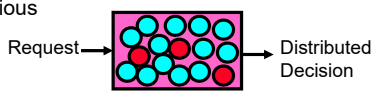
- Byazantine General's Problem (n players):
  - One General and n-1 Lieutenants
  - Some number of these (f) can be insane or malicious
- The commanding general must send an order to his n-1 lieutenants such that the following Integrity Constraints apply:
  - IC1: All loyal lieutenants obey the same order
  - IC2: If the commanding general is loyal, then all loyal lieutenants obey the order he sends

Byzantine General's Problem (con't)

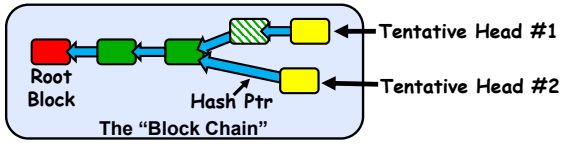
- Impossibility Results:
  - Cannot solve Byzantine General's Problem with n=3 because one malicious player can mess up things



  - With f faults, need n > 3f to solve problem
- Various algorithms exist to solve problem
  - Original algorithm has #messages exponential in n
  - Newer algorithms have message complexity O(n2)
    - » One from MIT, for instance (Castro and Liskov, 1999)
- Use of BFT (Byzantine Fault Tolerance) algorithm
  - Allow multiple machines to make a coordinated decision even if some subset of them (< n/3) are malicious

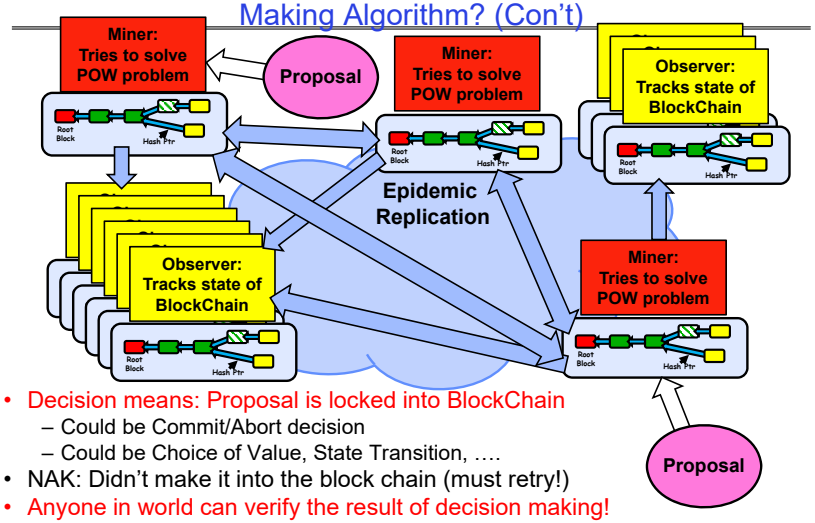


Is a BlockChain a Distributed Decision Making Algorithm?



- BlockChain: a chain of blocks connected by hashes to root block
  - The Hash Pointers are unforgeable (assumption)
  - The Chain has no branches except perhaps for heads
  - Blocks are considered "authentic" part of chain when they have authenticity info in them
- How is the head chosen?
  - Some consensus algorithm
  - In many BlockChain algorithms (e.g. BitCoin, Ethereum), the head is chosen by solving hard problem
    - » This is the job of "miners" who try to find "nonce" info that makes hash over block have specified number of zero bits in it
    - » The result is a "Proof of Work" (POW)
    - » Selected blocks above (green) have POW in them and can be included in chains
  - Longest chain wins

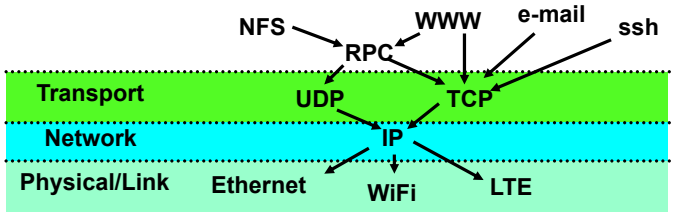
Is a Blockchain a Distributed Decision Making Algorithm? (Con't)



- Decision means: Proposal is locked into BlockChain
  - Could be Commit/Abort decision
  - Could be Choice of Value, State Transition, ….
- NAK: Didn't make it into the block chain (must retry!)
- Anyone in world can verify the result of decision making!

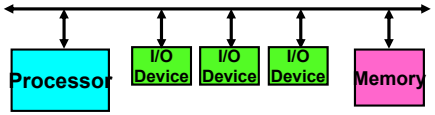
Network Protocols

- Networking protocols: 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:



Broadcast Networks

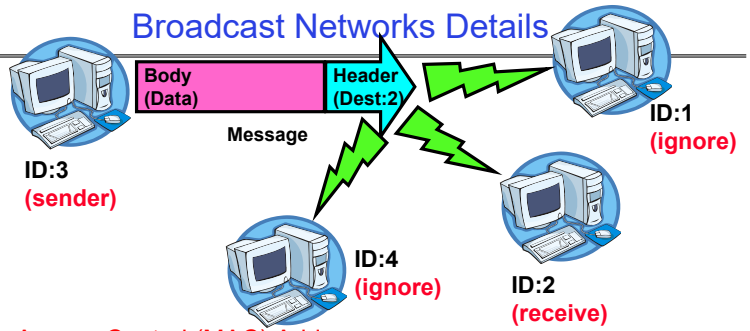
- Broadcast Network: Shared Communication Medium



  - Shared Medium can be a set of wires
    - » Inside a computer, this is called a bus
    - » All devices simultaneously connected to devices

  - Originally, Ethernet was a broadcast network
    - » All computers on local subnet connected to one another
  - More examples (wireless: medium is air): cellular phones (GSM, CDMA, and LTE), WiFi

Broadcast Networks Details

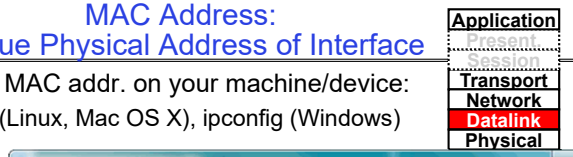


- Media Access Control (MAC) Address:
  - 48-bit physical address for hardware interface
  - Every device (in the world!?) has a unique address
- Delivery: When you broadcast a packet, how does a receiver know who it is for? (packet goes to everyone!)
  - Put header on front of packet: [Destination MAC Addr | Packet]
  - Everyone gets packet, discards if not the target
  - In Ethernet, this check is done in hardware
    - » No OS interrupt if not for particular destination

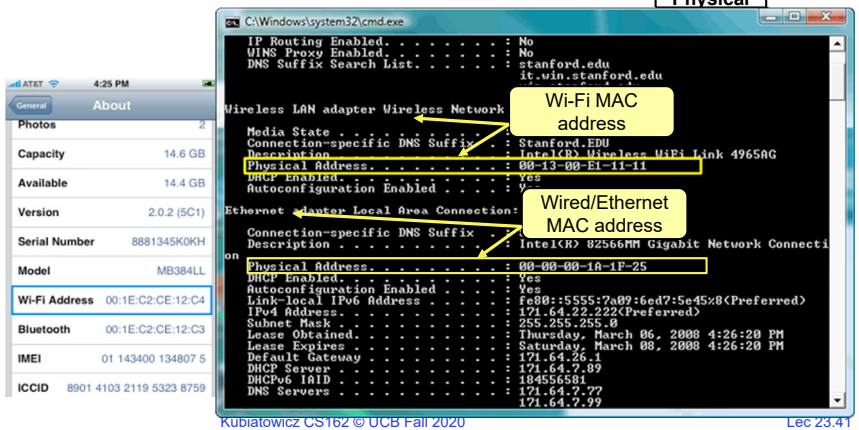
Carrier Sense, Multiple Access/Collision Detection

- Ethernet (early 80's): first practical local area network
  - It is the most common LAN for UNIX, PC, and Mac
  - Use wire instead of radio, but still broadcast medium
- Key advance was in arbitration called CSMA/CD: Carrier sense, multiple access/collision detection
  - Carrier Sense: don't send unless idle
    - » Don't mess up communications already in process
  - Collision Detect: sender checks if packet trampled.
    - » If so, abort, wait, and retry.
  - Backoff Scheme: Choose wait time before trying again
- How long to wait after trying to send and failing?
  - What if everyone waits the same length of time? Then, they all collide again at some time!
  - Must find way to break up shared behavior with nothing more than shared communication channel
- Adaptive randomized waiting strategy:
  - Adaptive and Random: First time, pick random wait time with some initial mean. If collide again, pick random value from bigger mean wait time. Etc.
  - Randomness is important to decouple colliding senders
  - Scheme figures out how many people are trying to send!

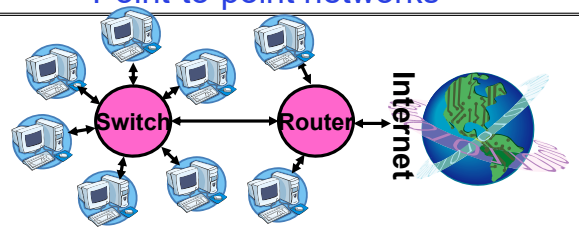
MAC Address: Unique Physical Address of Interface



- Can easily find MAC addr. on your machine/device:
  - E.g., ifconfig (Linux, Mac OS X), ipconfig (Windows)

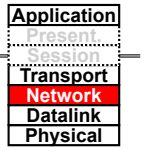


Point-to-point networks



- Why have a shared bus at all? Why not simplify and only have point-to-point links + routers/switches?
  - Originally wasn't cost-effective, now hardware is cheap!
- 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
  - Adaptively figures out which ports have which MAC addresses
- Router: a device that acts as a junction between physical networks to transfer data packets among them
  - Routes between switching domains using (for instance) IP addresses

The Internet Protocol (IP)



- Internet Protocol: Internet's network layer
- Service it provides: "Best-Effort" Packet Delivery
  - Tries it's "best" to deliver packet to its destination
  - Packets may be lost
  - Packets may be corrupted
  - Packets may be delivered out of order
- IP Is a Datagram service!
  - Routes across many physical switching domains (subnets)

IPv4 Address Space

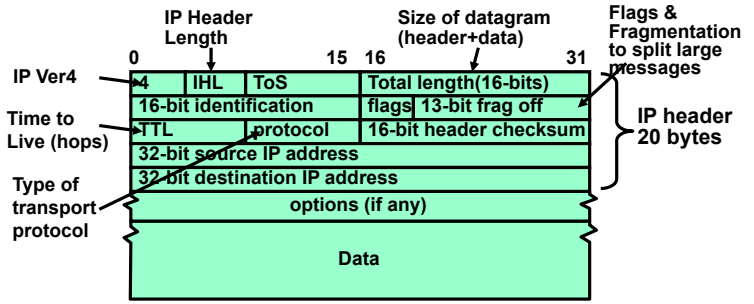
- IP Address: a 32-bit integer used as destination of IP packet
  - Often written as four dot-separated integers, with each integer from 0—255 (thus representing 8x4=32 bits)
  - Example CS file server is: 169.229.60.83 ≡ 0xA9E53C53
- Internet Host: a computer connected to the Internet
  - Host has one or more IP addresses used for routing
    - » Some of these may be private and unavailable for routing
  - Not every computer has a unique IP address
    - » Groups of machines may share a single IP address
    - » In this case, machines have private addresses behind a "Network Address Translation" (NAT) gateway
- Subnet: network connecting hosts with related IP addresses
  - A subnet is identified by 32-bit value, with the bits which differ set to zero, followed by a slash and a mask
    - » Example: 128.32.131.0/24 designates a subnet in which all the addresses look like 128.32.131.XX
    - » Same subnet: 128.32.131.0/255.255.255.0
  - Mask: The number of matching prefix bits
    - » Expressed as a single value (e.g., 24) or a set of ones in a 32-bit value (e.g., 255.255.255.0)
  - Often routing *within* subnet is by MAC address (smart switches)

Address Ranges in IPv4

- IP address space divided into prefix-delimited ranges:
  - Class A: NN.0.0.0/8
    - » NN is 1–126 (126 of these networks)
    - » 16,777,214 IP addresses per network
    - » 10.xx.yy.zz is private
    - » 127.xx.yy.zz is loopback
  - Class B: NN.MM.0.0/16
    - » NN is 128–191, MM is 0-255 (16,384 of these networks)
    - » 65,534 IP addresses per network
    - » 172.[16-31].xx.yy are private
  - Class C: NN.MM.LL.0/24
    - » NN is 192–223, MM and LL 0-255 (2,097,151 of these networks)
    - » 254 IP addresses per networks
    - » 192.168.xx.yy are private
- Address ranges are often owned by organizations
  - Can be further divided into subnets

IPv4 Packet Format

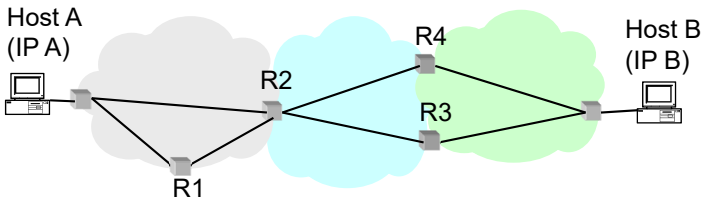
- IP Packet Format:



- IP Datagram: an unreliable, unordered, packet sent from source to destination
  - Function of network – deliver datagrams!

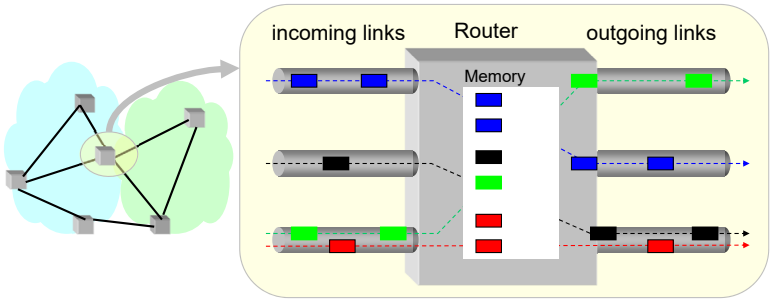
Wide Area Network

- **Wide Area Network** (WAN): network that covers a broad area (e.g., city, state, country, entire world)
  - E.g., Internet is a WAN
- WAN connects multiple physical (datalink) layer networks (LANs)
- Datalink layer networks are connected by **routers**
  - Different LANs can use different communication technology (e.g., wireless, cellular, optics, wired)



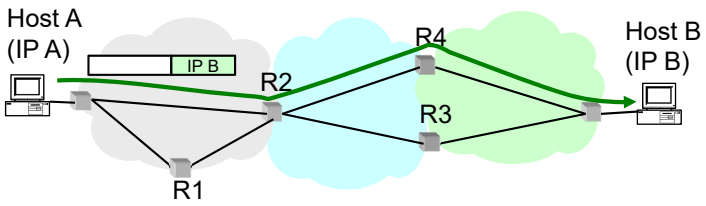
Routers

- **Forward** each packet received on an **incoming link** to an **outgoing link** based on packet's destination IP address (towards its destination)
- **Store & forward**: packets are buffered before being forwarded
- **Forwarding table**: mapping between IP address and the output link



Packet Forwarding

- Upon receiving a packet, a router
  - read the IP destination address of the packet
  - consults its forwarding table → output port
  - forwards packet to corresponding output port
- Default route (for subnets without explicit entries)
  - Forward to more authoritative router



IP Addresses vs. MAC Addresses

- Why not use MAC addresses for routing?
  - Doesn't scale
- Analogy
  - MAC address → SSN
  - IP address → (unreadable) home address
- MAC address: uniquely associated with device for the entire lifetime of the device
- IP address: changes as the device location changes
  - Your notebook IP address at school is different from home

IP Addresses vs. MAC Addresses

- Why does packet forwarding using IP addr. scale?
- Because IP addresses can be aggregated
  - E.g., all IP addresses at UC Berkeley start with **0xA9E5**, i.e., any address of form 0xA9E5**** belongs to Berkeley
  - Thus, a router in NY needs to keep a **single** entry for **all** hosts at Berkeley
  - If we were using MAC addresses the NY router would need to maintain **an entry for every** Berkeley host!!
- Analogy:
  - Give this letter to person with SSN: 123-45-6789 vs.
  - Give this letter to "John Smith, 123 First Street, LA, US"

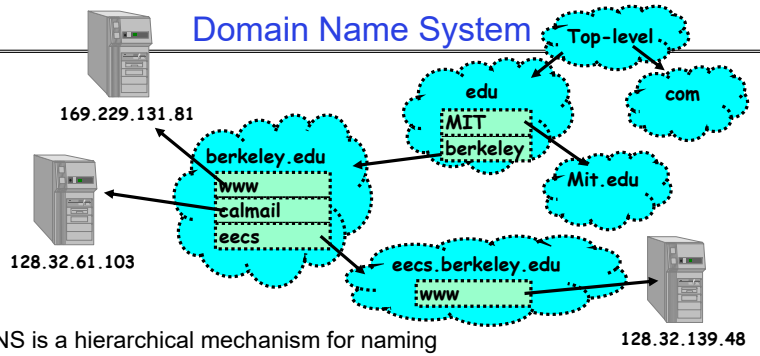
Setting up Routing Tables

- How do you set up routing tables?
  - Internet has no centralized state!
    - » No single machine knows entire topology
    - » Topology constantly changing (faults, reconfiguration, etc.)
  - Need dynamic algorithm that acquires routing tables
    - » Ideally, have one entry per subnet or portion of address
    - » Could have "default" routes that send packets for unknown subnets to a different router that has more information
- Possible algorithm for acquiring routing table
  - Routing table has "cost" for each entry
    - » Includes number of hops to destination, congestion, etc.
    - » Entries for unknown subnets have infinite cost
  - Neighbors periodically exchange routing tables
    - » If neighbor knows cheaper route to a subnet, replace your entry with neighbors entry (+1 for hop to neighbor)
- In reality:
  - Internet has networks of many different scales
  - Different algorithms run at different scales

Naming in the Internet

- How to map human-readable names to IP addresses?
  - E.g. www.berkeley.edu ⇒ 128.32.139.48
  - E.g. www.google.com ⇒ different addresses depending on location, and load
- Why is this necessary?
  - IP addresses are hard to remember
  - IP addresses change:
    - » Say, Server 1 crashes gets replaced by Server 2
    - » Or – google.com handled by different servers
- Mechanism: Domain Naming System (DNS)

Domain Name System



- DNS is a hierarchical mechanism for naming
  - Name divided in domains, right to left: www.eecs.berkeley.edu
- Each domain owned by a particular organization
  - Top level handled by ICANN (Internet Corporation for Assigned Numbers and Names)
  - Subsequent levels owned by organizations
- Resolution: series of queries to successive servers
- Caching: queries take time, so results cached for period of time

How Important is Correct Resolution?

- If attacker manages to give incorrect mapping:
  - Can get someone to route to server, thinking that they are routing to a different server
    - » Get them to log into "bank" – give up username and password
- Is DNS Secure?
  - Definitely a weak link
    - » What if "response" returned from different server than original query?
    - » Get person to use incorrect IP address!
  - Attempt to avoid substitution attacks:
    - » Query includes random number which must be returned
- In July 2008, hole in DNS security located!
  - Dan Kaminsky (security researcher) discovered an attack that broke DNS globally
    - » One person in an ISP convinced to load particular web page, then all users of that ISP end up pointing at wrong address
  - High profile, highly advertised need for patching DNS
    - » Big press release, lots of mystery
    - » Security researchers told no speculation until patches applied

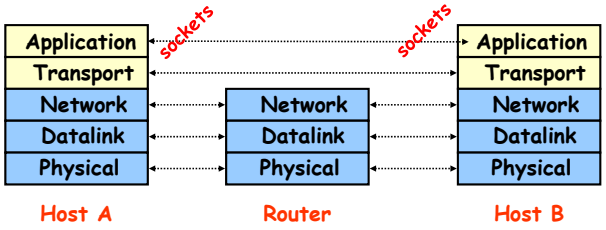
Network Layering

- Layering: building complex services from simpler ones
  - Each layer provides services needed by higher layers by utilizing services provided by lower layers
- The physical/link layer is pretty limited
  - Packets are of limited size (called the "Maximum Transfer Unit or MTU: often 200-1500 bytes in size)
  - Routing is limited to within a physical link (wire) or perhaps through a switch
- Our goal in the following is to show how to construct a secure, ordered, 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

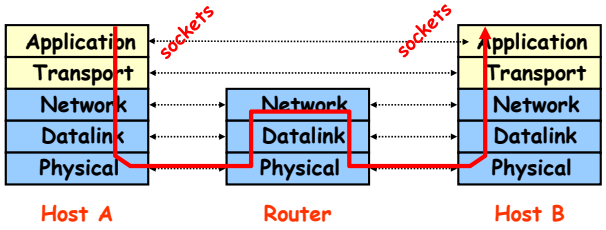
Internet Architecture: The Five Layers

- Lower three layers implemented everywhere
- Top two layers implemented only at hosts



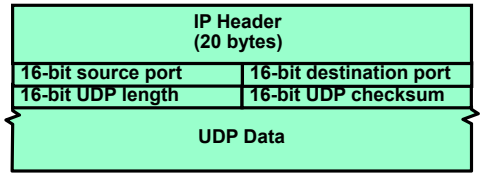
Internet Architecture: Five Layers

- Communication goes down to physical network
- Then from network peer to peer
- Then up to relevant layer



Building a messaging service on IP

- Process to process communication
  - Basic routing gets packets from machine→machine
  - What we really want is routing from process→process
    - » Add "ports", which are 16-bit identifiers
    - » A communication channel (connection) defined by 5 items: [source addr, source port, dest addr, dest port, protocol]
- For example: The Unreliable Datagram Protocol (UDP)
  - Layered on top of basic IP (IP Protocol 17)
    - » Datagram: an unreliable, unordered, packet sent from source user → dest user (Call it UDP/IP)



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

Summary (1/2)

- Two-phase commit: distributed decision making
  - First, make sure everyone guarantees they will commit if asked (prepare)
  - Next, ask everyone to commit
- Byzantine General's Problem: distributed decision making with malicious failures
  - One general, n-1 lieutenants: some number of them may be malicious (often "f" of them)
  - All non-malicious lieutenants must come to same decision
  - If general not malicious, lieutenants must follow general
  - Only solvable if $n \geq 3f+1$
- BlockChain protocols
  - Cryptographically-driven ordering protocol
  - Could be used for distributed decision making

Summary (2/2)

- Internet Protocol (IP): Datagram packet delivery
  - Used to route messages through routes across globe
  - 32-bit addresses, 16-bit ports
- DNS: System for mapping from names⇒IP addresses
  - Hierarchical mapping from authoritative domains
  - Recent flaws discovered
- Next time: TCP: Reliable byte stream between two processes on different machines over Internet (read, write, flush)
  - Uses window-based acknowledgement protocol
  - Congestion-avoidance dynamically adapts sender window to account for congestion in network