CS162
Operating Systems and Systems Programming
Lecture 23

TCP/IP (finished), Distributed Storage, Key Value Stores

April 25th, 2019

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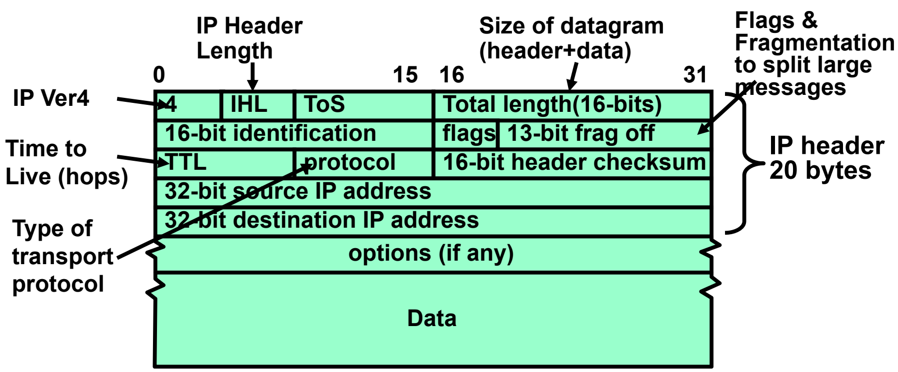
Recall: Network Layering

- 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

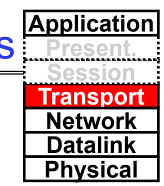
Recall: IPv4 Packet Format

- IP Packet Format:



- IP Protocol field:
  - 8 bits, distinguishes protocols such as TCP, UDP, ICMP
- IP Datagram: an unreliable, unordered, packet sent from source to destination
  - Function of network – deliver datagrams!

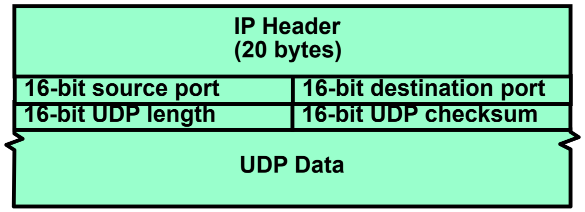
Recall: Internet Transport Protocols



- Datagram service (**UDP**): IP Protocol 17
  - No-frills extension of "best-effort" IP
  - Multiplexing/Demultiplexing among processes
- Reliable, in-order delivery (**TCP**): IP Protocol 6
  - Connection set-up & tear-down
  - Discarding corrupted packets (segments)
  - Retransmission of lost packets (segments)
  - Flow control
  - Congestion control
  - More on these in a moment!
- Other examples:
  - DCCP (33), Datagram Congestion Control Protocol
  - RDP (26), Reliable Data Protocol
  - SCTP (132), Stream Control Transmission Protocol
- Services not available
  - Delay and/or bandwidth guarantees
  - Sessions that survive change-of-IP-address
  - Security/denial of service resilience/…

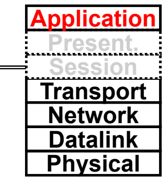
Example: UDP Transport Protocol

- 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)



  - UDP adds minimal header to deliver from process to process (i.e. the source and destination Ports)
- 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

Application Layer (7 - not 5!)

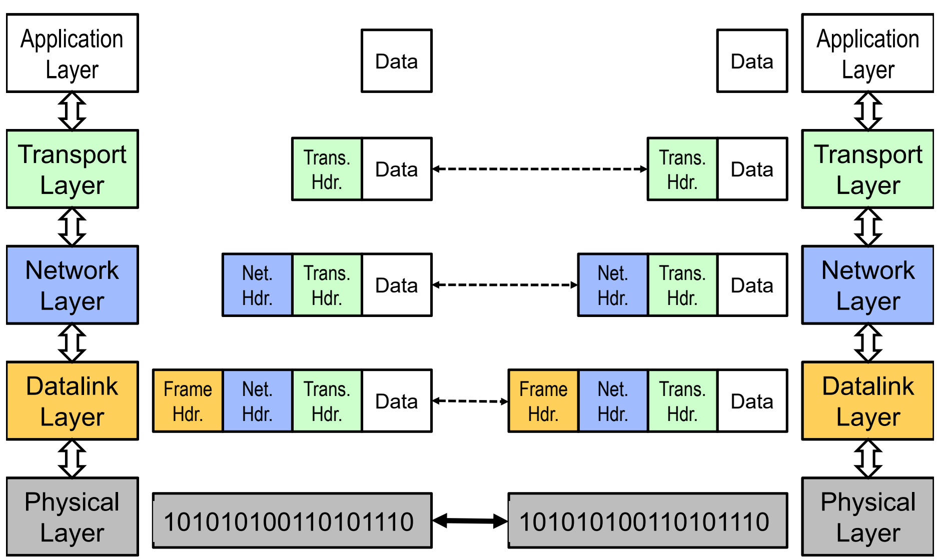


- **Service**: any service provided to the end user
- **Interface**: depends on the application
- **Protocol**: depends on the application

- Examples: Skype, SMTP (email), HTTP (Web), Halo, BitTorrent …

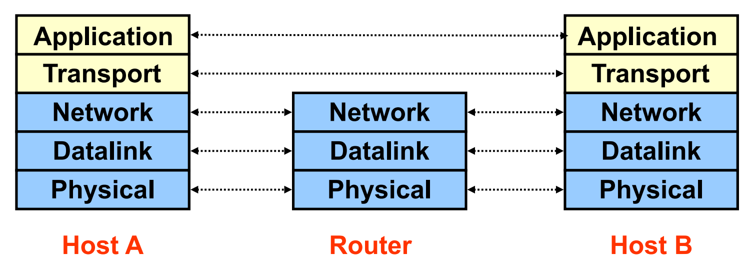
- What happened to layers 5 & 6?
  - "Session" and "Presentation" layers
  - Part of ***OSI*** architecture, but not Internet architecture
  - Their functionality is provided by application layer
    - » E.g. RPC is thought of as a "session" layer
    - » E.g. Encoding is a "Presentation" mechanism. MIME, XDR

Putting it all together



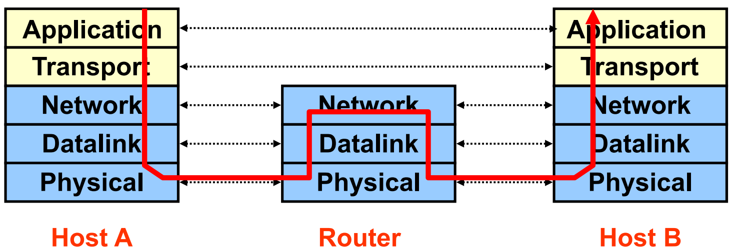
Five Layers Summary

- Lower three layers implemented everywhere
- Top two layers implemented only at hosts
- Logically, layers interacts with peer's corresponding layer

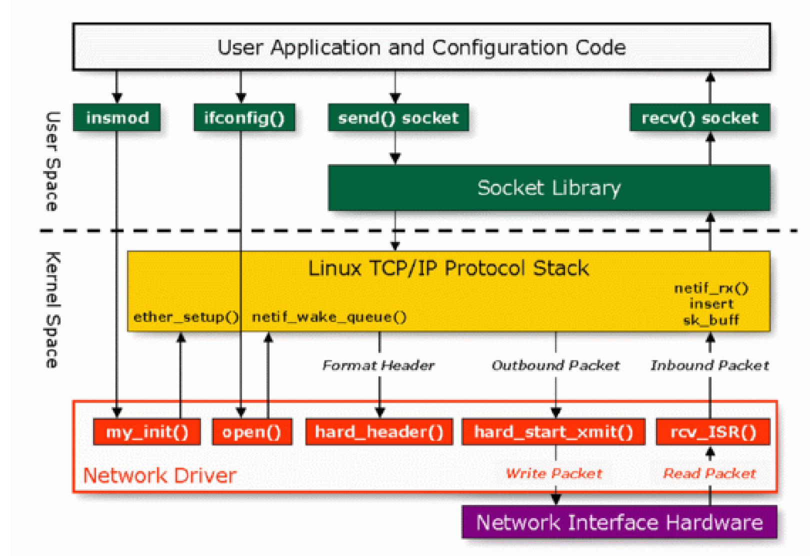


Physical Communication

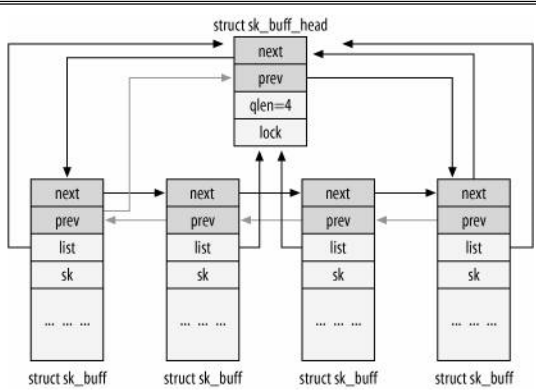
- Communication goes down to physical network
- Then from network peer to peer
- Then up to relevant layer



Linux Network Architecture

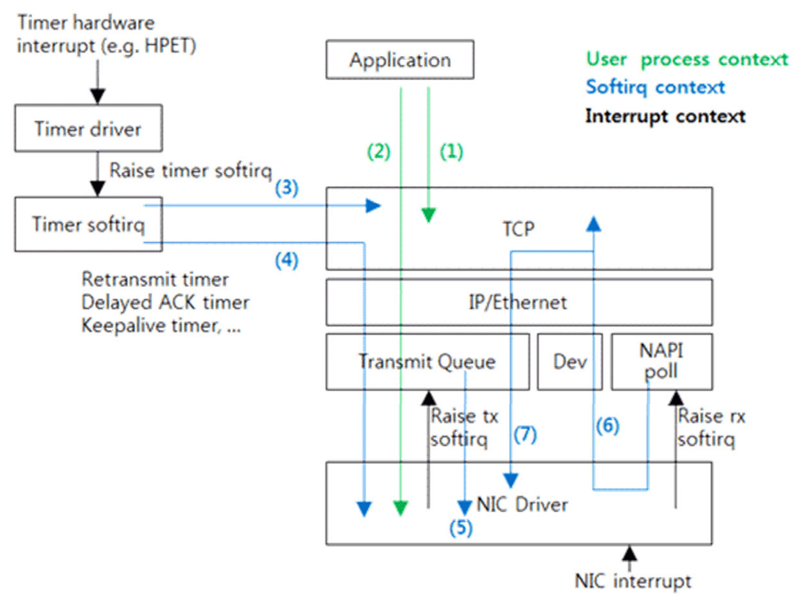


Network Details: sk_buff structure

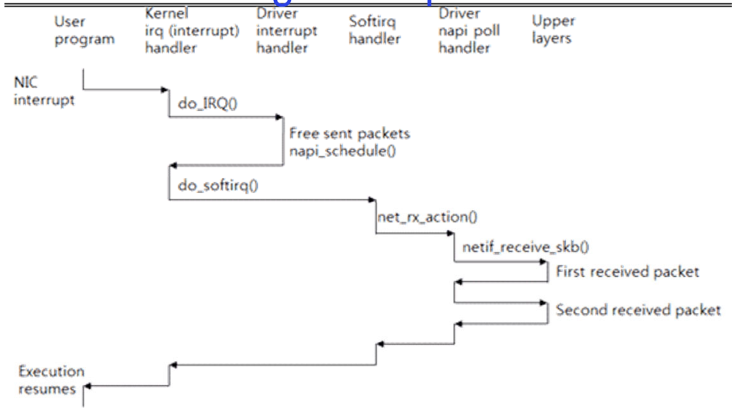


- Socket Buffers: `sk_buff` structure
  - The I/O buffers of sockets are lists of `sk_buff`
    - » Pointers to such structures usually called "`skb`"
  - Complex structures with lots of manipulation routines
  - Packet is linked list of `sk_buff` structures

Network Processing Contexts



Avoiding Interrupts: NAPI

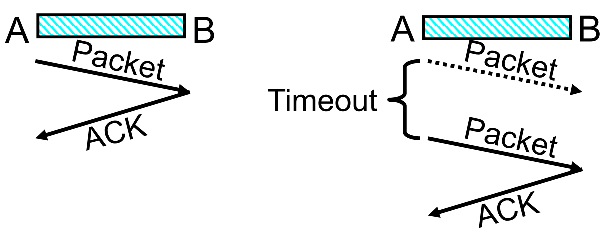


- NAPI ("New API"): Use polling to receive packets
  - Only some drivers actually implement this
- Exit hard interrupt context as quickly as possible
  - Do housekeeping and free up sent packets
  - Schedule soft interrupt for further actions
- Soft Interrupts: Handles reception and delivery

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 hosts 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 to make sure that packets actually make it to receiver
    - » Every packet received at least once
    - » Every packet received at most once
  - Can combine with ordering: every packet received by process at destination exactly once and in order

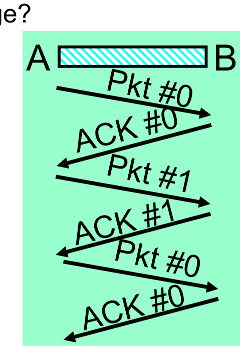
Using Acknowledgements



- 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 if ACK gets dropped? Or if message gets delayed?
    - » Sender doesn't get ACK, retransmits, Receiver gets message twice, ACK each

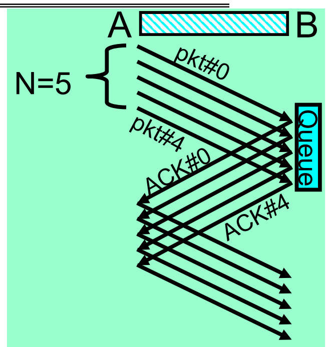
How to Deal with Message Duplication?

- Solution: put sequence number in message to identify re-transmitted packets
  - Receiver checks for duplicate number's; Discard if detected
- Requirements:
  - Sender keeps copy of unACK'd 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 number 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

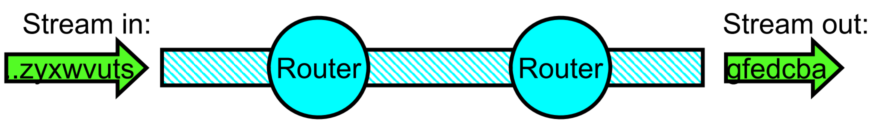
- Windowing protocol (not quite TCP):
  - Send up to N packets without ack
    - » Allows pipelining of packets
    - » Window size (N) < queue at destination
  - Each packet has sequence number
    - » Receiver acknowledges each packet
    - » ACK says "received all packets up to sequence number X"/send more
- ACKs serve dual purpose:
  - Reliability: Confirming packet received
  - Ordering: Packets can be reordered at destination
- 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



Administrivia

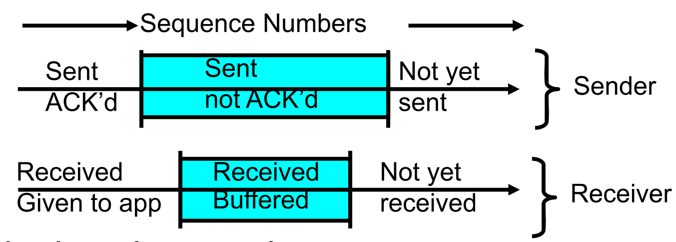
- Last Midterm: 5/2
  - Can have 3 handwritten sheets of notes – both sides
  - Focus on material from lecture 17-24, but all topics fair game!
- Midterm Time is now: 5-7PM
  - It is earlier, during class period (+30 minutes)
  - Please let us know if you conflict situation changed
  - Watch Piazza for room assignments
- Please come to class on 4/30!
  - HKN evaluations!
- Don't forget to do your group evaluations!
  - Very important to help us understand your group dynamics
  - Important to do this for Project 3 as well!
    - » Even though it will be after Midterm 3!

Transmission Control Protocol (TCP)



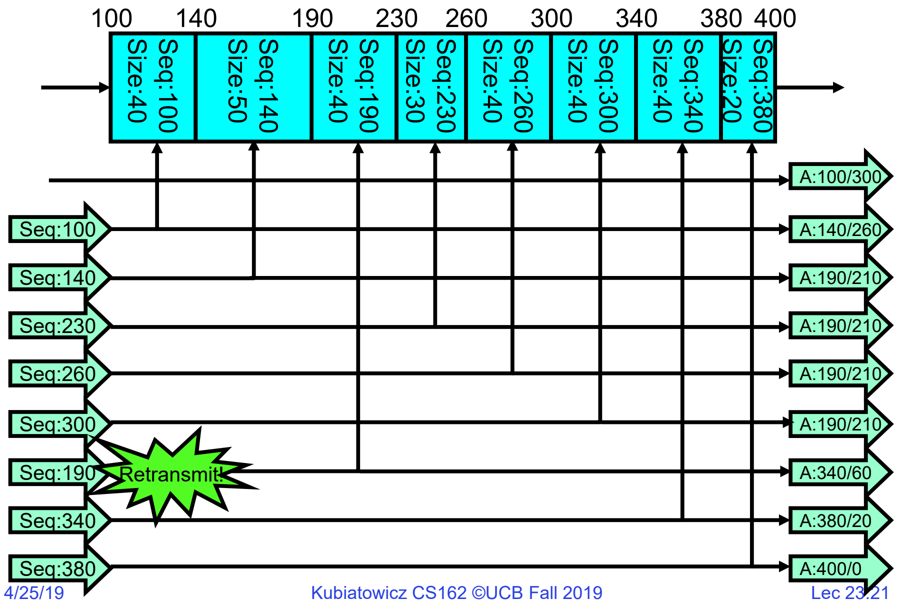
- Transmission Control Protocol (TCP)
  - TCP (IP Protocol 6) layered on top of IP
  - Reliable byte stream between two processes on different machines over Internet (read, write, flush)
- TCP Details
  - Fragments byte stream into packets, hands packets to IP
    - » IP may also fragment by itself
  - 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'd
    - » sent and not ACK'd
    - » not yet sent
  - Window (colored region) adjusted by sender
- Receiver has three regions:
  - Sequence regions
    - » received and ACK'd (given to application)
    - » received and buffered
    - » not yet received (or discarded because out of order)

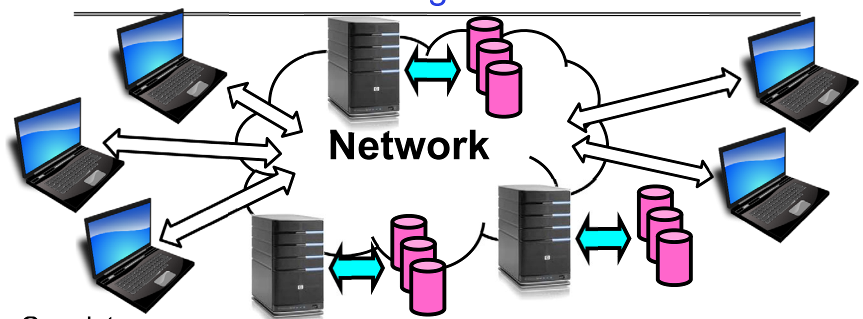
Window-Based Acknowledgements (TCP)



Congestion Avoidance

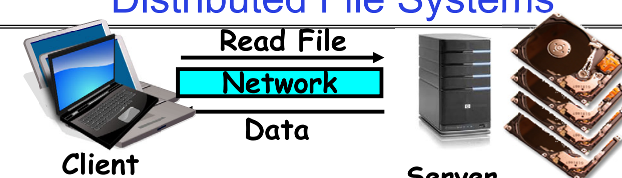
- Congestion
  - How long should timeout be for re-sending messages?
    - » Too long → wastes time if message lost
    - » Too short → retransmit even though ACK will arrive shortly
  - Stability problem: more congestion ⇒ ACK is delayed ⇒ unnecessary timeout ⇒ more traffic ⇒ more congestion
    - » 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
- TCP solution: "slow start" (start sending slowly)
  - If no timeout, slowly increase window size (throughput) by 1 for each ACK received
  - Timeout ⇒ congestion, so cut window size in half
  - "*Additive Increase, Multiplicative Decrease*"

Network-Attached Storage and the CAP Theorem

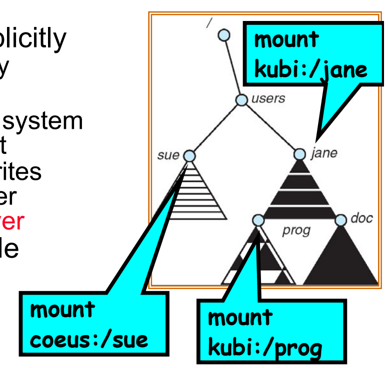


- Consistency:
  - Changes appear to everyone in the same serial order
- Availability:
  - Can get a result at any time
- Partition-Tolerance
  - System continues to work even when network becomes partitioned
- Consistency, Availability, Partition-Tolerance (CAP) Theorem: Cannot have all three at same time
  - Otherwise known as "Brewer's Theorem"

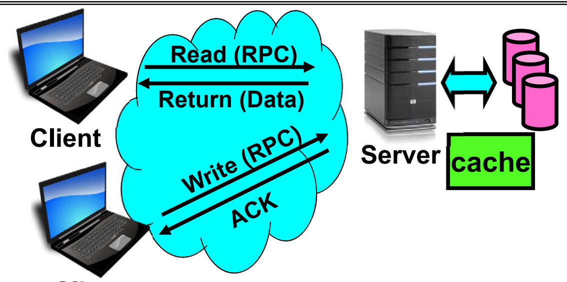
Distributed File Systems



- Distributed File System:
  - Transparent access to files stored on a remote disk
- Naming choices (always an issue):
  - *Hostname:*localname: Name files explicitly
    - » No location or migration transparency
  - *Mounting* of remote file systems
    - » System manager mounts remote file system by giving name and local mount point
    - » Transparent to user: all reads and writes look like local reads and writes to user e.g. /users/sue/foo→/sue/foo on server
  - *A single, global name space:* every file in the world has unique name
    - » Location Transparency: servers can change and files can move without involving user



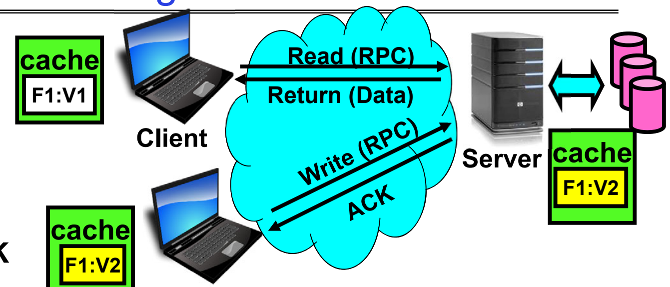
Simple Distributed File System



- Remote Disk: Reads and writes forwarded to server
  - Use Remote Procedure Calls (RPC) to translate file system calls into remote requests
  - No local caching/can be caching at server-side
- Advantage: Server provides completely consistent view of file system to multiple clients
- Problems? Performance!
  - Going over network is slower than going to local memory
  - Lots of network traffic/not well pipelined
  - Server can be a bottleneck

Use of caching to reduce network load

read(f1) →V1
read(f1)→V1
read(f1)→V1
read(f1)→V1



write(f1) →OK
read(f1)→V2

- Idea: Use caching to reduce network load
  - In practice: use buffer cache at source and destination
- Advantage: if open/read/write/close can be done locally, don't need to do any network traffic…fast!
- Problems:
  - Failure:
    - » Client caches have data not committed at server
  - Cache consistency!
    - » Client caches not consistent with server/each other

Failures

- What if server crashes? Can client wait until server comes back up and continue as before?
  - Any data in server memory but not on disk can be lost
  - Shared state across RPC: What if server crashes after seek? Then, when client does "read", it will fail
  - Message retries: suppose server crashes after it does UNIX "rm foo", but before acknowledgment?
    - » Message system will retry: send it again
    - » How does it know not to delete it again? (could solve with two-phase commit protocol, but NFS takes a more ad hoc approach)
- Stateless protocol: A protocol in which all information required to process a request is passed with request
  - Server keeps no state about client, except as hints to help improve performance (e.g. a cache)
  - Thus, if server crashes and restarted, requests can continue where left off (in many cases)
- What if client crashes?
  - Might lose modified data in client cache

Network File System (NFS)

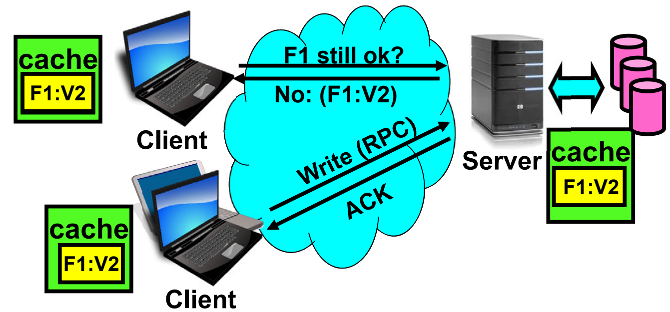
- Three Layers for NFS system
  - UNIX file-system interface: open, read, write, close calls + file descriptors
  - VFS layer: distinguishes local from remote files
    - » Calls the NFS protocol procedures for remote requests
  - NFS service layer: bottom layer of the architecture
    - » Implements the NFS protocol
- NFS Protocol: RPC for file operations on server
  - Reading/searching a directory
  - manipulating links and directories
  - accessing file attributes/reading and writing files
- Write-through caching: Modified data committed to server's disk before results are returned to the client
  - lose some of the advantages of caching
  - time to perform write() can be long
  - Need some mechanism for readers to eventually notice changes! (more on this later)

NFS Continued

- NFS servers are stateless; each request provides all arguments require for execution
  - E.g. reads include information for entire operation, such as `ReadAt(inumber,position)`, not `Read(openfile)`
  - No need to perform network open() or close() on file – each operation stands on its own
- Idempotent: Performing requests multiple times has same effect as performing it exactly once
  - Example: Server crashes between disk I/O and message send, client resend read, server does operation again
  - Example: Read and write file blocks: just re-read or re-write file block – no side effects
  - Example: What about "remove"? NFS does operation twice and second time returns an advisory error
- Failure Model: Transparent to client system
  - Is this a good idea? What if you are in the middle of reading a file and server crashes?
  - Options (NFS Provides both):
    - » Hang until server comes back up (next week?)
    - » Return an error. (Of course, most applications don't know they are talking over network)

NFS Cache consistency

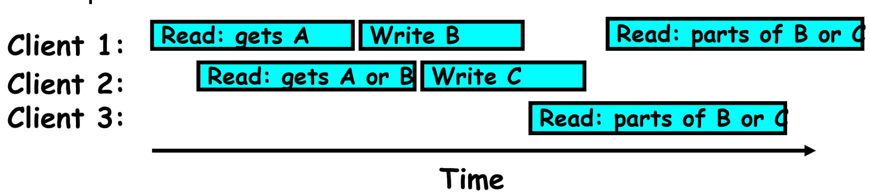
- NFS protocol: weak consistency
  - Client polls server periodically to check for changes
    - » Polls server if data hasn't been checked in last 3-30 seconds (exact timeout it tunable parameter).
    - » Thus, when file is changed on one client, server is notified, but other clients use old version of file until timeout.



  - What if multiple clients write to same file?
    - » In NFS, can get either version (or parts of both)
    - » Completely arbitrary!

Sequential Ordering Constraints

- What sort of cache coherence might we expect?
  - i.e. what if one CPU changes file, and before it's done, another CPU reads file?
- Example: Start with file contents = "A"



- What would we actually want?
  - Assume we want distributed system to behave exactly the same as if all processes are running on single system
    - » If read finishes before write starts, get old copy
    - » If read starts after write finishes, get new copy
    - » Otherwise, get either new or old copy
  - For NFS:
    - » If read starts more than 30 seconds after write, get new copy; otherwise, could get partial update

NFS Pros and Cons

- NFS Pros:
  - Simple, Highly portable
- NFS Cons:
  - Sometimes inconsistent!
  - Doesn't scale to large # clients
    - » Must keep checking to see if caches out of date
    - » Server becomes bottleneck due to polling traffic

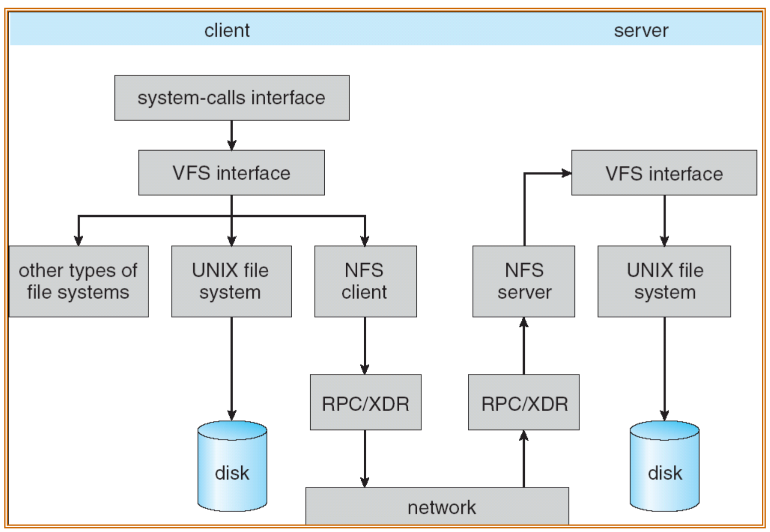
Andrew File System

- Andrew File System (AFS, late 80's) → DCE DFS (commercial product)
- Callbacks: Server records who has copy of file
  – On changes, server immediately tells all with old copy
  – No polling bandwidth (continuous checking) needed
- Write through on close
  – Changes not propagated to server until close()
  – Session semantics: updates visible to other clients only after the file is closed
    » As a result, do not get partial writes: all or nothing!
    » Although, for processes on local machine, updates visible immediately to other programs who have file open
- In AFS, everyone who has file open sees old version
  – Don't get newer versions until reopen file

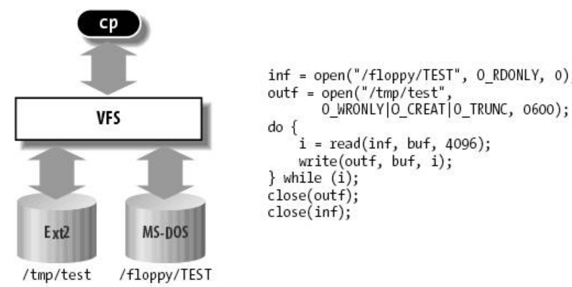
Andrew File System (con't)

- Data cached on local disk of client as well as memory
  – On open with a cache miss (file not on local disk):
    » Get file from server, set up callback with server
  – On write followed by close:
    » Send copy to server; tells all clients with copies to fetch new version from server on next open (using callbacks)
- What if server crashes? Lose all callback state!
  – Reconstruct callback information from client: go ask everyone "who has which files cached?"
- AFS Pro: Relative to NFS, less server load:
  – Disk as cache ⇒ more files can be cached locally
  – Callbacks ⇒ server not involved if file is read-only
- For both AFS and NFS: central server is bottleneck!
  – Performance: all writes→server, cache misses→server
  – Availability: Server is single point of failure
  – Cost: server machine's high cost relative to workstation

Implementation of NFS

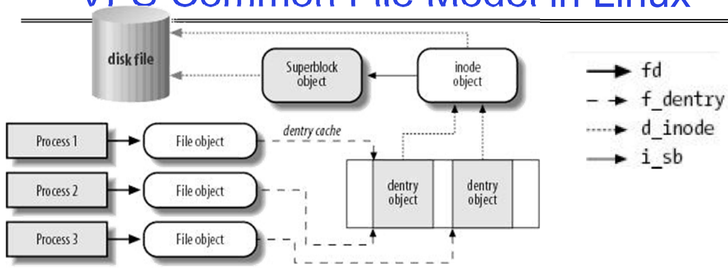


Enabling Factor: Virtual Filesystem (VFS)



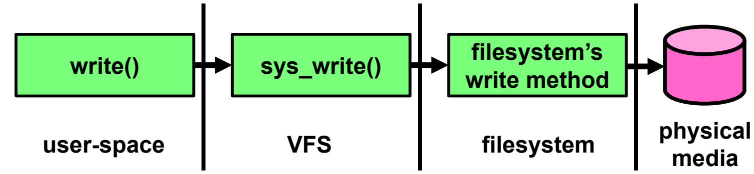
- VFS: Virtual abstraction similar to local file system
  – Provides virtual superblocks, inodes, files, etc
  – Compatible with a variety of local and remote file systems
    » provides object-oriented way of implementing file systems
- VFS allows the same system call interface (the API) to be used for different types of file systems
  – The API is to the VFS interface, rather than any specific type of file system
- In linux, "VFS" stands for "Virtual Filesystem Switch"

VFS Common File Model in Linux



- Four primary object types for VFS:
  – superblock object: represents a specific mounted filesystem
  – inode object: represents a specific file
  – dentry object: represents a directory entry
  – file object: represents open file associated with process
- There is no specific directory object (VFS treats directories as files)
- May need to fit the model by faking it
  – Example: make it look like directories are files
  – Example: make it look like have inodes, superblocks, etc.

Linux VFS



- An operations object is contained within each primary object type to set operations of specific filesystems
  – "super_operations": methods that kernel can invoke on a specific filesystem, i.e. `write_inode()` and `sync_fs()`.
  – "inode_operations": methods that kernel can invoke on a specific file, such as `create()` and `link()`
  – "dentry_operations": methods that kernel can invoke on a specific directory entry, such as `d_compare()` or `d_delete()`
  – "file_operations": methods that process can invoke on an open file, such as `read()` and `write()`
- There are a lot of operations!

Key Value Storage

- Handle huge volumes of data, e.g., PBs
  – Store (key, value) tuples
- Simple interface
  – **put**(key, value); // insert/write "value" associated with "key"
  – value = **get**(key); // get/read data associated with "key"
- Used sometimes as a simpler but more scalable "database"

Key Values: Examples

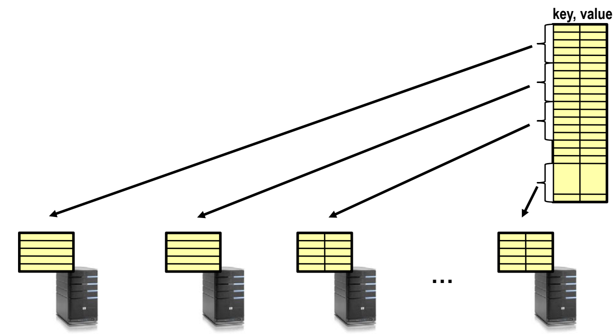
- Amazon:
  – Key: customerID
  – Value: customer p history, credit card, ..)
- Facebook, Twitter:
  – Key: UserID
  – Value: user profile (e.g., posting history, photos, friends, …)
- iCloud/iTunes:
  – Key: Movie/song name
  – Value: Movie, Song

Key-value storage systems in real life

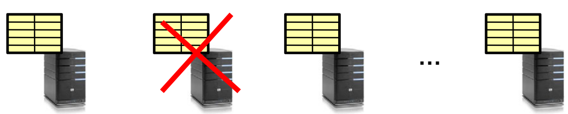
- **Amazon**
  - DynamoDB: internal key value store used to power Amazon.com (shopping cart)
  - Simple Storage System (S3)
- **BigTable/HBase/Hypertable:** distributed, scalable data storage
- **Cassandra**: “distributed data management system” (developed by Facebook)
- **Memcached:** in-memory key-value store for small chunks of arbitrary data (strings, objects)
- **eDonkey/eMule:** peer-to-peer sharing system
- …

Key Value Store

- Also called Distributed Hash Tables (DHT)
- Main idea: partition set of key-values across many machines



Challenges



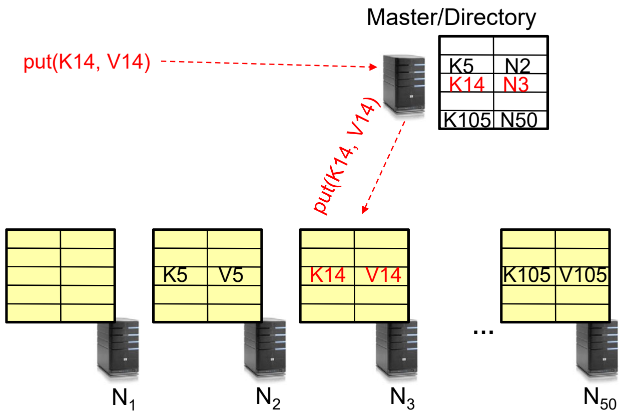
- **Fault Tolerance:** handle machine failures without losing data and without degradation in performance
- **Scalability:**
  - Need to scale to thousands of machines
  - Need to allow easy addition of new machines
- **Consistency:** maintain data consistency in face of node failures and message losses
- **Heterogeneity** (if deployed as peer-to-peer systems):
  - Latency: 1ms to 1000ms
  - Bandwidth: 32Kb/s to 100Mb/s

Important Questions

- **put(key, value)**:
  - where do you store a new (key, value) tuple?
- **get(key)**:
  - where is the value associated with a given “key” stored?
- And, do the above while providing
  - Fault Tolerance
  - Scalability
  - Consistency

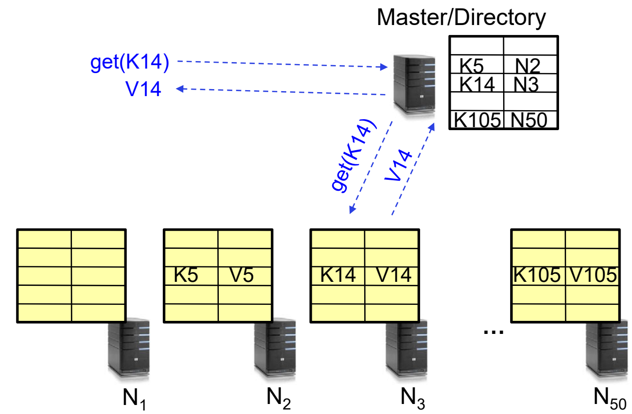
Directory-Based Architecture (1/4)

- Have a node maintain the mapping between **keys** and the **machines (nodes)** that store the **values** associated with the **keys**



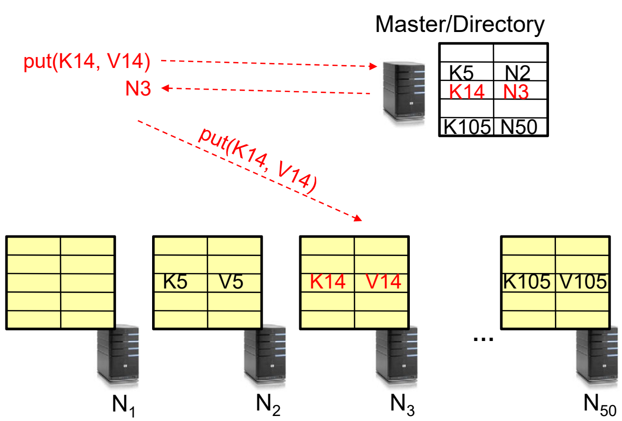
Directory-Based Architecture (2/4)

- Have a node maintain the mapping between **keys** and the **machines (nodes)** that store the **values** associated with the **keys**



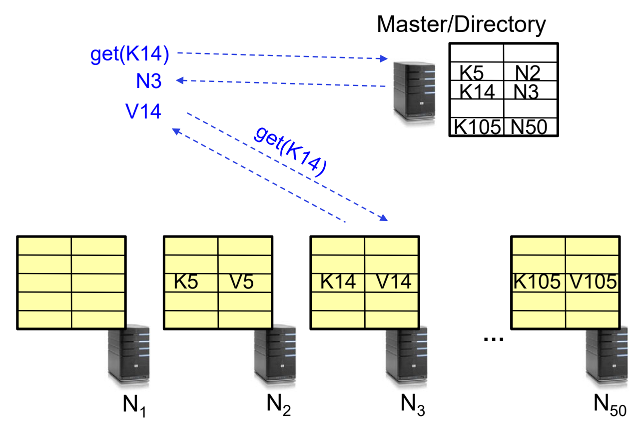
Directory-Based Architecture (3/4)

- Having the master relay the requests → **recursive query**
- Another method: **iterative query** (this slide)
  – Return node to requester and let requester contact node

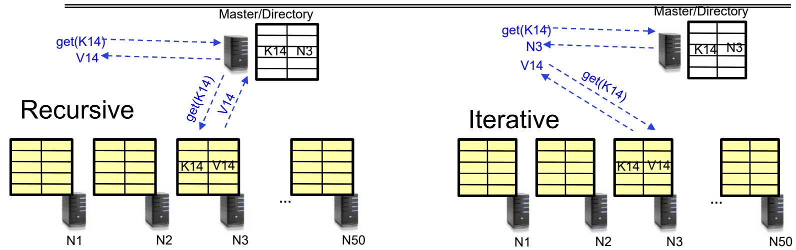


Directory-Based Architecture (4/4)

- Having the master relay the requests → **recursive query**
- Another method: **iterative query** (this slide)
  – Return node to requester and let requester contact node



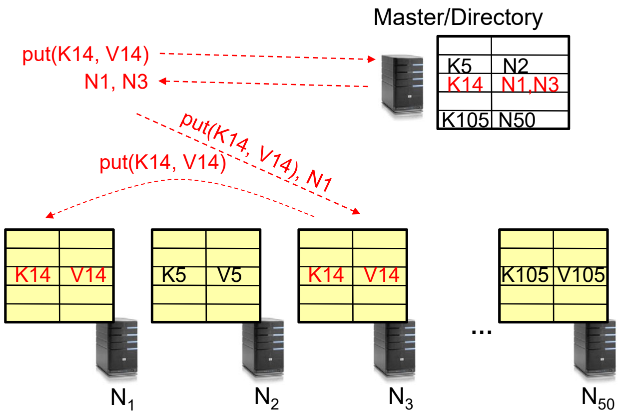
Discussion: Iterative vs. Recursive Query



- Recursive Query:
  - Advantages:
    - » Faster, as typically master/directory closer to nodes
    - » Easier to maintain consistency, as master/directory can serialize puts()/gets()
  - Disadvantages: scalability bottleneck, as all "Values" go through master/directory
- Iterative Query
  - Advantages: more scalable
  - Disadvantages: slower, harder to enforce data consistency

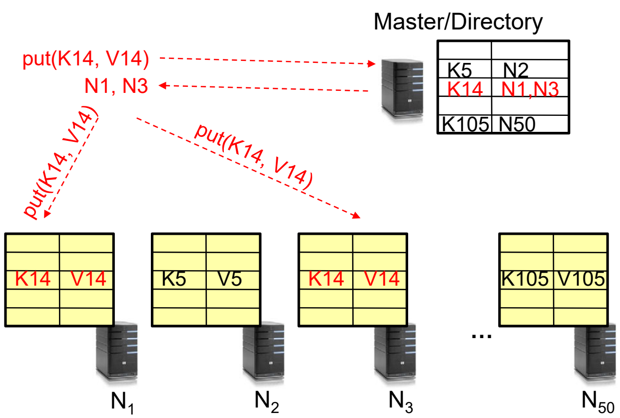
Fault Tolerance (1/3)

- Replicate value on several nodes
- Usually, place replicas on different racks in a datacenter to guard against rack failures



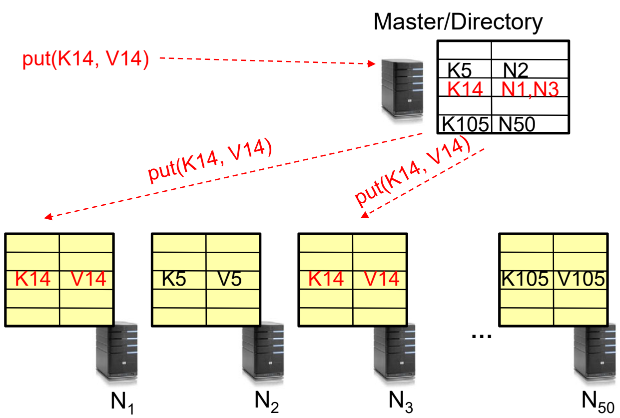
Fault Tolerance (2/3)

- Again, we can have
  - **Recursive** replication (previous slide)
  - **Iterative** replication (this slide)



Fault Tolerance (3/3)

- Or we can use **recursive** query and **iterative** replication…



Scalability

- Storage: use more nodes
- Number of requests:
  - Can serve requests from all nodes on which a value is stored in parallel
  - Master can replicate a popular value on more nodes
- Master/directory scalability:
  - Replicate it
  - Partition it, so different keys are served by different masters/directories
    - » How do you partition?

Scalability: Load Balancing

- Directory keeps track of the storage availability at each node
  - Preferentially insert new values on nodes with more storage available
- What happens when a new node is added?
  - Cannot insert only new values on new node. Why?
  - Move values from the heavy loaded nodes to the new node
- What happens when a node fails?
  - Need to replicate values from fail node to other nodes

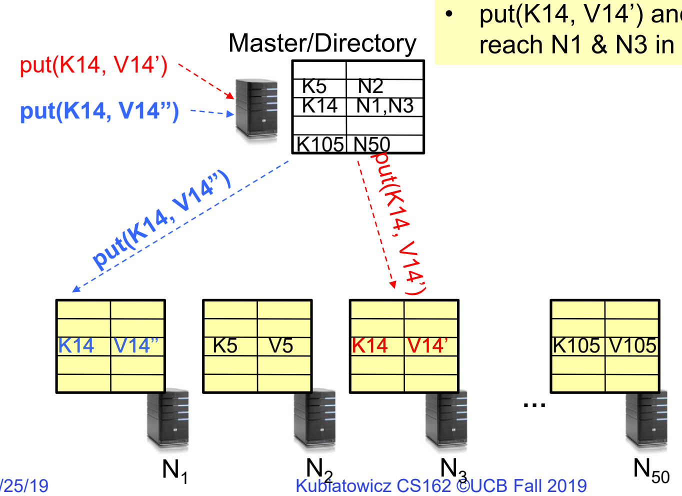
Consistency

- Need to make sure that a value is replicated correctly
- How do you know a value has been replicated on every node?
  - Wait for acknowledgements from every node
- What happens if a node fails during replication?
  - Pick another node and try again
- What happens if a node is slow?
  - Slow down the entire put()? Pick another node?
- In general, with multiple replicas
  - Slow puts and fast gets

Consistency (cont'd)

- If concurrent updates (i.e., puts to same key) may need to make sure that updates happen in the same order

- put(K14, V14') and put(K14, V14'') reach N1 & N3 in reverse order



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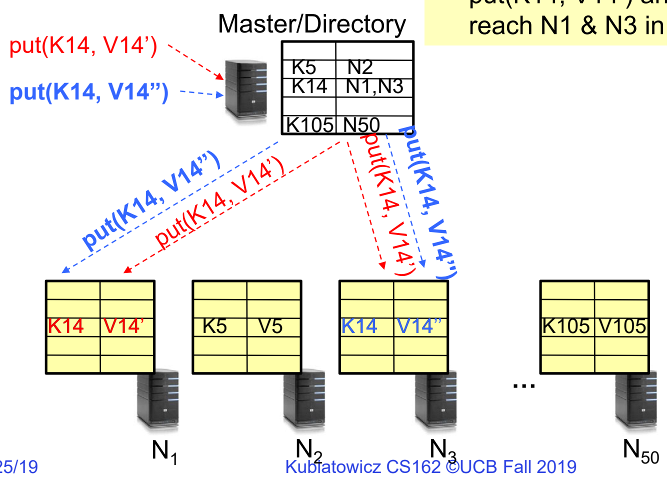
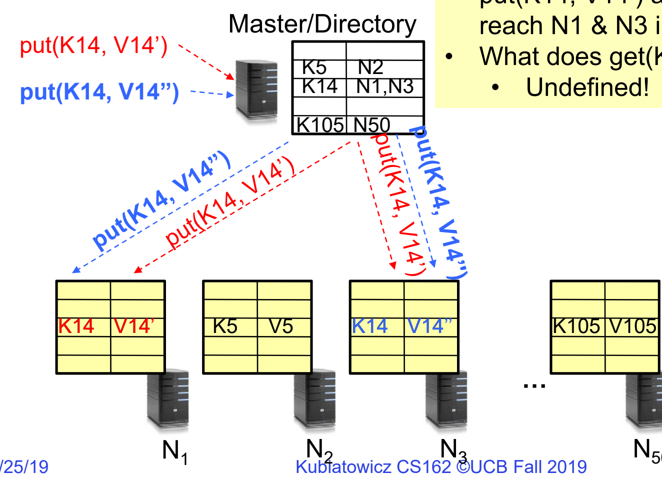


Consistency (cont'd)

- If concurrent updates (i.e., puts to same key) may need to make sure that updates happen in the same order

- put(K14, V14') and put(K14, V14'') reach N1 & N3 in reverse order
- What does get(K14) return?
  - Undefined!



Large Variety of Consistency Models

- Atomic consistency (linearizability): reads/writes (gets/puts) to replicas appear as if there was a single underlying replica (single system image)
  – Think "one updated at a time"
  – Transactions
- Eventual consistency: given enough time all updates will propagate through the system
  – One of the weakest form of consistency; used by many systems in practice
  – Must eventually converge on single value/key (coherence)
- *And many others: causal consistency, sequential consistency, strong consistency, …*

Quorum Consensus

- Improve put() and get() operation performance

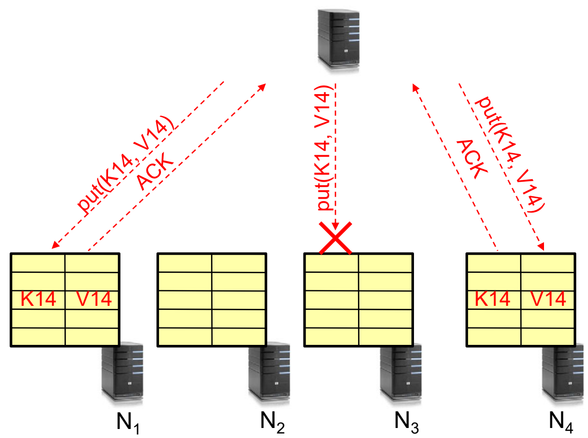
- Define a replica set of size N
  – put() waits for acknowledgements from at least W replicas
  – get() waits for responses from at least R replicas
  – W+R > N

- Why does it work?
  – There is at least one node that contains the update

- Why might you use W+R > N+1?

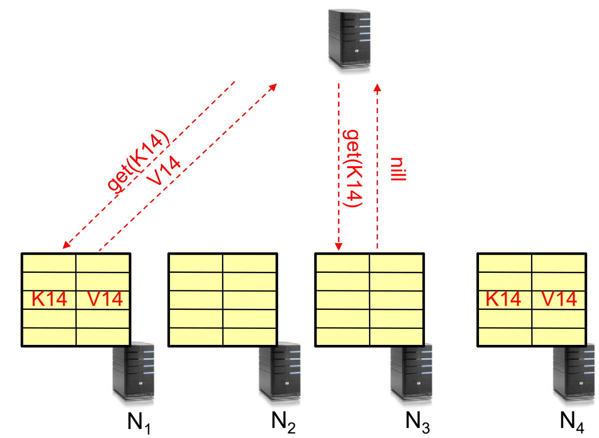
Quorum Consensus Example

- N=3, W=2, R=2
- Replica set for K14: {N1, N2, N4}
- Assume put() on N3 fails



Quorum Consensus Example

- Now, issuing get() to any two nodes out of three will return the answer

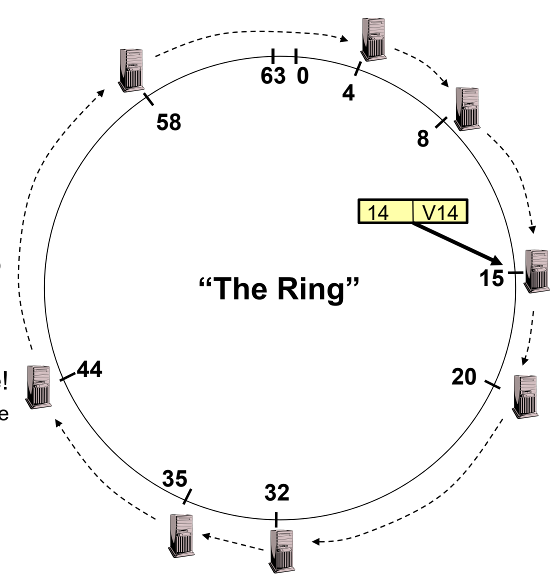


Scaling Up Directory

- Challenge:
  - Directory contains a number of entries equal to number of (key, value) tuples in the system
  - Can be tens or hundreds of billions of entries in the system!
- Solution: **Consistent Hashing**
  - **Provides mechanism to divide [key,value] pairs amongst a (potentially large!) set of machines (nodes) on network**
- Associate to each node a unique *id* in an *uni*-dimensional space $0..2^m-1 \Rightarrow$ Wraps around: Call this "the ring!"
  - Partition this space across *n* machines
  - Assume keys are in same uni-dimensional space
  - Each [Key, Value] is stored at the node with the smallest ID larger than Key

Key to Node Mapping Example

- Paritioning example with m = 8 → ID space: 0..63
  - Node 8 maps keys [5,8]
  - Node 15 maps keys [9,15]
  - Node 20 maps keys [16, 20]
  - …
  - Node 4 maps keys [59, 4]
- For this example, the mapping [14, V14] maps to node with ID=15
  - Node with smallest ID larger than 14 (the key)
- In practice, m=256 or more!
  - Uses cryptographically secure hash such as SHA-256 to generate the node IDs



Summary (1/2)

- Distributed File System:
  - Transparent access to files stored on a remote disk
  - Caching for performance
- VFS: Virtual File System layer
  - Provides mechanism which gives same system call interface for different types of file systems
- Cache Consistency: Keeping client caches consistent with one another
  - If multiple clients, some reading and some writing, how do stale cached copies get updated?
  - NFS: check periodically for changes
  - AFS: clients register callbacks to be notified by server of changes

Summary (2/2)

- Key-Value Store:
  - Two operations
    - » put(key, value)
    - » value = get(key)
  - Challenges
    - » Fault Tolerance → replication
    - » Scalability → serve get()'s in parallel; replicate/cache hot tuples
    - » Consistency → quorum consensus to improve put() performance