CS162
Operating Systems and Systems Programming
Lecture 15
Key-Value Storage, Network Protocols

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Key Value Storage

- Interface
  - **put**(key, value); // insert/write "value" associated with "key"
  - value = **get**(key); // get/read data associated with "key"
- Abstraction used to implement
  - File systems: value content → block
  - Sometimes as a simpler but more scalable "database"
- Can handle large volumes of data, e.g., PBs
  - Need to distribute data over hundreds, even thousands of machines

Key Values: Examples

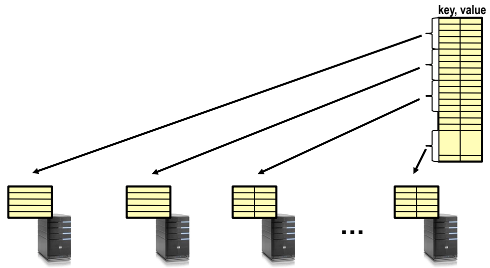
- Amazon:
  - Key: customerID
  - Value: customer profile (e.g., buying history, credit card, ..)
- Facebook, Twitter:
  - Key: UserID
  - Value: user profile (e.g., posting history, photos, friends, …)
- iCloud/iTunes:
  - Key: Movie/song name
  - Value: Movie, Song
- Distributed file systems
  - Key: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

System Examples

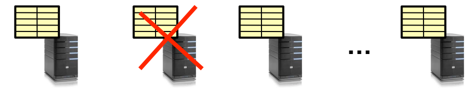
- **Google File System, Hadoop Dist. File Systems (HDFS)**
- **Amazon**
  - Dynamo: internal key value store used to power Amazon.com (shopping cart)
  - Simple Storage System (S3)
- **BigTable/HBase/Hypertable:** distributed, scalable data storage
- **Cassandra**: "distributed data management system" (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 a Distributed Hash Table (DHT)
- Main idea: partition set of key-values across many machines



Challenges



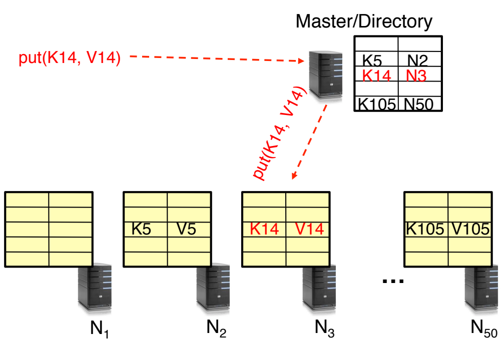
- **Fault Tolerance:** handle machine failures without losing data and without degradation in performance
- **Scalability:**
  - Need to scale to thousands of machines
  - Need to allow easy addition of new machines
- **Consistency:** maintain data consistency in face of node failures and message losses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

Key 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

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



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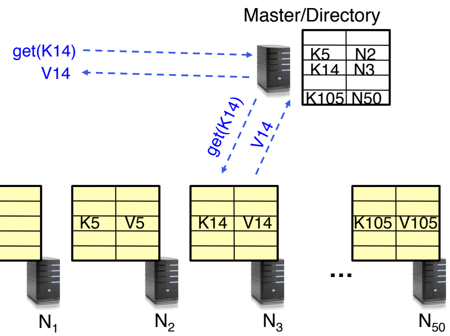
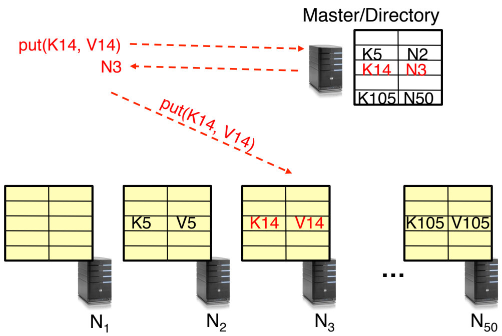


Directory-Based Architecture

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



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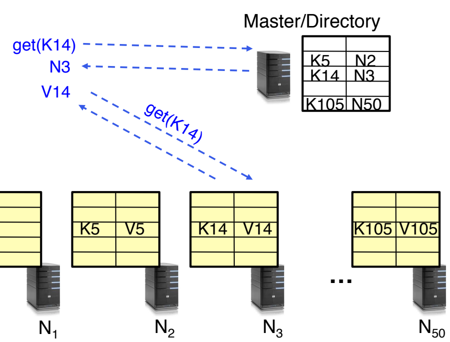
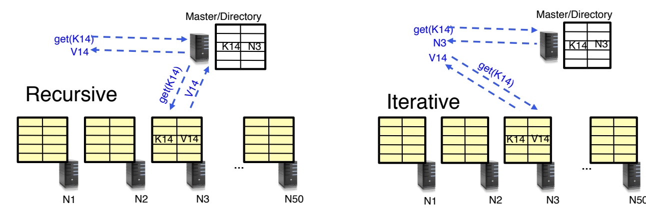


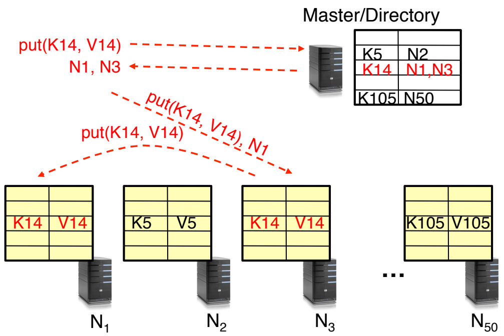
Discussion: Iterative vs. Recursive Query



- 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

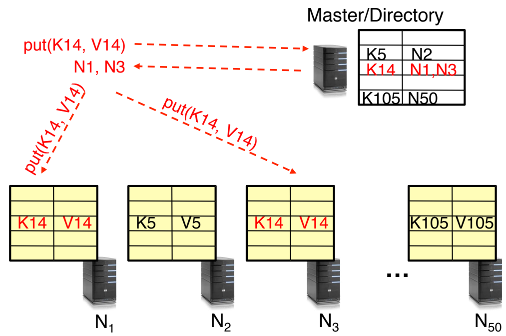
Fault Tolerance

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



Fault Tolerance

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



Scalability

- Storage: use more nodes
- Request Throughput:
  - 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? (p2p DHDT, end of semester)

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

Replication Challenges

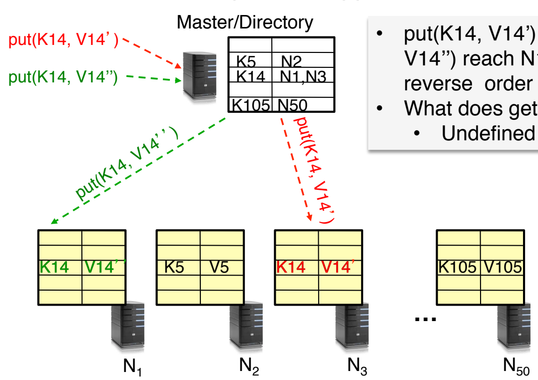
- Need to make sure that a value is replicated correctly
- How do you know a value has been replicated on every node?
  - Wait for acknowledgements from every node
- What happens if a node fails during replication?
  - Pick another node and try again
- What happens if a node is slow?
  - Slow down the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

Consistency

- How close does a distributed system emulate a single machine in terms of read and write semantics?
- **Q:** Assume **put(K14, V14')** and **put(K14, V14'')** are concurrent, what value ends up being stored?
- **A:** assuming **put()** is atomic, then either **V14'** or **V14''**, right?
- **Q:** Assume a client calls **put(K14, V14)** and then **get(K14)**, what is the result returned by **get()**?
- **A:** It should be V14, right?
- Above semantics, not trivial to achieve in distributed systems

Concurrent Writes (Updates)

- 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 and N3 in reverse order
- What does get(K14) return?
  - Undefined!

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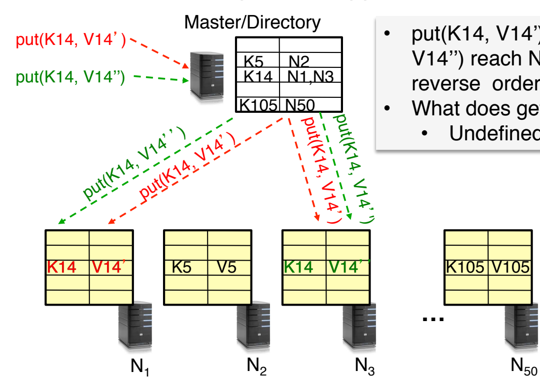
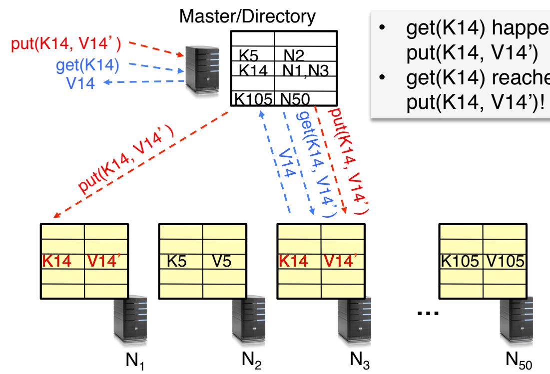


- put(K14, V14') and put(K14, V14'') reach N1 and N3 in reverse order
- What does get(K14) return?
  - Undefined!

Read after Write

- Read not guaranteed to return value of latest write
  - Can happen if Master processes requests in different threads

- get(K14) happens right after put(K14, V14')
- get(K14) reaches N3 before put(K14, V14')!



Consistency (cont'd)

- 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 (later in the class)
  - 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
  - And many others: causal consistency, sequential consistency, strong consistency, …

Strong Consistency

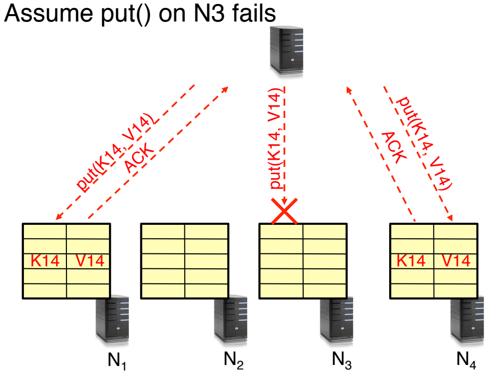
- Assume Master serializes all operations
- Challenge: master becomes a bottleneck
  - Not address here
- Still want to improve performance of reads/writes → quorum consensus

Quorum Consensus

- Improve **put()** and **get()** operation performance
- Define a replica set of size N
- **put()** waits for acks 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 you may use W+R > N+1?

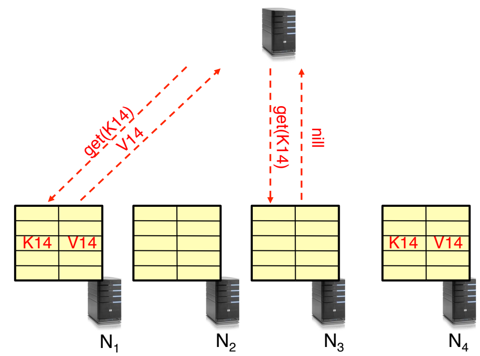
Quorum Consensus Example

- 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



Conclusions: Key Value Store

- Very large scale storage systems
- 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/get performance

Quiz 15.1: Key-Value Store

- Q1: True _ False _ On a single node, a key-value store can be implemented by a hash-table
- Q2: True _ False _ Master can be a bottleneck point for a key-value store
- Q3: True _ False _ Iterative puts achieve lower throughput than recursive puts
- Q4: True _ False _ With quorum consensus, we can improve read performance at expense of write performance

Quiz 15.1: Key-Value Store

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5min Break

Networking: This Lecture's Goals

- What is a protocol?
- Layering

Many slides generated from my lecture notes by Vern Paxson, and Scott Shenker.

What Is A Protocol?

- A protocol is an agreement on how to communicate
- Includes
  - 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

Examples of Protocols in Human Interactions

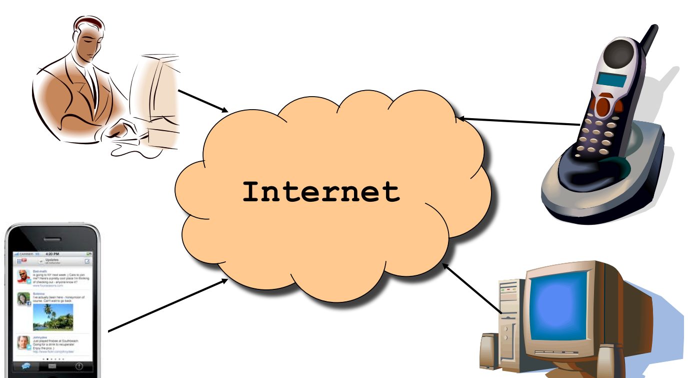
- Telephone
  1. (Pick up / open up the phone.)
  2. Listen for a dial tone / see that you have service.
  3. Dial
  4. Should hear ringing …
  5. Callee: "Hello?"
  6. Caller: "Hi, it's Alice …."
     Or: "Hi, it's me" (← what's *that* about?)
  7. Caller: "Hey, do you think … blah blah blah …" **pause**
  8. Callee: "Yeah, blah blah blah …" **pause**
  9. Caller: Bye
  10. Callee: Bye
  11. Hang up

Examples of Protocols in Human Interactions

Asking a question
1. Raise your hand.
2. Wait to be called on.

3. Or: wait for speaker to **pause** and vocalize

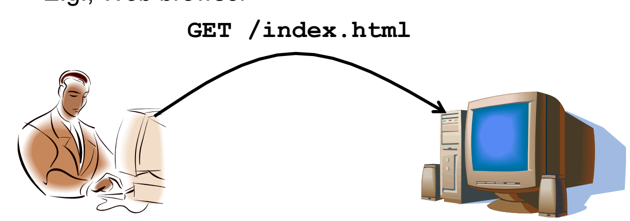
End System: Computer on the 'Net



Also known as a "host"…

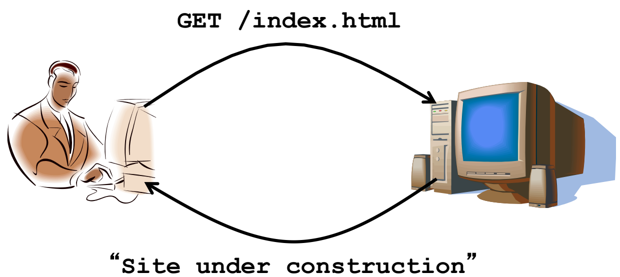
Clients and Servers

- Client program
  – Running on end host
  – Requests service
  – E.g., Web browser



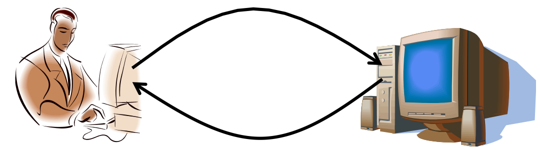
Clients and Servers

- Client program
  - Running on end host
  - Requests service
  - E.g., Web browser
- Server program
  - Running on end host
  - Provides service
  - E.g., Web server



Client-Server Communication

- Client "sometimes on"
  - Initiates a request to the server when interested
  - E.g., Web browser on your laptop or cell phone
  - Doesn't communicate directly with other clients
  - Needs to know the server's address
- Server is "always on"
  - Services requests from many client hosts
  - E.g., Web server for the *www.cnn.com* Web site
  - Doesn't initiate contact with the clients
  - Needs a fixed, well-known address



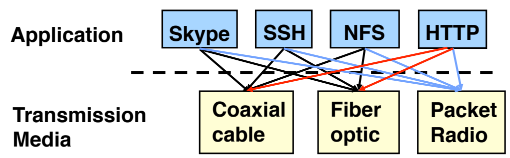
Peer-to-Peer Communication

- Not always-on server at the center of it all
  - Hosts can come and go, and change addresses
  - Hosts may have a different address each time
- Example: peer-to-peer file sharing (e.g., Bittorrent)
  - Any host can request files, send files, query to find where a file is located, respond to queries, and forward queries
  - Scalability by harnessing millions of peers
  - Each peer acting as both a client and server

The Problem

- Many different applications
  - email, web, P2P, etc.
- Many different network styles and technologies
  - Wireless vs. wired vs. optical, etc.
- How do we organize this mess?

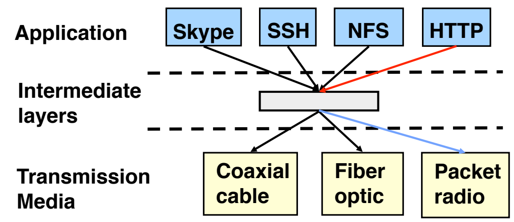
The Problem (cont'd)



- Re-implement every application for every technology?
- No! But how does the Internet design avoid this?

Solution: Intermediate Layers

- Introduce intermediate layers that provide set of abstractions for various network functionality & technologies
  - A new app/media implemented only once
  - Variation on "add another level of indirection"



Software System Modularity

Partition system into modules & abstractions:

- Well-defined interfaces give flexibility
  - ***Hides*** implementation - thus, it can be freely changed
  - Extend functionality of system by adding new modules
- E.g., libraries encapsulating set of functionality
- E.g., programming language + compiler abstracts away not only how the particular CPU works …
  - … but also the basic computational model
- Well-defined interfaces hide information
  - Isolate assumptions
  - Present high-level abstractions
  - **But can impair performance**

Network System Modularity

Like software modularity, but:

- Implementation distributed across many machines (routers and hosts)
- Must decide:
  - How to break system into modules
    - » **Layering**
  - What functionality does each module implement
    - » **End-to-End Principle**
- We will address these choices next lecture

Layering: A Modular Approach

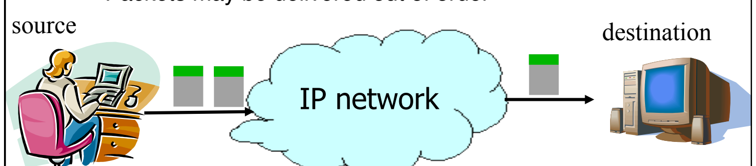
- Partition the system
  - Each layer solely relies on services from layer below
  - Each layer solely exports services to layer above
- Interface between layers defines interaction
  - Hides implementation details
  - Layers can change without disturbing other layers

Protocol Standardization

- Ensure communicating hosts speak the same protocol
  - Standardization to enable multiple implementations
  - Or, the same folks have to write all the software
- Standardization: Internet Engineering Task Force
  - Based on working groups that focus on specific issues
  - Produces "Request For Comments" (RFCs)
    - » Promoted to standards via rough consensus and running code
  - IETF Web site is ***http://www.ietf.org***
  - RFCs archived at ***http://www.rfc-editor.org***
- De facto standards: same folks writing the code
  - P2P file sharing, Skype, <your protocol here>…

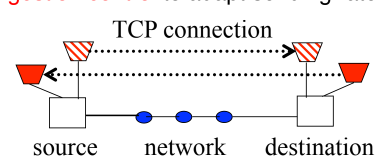
Example: The Internet Protocol (IP): "Best-Effort" Packet Delivery

- Datagram packet switching
  - Send data in packets
  - Header with source & destination address
- Service it provides:
  - Packets may be lost
  - Packets may be corrupted
  - Packets may be delivered out of order



Example: Transmission Control Protocol (TCP)

- Communication service
  - Ordered, reliable byte stream
  - Simultaneous transmission in both directions
- Key mechanisms at end hosts
  - Retransmit lost and corrupted packets
  - Discard duplicate packets and put packets in order
  - Flow control to avoid overloading the receiver buffer
  - Congestion control to adapt sending rate to network load



Quiz 15.2: Protocols

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- Q2: True _ False _ Protocols specify the implementation
- Q3: True _ False _ Layering helps to improve application performance
- Q4: True _ False _ "Best Effort" packet delivery ensures that packets are delivered in order
- Q5: True _ False _ In p2p systems a node is both a client and a server
- Q6: True _ False _ TCP ensures that each packet is delivered within a predefined amount of time

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Summary

- Roles of
  - Standardization
  - Clients, servers, peer-to-peer
- Layered architecture as a powerful means for organizing complex networks
  - Though layering has its drawbacks too
- Next lecture
  - Layering
  - End-to-end arguments