CS162
Operating Systems and Systems Programming
Lecture 24

Key-Value Stores (Finished)
Security + Cloud (a bit)

December 2nd, 2015

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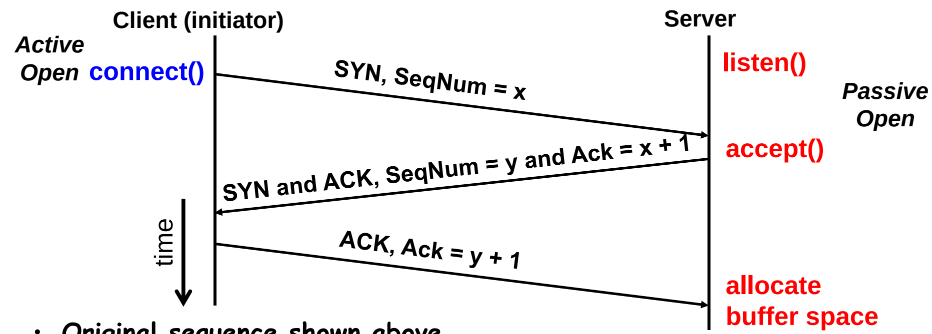
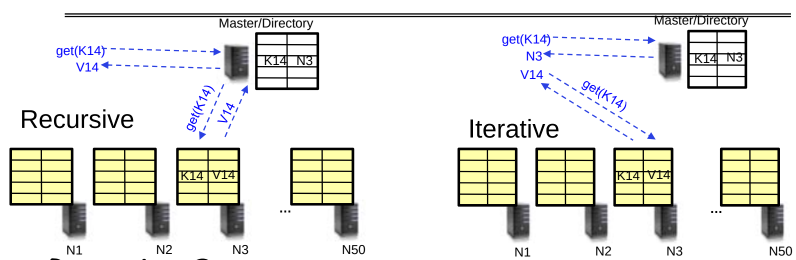
Recall: Open Connection: 3-Way Handshaking



- Original sequence shown above
- Vulnerabilities: Denial of service
  - SYN attack: send a huge number of SYN messages
  - Causes victim system to commit resources (e.g. 768 byte TCP/IP data structure)
- Alternatives: Do not commit resources until receive final ACK
  - SYN Cache: when SYN received, put small entry into cache and send SYN/ACK. If receive ACK, then put into listening socket
  - SYN Cookie: when SYN received, encode connection info into sequence number/other TCP header blocks, decode on ACK

Recall: 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

Scalability

- More Storage: use more nodes
- More 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

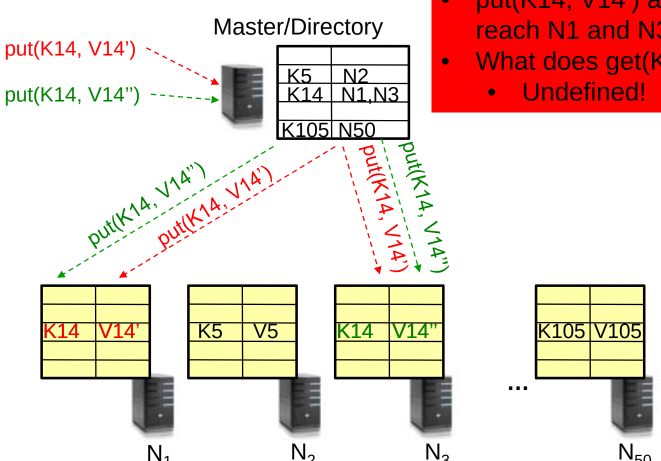
- Directory keeps track of the storage availability at each node
  - Preferentially insert new values on nodes with more storage available
- What happens when a new node is added?
  - Cannot insert only new values on new node. Why?
  - Move values from the heavy loaded nodes to the new node
- What happens 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 and N3 in reverse order
- What does get(K14) return?
  - Undefined!

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
  - 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

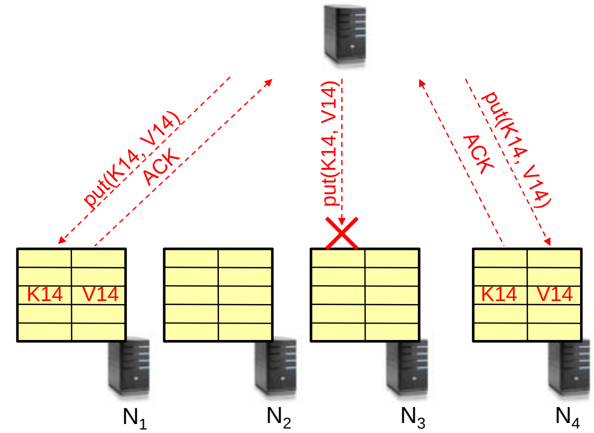
- Define a replica set of size N
  - put() waits for acknowledgements from at least W replicas
  - get() waits for responses from at least R replicas
  - W+R > N

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

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

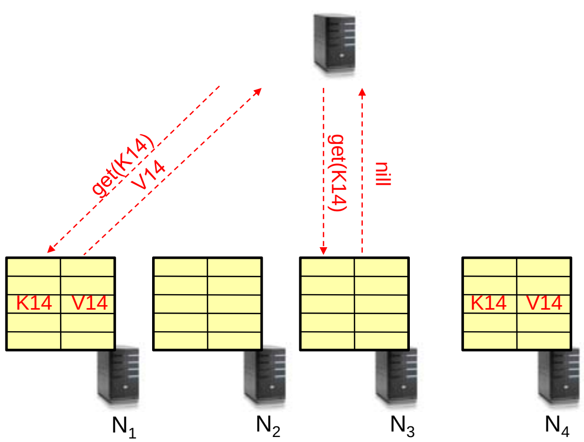
Quorum Consensus Example

- 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



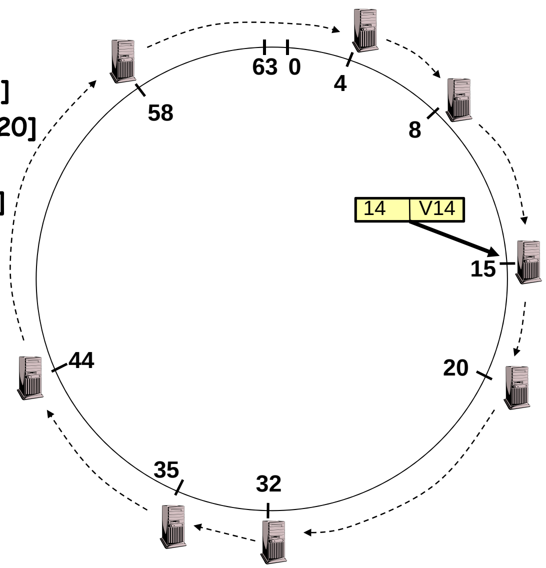
Scaling Up Directory

- 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
- Associate to each node a unique *id* in an *uni*-dimensional space $0..2^m-1$
  - Partition this space across *m* machines
  - Assume keys are in same uni-dimensional space
  - Each (Key, Value) is stored at the node with the smallest ID larger than Key

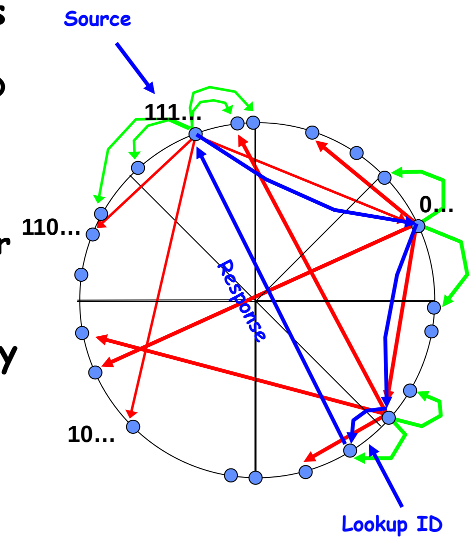
Key to Node Mapping Example

- m = 6 → 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]



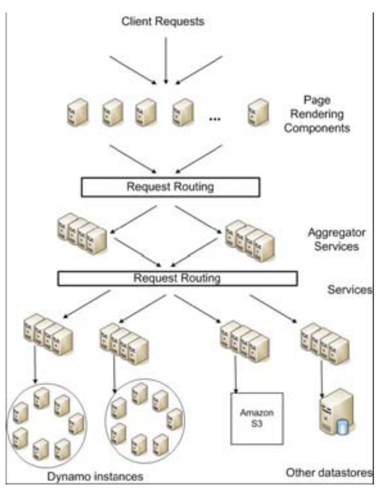
Lookup in Chord-like system (with Leaf Set)

- Assign IDs to nodes
  - Map hash values to node with closest ID
- Leaf set is successors and predecessors
  - All that's needed for correctness
- Routing table matches successively longer prefixes
  - Allows efficient lookups
- Data Replication:
  - On leaf set



DynamoDB Example: Service Level Agreements (SLA)

- Application can deliver its functionality in a bounded time:
  - Every dependency in the platform needs to deliver its functionality with even tighter bounds.
- Example: service guaranteeing that it will provide a response within 300ms for 99.9% of its requests for a peak client load of 500 requests per second
- Contrast to services which focus on mean response time



Service-oriented architecture of Amazon's platform

Administrivia

- Midterm 2 grading
  - In progress. To be done by end of weekend
    - » Will have until midweek (Wed) to put in regrade requests
  - Solutions have been posted
- Project 3 Extension:
  - Code: Wednesday (12/9), Report: Thursday (12/10)
- HW4 Assumptions:
  - Assume coordinator does not fail (unlike full 2-phase commit protocol)
- Take Peer Reviews seriously!
  - We look carefully at your grades *and* comments!
    - » Make sure to give us enough information to evaluate the group dynamic
  - Projects are a zero-sum game
    - » If you don't participate, you won't get the same grade as your partners!
    - » Your points can be given to your group members

Administrivia (2)

- Final topics (Monday, 12/7):
  - Go to poll on Piazza!
  - Current front runners:
    - » Quantum Computing
    - » Internet of Things
    - » Virtual Machines
- Final Exam
  - Friday, December 18th, 2015.
  - 3-6P, Wheeler Auditorium
  - All material from the course
    - » (excluding option lecture on 12/7)
    - » With slightly more focus on second half, but you are still responsible for all the material
  - Two sheets of notes, both sides
  - Will need dumb calculator
- Targeted review sessions: See posts on Piazza
  - Possibly 3 different sessions focused on parts of course

What is Computer Security Today?

- Computing in the presence of an adversary!
  - Adversary is the security field's defining characteristic
- Reliability, robustness, and fault tolerance
  - Dealing with Mother Nature (random failures)
- Security
  - Dealing with actions of a knowledgeable attacker dedicated to causing harm
  - Surviving malice, and not just mischance
- Wherever there is an adversary, there is a computer security problem!

Protection vs. Security

- Protection: mechanisms for controlling access of programs, processes, or users to resources
  - Page table mechanism
  - Round-robin schedule
  - Data encryption
- Security: use of protection mech. to prevent misuse of resources
  - Misuse defined with respect to policy
    - » E.g.: prevent exposure of certain sensitive information
    - » E.g.: prevent unauthorized modification/deletion of data
  - Need to consider external environment the system operates in
    - » Most well-constructed system cannot protect information if user accidentally reveals password – social engineering challenge

Security Requirements

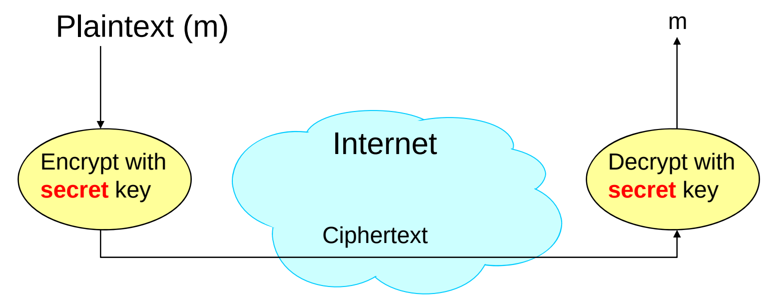
- Authentication
  - Ensures that a user is who is claiming to be
- Data integrity
  - Ensure that data is not changed from source to destination or after being written on a storage device
- Confidentiality
  - Ensures that data is read only by authorized users
- Non-repudiation
  - Sender/client can't later claim didn't send/write data
  - Receiver/server can't claim didn't receive/write data

Securing Communication: Cryptography

- Cryptography: communication in the presence of adversaries
- Studied for thousands of years
  - See the Simon Singh's The Code Book for an excellent, highly readable history
- Central goal: confidentiality
  - How to encode information so that an adversary can't extract it, but a friend can
- General premise: there is a key, possession of which allows decoding, but without which decoding is infeasible
  - Thus, key must be kept secret and not guessable

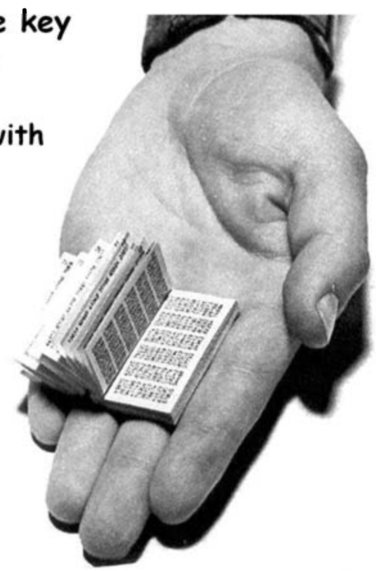
Using Symmetric Keys

- Same key for encryption and decryption
- Achieves confidentiality
- Vulnerable to tampering and replay attacks



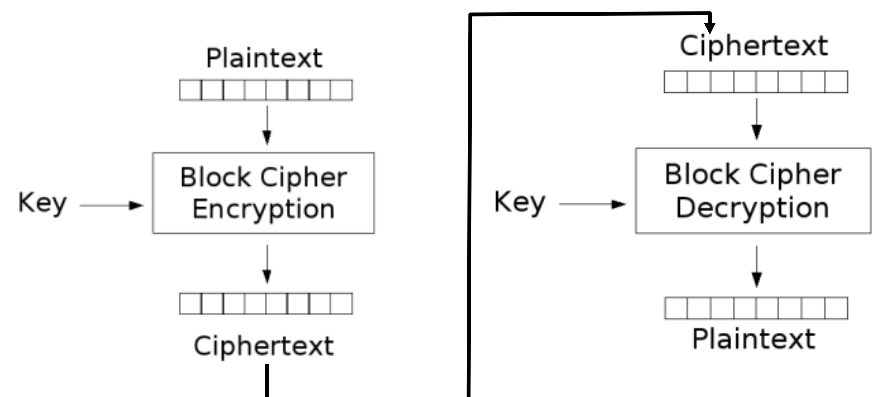
Symmetric Keys

- Can just XOR plaintext with the key
  - Easy to implement, but easy to break using frequency analysis
  - Unbreakable alternative: XOR with one-time pad
    - » Use a different key for each message



Block Ciphers with Symmetric Keys

- More sophisticated (e.g., block cipher) algorithms
  - Works with a block size (e.g., 64 bits)
- Can encrypt blocks separately:
  - Same plaintext⇒same ciphertext
- Much better:
  - Add in counter and/or link ciphertext of previous block

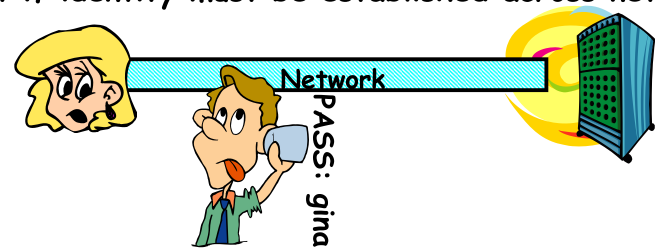


Symmetric Key Ciphers - DES & AES

- Data Encryption Standard (DES)
  - Developed by IBM in 1970s, standardized by NBS/NIST
  - 56-bit key (decreased from 64 bits at NSA's request)
  - Still fairly strong other than brute-forcing the key space
    - » But custom hardware can crack a key in < 24 hours
  - Today many financial institutions use Triple DES
    - » DES applied 3 times, with 3 keys totaling 168 bits
- Advanced Encryption Standard (AES)
  - Replacement for DES standardized in 2002
  - Key size: 128, 192 or 256 bits
- How fundamentally strong are they?
  - No one knows (no proofs exist)

Authentication in Distributed Systems

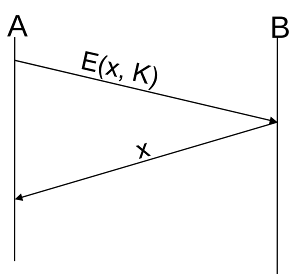
- What if identity must be established across network?



  - Need way to prevent exposure of information while still proving identity to remote system
  - Many of the original UNIX tools sent passwords over the wire "in clear text"
    - » E.g.: telnet, ftp, yp (yellow pages, for distributed login)
    - » Result: Snooping programs widespread
- What do we need? Cannot rely on physical security!
  - Encryption: Privacy, restrict receivers
  - Authentication: Remote Authenticity, restrict senders

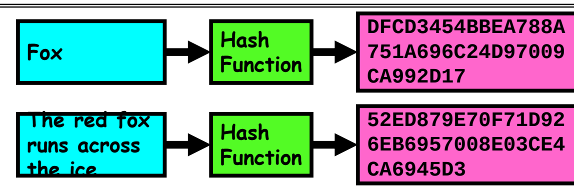
Authentication via Secret Key

- Main idea: entity proves identity by decrypting a secret encrypted with its own key
  - K – secret key shared only by A and B
- A can asks B to authenticate itself by decrypting a nonce, i.e., random value, x
  - Avoid replay attacks (attacker impersonating client or server)
- Vulnerable to man-in-the middle attack



Notation: E(m,k) – encrypt message m with key k

Secure Hash Function

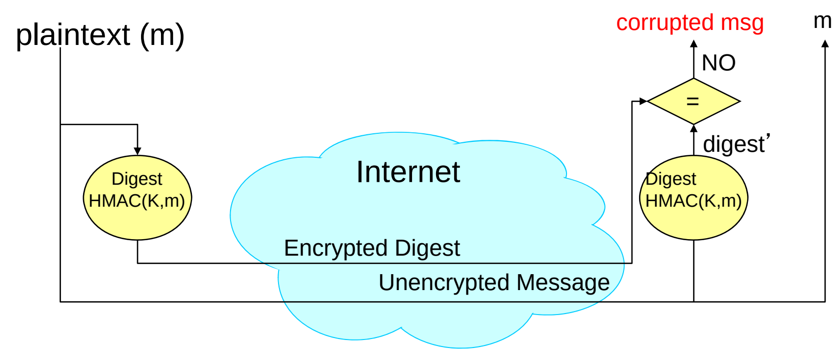


- Hash Function: Short summary of data (message)
  - For instance, $h_1=H(M_1)$ is the hash of message M_1
    - » h_1 fixed length, despite size of message M_1.
    - » Often, h_1 is called the "digest" of M_1.
- Hash function H is considered secure if
  - It is infeasible to find M_2 with $h_1=H(M_2)$; ie. can't easily find other message with same digest as given message.
  - It is infeasible to locate two messages, m_1 and m_2, which "collide", i.e. for which $H(m_1) = H(m_2)$
  - A small change in a message changes many bits of digest/can't tell anything about message given its hash

Integrity: Cryptographic Hashes

- Basic building block for integrity: cryptographic hashing
  - Associate hash with byte-stream, receiver verifies match
    - » Assures data hasn't been modified, either accidentally – or maliciously
- Approach:
  - Sender computes a secure digest of message m using H(x)
    - » H(x) is a publicly known hash function
    - » Digest d = HMAC (K, m) = H (K | H (K | m))
    - » HMAC(K, m) is a hash-based message authentication function
  - Send digest d and message m to receiver
  - Upon receiving m and d, receiver uses shared secret key, K, to recompute HMAC(K, m) and see whether result agrees with d

Using Hashing for Integrity



Can encrypt m for confidentiality

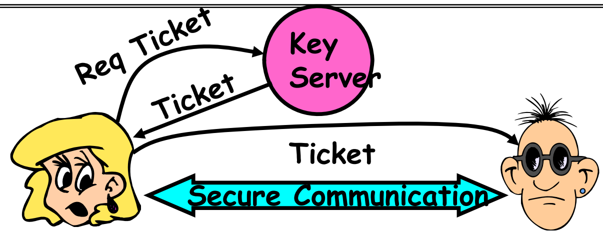
Standard Cryptographic Hash Functions

- MD5 (Message Digest version 5)
  - Developed in 1991 (Rivest), produces 128 bit hashes
  - Widely used (RFC 1321)
  - Broken (1996-2008): attacks that find collisions
- SHA-1 (Secure Hash Algorithm)
  - Developed in 1995 (NSA) as MD5 successor with 160 bit hashes
  - Widely used (SSL/TLS, SSH, PGP, IPSEC)
  - Broken in 2005, government use discontinued in 2010
- SHA-2 (2001)
  - Family of SHA-224, SHA-256, SHA-384, SHA-512 functions
- HMAC's are secure even with older "insecure" hash functions
  -

Key Distribution

- How do you get shared secret to both places?
  - For instance: how do you send authenticated, secret mail to someone who you have never met?
  - Must negotiate key over private channel
    - » Exchange code book
    - » Key cards/memory stick/others
- Third Party: Authentication Server (like Kerberos)
  - Notation:
    - » K_{xy} is key for talking between x and y
    - » $(\ldots)^K$ means encrypt message (…) with the key K
    - » Clients: A and B, Authentication server S
  - A asks server for key:
    - » A→S: [Hi! I'd like a key for talking between A and B]
    - » Not encrypted. Others can find out if A and B are talking
  - Server returns *session* key encrypted using B's key
    - » S→A: Message [Use K_{ab} (This is A! Use K_{ab})^{Ksb}] ^{Ksa}
    - » This allows A to know, "S said use this key"
  - Whenever A wants to talk with B
    - » A→B: Ticket [This is A! Use K_{ab}]^{Ksb}
    - » Now, B knows that K_{ab} is sanctioned by S

Authentication Server Continued [Kerberos]



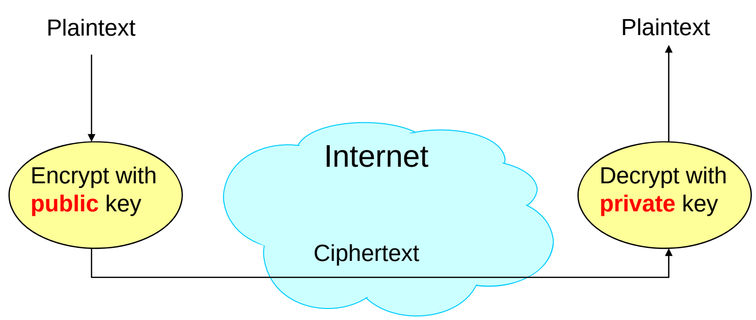
- Details
  - Both A and B use passwords (shared with key server) to decrypt return from key servers
  - Add in timestamps to limit how long tickets will be used to prevent attacker from replaying messages later
  - Also have to include encrypted checksums (hashed version of message) to prevent malicious user from inserting things into messages/changing messages
  - Want to minimize # times A types in password
    - » A→S (Give me temporary secret)
    - » S→A (Use $K_{temp\text{-}sa}$ for next 8 hours)^{Ksa}
    - » Can now use $K_{temp\text{-}sa}$ in place of K_{sa} in prototcol

Asymmetric Encryption (Public Key)

- Idea: use two different keys, one to encrypt (e) and one to decrypt (d)
  - A key pair
- Crucial property: knowing e does not give away d
- Therefore e can be public: everyone knows it!
- If Alice wants to send to Bob, she fetches Bob's public key (say from Bob's home page) and encrypts with it
  - Alice can't decrypt what she's sending to Bob …
  - … but then, neither can anyone else (except Bob)

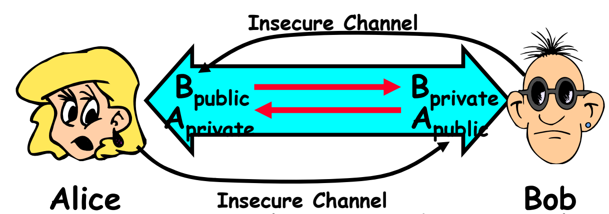
Public Key / Asymmetric Encryption

- Sender uses receiver's public key
  - Advertised to everyone
- Receiver uses complementary private key
  - Must be kept secret



Public Key Encryption Details

- Idea: K_{public} can be made public, keep $K_{private}$ private



- Gives message privacy (restricted receiver):
  - Public keys (secure destination points) can be acquired by anyone/used by anyone
  - Only person with private key can decrypt message
- What about authentication?
  - Use combination of private and public key
  - Alice→Bob: [(I'm Alice)^{Aprivate} Rest of message]^{Bpublic}
  - Provides restricted sender and receiver
- But: how does Alice know that it was Bob who sent her B_{public}? And vice versa…

Public Key Cryptography

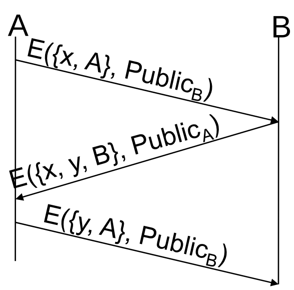
- Invented in the 1970s
  - Revolutionized cryptography
  - (Was actually invented earlier by British intelligence)
- How can we construct an encryption/decryption algorithm using a key pair with the public/private properties?
  - Answer: Number Theory
- Most fully developed approach: RSA
  - Rivest / Shamir / Adleman, 1977; RFC 3447
  - Based on modular multiplication of very large integers
  - Very widely used (e.g., ssh, SSL/TLS for https)
- Also mature approach: Eliptic Curve Cryptography (ECC)
  - Based on curves in a Galois-field space
  - Shorter keys and signatures than RSA

Properties of RSA

- Requires generating large, random prime numbers
  - Algorithms exist for quickly finding these (probabilistic!)
- Requires exponentiating very large numbers
  - Again, fairly fast algorithms exist
- Overall, much slower than symmetric key crypto
  - One general strategy: use public key crypto to exchange a (short) symmetric session key
    - » Use that key then with AES or such
- How difficult is recovering d, the private key?
  - Equivalent to finding prime factors of a large number
    - » Many have tried - believed to be very hard (= brute force only)
    - » (Though quantum computers could do so in polynomial time!)

Simple Public Key Authentication

- Each side need only to know the other side's public key
  - No secret key need be shared
- A encrypts a nonce (random num.) x
  - Avoid replay attacks, e.g., attacker impersonating client or server
- B proves it can recover x, generates second nonce y
- A can authenticate itself to B in the same way
- A and B have shared private secrets on which to build private key!
  - We just did secure key distribution!
- *Many more details to make this work securely in practice!*

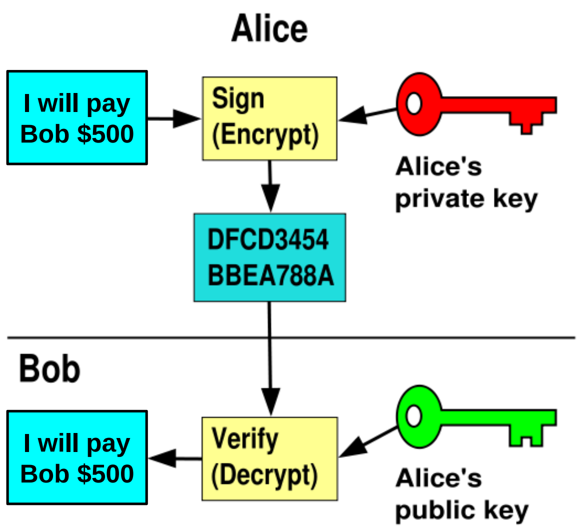


Notation: E(m,k) – encrypt message m with key k

Non-Repudiation: RSA Crypto & Signatures

- Suppose Alice has published public key KE
- If she wishes to prove who she is, she can send a message x encrypted with her private key KD (i.e., she sends E(x, KD))
  - Anyone knowing Alice's public key KE can recover x, verify that Alice must have sent the message
    - » It provides a signature
  - Alice can't deny it ⇒ non-repudiation
- Could simply encrypt a hash of the data to sign a document that you wanted to be in clear text
- Note that either of these signature techniques work perfectly well with any data (not just messages)
  - Could sign every datum in a database, for instance

RSA Crypto & Signatures (cont'd)



Digital Certificates

- How do you know K_E is Alice's public key?
- Trusted authority (e.g., Verisign) signs binding between Alice and K_E with its private key $KV_{private}$
  - C = E({Alice, K_E}, $KV_{private}$)
  - C: digital certificate
- Alice: distribute her digital certificate, C
- Anyone: use trusted authority's KV_{public}, to extract Alice's public key from C
  - D(C, KV_{public}) = D(E({Alice, K_E}, $KV_{private}$), KV_{public}) = {Alice, K_E}

Summary of Our Crypto Toolkit

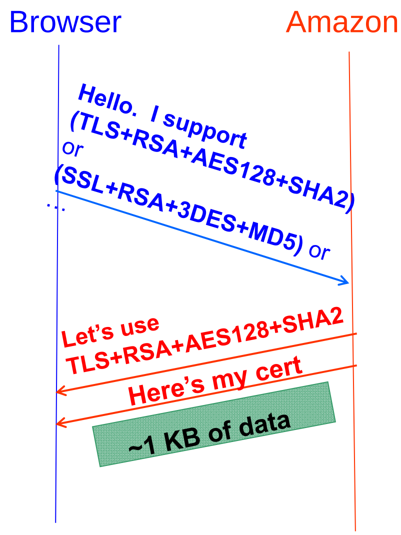
- If we can securely distribute a key, then
  - Symmetric ciphers (e.g., AES) offer fast, presumably strong confidentiality
- Public key cryptography does away with (potentially major) problem of secure key distribution
  - But: not as computationally efficient
    - » Often addressed by using public key crypto to exchange a session key
- Digital signature binds the public key to an entity

Putting It All Together - HTTPS

- What happens when you click on https://www.amazon.com?
- `https` = "Use HTTP over SSL/TLS"
  - SSL = Secure Socket Layer
  - TLS = Transport Layer Security
    - » Successor to SSL
  - Provides security layer (authentication, encryption) on top of TCP
    - » Fairly transparent to applications

HTTPS Connection (SSL/TLS) (cont'd)

- Browser (client) connects via TCP to Amazon's HTTPS server
- Client sends over list of crypto protocols it supports
- Server picks protocols to use for this session
- Server sends over its certificate
- (all of this is in the clear)



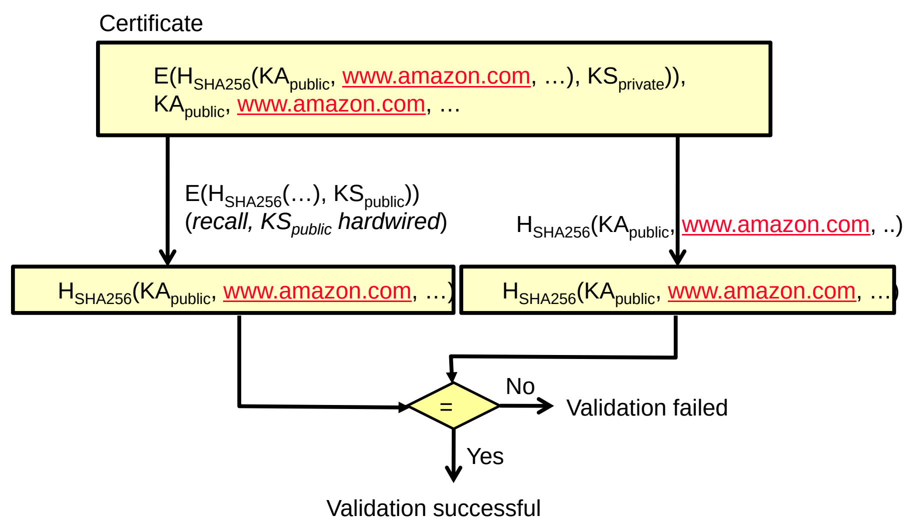
Inside the Server's Certificate

- Name associated with cert (e.g., Amazon)
- Amazon's RSA public key
- A bunch of auxiliary info (physical address, type of cert, expiration time)
- Name of certificate's signatory (who signed it)
- A public-key signature of a hash (SHA-256) of all this
  - Constructed using the signatory's private RSA key, i.e.,
  - Cert = $E(H_{SHA256}(KA_{public}$, www.amazon.com, …), $KS_{private}$))
    - » KA_{public}: Amazon's public key
    - » $KS_{private}$: signatory (certificate authority) private key
- …

Validating Amazon's Identity

- How does the browser authenticate certificate signatory?
  - Certificates of several certificate authorities (e.g., Verisign) are hardwired into the browser (or OS)
- If can't find cert, warn user that site has not been verified
  - And may ask whether to continue
  - Note, can still proceed, just without authentication
- Browser uses public key in signatory's cert to decrypt signature
  - Compares with its own SHA-256 hash of Amazon's cert
- Assuming signature matches, now have high confidence it's indeed Amazon …
  - … <u>assuming signatory is trustworthy</u>
  - *DigiNotar CA breach (July-Sept 2011): Google, Yahoo!, Mozilla, Tor project, Wordpress, … (531 total certificates)*

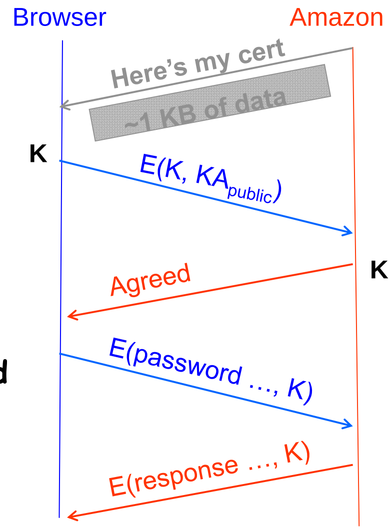
Certificate Validation



Can also validate using peer approach: https://www.eff.org/observatory

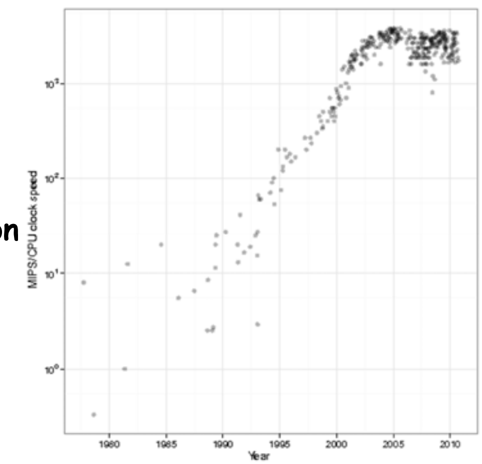
HTTPS Connection (SSL/TLS) cont'd

- Browser constructs a random ***session key*** K used for data communication
  - Private key for bulk crypto
- Browser encrypts K using Amazon's public key
- Browser sends $E(K, KA_{public})$ to server
- Browser displays 🔒
- All subsequent comm. encrypted w/ symmetric cipher (e.g., AES128) using key K
  - E.g., client can authenticate using a password



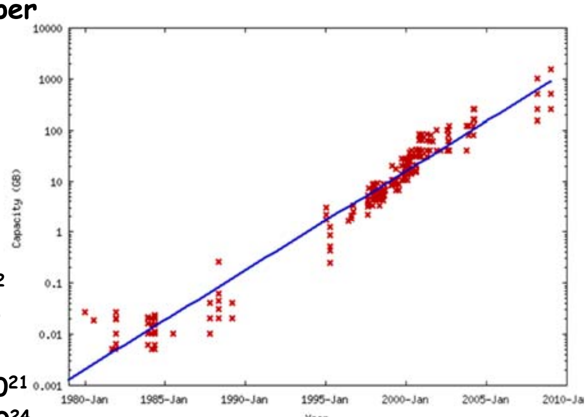
Background of Cloud Computing

- 1980's and 1990's: 52% growth in performance per year!
- 2002: The thermal wall
  - Speed (frequency) peaks, but transistors keep shrinking
- 2000's: Multicore revolution
  - 15-20 years later than predicted, we have hit the performance wall
- 2010's: Rise of Big Data

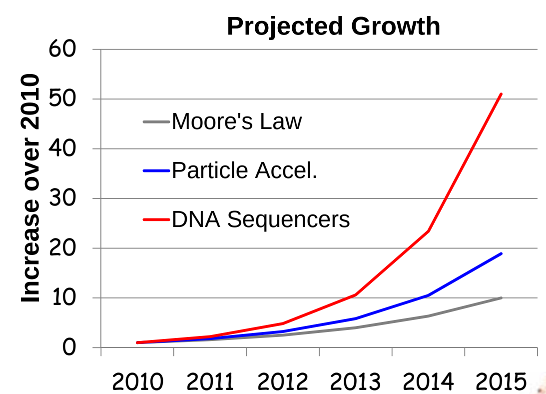


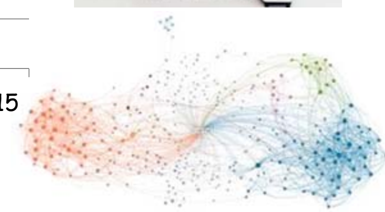
Data Deluge

- Billions of users connected through the net
  - WWW, FB, twitter, cell phones, …
  - 80% of the data on FB was produced last year
- Storage getting cheaper
  - Store more data!
  - 8TB drives common
  - 10TB announced
- Units of interest:
  - Gigabyte: $2^{30} \cong 10^9$
  - Terabyte: $2^{40} \cong 10^{12}$
  - Petabyte: $2^{50} \cong 10^{15}$
  - Exabyte: $2^{60} \cong 10^{18}$
  - Zettabyte: $2^{70} \cong 10^{21}$
  - Yottabyte: $2^{80} \cong 10^{24}$



Data Grows Faster than Moore's Law





Solving the Impedance Mismatch

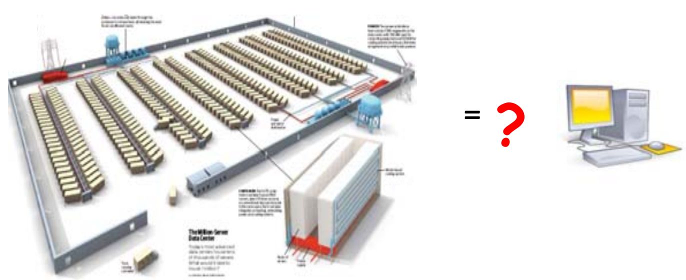
- Computers not getting faster, and we are drowning in data
  - How to resolve the dilemma?
- Solution adopted by web-scale companies
  - Go massively *distributed* and *parallel*

Enter the World of Distributed Systems

- Distributed Systems/Computing
  - *Loosely coupled* set of computers, communicating through message passing, solving a common goal
  - Tools: Msg passing, Distributed shared memory, RPC
- Distributed computing is *challenging*
  - Dealing with *partial failures* (examples?)
  - Dealing with *asynchrony* (examples?)
  - Dealing with *scale* (examples?)
  - Dealing with *consistency* (examples?)
- Distributed Computing versus Parallel Computing?
  - distributed computing ⇒ parallel computing + partial failures

The Datacenter is the new Computer

- "The datacenter as a computer" still in its infancy
  - Special purpose clusters, e.g., Hadoop cluster
  - Built from less reliable components
  - Highly variable performance
  - Complex concepts are hard to program (low-level primitives)



Datacenter/Cloud Computing OS

- If the datacenter/cloud is the new computer
  - What is its Operating System?
  - Note that we are not talking about a host OS
- Could be equivalent in benefit as the LAMP stack was to the .com boom – every startup *secretly* implementing the same functionality!
- Open source stack for a Web 2.0 company:
  - Linux OS
  - Apache web server
  - MySQL, MariaDB or MongoDB DBMS
  - PHP, Perl, or Python languages for dynamic web pages

Classical Operating Systems

- Data sharing
  - Inter-Process Communication, RPC, files, pipes, …
- Programming Abstractions
  - Libraries (libc), system calls, …
- Multiplexing of resources
  - Scheduling, virtual memory, file allocation/protection, …

Datacenter/Cloud Operating System

- Data sharing
  - Google File System, key/value stores
  - Apache project: Hadoop Distributed File System
- Programming Abstractions
  - Google MapReduce
  - Apache projects: Hadoop, Pig, Hive, Spark
- Multiplexing of resources
  - Apache projects: Mesos, YARN (MapReduce v2), ZooKeeper, BookKeeper, …

Google Cloud Infrastructure

- Google File System (GFS), 2003
  - Distributed File System for entire cluster
  - Single namespace
- Google MapReduce (MR), 2004
  - Runs queries/jobs on data
  - Manages work distribution & fault-tolerance
  - Collocated with file system
- Apache open source versions:
  Hadoop DFS and Hadoop MR


The Google File System

Sanjay Ghemawat, Howard Gobioff, and Shun-Tak Leung

Google

ABSTRACT

1. INTRODUCTION


MapReduce: Simplified Data Processing on Large Clusters

Jeffrey Dean and Sanjay Ghemawat

Google, Inc.

Abstract

GFS/HDFS Insights

- *Petabyte* storage
  - Files split into large blocks (128 MB) and replicated across several nodes
  - Big blocks allow high throughput sequential reads/writes
- Data *striped* on hundreds/thousands of servers
  - Scan 100 TB on 1 node @ 50 MB/s = 24 days
  - Scan on 1000-node cluster = 35 minutes

GFS/HDFS Insights (2)

- *Failures* will be the norm
  - Mean time between failures for 1 node = 3 years
  - Mean time between failures for 1000 nodes = 1 day
- Use *commodity* hardware
  - Failures are the norm anyway, buy cheaper hardware
- No complicated consistency models
  - Single writer, append-only data

MapReduce Programming Model

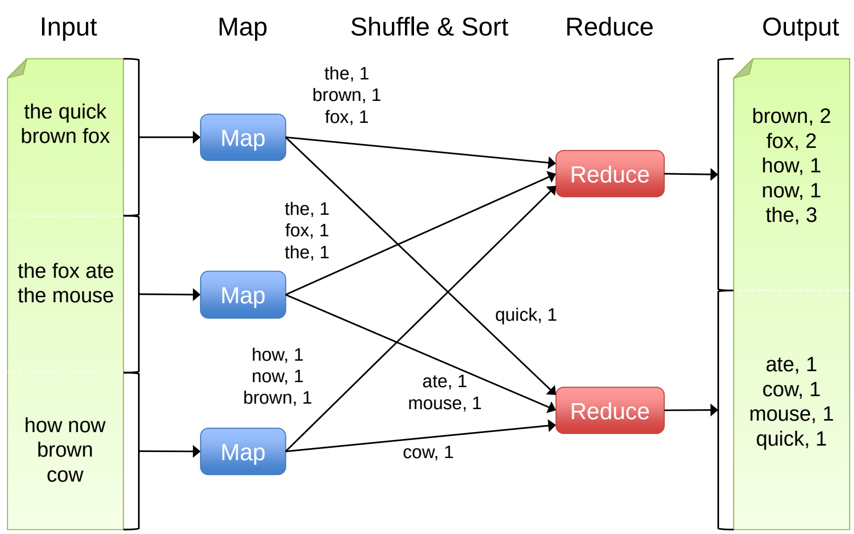
- Data type: key-value *records*
- Map function:

$$(K_{in}, V_{in}) \rightarrow list(K_{inter}, V_{inter})$$

- Reduce function:

$$(K_{inter}, list(V_{inter})) \rightarrow list(K_{out}, V_{out})$$

Word Count Execution



MapReduce Insights

- Restricted key-value model
  - Same fine-grained operation (Map & Reduce) repeated on big data
  - Operations must be deterministic
  - Operations must be idempotent/no side effects
  - Only communication is through the shuffle
  - Operation (Map & Reduce) output saved (on disk)

What is MapReduce Used For?

- At Google:
  - Index building for Google Search
  - Article clustering for Google News
  - Statistical machine translation
- At Yahoo!:
  - Index building for Yahoo! Search
  - Spam detection for Yahoo! Mail
- At Facebook:
  - Data mining
  - Ad optimization
  - Spam detection

MapReduce Pros

- Distribution is completely transparent
  - Not a single line of distributed programming (ease, correctness)
- Automatic fault-tolerance
  - Determinism enables running failed tasks somewhere else again
  - Saved intermediate data enables just re-running failed reducers
- Automatic scaling
  - As operations as side-effect free, they can be distributed to any number of machines dynamically
- Automatic load-balancing
  - Move tasks and speculatively execute duplicate copies of slow tasks (*stragglers)*

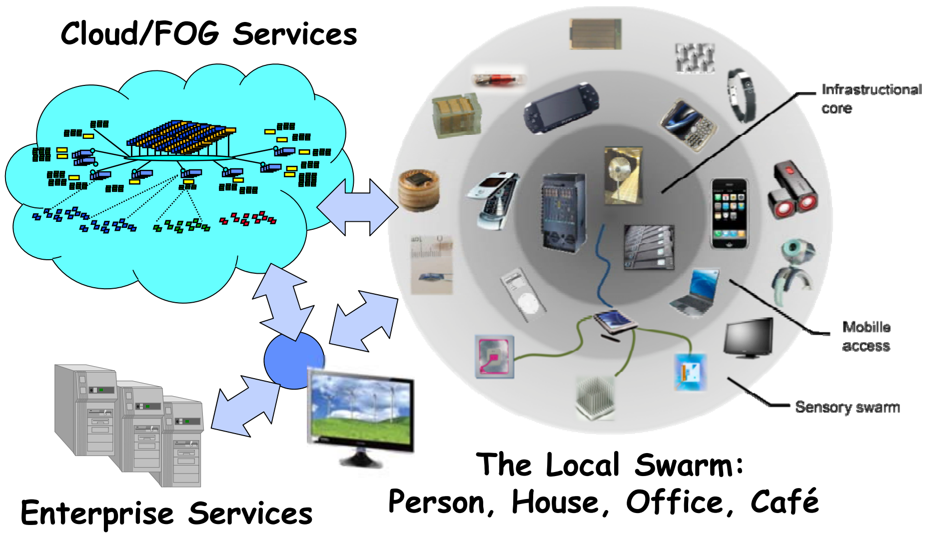
MapReduce Cons

- Restricted programming model
  - Not always natural to express problems in this model
  - Low-level coding necessary
  - Little support for iterative jobs (lots of disk access)
  - High-latency (batch processing)
- Addressed by follow-up research and Apache projects
  - Pig and Hive for high-level coding
  - Spark for iterative and low-latency jobs

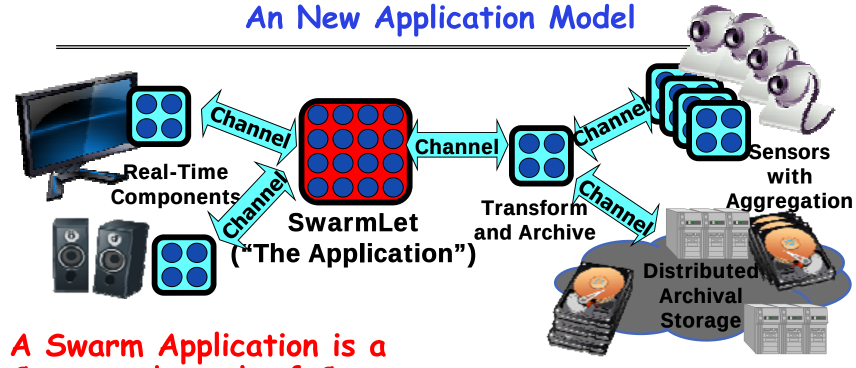
Future?

- Complete location transparency
  - Mobile Data, encrypted all the time
  - Computation anywhere any time
  - Cryptographic-based identities
  - Large Cloud-centers, Fog Computing
- Internet of Things?
  - Everything connected, all the time!
  - Huge Potential
  - Very Exciting and Scary at same time
- Better programming models need to be developed!
- Perhaps talk about this on Monday

Truly Distributed Apps: The Swarm of Resources

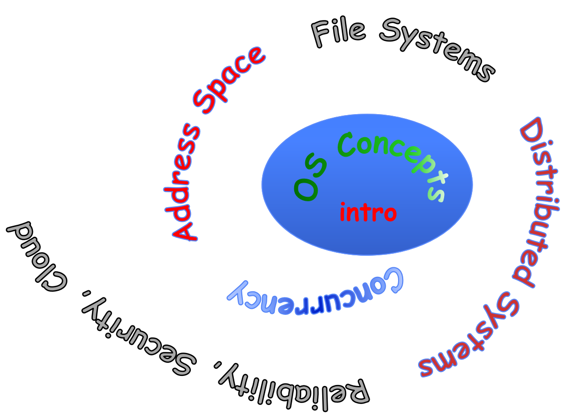


An New Application Model



- A Swarm Application is a Connected graph of Components
  - Globally distributed, but locality and QoS aware
  - Avoid Stovepipe solutions through reusability
- Many components are *Shared Services* written by programmers with a variety of skill-sets and motivations
  - Service Level Agreements (SLA) with micropayments

Thank you!



- Let's Thank the TAs!
- Thanks for helping us with this experimental version of the course… I think that it is going to be great!
- Good Bye!