15-441 Computer Networking

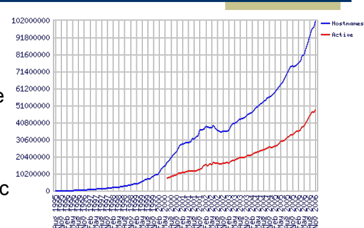
Web Caching,
Content Delivery Networks,
Consistent Hashing

Web history

- 1945: Vannevar Bush, “As we may think”, Atlantic Monthly, July, 1945.
  - describes the idea of a distributed hypertext system.
  - a “memex” that mimics the “web of trails” in our minds.
- 1989: Tim Berners-Lee (CERN) writes internal proposal to develop a distributed hypertext system
  - connects “a web of nodes with links”.
  - intended to help CERN physicists in large projects share and manage information
- 1990: Tim BL writes graphical browser for NeXT machines.

Web history (cont)

- 1992
  - NCSA server released
  - 26 WWW servers worldwide
- 1993
  - Marc Andreessen releases first version of NCSA Mosaic (Windows, Mac, Unix).



  - Web (port 80) traffic at 1% of NSFNET backbone traffic.
  - Over 200 WWW servers worldwide.
- 1994
  - Andreessen and colleagues leave NCSA to form "Mosaic Communications Corp" (Netscape).

Typical Workload (Web Pages)

- Multiple (typically small) objects per page
- File sizes are heavy-tailed
- Embedded references
- This plays havoc with performance. Why?
- Solutions?

- Lots of small objects means & TCP
  - 3-way handshake
  - Lots of slow starts
  - Extra connection state

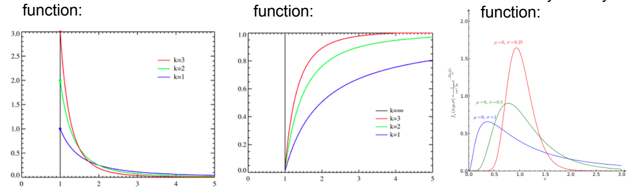
File Size and References Distributions

- File sizes
  - Pareto distribution for tail
  - Lognormal for body of distribution
- Number of embedded references also Pareto

Pareto: kx_m^k/x^{k+1} — Probability density function:

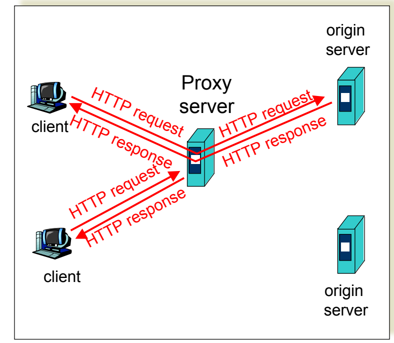
$\Pr(X < x) = 1 - (x_m/x)^k$ — Cumulative distribution function:

Log-Normal — Probability density function:



Web Proxy Caches

- User configures browser: Web accesses via cache
- Browser sends all HTTP requests to cache
  - Object in cache: cache returns object
  - Else cache requests object from origin server, then returns object to client



No Caching Example (1)

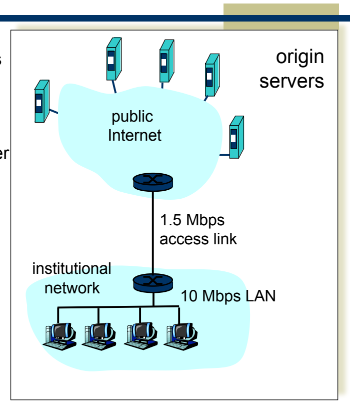
Assumptions

- Average object size = 100,000 bits
- Avg. request rate from institution's browser to origin servers = 15/sec
- Delay from institutional router to any origin server and back to router = 2 sec

Consequences

- Utilization on LAN = 15%
- Utilization on access link = 100%
- Total delay = Internet delay + access delay + LAN delay

= 2 sec + minutes + milliseconds



No Caching Example (2)

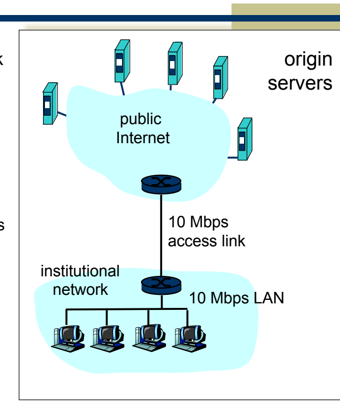
Possible solution

- Increase bandwidth of access link to, say, 10 Mbps
- Often a costly upgrade

Consequences

- Utilization on LAN = 15%
- Utilization on access link = 15%
- Total delay = Internet delay + access delay + LAN delay

= 2 sec + msecs + msecs

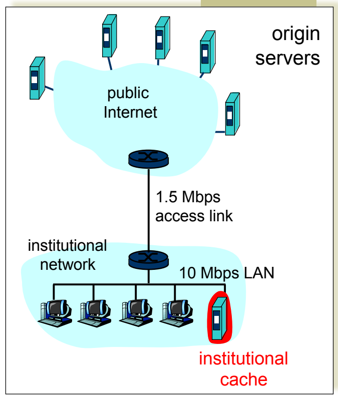


W/Caching Example (3)

Install cache
- Suppose hit rate is .4

Consequence
- 40% requests will be satisfied almost immediately (say 10 msec)
- 60% requests satisfied by origin server
- Utilization of access link reduced to 60%, resulting in negligible delays
- Weighted average of delays

= .6*2 sec + .4*10msecs < 1.3 secs



HTTP Caching

- Clients often cache documents
  - Challenge: update of documents
  - If-Modified-Since requests to check
    - HTTP 0.9/1.0 used just date
    - HTTP 1.1 has an opaque “entity tag” (could be a file signature, etc.) as well
- When/how often should the original be checked for changes?
  - Check every time?
  - Check each session? Day? Etc?
  - Use Expires header
    - If no Expires, often use Last-Modified as estimate

Example Cache Check Request

GET / HTTP/1.1

Accept: */*

Accept-Language: en-us

Accept-Encoding: gzip, deflate

If-Modified-Since: Mon, 29 Jan 2001 17:54:18 GMT

If-None-Match: "7a11f-10ed-3a75ae4a"

User-Agent: Mozilla/4.0 (compatible; MSIE 5.5; Windows NT 5.0)

Host: www.intel-iris.net

Connection: Keep-Alive

Example Cache Check Response

HTTP/1.1 304 Not Modified

Date: Tue, 27 Mar 2001 03:50:51 GMT

Server: Apache/1.3.14 (Unix) (Red-Hat/Linux) mod_ssl/2.7.1 OpenSSL/0.9.5a DAV/1.0.2 PHP/4.0.1pl2 mod_perl/1.24

Connection: Keep-Alive

Keep-Alive: timeout=15, max=100

ETag: "7a11f-10ed-3a75ae4a"

Problems

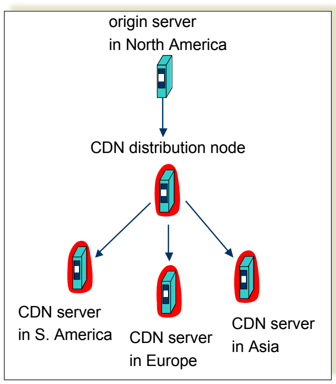
- Over 50% of all HTTP objects are uncacheable – why?
- Not easily solvable
  - Dynamic data → stock prices, scores, web cams
  - CGI scripts → results based on passed parameters
- Obvious fixes
  - SSL → encrypted data is not cacheable
    - Most web clients don't handle mixed pages well →many generic objects transferred with SSL
  - Cookies → results may be based on passed data
  - Hit metering → owner wants to measure # of hits for revenue, etc.

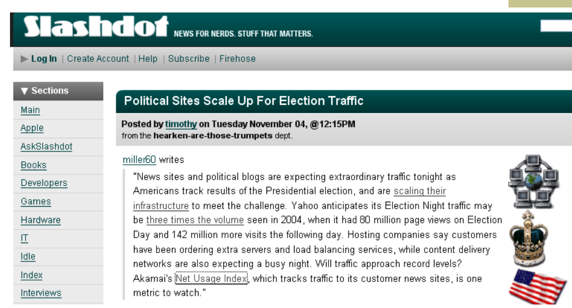
Caching Proxies – Sources for Misses

- Capacity
  - How large a cache is necessary or equivalent to infinite
  - On disk vs. in memory → typically on disk
- Compulsory
  - First time access to document
  - Non-cacheable documents
    - CGI-scripts
    - Personalized documents (cookies, etc)
    - Encrypted data (SSL)
- Consistency
  - Document has been updated/expired before reuse

Content Distribution Networks (CDNs)

- The content providers are the CDN customers.
- Content replication
- CDN company installs hundreds of CDN servers throughout Internet
  - Close to users
- CDN replicates its customers' content in CDN servers. When provider updates content, CDN updates servers

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Political Sites Scale Up For Election Traffic

Posted by timothy on Tuesday November 04, @12:15PM
from the hearken-are-those-trumpets dept.

miller60 writes

"News sites and political blogs are expecting extraordinary traffic tonight as Americans track results of the Presidential election, and are scaling their infrastructure to meet the challenge. Yahoo anticipates its Election Night traffic may be three times the volume seen in 2004, when it had 80 million page views on Election Day and 142 million more visits the following day. Hosting companies say customers have been ordering extra servers and load balancing services, while content delivery networks are also expecting a busy night. Will traffic approach record levels? Akamai's Net Usage Index, which tracks traffic to its customer news sites, is one metric to watch."

http://www.akamai.com/html/technology/nui/news/index.html

Content Distribution Networks & Server Selection

- Replicate content on many servers
- Challenges
  - How to replicate content
  - Where to replicate content
  - How to find replicated content
  - How to choose among known replicas
  - How to direct clients towards replica

Server Selection

- Which server?
  - Lowest load → to balance load on servers
  - Best performance → to improve client performance
    - Based on Geography? RTT? Throughput? Load?
  - Any alive node → to provide fault tolerance
- How to direct clients to a particular server?
  - As part of routing → anycast, cluster load balancing
    - Not covered ☹
  - As part of application → HTTP redirect
  - As part of naming → DNS

Application Based

- HTTP supports simple way to indicate that Web page has moved (30X responses)
- Server receives Get request from client
  - Decides which server is best suited for particular client and object
  - Returns HTTP redirect to that server
- Can make informed application specific decision
- May introduce additional overhead → multiple connection setup, name lookups, etc.
- While good solution in general, but…
  - HTTP Redirect has some design flaws – especially with current browsers

Naming Based

- Client does name lookup for service
- Name server chooses appropriate server address
  - A-record returned is “best” one for the client
- What information can name server base decision on?
  - Server load/location → must be collected
  - Information in the name lookup request
    - Name service client → typically the local name server for client

How Akamai Works

- Clients fetch html document from primary server
  - E.g. fetch index.html from cnn.com
- URLs for replicated content are replaced in html
  - E.g. <img src=“http://cnn.com/af/x.gif”> replaced with
    <img src=“http://a73.g.akamaitech.net/7/23/cnn.com/af/x.gif”>
- Client is forced to resolve aXYZ.g.akamaitech.net hostname

Note: Nice presentation on Akamai at www.cs.odu.edu/~mukka/cs775s07/Presentations/mklein.pdf

How Akamai Works

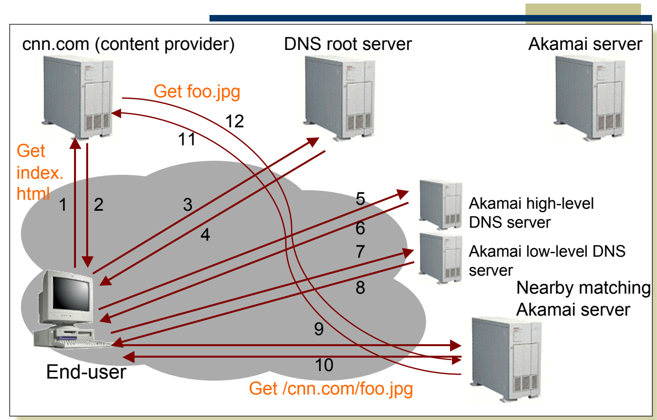
- How is content replicated?
- Akamai only replicates static content (*)
- Modified name contains original file name
- Akamai server is asked for content
  - First checks local cache
  - If not in cache, requests file from primary server and caches file

* (At least, the version we’re talking about today. Akamai actually lets sites write code that can run on Akamai’s servers, but that’s a pretty different beast)

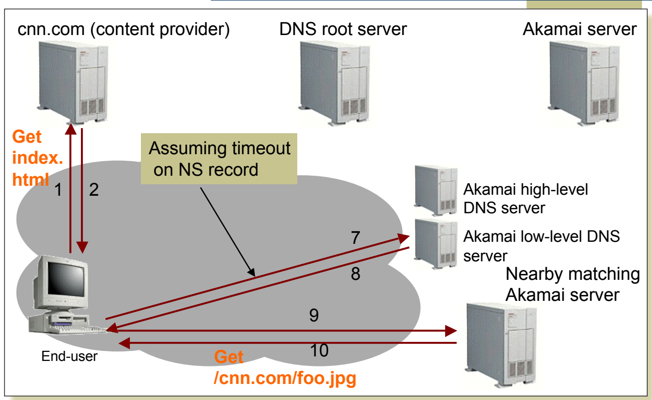
How Akamai Works

- Root server gives NS record for akamai.net
- Akamai.net name server returns NS record for g.akamaitech.net
  - Name server chosen to be in region of client’s name server
  - TTL is large
- G.akamaitech.net nameserver chooses server in region
  - Should try to chose server that has file in cache - How to choose?
  - Uses aXYZ name and hash
  - TTL is small → why?

How Akamai Works



Akamai – Subsequent Requests



Simple Hashing

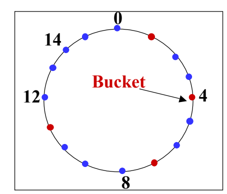
- Given document XYZ, we need to choose a server to use
- Suppose we use modulo
- Number servers from 1…n
  - Place document XYZ on server (XYZ mod n)
  - What happens when a servers fails? n → n-1
    - Same if different people have different measures of n
  - Why might this be bad?

Consistent Hash

- "view" = subset of all hash buckets that are visible
- Desired features
  - Smoothness – little impact on hash bucket contents when buckets are added/removed
  - Spread – small set of hash buckets that may hold an object regardless of views
  - Load – across all views # of objects assigned to hash bucket is small

Consistent Hash – Example

- Construction
  - Assign each of C hash buckets to random points on mod 2^n circle, where, hash key size = *n*.
  - Map object to random position on unit interval
  - Hash of object = closest bucket

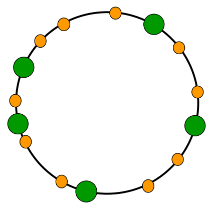


- Monotone → addition of bucket does not cause movement between existing buckets
- Spread & Load → small set of buckets that lie near object
- Balance → no bucket is responsible for large number of objects

Consistent Hashing

- **Main idea:**
  - map both keys and nodes to the same (metric) identifier space
  - find a "rule" how to assign keys to nodes

Ring is one option.



Consistent Hashing

- The consistent hash function assigns each node and key an *m*-bit identifier using SHA-1 as a base hash function
- **Node identifier:** SHA-1 hash of IP address
- **Key identifier:** SHA-1 hash of key

Identifiers

- *m* bit identifier space for both keys and nodes
- **Key identifier:** SHA-1(key)

  Key="LetItBe" $\xrightarrow{\text{SHA-1}}$ ID=60

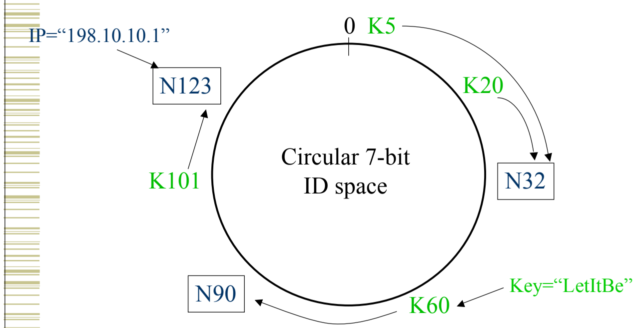
- **Node identifier:** SHA-1(IP address)

  IP="198.10.10.1" $\xrightarrow{\text{SHA-1}}$ ID=123

- How to map key IDs to node IDs?

Consistent Hashing Example

Rule: A key is stored at its successor: node with next higher or equal ID



Consistent Hashing Properties

- **Load balance:** all nodes receive roughly the same number of keys
- For N nodes and K keys, with high probability
  - each node holds at most $(1+\varepsilon)K/N$ keys
  - (provided that K is large enough compared to N)

Consistent Hash – Example

- Construction
  - Assign each of C hash buckets to random points on mod 2^n circle, where, hash key size = n.
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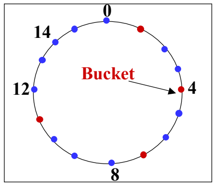
  - Hash of object = closest bucket



- Monotone → addition of bucket does not cause movement between existing buckets
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Load Balance

- Redirector knows all CDN server Ids
- Can track approximate load (or delay)
- To balance load:
  - W_i = Hash(URL, ip of s_i) for all i
  - Sort W_i from high to low
  - find first server with low enough load
- Benefits?
- How should "load" be measured?

Consistent Hashing not just for CDN

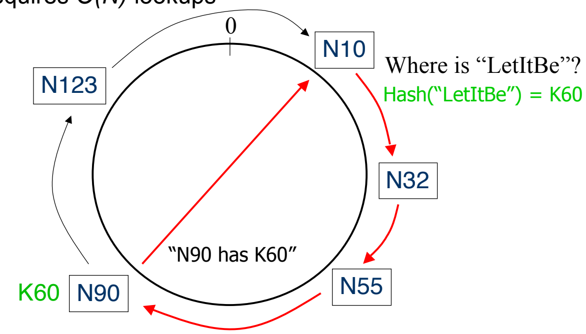
- Finding a nearby server for an object in a CDN uses centralized knowledge.
- Consistent hashing can also be used in a distributed setting
- P2P systems like BitTorrent, e.g., project 3, need a way of finding files.
- Consistent Hashing to the rescue.

Chord: Design Goals

- Load balance: Chord acts as a distributed hash function, spreading keys evenly over the nodes.
- Decentralization: Chord is fully distributed: no node is more important than any other.
- Scalability: The cost of a Chord lookup grows as the log of the number of nodes, so even very large systems are feasible.
- Availability: Chord automatically adjusts its internal tables to reflect newly joined nodes as well as node failures, ensuring that the node responsible for a key can always be found.

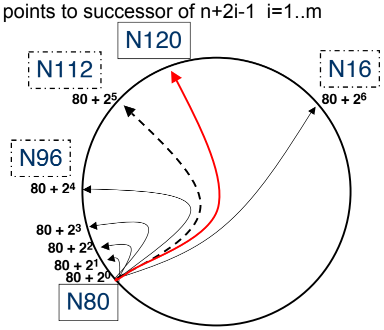
Lookups strategies

- Every node knows its successor in the ring
- Requires *O(N)* lookups



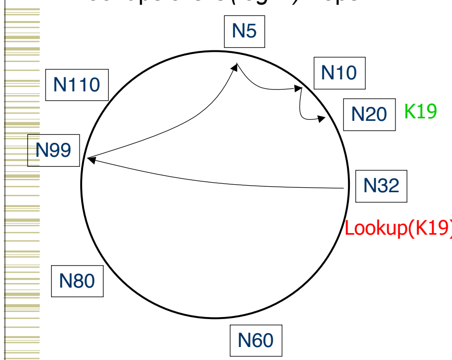
Reducing Lookups: Finger Tables

- Each node knows m other nodes in the ring (it has m fingers)
- Increase distance exponentially
- Finger i points to successor of n+2i-1 i=1..m



Faster Lookups

- Lookups are *O(log N)* hops



N32 finger table

F0 points to successor($32+2^0$) = 60
F1 points to successor($32+2^1$) = 60
F2 points to successor($32+2^2$) = 60
F3 points to successor($32+2^3$) = 60
F4 points to successor($32+2^4$) = 60
F5 points to successor($32+2^5$) = 80
F6 points to successor($32+2^6$) = 99

Look for a node identifier in the finger table that is less then the key identifier and closest in the ID space to the key identifier

Summary of Performance Results

- **Efficient:** *O(log N)* messages per lookup
- **Scalable:** *O(log N)* state per node
- **Robust:** survives massive membership changes

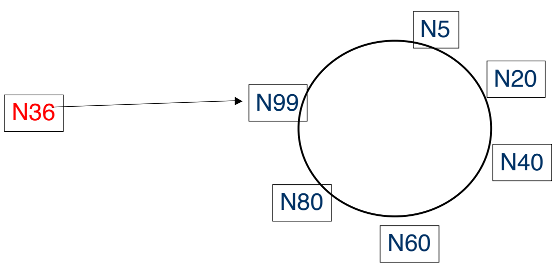
Joining the Ring

- Three step process
  - Initialize all fingers of new node
  - Update fingers of existing nodes
  - Transfer keys from successor to new node
- Two invariants to maintain
  - Each node's finger table is correctly maintained
  - *successor(k)* is responsible for *k (objects stored in correct place)*

Join: Initialize New Node's Finger Table

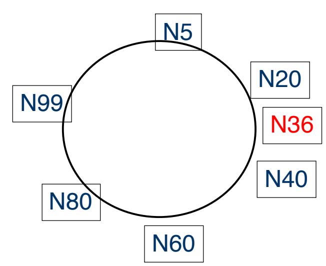
- Locate **any** node *p* in the ring
- Ask node *p* to lookup fingers of new node

1. Lookup(37,38,40,…,100,164)



Join: Update Fingers of Existing Nodes

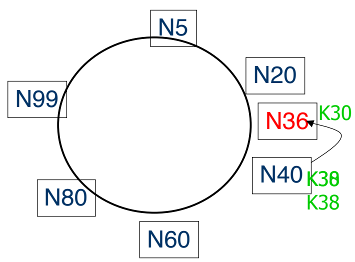
- New node calls update function on existing nodes



n becomes the ith fingerprint of node p if p precedes n by at least 2^{i-1} and i^{th} finger of node p succeeds n.

Join: Transfer Keys

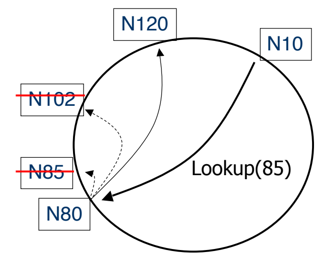
- Only keys in the range are transferred



Copy keys 21..36
from N40 to N36

Handling Failures

- **Problem:** Failures could cause incorrect lookup
- **Solution:** *Fallback:* keep track of a list of immediate successors



Handling Failures

- Use successor list
  - Each node knows *r* immediate successors
  - After failure, will know first live successor
  - Correct successors guarantee correct lookups
- Guarantee with some probability
  - Can choose *r* to make probability of lookup failure arbitrarily small

Joining/Leaving overhead

- When a node joins (or leaves) the network, only a fraction of the keys are moved to a different location.
- For *N* nodes and *K* keys, with high probability
  - when node *N*+1 joins or leaves, O(*K/N*) keys change hands, and only to/from node *N*+1

Summary

- Caching improves web performance
- Caching only at client is only partial solution
- Content Delivery Networks move data closer to user, maintain consistency, balance load
- Consistent Caching maps keys AND buckets into the same space
- Consistent caching can be fully distributed, useful in P2P systems using structured overlays