15-440 Distributed Systems

Lecture 15 – Consistent hashing and name-by-hash

Outline

Two uses of hashing that are becoming wildly popular in distributed systems:

- Content-based naming
- Consistent Hashing of various forms

Example systems that use them

- BitTorrent & many other modern p2p systems use content-based naming
- Content distribution networks such as Akamai use consistent hashing to place content on servers
- Amazon, Linkedin, etc., all have built very large-scale key-value storage systems (databases--) using consistent hashing

Dividing items onto storage servers

- Option 1: Static partition (items a-c go there, d-f go there, ...)
  - If you used the server name, what if "cowpatties.com" had 1000000 pages, but "zebras.com" had only 10? → Load imbalance
  - Could fill up the bins as they arrive → Requires tracking the location of every object at the front-end.

Hashing 1

- Let nodes be numbered 1..m
- Client uses a ***good*** hash function to map a URL to 1..m
- Say hash (url) = *x*, so, client fetches content from node *x*
- No duplication – not being fault tolerant.
- One hop access
- Any problems?
  - What happens if a node goes down?
  - What happens if a node comes back up?
  - What if different nodes have different views?

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Option 2: Conventional Hashing

- bucket = hash(item) % num_buckets
- Sweet! Now the server we use is a deterministic function of the item, e.g., sha1(URL) → 160 bit ID % 20 → a server ID
- But what happens if we want to add or remove a server?

Option 2: Conventional Hashing

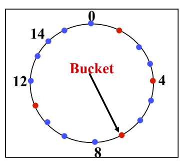
- Let 90 documents, node 1..9, node 10 which was dead is alive again
- % of documents in the wrong node?
  - 10, 19-20, 28-30, 37-40, 46-50, 55-60, 64-70, 73-80, 82-90
  - *Disruption coefficient* = ½ ☹

Consistent Hash

- "view" = subset of all hash buckets that are visible
- Desired features
  - Balanced – in any one view, load is equal across buckets
  - 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 circle
  - Hash of object = closest clockwise bucket



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

Detail - "virtual" nodes

- The way we outlined it results in moderate load imbalance between buckets (remember balls and bins analysis of hashing?)
- To reduce imbalance, systems often represent each physical node as k different buckets, sometimes called "virtual nodes" (but really, it's just multiple buckets).
- log n buckets gets you a very pleasing load balance - O(#items/n) with high probability, if #items large and uniformly distributed

Use of consistent hashing

- Consistent hashing was first widely used by Akamai CDN
- Also used in systems like Chord DHT
  - Provided key-value storage, designed to scale to millions or billions of nodes
  - Had a p2p lookup algorithm, completely decentralized, etc. Fun to read about; very influential, but not widely used outside of p2p systems.
- In practice, many more systems use consistent hashing where the people doing the lookups know the list of all storage nodes (tens to tens of thousands; not too bad) and directly determine who to contact

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

Hashing 2: For naming

- Many file systems split files into blocks and store each block on a disk.
- Several levels of naming:
  - Pathname to list of blocks
  - Block #s are addresses where you can find the data stored therein. (But in practice, they're logical block #s – the disk can change the location at which it stores a particular block... so they're actually more like names and need a lookup to location :)

A problem to solve...

- Imagine you're creating a backup server
- It stores the full data for 1000 CMU users' laptops
- Each user has a 100GB disk.
- That's 100TB and lots of $$$
- How can we reduce the storage requirements?

"Deduplication"

- A common goal in big archival storage systems. Those 1000 users probably have a lot of data in common -- the OS, copies of binaries, maybe even the same music or movies
- How can we detect those duplicates and coalesce them?
- One way: Content-based naming, also called content-addressable foo (storage, memory, networks, etc.)
- A fancy name for...

Name items by their hash

- Imagine that your filesystem had a layer of indirection:
  - pathname → hash(data)
  - hash(data) → list of blocks
- For example:
  - /src/foo.c -> 0xfff32f2fa11d00f0
  - 0xfff32f2fa11d00f0 -> [5623, 5624, 5625, 8993]
- If there were two identical copies of foo.c on disk ... We'd only have to store it once!
  - Name of second copy can be different

A second example

Several p2p systems operate something like:

- Search for "national anthem", find a particular file name (starspangled.mp3).
- Identify the files by the hash of their content (0x2fab4f001...)
- Request to download a file whose hash matches the one you want
- Advantage? You can verify what you got, even if you got it from an untrusted source (like some dude on a p2p network)

P2P-enabled Applications: Self-Certifying Names

- Name = Hash(pubkey, salt)
- Value = <pubkey, salt, data, signature>
  - can verify name related to pubkey and pubkey signed data
- Can receive data from caches, peers or other 3rd parties without worry

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Hash functions

- Given a universe of possible objects U, map N objects from U to an M-bit hash.
- Typically, |U| >>> 2^M.
  - This means that there can be collisions: Multiple objects map to the same M-bit representation.
- Likelihood of collision depends on hash function, M, and N.
  - Birthday paradox → roughly 50% collision with $2^{M/2}$ objects for a well designed hash function

Desirable Properties

- Compression: Maps a variable-length input to a fixed-length output
- Ease of computation: A relative metric...
- Pre-image resistance: For all outputs, computationally infeasible to find input that produces output.
- 2nd pre-image resistance: For all inputs, computationally infeasible to find second input that produces same output as a given input.
- collision resistance: For all outputs, computationally infeasible to find two inputs that produce the same output.

Longevity

- "Computationally infeasible" means different things in 1970 and 2012.
  - Moore's law
  - Some day, maybe, perhaps, sorta, kinda: Quantum computing.
- Hash functions are not an exact science yet.
  - They get broken by advances in crypto.

Real hash functions

Name	Introduced	Weakened	Broken	Lifetime	Replacement
MD4	1990	1991	1995	1-5y	MD5
MD5	1992	1994	2004	8-10y	SHA-1
MD2	1992	1995	abandoned	3y	SHA-1
RIPEMD	1992	1997	2004	5-12y	RIPEMD-160
HAVAL-128	1992	-	2004	12y	SHA-1
SHA-0	1993	1998	2004	5-11y	SHA-1
SHA-1	1995	2004	not quite yet	9+	SHA-2 & 3
SHA-2 (256, 384, 512)	2001	still good			
SHA-3	2012	brand new			

Using them

- How long does the hash need to have the desired properties (preimage resistance, etc)?
  - rsync: For the duration of the sync;
  - dedup: Until a (probably major) software update;
  - store-by-hash: Until you replace the storage system
- What is the adversarial model?
  - Protecting against bit flips vs. an adversary who can try 1B hashes/second?

Final pointer

- Hashing forms the basis for MACs - message authentication codes
  - Basically, a hash function with a secret key.
  - H(key, data) - can only create or verify the hash given the key.
  - Very, very useful building block

Summary

- Hashes used for:
    1. Splitting up work/storage in a distributed fashion
    2. Naming objects with self-certifying properties
- Key applications
    - Key-value storage
    - P2P content lookup
    - Deduplication
    - MAC