1. Comments on reviews
    a. Need to avoid just summarizing – web page asks you for:
        i. A one or two sentence summary of the paper
        ii. A description of the problem they were trying to solve
        iii. A summary of the contributions of the paper
        iv. The one or two largest flaws in the paper
        v. A discussion of how the ideas in the paper are applicable to real systems.
    b. Contributions –
        i. Writing a clear paper is not really a contribution
        ii. Discussing motivation rarely a contribution
        iii. Experimenting is not a contribution
        iv. Contribution is what moves the state of the art forward: what do you know after reading this paper that no body knew before this paper was written? E.g. how to distribute requests at high speed with locality, how to balance load while respecting locality?
    c. Evaluation –
        i. Papers never have a good enough evaluation
        ii. What is the purpose?
            1. Validation: prove you built something and it can work
            2. Parameter exploration: try with a variety of different assumptions/workloads, and find corners where it works well or doesn't
            3. Proof it works – basically need to run on a live workload, pretty much impossible in academia
        iii. Academic papers tend to do validation, exploration. Industry papers tend to do proof it works, without explaining why or what the limits are.
2. Topic 1: Scalability
    a. QUESTION: What are problems?
        i. These papers look at distributing load
    b. QUESTION: What is the context?
        i. How to build a web site or web cache to serve maximum load
        ii. Assume static documents (this is old …)
        iii. Assume shared back end storage (draw picture!)
    c. QUESTION: What are concerns?
        i. Avoid hotspots:
            1. Load on a single document can exceed capacity of a single machine
            2. Web workloads show huge variation in popularity – millions of hits per day vs none, and can exceed any server size in load.
        ii. Leverage memory
            1. Size of documents exceeds memory size of cache
            2. Want to use aggregate capacity of all machines
        iii. Reduce latency

1. Avoid multi-step lookups

d. Question: What are simple approaches:
    i. Round robin: distribute workload round robin to front ends
        1. Yields cache size equivalent to a single machine – all nodes hold same, popular data
    ii. Hierarchical cache / peer-to-peer caching
        1. Ask one cache, it talks to others
    iii. Problems:
        1. locality, making most of memory
        2. latency of talking to multiple machines

3. LARD
    a. Comments from reviews:
        i. Simulation study seems bogus
            1. But, they also tested a small cluster
            2. Note: this paper is from 1998, when large clusters were uncommon in academia
        ii. Tested environment very small
        iii. Back-end cache policy not part of the paper. QUESTION: Should it be (Linhai Song)
        iv. Data is static – but dynamic content often made from static pieces (e.g. pictures, videos), and many of the bytes come from the static pieces.
        v. Doesn't fit current multi-tier internet app, with front end caching (Akamai) and back end. But, still gets used in facebook with memcached servers and backend db servers (Lanyue Lu)
            1. Caching still very critical in data center
        vi. Assumption that all data fits on one node (Lanyue Lu)
            1. But assumes that all data does not fit in memory
        vii. Single front end server is a limitation
            1. QUESTION: why? Because it aggregates load information, has complete control over map
        viii. Is this a distributed system?
    b.
    c. NOTE: LARD is used in commercial products (layer 7 switching)
    d. QUESTION: What is basic system setup?
        i. Large web site with cacheable content (e.g. videos in Youtube, facebook pictures)
            1. Want to serve at cache rates, not disk rates
        ii. Any backend can server any data (all access common database)
            1. Used by Facebook for lots of things
        iii. Front end director parses requests, sends to a back end to be serviced
            1. Requests can queue in front end to avoid overloading back ends
        iv. Complexities:
            1. To parse HTTP request, need to terminate TCP connection, but want back end to send back data directly

2. Want to direct requests to balance load, but keep locality for caching

e. QUESTION: What are the goals?
    i. First: maintain locality to keep highest number of different items in memory
    ii. Second: spread load to leverage all resources in system
    iii. Core problem: load imbalance. Some items are popular, other are not as popular
        1. Popular content 1000s of times more popular than unpopular.
        2. Normal hashing to distribute work or round robin leads to hot nodes with too many hits
f. Techniques:
    i. Assign URLs to nodes
        1. How do it?
            a. Look at least loaded node
            b. QUESTION: What information is needed for this?
                i. Need centralized notion of least loaded node
            c. QUESTION: Do you have to choose the least loaded node?
                i. ANSWER: just pick two and choose less load
                    1. Avoids hot spots rather than picking global best
                    2. Can do better than picking best, because everybody picks the same best one
            d. QUESTION: What if load is out of date?
                i. Picking least load has problems because you concentrate load there
                ii. Better off picking a set randomly and choosing least loaded
        2. QUESTION: How do you measure load?
            a. I/O queue? Memory usage? CPU Load?
                i. Porcupine uses disk requests queue length
            b. LARD uses # of connections. Why?
                i. Info is available at front end, no need to ask for stale info from the back.
                ii. HTTP 1.0 closes connection after every request
                iii. Is good enough to work…
            c. Back-end cache policy not part of the paper.
                i. QUESTION: Should it be (Linhai Song)

    ii. Balancing load
        1. If a node has too much load, need to spill load
        2. QUESTION: How do this?
            a. If load exceeds threshold where latency suffers, look for underloaded node

        i. Prevents idle nodes
    b. If load exceeds twice threshold, spill to any node under high threshold (even if not lightly loaded)
3. QUESTION: Why does this work?
    a. Evens load beween low and high thresholds
4. QUESTION: How pick Thigh – highest load before shunting data to a low-load node?
    a. ANSWER: look at response time at high load. Generally, throughput increases then flattens as load increases (becomes saturated) and latency shoots up
    b. Set Thigh to be knee in curve where latency low, but are at peak throughput

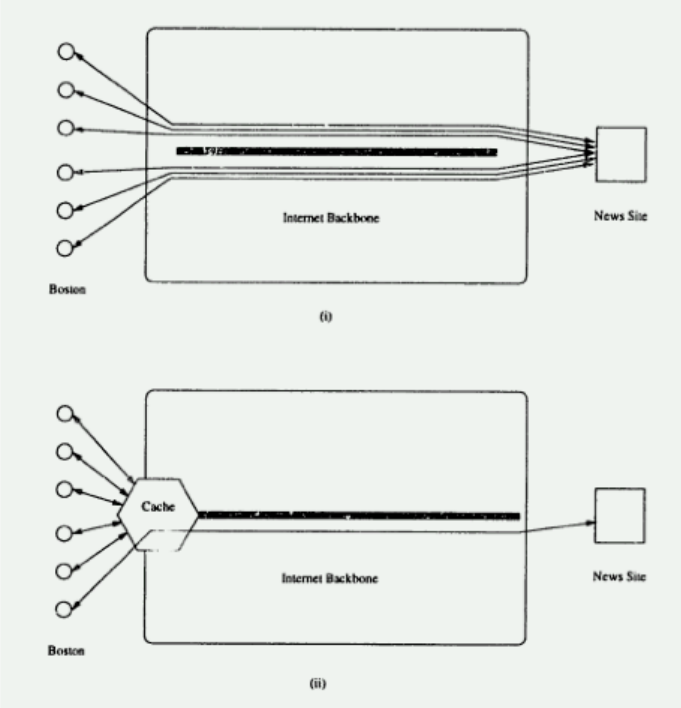
iii. Balancing load with replication: more than a single node of load
1. QUESTION: How do you know the right number of servers?
    a. If load < one whole machine, the answer is 1…
    b. Overload: keep adding servers until you don't get load imbalance
    c. Underload: keep removing servers until you do get load imbalance (but slowly)
    d.
2. Start increasing number of servers if one is overloaded by picking lightly loaded node
3. Always change the set – either keep increasing or stop and decrease
    a. Prevents sending a now-dead URL to somewhere
4. Comparision: TCP/IP
    a. Additive increase to slowly ramp up
    b. Multiplicative decrease to slow down (quickly avoid congestion)
5. Here: slowly move # of nodes up and down
6. NOTE: General technique to slowly adapt to load – increase until get it right, decrease until pain
7. NOTE: Front end is managing cache sizes in the backend, but knows nothing about the caches
    a. QUESTION: Why does this work?
    b. Feedback: # of connections relates to efficiency of back end
    c. Slow back ends have connections migrated off, fast ones get more
    d. Handling things fast means connections are open shorter time, have fewer active connections at once
        i. Littles law: # of active connections = arrival rate * service time

iv. TCP Handoff

1. Front end accepts TCP connection, gets HTTP request, parses URL
2. Then packages up TCP state and sends to back end
    a. Remembers in kernel to forward packets from flow to back end
    b. Back end replies directly to client (IP spoofing)
3. Note: after redirect, just need to forward packets, no other packet inspection (can be made fast)

g. What about recovery – what if front-end nodes fail?
    i. Can send load anywhere & rebuild map
h. What about state?
    i. Front end must maintain a table the size of URLs to do lookup
i. What about dynamic content?
    i. Dynamic content gets generated from some back end static content
    ii. Can send requests to location of the underlying static content
    iii. Could do dynamic generation in front end and pull underlying static content using LARD
j. Results:
    i. Does better than hashing content, because it can avoid hot spots and idle nodes
    ii. Does better than weighting (WRR), because it has locality so gets better use of caches
k. QUESTION: What are the big take-away ideas?
    i. Request placement for maximizing cache locality
    ii. Load balancing by evening loads (minimize difference between low/high)
    iii. Proxying to forward requests to best backend

4. Consistent hashing
    a. Notes from reviews:
        i.
    b. Problem solved: building a distributed cache
        i. QUESTION: What are the goals for the cache?
            1. Goal 1: reduce load on backbone (fewer requests to server)
            2. Goal 2: reduce latency to client
            3. Goal 3: fault tolerance – keeps working well if a cache fails
        ii. Constraints:
            1. allow set of cache servers to change
            2. Partition objects among cache servers
        iii. NOTE: only ½ the content is cacheable
            1. But many web pages have many objects (pictures, video, flash), and those binary objects are cacheable
            2. ½ is still a lot to reduce.
        iv. Invalidation: HTTP includes time-to-live fields, controls cacheability (for browser cache as well)
        v. Model: Any cache node can fetch and cache any web page
        vi. How do you get locality so that you use the memory capacity of a cache?

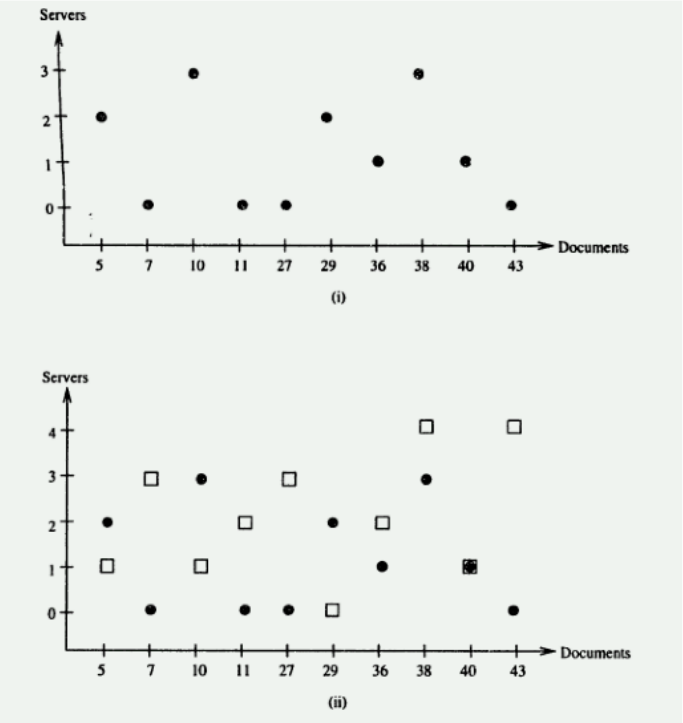


vii.

viii. NOTE: get scalability, because different sets of clients have a unique set of caches. This is client-side caching, not server-side caching (Different from LARD)

ix.

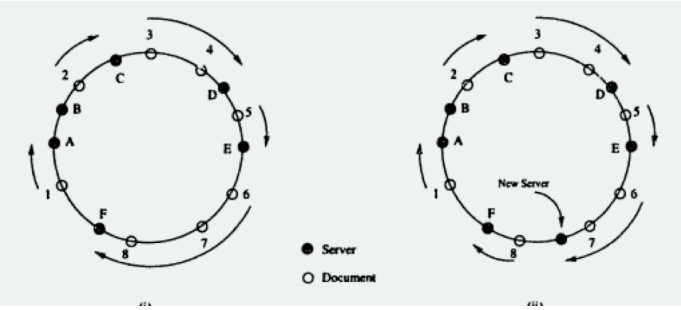
c. Constraints:
    i. Want to keep latency low, so now referrals/redirections/remote communication
    ii. Want to partition data so maximally use cache
d. QUESTION: What are some possible approaches?
    i. Cooperative caching / P2P: send request to one cache, it asks others if it does not have it
    ii. Hierarchical caching: send to cache, it asks its parent, etc.
    iii. Broadcast: send to all caches, the one with the data responds
e. General solution: hashing
    i. Have the client hash the URL to choose a cache
        1. Does location service without an extra hop by pushing it to client
    ii. H(url) = m*url + b mod q
        1. Problem: if number of nodes change (q), everything moves: (from d+1 mod 4 to d+1 mod 5)
        2. Problem: set of caches may change over time, don't want to lose locality
        3. If clients don’t learn of change immediately, don’t want to lose performance



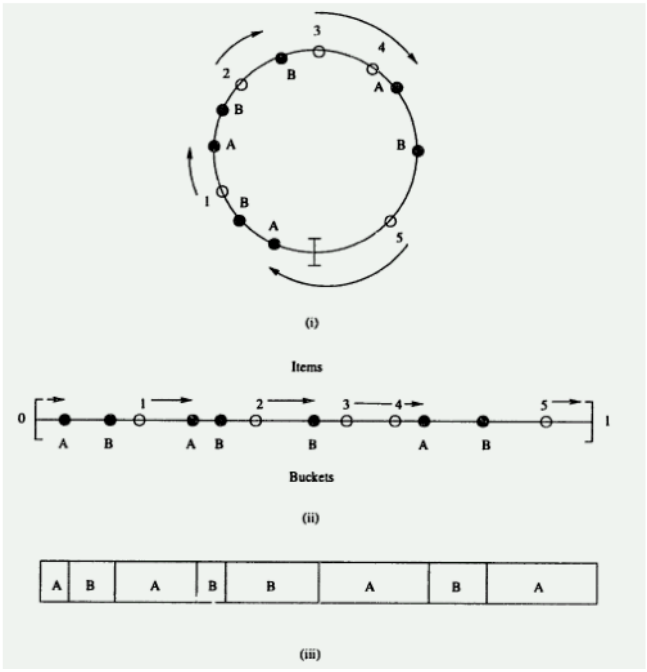
4.
5. Each change it set of servers is a **view**, would like data to keep locality across views

iii. Goal:
1. - balance – objects are assigned to buckets random
2. - monotonicity – when a bucket is added or removed, the only objects affected are those mapped to the bucket
3. - load – objects are assigned to the buckets evenly over a set of views
4. - spread – an object is mapped to a small number of buckets over a spread of views
5. QUESTION: Are these realistic goals? How else could you solve it?
    a. LARD: maintain a table of all URLs (but then need to update it …)

f. Solution: Consistent hashing
   i. General idea: add a layer of indirection into hashing instead of hashing directly to servers
   ii. Don't hash directly onto a bucket, hash on to a range of real numbers with ranges

iii. 

iv. Solution part 2: put each server at multiple locations, so things move from many places

v. 

vi. Change of view:

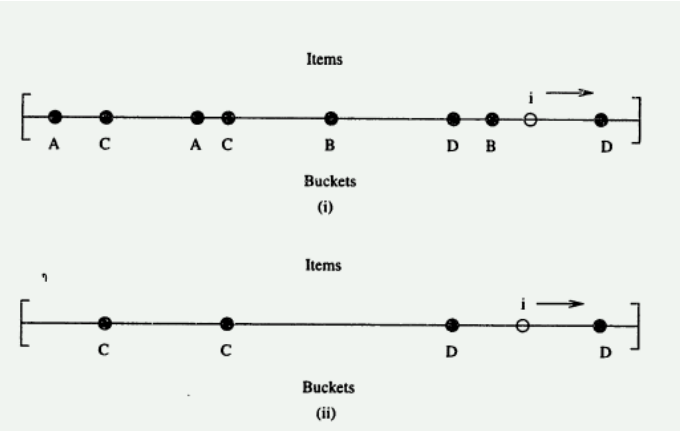


Figure 10: *Monotonicity for the family UC_{random}. In this figure the unit circle is depicted by an interval of length one, which is obtained by cutting the unit circle at an arbitrary point. (i) The mapping of points to the circle for a view $V_2 = A, B, C, D$ (m=2 in this example). The closest bucket point clockwise of i's point is one associated with the bucket D. (ii) For any view $V_1 \in V_2$ containing the bucket D (here $V_1 = C, D$), the point closest to i's point will still be D. .*

vii.

g. Details:
    i. hash function that takes URLs and outputs a number of 0 ... M
        1. URLs and caches are mapped to points on a circle 0 ... M
        2. Map caches in multiple places because there are relatively few compared to # of documents, and want even spread.
    ii. How to add cache?
        1. Move objects that are "closest" on circle to new cache
        2. note: map cache on multiple points of circle for uniform
        3. distribution of URLs to caches
        4. result: each URL is in a small number of caches
    iii. How to do lookup?
        1. First cache that succeeds hash(U) has document
        2. Can store tree with whole range, or partition range and have a tree per partition
    iv. How implement?
        1. Use DNS: have client hash URL into large number of virtual caches (e.g. 1000), then ask DNS for the physical cache associated with virtual cache
        2. DNS contains closest node for each 1000 virtual cache
h. QUESTION: how compare with LARD?
    i. Uses hash to spread load rather than lookup table
    ii. Is not load aware
        1. In their setting, detailed load information not available

iii. Is scalable: can have multiple DNS servers doing hashing (or all clients)

i. QUESTION: How handle load?
    i. Cannot do fully distributed (at all clients), as they don't have load information
    ii. Solution: spread hot content across more caches
        1. Step 0: identify hot virtual names in DNS resolver
        2. Step 1: take all names in one of the buckets for a cache and let them go to any server (round robin) (there may be many)
        3. Step 2: reduce number of servers for the virtual name until load goes up
            a. If picked wrong virtual server, will never go up
        4. Step 3: try with another virtual server (bucket)
j. Question: how handle geography of clients?
    i. Use it when determining virtual caches – can choose ones with a nearby resolver, which returns nearby caches. Done in client script
k. Fault tolerance:
    i. When a cache fails: can have fixed retry rule (e.g. next node on ring)
    ii. When a DNS server fails: can replicate, clients already know how to contact another DNS server
        1. DNS servers may need to communicate for the hot-page solution
l. Implementation: Akamai (simplified without geographic location):
    i. Content producer runs a tool to name a document with a hash function
        1. E.g. a604.akamai.com (604 is the hash bucket)
        2. Set time to live to be short (a few seconds) so can respond to load bursts
        3. NOTE: in paper, client did the hash, so was transparent to servers. Here, content producer does hash, so clients not modified.
    ii. DNS lookup of a604 returns result of hash function: set of servers that may contain document
    iii. Note: hashing may not be random, e.g. may try to cluster all objects in an web page to one cache to minimize DNS lookups

5. Comments:
a. Consistent hashing allows you to use hashing with locality as set of views change
b. Avoids need to remember everything in front end to keep locality
c. Lack of state makes dealing with hot spots hard
    i. Hashing spreads most load fairly evenly
    ii. Feedback + increase spread of a virtual server (number of IPs hosting that virtual server) helps
d. Compare to DHTs:
    i. DHTs typically forward requests multiple times, at minimum once, adding latency
    ii. DHTs don’t necessarily preserve locality, unless they rely on similar techniques, or scale well
e. How work with local cache?

    i. Claims its better to go right to this cache than consult local cache first (local cache adds latency)
    ii. Lacks complete load balancing (true)
f. Adds work to DNS server?
    i. But can add more dns servers …
g. Real world impact:
    i. Idea used in Dynamo for assigning key/values to servers
    ii. Idea used by Akamai for finding caches.