Distributed Cache Management

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Cache Systems

- Caching is based on the idea of replicating frequently accessed data items in lower latency storage units:
  - performance is the main goal here…
  - …but caches can also provide better availabilty, resource utilization…

- Caches are widely employed at a wide variety of levels:

Hardware:

–(Multi) Processor caches:

•SRAM vs DRAM

•Local SRAM vs Remote SRAM/DRAM

–Disk Caches:

•RAM vs Disk

Software:

–(Distributed) File Systems:

•Main Memory vs Disk

•Local FS vs Remote FS

–World Wide Web:

•browser vs forward/reverse proxy vs Web Server RAM vs Web Server Disk

–(Distributed) Database Systems:

•RAM vs Disk

•Local DBMS vs Remote DBMS

Distributed Cache Systems

- Locality principles still drive the design process, just like in the non distributed case…

- …but now distribution raises a number of additional issues…
  - high/unpredictable communication latency:
    - we don't want highly/unpredictable inconsistent caches!
  - possibility for cooperation among caches, but…
  - …need for system autonomy despite single caches failures
  - mutual effect of mutliple caching tiers on actual miss rates:
    - trickle-down effect
  - trackability:
    - how many hits on my web page?
  - security, just like in any distributed data replication scheme
  - …

Focus of this course

- The consistency requirements play a fundamental role in the design of a distributed cache management scheme…

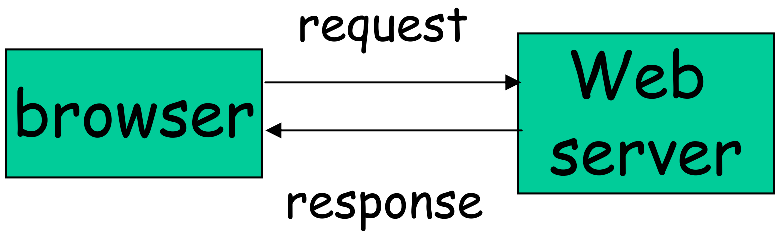
- Discussing the manifold formal consistency models presented in literature is out of the scope of this course - you're already seeing them in the Distributed Systems course.

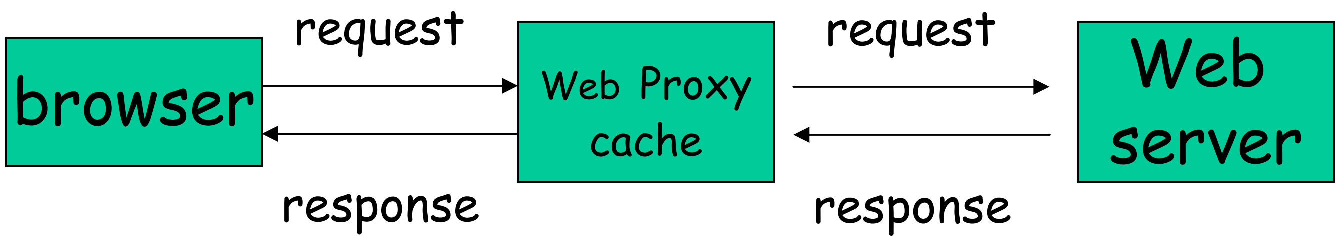
- We'll rather take a pragmatical approach and analyze two case studies representative of weak and strong consistency constraints:
  - WWW Caching
  - Transactional Caching

Web Caching

Simplest model:

- clients are read-only, only server updates data
- content staleness is tolerated



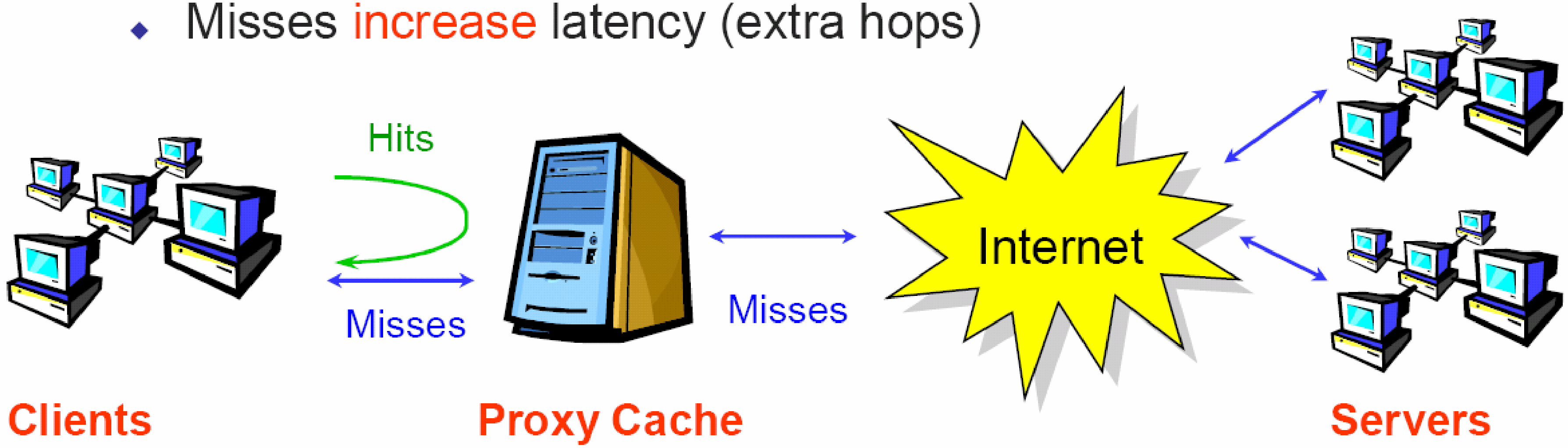


Why Web Caching?

- Cost
  - Original motivation for adopting caches (esp. internationally)
  - Caching saves bandwidth (bandwidth is expensive)
  - 50% byte hit rate cuts bandwidth costs in half
- Performance
  - User: Reduces latency
    - » RTT to cache lower than to server
  - Server: Reduces load
    - » Caches filter requests to server
  - Network: Reduces load
    - » Requests that hit in the cache do not travel all the way to server

Proxy Caching

- Proxy caching is one of the most common methods used to improve Web performance
  - Duplicate requests to the same document served from cache
  - Hits reduce latency, b/w, network utilization, server load
  - Misses increase latency (extra hops)



Where to cache?

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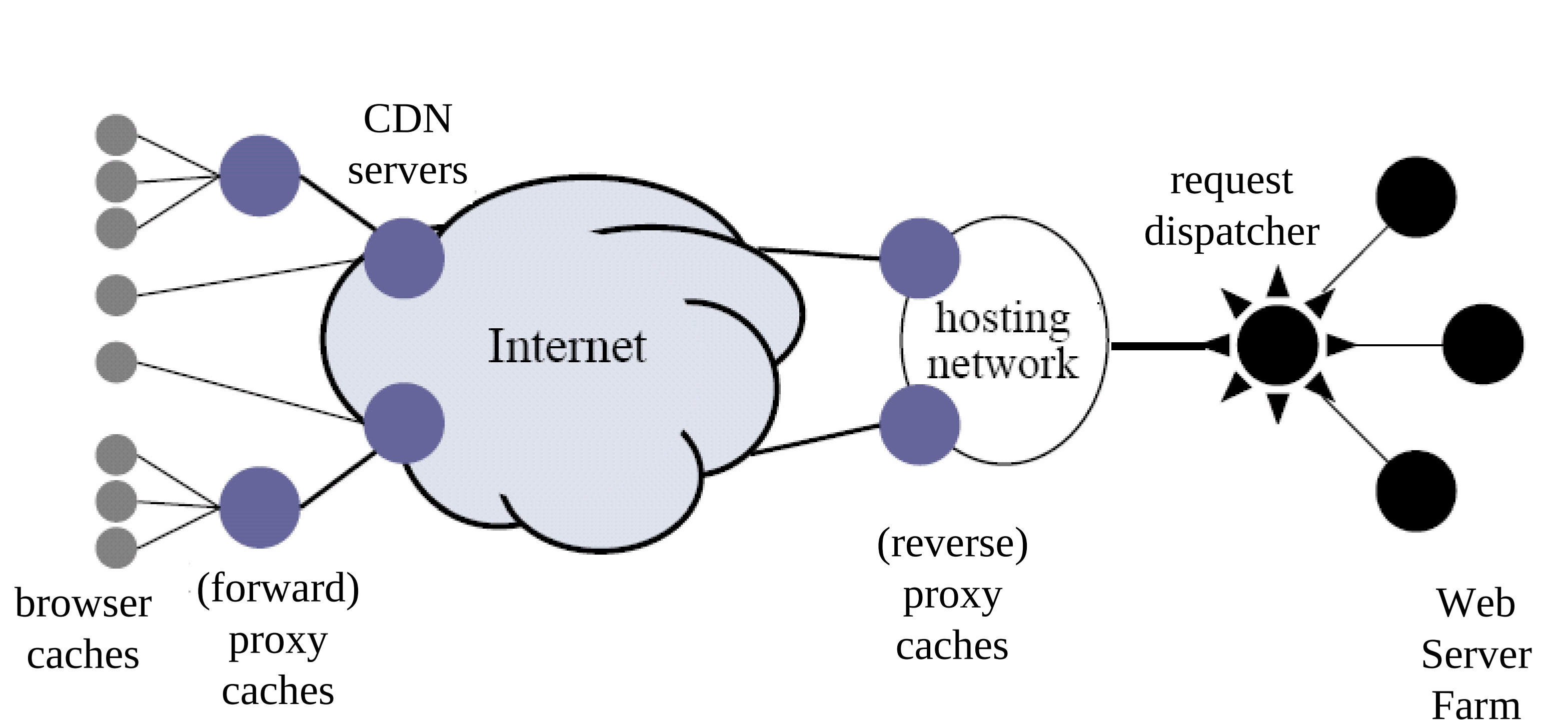
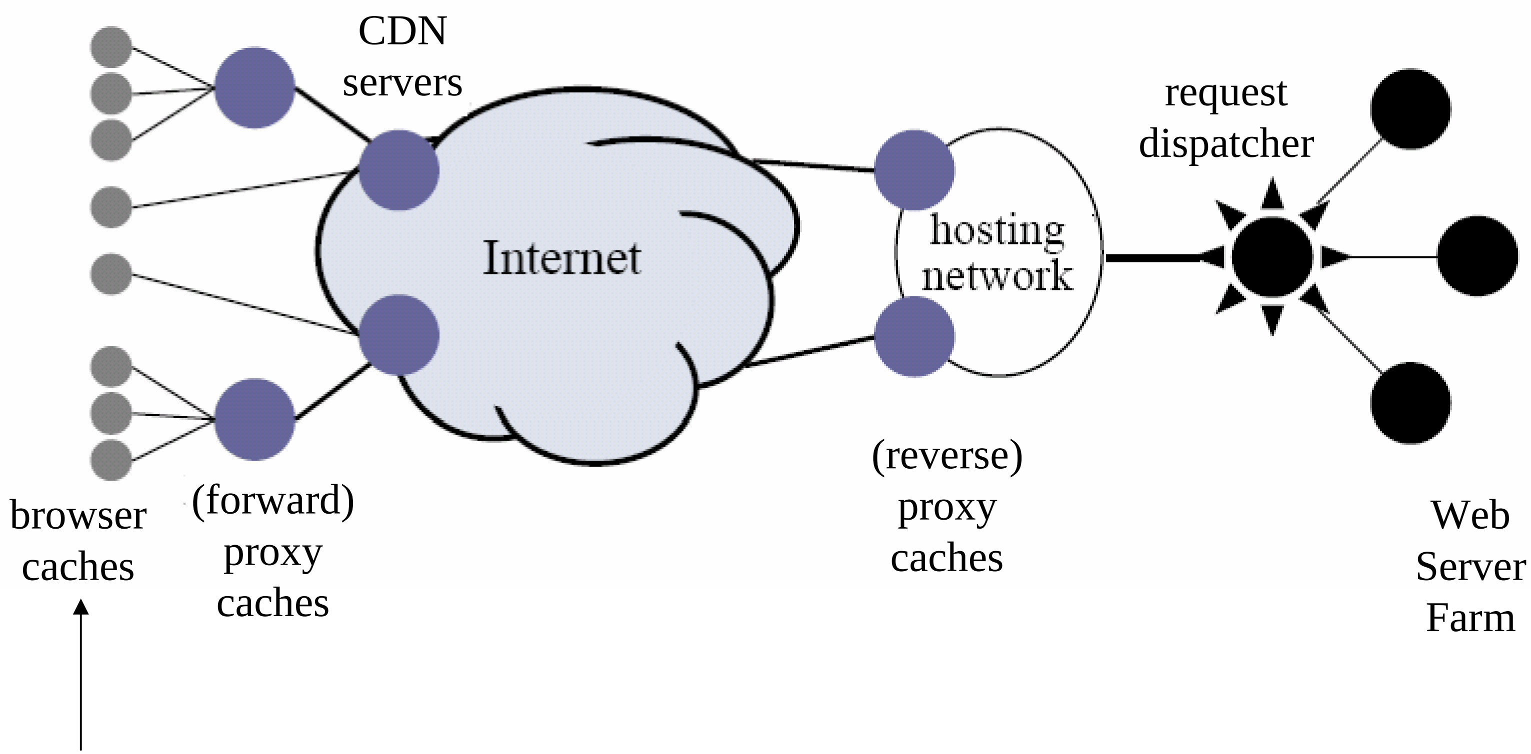


EVERYWHERE!

Where to cache?

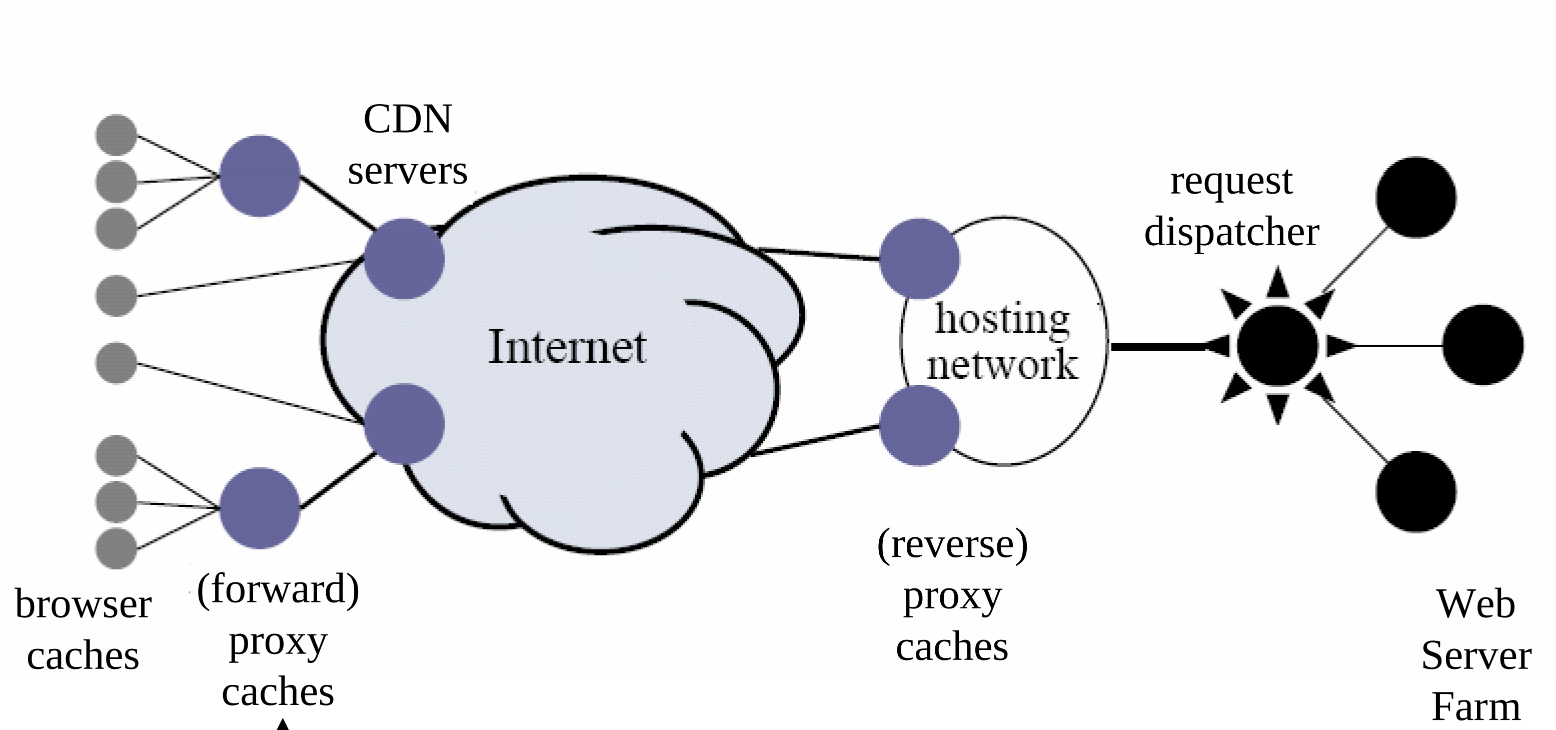


Browser (user)

- Small: 1MB memory, 7MB disk (Netscape)
  - » Note recursive caching (memory vs. disk)!
- 20% hit rate

ERYWHERE!

Where to cache?

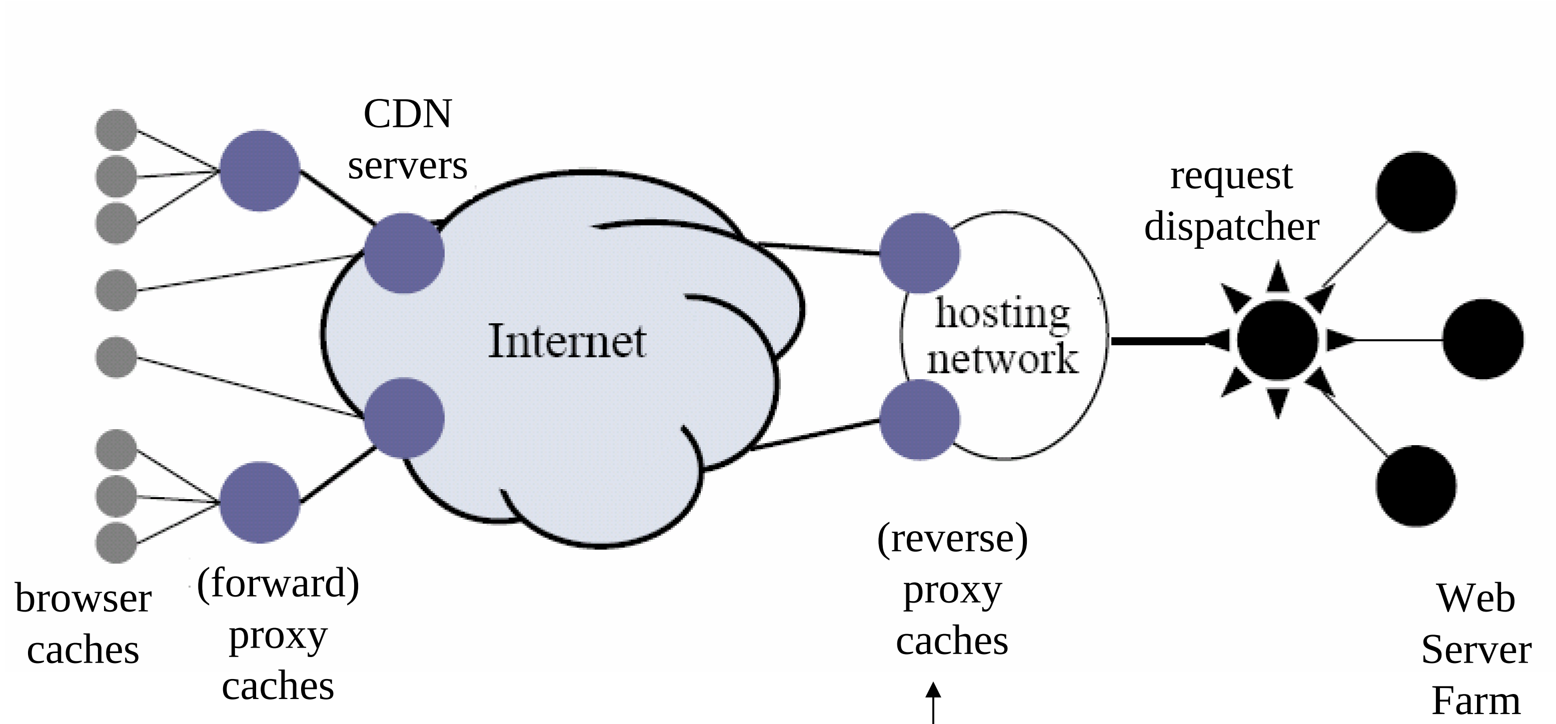


Organization (client-side proxy)

- Large: Gigabytes (with disk)
- 50% hit rate (for large client populations)
- Cache popular contents for a user community

ERE!

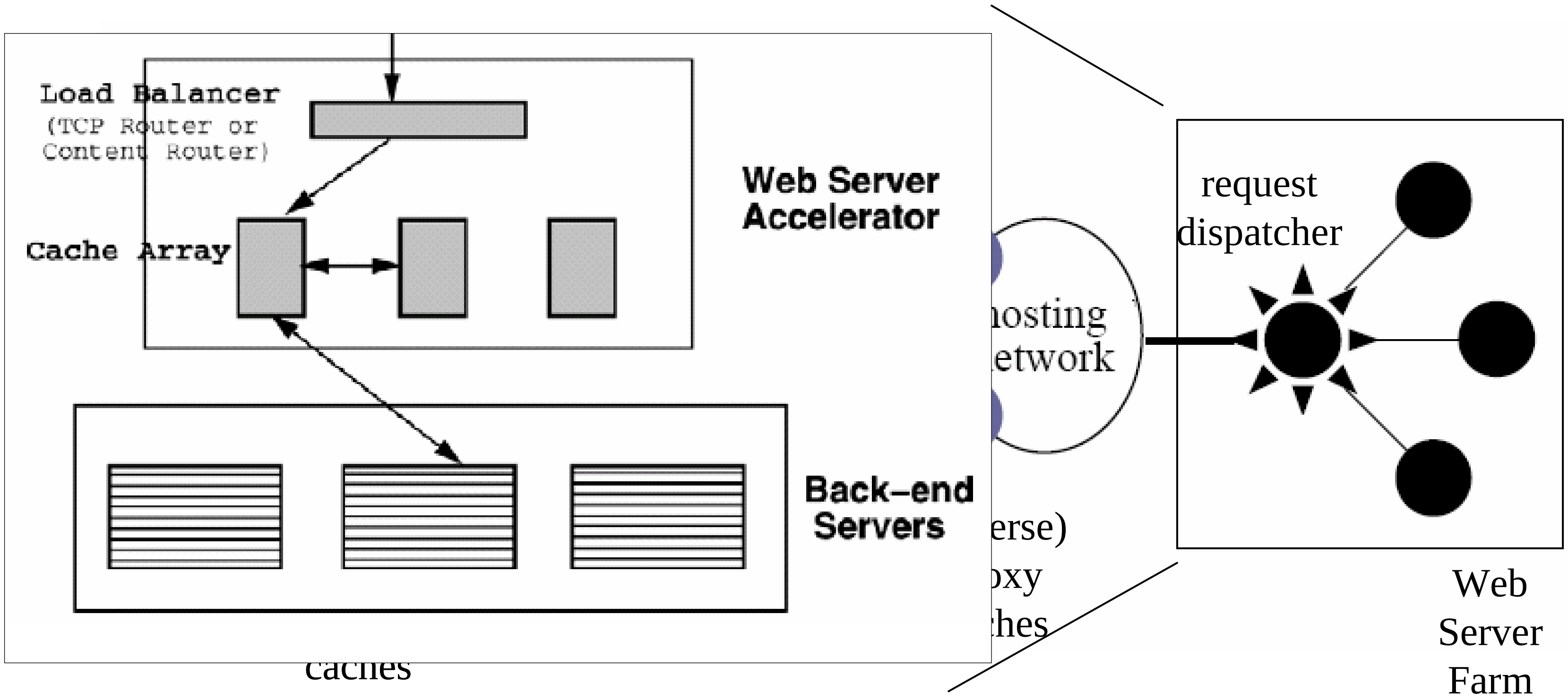
Where to cache?



Web’s site hosting provider
- Large: Gigabytes (with disk)
- Improve access to a logical set of contents

EVE

Where to cache?



In front of server (server-side accelerator)
- Large (gigabytes)

EVERYWHERE!

Web Traffic Characterization

- Research question: how do goals and traffic behavior shape strategies for deploying and managing proxy caches?
  - Replacement policy: what objects to retain in cache?
    - Large vs. small, relative importance of popularity and stability
  - Deployment: where to place the cache?
    - Close to server or client?
  - How many users per cache?
  - Prefetching?
- Since the Web is in active deployment on a large-scale, Web traffic characterization is an empirical science.
  - Science of mass behavior: observe and test hypotheses.

Zipf

- A number of studies observed that Web accesses can be modeled using *Zipf-like probability distributions*.
  - Rank objects by popularity: lower rank i ==> more popular.
  - The probability that any given reference is to the ith most popular object is p_i
    - Not to be confused with p_c, the percentage of cacheable objects.
- Zipf says: "p_i is proportional to $1/i^{\alpha}$, for some α with $0 < \alpha < 1$".
  - Higher α gives more skew: popular objects are *way* popular.
  - Lower α gives a more *heavy-tailed* distribution.
  - In the Web, α ranges from 0.6 to 0.8.
  - With $\alpha=0.8$, 0.3% of the objects get 40% of requests.

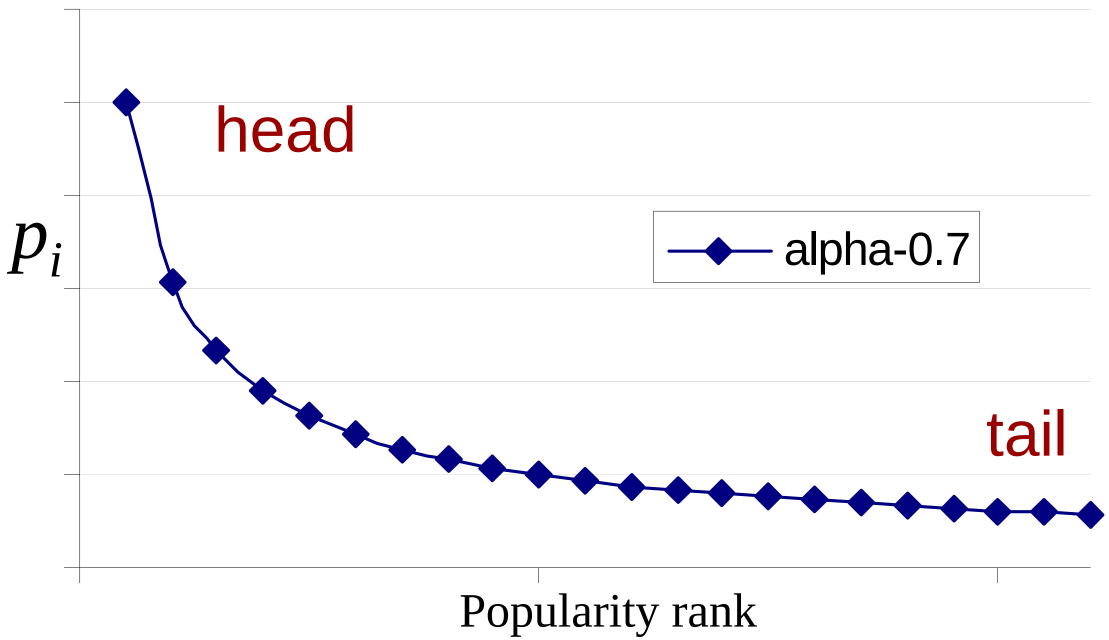
Zipf-like Reference Distributions

Probability of access to the object with popularity rank *i*:

$p_i \sim 1/i^{\alpha}$

such that:

$\Sigma p_i = 1$



(This is equivalent to a *power-law* or *Pareto* distribution.)

heavy tail

Importance of Traffic Models

- Analytical models like this help us to predict cache hit ratios (object hit ratio or byte hit ratio).
  - E.g., get object hit ratio as a function of size by integrating under segments of the Zipf curve
    - …assuming perfect LFU replacement
  - Must consider update rate
    - Do object update rates correlate with popularity?
  - Must consider object size
    - How does size correlate with popularity?
  - Must consider proxy cache population
    - What is the probability of object sharing?
  - Enables construction of synthetic load generators
    - SURGE

Object Popularity Implications

- The implications of the object popularity distribution are interesting
- Cache hit rate grows logarithmically with
  - Cache size
  - Number of users
  - Time
- Easy to get most of the benefit of caching
  - Beginning of the distribution
- Hard to get all
  - Tail of the distribution

Cache Misses

- There are a number of reasons why requests miss:
  - Compulsory (50%)
    - Object uncacheable (20%)
    - First access to an object (30%)
  - Capacity (<5%)
    - Finite resources (objects evicted, then referenced again)
  - Consistency (10%)
    - Objects change (“../today”) or die (deleted)

Uncacheable Objects

- Caches cannot handle all types of objects
  - Pages constructed from server-side programs
    - My Yahoo , E-commerce
  - Changing data
    - Stock quotes, sports scores, page counters
  - Queries
    - Web searches
  - Marked uncacheable
    - Server wants to see requests (e.g., hit counting)
  - Challenges
    - Difficult to solve, not one culprit

Caching More Caching More

- Approaches to caching more types of web content
  - Caching active data: Data sources may be dynamic, but not continuously (e.g., sports scores (Olympic web sites))
    - Snapshots generated from databases
    - Requires cooperation of server and database
  - Cache server-side program inputs and outputs
    - Need to recognize program+inputs
  - "Active caches" : Run programs (e.g., Java) at caches to produce data
    - Can handle almost anything dynamic
    - Need data sources, though&starts to become distributed server
  - Consistency mechanisms (more later)

Web Cache Consistency

"Requirements of performance, availability, and disconnected operation require us to relax the goal of semantic transparency."
- HTTP 1.1 specification

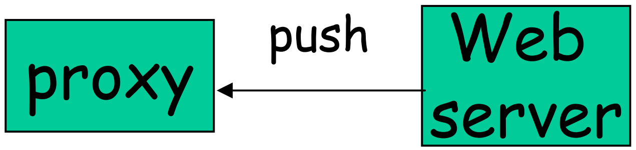
- Any caching/replication framework must take steps to ensure that the cache does not deliver old copies of modified objects.
- Issues for cache consistency in the Web:
  - large number of clients/proxies
  - most static objects don't change very often
  - weaker consistency requirements
    - Stale information might be OK, as long as it is "not too stale".

Consistency Issues

- Web pages tend to be updated over time
  - Some objects are static, others are dynamic
  - Different update frequencies (few minutes to few weeks)
- How can a proxy cache maintain consistency of cached data?
  - Send invalidate or update
  - Push versus pull

Push-based Approach

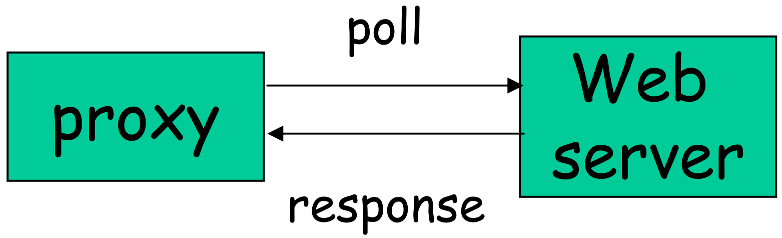
- Server tracks all proxies that have requested objects
- If a web page is modified, notify each proxy
- Notification types
  - Indicate object has changed [invalidate]
  - Send new version of object [update]
- How to decide between invalidate and updates?
  - Pros and cons?
  - One approach: send updates for more frequent objects, invalidate for rest



Push-based Approaches

- Advantages
  - Provide tight consistency [minimal stale data]
  - Proxies can be passive
- Disadvantages
  - Need to maintain state at the server
    - Recall that HTTP is stateless
    - Need mechanisms beyond HTTP
  - State may need to be maintained indefinitely
    - Not resilient to server crashes

Pull-based Approaches



- Proxy is entirely responsible for maintaining consistency
- Proxy periodically polls the server to see if object has changed
  - Use if-modified-since HTTP messages
- Key question: when should a proxy poll?
  - Server-assigned *Time-to-Live (TTL)* values
    - No guarantee if the object will change in the interim

Pull-based Approach: Intelligent Polling

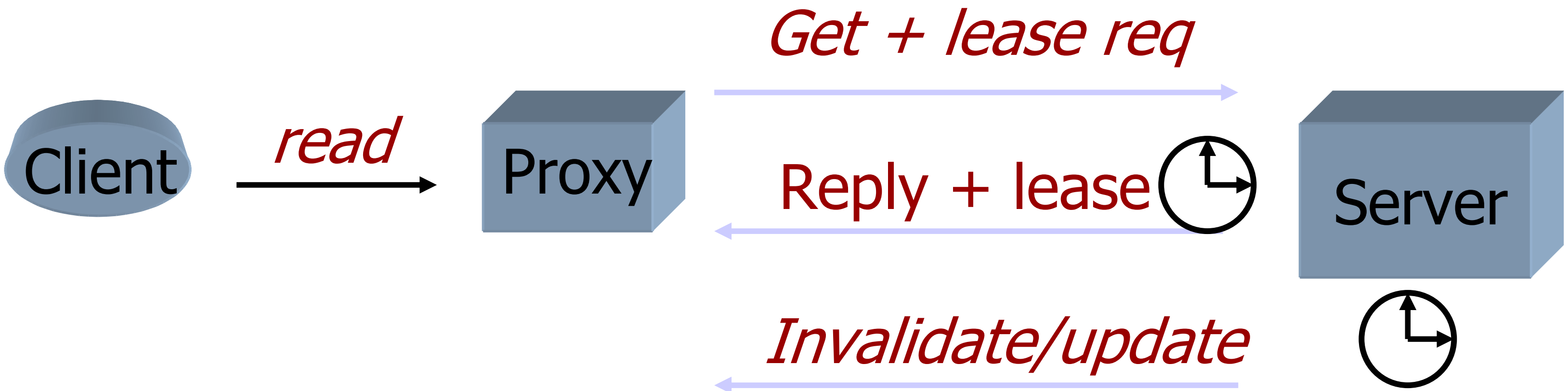
- Proxy can dynamically determine the refresh interval
  - Compute based on past observations
    - Start with a conservative refresh interval
    - Increase interval if object has not changed between two successive polls
    - Decrease interval if object is updated between two polls
    - Adaptive: No prior knowledge of object characteristics needed

Pull-based Approach

- Advantages
  - Implementation using HTTP (If-modified-Since)
  - Server remains stateless
  - Resilient to both server and proxy failures
- Disadvantages
  - Weaker consistency guarantees (objects can change between two polls and proxy will contain stale data until next poll)
    - Strong consistency only if poll before every HTTP response
  - More sophisticated proxies required
  - High message overhead

A Hybrid Approach: Leases

- Lease: duration of time for which server agrees to notify proxy of modification
- Issue lease on first request, send notification until expiry
  - Need to renew lease upon expiry
- Smooth tradeoff between state and messages exchanged
  - Zero duration => polling, Infinite leases => server-push
- Efficiency depends on the *lease duration*



Policies for Leases Duration

- Age-based lease
  - Based on bi-modal nature of object lifetimes
  - Larger the expected lifetime longer the lease
- Renewal-frequency based
  - Based on skewed popularity
  - Proxy at which objects is popular gets longer lease
- Server load based
  - Based on adaptively controlling the state space
  - Shorter leases during heavy load