Lecture Overview

- HTTP lecture briefly covered cache functionality
- In this lecture, we go into detail
  - Why do it
  - Where to do it
  - How it performs
    - Workloads and sharing
    - Uncacheability
    - Prefetching
    - Cache replacement
    - Consistency
    - Cooperative web caching
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

Caching in the Web

- Performance is a major concern in the Web
- 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?

- Answer: Everywhere
- Browser (user)
  - Small: 10MBs memory, 100MBs disk
    - Note recursive caching (memory vs. disk)!
  - 20% hit rate
- Organization (client-side proxy)
  - Large: Gigabytes (with disk)
  - 50% hit rate (for large client populations)
- In front of server (server-side accelerator)
  - Large (gigabytes)
- Server itself (in memory)

Proxy Cache Implementations

- Squid proxy cache most popular free cache
  - Research project
- Apache web server can be configured as cache
- Many cache products
  - NetworkAppliance, Inktomi, Infolibria, etc.

At this point
- Web caches are frequently used
- Issues well understood
- Let’s see how and why they work
  - Remember, it’s all about performance
Cache Performance

- Ideally, we want ~100% cache hit rate
  - In practice, we get around 50%
- Cache effectiveness is determined by the workload
- **Sharing** is the most important aspect of the workload
  - Requests hit in cache because object previously requested
  - Requests to popular objects hit in cache (only first is miss)
- Sharing obeys Zipf’s law
  - # requests \( n \) to an object is inversely proportional to its rank \( r \)
  - \( n = r^{-a} \), where \( a \) is a constant close to 1

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

Number of Users
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
Effect of Uncacheability

![Graph showing the impact of uncachability on hit rate.]

Uncacheability

<table>
<thead>
<tr>
<th>Reasons for Uncacheability</th>
<th>% of All Requests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Uncache (v1)</td>
<td>40.0</td>
</tr>
<tr>
<td>Overall Uncache (v2)</td>
<td>39.4</td>
</tr>
<tr>
<td>Response Status</td>
<td></td>
</tr>
<tr>
<td>Query</td>
<td>13.9</td>
</tr>
<tr>
<td>Pragma</td>
<td>7.7</td>
</tr>
<tr>
<td>CGI</td>
<td>6.2</td>
</tr>
<tr>
<td>Cache Control</td>
<td>5.7</td>
</tr>
<tr>
<td>Cookie</td>
<td>4.4</td>
</tr>
<tr>
<td>Method</td>
<td>1.4</td>
</tr>
<tr>
<td>Auth</td>
<td>1.0</td>
</tr>
<tr>
<td>Vary</td>
<td>0.3</td>
</tr>
<tr>
<td>Push Content</td>
<td>0.0</td>
</tr>
<tr>
<td>Single Reason</td>
<td>23.5</td>
</tr>
<tr>
<td>Two Or More Reasons</td>
<td>16.4</td>
</tr>
</tbody>
</table>
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)

Prefetching

- Let’s say we make everything cacheable
- We still have a high compulsory miss rate (30+%)  
  - Initial requests to objects
- What to do?
  - We can guess that objects will be requested in future
  - And request them now: *prefetch*
  - Fancy algorithms (markov models with conditional probs.)
  - Simple algorithms (only embedded)
    » Effective: 50% reduction in page latency
- Tradeoffs
  - Can increase cache hit rate, reduce latency
  - But, can be tough to determine what will be accessed
  - Accuracy (waste bandwidth), stale data (TCP-Nice)
Cache Capacity

- Caches have finite resources
  - Eventually, something is going to have to be evicted
- Choice is made by the cache replacement algorithm
  - Cache replacement is probably the most popular single web cache research topic
- It also probably has the least impact
  - Capacity misses comprise <5% of miss rate
  - Greatest benefit you could hope for is a 5% improvement
  - Basically, want an algorithm incorporating frequency and size
- General problem
  - Fancy algorithms evaluated with small, unrealistic cache sizes

Consistency

- Consistency ensures that objects are not stale
  - Always want version on server and in caches to be the same
- Objects have lifetimes (TTL)
  - Requests to expired objects have to go back to server If-Modified-Since (304)
  - If object hasn’t changed, return from cache
  - Otherwise server sends back changed object
  - Even if not modified, still suffer extra latency and server load
- TTLs tend to be conservative
  - Shorter TTLs to reduce potential for staleness
  - Results in many requests back to server (10-20%)
Server-Driven Consistency

- Servers know when objects change
- We can have them tell caches when they change
  - Send invalidations
- Leases used to synchronize caches and server
  - Object leases: Short, per-object TTLs
    - Server records that cache has copy to send invalidations
  - Volume leases: Long, per-site TTLs
    - Amortize lease renewal for many objects
- Key issues
  - State to keep track of objects in proxy caches (can scale)
  - Load induced by bursts of invalidations (pace them)

Cooperative Caching

- Sharing and/or coordination of cache state among multiple Web proxy cache nodes
  - NLANR cache hierarchy most widely known
Cooperative Caching

- Idea: Increase number of users using caching system
  - Have caches “cooperate” and share content, users
  - Caches send their misses to other caches (e.g., to a parent cache in a hierarchy)
  - Can greatly increase number of users in system (and hit rate)
- Cooperative caching has also been a popular topic
  - I’ve even worked on it (part of my thesis)
- Many interesting issues: architecture, request routing, updates, scalability
- Utility depends on scale
  - Works well for small scales (depts.), but not very necessary
  - Some benefit for medium-scale (large city)
  - Large scale (national) not worth the complexity

Cooperative Cache Performance

- Model of large-scale cache performance
  - Various degrees of object rate of change
Summary

- Web caching
  - Used every step of the way
  - Proxy caches give us about 50% hit rate
  - Many techniques for improving cache effectiveness
  - But cannot be the only answer
- Current research
  - Content distribution networks (caches are components)
  - Streaming media (video, audio) caches