

# Chapter 1

## Web Proxy Caching

### 1 Introduction

Computer systems employ a storage hierarchy that is composed of many types of storage devices with different access costs. Upper level storage devices provide faster data accesses over lower level storage devices. Caching is a technique to place data on upper level storage devices to reduce data access latencies. Caching has been extensively applied to diverse areas in computing systems including computer architecture[43] and database systems[40], to name a few. This chapter covers how the idea of caching is applied to the World-Wide-Web environments.

#### 1.1 Motivation

The World Wide Web is a large distributed system based on a client-server architecture. web clients request information from web servers which provide information through the network. The web community is growing so quickly that the number of clients accessing web servers is increasing nearly tremendously. This rapid increase of web clients generates more web traffic and higher server loads, which makes the web slower. How can we lessen web traffic and server loads and reduce the latency web users face when downloading web objects?

Several approaches have been proposed to increase the performance of the web. Trying to scale server and network bandwidth to keep up with increasing demand is one simple but expensive solution. Several observations suggest that a cache-based approach can help improve performance for lower cost. First, a single client often requests the same web object several times during a small interval of time by visiting a home page of a certain web service. Second, web object accesses are non-uniform over all web servers; a small set of “popular” servers faces a disproportionate share of total server load[9, 23]. Further, different users often request the same web object from these highly loaded servers. If we can store commonly requested objects on a place that web clients can locate faster, users will see lower latency when browsing. Web caches are the systems that keep copies of frequently accessed objects closer to clients in terms of web objects flow. The development of web caching has spurred new researches in many areas [10, 90].

Information providers publish their information on the World Wide Web in a variety of formats. Usually information in the web is referred as *documents* or *web pages*. In terms of caching, unit of information in the web are not exactly simple documents or pages. Instead,

a piece of a document or a part of stream information may be a unit of caching. So, we will use *web object* as a more generic term to represent a unit of web caching.

*Web caching is managing copies of web objects closer to clients to enable clients to see lower latency when accessing to objects.*

## 1.2 Types of Web Caching

Web caching can be done using varying degrees of cache level; from zero to many levels. As a client requests a web object, it flows from a server, through a network, and to the client. Between a client and a server may be one or more proxy servers.

There are three kinds of caches according to where copied objects are stored and managed.

### 1.2.1 Browser Cache

A web browser cache stores local copies of web objects which have been accessed recently based on a specific cache management policy. As it keeps copies for a client only, the browser cache does not represent any shared accesses between clients. There are two forms of client caches[2]. A *persistent* client cache keeps web objects between invocations of the web browser. A *non-persistent* client cache removes cached copies when the user quits the browser.

### 1.2.2 Proxy Cache

In general, a proxy is a special HTTP server that can run on a firewall machine[65]. A firewall is a security system to protect a networked servers from intentional or accidental damage of unauthorized access, which is implemented by either hardware or software. Proxying is a standard method for allowing accesses through a firewall without forcing each client to include customized support a special firewall environment. The proxy cache is located on a machine on the path from multiple clients to multiple servers. The same proxy can be used by all clients within a given subnet. This makes it efficient for a proxy to do caching of web objects requested by a number of clients. When a single proxy cache communicates solely with its clients and servers, it is called an *isolated cache*. It is possible to use a set of caching proxies which cooperate with each other to improve performance. They are called *cooperative caches*. The configuration may be hierarchical so that the caches can be identified as first level caches, second level caches, and so on. It may be also non-hierarchical.

### 1.2.3 Server Cache

Server caching is another term for placing a cache in front of a web server. This is called “server” caching because it is implemented by the administrators of the web servers, rather than by the clients. The goal here is to cache and distribute web objects from the servers and to offload the processing of client requests. The server cache is referred sometimes as “reverse proxy” cache[79], “HTTP accelerator” [62]or “surrogate origin server[74]<sup>1</sup>.

### 1.2.4 Caching Hierarchy

Figure 1.1 shows various forms of connections from a client to servers using intermediate levels of caching. The simplest form is using no caching at all as in Figure 1.1 A). When a

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<sup>1</sup>In this chapter, we will use those terms interchangeably

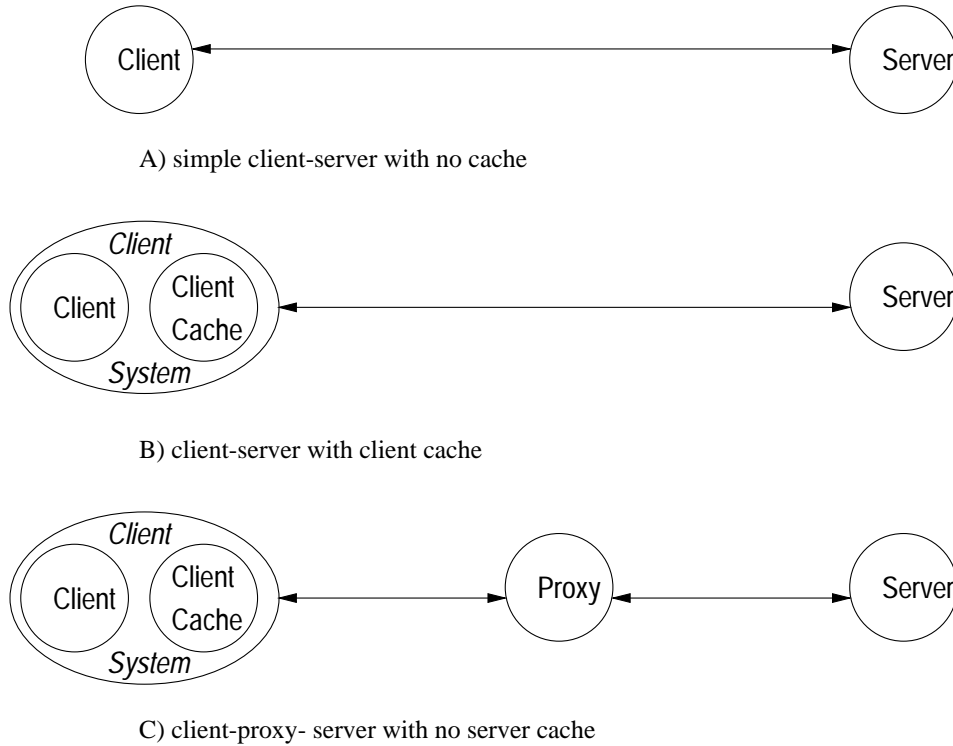


Figure 1.1: Many forms of client-server connection.

client requests a web object, it is always served from a web server. So the latency always depends on the network traffic and server workloads. Usually a client system is composed of a web browser which has the capability of caching (Figure 1.1 B). In this configuration, a client cache keeps recently accessed web objects by the client. When the client tries to access one of the web objects that are already in the client cache, it will be served from the client cache if it is believed not to be stale without connecting a web server. Note that a client cache reflects only for the previous accesses from a client. Figure 1.1 C) shows the intervention of a proxy cache for web object traffic. A proxy cache between clients and web servers can keep shared accesses on web objects among different clients. So web objects that are frequently accessed from multiple clients can be accessed with reduced latency from the proxy cache. The more complex form might be using many levels of intermediate caches including a client cache, a set of proxy caches, and a set of server caches. A client may also be connected to several servers with a combination of diverse forms of connections described above.

Hierarchical web proxy cache structures are similar to memory hierarchies [29]. Figure 1.2 shows an example caching hierarchy.

At each level, requests are processed with cache misses propagating a request down the hierarchy one more level.

Web browser caches form a top of the hierarchy. By configuring browsers to direct web object requests to a nearby proxy server, the proxy cache provides the second level of caching. The proxy cache then sees requests for all misses in the browser cache. Some proxy caches can be organized to act as a third-level cache as well. The lowest-level proxy cache is typically a cooperative cache that connects lower-level proxy caches to each other so that a miss in one cache can be satisfied by one of its siblings. At the bottom of the hierarchy are

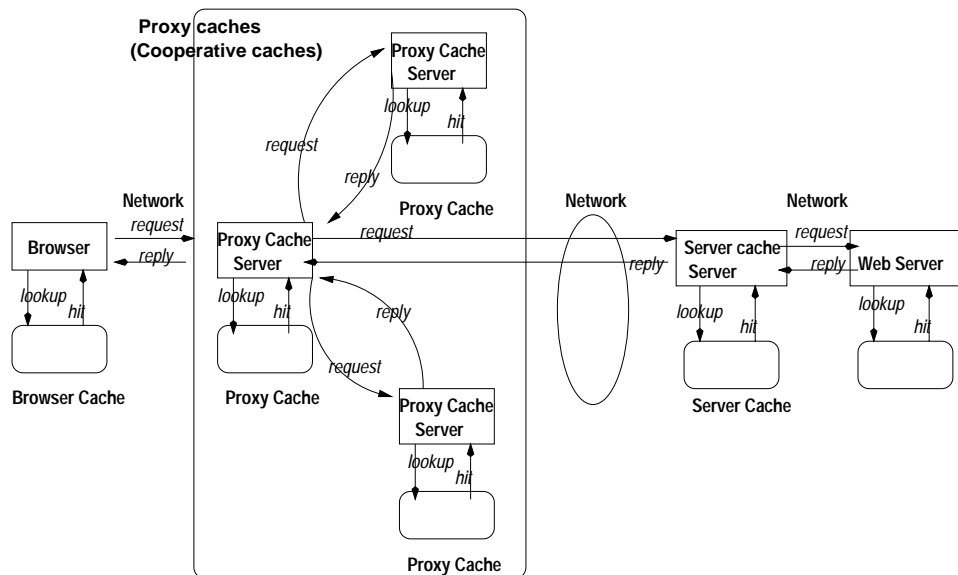


Figure 1.2: An example web cache hierarchy.

the server caches which are closest to web servers. If requests for web objects are satisfied at higher levels of the cache hierarchy, then the cost of accesses can be significantly reduced.

### 1.3 Contrasting Web Cache Styles

A browser cache tries to reduce retrieval latency for a user by keeping their previously accessed web objects in a client's memory and disk. A browser supports the necessary functions for cache management including determination of cache size, maximum retention period and mechanism to maintain consistency of copies and so on. For the user's perspective, reducing latency is the most significant factor over larger network efficiency considerations. This goal might conflict with the goals of an organization or network system. In order to reduce latency, some browser caching provides an aggressive form of preloading of web objects which the user is likely to access. However, this may cause an unnecessary increase in network traffic.

Proxy caches lie in the middle of network and receive requests from many clients. So the requests seen by a proxy cache are interleaved across users. When requests are satisfied from a proxy cache, network traffic will be reduced because those requests need not be sent to servers. Cache hits also reduce client latency and server workload. As the proxy cache manages web objects requests from multiple clients, it is focused on improving global performance. Efficient management of cache space is more important in this case than for a browser cache. There are a number of issues to be considered for proxy caches and they will be discussed in the following sections.

Server caches are similar to proxy caches. However they accept only traffic for their web servers so that they act as a true web server from the client's perspective. These caches are not for end users, but deployed and maintained for large web publishers. The focuses of server caches are primarily the scalability and server workload problems faced by popular web sites. Decreasing network traffic to web server is also a concern of these caches. It can also enhance security by forcing clients to communicate through an intermediate layer

instead of directly with the true originating server.

Web caching needs to consider different issues compared to other caching systems in traditional client-server environments. Usually, traditional caching assumes that the data to be cached has a fixed size (i.e. pages or blocks). Time to load a page is also assumed to be fixed (i.e. main memory access time, or some I/O access time). But web objects exhibit large variations in size from a few hundred bytes to several megabytes. Additionally, in the web environment, times needed to load web objects are variable and often difficult to predict. Further, web caching systems can still be useful with relatively weak consistency models - unlike a memory hierarchy, where weak consistency is wholly unacceptable. These differences make approaches for traditional caching do not fit for the problem of caching in a web environment.

#### 1.4 Why Focus on Proxy Caching ?

Proxy caches have been the subject of significant academic research[8, 39, 65] and also a significant area of commercial development[1]. While an individual browser cache or server cache is beneficial to only a specific client or a web server site, a single proxy cache can benefit multiple clients and multiple servers at the same time.

A proxy cache has several potential advantages [39]. It can reduce latency on requests for cached pages because those requests need not be directed to original servers. As only missed requests from a proxy cache or explicitly requested ones to the server are sent to servers through the network, proxy caching can reduce both overall network load and server load. When a remote server is unavailable because of network disconnections or failures, cached copies are still available to users.

However, proxy caching has several potential disadvantages, too. The basic problem associated with caching is that the object returned to a user may be different from the originating server's current object if the objects has changed at that server since the last cache update. Cache consistency mechanisms need to be applied to address this problem<sup>2</sup>. Deploying proxy caching may also increase latency on requests for objects which are not cached. For every request on web objects, it should be checked always whether the requested object exists in the cache in a valid form. When the valid web object is not found in the cache, the request will be passed to the origin server. It also incurs costs in administrative complexity, disk and memory space, and processing power. As a side effect of caching, objects hit counts in a server may not reflect users' real object access tendencies or true object popularity because user requests met from upper levels of caches will not be seen from the server.

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<sup>2</sup>In Section 5, we will discuss this problem in detail.

## 2 Web Traffic Characteristics

The analysis of web traffic characteristics is important because specific access properties can be exploited to develop more efficient web caches.

Two of the most important characteristics of web traffic for web cache design are access frequency of a web object, and temporal locality of reference in web request streams. It is a common belief that the frequency of web object access is not uniform for all web objects. Several early studies [4, 23, 39] have found that the relative frequency with which web pages are requested follows Zipf's law[99]. Zipf's law maintains that the relative probability of a request for the  $i$ 'th most popular page is proportional to  $1/i$ . However, recent studies[14, 72] argue that long-term popularity of web request stream does not follow Zipf's law precisely, but instead follows Zipf-like distribution with a variable exponent<sup>3</sup>.

The tendency that recently accessed objects are more likely to be accessed again in the near future represents temporal locality of reference. Temporal locality of reference in web request streams has been observed in many studies[6, 15, 47].

There is an inherent relationship between the temporal locality and skewed access distribution of web traffic characteristics. That is, the popularity of frequency of access is one of the major determinants of the temporal locality. For objects with high popularity, temporal locality can be easily found. However, there are other contributors to temporal locality, which is *temporal correlation* of repeated requests to the same web object[47, 49, 50]. The precise identification and characterization of web traffic properties can help improve the efficiency of web caches.

Usually, workload characterization is done by analyzing traces of web traffic. Workload means a sequence of access requests for web objects. Web workloads may be generated or recorded from the perspective of browsers, proxies, and servers. Workloads from clients can be valuable in evaluating user-level performance metrics and access patterns. As clients workload is gathered from a single client's perspective, it has limited value when looking at system-level performance metrics or the study of global properties. Server workloads are often easy to find, as many servers log the requests they service. But workloads obtained from server logs do not reflect the access patterns of individual users. Thus, while they are useful when evaluating system-level performance metrics such as network bandwidth demand and server load, they are less effective when studying user-level performance metrics such as service time. A caching proxy often functions as a second (or higher) level cache. That means that only the misses from web clients are passed to the proxy. Workloads obtained from proxies usually do not exhibit per-user temporal locality of reference, but do track the traffic generated by a large number of users simultaneously.

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<sup>3</sup>It follows  $1/i^\alpha$ , where  $\alpha$  usually takes on some value less than 1.

### 3 How A Proxy Cache Works

The basic functionality implemented by a web proxy cache is depicted in Figure 1.3. User requests come into the cache as users browse the web; whatever happens within the cache, the result seen by the user is a returned web page. This user experience is captured in the top- and bottom-most blocks in the flow diagram: URL requests come into the system, and the system replies with pages. Performance is measured from the user's perspective, although there are a number of different measures proposed in the literature.

These user requests come into the proxy cache as HTTP commands. The user is presented with the view of a single proxy cache, but the cache may be internally distributed and repeated accesses may result in a different server processing the requests. Within the context of this flow diagram: the inflow of requests may be directed at a large number of "In Cache?" systems, each operating on a different computer.

When a request is received, the first operation performed determines whether the requested object has already been stored in the cache. This is simply a question of querying the contents of the cache, and returning a boolean result. Again, the cache may store objects in a distributed fashion, resulting in a more complex operation to service this query.

If the object was found to be in the cache, the system then checks to see if the cached copy is "valid." The definition of valid varies from implementation to implementation; this is where the proxy cache designer can control the consistency model that is in place and the scope of objects that are considered cacheable.

The weakest consistency model for a proxy cache always returns "Yes" at this point: all cached objects are considered valid. Similarly, the strongest consistency model always returns "No" at this point: the object is reloaded for every request. In between these extremes lie the consistency models of interest, using checks like the age of a cached object, time-to-live information from the server or dozens of other possible metrics. Valid objects are returned directly to the user.

The set of objects that are considered cacheable is also defined at this stage. Web objects might be considered uncacheable because they are too large (i.e. long video streams) or because they are likely to change with each access (i.e. cgi content). A proxy cache could rule out caching cgi content by always declaring any object with "cgi-bin" in the name to be invalid. A similar approach could insure that only HTML (and not ASP, AVI, etc...) content is cached.

If a cached object is invalid or if the object was not found within the cache, the system retrieves the data from the originating server. After the data has been downloaded, the system faces the task of caching it. This stage of the process includes the replacement policy component of web proxy cache design: when the cache does not have the space to store the downloaded object, it must evict objects from the cache to make room.

The policy used to select which objects are to be removed from the cache is designer-controlled. Further, the policy that determines when the cache is full is designer-controlled: the cache can impose restrictions on the number of cached objects from a single server or domain, or any other restrictions on cached objects the designer wants. Available cache space need not be the only consideration when deciding if replacement is needed, but it surely must be one of them.

Similarly, the system need not restrict the set of retrieved objects to those requested by the user - although the cache will need to retrieve the objects needed to satisfy user requests as they come in. A proxy cache could be built to retrieve (and then pass on to the "cache object" stage) documents without an explicit user request. This technique is known as "prefetching": downloading objects before an explicit request has been made for them. Whether to implement such a system, and what the list of prefetched objects should be, are

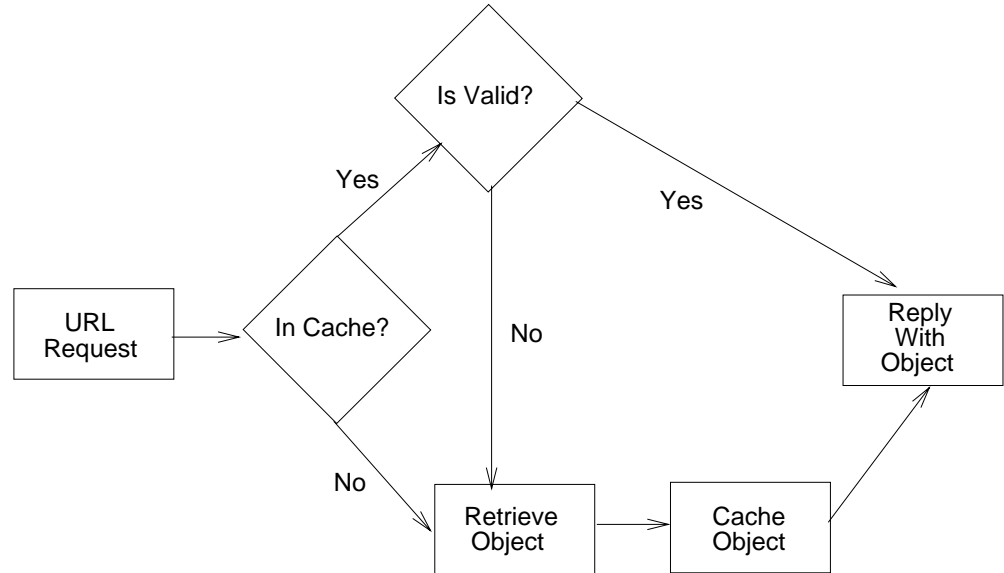


Figure 1.3: Basic flow diagram of a proxy cache.

both decisions left up to the proxy cache designer.

Within this overview of web proxy cache functionality, we highlight 6 issues for further discussion:

- **Proxy Cache Performance:** How can we quantify the performance of a web proxy cache, and when are the various measures appropriate.
- **Cache Consistency Model:** What guarantees does a particular web proxy cache make about the difference between cached objects and the current state of content on originating servers.
- **Replacement Policy:** When a proxy cache must evict some “old” cached objects to make space for new ones, which objects are evicted.
- **Cacheability:** Which web objects are uncacheable, and how to improve the cacheability for some kinds of web objects.
- **Prefetching:** How can a proxy cache improve performance by retrieving content ahead of specific user requests.
- **Architecture:** How can a proxy cache designer assemble proxy caches to deliver better overall performance for a large community of users.

Each of these issues concerns the design of one or more steps of a proxy cache system, and has been the subject of significant academic and commercial research. Building a web proxy cache requires deciding how to handle each of these issues; building a proxy cache well-suited to your goals requires understanding the choices available when facing each of them.



## 4 Quantifying Performance

### 4.1 Performance Metrics

Many different performance metrics have been proposed in the literature. We focus on 5 quantities that are widely measured and used by practitioners.

**Hit Ratio** is the number of requests that hit in the proxy cache as a percentage of total requests.

**Byte Hit Ratio** is the number of bytes that hit in the proxy cache as the percentage of the total number of bytes requested.

**Latency Reduction** is the percentage of the sum of downloading latency for the pages that hit in cache over the sum of all downloading latencies.

**Hop Reduction** is the ratio between the total number of the hops of cache hits and the total number of the hops of all accesses. The “hops” value can be the number of network hops travelled by a document, to model the case when the proxy tries to reduce the overall load on Internet routers, or it can be the monetary cost associated with fetching the document, to model the case when the proxy has to pay for documents travelling through different network carriers.

**Weighted-Hop Reduction** is the corresponding ratio for the total number of hops times “packet savings” on cache hits.

Which Performance Metric is most important? There isn’t one right answer. It is also very hard to assign weights to various performance measurements, since different users have different priorities. For network architects with expensive, congested, or low-bandwidth WAN links, hit ratio is probably more important. But if bandwidth is plentiful, response time and throughput matter most.

## 5 Cache Consistency

### 5.1 Overview

Though web proxy caching provides several beneficial effects, it introduces a new problem not present in cacheless web environment. As there can be more than one copy of a given web object from caching, a user might see an old copy of a requested object when it has been changed since the cache last copied it. For web caches to be useful, cached copies need to be updated when the original objects change. When cached copies are not up-to-date, they are considered to be “stale”. Cache consistency mechanisms insure that cached copies of objects obey certain rules - a cache consistency policy - with respect to their being out of date[26, 42].

Current consistency models for web cache maintenance can be divided into two categories. Strong consistency is the model which ensures that a stale copy of data will never be returned to a user. However, no proxy caches implement the strong consistency model because of the unbounded message delays in the Internet and the limited utility of a strong-consistent proxy cache. Weak consistency is a broad class of models in which a stale data might be returned to the user. So, weak consistency may not always be satisfactory. Users should be aware that the cache might occasionally return a stale data.

In order to maintain strong consistency, a proxy cache must know exactly when the original objects change in order to reflect those changes in its own copies. However, there is no way for the cache to know when objects change without either asking the server or providing a mechanism whereby servers can inform caches about changes. For the weak consistency case, a proxy cache should determine whether a copied object should be considered as up-to-date or not. A proxy cache can use some information from the server alongside its own decision algorithms to estimate the validity of the copied data more accurately. Such estimation might not always be correct, resulting in the cache occasionally returning stale data.

Cache consistency algorithms have been extensively studied in the context of traditional distributed file systems and client/server database systems. Most of the traditional algorithms guarantee strong consistency and require servers to maintain state about the data cached by clients. However, the web is fundamentally different from a distributed file system and a client/server system in its access patterns[42]. Also, the scale of the web is orders of magnitude larger than any distributed file system, making these schemes intractable for web cache consistency. As changes for an object are made from a single web site, caches should never observe conflicting update instructions, and that may make the consistency issues simpler. Such different environments may make the techniques used in conventional systems not be adequate for caching on the Web.

### 5.2 HTTP mechanisms to support cache consistency

HTTP[12, 26] defines several headers which were specifically designed to support caching. Though the HTTP specification specifies certain behaviors for web caches, it does not specify how to keep cached objects up to date.

The HTTP GET message is used to retrieve a web object given its URL. However GET alone does not guarantee that it will return a fresh object. HTTP headers that may affect caching can be classified into two categories. The first category includes headers appended to retrieve a web object for cache control. The second category includes headers appended when a web object is returned.

### 5.2.1 HTTP Headers Appended to a GET Message

- *If-Modified-Since:date* : When appended to a GET message, a web object will be returned only if its last modification date is greater than the date in the If-Modified-Since header which is the last time a cache obtained a new copy from the originating server. Otherwise, "a Not Modified 304 reply" is returned. A GET message with attached If-Modified-Since header is called a conditional GET.
- *Pragma:no-cache* : When appended to a GET message, it indicates that a cache may not return a cached object. Instead, it must return a fresh version of the object retrieved from the object's origin server. Most browsers offer a "Reload" button which retrieves an object using this header.

### 5.2.2 HTTP Headers Returned in Response to the GET Message

- *Expires:date* : This header notifies caches of the time until the object could be considered fresh. After that time, every request for the object should be sent to the originating server to see if the object has changed. Expires headers will be specially effective for web objects for which it is relatively easy to estimate expirations. For example, static images which don't change much or objects that tend to change regularly are good candidates for this approach.
- *Last-Modified:date* : This header returns the time the object was last modified to create the current version. This header is mandatory. Every object returned from a GET message will have this header. The last-modified time of an object can be a unique version identifier for the object. If cached objects have identical *Last-Modified:date* headers then the contents of those objects are guaranteed to be identical.
- *Date:date* : This header provides the last time an object was considered to be fresh. This is not the same as an object's Last-Modified date. This may inform users how stale an object might possibly be. For example, when an object's *Date:date* is recent, then it means the object's information is quite up-to-date even if the content of the object was created long before. So, this header reveals very important information for users.

### 5.2.3 Headers in HTTP 1.1 for Cache Control

While the "Expires:date" header can support control of caching to some extent, the HTTP 1.0 protocol does not provide much support for controlling when an object is cacheable or how a cache can manipulate it. HTTP 1.1 provides a new class of headers that makes it possible to define how caches should handle different web objects.

Some of the interesting options for *Cache-Control: options* response headers are as follows.

- *max-age=[seconds]* : This header specifies the maximum duration when an object may be considered to be fresh. This option supersedes the *Expires* header. Clients may send this header in order to explicitly and flexibly specify the degree of staleness acceptable to the user. Note that *no-cache* Pragma directive could only be used to flush caches unconditionally.
- *s-maxage=[seconds]* : This header specifies the max-age only for proxy caches.

	Strong Consistency	Weak Consistency
Client-based	Check-every-time	Never-check Expiration-based Piggyback-based Validation
Server-based	Invalidation-based Lease-based	Piggyback-based Invalidation

Table 1.1: Category of Cache Consistency Maintenance Approaches

- *public* : This header marks the response as cacheable regardless of whether it should be cacheable or not. Using this header, even an authenticated web object will be cacheable.
- *no-cache* : This header forces caches (both proxy and browser) to submit the request to the originating server for validation before releasing a cached copy every time.
- *must-revalidate* : This header asks caches to strictly obey any freshness information given for an object. HTTP allows caches to determine whether they will use the given freshness information or not. However, if this header is specified, caches should follow the freshness information for an object, and without modification.
- *proxy-revalidate* : This header is similar to "must-revalidate" but it only applies to proxy caches.

### 5.3 Metrics for the Degree of Consistency

When a web object in a server is changed, cached copy of that object becomes *stale* till the change is reflected to the cached object. The primary goal of cache consistency mechanism is to keep cached web objects up-to-date. The notion of staleness has been frequently referred in the context of a single web object, in which a cached web object is stale if it is not up-to-date. The time elapsed since the original object in the server has changed but the cached copy is not up-to-date is referred as *age*. If age of a cached object is 0, its staleness should be 0. Though age might be used as a metric for staleness, it is not same to the staleness.

The usual metric for staleness used in the literature is the number of out-of-date objects forwarded to the users over the total user requests[42, 63]. This is similar to stale cache hit ratio which means the number of known stale cache hits divided by the number of total requests (both serviced from the cache and retrieved from the server) [56, 57, 55]

### 5.4 Approaches for Cache Consistency

In order to keep consistency, several approaches have been proposed in the literature. They provide a spectrum of consistency levels based on the consistency guarantees supported by each mechanism. Further, different approaches interact with different parts of the caching system, which can lead to different consistency guarantees. In a client-based approach, the requests that maintain consistency are initiated by a client. In order to keep certain degree of consistency, it is necessary for clients to perform certain actions or to provide certain information to servers. For a server-based approach, the requests that maintain consistency are initiated by the server.

Table 5.4 shows the spectrum of several approaches. We will now describe the basic mechanisms of the approaches in each category.

### 5.4.1 Client-Based Strong Consistency Mechanisms

#### Check-Every-Time

This approach requires that proxy caches ask the server every time to determine if the data has changed. Thus, clients will never get stale data. Specifically, when a cache receives a GET or conditional GET message for a cached object, it always sends a conditional GET message to the next higher cache or server by passing the Last-Modified date of the cached object as the date in the *If-Modified-Since* header.

Check-Every-Time is one of the simplest consistency algorithms. The advantage is that it does not require any state<sup>4</sup> to be maintained at the server. Also the server doesn't need to block on a write request. Those advantages are from the fact that proxy is responsible for maintaining cache consistency. However, this approach has a large message overhead because it has to communicate with the originating server for every object request. It also increases the response time since the proxy waits until it gets the result of every check.

Because of its high message overhead, this mechanism is rarely used for a consistency mechanism in current proxy caching systems. However it can be used as a part of a consistency mechanism for web objects which are uncacheable<sup>5</sup>.

### 5.4.2 Client-Based Weak Consistency Mechanisms

#### Never-Check

This is the simplest consistency mechanism. It will never try to determine the freshness of a cached object without an explicit request for a validity check. Specifically, a cache will never send If-Modified-Since messages to check whether cached objects are valid or not. The responsibility of cache consistency lies solely on a client. In order to access a fresh object, clients will have to explicitly refresh the object using "Pragma:no-cache" message.

#### Expiration-based

This approach assumes that a cached object remains valid for a *Time-To-Live(TTL)* period, which is an *a priori* estimate of how long the object will remain unchanged after a client validates the object[42]. Current web caches consider a cached copy valid until it's TTL expires. Any GET requests made before the TTL of the corresponding object expires will return the cached objects by assuming those objects are still fresh. For requests on objects whose TTL are expired, GET or conditional GET(*If-Modified-Since* message) requests are sent to the upper level cache or the originating server to check whether those objects have changed.

With this approach, choosing the appropriate value of the TTL represents a trade off. If it is long enough, it will reduce validations for the number of object requests. On the other hand, a long TTL increases the likelihood that a cache will return stale objects.

The adaptive TTL(also called the Alex protocol[17]) handles the problem by adjusting the TTL duration of an object according to observations of the lifetime of the object. It takes advantage of the fact that object lifetime distributions tend to be bimodal, which is based on the assumption that young files are modified more frequently than old files and that the old files are less likely to be modified. This implies that validity checks for the older objects can be made less frequently. With adaptive TTL, a cache manager assigns a TTL

<sup>4</sup>For example, states on which clients have copies for which objects will be helpful.

<sup>5</sup>The circumstances when an object is uncacheable will be discussed in the cacheability issues in Section 7

value to an object, which is a percentage of the object's current age (i.e. current time minus the last modified time of the object).

Expiration-based approaches are now the most widely used. But stale objects can still be returned to users.

### **Piggyback-based Validation**

This approach is based on piggybacking cache state information onto HTTP requests to servers [54, 56]. Whenever a proxy cache communicates with a server, it piggybacks a list of its cached objects from that server. These cached objects might be stale, and the purpose of the exchange is to determine object-by-object which are actually stale. The possibly stale objects are either objects with unknown expiration time or with expired TTLs. The server then replies to the proxy cache with a list of cached stale objects on the list. The cache can update its data to remove any stale objects. Then a relatively short expiration duration (i.e. one hour) threshold is set at the proxy cache. If any access on a cached object is made during this duration, it is considered as fresh. Otherwise, the object is validated using a *IF-Not-Modified* request to the origin server.

Piggyback-based validation does not require any new connection between proxies and servers. However the proxy must maintain a list of cached objects for each server, and a server must process validation requests from caches. The performance of this approach depends on the number of requests from a proxy to a server and the number of objects cached at a proxy for a particular server. If there are few requests from a proxy server to a server, then chances for the cached objects to be validated will decrease greatly. A piggyback-based validation approach will then evolve into a check-every-time strong consistency mechanism. When there are many requests from a proxy, the proxy cache contents will be validated as much. In this extreme case, this approach is like an expiration-based weak consistency approach.

## **5.4.3 Server-Based Strong Consistency Mechanisms**

### **Invalidation-Based**

Invalidation is based on servers notifying caches of object changes [63]. In order to do this, servers keep track of which clients are caching which objects. A server notifies the clients with copies, and receives acknowledgements from the clients before any modifications.

This approach is optimal in the number of control messages exchanged between servers and the proxies. However it may require a significant amount of state to be maintained. When there are a large number of clients, this approach suffers from burdening the server with a large bookkeeping load. In addition, a server might send invalidation messages for clients that are no longer caching corresponding objects. The read cost is low because a client is guaranteed that a cached object is valid until told otherwise. However, when an object is modified, the server must invalidate the cached objects - so the write cost is high. Furthermore, if a client has crashed or if a network partition separates a server from a client, then a write may be delayed indefinitely. A study [63] shows that overhead for an invalidation-based approach is comparable to the expiration-based weak consistency approaches based on expiration.

### **Lease-Based**

Invalidation-based approaches require a significant amount of state to be maintained while expiration-based approaches impose a large control message overhead. Lease-based approaches try to support strong consistency while providing a smooth tradeoff between the state space overhead and the number of control messages exchanged.

In lease-based approaches [30, 96], the server grants a lease to each request from a proxy. A lease is an associated timeout duration in which a server guarantees to provide invalidation for modified objects. To read an object, a client first acquires a lease for it. The client may then read the cached copy until the lease expires. When an object is modified, the object's server invalidates the cached objects of all clients whose leases have not expired. To read the object after the lease expires, a client first contacts the server to renew the lease. The duration of the lease determines the server and network overhead. The smaller the lease duration, the smaller the server state space overhead, but at the cost of a larger number of control messages exchanged and vice versa. When lease duration is infinite, this approach reduces to an invalidation-based approach. When lease duration is zero, this approach reduces to an expiration-based approach.

Strong consistency can be maintained for server failures in the lease-based approach. If a client or network failure prevents a server from invalidating a client's cache, the server need only wait until the lease expires before performing the write. By contrast, invalidation-based approaches may force the write to wait indefinitely. Leases also improve the scalability of writes. They enable a server to contact only recently active clients (those holding leases on the object) rather than contacting all clients that have ever read the object.

#### 5.4.4 Server-Based Weak Consistency Mechanisms

##### Piggyback-Based Invalidation

This approach is based on piggybacking. The server replies to proxy requests with the requested object and a list of modified objects from the list of objects that proxy has previously retrieved[57].

To improve the efficiency of these algorithms, servers and proxies exchange caching information at the level of volumes - collections of web objects. Servers partition the set of objects at a site into volumes, either a single site-wide volume or related subsets of objects. Each volume has a unique identifier and a current version. When a server receives a request from a proxy client containing the client's last known version of the volume, it piggybacks a list of objects in that volume that have been modified since the client-supplied version. The proxy client invalidates cached entries on the list and can extend the lifetime of entries not on the list.

Servers maintain volume, but no proxy-specific information. Whenever an object changes within a volume, the server updates the volume version and records the object that changed between the previous and current versions. Each proxy client maintains the current set of server volume identifiers and versions for the objects in its cache. When a proxy needs to request an object from a server, it looks up the current volume identifier and version for the object and piggybacks this information as part of the request. If the volume identifier is unknown or if the proxy does not have a version for the volume, then it requests such information to be piggybacked in the reply.

In response, the server piggybacks the volume identifier, the current volume version and a list of objects from this volume that have changed between the proxy-supplied and current version. The proxy client updates its volume version, uses the list to invalidate cached entries from this volume and possibly extends the expiration time for volume resources that were not invalidated.

When this approach is combined with piggyback cache validation, it is reported to provide nearly strong cache coherency with a staleness ratio of 0.001 and a 6-9% reduction in overall costs in comparison to the best TTL-based policy[57]. However, this mechanism requires changes to existing web servers for implementation.



## 6 Replacement Policies

### 6.1 Why We Research Replacement Policies

A cache server has a fixed amount of storage for storing objects. When this storage space is full, the cache must remove some objects in order to make room for newly requested objects. The cache replacement policy determines which objects should be removed from the cache. The goal of the replacement policy is to make the best use of available resources, such as disk, memory space and network bandwidth. Since web use is the dominant cause of network backbone traffic today, the choice of cache replacement policies can have a significant impact on global network traffic.

### 6.2 Factors to be Considered

#### 6.2.1 Live Documents

We say a document is live if that document will be requested in future. The cache only needs to retain live documents to achieve the maximum hit rate. Live documents are a small fraction of all documents. Thus it is more appropriate to consider documents to be dead if they have not been requested for more than some reasonably large time.

#### 6.2.2 Interaccess time

Interaccess time is the time between successive document requests. Documents having lower interaccess times are the documents that are more likely to be requested in the future. Due to always selecting the document with the largest interaccess time to be evicted, the LRU algorithm is the best replacement algorithm for reducing average cached-object interaccess time.

#### 6.2.3 Number of Previous Accesses

Using the number of previous accesses made to a document is a good indication. We can use it to evaluate whether the document will be requested in the future. However, since it does not include any aging information about the document, this cannot be used alone as the deciding factor.

#### 6.2.4 Document Size

The document size is another important factor for caching. In proxy caching the cached documents can be of different sizes. Having more documents in the cache will likely lead to a higher hit ratio, so one might choose to cache more small documents at the expense of performance for larger documents.

#### 6.2.5 Latency

It is also important to consider the cost incurred in acquiring the document. The more expensive the document to download, the better it is to retain the document in the cache because the penalty for a cache miss is greater.

### 6.3 Existing Replacement Algorithms

Existing replacement algorithms are classified into three categories, according to whether they exploit access recency and access frequency, and whether they are sensitive to the variable cost and size of objects.

#### 6.3.1 Recency-Based Policies

The Least Recently Used algorithm (LRU) [25] is the most widely used cache replacement algorithm, as it captures recency and is superior to other simple policies like FIFO and Random. Since Web traffic exhibits temporal locality of reference, LRU is widely applied in Web servers, client applications, and proxy servers. A disadvantage of LRU is that it does not consider variable-size or variable-cost objects.

The LRU-MIN [2] algorithm is a policy derived from LRU that tries to minimize the number of documents evicted by applying LRU only to the documents whose size is above some threshold. The threshold is adaptive: if there is not enough space left, the threshold will be lowered and the policy reapplied.

The GreedyDual-Size (GDS) algorithm [15] is an algorithm that can achieve very good overall performance by considering locality, size and latency/cost and combining them effectively. GDS is a variation on a simple algorithm named GreedyDual (GD) [97], which deals with uniform-size variable-cost objects. It assigns a value  $H$  to each cached page  $p$ . At first, when a page is brought into cache,  $H$  is set to be the cost of bringing the page into the cache. When a replacement is needed, the page with the lowest  $H$  value,  $min_H$ , is replaced, and then all pages reduce their  $H$  values by  $min_H$ . If a page is accessed, its  $H$  value is restored to the cost of bringing it into the cache. Thus, the  $H$  values of recently accessed pages retain a larger portion of the original cost than those of pages that have access. This algorithm integrates the locality and cost concerns very well.

#### 6.3.2 Frequency-Based Policies

The basic frequency-based replacement algorithm is Least Frequency Used (LFU) [25]. It always removes the object with the lowest reference count.

Server-weighted LFU (swLFU) [53] is a simple generalization of LFU. It permits servers to increase the allocation of shared cache space to the URLs they host, thereby reducing server workloads. Weights in swLFU represent the extent to which servers value cache hits. Lots of simulation results demonstrate that under a particular artificial assignment of valuations to servers in actual trace data sets, swLFU delivers higher aggregate value to servers than LRU or LFU, and furthermore can provide reasonable variable QoS to servers.

Hybrid [95] algorithm is aimed at reducing the total latency. It not only considers the connection time of a server and the network bandwidth that would be achieved to the server, but considers document size and number of document access. And it combines them in an efficient way. A function is computed for each document which is designed to capture the utility of retaining a given document in the cache. The document with the smallest function value is then removed. Performance Experiments show that Hybrid is a robust policy. When using download rate along with other factors, Hybrid is superior for LFU and LRU.

#### 6.3.3 Recency/Frequency-based Policies

- Fixed Cost/Fixed Size Algorithms

Several studies have considered both recency and frequency information under a fixed cost/fixed size assumption.

The LRU-K[75] algorithm is to keep track of the times of the last  $K$  references to popular database pages, using this information to statistically estimate the interarrival time of such references on a page by page basis. Many simulation results prove that the LRU-K algorithm has significant cost/performance advantages over conventional algorithms like LRU, since LRU-K can discriminate better between frequently referenced and infrequently referenced pages. Moreover, unlike the approach of manually tuning the assignment of page pools to multiple buffer pools, this algorithm is self-reliant in that it does not depend on any external hints.

The LFU-DA algorithm [5] is a frequency-based algorithm with dynamic aging. On a fetch or a hit, the object value is set to the reference count plus the minimum reference count in the cache. Simulations with large traces indicate LFU-DA obtains the highest byte-hit-ratio. Furthermore, the LFU-DA policy may be useful in other caching environments where frequency is an important characteristic but where LFU has not been utilized due to cache pollution concerns.

The Least Recently/Frequently Used (LRFU) [60] policy is a new block replacement policy that includes both the LRU and LFU policies, depending on the different weights given to recency and frequency. Simulation results show that if the cache size is large enough to hold most of the working set, the point near the LFU extreme on the spectrum gives the lowest miss rate. This superior performance of the LRFU policy results from the fact that it considers the frequency factor as well as the recency factor when it decides the block to be replaced.

- Variable Cost/Size Algorithms

To deal with variable cost/size, generalizations of the above techniques have also been proposed.

In [86], the Least Normalized Cost Replacement algorithm for proxy caching on the Web (LNC-W3) is proposed as a generalization of LRU-K to deal with variable-cost and variable-size Web objects. It computes the average reference rate and uses that to estimate the profit of caching an object. Simulation indicated that LNC-W3 obtains higher delay saving ratios than those achieved through LRU and LRU-K.

In another direction, since GD-size policies do not take into account how many times the object was accessed in the past, several studies proposed generalizations of the GreedyDual-Size algorithm to incorporate frequency. These algorithms include GreedyDual-Size-Popularity (GDSP) [48] policy, GreedyDual-Size with Frequency policy (GDSF) [5] and greedyDual-Least Frequently Used (GD-LFU) [55] algorithm.

Lowest Relative Value algorithm (LRV) [64] includes the cost and size of a document in the calculation of a value that estimates the utility of keeping a document in the cache. Among all documents, LRV evicts the one with the lowest value. Thus, LRV takes into account locality, cost and size of a document. The performance simulation of LRV, compared to other algorithms, such as LRU and LFU shows that LRV features a consistently higher BHR than other policies in all conditions. The same happens for the HR. LRV is particularly useful in the presence of small caches.

Following is a table that summarizes the factors and corresponding replacement algorithms that consider such factor.

Factors to be considered	Replacement Algorithms
Live Documents	LRU, LRU-MIN, GD, GDS, LFU-DA, LRU-K,
Interaccess time	LRFU, LRU, LRU-MIN, LRU-K, LRFU, LRV
Number of Previous Accesses	LFU, swLFU, Hybrid Policy, LRU-K, LFU-DA, LRFU, GDSP, GD-LFU
Document Size	LRU-MIN, GD, GDS, LNC-W3, GDSP, GDSE, GD-LFU
Latency	GD, GDS, Hybrid Policy, LNC-W3, GDSE, GD-LFU, LRV

Table 1.2: Factors and corresponding replacement algorithms

## 7 Cacheability

The complexity of web objects makes cacheability unique problems in web caching. As summarized in [93, 94], the total percentage of uncacheable objects in web access workloads may vary from 15% to 50%. Although those results are computed from different workloads using different methods in counting uncacheable objects, they all show that the effectiveness of caching can be greatly impaired by the existence of uncacheable objects. In this section, we first introduce what kind of web objects are usually considered uncacheable by proxy caches and how to identify those uncacheable web objects. Then we discuss some research attempts in caching certain kind of “uncacheable” objects.

### 7.1 Uncacheable Web Objects

Web objects can be considered uncacheable by the proxy cache for different reasons. Here is some major consideration.

First, some web objects are uncacheable by nature. For example, web objects that require authentication upon retrieval shouldn't be cached. Some web objects are user specific, or context specific, which means that the result of the request depends on who is requiring it or on the context of the request when it is made. These kind of web objects should not be cached also since proxy cache usually don't make decisions (return cached copy or not) according to individual user and context.

Second, web objects with small benefit gained by caching them or large cost to keep them in the cache are usually considered uncacheable. Objects that are changing too fast, for example, dynamic generated objects, and objects that are too large are all belong to this category. If an object is too dynamic, then the cached copy will be stale very soon, and need to be fetched from the server again upon the next request. Thus it is no good for the proxy cache to maintain them in the cache at all. If an object is too large, then caching it will cause the eviction and reloading of a lot of small objects, which degrade the performance of the cache over all. Thus, a lot of proxy caches put a threshold on the size of cacheable web objects.

Finally, there are some web objects that are set to be uncacheable by the servers due to some reasons although they are cacheable to the proxy caches. For example, some web servers want to get the real access statistics for advertisement, so they don't want their web pages to be cached by the proxy caches.

### 7.2 How to Decide Cacheability

It is the proxy caches that decide which web objects are uncacheable, while the information used to make the decision is provided by the web servers. Here is the source of the information that the proxy caches usually use to decide the cacheability of web objects. Detailed description can be found in [98].

**URL** Dynamic generated objects can usually be identified from the URLs of the requests. Their URL always include "?", "=", "/cgi-bin/", ".cgi", ".pl" or ".asp", etc.

**HTTP header** The HTTP response header contains the following information always imply that the object is uncacheable.

- pragma: no-cache.
- Authorization.

- Cache-Control: no-cache / private / no-store.
- Set-Cookie. Objects including cookies are usually user specific or context specific.
- No Last Modified Date or the Last modified Date is the request time. These objects are often dynamically generated.
- size: above threshold.

**HTTP status codes** A lot of HTTP status codes imply that the response is uncacheable. For example, a response with code "302 Moved Temporarily" with no expire date is uncacheable.

### 7.3 Improving Cacheability

Since the web objects are uncacheable due to different reasons, different approaches are used to cache certain web objects which are otherwise considered uncacheable. There are two major efforts in doing so. One is dynamic generated objects caching. The other is the caching technique for large multimedia files, which is called stream caching.

#### 7.3.1 Caching Dynamic Generated Objects

A dynamic generated object usually consist of a static portion and a dynamic portion. Douglis et. al. [27] extended HTML to allow the explicit separation of these parts. The static portions can then be cached, while the dynamic portions can be retrieved from the server upon each request.

When the dynamic part of the web object is generated from a applets, Cao et. al.[16] propose an Active Cache scheme allowing the servers to supply the applets with the web objects. The proxy caches can then cache the applet and invoke it upon each request of the object.

The Dynamic Content Caching Protocol proposed by Smith et.[87] allow the server to specify how the web objects should be cached. Using their protocol, those dynamic generated objects that can be used as temporary results for a request are specified by the server. The proxy caches will cache those objects and return them as temporary results while the real object is being retrieved from the server. This scheme allows clients to browse partial or related or similar results while waiting for more accurate information.

#### 7.3.2 Stream Caching

Real time streams such as video are several orders of magnitude larger than normal web objects. This limits their cacheability in the ordinary proxy caches. However, the increasing demand of video and audio streams makes stream caching of particular interest in proxy caching.

Since it's unrealistic to cache the whole stream, the solution in caching large streams in proxy caches is to partially cache them or approximately cache them.

The prefix caching scheme proposed by Seny et.[88] divide the multimedia streams into some clips. The proxy cache only store a prefix consisting of the initial frames of each clip. Upon receiving a request for the stream, the proxy cache immediately return the prefix to the client, while simultaneously requesting the remaining frames from the server. They claim that in addition to the latency reduction, store the prefix of the stream aids the proxy caches performing work ahead smoothing which is out of the scope of this chapter.

By expressing the stream in different level of qualities, the approximation of the stream instead of the entire stream can be cached. Rejaie et. al.[80] present a fine-grain replacement

algorithm to store the streams with different qualities in the proxy caches such that the quality of a cached stream is proportional to its popularity.

## 8 Prefetching

Prefetching is a technique using the prediction of the user's future access to retrieve data and thus improve the efficiency of caching. By studying some web proxy trace, Kroeger et. al. [59] found that local proxy caching with unlimited cache size could reduce latency by at best 26%, while prefetching could reduce latency by at the best 57% and a combined caching and prefetching proxy could provide at the best a 60% latency reduction. Although this boundary was only derived from limited traces, it shows the potential of prefetching in improving the performance of caching. However, the benefit gained by prefetching comes with the cost of increasing network traffic and server workload. For proxy cache, the space balance between caching and prefetching need also to be studied carefully when prefetching is employed. In this section, we introduce different kind of prefetching techniques and different prediction algorithms.

### 8.1 Prefetching techniques

Prefetching can happen between web servers and proxy caches or between proxy caches and browser caches. In the first case, proxy cache act as client, prefetching web documents in local cache. In the second case, proxy cache act server, providing web objects for client prefetching.

The information used for prediction algorithm can either come form the statistics of access history or from the accessed objects themselves. For example, the hyper-links in HTML pages can be the candidates for prefetching. Prefetching using the statistics from the history information can can be further classified into server based prefetching, local based prefetching, and hybrid prefetching.

- **Server based** In server based prefetching, the information for prediction is gathered by the server. The server use access history from a lot of clients to make the prediction. The server can either push the prefetched objects to the client, or give the client the prefetching information and let the client decide what to prefetch. Proxy caches can either act as a server or act as a client here depending where the prefetching happens.
- **Local based** In the local based prefetching, the client use it own access history to make predictions and send request to the server. The client here can be a browser cache using one user's history or a proxy cache using a lot of user's access history.
- **Hybrid** In this approach, the predictions from the server and from the client are combined for prefetching.

While the web objects themselves are usually prefetched based upon prediction, it might increase the network traffic and server load dramatically, Thus an alternative of prefetching connections is also brought up by Cohen et.[20]. In connection prefetching, the host-names can be pre-resolved, the TCP connection can be pre-established, and "dummy" HTTP HEAD request maybe pre-send to pre-warm the connection. Their trace-based simulations show that connection prefetching has better performance improvement per bandwidth than object prefetching.

The prediction and prefetching of web objects can be conducted immediately upon each request. Or they can be delayed and executed only at suitable periods. This is because the bandwidth usage due to HTTP traffic often varies considerably over time. Prefetching web objects at off-peak periods only use the extra otherwise unused bandwidth, thus save the network resources. This technique is also called "bandwidth smoothing" [67].



## 8.2 Prediction Algorithms

The performance of prefetching is mainly decided by the precision and efficiency of the prediction algorithm. If the prediction is imprecise, it will lead to too much network traffic. If the algorithm requires too much computation in each prediction step, it will be unpractical to be used in reality. Below, we briefly introduce some of the prediction algorithms.

### 8.2.1 Prediction by Object Linkage

For each user accessed HTML page, the Interactive Prefetching Algorithm proposed in [19] just prefetch all its referenced pages.

### 8.2.2 Prediction by Access Pattern

The history access patterns of one or a lot of users can be used for the prediction of that user or other user's future access. For example, if object  $B$  is accessed immediately after the access of object  $A$ , and it is found from the access history that after  $AB$  is accessed, the probability that object  $C$  is accessed next is 80%, then object  $C$  can be prefetched to be cache before the user's next request. The Prediction by Partial Matching (PPM) algorithm and its variations [33, 76, 34] and the data mining algorithm used in [7] are all this kind of algorithms.

The PPM algorithm keeps track of the sequence of  $l$  accessed objects following a sequence of  $m$  objects. The data structure is typically a collection of trees. For prediction, the past up to  $m$  references are matched against the collection of trees and produce a set of sequences as the prediction. of the next  $l$  steps. Only candidates whose probability of access are higher than a certain threshold are considered for prefetching.

The data mining algorithm divide the access workload into a set of sequences. This set is call the training set. For a sequence  $S'$ , it's support in sequence  $S$  is defined as the number of times that  $S'$  appears in  $S$  as subsequences. The support of  $S'$  in the whole training set is defined as the sum of it's support in all the sequence in the training set. Then all the frequently appeared subsequence with support higher than a threshold can be computed from the training data. For prediction, given a user access sequence  $(e_1, \dots, e_m)$ , extend it to  $(e_1, \dots, e_m, e)$  for all possible object of  $e$ . For all suffixes of each extension, the extensions with greater support and longer matches are given a higher weight. The extension with the highest weight is then used as prediction for prefetching.

### 8.2.3 Prediction by Popularity

The server can compute the most popular objects from all it's users' access history. It then can push those popular objects to the client's cache as a prediction of the future access. The Top-10 approach proposed in [68] combines the servers' knowledge of their most popular objects with the clients' access profiles. Based on these profiles, servers regularly forward the clients their most popular objects upon request.

## 9 Web Proxy Cache Architecture

Here we discuss the higher-level architectural issues involved in web proxy cache design. Back in section 2 of this chapter we presented a high level picture of how a web proxy cache functions. The first web proxies implemented this flow diagram with a single computer and still faced a wide variety of issues in the quest for better performance. As web use has increased so has the load on web proxy caches [18]. This led to the development of more complex proxy cache systems, designed to handle large user bases and workloads[61, 91]. When traditional single-system proxy caches could not provide adequate performance, proxy cache designers began to consider more complex web proxy cache architectures[13, 52].

Across the spectrum of architectures, there are systems that can more efficiently manage cached objects, provide more cache storage space and provide increased processing power to service more user requests. These caches employ a variety of techniques ranging from more efficiently accessing local disks to employing a large number of systems in a distributed fashion to achieve these goals. With this potential for increased performance come new cache design issues:

- efficiently accessing a collection of distributed cached objects
- insuring coherence within a distributed multi-system cache,
- communicating among cache processors to maximize request processing efficiency
- load balancing across cache processors.

Further, as proxy caches become more popular, user's may see their requests routed through several autonomous and unrelated proxy caching systems on the trip between client and server.

Two new issues arise from the multiple-levels-of-proxy-cache phenomenon. First, a new meta-level proxy cache architecture has appeared where individual proxy cache systems act as nodes within a web-wide distributed web proxy cache. And second, we see proxy caches appearing on both the supply – content provider – and demand – user – sides of the web.

The discussion below will address these points within the context of web proxy cache architecture. Specifically, we consider the issue of how to structure a web proxy cache to achieve good performance when facing a large workload involving a large number of web objects. First we will cover the issue of what medium should be used to store cache objects. Then we will discuss different design alternatives for distributed cache systems. With an understanding of the different distributed cache architectures that have been designed and tested, we next discuss the relationship between supply- and demand-side proxy caches. We conclude with a discussion of the interactions among proxy cache systems and meta-level proxy cache architecture that these interactions present.

### 9.1 Disk vs. Memory Based Caching

The first issue to consider when architecting a web proxy cache is the storage medium for cached objects. Caches have been implemented using disk, memory and a combination of those two for the storage of cached data. While other techniques have surely been tried, we will confine our discussion to just the disk and memory alternatives.

The performance characteristics of memory and disk are well studied, and are documented in their own literature [77]. Three characteristics are important for the discussion here: performance, cost and size. Memory performance, measured both in terms of latency and bandwidth, is better than disk. In exchange for this advantage it is significantly more

expensive. Lastly, memory systems tend to have lower size limits than disk systems for a variety of reasons<sup>6</sup>.

Many web proxy caching systems in use today rely on disk storage because of the size and cost constraints [18, 66, 78]. Consequently, there has been significant research into the performance effects of using disk in a web proxy cache. In [81], Rousskov and Soloviev found that roughly 30% of total cache hit response time in their experiments was taken up with disk access within the proxy cache. Mogul reports that disk costs exceed the latency reductions from caching for a proxy installed at his company[70]. Later work by Maltzhan et al. in [66] reports that in fairly common situations web proxies introduce more latency than they alleviate because of disk access costs. Their essential result is that disk-only caching can be worse than no caching at all when disk use is not carefully optimized.

Two routes of attack have been proposed in the literature: using memory as a cache within a web proxy cache, and optimizing a proxies use of disk storage. Significant progress has been reported along both routes. The cache-within-a-cache approach is simply the recursive application of caching to an existing proxy cache. For the internal cache, disk holds a complete collection of the cached objects while some subset of objects are duplicated in memory to accelerate access time.

Three approaches to implementing such a system are compared in [68]. Those authors found that this type of memory cache could significantly improve performance. In experiments, a 512 KB memory cache achieved an internal hit rate of over 50%, and an 8 MB memory cache achieved a 90% internal hit rate.

These results make a compelling case for taking a combined memory and disk approach when building a web proxy cache. Implementing a memory cache within a web proxy cache reduces the disk access problem because no disk access is required for internal cache hits. But this approach does not address the performance problems associated with internal cache misses, which will still incur the disk access cost we have already stated is great enough to overwhelm the gains of caching.

This issue is specifically addressed by Markatos et al. in [69], which proposes several optimizations aimed at disk use within web proxy caches. First, those authors find that the storage of each cached web object in its own file incurs a large performance penalty due to filesystem overhead (creating files, opening files, etc...). Simply storing several web objects per file increases system performance by an order of magnitude in their tests.

Further, they find that inefficiently managing disk writes incurs a cost of a factor of 2 in overall performance. Lastly, they find that while web clients do exhibit temporal locality of reference individually, proxy servers handle requests from a large number of clients in an interleaved fashion thereby eliminating the ability to access disk in a similarly local fashion. Addressing this issue is more difficult than addressing the previous two observations, but they still report a doubling of performance in experiments with a first attempt at resolving this last issue.

## 9.2 Distributed Cache Systems

Improving the performance of cached object storage addresses performance at the stage of replying to requests that hit in the cache. Even before a proxy cache returns a requested web object to a user, significant processing is done: the object may be retrieved from a remote server, some objects may be evicted from the cache, and the system may update internal

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<sup>6</sup>While a full discussion of this issue is beyond the scope of this chapter, it suffices here to state that many computer systems cannot handle more than 2 GB of memory for address space reasons. Even other systems which do not face this limitation still have memory size limits imposed by the hardware (i.e. how many memory chips can i plug in).

state to handle future requests. Increasing the user base associated with a web proxy cache increases this load linearly with the number of user requests. If the number of requests is too high the cache can become swamped even if every request is a cache hit.

The web proxy cache model we have considered so far imagines a single system serving a community of users. For many large-scale web proxy cache systems this model is inadequate [18, 36, 52, 66, 71]. Large proxy caching systems often employ a collection of computers in a distributed fashion in an attempt to increase overall performance. Following Karger et al [52], large proxy caches are built to solve two main problems:

- preventing servers from being swamped with requests
- minimizing cache storage requirements

The issue of decreasing the latency web user’s experience during times of high load is secondary for these systems. If a server has sufficient processing power to reply to a new user request (i.e. that server is not swamped), then the latency issues devolve into cache hit rate, miss penalty and so on. These issues are discussed elsewhere in the chapter. Here we focus solely on building web proxy caching systems that can handle large workloads and can cache large numbers of web objects.

A classification of different distributed cache architectures into three classes is provided in [35]. We follow their naming system here. The simplest class of distributed proxy cache is an “Isolated Proxy Cache”: a set of proxy caches that do not intercommunicate. These caches do, however, have with some mechanism to assign each incoming user request to a constituent cache. One step up in complexity are the “Partitioned Caches.” Each cache in a distributed cache implementing the distributed architecture is responsible for caching a subset of the web, and only handles user requests for URLs that fall into it’s subset. The web is partitioned into subsets, subsets are assigned to constituent caches, and the constituents then operate independently.

The most complex distributed proxy caches are the “Collective Caches Supporting Remote Queries” – referred to as just Collective Caches here. An individual cache within a collective cache executes an additional step after making the determination that an object is not in the local cache - it requests the object from the other members of the collective. Only if this request does not produce a copy of the object (i.e. no member of the collective has already cached the object) does the proxy contact the originating server.

Our discussion proceeds by addressing the two problem distributed proxy caches are built to solve. We will refer to this classification of caches to illustrate which aspects of the proxy caching problem each distributed cache architecture addresses.

### 9.2.1 Avoiding Server Swamping

Avoiding server swamping is a variant of the load balancing problem [38, 66, 89]. We do not aim to insure that load is equal across all web servers, just to decrease the probability that a user’s request take a “long time” to process because the queried server faces more load than it can efficiently handle. A distributed cache with  $N$  constituent caches has in total  $N$  times the processing power of each constituent cache. Say each constituent cache can handle load  $L$  before being swamped. The goal here is to design a distributed cache system that can handle load as near to  $NL$  as possible without any part of the system being swamped.

The isolated cache architecture does make progress towards this goal. The effectiveness of a distributed cache implementing the “Isolated Proxy Caches” architecture towards resolving the swamping problem is determined by the mechanism that assigns user requests

to constituent caches. A simple mechanism like round-robin DNS [31] is adequate to perform this purpose. Other mechanisms have been proposed, and some web browsers can be configured to include this functionality [24]. But the performance of these systems has been measured at far below the levels achievable with more tightly-integrated architectures [35, 36].

Partitioned Caches suffer from a different set of performance problems. Any given request is assigned to one cache within a partitioned cache, independent of which client initiated the request. This mapping is implemented with the proxy auto-configuration [21] feature of a browser. There are two problems here. First, the mapping is static at any given time. And second, there is no automated mechanism for updating the mapping if the set of available caches changes. That the mapping is static means that network performance characteristics do not figure into the pairing of request and cache. This has been shown to decrease performance [38, 52, 71].

The inability of the client to maintain an accurate picture of the set of available caches is both a correctness and a performance problem. If a distributed proxy cache using the partitioned architecture does not allow communication among constituent caches, a page request to the “wrong” cache will result in a miss every time. This “wrong” cache will never cache the object because it does not belong to the subset of web objects it manages. If this cache does communicate with the other constituent caches, the request will be redirected to the “correct” proxy. In this case the second problem - that of never caching the object - disappears, but in its place we have a new performance issue: web object requests will face the added latency of being routed through the partitioned cache network because the user has an incorrect mapping from objects to caches. This has been addressed as both a theoretical problem [52] and as a performance problem observed in experiments [35].

A collective cache capable of routing requests internally has a much freer hand in dealing with the server swamping problem. These systems do not have the static assignments that proved troublesome for isolated and partitioned caches. This is no guarantee that these systems will handle the swamping problem well. Several researchers have found that some collective caches do not avoid swamping any better partitioned and isolated caches. Specifically, experiments have found that early collective caches like Squid and Harvest have scalability problems dealing with swamping [32, 35, 89] Specifically, in [32] it is reported that many Internet Cache Protocol [92] based caches [11, 28, 41] face a cache-maintenance workload that is quadratic in cache size.

Karger et al. take a more rigorous approach to this problem in [52]. We note here that this paper describes the academic precursor to the Akamai system, which was designed by some of the same authors, and provides a good technical source of information on how Akamai presumably works. They begin by defining a random mapping among constituent caches, clients, objects and requests. Clients do not see the full set of constituent caches. Instead each client is presented with a “view” of the set of caches. This view may be significantly smaller than the true set of constituent caches, and may vary from client to client. Whatever the view, they consider random mappings with several properties:

- adding or removing caches from a view does not cause a “large” change in how client requests are assigned to constituent caches
- across all client’s views the number of constituent caches handling any individual object is small
- similarly, the number of objects handled by any individual constituent cache is as small as possible

If clients choose which entry point to the collective cache with such a mapping, they are able to prove probabilistic bounds on the load of any constituent cache. The result are statements of the form: with 95% confidence, no constituent cache will receive more than 75% of the load that it can handle. The reader is directed to the paper for a more technical treatment. The essential point here is that, under certain conditions, one can construct a collective cache that probabilistically solves the server swamping problem.

### 9.2.2 Minimizing Cache Storage Use

Distributed caches provide more total cached object storage space, but different proxy cache classes take advantage of the space in different ways. The isolated cache model, with  $N$  constituent caches, assumes  $N$  independent storage spaces for cache objects. The same object may be cached up to  $N$  times in the whole system. This is clearly not the most efficient possible use of space - but it is the best an isolated cache can do, since there is no communication among constituent caches. These caches make no attempt to minimize storage use; in exchange they do not pay any performance cost for maintaining a more efficient use of space.

At the other extreme are the partitioned caches. These caches are very efficient space users, since there is at most one copy of any cache object in the entire system at any one time [35]. This says nothing of the storage load balance across systems. If all requests are for the objects cached by a single constituent cache, that cache will likely fill up while all other constituent caches remain empty.

The more interesting cases are the collective caches. These systems have the internal communication facilities to be as space efficient as partitioned caches (and perhaps more so), but also can control the balance between space efficiency and performance. The performance gains possible from sharing the available space efficiently among constituent caches has been demonstrated in several studies [66, 89], where 50%-100% improvements in hit rate were observed when cached object replication was reduced to make space for the caching of more distinct web objects. Even systems where overall space efficiency was not a concern - and consequently did nothing to reduce cached object replication - demonstrated that the collective cache concept can increase performance [58].

There are proxy cache that dynamically control the balance between performance and space efficiency. The CRISP system [38] maintains a global list of all objects cached in all constituent caches with a “central mapping service”. This allows the cache to insure that no object is cached twice while still insuring that all requests for a cached object will result in a cache hit, regardless of which constituent cache receives the request. The cost of this service is added latency in servicing requests. The designers of CRISP provide two reasons they believe this is not a significant performance problem. In brief, they are:

- the mapping server can be made fast enough to add no user-perceived delay in object retrieval
- if the mapping server becomes a bottleneck, one can partition the mapping of URLs across a collection of mapping servers, similar to the partition proxy cache design

They concede that these conditions can only hold in a proxy cache environment where the constituent caches face low latency for communication with the mapping server. CRISP is only worth considering if your situation meets these criteria.

For a truly large-scale widely distributed web proxy cache a CRISP-like central-directory approach is not appropriate because such a situation does not meet any of the criteria listed above. We would much prefer to have provable bounds on per-constituent storage

requirements for a given number of web objects. Karger et. al. provide such a bound within their web proxy cache model [52]. In their case, again presumably the Akamai case, they prove that per-constituent cache storage grows with the log of total cached-content size with high confidence. The aforementioned random-assignment scheme is used to assign object to constituent caches. We are not guaranteed that each object is assigned to exactly one cache as we are with the partitioned case, but the mapping is restricted as above, and this allows one to prove this bound with high confidence.

Consequently, while this architecture may cache the same object twice - an inefficiency not permitted by some of the simpler distributed cache architectures discussed above - it does provide probabilistic guarantees that the cache is space-efficient overall while still addressing the server swamping problem. We also see this pair of properties in CRISP. Each of these architectures relies on a different mechanism to achieve these goals. The former relies on constructing a random mapping among objects, requests, clients and constituent caches; the later employs a central map, recording all cached objects on all constituent caches. Experiments have confirmed that the random mapping approach achieves better performance [51]. But the only implementations of this system that the authors are aware of are Akamai and the research prototypes used for experiments. CRISP and its derivative systems are freely available and widely used [78]. These systems also serve as the constituent caches of the NLANR global cache hierarchy[73]. Anyone is free to join this hierarchy, and thereby gain access to a large distributed cache system.

### 9.3 Supply and Demand Proxy Caches

Web proxy caches were originally conceived as systems to improve web access latency on the client side - to reduce the latency users experience when retrieving content [65, 91]. Recently proxy caches have appeared that aim to improve the performance of content distribution in addition to retrieval. We refer to this systems as demand-side (content retrieval) and supply-side (content distribution) similarly to [37].

There are many available demand-side caching packages which are installed at many sites around the world [78]. Facilities, like NLANR's Global Caching Hierarchy [73], exist that allow different sites to share caching resources. These systems are designed to increase performance by locating copies of requested objects within their cache structure more quickly than a user could retrieve them from the originating server. Sites that would like to use web caching to reduce web access latency and network traffic should look to demand-side web caching tools for assistance.

There is another type of proxy cache out there that aims to improve performance by reducing the load faced by web servers directly, by transferring the task of serving popular objects to other systems. These systems are known as Content Distribution Networks (CDNs). There are many examples available, including [44, 45, 46]. Unlike demand-side systems which cache objects as they are requested by users, CDN web proxy caching systems only cache objects for companies that pay for the space. Web sites that are cached by CDNs are modified so that web object links point to the proxy cache servers (i.e. so-called "internal" links on the CNN website point to servers in the akamai.com domain).

Content providers looking to improve performance or simply to outsource the job of content delivery, should look to these CDNs. While it impossible to know exactly how each of these commercial systems works, at least in the case of Akamai, we have access to the precursor academic literature that led to the development of the system. We discuss this work above, and again refer interested readers to [51] and [52] for a highly technical treatment. [Sandpiper and Mirror Image appear to have exploded, so no information is available. It doesn't seem like a good idea to leave only one example of a CDN.]

As a result of the formation of supply- and demand-side web caching systems, research has begun on the development of proxy caches designed to work between these two ends. Gadde et. al. introduce the interior cache concept in [37]. The most important conclusion of that paper is that CDNs do little to improve average web access latency when only a small fraction of web objects are served with supply-side caching. These results were obtained from measurements made with the NLANR Global Caching Hierarchy [73]. While this is not a true interior caching system, it is a very large demand-side cache, which the others of the paper assume extends into the interior portion of the web. Their work is of a modeling nature, and the authors are not aware of any specially designed interior caching systems at this time.

## 9.4 Meta-Architecture

When as user accesses the web, their object requests potentially pass through many levels of web caching including: browser caches, demand-side proxy caches, interior proxy caches, supply-side proxy caches and caching mechanisms within web servers. These caches are autonomous systems, and make caching decisions at their level without consulting the other web caches that may be involved in one particular object request. The reason for this freedom is simple: keeping such a large number of caches consistent would be extremely difficult and would likely kill most of the benefit from caching in the first place.

So what sequence of caches do we find when accessing information on the web? For low traffic sites, the answer is generally that only the browser cache comes into play. If the user accessing the information is configured to use a local proxy cache (this is a demand-side proxy cache), then a second level of caching comes in. When the web object being requested comes from a high traffic site, it is likely a more complex transaction. The user's request is first checked against the local browser cache. If that misses the local proxy cache is checked.

So far the path is identical for all web objects. If the proxy cache misses, it then needs to load the page from the originating server. This is where high-traffic sites can behave differently from low-traffic ones. If a site is using a supply-side caching service, there request must travel through more levels of caching before reaching the content. The proxy's attempt to load the page will then propagate through the supply-side cache until the content is found. This many involve communication within this proxy cache, as discussed above, including possibly retrieving a fresh copy of the object from the originating server. An experiment conducted by one of the authors revealed the following chain of events to access a page on the CNN web site:

- check against browser cache, miss
- check against local proxy cache, miss
- retrieve object from CNN (unknown caching within their web server) which is mainly pointers to Akamai
- send requests to Akamai to retrieve the “real” content, which are handled using Akamai's internal supply-side proxy caching algorithms

This listing ignores the cache-update process that takes place as the content travels up each level of the caching hierarchy (i.e. the browser cache probably caches a copy of the page once it has been retrieved, likewise for the local proxy cache, and so on down the list).

The potential for hybrid cache architectures is great. Even the simplest web proxy cache often plays the role of a single caching entity within a large, weakly consistent, distributed caching system. It might be the case that the only communication within this system takes



place as HTTP requests driven by user page-loads. But the entire collection of systems involved in delivering content to the user can be thought of as the constituents of a large caching system. And all of the caching taking place between the browser cache and the server's internal caching are part of the large, distributed proxy cache seen by the user.

Research into handling these large across-the-web systems is just beginning, but earlier work has demonstrated that both demand- and supply-side web proxy caches can increase overall system performance.

## 10 Performance Measurement

Using a benchmark, customers can not only test the performance of a proxy running on different software and hardware platforms, but also compare different proxy implementations and choose one that best matches the customer's requirements.

In this section, we mainly describe the Wisconsin Proxy Benchmark, Poly-graph and IRCache web cache performance bake-offs.

### 10.1 The Wisconsin Proxy Benchmark

The Wisconsin Proxy Benchmark (WPB) [3] was one of the first publicly available cache benchmarking tools. The main feature of WPB is that it tries to replicate the workload characteristics found in real-life Web proxy traces. WPB consists of Web client and Web server processes. First, it generate server responses whose sizes follow the heavy tailed Pareto distribution described in [22]. Since heavy-tail distribution of file sizes impact proxy behavior, it is important to include very large files with a non-negligible probability. As it must handle files with a wide range of sizes. Second, the benchmark generates a request stream that has the same temporal locality as those found in real proxy traces. Third, Since the benchmark is often run in a local area network and there is no nature way to incur long latencies when fetching documents from the servers, the benchmark let the server process delay sending back responses to the proxy to emulate Web server latency. However, Web server latencies affect the resource requirements at the proxy system. Thus, the benchmark supports configurable server latencies in testing proxy systems.

The main performance data collected by the benchmark are latency, proxy hit ratio, byte hit ratio, and number of client errors. There is no single performance number since different environments weight the four performance metrics differently. Proxy throughput is estimated to be the request rate dividing by the request latency.

#### 10.1.1 The distinguishing features of WPB

- Support for studying the effect of adding disk arms

Using WPB, the impact of spreading the cached files over multiple disks on proxy performance has been analysed. The simulation results indicate that disk is the main bottleneck during the operation of busy proxies. Adding an extra disk reduces the bottleneck in the disk.

- Effect of handling lowbandwidth (modem-based) clients

The impact of low bandwidth connections on proxy performance has been analysed. A modem emulator which introduces delays to each IP packet transmitted in order to achieve a certain effective bandwidth that is smaller than the one provided by the network connection.

#### 10.1.2 Some interesting findings through use of WPB

- By increasing the number of disks, queueing overheads are reduced, the time spent servicing each disk request are also shortened. To some proxy caching systems, this also reflects on the overall performance of the proxy.
- Latency advantages due to caching are essentially erased when considering the overall profit to modem-based clients.

While WPB addresses a number of important benchmarking requirements, such as initial support for temporal processes, it has some limitations. These include lack of support for modeling spatial locality, persistent HTTP 1.1 connections, DNS lookups, and realistic URLs.

## 10.2 Polygraph

Polygraph [82, 10] is a recently developed, publicly available cache benchmarking tool developed by NLANR. It can simulate web clients and servers as well as generate workloads that try to mimic typical Web access. Polygraph can be configured to send HTTP requests through a proxy. High-performance simulation allows to stress test various proxy components. The benchmarking results can be used for tuning proxy performance, evaluation of caching solutions, and for many other interesting activities.

Polygraph has a client and a server component, each of which uses multiple threads to generate or process requests. This allows Polygraph to simulate concurrent requests from multiple clients to multiple servers. Polygraph can generate different types of workload to simulate various types of content popularity. For example, requests can be generated which obey a Zipf-like distribution, which is largely believed to be a good estimate of real web usage patterns[14].

### 10.2.1 Distinguishing features of Polygraph

- It is capable of generating a whole spectrum of Web proxy workloads that either approximate real-world traffic patterns, or are designed to stress a particular proxy component.
- Polygraph is able to generate complex, high request rate workloads with negligible overhead.

Polygraph is a high performance cache benchmarking tool. It can evaluate the performance of various caching systems, using cache-specific performance metrics, such as amount of bandwidth saved, response time, hit rate, and various scalability metrics.

More recently, Polygraph has been playing an increasing role in holding open benchmark Web Caching Bake-off's as a way of inspiring the development community and encouraging competition towards good caching solutions. A summary of their study comparing a number of commercial and academic systems can be found at [84].

## 10.3 IRCache Web Cache performance bake-offs

Bake-off [84, 85, 83] implies testing several independent implementations of similar products, taking place within a short period of time and usually at the same location. Every product is tested under the same conditions. Bake-off results are used to evaluate the performance of Web caching proxies.

### 10.3.1 Why Bake-offs

- Fair Competition  
Test labs, audited on-site tests, and even SPEC-like reports are considered to be “fair”. That is, they give equal opportunities to participants to win. So what makes Caching bake-offs special?

The primary reason is highly competitive and unstable environment. New product releases and even companies appear virtually every month. Benchmarking workload improvements are also quite common. In such atmosphere, two test results obtained a few month apart are by default unfair to compare. A vendor who gets the last test “slot”, essentially has a big advantage over the vendor who opened the test sequence. Thus, we have to test a lot of products in a short time interval.

- Test auditing

Web proxy benchmarking often requires complex test setup that involves many sophisticated components. Our experience shows that expertise and a lot of extra effort is required to guarantee the correctness of the setup. The auditing requires physical presence of the auditor during all stages of the tests.

### 10.3.2 Web Polygraph

Polygraph is a high-performance proxy benchmark. It can generate about 1000 requests per second between a client-server pair on a 100baseT network. Furthermore, Polygraph allows you to specify a number of important workload parameters such as hit ratio, cachability, response sizes, and server-side delays.

The cache-off Workload is PolyMix-3. The advantage of PolyMix-3 is that the device under test is more likely to have steady state conditions during the measurement phases. Also PolyMix-3 servers use a Zipf(16) distribution to close active connections. The servers also timeout idle persistent connection after 15 sec of inactivity, just like many real servers would do.

In order to compare the performance of different caching products under identical conditions, we proposed to hold a “bake-off”. The basic idea is that everyone comes together for a few days in one location and puts their products through a series of tests. Because all tests occur at the same time and place, under identical conditions, comparisons can be made between the participant’s results.

Simulation results have shown that the Bake-off is a high quality, independent verification of product performance in the proxy caching community.

## 11 Conclusion

As an approach to improve the web service performance, the technique of proxy caching effectively reduces the network traffic, improves server availability and minimize the user access latency. In this chapter, we introduce the functionality of proxy caches, highlight the important issues to in studying proxy caching. Among these topics, performance, consistency policy, replacement policy and cacheability are the most basic issues that need to be considered in building any proxy cache. Prefetching, dynamic content caching and stream caching are techniques studied by a lot of researchers to improve the performance of proxy caching. When a set of proxy caches are configured to work together, the architecture and coordination of caches add to another important issue in proxy cache design. All the above issues have been and still remain to be the active subjects of significant academic research and commercial development.

In the long run, as the latency of network transfer continues to drop, someone might doubt the usefulness of web caching. However, since the interest of web users will remain skewed, and the demands for bandwidth is still increasing fast, web caching can still alleviate the server bottleneck, and improve the resource availability. Even maybe low, bandwidth will always remain some cost, and communication is always likely to be more expensive than computation, thus caching will continue to be helpful as network get faster.



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