Computer Networks - Chapter 2 (Book)

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2. Application Layer

2.2 The Web and HTTP

2.2.1 Overview of HTTP

The `HyperText Transfer Protocol (HTTP)`, the Web's application-layer protocol, is at the heart of the Web. The client program and server program, which both implement HTTP, talk to each other by exchanging HTTP messages. HTTP defines the structure of these messages and how the client and server exchange the messages.

A `Web page` consists of objects. An `object` is simply a file - such as an HTML file, a JPEG image, or a video clip - that is addressable by a single URL.

Because `Web browsers` implement the client side of HTTP, we will use the words *browser* and *client* interchangeably. `Web servers`, which implement the server side of HTTP, house Web objects, each addressable by a URL.

When a user requests a Web page, the browser sends HTTP request messages for the objects in the page to the server. The server receives the requests and responds with HTTP response messages that contain the objects. HTTP uses TCP as its underlying transport protocol.

It is important to note that the server sends requested files to clients without storing any state information about the client. Because an HTTP server maintains no information about the clients, HTTP is said to be a `stateless protocol`.

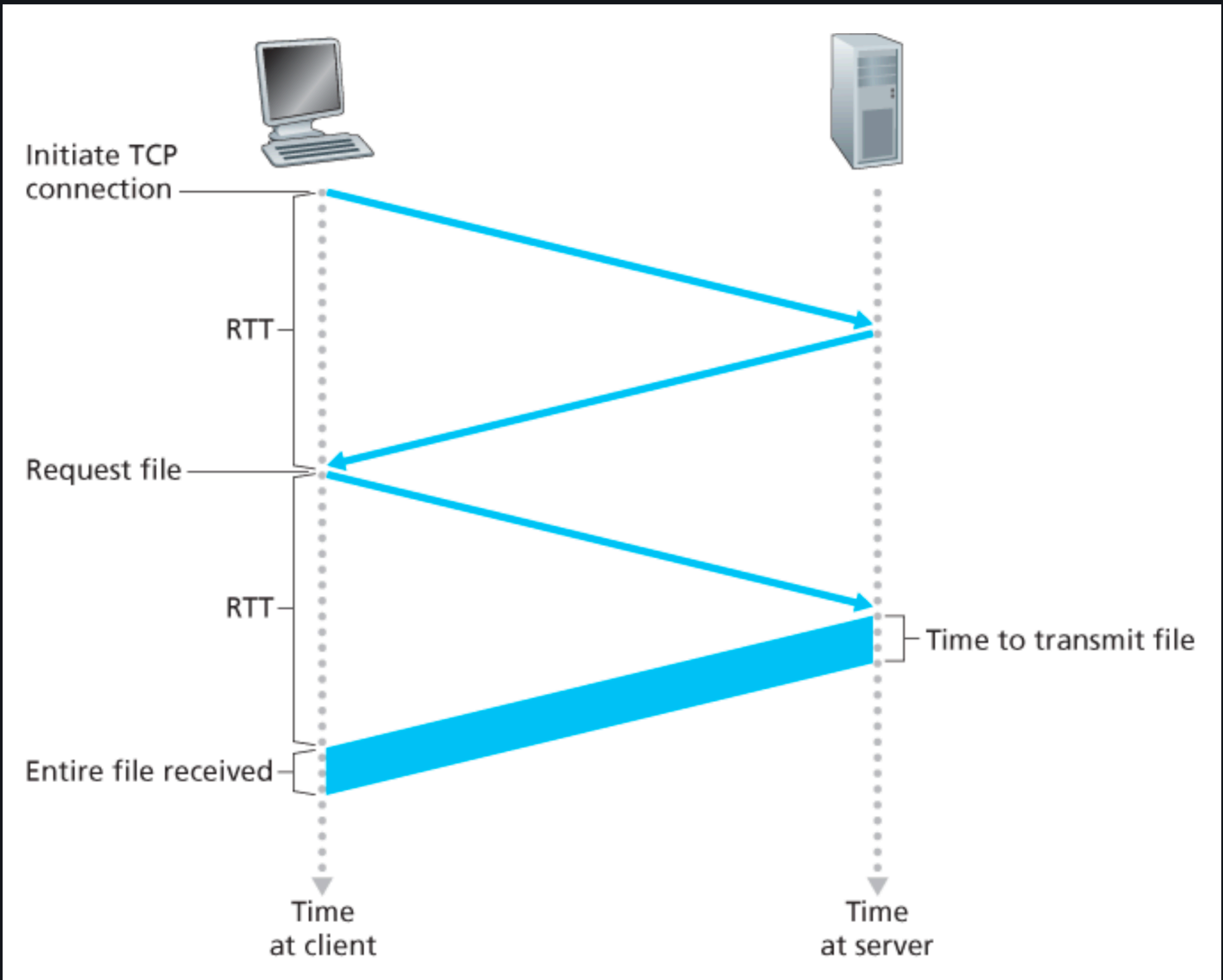
2.2.2 Non-Persistent and Persistent Connections

When the client-server interaction is taking place over TCP, the application developer needs to make a decision - should each request/response pair be sent over a *separate* TCP connection, or should all of the requests and their corresponding responses be sent over the *same* TCP connection? In the former approach, the application is said to use `non-persistent connections`; and in the latter approach, `persistent connections`.

HTTP with Non-Persistent Connections

Let's suppose a Web page consists of a base HTML file and 10 JPEG images, and that all 11 of these objects reside on the same server. Assume non-persistent connections, where each TCP connection is closed after the server sends the object - the connection does not persist for other objects. Thus, in the assumed example, when a user requests the Web page, 11 TCP connections are generated.

To this end, we define the `round-trip time (RTT)`, which is the time it takes for a small packet to travel from client to server and then back to the client. The RTT includes packet-propagation delays, packet-queuing delays in intermediate routers and switches, and packet-processing delays.



Thus, roughly, the `total response time` is two RTTs plus the transmission time at the server of the HTML file.

HTTP with Persistent Connections

Non-persistent connections have some shortcomings:

1. For each connection (aka for each object), TCP buffers must be allocated and TCP variables must be kept in both the client and server. This can place a significant burden on the Web server.
2. Each object suffers a delivery delay of two RTTs - one RTT to establish the TCP connection and one RTT to request and receive an object.

With HTTP 1.1 persistent connections, the server leaves the TCP connection open after sending a response. Subsequent requests and responses between the same client and server can be sent over the same connection. Typically, the HTTP server closes a connection when it isn't used for a certain time.

The default mode of HTTP uses persistent connections with pipelining.

2.2.3 HTTP Message Format

The HTTP specifications include the definitions of the HTTP message formats. There are two types of HTTP messages, request messages and response messages.

HTTP Request Message

Below we provide a typical HTTP request message:

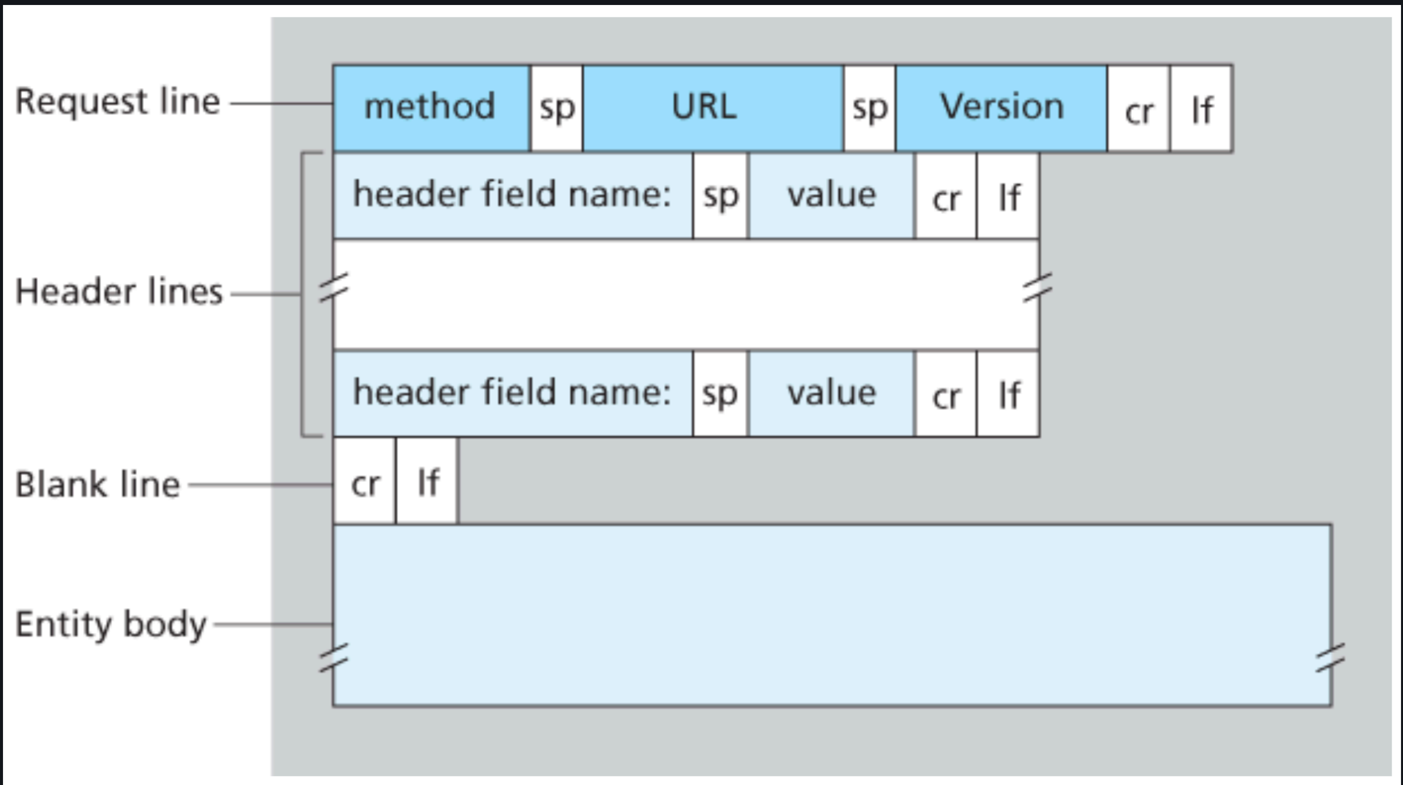
```
GET /somedir/page.html HTTP/1.1
Host: www.someschool.edu
Connection: close
User-agent: Mozilla/5.0
Accept-language: fr
```

Although this particular request message has five lines, a request message can have many more lines or as few as one line. The first line of an HTTP request message is called the `request line`; the subsequent lines are called the `header lines`. The request line has three fields: the method field, the URL field, and the HTTP version field. The method field can take on several different values, including `GET`, `POST`, `HEAD`, `PUT`, and `DELETE`.

Let's look closer at the header lines in the example:

- `Host`: specifies the host on which the object resides
- `Connection: close`: tells the server that it doesn't bother with persistent connections
- `User-agent`: specifies the user agent, that is, the browser type making the HTTP request
- `Accept-language`: indicates that the user prefers to receive a French version of the object, if such an object exists on the server

The general form of an HTTP request message looks as follows:



The `HEAD` method is similar to the `GET` method with the difference being, that the sever responds only with an HTTP message and leaves out the requested object (often used for debugging).

The `PUT` method is often used in conjunction with Web publishing tools and forms. It allows a user to upload an object to a specific path on a specific Web server.

The `DELETE` method allows a user, or an application, to delete an object on a Web server.

HTTP Response Message

The HTTP response message below could be the response to the example request message from above:

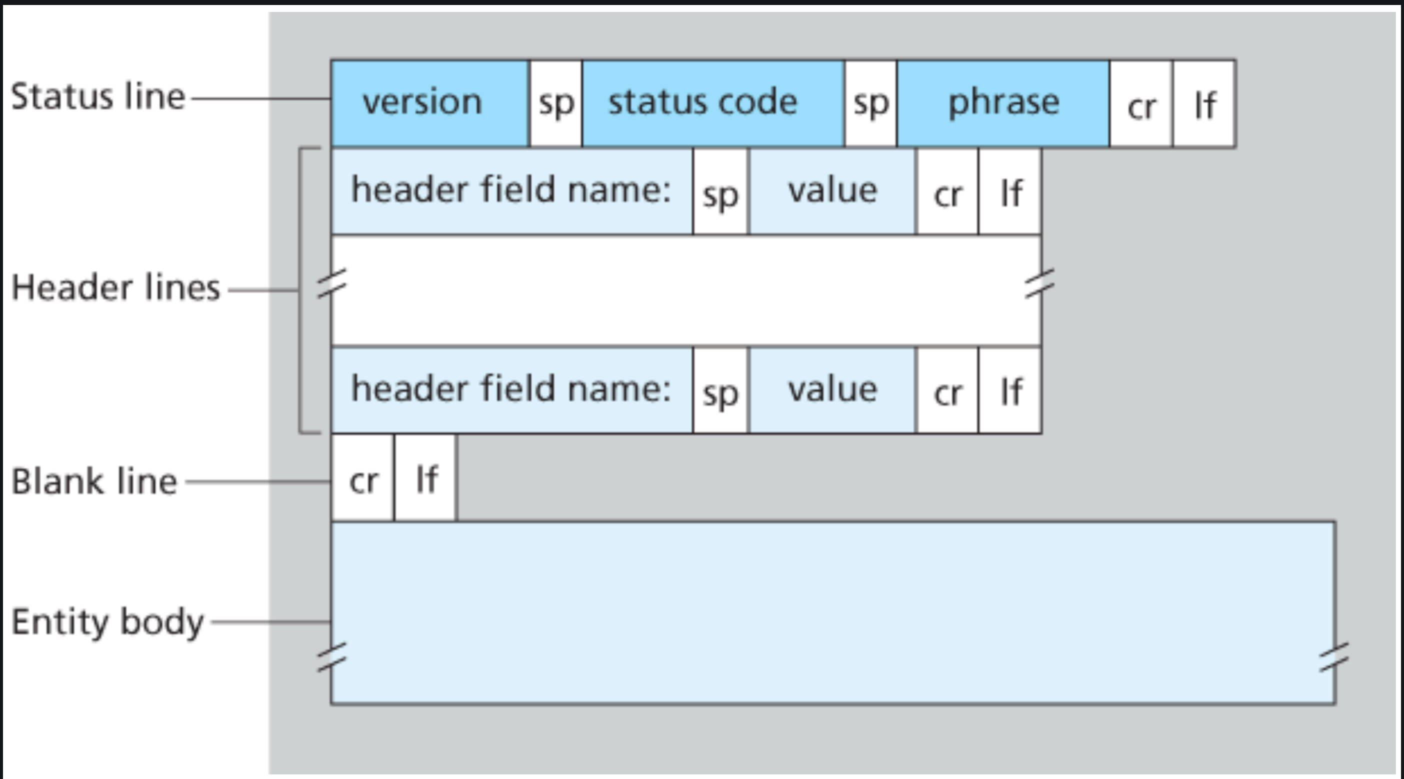
```
HTTP/1.1 200 OK
Connection: close
Date: Tue, 18 Aug 2015 15:44:04 GMT
Server: Apache/2.2.3 (CentOS)
Last-Modified: Tue, 18 Aug 2015 15:11:03 GMT
Content-Length: 6821
Content-Type: text/html

(data data data data data ...)
```

The message has three sections: an initial `status line`, six `header lines`, and then the `entitiy body`. The entitiy body contains the requested object itself. The status line has three fields: the protocol version field, a status code, and a corresponding status message.

Let's look closer at the header lines of our example:

- `Connection: close` : indicates that the server is going to close the TCP connection after sending the message
- `Date` : indicates the time and date when the HTTP response was created and sent by the server
- `Server` : indicates that the message was generated by an Apache Web server
- `Last-Modified` : indicates the date and time when the object was created or last modified
- `Content-Length` : indicates the number og bytes in the object being sent
- `Content-Type` : indicates that the object in the entity body is HTML text



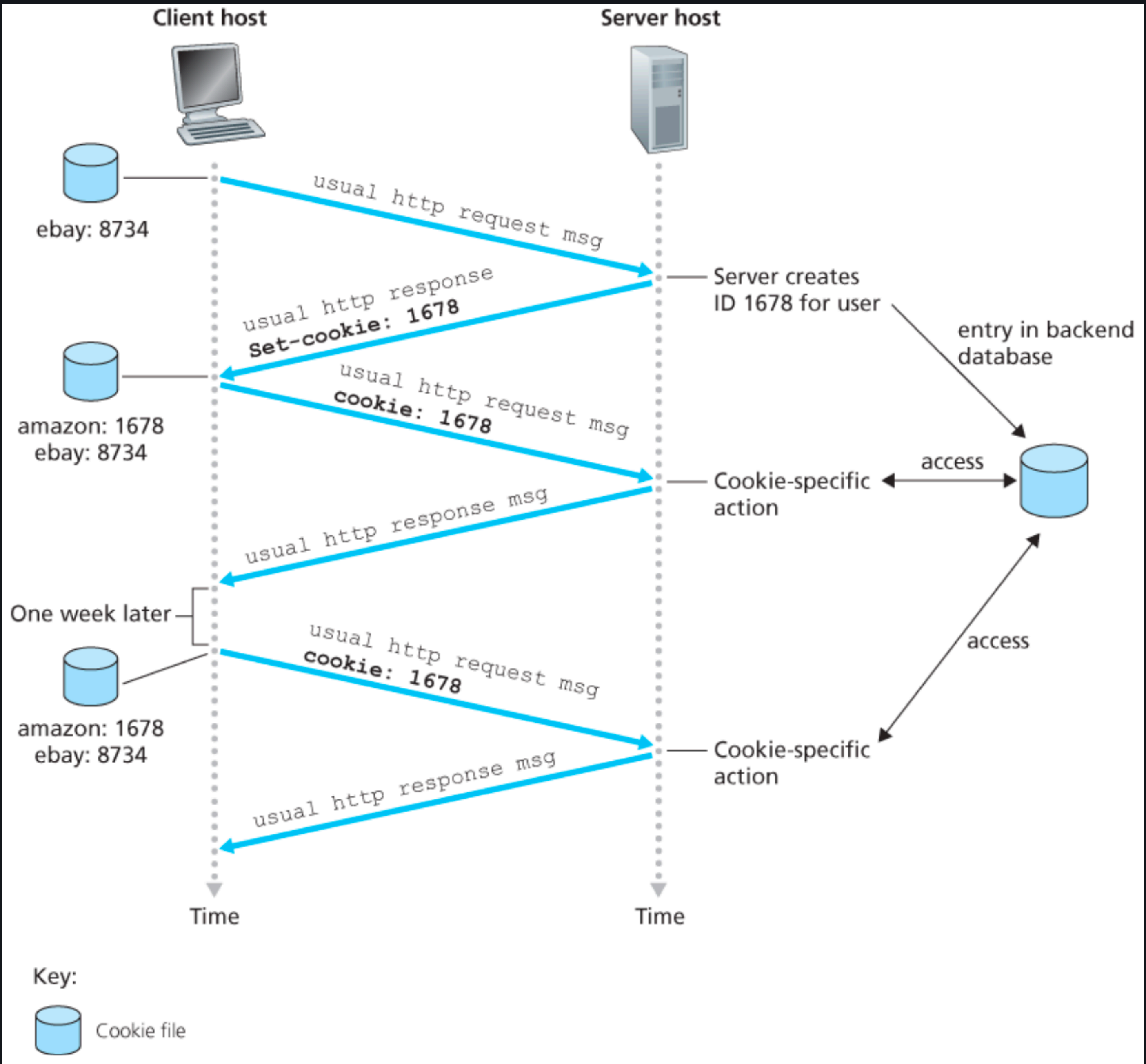
Some common status codes and associated phrases include:

- `200 OK` : Request succeeded and the information is returned in the response.
- `301 Moved Permanently` : Requested object has been permanently moved, the new URL is specified in `Location` header of the response message.
- `400 Bad Request` : Generic error code indicating that the request could not be understood by the server.
- `404 Not Found` : The requested document does not exists on this server.
- `505 HTTP Version Not Supported` : The requested HTTP protocol version is not supported by the server.

2.2.4 User-Server Interaction: Cookies

We mentioned above that an HTTP server is stateless. However, it is often desireable for a Web site to identify users, either because the server wishes to restrict user access or beause it wants to serve content as a function of the user identity. For these purposes, HTTP uses `cookies` .

Cookie technology has four components: (1) a cookie header line in the HTTP response message, (2) a cookie header line in the HTTP request message, (3) a cookie file kept on the user's end system and managed by the user's browser, and (4) a back-end database at the Web site.



Suppose Susan contacts `Amazon.com` for the first time. When the request comes in, the Amazon Web server creates a unique identification number for Susan and stores it in its back-end database. The Amazon Web server then responds to Susan's browser, including in the HTTP response a `Set-cookie` header, which contains the id number. The header might be:

```
Set-cookie: 1678
```

As Susan continues to browse the Amazon site, each time she requests a Web page, her browser consults her cookie file, extracts her id number for this site, and puts a cookie header linea in the HTTP request as follows:

```
Cookie: 1678
```

Although the Amazon Web site does not encessarily know Susan's name, it knows exactly which pages user 1678 visited, in which order, and at what times!

2.2.5 Web Caching

A `Web cache` - also called a `proxy server` - is a network that satisfies HTTP requests on the behalf of an origin Web server. The Web cache has its own disk storage and keeps copies of recently requested objects in this storage.

Typically a Web cache is purchased and installed by an ISP. For example, a university might install a cache on its campus network and configure all of the campus browsers to point to the cache.

There are two main reasons to deploy Web caching in the Internet:

1. A Web cache can substantially reduce the response time for a client request.
2. Web caches can substantially reduce traffic on an institution's access link to the Internet.

The Conditional GET

HTTP has a mechanism that allows a cache to verify that its objects are up to date. This mechanism is called the `conditional GET`. An HTTP request message is a so-called conditional GET message if (1) the request message uses the `GET` method and (2) the request message includes an `If-Modified-Since` header line.

Let's walk through an example: First, on behalf of a requesting browser, a proxy cache sends a request message to a web server:

```
GET /fruit/kiwi.gif HTTP/1.1
Host: www.exotiquecuisine.com
```

Second, the Web server sends a response message with the requested object to the cache:

```
HTTP/1.1 200 OK
Date: Sat, 3 Oct 2015 15:39:29
Server: Apache/1.3.0 (Unix)
Last-Modified: Wed, 9 Sep 2015 09:23:24
Content-Type: image/gif

(data data data data data ...)
```

Third, one week later, another browser requests the same object via the cache. The cache performs an up-to-date check by issuing a conditional GET. Specifically, the cache sends:

```
GET /fruit/kiwi.gif HTTP/1.1
Host: www.exotiquecuisine.com
If-modified-since: Wed, 9 Sep 2015 09:23:24
```

Suppose the object has not been modified since 9 Sep 2015 09:23:24. Then, fourth, the Web server sends a response message to the cache:

```
HTTP/1.1 304 Not Modified
Date: Sat, 10 Oct 2015 15:39:29
Server: Apache/1.3.0 (Unix)

(empty entity body)
```

2.4 DNS - The Internet's Directory Service

Just as humans can be identified in many ways, so too can Internet hosts. One identifier for a host is its `hostname`. But because those consist of variable-length alphanumeric characters, they would be difficult to process by routers. For these reasons, hosts are also identified by so-called `IP addresses`.

An IP address consists of four bytes in a hierarchical structure. An IP address looks like `121.7.106.83`, where each period separates one of the bytes expressed in decimal notation from `0` to `255`.

2.4.1 Services Provided by DNS

We have just seen that there are two ways to identify a host - by a hostname and by an IP address. This fact results in a need of a directory service that translates hostnames to IP addresses. This is the main task of the Internet's `domain name system (DNS)`.

The DNS is (1) a distributed database implemented in a hierarchy of `DNS servers`, and (2) an application-layer protocol that allows hosts to query the distributed database. The DNS protocol runs over UDP and uses port 53.

DNS provides a few other important services in addition to translating hostnames to IP addresses:

- `Host aliasing`: A host with a complicated hostname can have one or more alias names. For example, `relay1.west-coast.enterprise.com` could have an alias such as `enterprise.com`. In this case, the first hostname is called the `canonical hostname`.
- `Mail server aliasing`: DNS can be invoked by a mail application to obtain the canonical hostname for a supplied alias hostname as well as the IP address of the host.
- `Load distribution`: DNS is also used to perform load distribution among replicated servers, such as replicated Web servers. For replicated Web servers, a set of IP addresses is thus associated with one canonical hostname.

2.4.2 Overview of How DNS Works

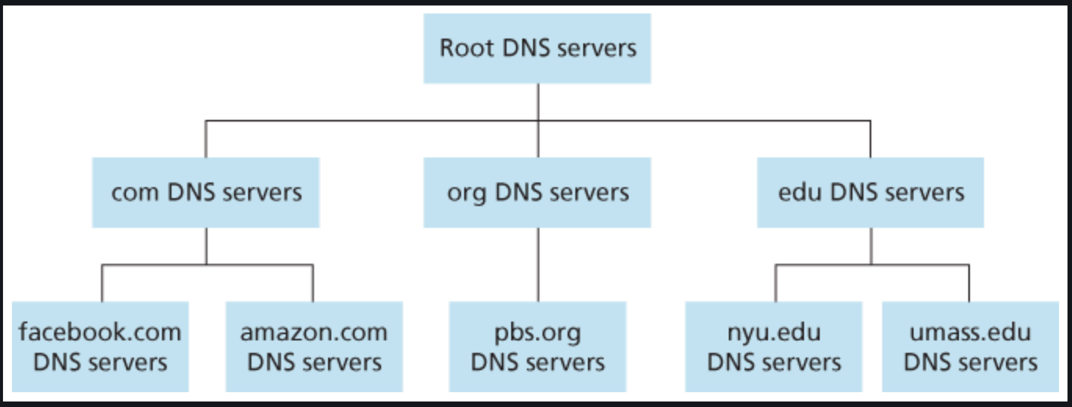
Suppose some application needs to translate a hostname that needs to be translated. The application will invoke the client side of DNS, specifying the hostname that needs to be translated. DNS in the user's host then takes over, sending a query message into the network. After a delay, DNS in the user's host receives a DNS reply message that provides the desired mapping.

A simple design for DNS would have one DNS server that contains all the mappings. The problem with this `centralized design` include:

- *Single point of failure*: If the DNS server crashes, so does the Internet.
- *Traffic volume*: A single DNS would have to handle all DNS queries.
- *Distant centralized database*: A single DNS server cannot be "close" to all the querying clients.
- *Maintenance*: The single DNS server would have to keep records for all Internet hosts.

A Distributed, Hierarchical Database

In order to deal with the issue of scale, the DNS uses a large number of servers, organized in a hierarchical fashion distributed around the world. To a first approximation, there are three classes of DNS servers - root DNS servers, top-level domain (TLD) DNS servers, and authoritative DNS servers - organized in a hierarchy as show in the figure below:

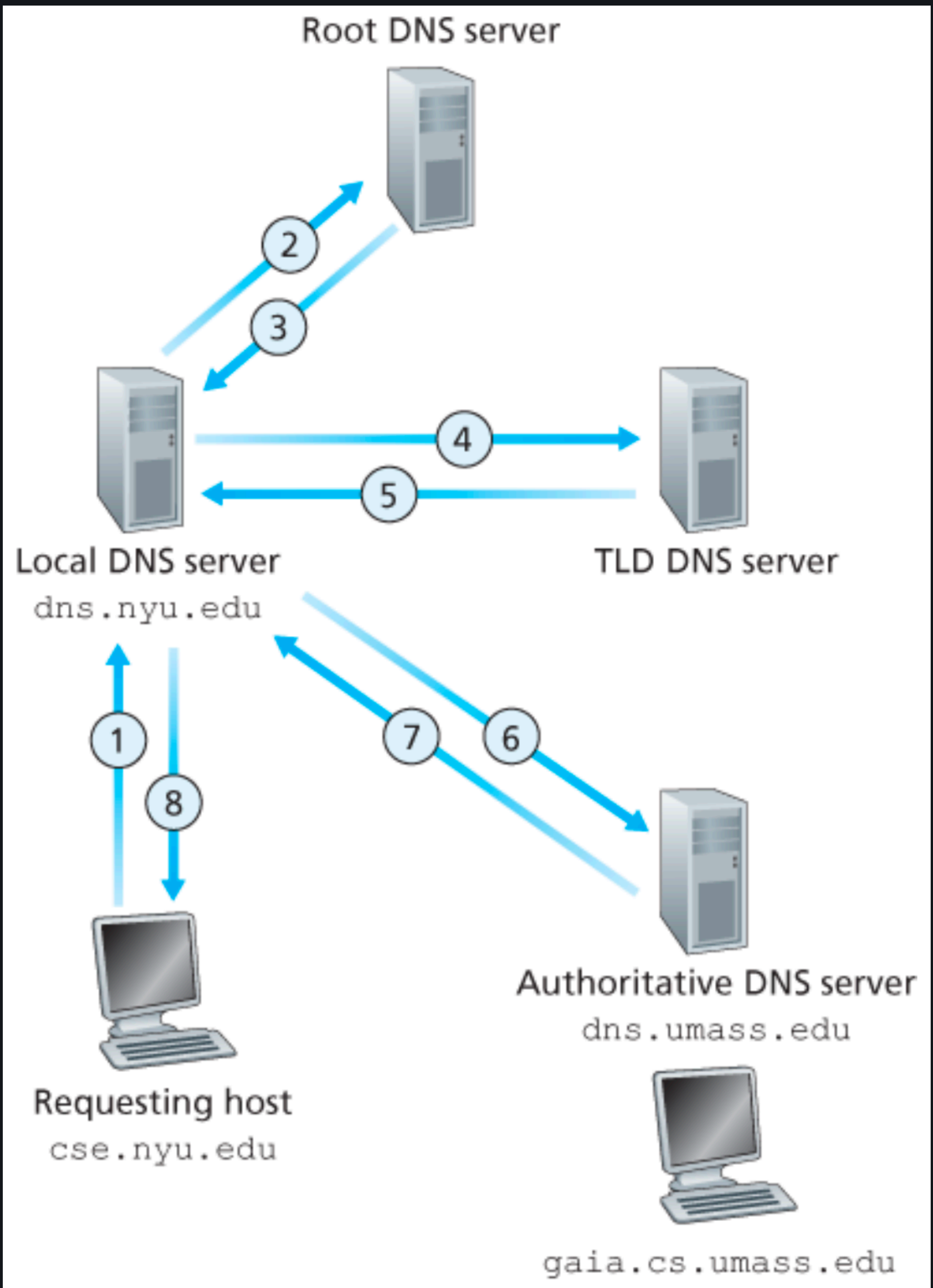


Let's take a closer look at these three classes of DNS servers:

- `Root DNS servers` : There are over 400 root name servers scattered all over the world. These root name servers are managed by 13 different organizations.
- `Top-level domain (TLD) servers` : For each of the top-level domains - such as `.com` , `.org` , or `.edu` - there is a TLD server (or server cluster).
- `Authoritative DNS servers` : Every organization with publicly accessible hosts on the Internet must provide publicly accessible DNS records that map the names of those hosts to IP addresses.

There is also another important type of DNS server called the `local DNS server` . A local DNS server does not strictly belong to the hierarchy of servers but is nevertheless central to the DNS architecture. Each ISP - such as a residential ISP or an institutional ISP - has a local DNS server.

Let's look at an example where the host `cse.nyu.edu` desires the IP address of `gaia.cs.umass.edu` . Then the sent queries are shown in the picture below:



The example above makes use of both `recursive queries` and `iterative queries`. The query *(1)* is a recursive query, since it asks `dns.nyu.edu` to obtain the mapping on its behalf. The subsequent queries are all iterative since all of the replies are directly returned to `dns.nyu.edu`.

DNS Caching

The idea behind `DNS caching` is very simple. In a query chain, when a DNS server receives a DNS reply, it can cache the mapping in its local memory. If a hostname/IP address pair is cached in a DNS server and another query arrives to the DNS server for the same hostname, the DNS server can provide the desired IP address, even if it is not authoritative for the hostname.

A local DNS server can also cache the IP address of TLD servers, thereby allowing the local DNS server to bypass the root DNS servers in a query chain.

2.4.3 DNS Records and Messages

The DNS servers that together implement the DNS distributed database store `resource records (RRs)`, including RRs that provide hostname-to-IP address mappings.

A resource record is a four-tuple that contains the following fields:

```
(Name, Value, Type, TTL)
```

`TTL` is the time to live of the resource record. It determines when a resource should be removed from a cache. The meaning of `Name` and `Value` depend on `Type`:

- `Type = A`: Then `Name` is a hostname and `Value` is the IP address for the hostname. Thus, a Type A record provides the standard hostname-to-IP address mapping. Example: `(relay1.bar.foo.com, 145.37.93.126, A)`
- `Type = NS`: Then `Name` is a domain and `Value` is the hostname of an authoritative DNS server that knows how to obtain the IP addresses for hosts in the domain. Example: `(foo.com, dns.foo.com, NS)`
- `Type = CNAME`: Then `Value` is the canonical hostname for the alias hostname `Name`. Example: `(foo.com, realy1.bar.foo.com, CNAME)`
- `Type = MX`: Then `Value` is a canonical hostname for the alias hostname `Name`. Note that by using the MX record, a company can have the same aliased name for its mail server and for one of its other servers.

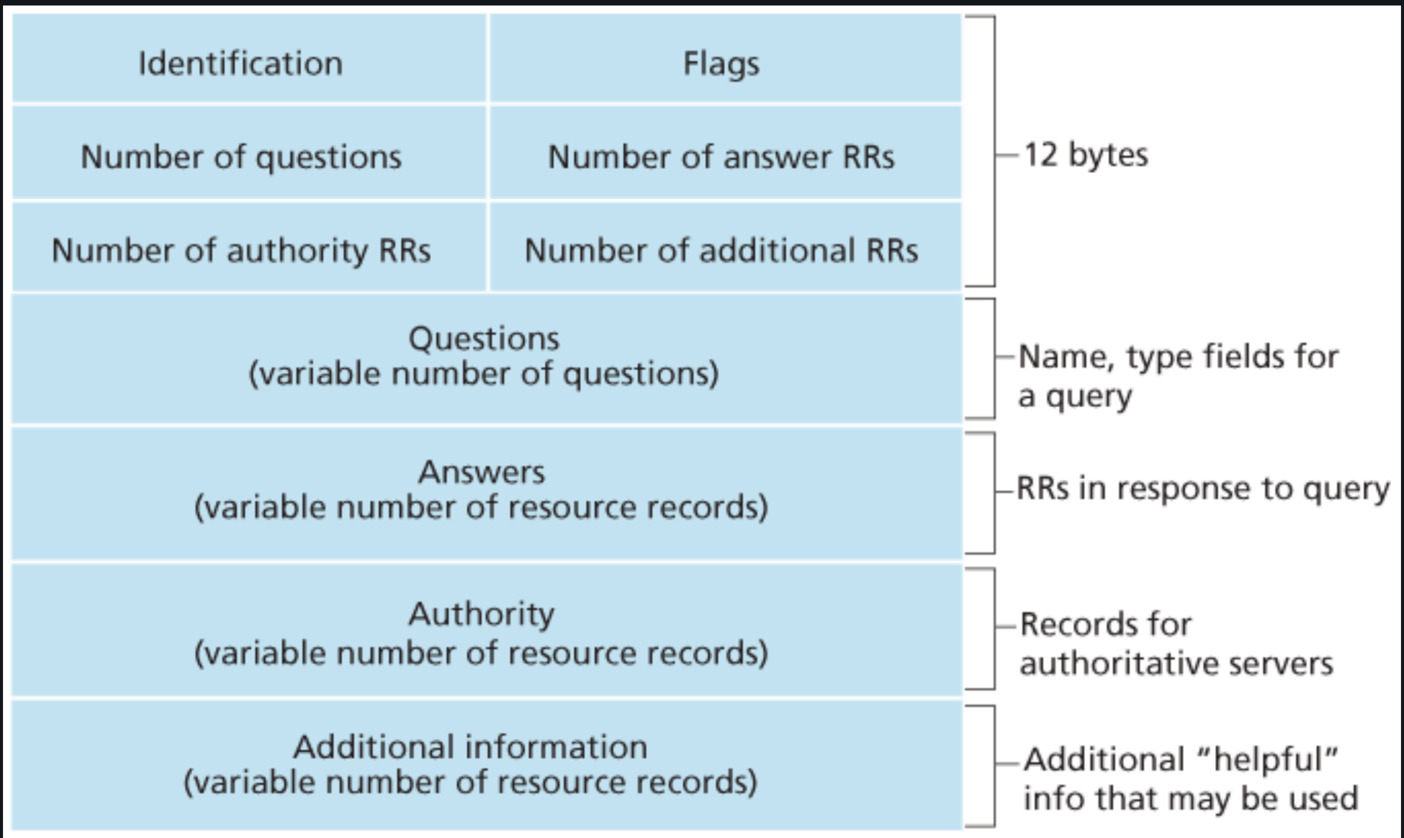
If a DNS server is authoritative for a particular hostname, then the DNS server will contain the Type A record for the hostname. If a server is not authoritative for a hostname, then the server will contain a Type NS record for the domain that includes the hostname. It will also contain a Type A record that provides the IP address of the DNS server in the `Value` field of the NS record.

DNS Messages

Earlier in this section, we referred to DNS query and reply messages. These are the only two kinds of DNS messages.

- The first 12 bytes is the `header section`, which has a number of fields. The first field is a 16-bit number that identifies the query.

- Furthermore there are a number of flags in the `flag field`:
    - 1-bit query/reply flag indicates whether the message is a query (0) or a reply (1)
    - 1-bit authoritative flag is set in a reply message when a DNS server is authoritative for the queried name
    - 1-bit recursion-desired flag, set when a client desires that the DNS server performs recursion when it doesn't have the record.
    - 1-bit recursion-available field, set in a reply if the DNS server supports recursion.
- In the header, there are also four `number-of fields`. These fields indicate the number of occurences of the four types of data sections that follow the header.
- The `question section` contains information about the query that is being made. This section includes (1) a name field that contains the name that is being queried, and (2) a type field that indicates the type of question being asked about the name.
- In a reply from a DNS server, the `answer section` contains the resource records for the name that was originally queried. A reply can return multiple RRs in the answer, since a hostname can have multiple IP addresses.
- The `authority section` contains records of other authoritative servers.
- The `additional section` contains other helpful records.



Inserting Records into the DNS Database

A `registrar` is a commercial entity that verifies the uniqueness of the domain name, enters the domain name into the DNS database.

When you register, let's say, the domain name `networkutopia.com` with some registrar, you also need to provide the registrar with the names and IP addresses of your primary and secondary authoritative DNS servers. For each of these two authoritative DNS servers, the registrar would then make sure that a Type NS and a Type A record are entered into the TLD com servers:

```
(networkutopia.com, dns1.networkutopia.com, NS)
(dns1.networkutopia.com, 212.212.212.1, A)
```

2.6 Video Streaming and Content Distribution Networks

2.6.1 Internet Video

A `video` is a sequence of images, typically being displayed at a constant rate, for example, at 24 or 30 images per second. An uncompressed, digitally encoded image consists of an array of pixels, with each pixel encoded into a number of bits to represent luminance and color.

Today's off-the-shelf compression algorithms can compress a video to essentially any bit rate desired. Of course, the higher the bit rate, the better the image quality and the better the overall user viewing experience.

2.6.2 HTTP Streaming and DASH

In `HTTP streaming`, the video is simply stored at an HTTP server as an ordinary file with a specific URL. When the user wants to see the video, the client establishes a TCP connection with the server and issues an HTTP `GET` request for that URL. On the client side, the bytes are collected in a client application buffer. Once the number of bytes in this buffer exceeds a predetermined threshold, the client application begins playback.

This approach has a major shortcoming: All clients receive the same encoding of the video, despite the large variations in the amount of bandwith available to a client.

This lead to the developement of a new type of HTTP-based streaming, often referred to as `Dynamic Adaptive Streaming over HTTP (DASH)`. In DASH, the video is encoded into several different versions, with each version having a different bit rate. The client dynamically requests chunks of video segments of a few seconds in length. DASH also allows a client to adapt to the available bandwidth if the available end-to-end bandwidth changes during the session. With DASH, each video is stored on the HTTP server, each with different URL. The HTTP server also has a `manifest file`, which provides a URL for each version along with its bit rate.

2.6.3 Content Distributed Networks

For an Internet video company, perhaps the most straightforward approach to providing streaming video service is to build a single massive data center and stream the videos directly from the data center to clients worldwide. This approach has three major probles though:

1. If the client is far from the data center, packets will cross many communication links. If one of these links provides a throughput that is less than the video consumption rate, then so will the end-to-end throughput be.
2. Popular videos will likely be sent many times over the same communication links. Not only will this waste network bandwidth, but the Internet video company will be paying its provider ISP for sending the same bytes into the Internet over again.
3. A single data center represents a single point of failure - if the data center goes down, it would not be able to distribute any video streams.

Therefore, almost all major video-streaming companies make use of `Content Distribution Networks (CDNs)`. A CDN manages servers in multiple geographically distributed locations and attempts to direct user requests to a CDN location that will provide the best user experience.

The CDN may be a `private CDN`, that is, owned by the content provider itself, or a `third-party CDN` that distributes content on behalf of multiple content providers.

CDNs typically adopt one of two different server placement philosophies:

- `Enter Deep`: One philosophy is to *enter deep* into the access networks of Internet Service Providers, by deploying server clusters in access ISPs all over the world. The goal is to get close to end users, thereby improving user-perceived delay at the cost of higher maintenance.
- `Bring Home`: A second philosophy is to *bring the ISPs home* by building large clusters at a smaller number of sites. Instead of getting inside the access ISPs, these CDNs typically place their clusters in Internet Exchange Points (IXPs). This results in lower maintenance and management overhead, possibly at the expense of higher delay and lower throughput to end users.

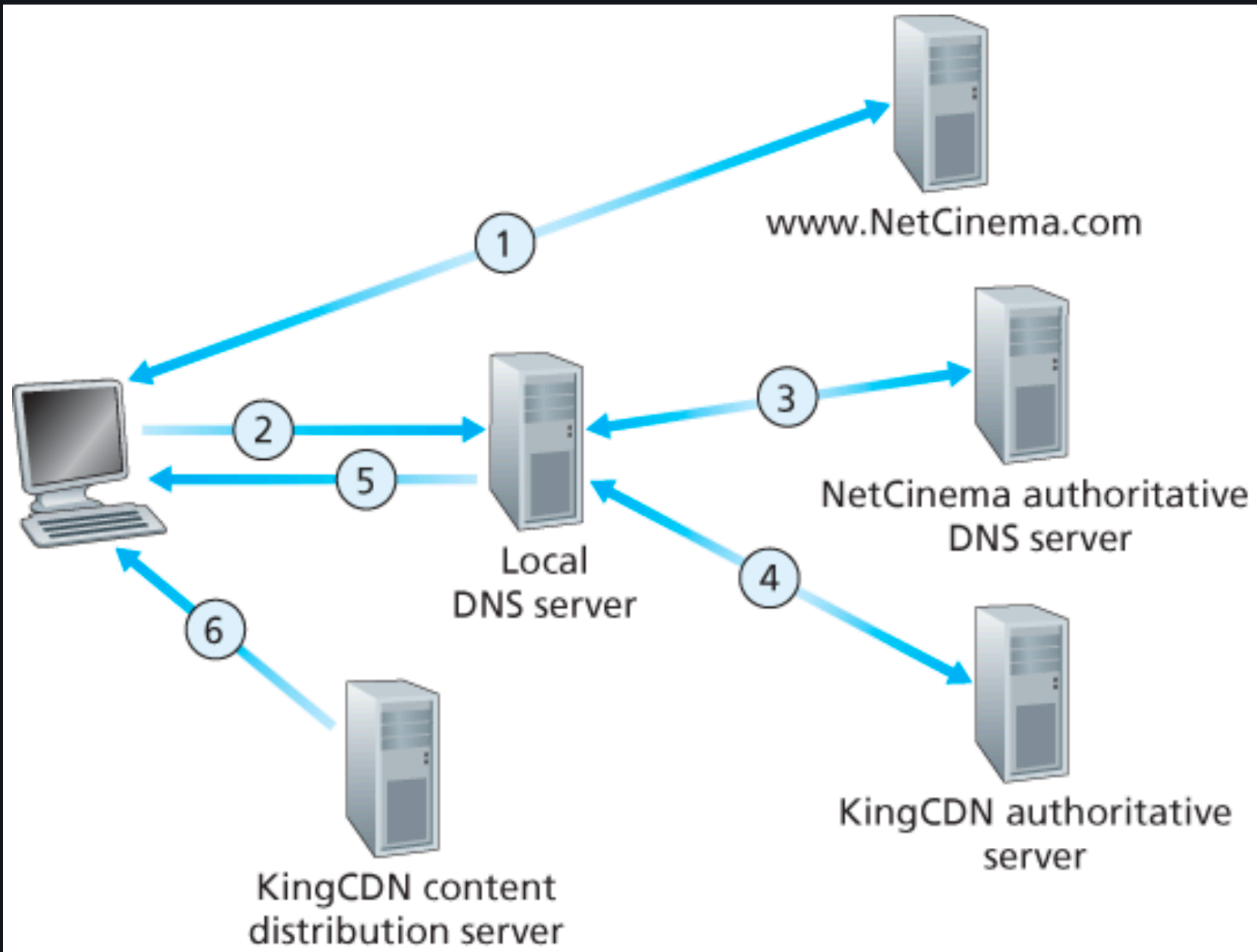
CDN Operation

When a browser in a user's host is instructed to retreive a specific video, the CDN must intercept the request so that it can (1) determine a suitable CDN server cluster for that client at the time, and (2) redirect the client's request to a server in that cluster.

Most CDNs take advantage of DNS to intercept and redirect requests. We illustrate the involvement of DNS in the following example:

Suppose a content provider, NetCinema, employs a third-party CDN company, KingCDN, to distribute its videos to its customers. The movie "Transformers 7" might be assigned `http://video.netcinema.com/6Y7B23V`. Six steps the occurs, also shown in the figure below:

1. User vists the Web page at NetCinema.
2. User clicks on the link of "Transformers 7" and the user's host sends a DNS query for `video.netcinema.com`.
3. The user's Local DNS Server (LDNS) realys the query to an authoritative DNS server for NetCinema. Instead of returning the IP address, the DNS server returns to the LDNS a hostname in the KingCDN's domain, for example `a1105.kingcdn.com`.
4. From this point on, the DNS query enters into KingCDN's private DNS infrastructure. The user's LDNS sends a second query and KingCDN's DNS system will eventually return the IP addresses of a KingCDN content server to the LDNS.
5. The LDNS forwards the IP address of the content-serving CDN node to the user's host.
6. Once the client receives the IP address for a KingCDN content server, it establishes a direct TCP connection with the server at that IP address and issues an HTTP GET request for the video.



Cluster Selection Strategies

At the core of any CDN deployment is a `cluster selection strategy`, that is, a mechanism for dynamically directing clients to a server cluster or a data center within the CDN. CDNs generally employ proprietary cluster selection strategies:

1. One simple strategy is to assign the client to the cluster that is `geographically closest`. Such a solution can reasonably well for a large fraction of the clients. However, for some clients, the solution may perform poorly, since the geographically closest cluster may not be the closest cluster in terms of length or number of hops of the network path.
2. CDNs can instead perform periodic `real-time measurements` of delay and loss performance between their clusters and clients. For instance, a CDN can have each of its clusters periodically send propbes to all the LDNSs around the world. One drawback of this approach is tha many LDNSs are configured to not respond to such probes.

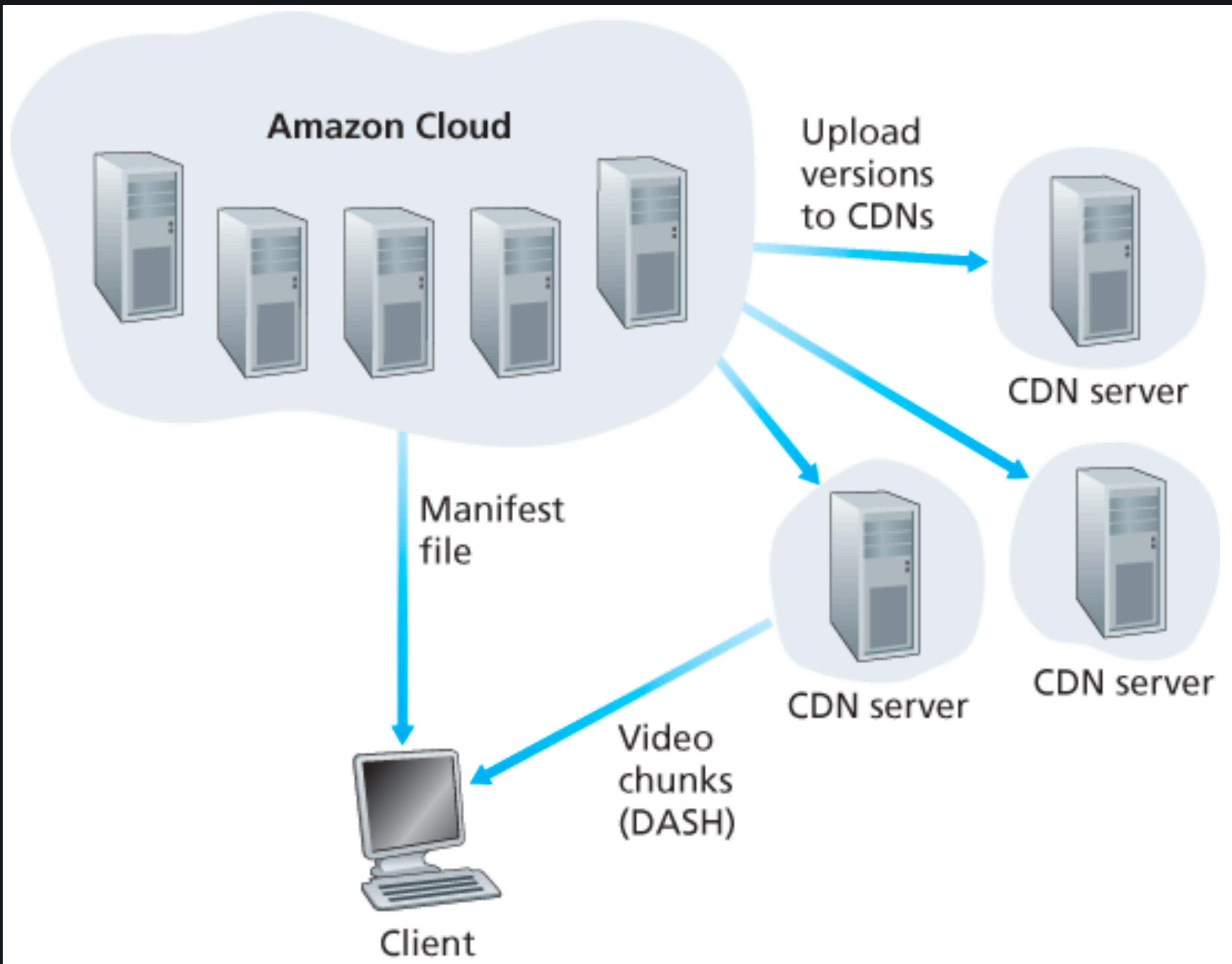
2.6.4 Case Studies: Netflix, YouTube, and Kankan

Netflix

Generating 37% of the downstream traffic in residential ISPs in North America in 2015, Netflix has become the leading service provider for online movies and TV series in the United States.

As shown in the figure below, Netflix's Web site runs entirely on Amazon servers in the Amazon cloud. Additionally, the Amazon cloud handles the following critical functions:

- *Content ingestion*: Before Netflix can distribute a movie to its customers, it must first ingest and process the movie.
- *Content processing*: The machines in the Amazon cloud create many different formats for each movie, suitable for a diverse array of client video players.
- *Uploading versions to its CDN*: Once all of the versions of a movie have been created, the hosts in the Amazon cloud upload the versions to its CDN.



Netflix has since created its own private CDN, from which it now streams all of its videos. To create its own CDN, Netflix has installed server racks both in IXPs and within residential ISPs themselves. Netflix does not use pull-caching to populate its CDN servers in the IXPs and ISPs. Instead, Netflix distributes by pushing the videos to its CDN servers during off-peak hours. For those locations that cannot hold the entire library, Netflix pushes only the most popular videos, which are determined on a day-to-day basis.

When a user selects a movie to play, Netflix software, running in the Amazon cloud, first determines which of its CDN servers have copies of the movies. Among those servers, the software then determines the "best" server for the client request.

The client and the determines CDN server then directly interact using a proprietary version of DASH. Specifically, the client uses the byte-range header in HTTP GET request messages, to request chunks from the different versions of the movie. Netflix uses chunks that are approximately four-seconds long.

YouTube

As with Netflix, YouTube makes extensive use of CDN technology to distribute its videos. Similar to Netflix, Google uses its own private CDN and has installed server clusters in many hundreds of different IXP and ISP locations.

Unlike Netflix, however, Google uses pull caching and DNS redirect. Most of the time, Google's cluster-selection strategy directs the client to the cluster for which the RTT between client and cluster is the lowest.

YouTube employs HTTP streaming, often making a small number of different versions available for a video, each with a different bit rate and corresponding quality level. YouTube does not employ adaptive streaming (such as DASH), but instead requires the user to manually select a version.

Kankan

Since 2011, Kankan has been deploying P2P video delivery with great success, with tens of millions of users every month.

When a peer wants to see a video, it contacts a tracker to discover other peers in the system that have a copy of that video. This requesting peer then requests chunks of the video parallel from the other peers that have the video.

Specifically, Kankan now deploys a few hundred servers within China and pushes video content to the servers. In most cases, the client requests the beginning of the content from CDN servers, and in parallel requests content from peers. When the total P2P traffic is sufficient for video playback, the client will cease streaming from the CDN and only stream from peers.