ricocheting around the Internet. The idea behind DNS caching is very simple. In a query chain, when a DNS server receives a DNS reply (containing, for example, a mapping from a hostname to an IP address), it can cache the mapping in its local memory. For example, in Figure 2.19, each time the local DNS server `dns.nyu.edu` receives a reply from some DNS server, it can cache any of the information contained in the reply. 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. Because hosts and mappings between hostnames and IP addresses are by no means permanent, DNS servers discard cached information after a period of time (often set to two days).

As an example, suppose that a host `apricot.nyu.edu` queries `dns.nyu.edu` for the IP address for the hostname `cnn.com`. Furthermore, suppose that a few hours later, another NYU host, say, `kiwi.nyu.edu`, also queries `dns.nyu.edu` with the same hostname. Because of caching, the local DNS server will be able to immediately return the IP address of `cnn.com` to this second requesting host without having to query any other DNS servers. A local DNS server can also cache the IP addresses of TLD servers, thereby allowing the local DNS server to bypass the root DNS servers in a query chain. In fact, because of caching, root servers are bypassed for all but a very small fraction of DNS queries.

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. Each DNS reply message carries one or more resource records. In this and the following subsection, we provide a brief overview of DNS resource records and messages; more details can be found in [Albitz 1993] or in the DNS RFCs [RFC 1034; RFC 1035].

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. In the example records given below, we ignore the `TTL` field. The meaning of `Name` and `Value` depend on `Type`:

- If `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. As an example, `(relay1.bar.foo.com, 145.37.93.126, A)` is a Type A record.

- If `Type=NS`, then `Name` is a domain (such as `foo.com`) and `Value` is the hostname of an authoritative DNS server that knows how to obtain the IP addresses for hosts in the domain. This record is used to route DNS queries further along in the query chain. As an example, `(foo.com, dns.foo.com, NS)` is a Type NS record.
- If `Type=CNAME`, then `Value` is a canonical hostname for the alias hostname `Name`. This record can provide querying hosts the canonical name for a hostname. As an example, `(foo.com, relay1.bar.foo.com, CNAME)` is a CNAME record.
- If `Type=MX`, then `Value` is the canonical name of a mail server that has an alias hostname `Name`. As an example, `(foo.com, mail.bar.foo.com, MX)` is an MX record. MX records allow the hostnames of mail servers to have simple aliases. 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 (such as its Web server). To obtain the canonical name for the mail server, a DNS client would query for an MX record; to obtain the canonical name for the other server, the DNS client would query for the CNAME record.

If a DNS server is authoritative for a particular hostname, then the DNS server will contain a Type A record for the hostname. (Even if the DNS server is not authoritative, it may contain a Type A record in its cache.) 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. As an example, suppose an edu TLD server is not authoritative for the host `gaia.cs.umass.edu`. Then this server will contain a record for a domain that includes the host `gaia.cs.umass.edu`, for example, `(umass.edu, dns.umass.edu, NS)`. The edu TLD server would also contain a Type A record, which maps the DNS server `dns.umass.edu` to an IP address, for example, `(dns.umass.edu, 128.119.40.111, A)`.

DNS Messages

Earlier in this section, we referred to DNS query and reply messages. These are the only two kinds of DNS messages. Furthermore, both query and reply messages have the same format, as shown in Figure 2.21.The semantics of the various fields in a DNS message are as follows:

- 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. This identifier is copied into the reply message to a query, allowing the client to match received replies with sent queries. There are a number of flags in the flag field. A 1-bit query/reply flag indicates whether the message is a query (0) or a reply (1). A 1-bit authoritative flag is

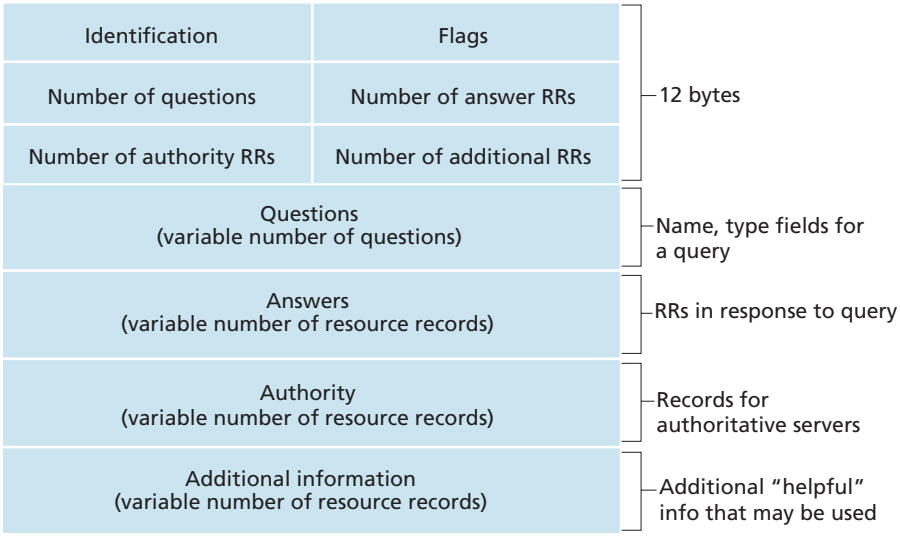

Figure 2.21 ♦ DNS message format

set in a reply message when a DNS server is an authoritative server for a queried name. A 1-bit recursion-desired flag is set when a client (host or DNS server) desires that the DNS server perform recursion when it doesn't have the record. A 1-bit recursion-available field is 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 occurrences 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—for example, a host address associated with a name (Type A) or the mail server for a name (Type MX).
- In a reply from a DNS server, the *answer section* contains the resource records for the name that was originally queried. Recall that in each resource record there is the `Type` (for example, A, NS, CNAME, and MX), the `Value`, and the `TTL`. A reply can return multiple RRs in the answer, since a hostname can have multiple IP addresses (for example, for replicated Web servers, as discussed earlier in this section).
- The *authority section* contains records of other authoritative servers.
- The *additional section* contains other helpful records. For example, the answer field in a reply to an MX query contains a resource record providing the canonical hostname of a mail server. The additional section contains a Type A record providing the IP address for the canonical hostname of the mail server.

How would you like to send a DNS query message directly from the host you're working on to some DNS server? This can easily be done with the **nslookup program**, which is available from most Windows and UNIX platforms. For example, from a Windows host, open the Command Prompt and invoke the nslookup program by simply typing "nslookup." After invoking nslookup, you can send a DNS query to any DNS server (root, TLD, or authoritative). After receiving the reply message from the DNS server, nslookup will display the records included in the reply (in a human-readable format). As an alternative to running nslookup from your own host, you can visit one of many Web sites that allow you to remotely employ nslookup. (Just type "nslookup" into a search engine and you'll be brought to one of these sites.) The DNS Wireshark lab at the end of this chapter will allow you to explore the DNS in much more detail.

Inserting Records into the DNS Database

The discussion above focused on how records are retrieved from the DNS database. You might be wondering how records get into the database in the first place. Let's look at how this is done in the context of a specific example. Suppose you have just created an exciting new startup company called Network Utopia. The first thing you'll surely want to do is register the domain name `networkutopia.com` at a registrar. A **registrar** is a commercial entity that verifies the uniqueness of the domain name, enters the domain name into the DNS database (as discussed below), and collects a small fee from you for its services. Prior to 1999, a single registrar, Network Solutions, had a monopoly on domain name registration for `com`, `net`, and `org` domains. But now there are many registrars competing for customers, and the Internet Corporation for Assigned Names and Numbers (ICANN) accredits the various registrars. A complete list of accredited registrars is available at `http://www.internic.net`.

When you register 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. Suppose the names and IP addresses are `dns1.networkutopia.com`, `dns2.networkutopia.com`, `212.2.212.1`, and `212.212.212.2`. 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. Specifically, for the primary authoritative server for `networkutopia.com`, the registrar would insert the following two resource records into the DNS system:

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

You'll also have to make sure that the Type A resource record for your Web server `www.networkutopia.com` and the Type MX resource record for your mail server `mail.networkutopia.com` are entered into your authoritative DNS

FOCUS ON SECURITY

DNS VULNERABILITIES

We have seen that DNS is a critical component of the Internet infrastructure, with many important services—including the Web and e-mail—simply incapable of functioning without it. We therefore naturally ask, how can DNS be attacked? Is DNS a sitting duck, waiting to be knocked out of service, while taking most Internet applications down with it?

The first type of attack that comes to mind is a DDoS bandwidth-flooding attack (see Section 1.6) against DNS servers. For example, an attacker could attempt to send to each DNS root server a deluge of packets, so many that the majority of legitimate DNS queries never get answered. Such a large-scale DDoS attack against DNS root servers actually took place on October 21, 2002. In this attack, the attackers leveraged a botnet to send truck loads of ICMP ping messages to each of the 13 DNS root IP addresses. (ICMP messages are discussed in Section 5.6. For now, it suffices to know that ICMP packets are special types of IP datagrams.) Fortunately, this large-scale attack caused minimal damage, having little or no impact on users' Internet experience. The attackers did succeed at directing a deluge of packets at the root servers. But many of the DNS root servers were protected by packet filters, configured to always block all ICMP ping messages directed at the root servers. These protected servers were thus spared and functioned as normal. Furthermore, most local DNS servers cache the IP addresses of top-level-domain servers, allowing the query process to often bypass the DNS root servers.

A potentially more effective DDoS attack against DNS would be send a deluge of DNS queries to top-level-domain servers, for example, to all the top-level-domain servers that handle the .com domain. It would be harder to filter DNS queries directed to DNS servers; and top-level-domain servers are not as easily bypassed as are root servers. But the severity of such an attack would be partially mitigated by caching in local DNS servers.

DNS could potentially be attacked in other ways. In a man-in-the-middle attack, the attacker intercepts queries from hosts and returns bogus replies. In the DNS poisoning attack, the attacker sends bogus replies to a DNS server, tricking the server into accepting bogus records into its cache. Either of these attacks could be used, for example, to redirect an unsuspecting Web user to the attacker's Web site. These attacks, however, are difficult to implement, as they require intercepting packets or throttling servers [Skoudis 2006].

In summary, DNS has demonstrated itself to be surprisingly robust against attacks. To date, there hasn't been an attack that has successfully impeded the DNS service.

servers. (Until recently, the contents of each DNS server were configured statically, for example, from a configuration file created by a system manager. More recently, an UPDATE option has been added to the DNS protocol to allow data to be dynamically added or deleted from the database via DNS messages. [RFC 2136] and [RFC 3007] specify DNS dynamic updates.)

Once all of these steps are completed, people will be able to visit your Web site and send e-mail to the employees at your company. Let's conclude our discussion of DNS by verifying that this statement is true. This verification also helps to solidify what we have learned about DNS. Suppose Alice in Australia wants to view the Web page `www.networkutopia.com`. As discussed earlier, her host will first send a DNS query to her local DNS server. The local DNS server will then contact a TLD `com` server. (The local DNS server will also have to contact a root DNS server if the address of a TLD `com` server is not cached.) This TLD server contains the Type NS and Type A resource records listed above, because the registrar had these resource records inserted into all of the TLD com servers. The TLD com server sends a reply to Alice's local DNS server, with the reply containing the two resource records. The local DNS server then sends a DNS query to `212.212.212.1`, asking for the Type A record corresponding to `www.networkutopia.com`. This record provides the IP address of the desired Web server, say, `212.212.71.4`, which the local DNS server passes back to Alice's host. Alice's browser can now initiate a TCP connection to the host `212.212.71.4` and send an HTTP request over the connection. Whew! There's a lot more going on than what meets the eye when one surfs the Web!

2.5 Peer-to-Peer File Distribution

The applications described in this chapter thus far—including the Web, e-mail, and DNS—all employ client-server architectures with significant reliance on always-on infrastructure servers. Recall from Section 2.1.1 that with a P2P architecture, there is minimal (or no) reliance on always-on infrastructure servers. Instead, pairs of intermittently connected hosts, called peers, communicate directly with each other. The peers are not owned by a service provider, but are instead desktops and laptops controlled by users.

In this section we consider a very natural P2P application, namely, distributing a large file from a single server to a large number of hosts (called peers). The file might be a new version of the Linux operating system, a software patch for an existing operating system or application, an MP3 music file, or an MPEG video file. In client-server file distribution, the server must send a copy of the file to each of the peers—placing an enormous burden on the server and consuming a large amount of server bandwidth. In P2P file distribution, each peer can redistribute any portion of the