CS3281 / CS5281

Networking

CS3281 / CS5281

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Intro to Sockets

- Sockets: method for IPC between applications
  - Can be on the same host
  - Can be on a different host connected by a network
- Typical organization: client-server
  - The client makes requests
    - Example: a web browser
  - The server responds to requests
    - Example: an Apache web server
- Communication involves a network protocol
  - Usually multiple layers of network protocols
- We'll cover TCP/IP
  - Also called the Internet protocol suite

Big Picture: The Internet

- Began in 1960s: as network that could connect computers that were far away
  - Funding came from DARPA, and first ARPANET message was sent from UCLA to Stanford (350 miles) in 1969
- Originally linked research operations and CS departments
  - Spread to the commercial world in the 1990s and become "the Internet"
- Today: the Internet links millions of loosely connected, independent networks
- Data is through the networks in "packets" called IP (Internet Protocol) packets
  - Transported in one or more physical packets, like Ethernet or WiFi
  - Each IP packet passes through multiple gateways
    - Each gateway passes the packet to a gateway closer to the ultimate destination
- An internet (lowercase i) connects different computer networks
  - The Internet (capital I) refers to the TCP/IP internet that connects millions of computers
  - Some modern style guides do not capitalize "Internet." We do here for conceptual clarity.

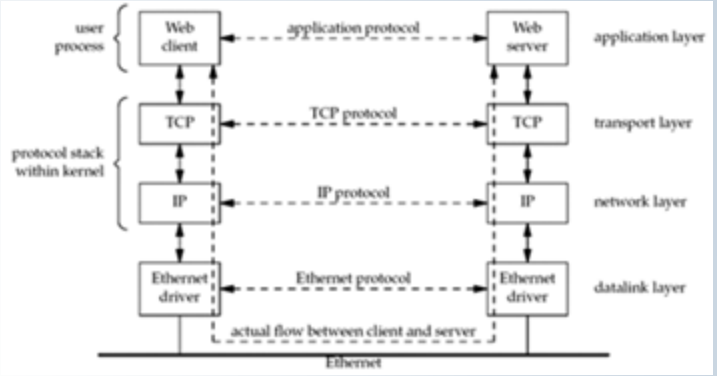
https://en.wikipedia.org/wiki/Capitalization_of_Internet

The Internet (cont.)

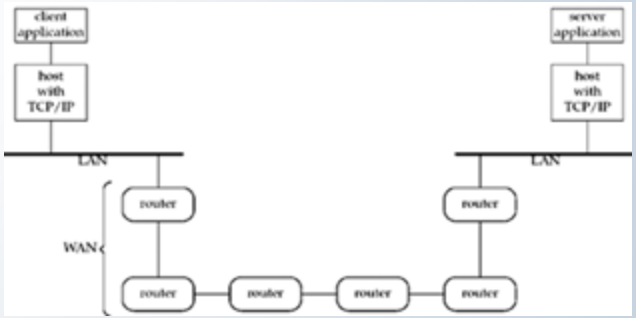
- The core protocol is the Internet Protocol
  - Defines a uniform transport mechanism and a common format for information in transit
  - IP packets are carried by different kinds of hardware using their own protocols
- The Transmission Control Protocol (TCP) sits on top of IP
  - TCP provides a reliable mechanism for sending arbitrarily long sequences of bytes
- Above TCP, higher-level protocols use TCP to provide services that we think of as “the Internet”
  - Examples: browsing, e-mail, file sharing
- All of these protocols taken together define the Internet

Protocol Layers

- Example on the right:
  - Web servers and web clients communicate using TCP
  - TCP uses the Internet Protocol (IP)
  - IP uses a data link protocol (like Ethernet)
- The client and server use an application protocol
  - The transport layers use the TCP protocol
- Information flows down the protocol stack on one side, back up on the other
- Client and server are in user space
  - TCP, IP, data link in kernel space (usually)



On the same LAN



On different LANs

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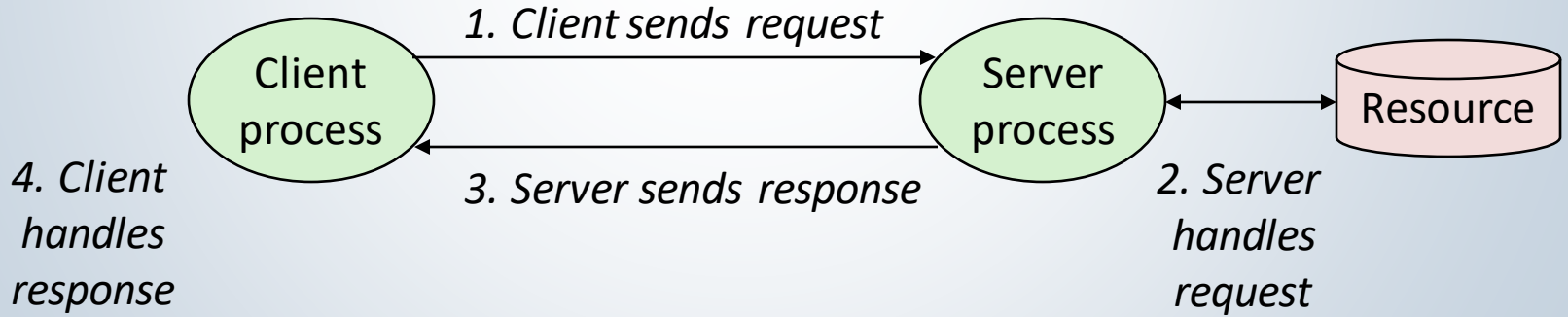
Sockets

- What is a socket?
  - To the kernel, a socket is an endpoint of communication
  - To an application, a socket is a file descriptor that lets the application read/write from/to the network
    - ***Remember:*** All Unix I/O devices, including networks, are modeled as files
- Clients and servers communicate with each other by reading from and writing to socket descriptors

- The main distinction between regular file I/O and socket I/O is how the application "opens" the socket descriptors

A Client-Server Transaction

- Most network applications are based on the client-server model:
  - A ***server*** process and one or more ***client*** processes
  - Server manages some ***resource***
  - Server provides ***service*** by manipulating resource for clients
  - Server activated by request from client (vending machine analogy)



Note: clients and servers are processes running on hosts (can be the same or different hosts)

Sockets and Client/Server Communications

- Each application creates a socket
- The server binds its socket to a well-known address so clients can locate it

```
fd = socket(domain, type, protocol);
```

- Domain determines:
  - Format of address, and range of communication (same or different hosts)
    - AF_UNIX, AF_INET, AF_INET6
- Type: stream or datagram
- Protocol: generally 0
  - Nonzero for some types like raw sockets (passes directly from data link to application)

Property	Socket type	
	Stream	Datagram
Reliable delivery?	Y	N
Message boundaries preserved?	N	Y
Connection-oriented?	Y	N

Stream Sockets

- Stream sockets provide reliable, bidirectional, byte-stream communication
  - Reliable: Either the transmitted data arrives intact at the receiving end, or we receive notification of a probable failure in transmission
  - Bidirectional: data may be transmitted in either direction
  - Byte-stream: no message boundaries
    - Example: receiver doesn't know if the sender originally sent two 1-byte messages or one 2-byte message
- Operate in connected pairs (aka connection oriented)
  - *Peer* socket: socket at the other end of a connection
  - *Peer* address: address of that socket
  - *Peer* application: application using the peer socket
    - *Peer* is equivalent to *remote* or *foreign*

Datagram Sockets

- Allow data to be exchanged in the form of messages called *datagrams*
  - Message boundaries are preserved
  - Data transmission is not reliable
    - Data may arrive out of order, be duplicated, or not arrive at all
  - Example of a connectionless socket
    - Doesn't need to be connected to another socket in order to be used
- In the Internet domain:
  - Datagram sockets use UDP
  - Stream sockets use* TCP

**Almost always*

Protocols and Communication

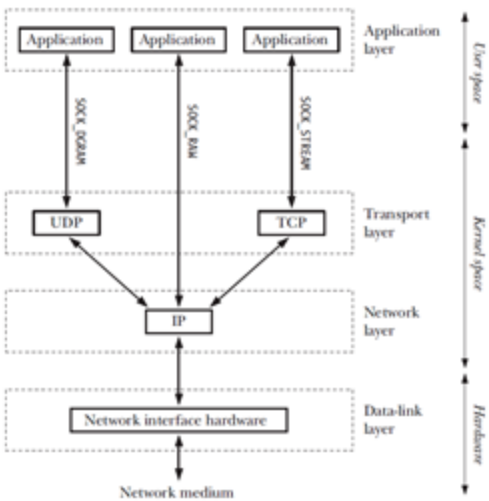


Figure 58-2: Protocols in the TCP/IP suite

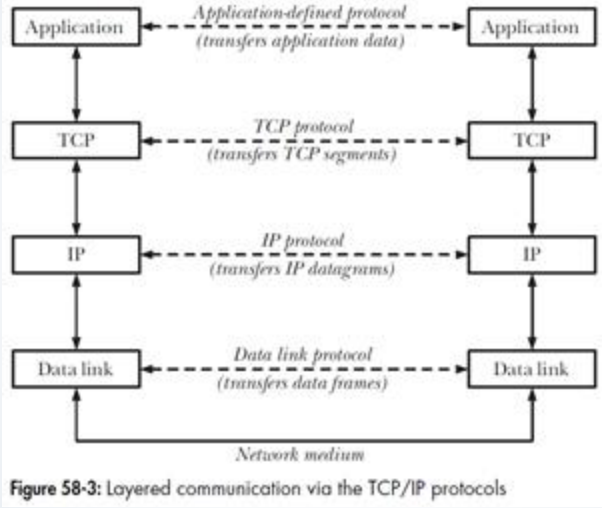


Figure 58-3: Layered communication via the TCP/IP protocols

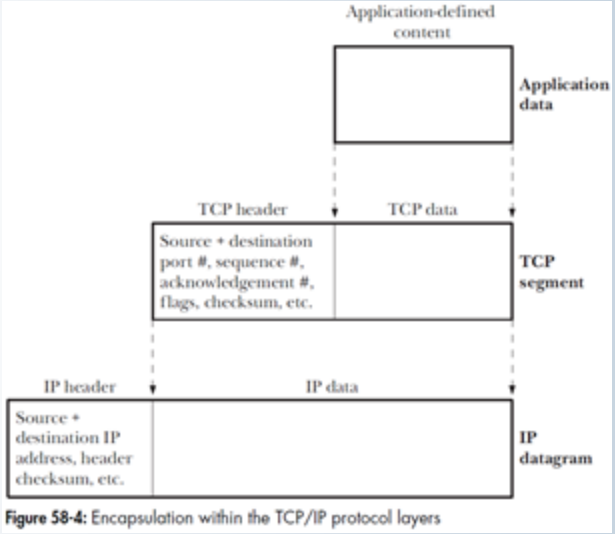


Figure 58-4: Encapsulation within the TCP/IP protocol layers

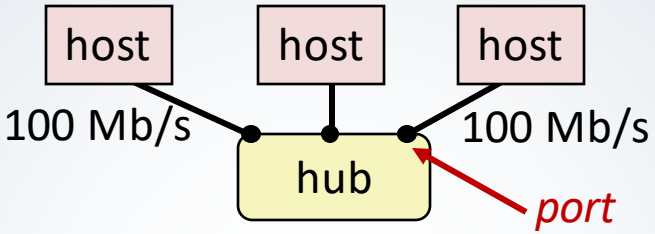
Global IP Internet (Upper Case)

- Most famous example of an internet
- Based on the TCP/IP protocol family
  - IP (Internet Protocol) :
    - Provides *basic naming scheme* and unreliable *delivery capability* of packets (datagrams) from *host-to-host*
  - UDP (Unreliable Datagram Protocol)
    - Uses IP to provide *unreliable* datagram delivery from *process-to-process*
  - TCP (Transmission Control Protocol)
    - Uses IP to provide *reliable* byte streams from *process-to-process* over *connections*
- Accessed via a mix of Unix file I/O and functions from the *sockets interface*

Computer Networks

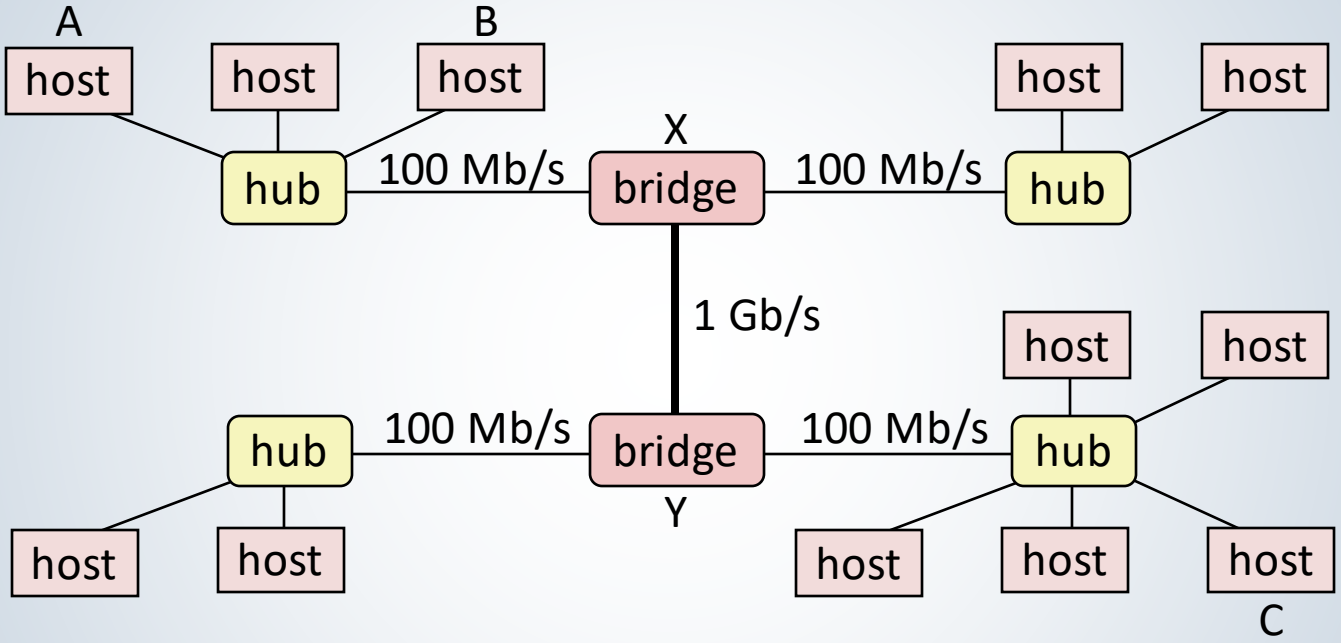
- A *network* is a hierarchical system of boxes and wires organized by geographical proximity
  - SAN (System Area Network) spans cluster or machine room
    - Switched Ethernet, Quadrics QSW, …
  - LAN (Local Area Network) spans a building or campus
    - Ethernet is most prominent example
  - WAN (Wide Area Network) spans country or world
    - Typically high-speed point-to-point phone lines
- An *internetwork (internet)* is an interconnected set of networks
  - The Global IP Internet (uppercase "I") is the most famous example of an internet (lowercase "i")
- Let's see how an internet is built from the ground up

Lowest Level: Ethernet Segment



- Ethernet segment consists of a collection of *hosts* connected by wires (twisted pairs) to a *hub*
- Spans room or floor in a building
- Operation
  - Each Ethernet adapter has a unique 48-bit address (MAC address)
    - E.g., 00:16:ea:e3:54:e6
  - Hosts send bits to any other host in chunks called ***frames***
  - Hub copies each bit from each port to every other port
    - Every host sees every bit
    - Note: Hubs are on their way out. Bridges (switches, routers) became cheap enough to replace them

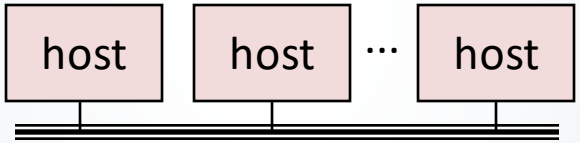
Next Level: Bridged Ethernet Segment



- Spans building or campus
- Bridges cleverly learn which hosts are reachable from which ports and then selectively copy frames from port to port

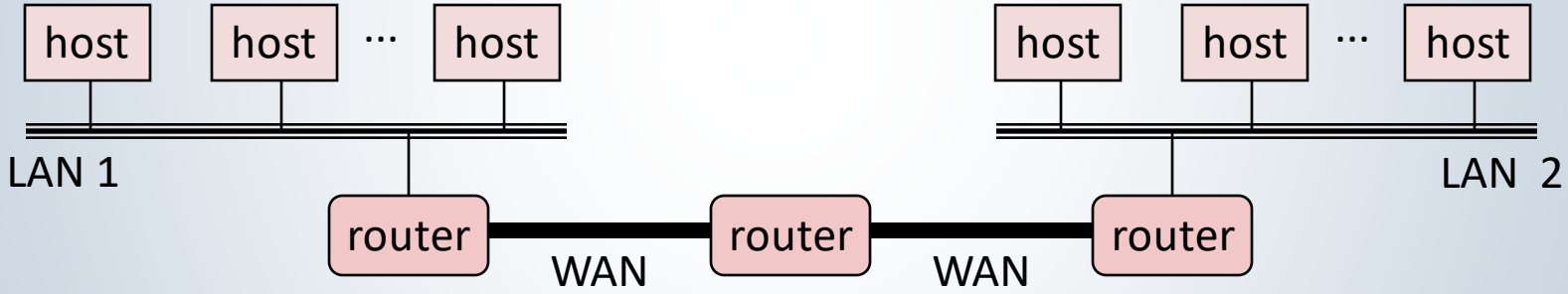
Conceptual View of LANs

- For simplicity, hubs, bridges, and wires are often shown as a collection of hosts attached to a single wire:



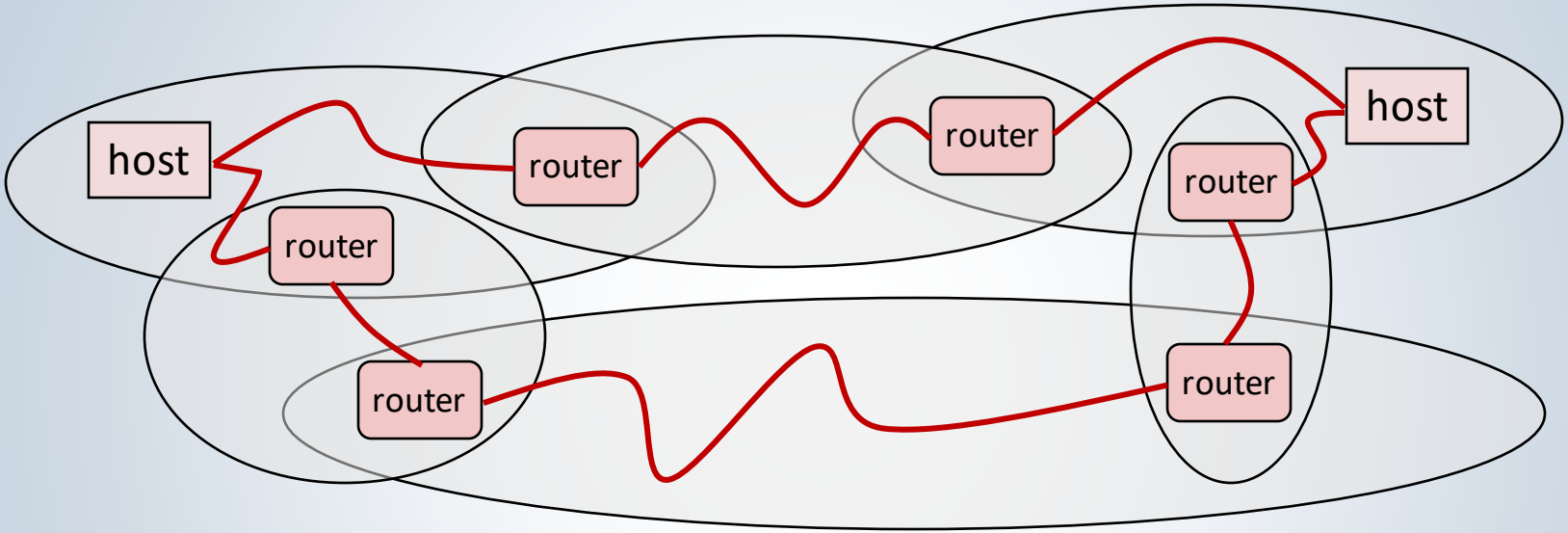
Next Level: Internets

- Multiple incompatible LANs can be physically connected by specialized computers called *routers*
- The connected networks are called an *internet* (lower case)



LAN 1 and LAN 2 might be completely different, totally incompatible (e.g., Ethernet, Fibre Channel, 802.11, T1-links, DSL, …)*

Logical Structure of an Internet



- Ad hoc interconnection of networks
  - No particular topology
  - Vastly different router & link capacities
- Send packets from source to destination by hopping through networks
  - Router forms bridge from one network to another
  - Different packets may take different routes

The Notion of an Internet Protocol

- How is it possible to send bits across incompatible LANs and WANs?

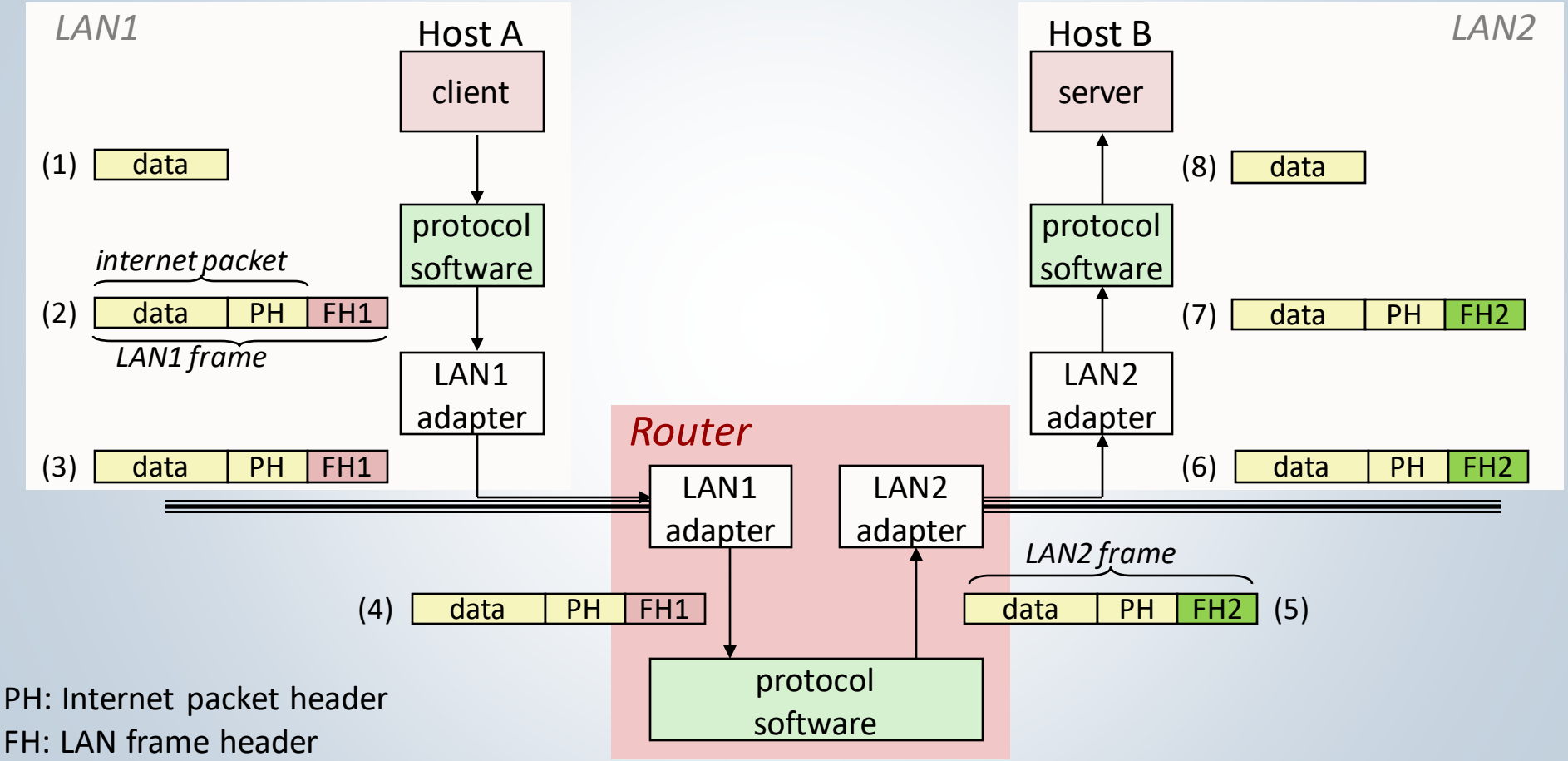
- Solution: *protocol* software running on each host and router
  - Protocol is a set of rules that governs how hosts and routers should cooperate when they transfer data from network to network.
  - Smooths out the differences between the different networks

What Does an Internet Protocol Do?

- Provides a *naming scheme*
  - An internet protocol defines a uniform format for ***host addresses***
  - Each host (and router) is assigned at least one of these internet addresses that uniquely identifies it

- Provides a *delivery mechanism*
  - An internet protocol defines a standard transfer unit (***packet***)
  - Packet consists of ***header*** and ***payload***
    - Header: contains info such as packet size, source and destination addresses
    - Payload: contains data bits sent from source host

Transferring Internet Data via Encapsulation



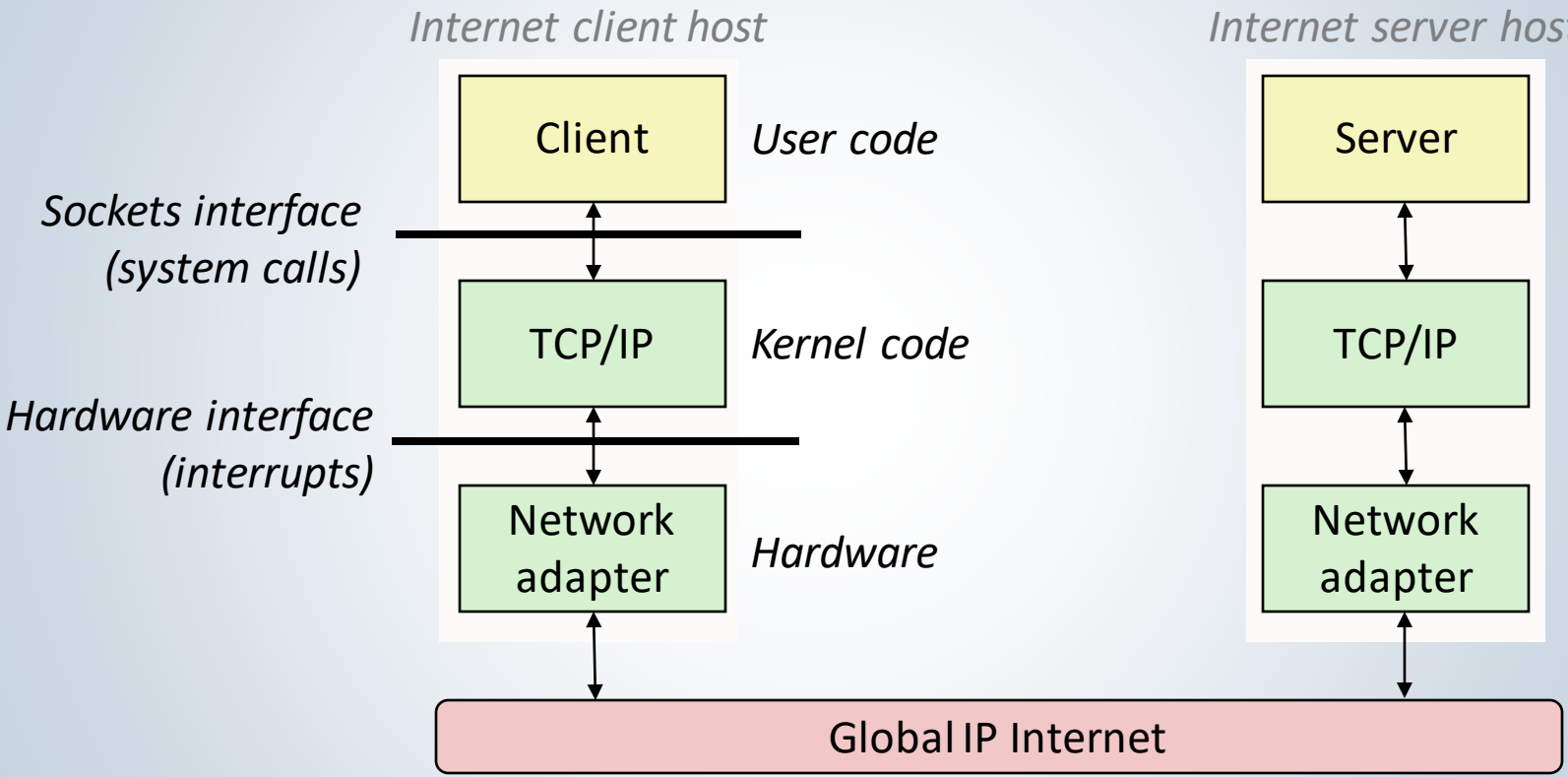
PH: Internet packet header
FH: LAN frame header

Other Issues

- We are glossing over a number of important questions:
  - What if different networks have different maximum frame sizes? (segmentation)
  - How do routers know where to forward frames?
  - How are routers informed when the network topology changes?
  - What if packets get lost?

- These (and other) questions are addressed by the area of systems known as *computer networking*

Organization of an Internet Application



A Programmer's View of the Internet

1. Hosts are mapped to a set of 32-bit *IP addresses*
   – 128.2.203.179

2. The set of IP addresses is mapped to a set of identifiers called Internet *domain names*
   – 129.59.107.38 is mapped to www.isis.vanderbilt.edu

3. A process on one Internet host can communicate with a process on another Internet host over a *connection*

IP Addresses

- 32-bit IP addresses are stored in an *IP address struct*
  - IP addresses are always stored in memory in *network byte order* (big-endian byte order)
    - x86, ARM, risc-v all little endian
  - True in general for any integer transferred in a packet header from one machine to another
    - E.g., the port number used to identify an Internet connection

```
/* Internet address structure */
struct in_addr {
    uint32_t  s_addr; /* network byte order (big-endian) */
};
```

Dotted-Decimal Notation

- By convention, each byte in a 32-bit IP address is represented by its decimal value and separated by a period
  - IP address: **0x8002C2F2 = 128.2.194.242**

Internet Connections

- Clients and servers communicate by sending streams of bytes over *connections*. Each connection is:
  - *Point-to-point*: connects a pair of processes.
  - *Full-duplex*: data can flow in both directions at the same time,
  - *Reliable*: stream of bytes sent by the source is eventually received by the destination in the same order it was sent.

- *A socket* is an endpoint of a connection
  - *Socket address* is an `IPaddress:port` pair

- A *port* is a 16-bit integer that identifies a process:
  - ***Ephemeral port*:** Assigned automatically by client kernel when client makes a connection request.
  - ***Well-known port:*** Associated with some *service* provided by a server (e.g., port 80 is associated with Web servers)

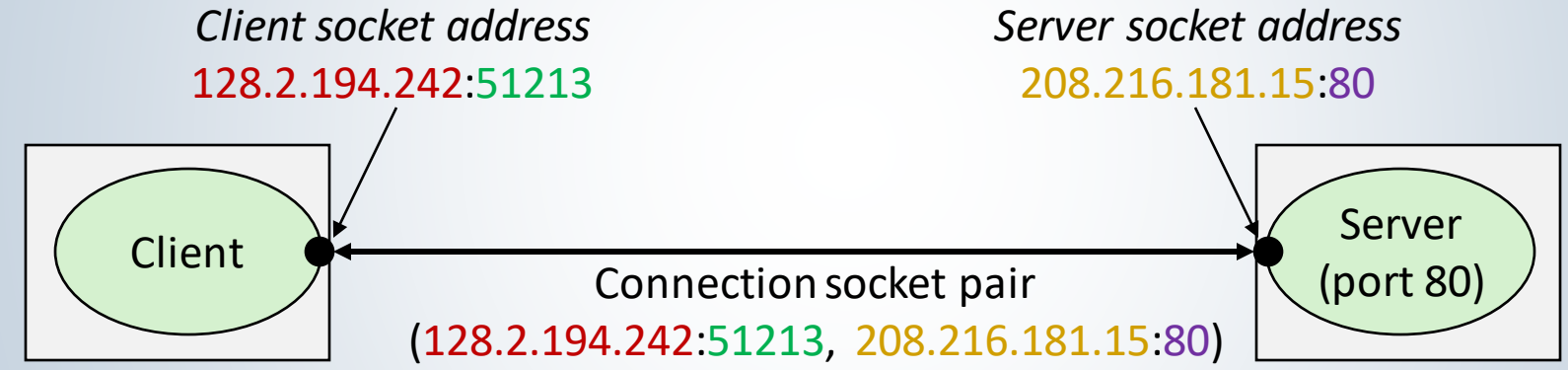
Well-Known Ports and Service Names

- Popular services have permanently assigned *well-known ports and* corresponding *well-known service names*:
  - echo server: 7/echo
  - ssh servers: 22/ssh
  - email server: 25/smtp
  - Web servers: 80/http, 443/https

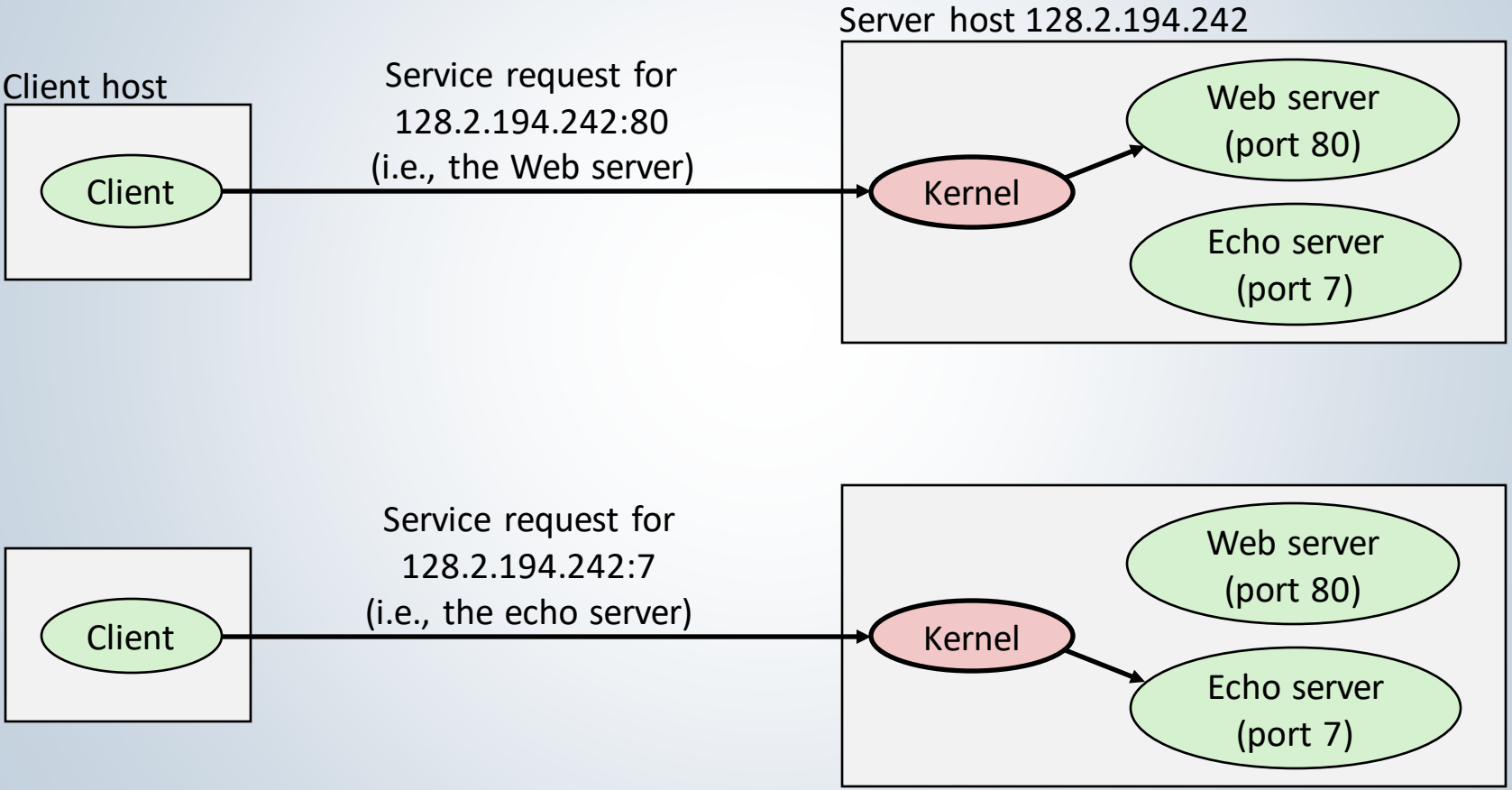
- Mappings between well-known ports and service names is contained in the file `/etc/services` on each Linux machine.

Anatomy of a Connection

- A connection is uniquely identified by the socket addresses of its endpoints (*socket pair*)
  - `(cliaddr:cliport, servaddr:servport)`



Using Ports to Identify Services



Sockets Interface

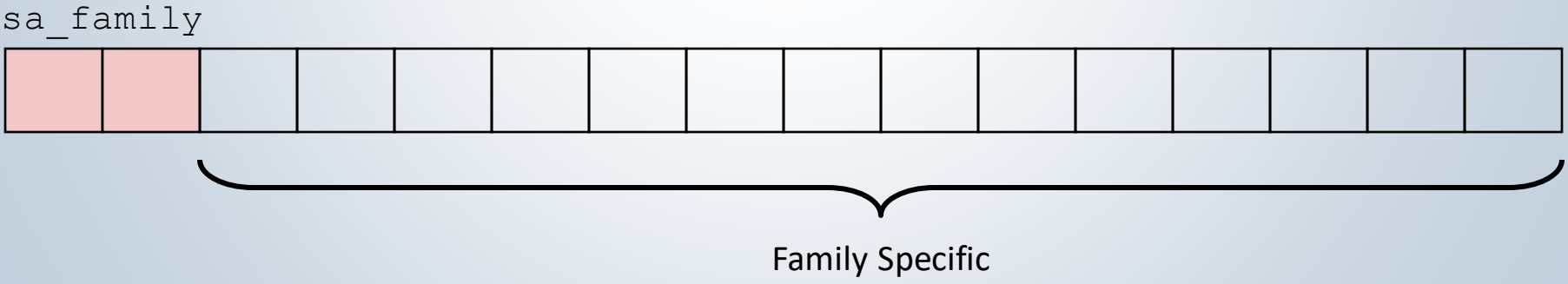
- Set of system-level functions used in conjunction with Unix I/O to build network applications.
- Created in the early 80's as part of the original Berkeley distribution of Unix that contained an early version of the Internet protocols.
- Available on all modern systems
  - Unix variants, Windows, OS X, IOS, Android, ARM

Socket-Address Structures

- Generic socket address:
  - For address arguments to **`connect`**, **`bind`**, and **`accept`**
  - Necessary only because C did not have generic (**`void *`**) pointers when the sockets interface was designed
  - For casting convenience, we adopt the Stevens convention:

    `typedef struct sockaddr SA;`

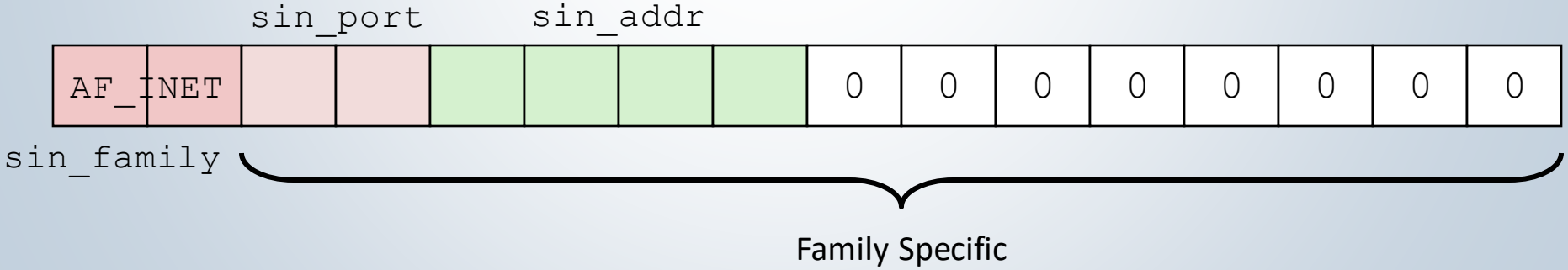
```
struct sockaddr {
  uint16_t  sa_family;    /* Protocol family */
  char      sa_data[14];  /* Address data.  */
};
```



Socket Address Structures

- Internet-specific socket address:
  - Must cast (`struct sockaddr_in *`) to (`struct sockaddr *`) for functions that take socket address arguments.

```
struct sockaddr_in  {
  uint16_t        sin_family;  /* Protocol family (always AF_INET) */
  uint16_t        sin_port;    /* Port num in network byte order */
  struct in_addr  sin_addr;    /* IP addr in network byte order */
  unsigned char   sin_zero[8]; /* Pad to sizeof(struct sockaddr) */
};
```



Key Socket Calls

- socket() creates a new socket
- bind() binds a socket to an address
- listen() lets a TCP socket to accept incoming connections from other sockets
- accept() accepts a connection from a peer application
- connect() establishes a connection with another socket
- Socket I/O can be done using
  - read() and write(), or
  - send(), recv(), sendto(), recvfrom()

Client-Server Example

```c
void server()
{
  int fd;
  struct sockaddr_in in_addr;
  memset(&in_addr, 0, sizeof(struct sockaddr_in));

  if ((fd = socket(AF_INET, SOCK_STREAM, 0)) == -1) {
    exit_with_error("Server error with socket");
  }

  in_addr.sin_family = AF_INET;
  in_addr.sin_port = 5001;
  inet_pton(AF_INET, "0.0.0.0", &in_addr.sin_addr);

  if (bind(fd, (struct sockaddr *) &in_addr, sizeof(struct sockaddr_in))) {
    exit_with_error("Server error with bind");
  }

  if (listen(fd, 0)) {
    exit_with_error("Server error with listen");
  }

  int port;
  struct sockaddr_in client_info;
  socklen_t client_size = sizeof(client_info);
  memset(&client_info, 0, sizeof(client_info));

  if ((port = accept(fd, (struct sockaddr *) &client_info, &client_size)) == -1) {
    exit_with_error("Server error with accept");
  }

  int ret, total = 0;
  char buf[100];
  while ((ret = read(port, buf + total, sizeof(buf) - 1 - total))) {
    if (ret == -1) {
      exit_with_error("Server error with read");
    }
    total += ret;
  }

  buf[total] = 0;
  printf("Server received: %s, total = %d\n", buf, total);
}
```

```c
void client(int port)
{
  int fd;
  struct sockaddr_in in_addr;
  memset(&in_addr, 0, sizeof(struct sockaddr_in));

  if ((fd = socket(AF_INET, SOCK_STREAM, 0)) == -1) {
    exit_with_error(0);
  }

  in_addr.sin_family = AF_INET;
  in_addr.sin_port = 5001;
  inet_pton(AF_INET, "127.0.0.1", &in_addr.sin_addr);

  if (connect(fd, (struct sockaddr *)&in_addr, sizeof(struct sockaddr_in))) {
    exit_with_error("Client error with connect");
  }

  int ret, sent = 0;
  char *msg = "Hello, server!";
  while (sent != strlen(msg)) {
    ret = write(fd, msg + sent, strlen(msg) - sent);
    if (ret == -1)
      exit_with_error("Client error with write");
    else
      sent += ret;
    printf("sent = %d\n", sent);
  }
}
```

```c
void exit_with_error(char *msg)
{
  perror(msg);
  exit(1);
}
```

Client-Server Example

```c
void server()
{
  int fd;
  struct sockaddr_in in_addr;
  memset(&in_addr, 0, sizeof(struct sockaddr_in));

  if ((fd = socket(AF_INET, SOCK_STREAM, 0)) == -1) {
    exit_with_error("Server error with socket");
  }

  in_addr.sin_family = AF_INET;
  in_addr.sin_port = 5001;
  inet_pton(AF_INET, "0.0.0.0", &in_addr.sin_addr);

  if (bind(fd, (struct sockaddr *) &in_addr, sizeof(struct sockaddr_in))) {
    exit_with_error("Server error with bind");
  }

  if (listen(fd, 0)) {
    exit_with_error("Server error with listen");
  }

  int port;
  struct sockaddr_in client_info;
  socklen_t client_size = sizeof(client_info);
  memset(&client_info, 0, sizeof(client_info));

  if ((port = accept(fd, (struct sockaddr *) &client_info, &client_size)) == -1) {
    exit_with_error("Server error with accept");
  }

  int ret, total = 0;
  char buf[100];
  while ((ret = read(port, buf + total, sizeof(buf) - 1 - total))) {
    if (ret == -1) {
      exit_with_error("Server error with read");
    }
    total += ret;
  }

  buf[total] = 0;
  printf("Server received: %s, total = %d\n", buf, total);
}
```

IPv4 socket address structure

```c
struct in_addr {                    /* IPv4 4-byte address */
    in_addr_t s_addr;               /* Unsigned 32-bit integer */
};

struct sockaddr_in {                /* IPv4 socket address */
    sa_family_t    sin_family;      /* Address family (AF_INET) */
    in_port_t      sin_port;        /* Port number */
    struct in_addr sin_addr;        /* IPv4 address */
    unsigned char  __pad[X];        /* Pad to size of 'sockaddr'
                                       structure (16 bytes) */
};
```

Generic socket address structure

```c
struct sockaddr {
    sa_family_t sa_family;          /* Address family (AF_* constant) */
    char        sa_data[14];        /* Socket address (size varies
                                       according to socket domain) */
};
```

```c
#include <sys/socket.h>

int bind(int sockfd, const struct sockaddr *addr, socklen_t addrlen);
```

Returns 0 on success, or −1 on error

```c
#include <sys/socket.h>

int listen(int sockfd, int backlog);
```

Returns 0 on success, or −1 on error

```c
#define __ss_aligntype uint32_t         /* On 32-bit architectures */
struct sockaddr_storage {
    sa_family_t ss_family;
    __ss_aligntype __ss_align;          /* Force alignment */
    char __ss_padding[SS_PADSIZE];      /* Pad to 128 bytes */
};
```

Large enough for IPv4 or IPv6

```c
#include <sys/socket.h>

int accept(int sockfd, struct sockaddr *addr, socklen_t *addrlen);
```

Returns file descriptor on success, or −1 on error

Client-Server Example

```
void client(int port)
{
  int fd;
  struct sockaddr_in in_addr;
  memset(&in_addr, 0, sizeof(struct sockaddr_in));

  if ((fd = socket(AF_INET, SOCK_STREAM, 0)) == -1) {
    exit_with_error(0);
  }

  in_addr.sin_family = AF_INET;
  in_addr.sin_port = 5001;
  inet_pton(AF_INET, "127.0.0.1", &in_addr.sin_addr);

  if (connect(fd, (struct sockaddr *)&in_addr, sizeof(struct sockaddr_in))) {
    exit_with_error("Client error with connect");
  }

  int ret, sent = 0;
  char *msg = "Hello, server!";
  while (sent != strlen(msg)) {
    ret = write(fd, msg + sent, strlen(msg) - sent);
    if (ret == -1)
      exit_with_error("Client error with write");
    else
      sent += ret;
    printf("sent = %d\n", sent);
  }
}
```

IPv4 socket address structure

```
struct in_addr {                    /* IPv4 4-byte address */
    in_addr_t s_addr;               /* Unsigned 32-bit integer */
};

struct sockaddr_in {                /* IPv4 socket address */
    sa_family_t    sin_family;      /* Address family (AF_INET) */
    in_port_t      sin_port;        /* Port number */
    struct in_addr sin_addr;        /* IPv4 address */
    unsigned char  __pad[X];        /* Pad to size of 'sockaddr'
                                       structure (16 bytes) */
};
```

```
#include <arpa/inet.h>

int inet_pton(int domain, const char *src_str, void *addrptr);
```

Returns 1 on successful conversion, 0 if *src_str* is not in presentation format, or −1 on error

```
#include <sys/socket.h>

int connect(int sockfd, const struct sockaddr *addr, socklen_t addrlen);
```

Returns 0 on success, or −1 on error

Basic write() library call uses a generic file descriptor

```
void exit_with_error(char *msg)
{
  perror(msg);
  exit(1);
}
```

Print the last error encountered during a system call or library function