Socket Programming

EE 122: Intro to Communication Networks

Fall 2006 (MW 4-5:30 in Donner 155)

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http://inst.eecs.berkeley.edu/~ee122/

Materials with thanks to Artur Rivilis, Jennifer Rexford, Ion Stoica and colleagues at Princeton and UC Berkeley

Announcements

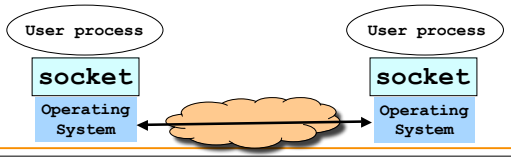
- Project #1 out today, **due Thu Sep 28**.
- Vern & Dilip away this week.
  - I will be covering Dilip's Friday section + office hours (in my office)
- **No Lecture Wed Sept. 13**

Overview

- Socket Programming: how applications use the network
  - Sockets are a C-language programming interface between Layer 7 (applications) and Layer 4 (transport)
  - Interface is quite general and fairly abstract
  - Use of interface differs somewhat between clients & servers

Socket: End Point of Communication

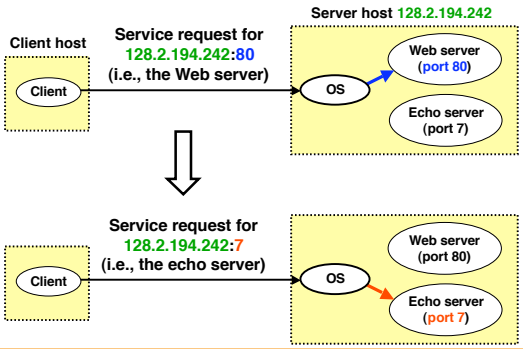
- Sending message from one process to another
  - Message must traverse the underlying network
- Process sends and receives through a "socket"
  - In essence, the doorway leading in/out of the house
- Socket as an Application Programming Interface
  - Supports the creation of network applications



Identifying the Receiving Process

- Sending process must identify the receiver
  - Address of the receiving end host
  - Plus identifier (port) that specifies the receiving process
- Receiving host
  - Destination address uniquely identifies the host
    - IP address is a 32-bit quantity
- Receiving process
  - Host may be running many different processes
  - Destination port uniquely identifies the socket
    - Port number is a 16-bit quantity

Using Ports to Identify Services



Knowing What Port Number To Use

- Popular applications have "well-known ports"
  - E.g., port 80 for Web and port 25 for e-mail
  - Well-known ports listed at http://www.iana.org
    - Or see /etc/services on Unix system
- Well-known vs. ephemeral ports
  - Server has a well-known port (e.g., port 80)
    - By convention, between 0 and 1023; privileged
  - Client gets an unused "ephemeral" (i.e., temporary) port
    - By convention, between 1024 and 65535
- Uniquely identifying the traffic between the hosts
  - The two IP addresses plus the two port numbers
    - Sometimes called the "four-tuple"
  - And: underlying transport protocol (e.g., TCP or UDP)
    - With the above, called the "five-tuple"

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Delivering the Data: Division of Labor

- Network
  - Deliver data packet to the destination host
  - Based on the destination IP address

- Operating system
  - Deliver data to the destination socket
  - Based on the protocol and destination port #
- Application
  - Read data from the socket
  - Interpret the data (e.g., render a Web page)

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UNIX Socket API

- Socket interface
  - Originally provided in Berkeley UNIX
  - Later adopted by all popular operating systems
  - Simplifies porting applications to different OSes
- In UNIX, everything is like a file
  - All input is like reading a file
  - All output is like writing a file
  - File is represented by an integer file descriptor
- System calls for sockets
  - Client: create, connect, **write/send**, read, close
  - Server: create, bind, listen, accept, **read/recv**, **write/send**, close

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Types of Sockets

- Different types of sockets implement different service models
  - Stream: SOCK_STREAM
  - Datagram: SOCK_DGRAM
- Stream socket (TCP)
  - Connection-oriented (includes *establishment* + *termination*)
  - Reliable (lossless) and in-order delivery guaranteed.
  - At-most-once delivery, no duplicates
  - E.g., SSH, HTTP (Web), SMTP (email)
- Datagram socket (UDP)
  - Connectionless (just data-transfer of packets)
  - "Best-effort" delivery, possibly lower variance in delay
  - E.g., IP Telephony (Skype), simple request/reply protocols (hostname → address lookups via DNS; time synchronization via NTP)

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Using Stream Sockets

- No need to packetize data
- Data arrives in the form of a "byte stream"
- Receiver needs to separate messages in stream

TCP may send the messages joined together, "`Hi there!Hope you are well`" or may send them separately, or might even split them like "`Hi there!Ho`" and "`pe you are well`"

application
transport
network
data-link
physical

User application sends messages "`Hi there!`" and "`Hope you are well`" separately

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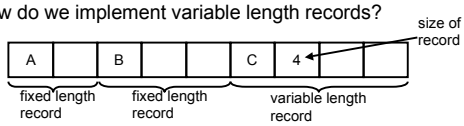
Recovering message boundaries

- Stream socket data separation:
  - Use records (data structures) to partition data stream
  - How do we implement variable length records?



  - What if field containing record size gets corrupted?
    - Not possible! Why?

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Datagram Sockets

- User packetizes data before sending
- Maximum size of 64 KB
- Using previous example, "`Hi there!`" and "`Hope you are well`" definitely sent in separate packets at network layer
  - Message boundaries preserved
  - But note: your message had better fit within 64 KB or else you'll have to layer your own boundary mechanism on top of the datagram delivery anyway

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Typical Client Program

- Prepare to communicate
  - Create a socket
  - Determine server address and port number
  - Initiate the connection to the server
- Exchange data with the server
  - Write data to the socket
  - Read data from the socket
    - Note, single socket supports both reading *and* writing
  - Do stuff with the data (e.g., render a Web page)
- Close the socket

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Creating a Socket: socket()

- Operation to create a socket
  - *int socket(int domain, int type, int protocol)*
  - Returns a descriptor (or handle) for the socket
  - Originally designed to support any protocol suite
- Domain: protocol family
  - Use PF_INET for the Internet
- Type: semantics of the communication
  - SOCK_STREAM: reliable byte stream
  - SOCK_DGRAM: message-oriented service
- Protocol: specific protocol
  - UNSPEC: unspecified. No need for us to specify, since PF_INET plus SOCK_STREAM already implies TCP, or SOCK_DGRAM implies UDP.

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Connecting the Socket to the Server

- Translate the server's name to an address
  - *struct hostent *gethostbyname(char *name)*
  - *name*: the name of the host (e.g., "www.cnn.com")
  - Returns a structure that includes the host address
    - Or NULL if host doesn't exist
- Identifying the service's port number
  - *struct servent *getservbyname(char *name, char *proto)*
  - E.g., *getservbyname*("http", "tcp")
- Establishing the connection
  - *int connect(int sockfd, struct sockaddr *server_address, socketlen_t addrlen)*
  - Arguments: socket descriptor, server address, and address size
  - Returns 0 on success, and -1 if an error occurs

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Sending and Receiving Data

- Sending data
  - *ssize_t write(int sockfd, void *buf, size_t len)*
  - Arguments: socket descriptor, pointer to buffer of data to send, and length of the buffer
  - Returns the number of characters written, and -1 on error
- Receiving data
  - *ssize_t read(int sockfd, void *buf, size_t len)*
  - Arguments: socket descriptor, pointer to buffer to place the data, size of the buffer
  - Returns the number of characters read (where 0 implies "end of file"), and -1 on error
- Closing the socket
  - *int close(int sockfd)*

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Sending and Receiving Data, con't

- Note: instead of using *write()*, you can instead use *send()*, which is intended for use with sockets.
  - Only difference is *send()* takes one additional argument of flags, which for most purposes don't matter
- Similarly, instead of using *read()*, you can instead use *recv()*
  - Again, only difference is one additional argument of flags
- Important to realize they're basically equivalent, since you see both pairs of calls used (sometimes intermingled).

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Byte Ordering

- We talk about two numeric presentations:
  - Big Endian
    - Architectures: Sun SPARC, Motorola 68000, PowerPC 970, IBM System/360
    - The most significant byte stored in memory at the lowest address.
    - Example: **4A3B2C1D** hexadecimal will be stored as:

Lowest address here

4A	3B	2C	1D

    - This is network-byte order.
  - Little Endian
    - Architectures: Intel x86, AMD64, DEC VAX
    - The least significant byte stored in memory at the lowest address.
    - Example: **4A3B2C1D** hexadecimal will be stored as:

1D	2C	3B	4A

- What problems can arise because of this?
- What can we do to solve them?

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Byte Ordering Solution

- The networking API provides us the following functions:

```
uint16_t htons(uint16_t host16bitvalue);
uint32_t htonl(uint32_t host32bitvalue);
uint16_t ntohs(uint16_t net16bitvalue);
uint32_t ntohl(uint32_t net32bitvalue);
```

- Use for all 16-bit and 32-bit binary numbers (*short*, *int*) to be sent across network
- 'h' stands for "host order"
- These routines do nothing on big-endian hosts
- Note: common mistake is to forget to use these

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Why Can't Sockets Hide These Details?

- Dealing with endian differences is tedious
  - Couldn't the socket implementation deal with this
  - … by swapping the bytes as needed?
- No, swapping depends on the data type
  - Two-byte short int: (byte 1, byte 0) vs. (byte 0, byte 1)
  - Four-byte long int: (byte 3, byte 2, byte 1, byte 0) vs. (byte 0, byte 1, byte 2, byte 3)
  - String of one-byte charters: (char 0, char 1, char 2, …) in both cases
- Socket layer doesn't know the data types
  - Sees the data as simply a buffer pointer and a length
  - Doesn't have enough information to do the swapping

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5 Minute Break

Questions Before We Proceed?

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Servers Differ From Clients

- Passive open
  - Prepare to accept connections
  - … but don't actually establish one
  - … until hearing from a client

- Hearing from multiple clients
  - Allow a backlog of waiting clients
  - ... in case several try to start a connection at once
- Create a socket for each client
  - Upon accepting a new client
  - … create a *new* socket for the communication

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Typical Server Program

- Prepare to communicate
  - Create a socket
  - Associate local address and port with the socket
- Wait to hear from a client (passive open)
  - Indicate how many clients-in-waiting to permit
  - Accept an incoming connection from a client
- Exchange data with the client over new socket
  - Receive data from the socket
  - Do stuff to handle the request (e.g., get a file)
  - Send data to the socket
  - Close the socket
- Repeat with the next connection request

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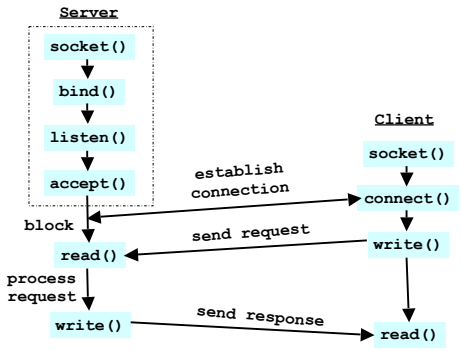
Server Preparing its Socket

- Bind socket to the local address and port number
  - *int bind (int sockfd, struct sockaddr *my_addr, socklen_t addrlen)*
  - Arguments: socket descriptor, server address, address length
  - Returns 0 on success, and -1 if an error occurs
- Define how many connections can be pending
  - *int listen(int sockfd, int backlog)*
  - Arguments: socket descriptor and acceptable backlog
  - Returns 0 on success, and -1 on error

Accepting a New Client Connection

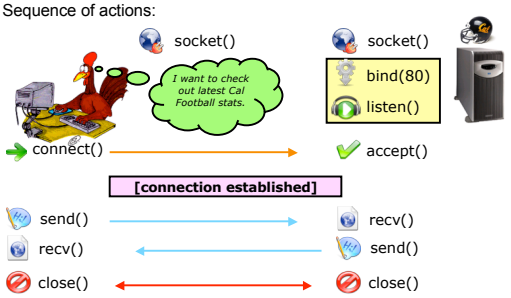
- Accept a new connection from a client
  - *int accept(int sockfd, struct sockaddr *addr, socklen_t *addrlen)*
  - Arguments: socket descriptor, structure that will provide client address and port, and length of the structure
  - Returns descriptor for a new socket for this connection
- Questions
  - What happens if no clients are around?
    - The *accept()* call blocks waiting for a client
  - What happens if too many clients are around?
    - Some connection requests don't get through
    - … But, that's okay, because the Internet makes no promises

Putting it All Together



Same, But Emphasizing the Client

- Stream socket: Transmission Control Protocol (TCP)
- Note, does not create any state inside the network
- Sequence of actions:



Let's Look At Some Code

(though you'll still need to read the manual pages too …)

Header Files

```
#include <unistd.h>     /* access to system calls */
#include <sys/types.h> /* widely used types */
#include <errno.h>      /* error codes / perror() */
#include <netdb.h>      /* gethostbyname() & friends */
#include <arpa/inet.h> /* htons() & friends */
#include <sys/socket.h> /* socket structs */
#include <netinet/in.h> /* Internet sockets, including
                           sockaddr_in */
```

Socket Creation (Client + Server)

```
int sock;
if ((sock = socket(AF_INET, SOCK_STREAM,
                        IPPROTO_TCP)) < 0) {
    perror("Failed to create TCP socket");
    abort ();
}
```

- Handling errors that occur rarely usually consumes most of systems code

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Server Reusing Its Port

- After TCP connection closes, it waits several minutes before freeing up the associated port
- But server port numbers are fixed ⇒ must be reused
- *Solution*:

```
int optval = 1;
if ((sock = socket (AF_INET, SOCK_STREAM, 0)) < 0)
   {
     perror ("couldn't create TCP socket");
     abort ();
   }
 /* Note, this call must come *before* call to bind() */
 if (setsockopt (sock, SOL_SOCKET, SO_REUSEADDR,&optval,
        sizeof (optval)) < 0)
   {
     perror ("couldn't reuse address");
     abort ();
   }
```

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Serving Binding Port to Socket

- Want port at server end to use a particular number

```
struct sockaddr_in sin;

memset (&sin, 0, sizeof (sin));

sin.sin_family = AF_INET;
sin.sin_addr.s_addr = IN_ADDR;
sin.sin_port = htons (server_port);

if (bind(sock, (struct sockaddr *) &sin, sizeof (sin))
  < 0) {
     perror("cannot bind socket to address");
     abort();
}
```

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Server waits for incoming connections

- Backlog parameter specifies max number of established connections waiting to be accepted (using **accept**()) – What would happen if you didn't bother with a backlog?

```
if (listen (sock, 5) < 0) {
     perror ("error listening");
     abort ();
}
```

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Client Establishes connection

```
struct sockaddr_in sin;

struct hostent *host = gethostbyname (argv[1]);
in_addr_t server_addr = *(in_addr_t *) host->h_addr_list[0];
unsigned short server_port = atoi (argv[2]);

memset (&sin, 0, sizeof (sin));

sin.sin_family = AF_INET;
sin.sin_addr.s_addr = server_addr; /* already in network
  order */
sin.sin_port = htons (server_port);

if (connect(sock, (struct sockaddr *) &sin, sizeof (sin)) <
  0) {
     perror("cannot connect to server");
     abort();
}
```

Must do this for all networking API calls.

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Server Accepts Incoming Connection

```
sockaddr_in addr;
int addr_len = sizeof (addr);
int sock;

sock = accept (tcp_sock, (struct sockaddr *)
                &addr, &addr_len);

if (sock < 0) {
     perror ("error accepting connection");
     abort ();
}
```

Always do error checking.

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Sending Data Stream

- Now that the connection is established, we want to send data:

```
int send_packets (char *buffer, int buffer_len)
{
  sent_bytes = send (sock, buffer, buffer_len, 0);

  if (send_bytes < 0)
    perror ("send() failed");

  return 0;
}
```

Again, can use **`write`**`()` instead of **`send`**`()`.

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Receiving Data Stream

- Receiving is nearly symmetric:

```
int receive_packets (char *buffer, int buffer_len)
{
  int num_received = recv(sock,buffer,buffer_len,0);

  if (num_received < 0)
     perror ("recv() failed");

  else if (num_received == 0)
     /* sender has closed connection */
     return EOF;

  else
     return num_received; /* might not be a full record!*/
}
```

Again, can use **`read`**`()` instead of **`recv`**`()`.

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Datagram Sockets

- Similar to stream sockets, except:
  - Sockets created using SOCK_DGRAM instead of SOCK_STREAM
  - No need for connection establishment and termination
  - Uses **`recvfrom`**`()` and **`sendto`**`()` in place of **`recv`**`()` (or **`read`**`()`) and **`send`**`()` (**`write`**()) respectively
  - Data sent in packets, not byte-stream oriented

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How to handle multiple connections?

- Where do we get incoming data?
  - Stdin / keyboard input
  - Sockets (both datagram and stream)
  - Asynchronous: don't know when data will arrive
- Solution: I/O multiplexing using **select**()
  - Efficient for our purposes(preferred method).
- Solution: I/O multiplexing using polling
  - Inefficient - avoid.
- Solution: Multithreading (POSIX et al)
  - More complex, but can scale further
  - Not covered, but feel free to try.

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I/O Multiplexing: Select (1)

- Select()
  - Wait on multiple file descriptors/sockets and timeout
  - Application does not consume CPU while waiting
  - Return when file descriptors/sockets are ready to be read or written or they have an error, or timeout exceeded
- Advantages
  - Simple
  - At smaller scales (up to many dozens of descriptors), efficient
- Disadvantages
  - Does not scale to large number of descriptors/sockets
  - More awkward to use than it needs to be

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I/O Multiplexing: Select (2)

```
fd_set read_set;
struct timeval time_out;
while (1) {
set up parameters for select()
   FD_ZERO (read_set);
   FD_SET (fileno(stdin), read_set);
   FD_SET (sock, read_set);
   time_out.tv_usec = 100000; time_out.tv_sec = 0;
run select()
   select_retval = select(MAX(stdin, sock) + 1, &read_set, NULL,
                          NULL, &time_out);
interpret result
   if (select_retval < 0) {
       perror ("select");
       abort ();
   }
   if (select_retval > 0) {
       if (FD_ISSET(sock, read_set)) {
           if (receive_packets(buffer, buffer_len, &bytes_read)
!= 0) {
               break;
           }
       if (FD_ISSET(fileno(stdin), read_set)) {
           if (read_user(user_buffer, user_buffer_len,
                         &user_bytes_read) != 0) {
               break;
           }
       }
   }
}
```

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I/O Multiplexing: Select (3)

- Explanation:
  - FD_ZERO(fd_set *set) -- clears a file descriptor set
  - **FD_SET(int fd, fd_set *set) -- adds *fd* to the set**
  - FD_CLR(int fd, fd_set *set) -- removes *fd* from the set
  - **FD_ISSET(int fd, fd_set *set) -- tests to see if *fd* is in the set**
- When does the call return?
  - An error occurs on an fd.
  - Data becomes available on an fd.
  - (Other cases you needn't worry about now)
- What do I check?
  - You use FD_ISSET to see if a particular fd is set, and if it is then you need to handle it in some way.
  - All non-active fds are cleared (so you need to reset the fd_set if you want to select again on a certain fd).
  - More than one fd set may be set after select returns.

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Common Mistakes + Hints

- Common mistakes:
  - Byte-ordering!
  - Use of `select()`
  - Separating records in TCP stream
  - Not coping with a **read**() that returns only part of a record
  - Server can't bind because old connection hasn't yet gone away
  - Not knowing what exactly gets transmitted on the wire
    - Use **tcpdump** (covered in Section next week) or **Ethereal**
- Hints:
  - **Use man pages**
  - Check out Web (ex. Beej's Guide), programming books
  - Look at sample code.

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Next Lecture

- IP: the "waist" of the Internet's layering "hourglass"
- Read P&D: 3.1, 4.1.1, 4.1.2
- **No lecture on Wed Sept. 13**
  - Next lecture is Mon Sept. 18

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Socket API Reference

- **struct hostent *gethostbyname(const char *name);**
  - **struct hostent {**
    - **char *h_name; --** Official name of the host.
    - **char **h_aliases; --** A terminated array of alternate names for the host.
    - **int h_addrtype; --** The type of address being returned; usually *AF_INET*.
    - **int h_length; --** The length of the address in bytes.
    - **char **h_addr_list; --** A zero-terminated array of network addresses for the host. Host addresses are in Network Byte Order.

    };
- **int gethostname(char *hostname, size_t size);**
  Returns the name of the computer that your program is running on.
- **int socket(int domain, int type, int protocol);**
- **int bind(int sockfd, struct sockaddr *my_addr, int addrlen);**
- **int connect(int sockfd, struct sockaddr *serv_addr, int addrlen);**
- **int accept(int sockfd, void *addr, int *addrlen);**
- **int send(int sockfd, const void *msg, int len, int flags);**
- **int recv(int sockfd, void *buf, int len, unsigned int flags);**
- **setsockopt(int *s*, int *level*, int *optname*, const void **optval*, socklen_t *optlen*);**

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C Programming Reference

- **void * memcpy (void * *dest*, const void * *src*, size_t *num*);**

  Copies *num* bytes from *src* buffer to memory location pointed by *dest*.
- **void * memset (void * *buffer*, int *c*, size_t *num*);**

  Sets the first *num* bytes pointed by *buffer* to the value specified by *c* parameter.
- **void * memmove(void **s1*, const void **s2*, size_t *n*);**

  Copies *n* bytes from memory areas *s2* to *s1*. It returns *s1*. If *s1* and *s2* overlap, all bytes are copied in a preserving manner.
- **void perror(const char *s);**

  Print a system error message.
- ***int* select(*int nfds*, *fd_set *readfds*, *fd_set *writefds*, *fd_set *exceptfds*, *struct timeval *timeout*);**

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