Communication Networks
(0368-3030) / Spring 2011
The Blavatnik School of Computer Science,
Tel-Aviv University

Allon Wagner
Staff

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Homework

- 3 practical assignments
  - “hands-on” network programming
  - C / C++
- 4-5 theoretical assignments
  - will probably include some guided-reading – bonus points
  - Guided-reading is considered part of the material for the final exam
- Moodle forum for HW related questions
Requirements & Grading

- Final Exam 60%
- Practical HW assignments 20%
- Theoretical HW assignments 20%

- Submission of all the assignments is mandatory
- HW may be submitted in pairs
- There will be a closed-books final exam
  - You may bring 4 pages (i.e. 2 two-sided sheets) with you to the exam
Textbooks & Online Material

• Course website:

• Main textbook:

• Other references:
  ▫ An Engineering Approach to Computer Networking, by S. Keshav.

• Wikipedia, and lots of online material
Why study computer networks?

• An interface between theory (algorithms, mathematics) and practice
• Understanding the design principles of a truly complex system
• Industry-relevant knowledge
• Fun!

• Challenges in teaching computer networks
• Students’ feedback
Introduction
Protocols

- A protocol defines:
  - Format (Syntax)
  - Conversation logic
  - → Finite state machine!

- Open/proprietary
Networking is a complex task

- Solution: modularity
  - Layering
  - Transparency
  - Each layer is dependent only on the interfaces defined by the layers above and below it
  - Each layer “talks” only to its equivalent on the remote side
  - Each layer is implemented by a protocol
Layering

Layer 5 protocol
Layer 4 protocol
Layer 3 protocol
Layer 2 protocol
Layer 1 protocol

Physical medium
Layering Models

- **OSI Reference Model**
  - 7 layers
  - Defined by ISO (International Standards Organization)
  - Widely used as a reference model, but seldom implemented

- **TCP/IP Reference Model**
  - 5 layers
  - Protocols came first, the model is actually a description of their workings.
  - The TCP/IP suite is the backbone of today’s Internet.
Overview of the 5-layers model

- Physical layer
  - Transmits raw bits over a communication channel
- Data link layer
  - Control layer over the physical layer
  - Framing
- Network layer
  - Delivers packets from source to destination across the network
  - Routing vs. Forwarding
  - In TCP/IP: IP is the forwarding protocol
Overview of the 5-layers model (cont.)

- **Transport layer**
  - Delivers data between a program on the source machine to a peer program on the host machine.
  - First end-to-end layer!
  - In TCP/IP:
    - TCP: reliable, connection-oriented
    - UDP: unreliable, connectionless

- **Application layer**
  - A protocol (sometimes a protocol stack) to implement the desired application service.
  - Examples:
    - Mail: SMTP, POP3, IMAP
    - Remote control: Telnet
    - File transfer and sharing: FTP, Bittorrent
    - Instant messaging: XMPP (Jabber)
Encapsulation

**message**

**segment**

**datagram/packet**

**frame**

**source host**

**destination host**

**router**

- **M** – message
- **H_t** – transport header
- **H_n** – network header
- **H_l** – link header
- **T_l** – link trailer
HW Objective: Write a network application

• Design an application protocol
  ▫ Syntax
  ▫ Semantics
  ▫ Conversation logic

• Implement via socket programming
  ▫ An interface to the OS’s transport layer
Socket Programming – Part I

Recommended References:
Beej's Guide to Network Programming
http://beej.us/guide/bgnet/
Unix Network Programming \ W. Richard Steven

Slides for this topic, as well as other topics along the course, are partly based on the work of previous teaching assistants to this course: Hillel Avni, Yahav Nussbaum, David Raz, Motti Sorani, Alex Kesselman.
IP Address / Domain Names

• “Uniquely” identifies a “host” on the network
  ▫ Not really, we’ll get to that later in the course
• A 32-bit number
  ▫ For convenience represented as 4 numbers in the range 0-255
  ▫ e.g. 132.67.192.133
• Domain names
  ▫ 132.67.192.133 = nova.cs.tau.ac.il
Port

- A 16-bit number (i.e., 0-65535)
- Identifies a service on the host
  - Again, not quite, we’ll get to that later, blah-blah.
  - For instance: HTTP = 80, SMTP = 25, Telnet = 23

- A socket is a combination of IP + port
  - 132.67.192.133 : 80
Port (cont.)

• The server listens on a certain port
• The client randomly chooses a port to which the server answers

• For instance
  94.127.73.5 : 1902 ↔ 132.67.192.133 : 80
Relevant Headers

• #include <sys/socket.h>
  ▫ Sockets
• #include <netinet/in.h>
  ▫ Internet addresses
• #include <arpa/inet.h>
  ▫ Working with Internet addresses
• #include <netdb.h>
  ▫ Domain Name Service (DNS)
• #include <errno.h>
  ▫ Working with errno to report errors
Address Representation

```c
struct sockaddr {
    u_short sa_family;
    char sa_data[14];
};
```

- **sa_family**
  - specifies which address family is being used
  - determines how the remaining 14 bytes are used
Address Representation – Internet Specific

```c
struct sockaddr_in {
    short sin_family; /* = AF_INET */
    u_short sin_port;
    struct in_addr sin_addr;
    char sin_zero[8]; /* unused */
};

struct in_addr {
    uint32_t s_addr;
}
```

- Except for `sin_family`, all contents are in network order
Big Endian / Little Endian

• Memory representation of multi-byte numbers:
  ▫ $2882400018_{10} = \text{ABCDEF12}_{16}$
  ▫ Big Endian: 0xAB CD EF 12
  ▫ Little Endian: 0x 12 EF CD AB

• Hosts on the web use both orders
• On the network all use big endian ( = network order).
• Numbers used for port number, IP etc. should thus be converted
  ▫ `htonl()` / `ntohl()` / `htons()` / `ntohs()`
## Reliable vs. Unreliable Sockets

<table>
<thead>
<tr>
<th>SOCK_STREAM</th>
<th>SOCK_DGRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>reliable transport</td>
<td>unreliable transport</td>
</tr>
<tr>
<td>connection-oriented</td>
<td>connectionless</td>
</tr>
<tr>
<td>keeps state</td>
<td>stateless</td>
</tr>
<tr>
<td>more resources needed</td>
<td>lightweight</td>
</tr>
<tr>
<td>TCP</td>
<td>UDP</td>
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</tbody>
</table>
Session overview

- We will start with reliable transport (TCP)

<table>
<thead>
<tr>
<th>Client</th>
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<th>Server</th>
</tr>
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<tr>
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<td>connect()</td>
<td>← session setup →</td>
<td>accept()</td>
</tr>
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<td>send()</td>
<td>data transfer →</td>
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</tr>
<tr>
<td>recv()</td>
<td>← data transfer</td>
<td>send()</td>
</tr>
<tr>
<td>close()</td>
<td>← terminate session →</td>
<td>close()</td>
</tr>
</tbody>
</table>
Socket Creation – socket()

- `int socket(int domain, int type, int protocol);`
- **domain**: PF_INET for IPv4
- **type**: for our purposes either `SOCK_STREAM` or `SOCK_DGRAM`
- **protocol**: can be set to 0 (default protocol)
- Returns the new socket descriptor to be used in subsequent calls, or -1 on error (and errno is set accordingly).
- Don’t forget to close the socket when you’re done with it
Bind socket to IP and port – bind()

- int **bind**(int sockfd, const struct sockaddr *my_addr, socklen_t addrlen);

- sockfd : socket descriptor
- my_addr: address to associate with the socket
  - The IP portion often set to INADDR_ANY which means “local host”
- addrlen: set to sizeof(my_addr)
- Returns 0 on success, or -1 on error (and errno is set accordingly).
Wait for an incoming call – listen()

- `int listen(int sockfd, int backlog);`
- `sockfd`: socket descriptor
- `backlog`: number of pending clients allowed, before starting to refuse connections.
- Returns 0 on success, or -1 on error (and errno is set accordingly).
Accept an incoming connection – accept()

- int accept(int sockfd, struct sockaddr *addr, socklen_t *addrlen);
  - sockfd: socket descriptor
  - addr: filled in with the address of the site that's connecting to you.
  - addrlen: filled in with the sizeof() the structure returned in the addr parameter
  - Returns the newly connected socket descriptor, or -1 on error, with errno set appropriately.
  - Don’t forget to close the returned socket when you’re done with it
Server-side example

```c
sock = socket(PF_INET, SOCK_STREAM, 0);
myaddr.sin_family = AF_INET;
myaddr.sin_port = htons(80);
myaddr.sin_addr = htonl(INADDR_ANY);
bind(sock, &myaddr, sizeof(myaddr));
listen(sock, 5);

sin_size = sizeof(struct sockaddr_in);
new_sock = accept(sock, (struct sockaddr*)
       &their_addr, &sin_size);
```

• In real-life code, don’t forget to check for errors
Session overview

- Reliable transport (TCP)

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<thead>
<tr>
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<td>← terminate session →</td>
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</table>
Connect to a listening socket – connect()

- int **connect**(int sockfd, const struct sockaddr *serv_addr, socklen_t addrlen);
  - sockfd: socket descriptor
  - serv_addr: the address you’re connecting to.
  - addrlen: filled with sizeof(serv_addr)
  - Returns 0 on success, or -1 on error (and errno is set accordingly).

Most of the times, no bind() is required on the client side:
  - If bind() wasn’t called, the local IP address and a random high port are used.
Client-side example

sock = socket(PF_INET, SOCK_STREAM, 0);

dest_addr.sin_family = AF_INET;
dest_addr.sin_port = htons(80);
dest_addr.sin_addr = htonl(0x8443FC64);

connect(sock, (struct sockaddr*)
  &dest_addr, sizeof(struct sockaddr));

• In real-life, the server’s IP is not hard-coded
• In real-life code, don’t forget to check for errors
Session overview

- Once the session is initiated, both parties are equal:
  - Both can send and receive data
  - Both can decide it’s time to close the connection
- As long as the listening socket is open, it can accept new incoming clients
  - by calling accept()
Closing a connection – close()

- **int close(int sockfd);**
- **sockfd** : socket descriptor
- returns 0 on success, or -1 on error (and errno is set accordingly)

- After we close a socket:
  - If the remote side calls **recv()**, it will return 0.
  - If the remote side calls **send()**, it will receive a signal SIGPIPE and send() will return -1 and errno will be set to EPIPE.

- **shutdown()** can be used to close only one side of the session
  - Rarely used
  - Refer to the man pages
Session overview

- Unreliable transport (UDP)

<table>
<thead>
<tr>
<th>Client</th>
<th>UDP</th>
<th>Server</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>socket()</td>
</tr>
<tr>
<td>socket()</td>
<td></td>
<td>bind()</td>
</tr>
<tr>
<td>sendto()</td>
<td>data transfer →</td>
<td>recvfrom()</td>
</tr>
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<td>sendto()</td>
</tr>
<tr>
<td>close()</td>
<td></td>
<td>close()</td>
</tr>
</tbody>
</table>
Sending data (TCP + UDP)

- TCP: `ssize_t send(int socket, const void *buffer, size_t length, int flags);`
- UDP: `ssize_t sendto(int socket, const void *buffer, size_t length, int flags, const struct sockaddr *dest_addr, socklen_t dest_len);`
- buffer, length: buffer of the data to send, and number of bytes to send from it.
- flags: send options. Refer to the man pages. Use 0 for “no options”.
- In unconnected sockets (UDP) you specify the destination in each sendto().
Partial send

- send() and sendto() return the number of bytes actually sent, or -1 on error (and errno is set accordingly).
- The number of bytes actually sent might be less than the number you asked it to send.
A code considering that
(Use it for TCP. For UDP it makes less sense – we will discuss later)

```c
int sendall(int s, char *buf, int *len) {
    int total = 0;        // how many bytes we've sent
    int bytesleft = *len; // how many we have left to send
    int n;

    while(total < *len) {
        n = send(s, buf+total, bytesleft, 0);
        if (n == -1) { break; }
        total += n;
        bytesleft -= n;
    }
    *len = total; // return number actually sent here
    return n == -1 ? -1:0; // -1 on failure, 0 on success
}
```

Source: Beej's Guide to Network Programming
Receiving data (TCP + UDP)

- TCP: `ssize_t recv(int socket, void *buffer, size_t length, int flags);`
- UDP: `ssize_t recvfrom(int socket, void *buffer, size_t length, int flags, struct sockaddr *from_addr, socklen_t from_len);`
- buffer, length: allocated space for the received data, and its size ( = max data received by this call )
- flags: receive options. Refer to the man pages. Use 0 for “no options”.
Receiving data (TCP + UDP) (cont.)

• recv() and recvfrom() return the number of bytes received, or -1 if an error occurred (and errno is set accordingly).
• In TCP sockets, 0 is returned if the remote host has closed its connection.
  ▫ This is often used to determine if the remote side has closed the connection.
• In unconnected sockets (UDP) from_addr will hold upon return the source address of the received message.
• from_len should be initialized before the call to sizeof(from_addr). It is modified on return to indicate the actual size of the address stored in from_addr.
Translating a host name to an IP address

- `struct hostent *gethostbyname(const char *name);`
  - deprecated
- `int getaddrinfo(const char *hostname, const char *servname, const struct addrinfo *hints, struct addrinfo **res);`
- Supports many options and thus seems complex, but basic use is simple.
  - Refer to Beej’s guide for more info and for a simple example of its use:
- Don’t forget to use `freeaddrinfo()` to release memory when you’re done with `getaddrinfo`’s result.
Other Useful Functions

- `inet_ntop()`, `inet_pton()`
  - Convert IP addresses to human-readable text and back
- `getpeername()`
  - Return address info about the remote side of the connection.
  - Used after calling accept() (server) or connect() (client)
- `gethostname()`
  - Returns the standard host name for the current processor
What do we send?

Tips for defining a protocol
Binary protocols

- Uniform endianness for numbers
- String representation:
  - Bad: decide on maximal length
    hello =
    0x 68 65 6C 6F 00 00 00 00
  - Better: use a length field
    hello =
    0x 05 00 68 65 6C 6F
    (note that the integer is in little endian)
- Length field can also be applied to fields of variable length (e.g., options)

An example:
- A DNS response for the query www.icann.org:
  91 73 81 80 00 01 00 01 00 00
  00 00 03 77 77 77 05 69 63 6E
  03 6F 72 67 00 00 01 00 01 00 00 02
  58 00 04 00 20 07
- For instance, bytes 0-1 are transaction ID, bytes 2-3 hold various flags.
- Text view:
  s........www.icann.org...........X....
Textual Protocols – An example

HTTP request for the page
http://www.ietf.org/rfc/rfc3514.txt

GET /rfc/rfc3514.txt HTTP/1.1
Host: www.ietf.org
Accept:
   text/html,application/xhtml+xml,application/xml;q=0.9,*/*;q=0.8
Accept-Language: en-us,en;q=0.5
Accept-Encoding: gzip, deflate
Accept-Charset: ISO-8859-1,utf-8;q=0.7,*;q=0.7
Keep-Alive: 115
Connection: keep-alive

The response:
HTTP/1.1 200 OK
Date: Sun, 13 Feb 2011 14:32:45 GMT
Last-Modified: Fri, 28 Mar 2003 18:36:14 GMT
Content-Encoding: gzip
Content-Length: 4486
Keep-Alive: timeout=15, max=100
Connection: Keep-Alive
Content-Type: text/plain
## Know the difference between TCP and UDP

<table>
<thead>
<tr>
<th>TCP</th>
<th>UDP</th>
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<tbody>
<tr>
<td>• Reliable</td>
<td>• Unreliable</td>
</tr>
<tr>
<td>• Transfers a <em>stream</em> of data</td>
<td>▪ Should consider that when working with UDP</td>
</tr>
<tr>
<td>▫ send() and recv() do not necessarily match message boundaries!</td>
<td>▫ e.g., set a timeout when sending a query and waiting for a response</td>
</tr>
<tr>
<td>▫ Can receive multiple messages together / parts of messages.</td>
<td>▪ Transfers <em>datagrams</em></td>
</tr>
<tr>
<td>▫ The application protocol must define a way to separate messages within the stream.</td>
<td></td>
</tr>
<tr>
<td>• Affected by congestion – avoidance mechanism etc.</td>
<td></td>
</tr>
</tbody>
</table>

**TCP**

- Reliable
- Transfers a *stream* of data
  - send() and recv() do not necessarily match message boundaries!
  - Can receive multiple messages together / parts of messages.
  - The application protocol must define a way to separate messages within the stream.
- Affected by congestion – avoidance mechanism etc.

**UDP**

- Unreliable
  - Should consider that when working with UDP
  - e.g., set a timeout when sending a query and waiting for a response
- Transfers *datagrams*
Word of caution - packing

- Assume you want to have a struct represent your protocol header (or part of it)

```c
struct ProtocolHeader {
    unsigned short datagramLength;
    unsigned short datagramType;
    unsigned char flag;
    //...
};
```
Word of caution – packing (cont.)

- Compiler may add padding to guarantee alignment
  - Simply sending the struct “as-is” is not portable

- Output:
  - 0 4 8 16
  - S’s size is: 24

```c
#include <stdio.h>
#include <stddef.h>

struct S {
    short i;       // 2 bytes
    int j;         // 4 bytes
    char k;        // 1 byte
    double l;      // 8 bytes
};

int main() {
    printf("%ld ", offsetof(S, i));
    printf("%ld ", offsetof(S, j));
    printf("%ld ", offsetof(S, k));
    printf("%ld\n", offsetof(S, l));
    printf("S's size is: %ld\n\n", sizeof(S));
}
```
Word of caution – packing (cont.)

- Possible solution: use `#pragma pack` and `#pragma pop`
  - Code portability issues

- Output:
  - 0 2 6 7
  - T’s size is: 15

```c
#include <stdio.h>
#include <stddef.h>

#pragma pack(push, 1)
struct T {
  short i; // 2 bytes
  int j;   // 4 bytes
  char k;  // 1 byte
  double l; // 8 bytes
};
#pragma pack(pop)

int main()
{
  printf("%ld ", offsetof(T, i));
  printf("%ld ", offsetof(T, j));
  printf("%ld ", offsetof(T, k));
  printf("%ld\n", offsetof(T, l));
  printf("T's size is: %ld\n\n", sizeof(T));
}
```
Socket Programming – Part II

Handling blocking calls
Blocking function calls

- Many of the functions we saw block until a certain event
  - accept: until a client initiates a session
  - connect: until the connection is (half) established
  - recv, recvfrom: until a data is received
  - send, sendto: until data is pushed into the socket’s buffer
- For simple programs, blocking is convenient
- What about more complex programs?
  - multiple connections
  - simultaneous sends and receives
  - simultaneously doing non-networking processing
How do we handle blocking?

- Initiate multiple threads
- Do not allow blocking by the use of `fcntl()`
- Call a function only when it’s guaranteed not to block
  - `select()`, `pselect()`, `poll()`, `ppoll()`
  - `select()` gets a set of fd’s and returns which of them is
    - Read-ready: `recv()` (data socket) or `accept()` (listening socket) will not block
    - Write-ready: `send()` will not block
select()

- `int select(int nfds, fd_set *readfds, fd_set *writefds, fd_set *exceptfds, struct timeval *timeout);`
- `nfds`: highest-numbered file descriptor in any of the three sets, plus 1.
- `readfds, writefds, exceptfds`: sets of fd’s to see if they’re read-ready, write-ready or except-ready
  - “Exceptional conditions” are not errors, but rather states of the sockets (e.g. TCP’s urgent ptr is set).
  - Any set can be replaced with NULL → the corresponding condition will not be checked.
select() (cont.)

- Returns when at least one of the watched fd’s becomes ready, or when the timeout expires
  - Returns the total number of ready fd’s in all the sets. The sets are changed to indicate which fd’s are ready.
  - Returns 0 if timeout expired
  - Returns -1 on error (and errno is set accordingly).
Working with `fd_set`

- `fd_set` is just a bit vector
- `void FD_ZERO (fd_set *set)`
  - Initializes to an empty set
- `void FD_SET (int fd, fd_set *set)`
  - Adds `fd` to the set
- `int FD_ISSET (int fd, fd_set *set)`
  - Returns non-zero value if `fd` is in the set, 0 otherwise
- `void FD_CLR (int fd, fd_set *set)`
  - Removes `fd` from the set
- `stdin`, `stdout`, `stderr` are associated with `fd`’s 0, 1, 2 respectively
select’s timeout argument

```c
struct timeval {
    long tv_sec; /* seconds */
    long tv_usec; /* microseconds, always less than 10^6 */
};
```

- Pass (0,0) to return immediately
- Pass NULL pointer to wait indefinitely until one of the fd’s is ready
- Some OS’s decrease the time elapsed, some don’t
  - Linux does
select example:
reading from multiple active sockets
fd_set read_fds;

// main loop of the program
for(;;) {
    FD_ZERO(&read_fds); // reset fd set
    FD_SET(listening_sock, &read_fds);
    for(/* for each active client with fd = client_sock */) {
        FD_SET(client_sock, &read_fds);
    }
    fdmax = //... the highest fd in read_fds

    select(fdmax + 1, &read_fds, NULL, NULL, NULL);

    if (FD_ISSET(listening_sock, &read_fds)) {
        // listening socket is read-ready: a new client is available.
        // new_client_sock = accept(listening_sock, ...
    }

    for(/* for each active client with fd = client_sock */) {
        if (FD_ISSET(client_sock, &read_fds)) {
            // client socket is read ready - unread data is available
            // nbytes = recv(client_sock, ...
        }
    } // END main program loop