CSC209 Summer 2015 — Software Tools and Systems Programming

www.cdf.toronto.edu/~csc209h/summer/

Week 11 — July 23, 2015

Peter McCormick
pdm@cs.toronto.edu

Some materials courtesy of Karen Reid

Announcements

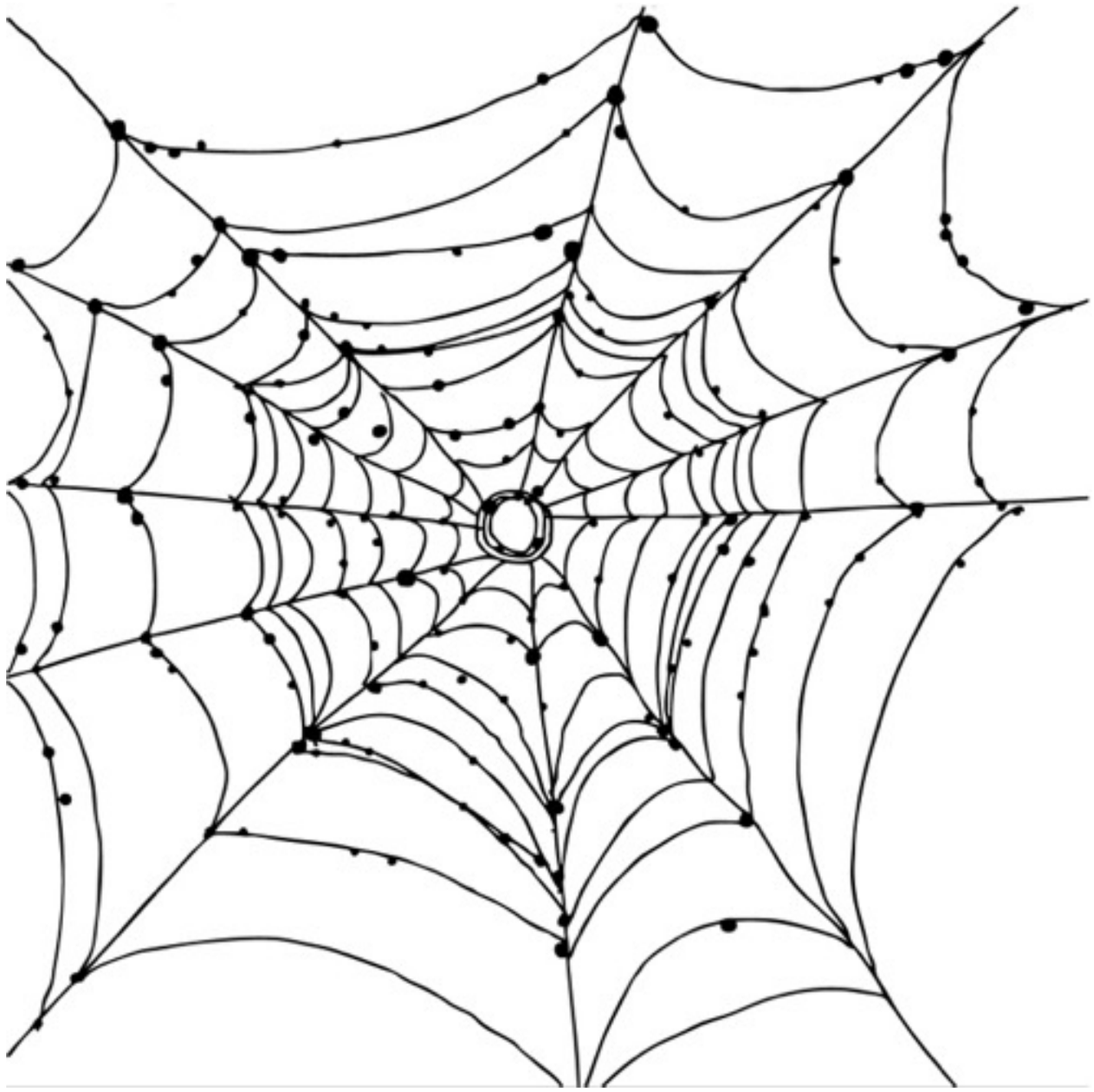
- **Final exam date has been determined:**
  - **Tuesday, August 11 (evening)**
  - http://www.artsci.utoronto.ca/current/exams/reminder
- No tutorial tonight

Agenda

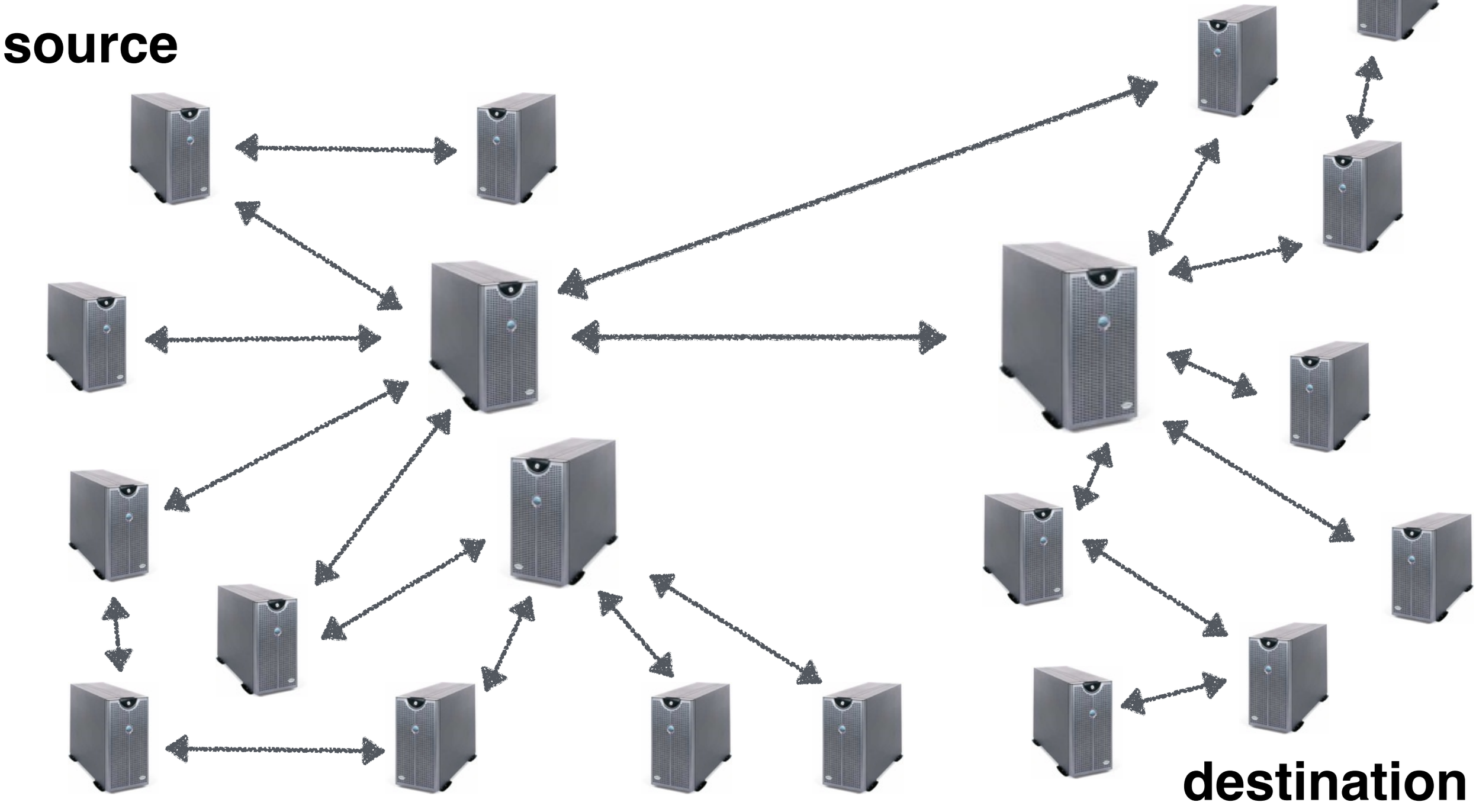
- Last week recap
- `setsockopt`
- I/O multiplexing

Last Week Recap

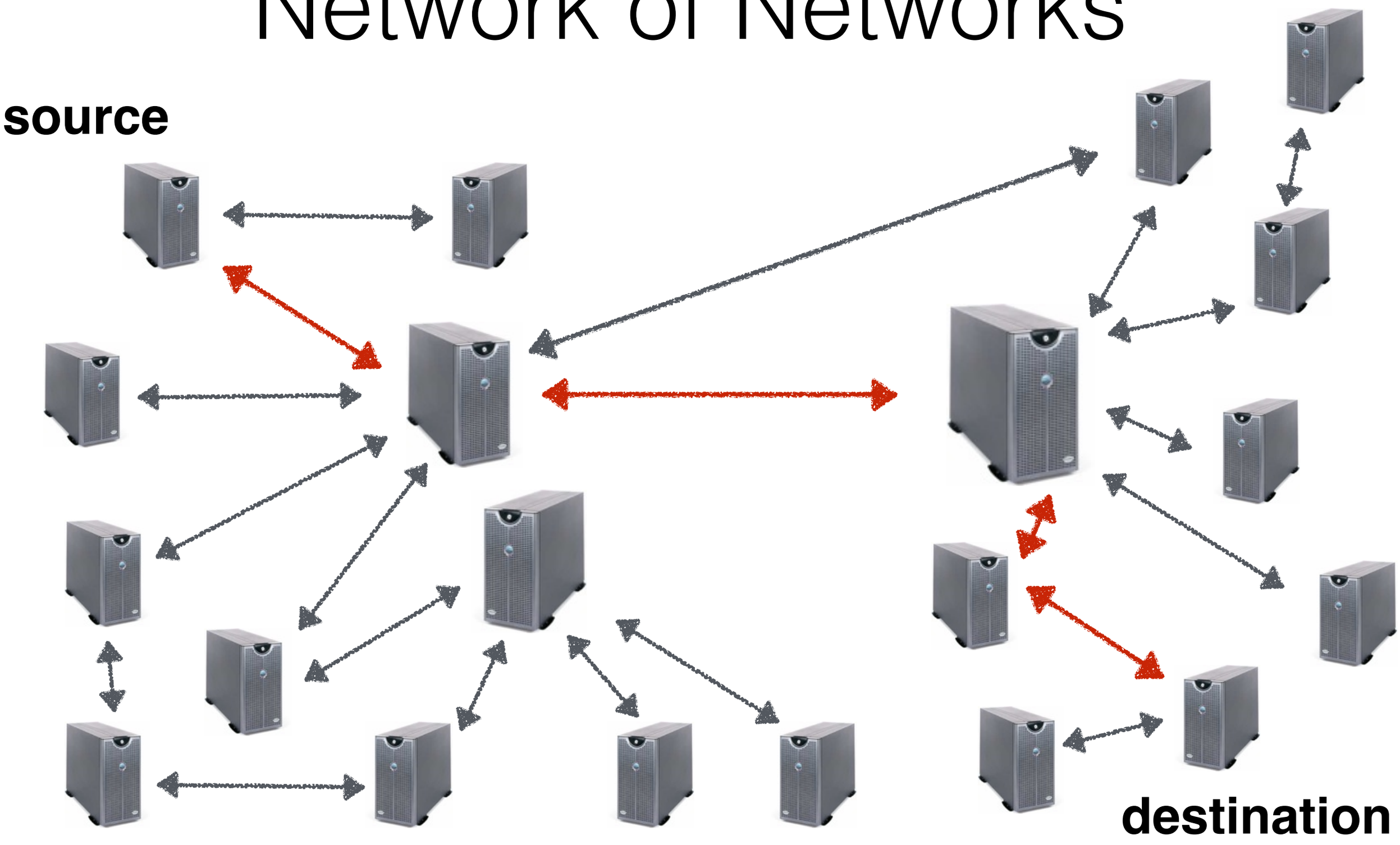
Web of Hyper Links *vs* Network of Hops



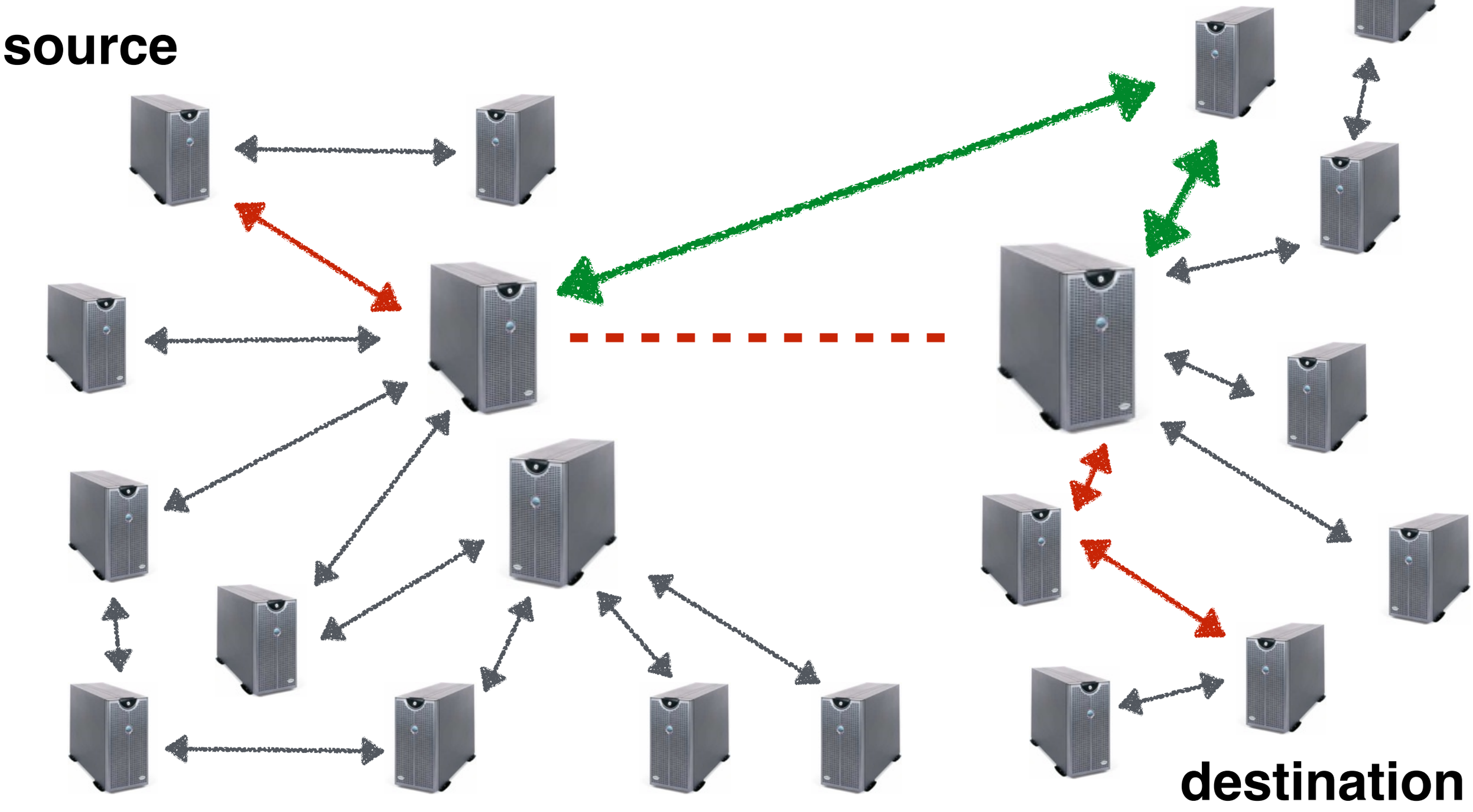
Web of Hyper Links *vs* Network of Networks



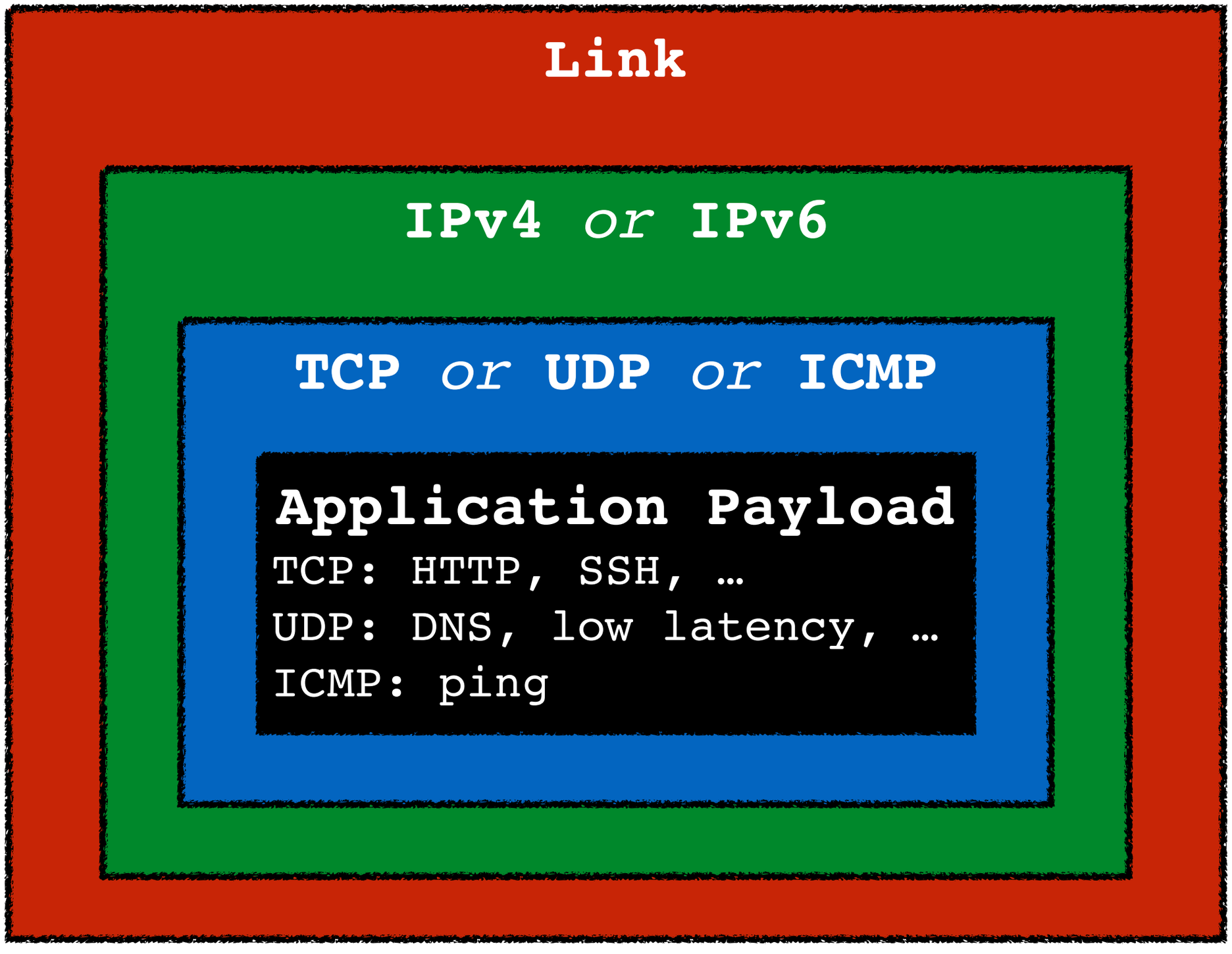
Web of Hyper Links *vs* Network of Networks



Web of Hyper Links *vs* Network of Networks

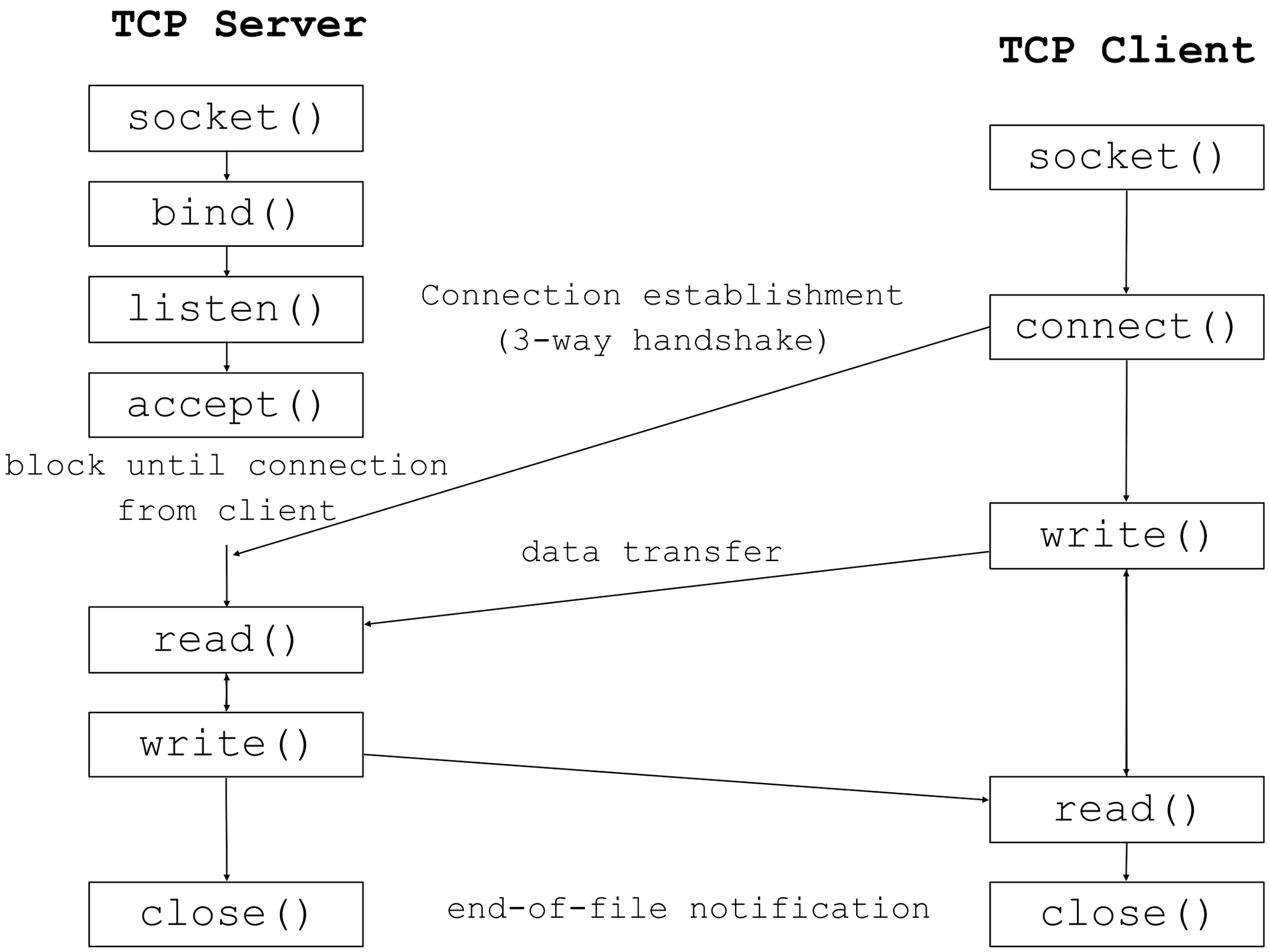


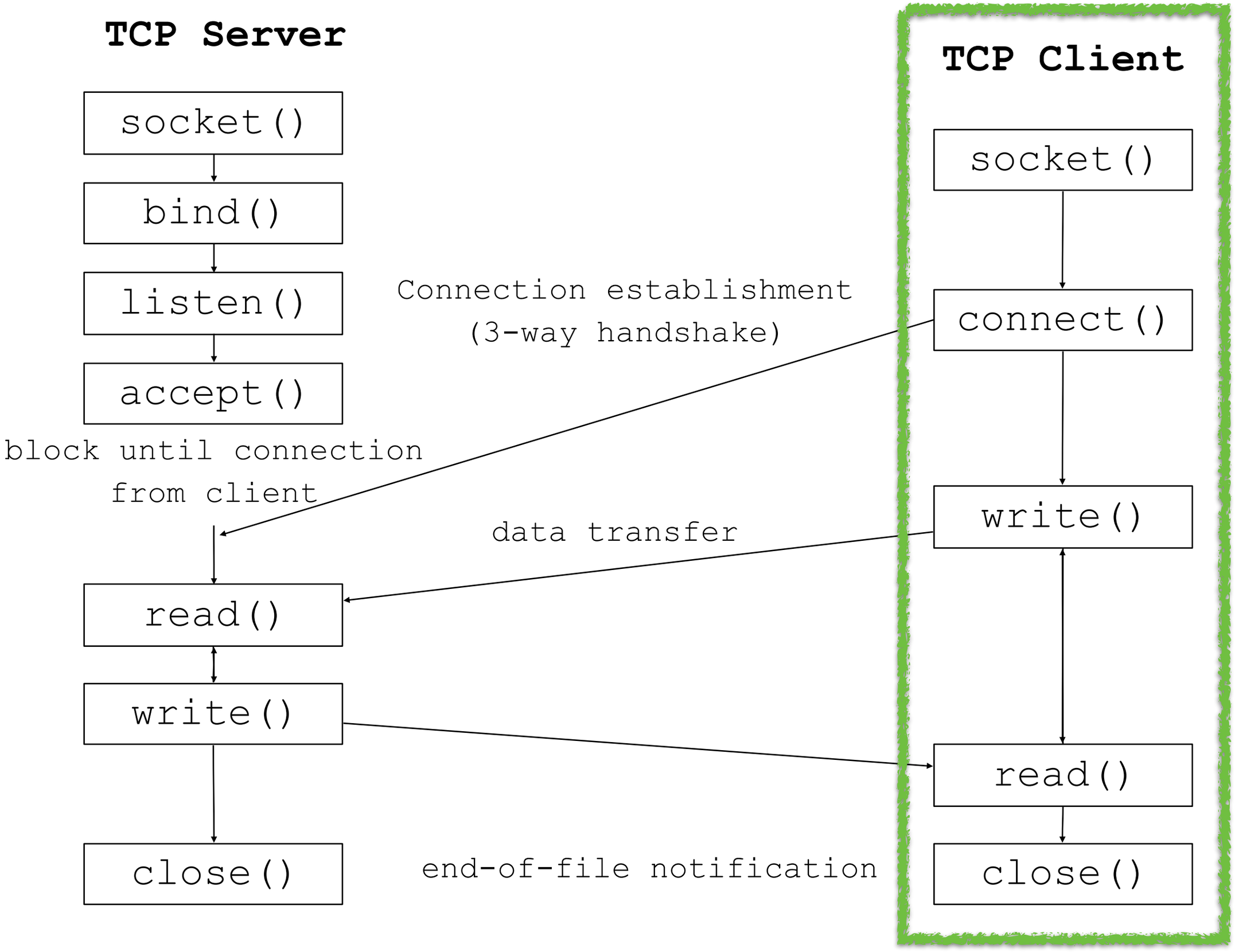
Packets as Onions

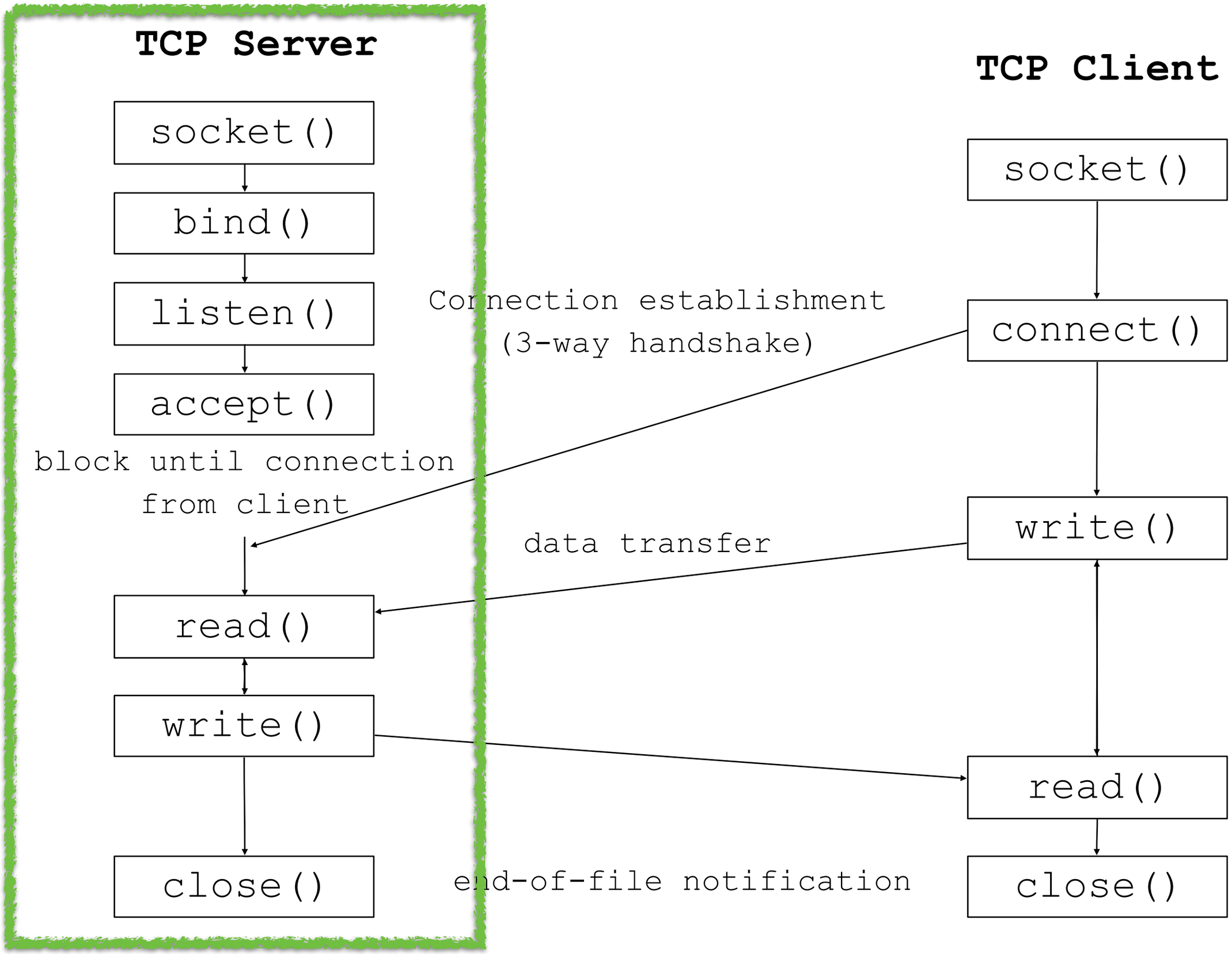


Assorted Terminology

- Packet contains ***headers*** as metadata (source and destination information, ports, protocol specific bits, etc.)
- Packets travel end-to-end by being forwarded over multiple hops by multiple interior ***routers***
- Locations identified by numeric IPv4 ***addresses***, example 128.100.31.200
- DNS to ***resolve*** names to addresses
- TCP as a ***client/server*** model for conversational, connection-oriented interactions
- An unreliable IP network made to appear ***reliable*** thanks to TCP
- ***Request/response*** protocols like HTTP


TCP Server
TCP Client
socket()
bind()
listen()
accept()
block until connection
from client
Connection establishment
(3-way handshake)
socket()
connect()
write()
data transfer
read()
write()
read()
close()
end-of-file notification
close()


TCP Server
socket()
bind()
listen()
accept()
block until connection
from client
read()
write()
close()
Connection establishment
(3-way handshake)
data transfer
end-of-file notification
TCP Client
socket()
connect()
write()
read()
close()


TCP Server
socket()
bind()
listen()
accept()
block until connection
from client
read()
write()
close()
TCP Client
socket()
connect()
write()
read()
close()
Connection establishment
(3-way handshake)
data transfer
end-of-file notification

Connection-Oriented

Server:

- Create a socket: **`socket()`**
- Assign a name to a socket: **`bind()`**
- Establish a queue for connections: **`listen()`**
- Get a connection from the queue: **`accept()`**

Client:

- Create a socket: **`socket()`**
- Initiate a connection: **`connect()`**

netcat (**`nc`**): a command line utility for acting as either a socket client or a socket server

Use *`/bin/nc`* on CDF!

Run a server *and* client using `netcat`

Server (*listening*):

```
wolf:~$ /bin/nc -vlk localhost 209##
```

Client (*connecting*):

```
wolf:~$ /bin/nc –v localhost 209##
```

NB: Other students may be using the same port number so if necessary find one that is free!

setsockopt — set options on a socket

`setsockopt` — set options on a socket

```
int setsockopt(int sockfd,
               int level,
               int optname,
               const void *optval,
               socklen_t optlen);
```

- Remember that the socket API's can be used with more than just TCP/IP stream sockets, so we need to generally remind system calls about what we need!
  - Like setting **`sin_family`** to **`AF_INET`** in **`struct sockaddr_in`**'s

`setsockopt` — set options on a socket

```
int setsockopt(int sockfd,
               int level,
               int optname,
               const void *optval,
               socklen_t optlen);
```

- **`level`**: indicate which part of the networking stack should interpret this option
  - **`SOL_SOCKET`**: set a socket-level option
  - **`IPPROTO_TCP`**: set options referring to the TCP layer

`setsockopt` — set options on a socket

```
int setsockopt(int sockfd,
               int level,
               int optname,
               const void *optval,
               socklen_t optlen);
```

- `optname`: a level-dependent option name
- For `SOL_SOCKET` level, a few examples:
  - `SO_REUSEADDR`: allow reuse of local addresses
  - `SO_KEEPALIVE`: attempt to keep a connection open even when nothing is being transmitted
  - See `socket(7)` for more!

`setsockopt` — set options on a socket

```
int setsockopt(int sockfd,
               int level,
               int optname,
               const void *optval,
               socklen_t optlen);
```

- Since this is a *generic* interface, **`optval`** is an opaque **`void`** pointer to a variable type that will depend on **`level`** and **`optname`**

- The size of that value must be passed in via **`optlen`**

- Many **`SOL_SOCKET`** socket options expect an integer sized boolean flag

`setsockopt` — set options on a socket

```
// Enable the SO_REUSEADDR option on sockfd
int optval = 1; // Boolean true

int rc = setsockopt(
    sockfd,
    SOL_SOCKET,
    SO_REUSEADDR,
    (void *) &optval,
    sizeof (optval) /* ==sizeof (int) */
  );
```

`setsockopt` — set options on a socket

```
int setsockopt(int sockfd,
               int level,
               int optname,
               const void *optval,
               socklen_t optlen);
```

- See also **`getsockopt`** to *retrieve* current options

What does `SO_REUSEADDR` *do*, and why do we care about *any* of these options?

bind: Address already in use

simpleserver1.c

- socket
- **bind**
- **listen**
- repeatedly **accept**
  - **read** until end-of-stream
  - **close**

Enabling `SO_REUSEADDR` fixes this for us

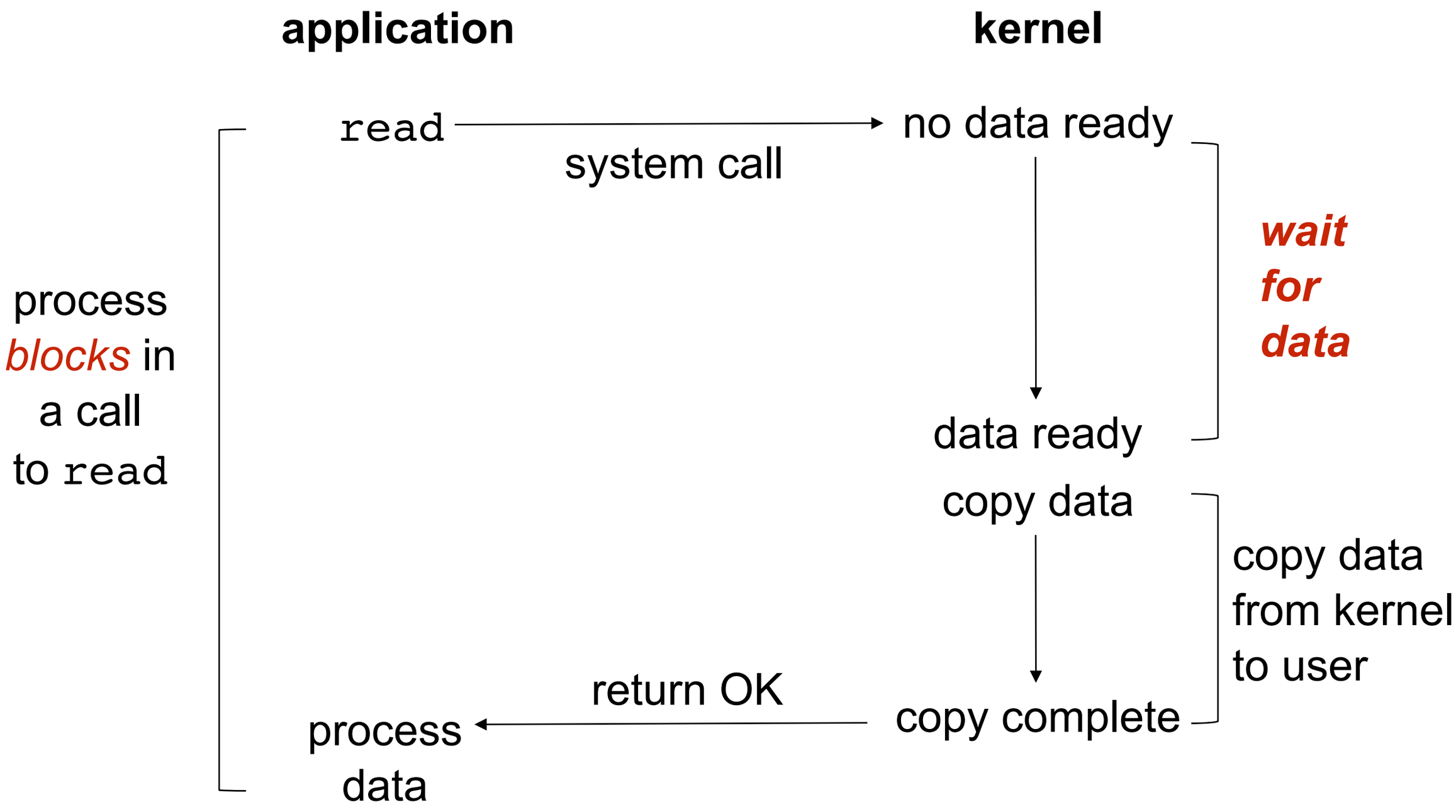
Dealing with Multiple Connections with I/O Multiplexing

Kerrisk 63

Dealing with Multiple Connections

- The **`read`** system call accepts only a single descriptor, and (for sockets) will block until the other end of that socket connection sends us something

Blocking I/O Model



Dealing with Multiple Connections

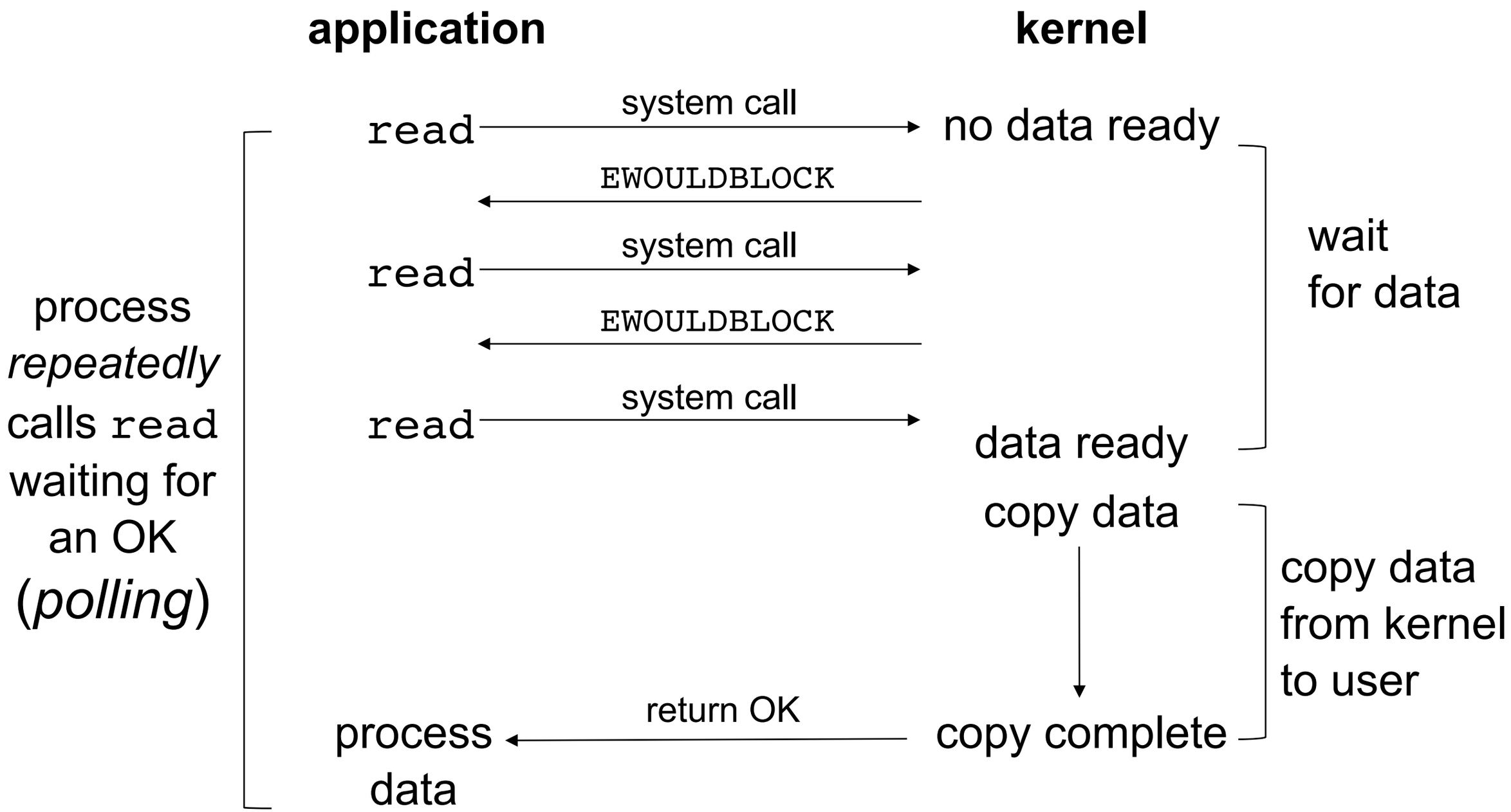
- What if you have more than one socket to read from at a time?

dualclient1.c

Dealing with Multiple Connections

- It's possible to put sockets into a *non-blocking* mode, where the **`read`** system call returns immediately and signals an error if it would otherwise have to block waiting for data

Non-blocking I/O Model



Polling Busy-loop Approach:

set all sockets to be *non-blocking*…

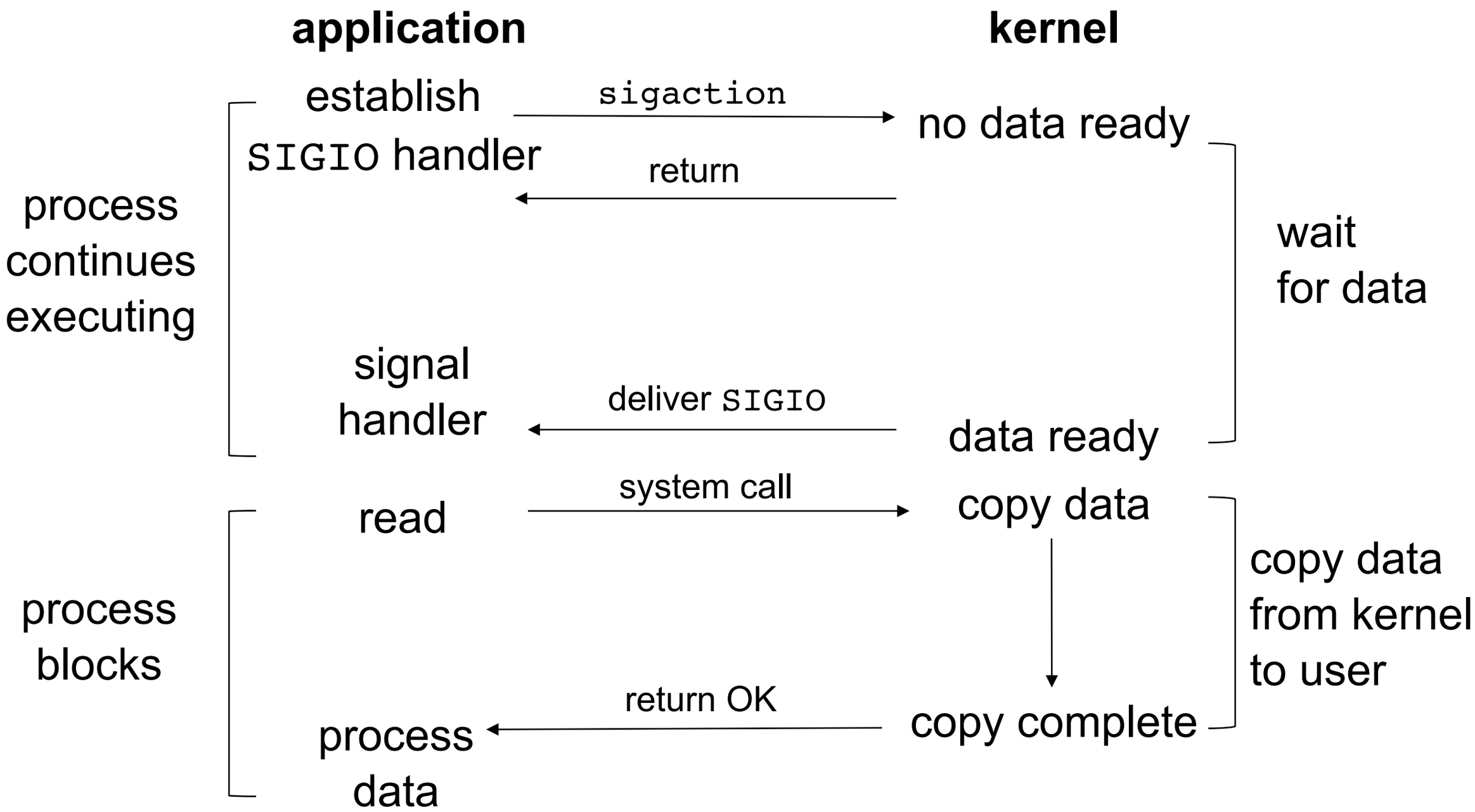
```
while (1) {
   for each sockfd that is currently connected {
      int rc = read(sockfd, …)
      if (rc == -1 && errno == EWOULDBLOCK):
         continue;

      process read data …
   }

   rinse & repeat…
}
```

It’s also possible to setup the kernel to deliver *signals* to your process when I/O is ready

Signal Driven I/O Model



soloserver.c

- `socket` and `setsockopt`
- `bind`
- `listen`
- repeatedly `accept`
  - `read` until end-of-stream
  - `close`

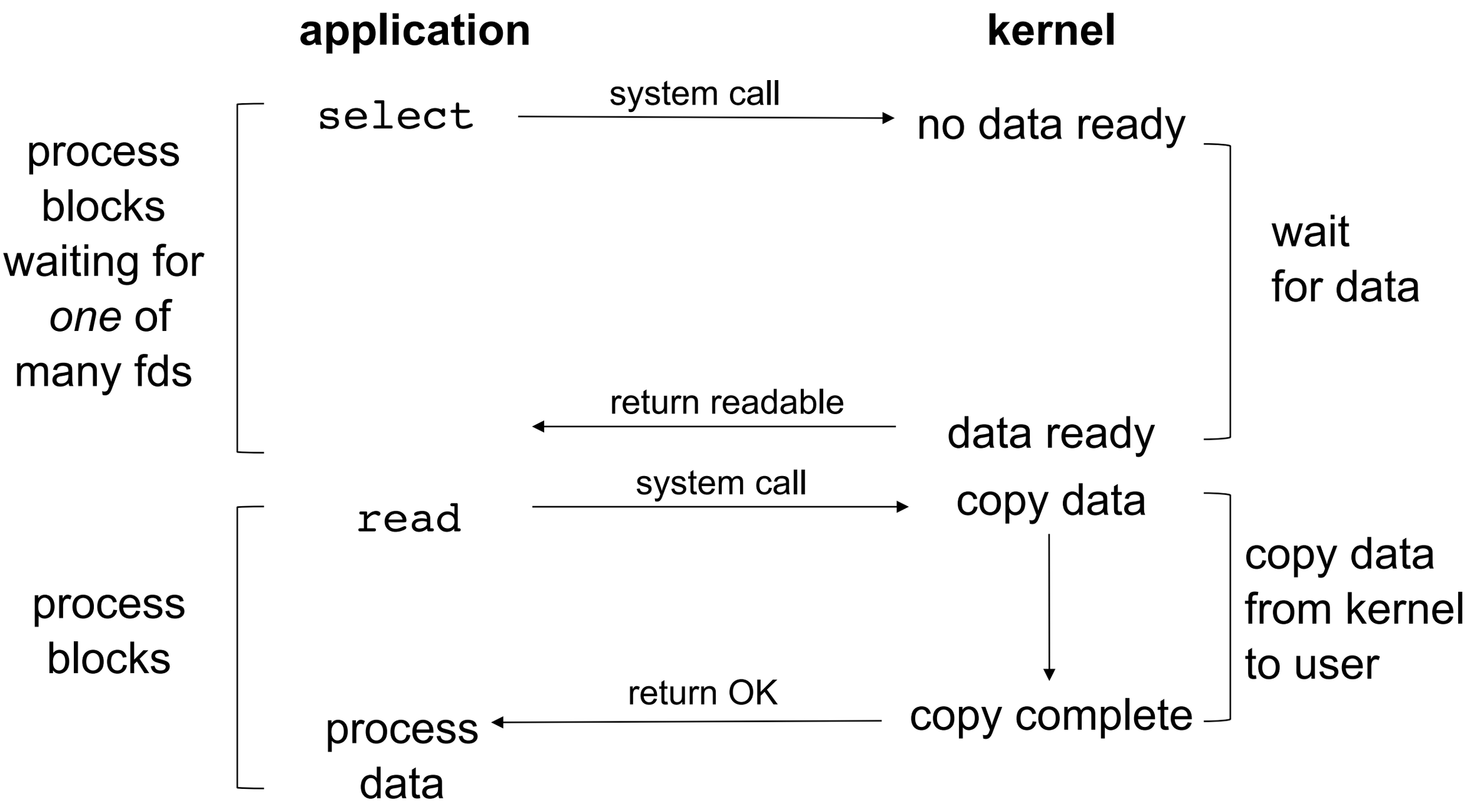
What happens if *two* clients ***simultaneously*** try to connect to `soloserver`?

- `socket` and `setsockopt`
- `bind`
- `listen`
- repeatedly `accept`
  - `read` until end-of-stream
  - `close`

What We Want: a mechanism whereby the kernel tells us which descriptors are available to read *now*, and then read *only* from those

select

I/O Multiplexing Model



`select` — synchronous I/O multiplexing

```
int select(int max_fd_plus_1,
           fd_set *readfds,
           fd_set *writefds,
           fd_set *exceptfds,
           struct timeval *timeout);
```

- The most sophisticated system call interface we have seen yet!

`select` — synchronous I/O multiplexing

```
int select(int max_fd_plus_1,
           fd_set *readfds,
           fd_set *writefds,
           fd_set *exceptfds,
           struct timeval *timeout);
```

- Returns when (*blocks until*) either:
  - The (optionally non-`NULL`) `timeout` has expired, *or*
  - When at least one of the file descriptors in one of the sets is *ready* for I/O
- If timeout duration is 0, returns immediately after checking descriptors

Readiness

- Ready to ***read*** when:
  - There is data in the receive buffer to be read
  - End-of-file state on file descriptor
  - The socket is a listening socket and there is a connection pending
  - A socket error is pending
- Generally most interested in read readiness

Readiness

- Ready to ***write*** when:
  - There is space available in the write buffer
  - A socket error is pending
- Useful if you plan on writing a lot of bytes (otherwise connection can block waiting for buffer space to become available)

Readiness

- Ready to handle ***exception condition*** when:
  - TCP out-of-band data

struct timeval

```
struct timeval {
  long tv_sec;   /* seconds */
  long tv_usec;  /* microseconds */
};
```

- The optional `timeout` specifies how long we are willing to wait for descriptors readiness before returning anyways

- If timeout is `NULL`, block waiting forever (or until a signal is delivered)

- If timeout durations are 0, test descriptors and return immediately

Descriptor Sets

- `fd_set` is a datatype for holding sets of file descriptors

- Since descriptors are non-negative integers, they are typically implemented as a *bit set* (using an array of integers)

  - Bit *N* is set to 1 iff file descriptor *N* is in the set

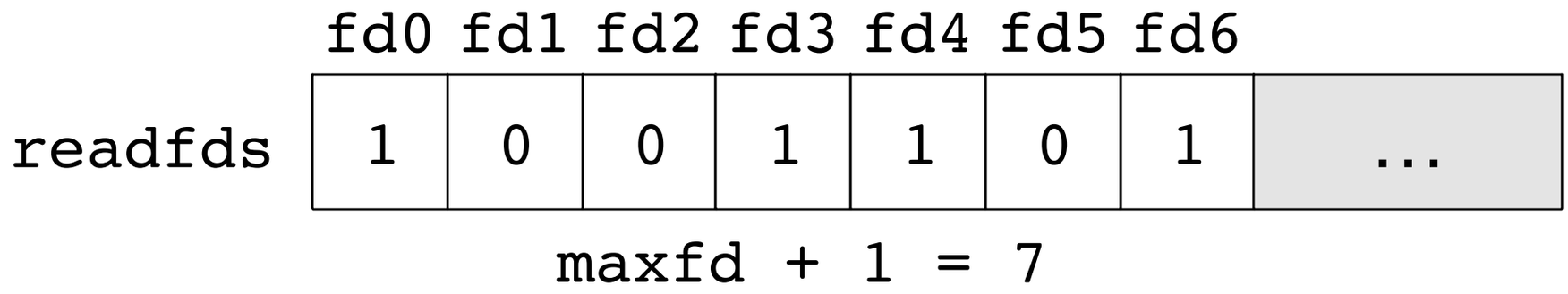
Descriptor Sets

- We indicate our interest in the read/write/exception readiness of a file descriptor by adding it to the appropriate set before the **`select`** call

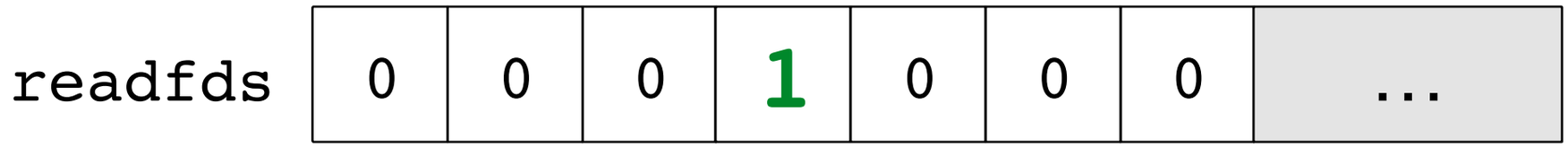
- The **`select`** call will modify *all* of the sets, clearing all bits except for the ones corresponding to file descriptors which are now ready

- After the call, we check each relevant bit of the set to see what is ready

Before `select`:



After `select`:



`select` has informed you that **`FD 3`** is ready for reading!

Descriptor Sets

- Implementation details are hidden in the **`fd_set`** data type

  - **`FD_SETSIZE`** is the number of descriptors in the data type

    - This is a fixed maximum, thus there is a hard limit on the number of descriptors you can select over!

- **`max_fd_plus_1`** specifies the number of descriptors to test, so that the call doesn't have to check all of the fixed maximum of descriptors unnecessarily

Descriptor Sets

- *void* **FD_ZERO**(*fd_set* *fdset);
  - Zero out all bits in the set (removing all descriptors)
- *void* **FD_SET**(*int* fd, *fd_set* *fdset);
  - Add a specific descriptor (set a bit) to the set
- *void* **FD_CLR**(*int* fd, *fd_set* *fdset);
  - Remove a specific descriptor (clear a bit) to the set
- *int* **FD_ISSET**(*int* fd, *fd_set* *fdset);
  - Check whether a specific descriptor is in the set (whether the bit is 1)

Using `select`

1. *Setup* read/write/except sets for your descriptors of interest (noting the largest FD you added)

2. *Setup* an optional timeout value

3. *Call* **`select`**

4. For each descriptor you initially added:

    - Check whether the FD is still in the given set. If it is, then you know that it is ready for I/O

selectstdin.c

dualclient2.c

multiserver.c

- `select` has some problems
  - Fixed number of descriptors in sets
  - Large overhead of doing the setup, call and checking return values in order to process ~1 descriptor (doesn't scale for large servers)
- Alternative Unix APIs for multiplexing I/O exist
  - `poll`
  - `epoll` (Linux specific)
  - `kqueue` (FreeBSD and Mac OS X specific)
  - Windows has its own APIs and idioms

Suggested Exercises

https://github.com/pdmccormick/csc209-summer-2015/blob/master/lectures/week11/README.md

Next Week

- Regularly scheduled office hour on Tuesday
- A4 to be released within next couple of days

Extra Slides

Implementing Bit Sets in C

Arrays of bit strings

- FD_SETSIZE is bigger than 32.

```
struct bits {
  unsigned int field[N];
}
typedef struct bits Bitstring;
Bitstring a, b;
setzero(&a);
b = a;
a.field[0] = ~0;
```

Setting and unsetting

```
int set(unsigned int bit, Bitstring *b) {
   int index = bit / 32;
   b->field[index] |= 1 << (bit % 32);
   return 1;
}

int unset(unsigned int bit, Bitstring *b) {
   int index = bit / 32;
   b->field[index] &= ~(1 << (bit % 32));
}
```

Testing and emptying

```
int ifset(unsigned int bit, Bitstring *b) {
   int index = bit / 32;
   return ( (1 << (bit % 32))
            & b->field[index]);
}

int setzero(Bitstring *b){
   if(memset(b,0, sizeof(Bitstring)) == NULL)
      return 0;
   else
      return 1;
}
```

Printing

```
char *intToBinary(unsigned int number) {
  char *binaryString = malloc(32+1);
  int i;
  binaryString[32] = '\0';
  for (i = 31; i >= 0; i--) {
    binaryString[i] = ((number & 1) + '0');
    number = number >> 1;
  }
  return binaryString;
}
```