CS162
Operating Systems and Systems Programming
Lecture 6

Abstractions 4: Sockets, I/O, IPC (finished)

February 1st, 2024

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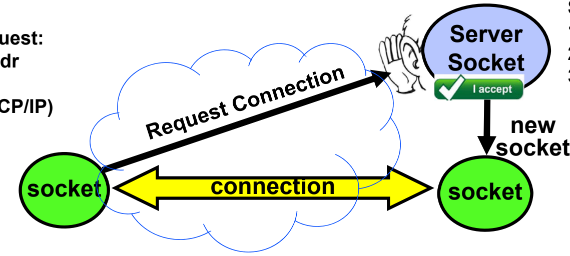
Recall: Connection Setup over TCP/IP

Client Side

Server Side

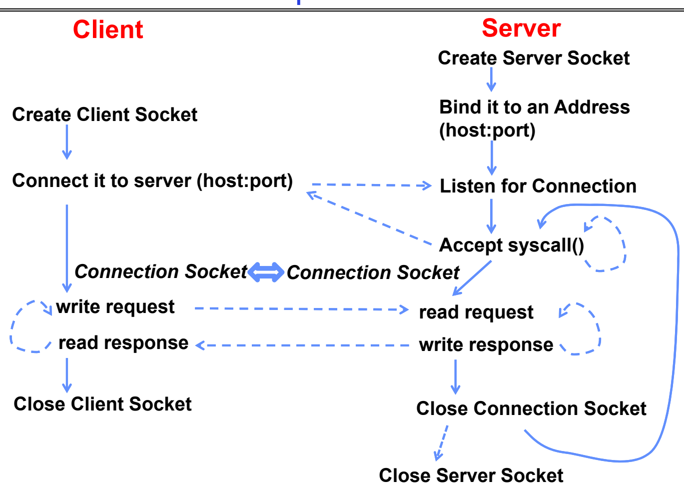
Connection request:
1. **Client IP addr**
2. **Client Port**
3. **Protocol (TCP/IP)**

Server Listening:
1. **Server IP addr**
2. **well-known port,**
3. **Protocol (TCP/IP)**



- 5-Tuple identifies each connection:
  1. Source IP Address
  2. Destination IP Address
  3. Source Port Number
  4. Destination Port Number
  5. Protocol (always TCP here)
- Often, Client Port "randomly" assigned
  – Done by OS during client socket setup
- Server Port often "well known"
  – 80 (web), 443 (secure web), 25 (sendmail), etc
  – Well-known ports from 0—1023

Recall: Simple Web Server



Client Code

```
char *host_name, *port_name;

// Create a socket
struct addrinfo *server = lookup_host(host_name, port_name);
int sock_fd = socket(server->ai_family, server->ai_socktype,
                     server->ai_protocol);

// Connect to specified host and port
connect(sock_fd, server->ai_addr, server->ai_addrlen);

// Carry out Client-Server protocol
run_client(sock_fd);

/* Clean up on termination */
close(sock_fd);
```

Client-Side: Getting the Server Address

```
struct addrinfo *lookup_host(char *host_name, char *port) {
  struct addrinfo *server;
  struct addrinfo hints;
  memset(&hints, 0, sizeof(hints));
  hints.ai_family = AF_UNSPEC;         /* Includes AF_INET and AF_INET6 */
  hints.ai_socktype = SOCK_STREAM;     /* Essentially TCP/IP */

  int rv = getaddrinfo(host_name, port_name, &hints, &server);
  if (rv != 0) {
    printf("getaddrinfo failed: %s\n", gai_strerror(rv));
    return NULL;
  }
  return server;
}
```


Server Code (v1)

```
// Create socket to listen for client connections
char *port_name;
struct addrinfo *server = setup_address(port_name);
int server_socket = socket(server->ai_family,
                           server->ai_socktype, server->ai_protocol);
// Bind socket to specific port
bind(server_socket, server->ai_addr, server->ai_addrlen);
// Start listening for new client connections
listen(server_socket, MAX_QUEUE);

while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  serve_client(conn_socket);
  close(conn_socket);
}
close(server_socket);
```


Server Address: Itself (wildcard IP), Passive

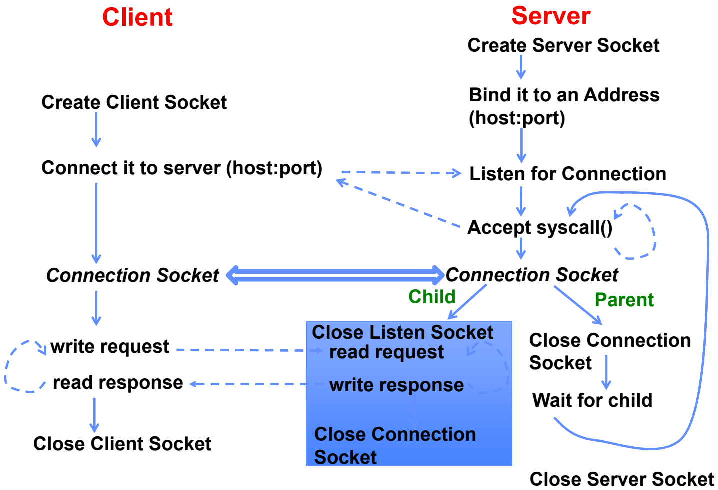
```
struct addrinfo *setup_address(char *port) {
  struct addrinfo *server;
  struct addrinfo hints;
  memset(&hints, 0, sizeof(hints));
  hints.ai_family = AF_UNSPEC;           /* Includes AF_INET and AF_INET6 */
  hints.ai_socktype = SOCK_STREAM;       /* Essentially TCP/IP */
  hints.ai_flags = AI_PASSIVE;           /* Set up for server socket */

  int rv = getaddrinfo(NULL, port, &hints, &server);  /* No address! (any local IP) */
  if (rv != 0) {
    printf("getaddrinfo failed: %s\n", gai_strerror(rv));
    return NULL;
  }
  return server;
}
```

- **Accepts any connections on the specified port**

How Could the Server Protect Itself?

- Handle each connection in a separate process
  - This will mean that the logic serving each request will be "sandboxed" away from the main server process
- In the following code, keep in mind:
  - `fork()` will duplicate *all* of the parent's file descriptors (i.e. pointers to sockets!)
  - We keep control over accepting new connections in the parent
  - New child connection for each remote client

Server With Protection (each connection has own process)



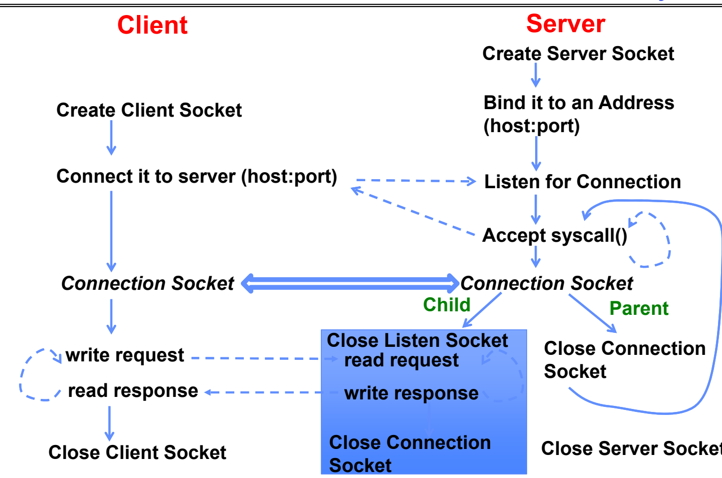
Server Code (v2)

```
// Socket setup code elided…
listen(server_socket, MAX_QUEUE);
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);
    exit(0);
  } else {
    close(conn_socket);
    wait(NULL);
  }
}
close(server_socket);
```


How to make a Concurrent Server

- So far, in the server:
  - Listen will queue requests
  - Buffering present elsewhere
  - But server *waits* for each connection to terminate before servicing the next
    - » This is the standard shell pattern
- A concurrent server can handle and service a new connection before the previous client disconnects
  - Simple – just don't wait in parent!
  - Perhaps not so simple – multiple child processes better not have data races with one another through file system/etc!

Server With Protection and Concurrency



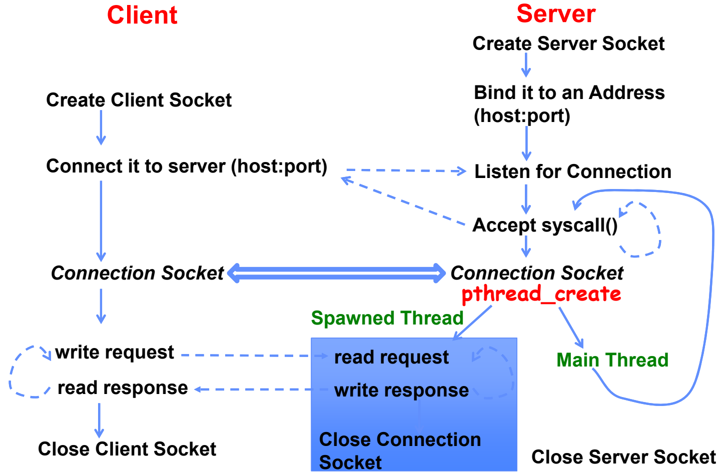
Server Code (v3)

```
// Socket setup code elided…
listen(server_socket, MAX_QUEUE);
while (1) {
  // Accept a new client connection, obtaining a new socket
  int conn_socket = accept(server_socket, NULL, NULL);
  pid_t pid = fork();
  if (pid == 0) {
    close(server_socket);
    serve_client(conn_socket);
    close(conn_socket);
    exit(0);
  } else {
    close(conn_socket);
    //wait(NULL);
  }
}
close(server_socket);
```


Faster Concurrent Server (without Protection)

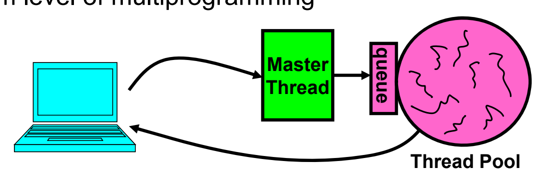
- Spawn a new *thread* to handle each connection
  - Lower overhead spawning process (less to do)
- Main *thread* initiates new client connections without waiting for previously spawned threads
- Why give up the protection of separate processes?
  - More efficient to create new threads
  - More efficient to switch between threads
- Even more potential for data races (need synchronization?)
  - Through shared memory structures
  - Through file system

Server with Concurrency, without Protection



Thread Pools: More Later!

- Problem with previous version: Unbounded Threads
  - When web-site becomes too popular – throughput sinks
- Instead, allocate a bounded “pool” of worker threads, representing the maximum level of multiprogramming




```
master() {
   allocThreads(worker,queue);
   while(TRUE) {
      con=AcceptCon();
      Enqueue(queue,con);
      wakeUp(queue);
   }
}
```

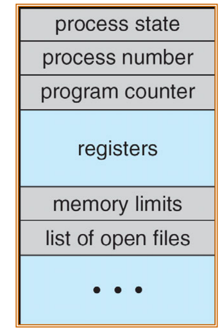
```
worker(queue) {
   while(TRUE) {
      con=Dequeue(queue);
      if (con==null)
         sleepOn(queue);
      else
         ServiceWebPage(con);
   }
}
```

Administrivia

- Project 1 in full swing! Released Yesterday!
  - We expect that your design document will give intuitions behind your designs, not just a dump of pseudo-code
  - Think of this you are in a company and your TA is you manager
- Paradox: need code for design document?
  - Not full code, just enough prove you have thought through complexities of design
- Should be attending your permanent discussion section!
  - Discussion section attendance is mandatory, but don't come if sick!!
    - » We have given a mechanism to make up for missed sections—see EdStem
- Midterm 1: February 15th, 8-10PM (Two weeks from today!)
  - Fill out conflict request form!

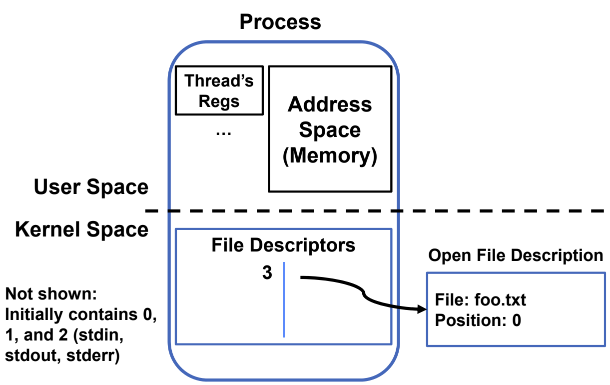
Recall: The Process Control Block

- Kernel represents each process as a process control block (PCB)
  - Status (running, ready, blocked, …)
  - Register state (when not ready)
  - Process ID (PID), User, Executable, Priority, …
  - Execution time, …
  - Memory space, translation, …
- Kernel *Scheduler* maintains a data structure containing the PCBs
  - Give out CPU to different processes
  - This is a Policy Decision
- Give out non-CPU resources
  - Memory/IO
  - Another policy decision



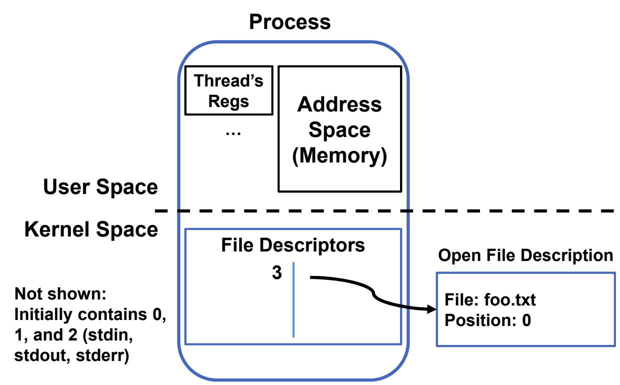
Process Control Block

Process-Specific File Descriptor Table inside Kernel



Suppose that we execute open("foo.txt") and that the result is 3

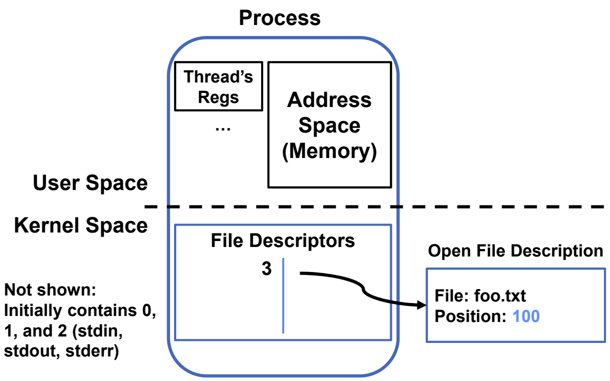
Process-Specific File Descriptor Table inside Kernel



Suppose that we execute open("foo.txt") and that the result is 3

Next, suppose that we execute read(3, buf, 100) and that the result is 100

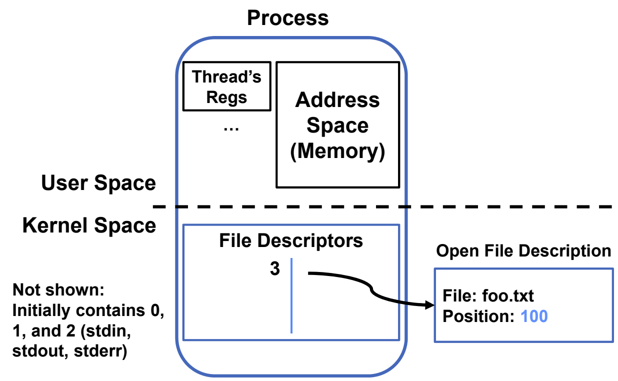
Process-Specific File Descriptor Table inside Kernel



Suppose that we execute open("foo.txt") and that the result is 3

Next, suppose that we execute read(3, buf, 100) and that the result is 100

Process-Specific File Descriptor Table inside Kernel

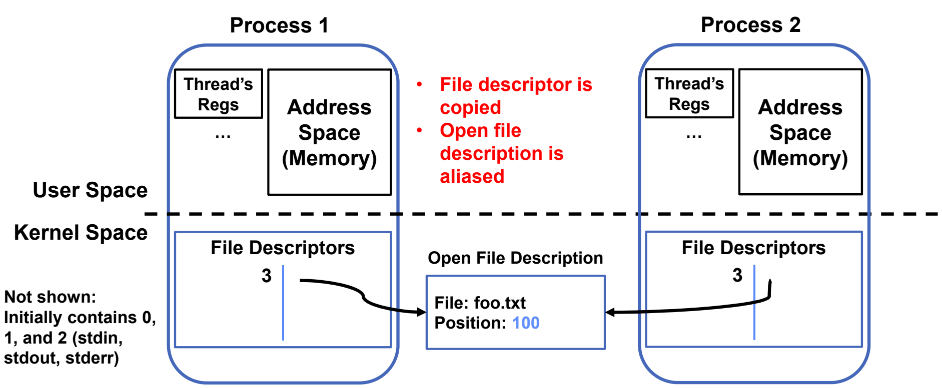


Suppose that we execute open("foo.txt") and that the result is 3

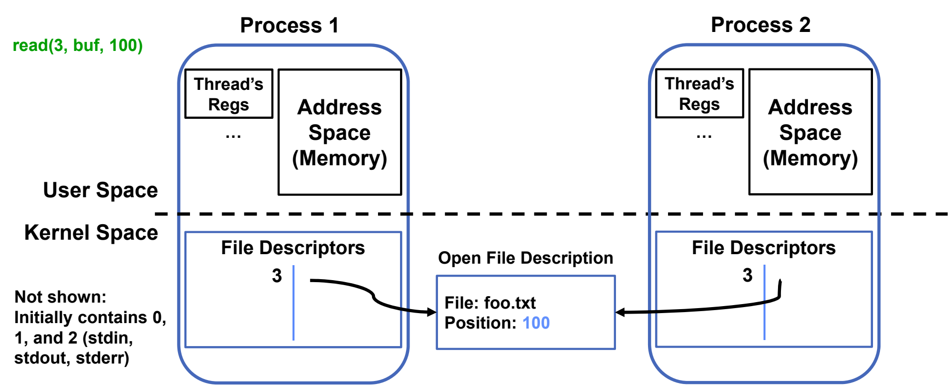
Next, suppose that we execute read(3, buf, 100) and that the result is 100

Finally, suppose that we execute close(3)

Instead of Closing, let's `fork()`!



Open File Description is *Aliased*



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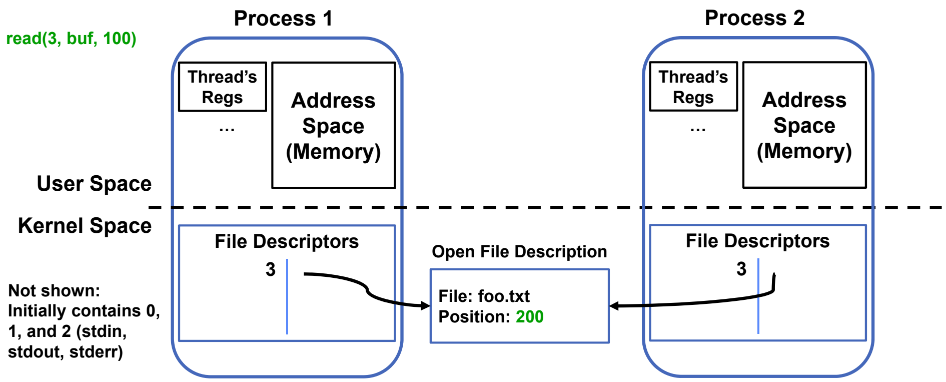

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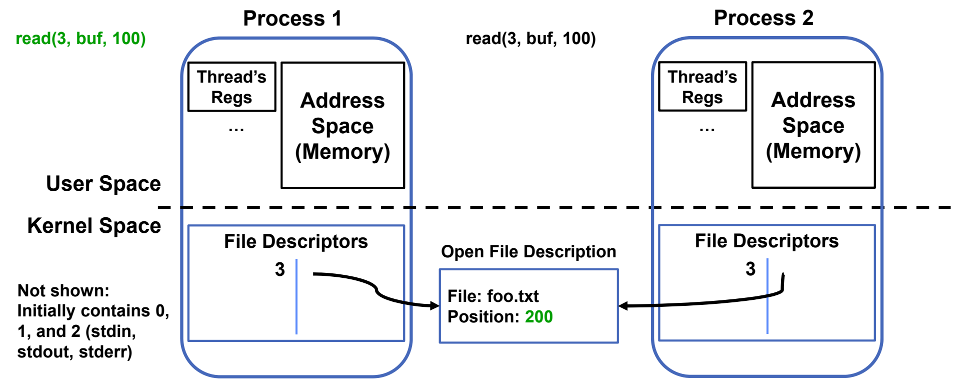
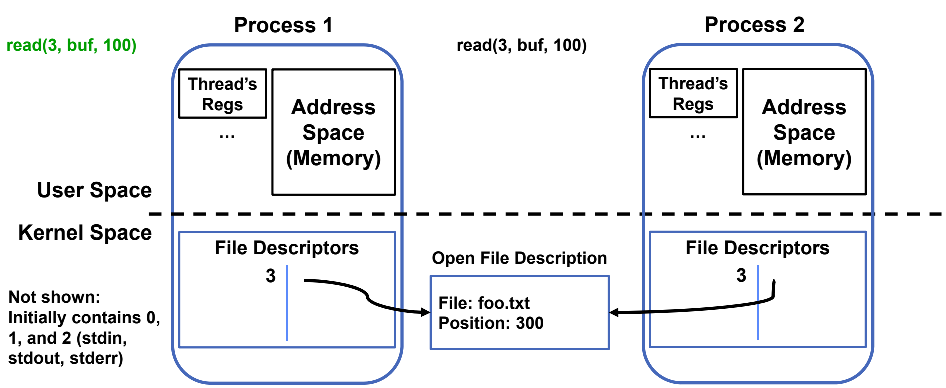
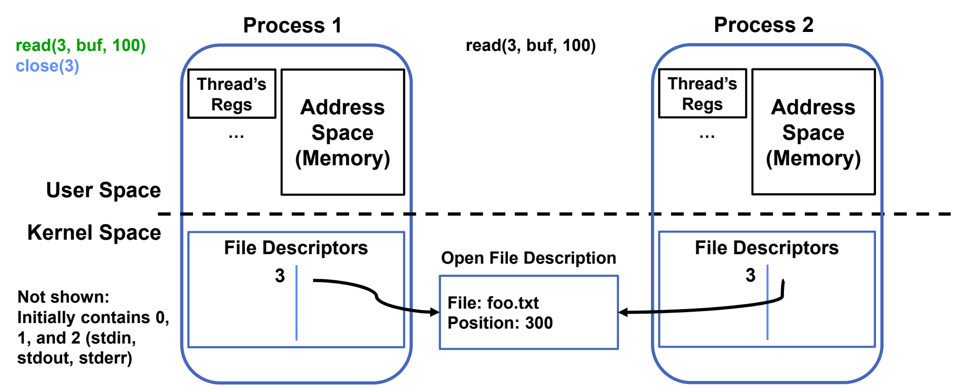


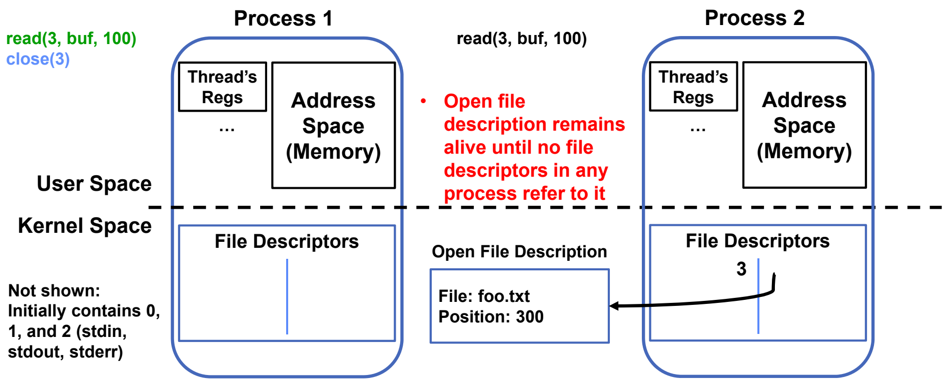
Open File Description is *Aliased*



File Descriptor is *Copied*



File Descriptor is *Copied*



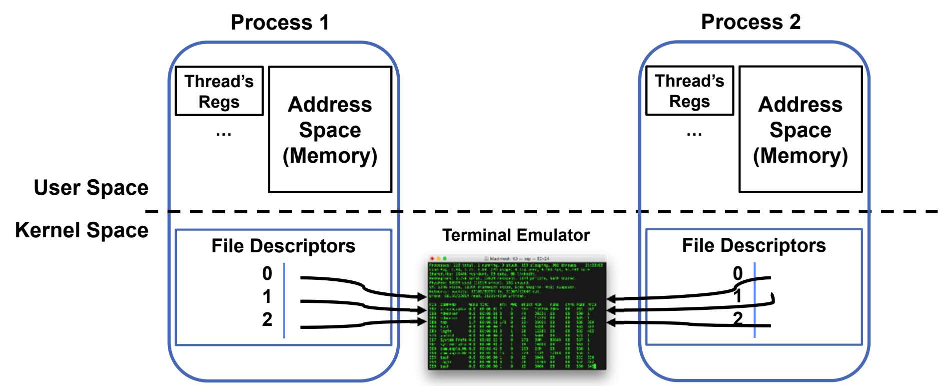
Why is Aliasing the Open File Description a Good Idea?

- It allows for *shared resources* between processes

Example: Shared Terminal Emulator

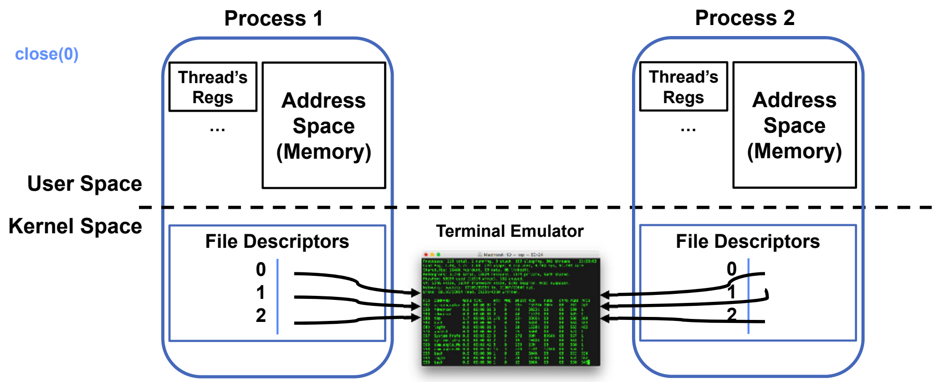
- When you `fork()` a process, the parent's and child's `printf` outputs go to the same terminal

Example: Shared Terminal Emulator



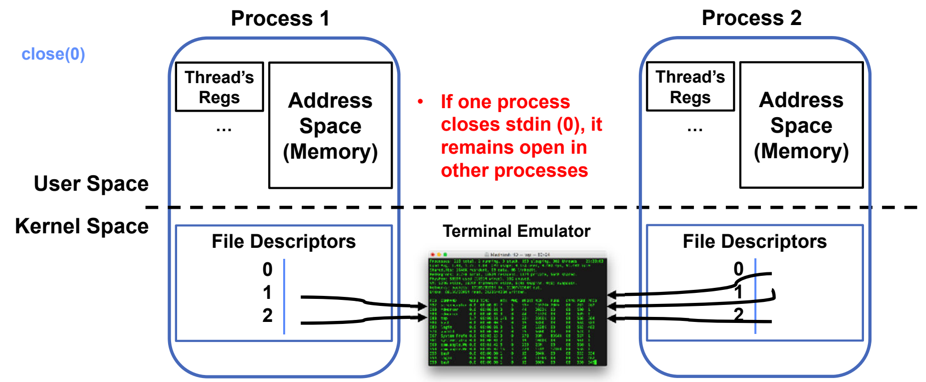
Example: Shared Terminal Emulator

close(0)



Example: Shared Terminal Emulator

close(0)



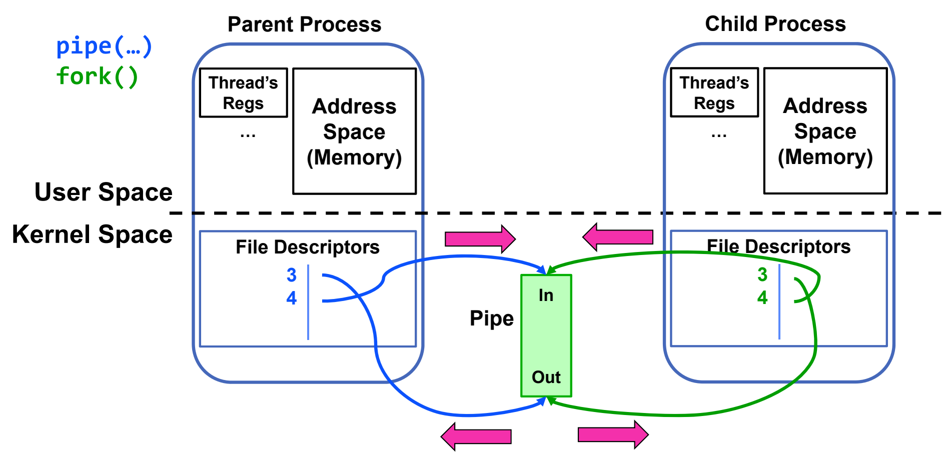
Single-Process Pipe Example (not that interesting yet!)

```
#include <unistd.h>
int main(int argc, char *argv[])
{
  char *msg = "Message in a pipe.\n";
  char buf[BUFSIZE];
  int pipe_fd[2];
  if (pipe(pipe_fd) == -1) {
    fprintf (stderr, "Pipe failed.\n"); return EXIT_FAILURE;
  }
  ssize_t writelen = write(pipe_fd[1], msg, strlen(msg)+1);
  printf("Sent: %s [%ld, %ld]\n", msg, strlen(msg)+1, writelen);

  ssize_t readlen  = read(pipe_fd[0], buf, BUFSIZE);
  printf("Rcvd: %s [%ld]\n", msg, readlen);

  close(pipe_fd[0]);
  close(pipe_fd[1]);
}
```

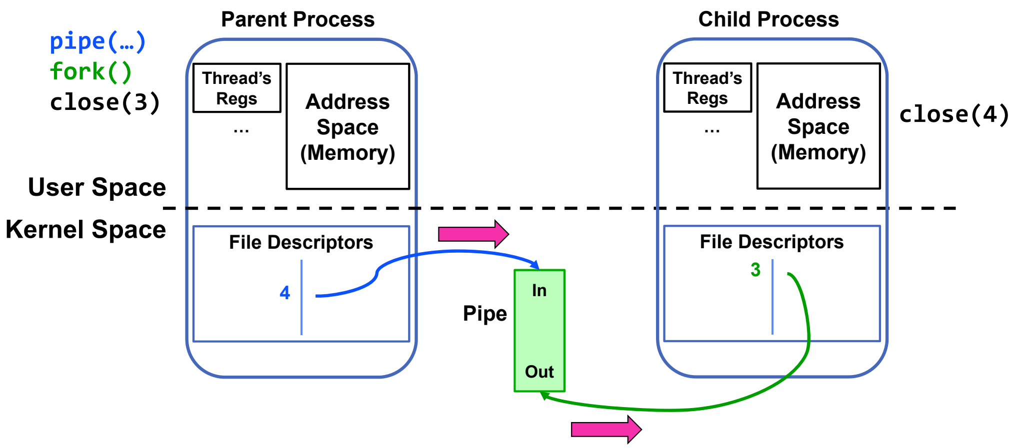
Could be useful for multithreaded processes…

Example: Pipes *Between* Processes

`pipe(…)`
`fork()`



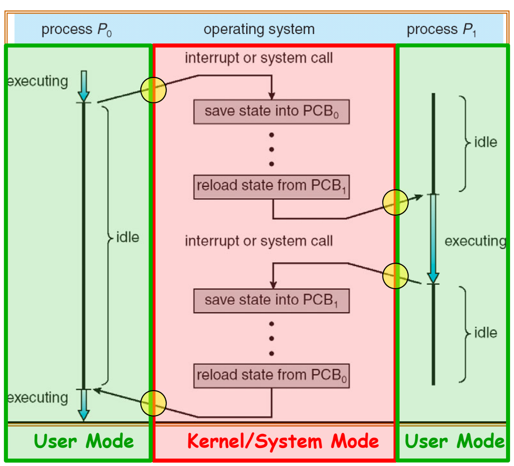
Example: Channel from Parent ⇒ Child



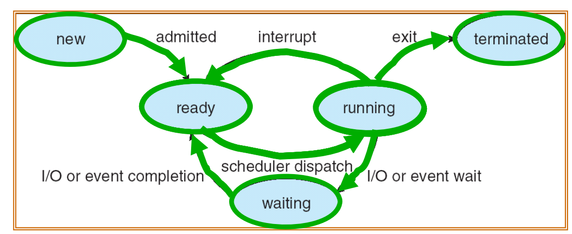
Inter-Process Communication (IPC): Parent ⇒ Child

```
// continuing from earlier
pid_t pid = fork();
if (pid < 0) {
  fprintf (stderr, "Fork failed.\n");
  return EXIT_FAILURE;
}
if (pid != 0) {
  close(pipe_fd[0]); // Not using this descriptor!
  ssize_t writelen = write(pipe_fd[1], msg, msglen);
  printf("Parent: %s [%ld, %ld]\n", msg, msglen, writelen);
} else {
  close(pipe_fd[1]); // Not using this descriptor!
  ssize_t readlen  = read(pipe_fd[0], buf, BUFSIZE);
  printf("Child Rcvd: %s [%ld]\n", msg, readlen);
}
```


Recall: CPU Switch From Process A to Process B

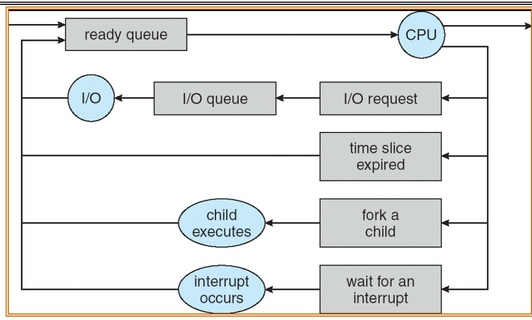


Lifecycle of a Process



- As a process executes, it changes state:
  - new: The process is being created
  - ready: The process is waiting to run
  - running: Instructions are being executed
  - waiting: Process waiting for some event to occur
  - terminated: The process has finished execution

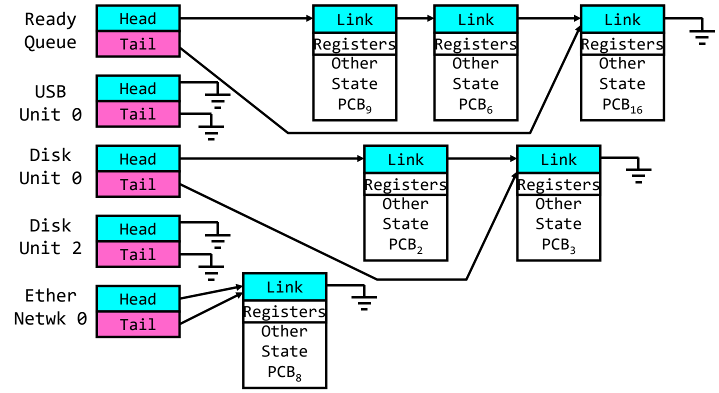
Process Scheduling



- PCBs move from queue to queue as they change state
  - Decisions about which order to remove from queues are Scheduling decisions
  - Many algorithms possible (few weeks from now)

Ready Queue And Various I/O Device Queues

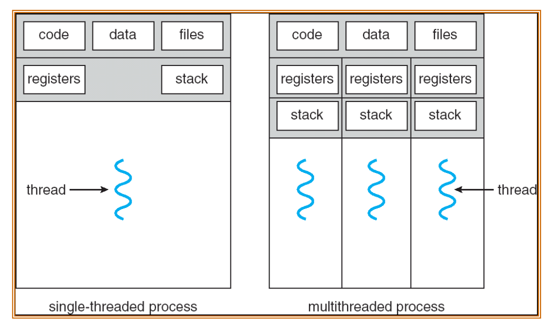
- Process not running ⇒ PCB is in some scheduler queue
  - Separate queue for each device/signal/condition
  - Each queue can have a different scheduler policy



Recall: Modern Process with Threads

- Thread: *a sequential execution stream within process* (Sometimes called a "Lightweight process")
  - Process still contains a single Address Space
  - No protection between threads
- Multithreading: *a single program made up of a number of different concurrent activities*
  - Sometimes called multitasking, as in Ada …
- Why separate the concept of a thread from that of a process?
  - Discuss the "thread" part of a process (concurrency)
  - Separate from the "address space" (protection)
  - Heavyweight Process ≡ Process with one thread

Recall: Single and Multithreaded Processes

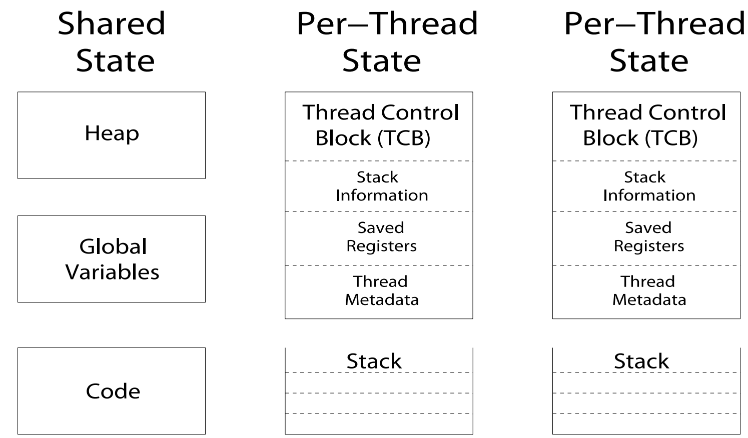


- Threads encapsulate concurrency: "Active" component
- Address spaces encapsulate protection: "Passive" part
  - Keeps buggy program from trashing the system
- Why have multiple threads per address space?

Recall: Thread State

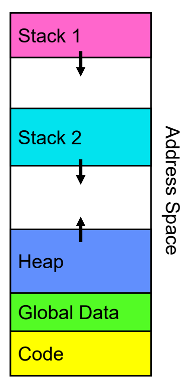
- State shared by all threads in process/address space
  - Content of memory (global variables, heap)
  - I/O state (file descriptors, network connections, etc)
- State "private" to each thread
  - Kept in TCB ≡ Thread Control Block
  - CPU registers (including, program counter)
  - Execution stack – what is this?
- Execution Stack
  - Parameters, temporary variables
  - Return PCs are kept while called procedures are executing

Shared vs. Per-Thread State



Memory Footprint: Two-Threads

- If we stopped this program and examined it with a debugger, we would see
  - Two sets of CPU registers
  - Two sets of Stacks
- Questions:
  - How do we position stacks relative to each other?
  - What maximum size should we choose for the stacks?
  - What happens if threads violate this?
  - How might you catch violations?

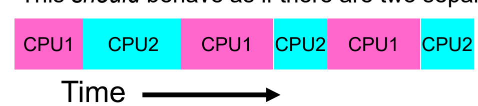


Recall: Use of Threads

- Version of program with Threads (loose syntax):

```
main() {
   ThreadFork(ComputePI, "pi.txt" ));
   ThreadFork(PrintClassList, "classlist.txt"));
}
```

- What does `ThreadFork()` do?
  - Start independent thread running given procedure
- What is the behavior here?
  - Now, you would actually see the class list
  - This *should* behave as if there are two separate CPUs



The Core of Concurrency: the Dispatch Loop

- Conceptually, the scheduling loop of the operating system looks as follows:

```
Loop {
   RunThread();
   ChooseNextThread();
   SaveStateOfCPU(curTCB);
   LoadStateOfCPU(newTCB);
}
```

- This is an *infinite* loop
  – One could argue that this is all that the OS does
- Should we ever exit this loop???
  – When would that be?

Conclusion

- Recall: Everything is a file!
  – **`open()`**, **`read()`**, **`write()`**, and **`close()`** used for wide variety of I/O:
  – Devices (terminals, printers, etc.)
  – Regular files on disk
  – Networking (sockets)
  – Local interprocess communication (pipes, sockets)
- Processes have two parts
  – Threads (Concurrency)
  – Address Spaces (Protection)
- Various textbooks talk about *processes*
  – When this concerns concurrency, really talking about thread portion of a process
  – When this concerns protection, talking about address space portion of a process
- Stack is essential part of computation
  – Every thread has two stacks: user-level (in address space) and kernel
  – The kernel stack + support often called the "kernel thread"