Signals, Processes, & Threads

CS 256/456

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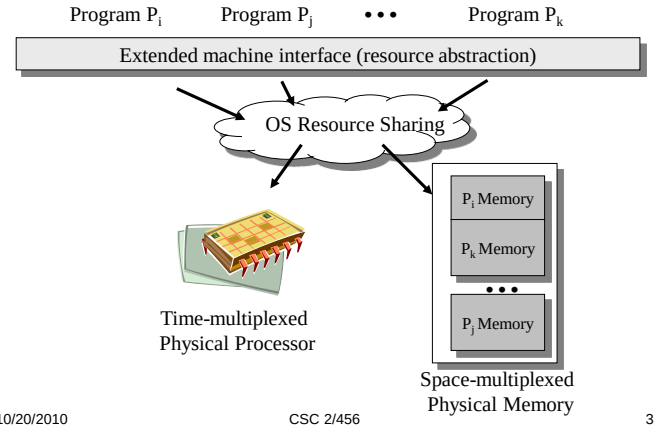
What is an Operating System?

- Software that abstracts the computer hardware
  - Hides the messy details of the underlying hardware
  - Presents users with a resource abstraction that is easy to use
  - Extends or virtualizes the underlying machine
- Manages the resources
  - Processors, memory, timers, disks, mice, network interfaces, printers, displays, …
  - Allows multiple users and programs to share the resources and coordinates the sharing, provides protection

Resource Sharing



Resource Abstraction

```
load(block, length, device);
seek(device, track);
out(device, sector)
```

```
write(char *block, int len, int device,
                  int track, int sector) {
   ...
  load(block, length, device);
  seek(device, track);
  out(device, sector);
   ...
}
```

```
write(char *block, int len, int device,int addr);
```

```
fprintf(fileID, "%d", datum);
```

Under the Abstraction

- functional complexity
- a single abstraction over multiple devices
- replication → reliability

Processes

- Def: A *process* is an instance of a running program.
  - One of the most profound ideas in computer science.
  - Not the same as "program" or "processor"
- Process provides each program with two key abstractions:
  - Logical control flow
    - Each program seems to have exclusive use of the CPU.
  - Private address space
    - Each program seems to have exclusive use of main memory.
- How are these Illusions maintained?
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system

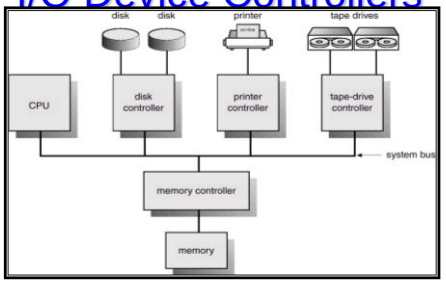
System Calls and Interfaces/Abstractions

- Examples: Win32, POSIX, or Java APIs
- Process management
  - fork, waitpid, execve, exit, kill
- File management
  - open, close, read, write, lseek
- Directory and file system management
  - mkdir, rmdir, link, unlink, mount, umount
- Inter-process communication
  - sockets, ipc (msg, shm, sem)

Today

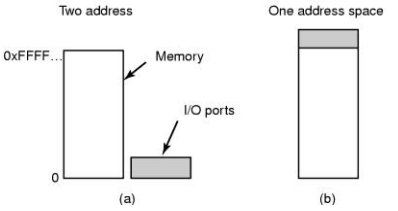
- System calls
  - Signals and pipes
- Process
  - Process concept
  - A process's image in a computer
  - Operations on processes

I/O Device Controllers



- I/O devices have both mechanical component & electronic component
- The electronic component is the device controller
  - It contains control logic, command registers, status registers, and on-board buffer space

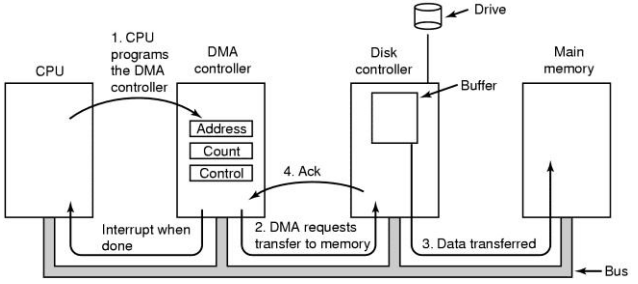
I/O Ports & Memory-Mapped I/O



I/O methods:
- Separate I/O and memory space; special I/O commands (IN/OUT)
- Memory-mapped I/O

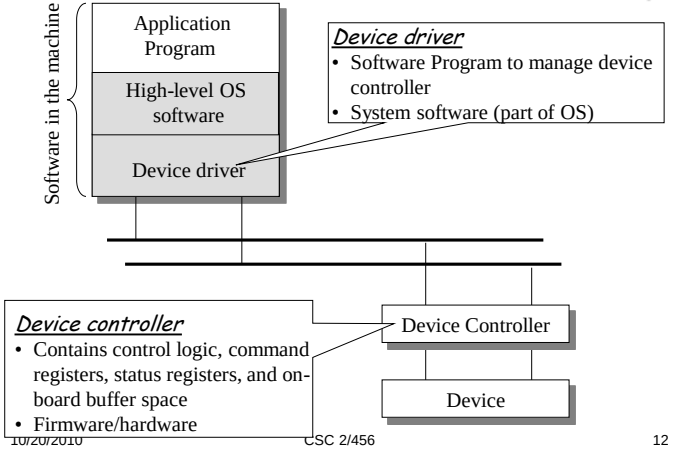
Issues with them:
- Convenience/efficiency when using high-level language;
- Protection mechanisms;
- Data caching

Direct Memory Access (DMA)



- Are the addresses CPU sends to the DMA controller virtual or physical addresses?
- Can the disk controller directly read data into the main memory (bypassing the controller buffer)?

The Device-Controller-Software Relationship



I/O Operations

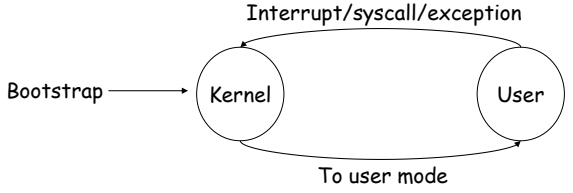
- How is I/O done?
  - I/O devices are much slower than CPU
- Synchronous (polling)
  - After I/O starts, busy-wait while polling the device status register until it shows the operation completes
- Asynchronous (interrupt-driven)
  - After I/O starts, control returns to the user program without waiting for I/O completion
  - Device controller later informs CPU that it has finished its operation by causing an *interrupt*
  - When an interrupt occurs, current execution is put on hold; the CPU jumps to a service routine called an "interrupt handler"

System Protection

- User programs (programs not belonging to the OS) are generally not trusted
  - A user program may use an unfair amount of resource
  - A user program may maliciously cause other programs or the OS to fail
- Need protection against untrusted user programs; the system must differentiate between at least two modes of operations
  1. *User mode* – execution of user programs
     - untrusted
     - not allowed to have complete/direct access to hardware resources
  2. *Kernel mode* (also *system mode* or *monitor mode*) – execution of the operating system
     - trusted
     - allowed to have complete/direct access to hardware resources
- Hardware support is needed for such protection

Transition between User/Kernel Mode

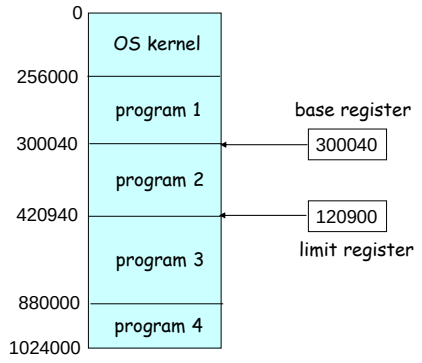
- When does the machine run in kernel mode?
  - after machine boot
  - interrupt handler
  - system call
  - exception



Memory Protection

- Goal of memory protection?
  - A user program can't use arbitrary amount of memory
  - A user program can't access data belonging to the operating system or other user programs
- How to achieve memory protection?
  - Indirect memory access
    - Memory access with a virtual address which needs to be translated into physical address
  - Add two registers that determine the range of legal addresses a program may access:
    - Base register – holds the smallest legal physical memory address
    - Limit register – contains the size of the range
    - Memory outside the defined range is protected

Hardware Address Protection

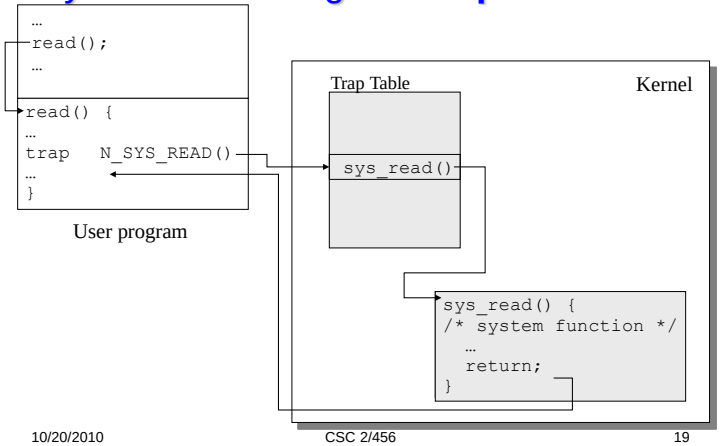


- Address of each memory address is checked against "base" and "base+limit"
- Trap to the OS kernel if it falls outside of the range (an exception)

Protection of I/O Devices

- User programs are not allowed to directly access I/O devices
  - Special I/O instructions can only be used in kernel mode
  - Controller registers can only be accessed in kernel mode
- So device drivers, I/O interrupt handlers must run in kernel mode
- User programs perform I/O through requesting the OS (using system calls)

System Call Using the **Trap** Instruction



CPU Protection

- Goal of CPU protection
  - A user program can't hold the CPU for ever
- *Timer* – interrupts computer after specified period to ensure the OS kernel maintains control
  - Timer is decremented every clock tick
  - When timer reaches the value 0, an interrupt occurs
  - CPU time sharing is implemented in the timer interrupt

Simple Shell `eval` Function

```
void eval(char *cmdline)
{
    char *argv[MAXARGS]; /* argv for execve() */
    int bg;              /* should the job run in bg or fg? */
    pid_t pid;           /* process id */

    bg = parseline(cmdline, argv);
    if (!builtin_command(argv)) {
        if ((pid = Fork()) == 0) {   /* child runs user job */
            if (execve(argv[0], argv, environ) < 0) {
                printf("%s: Command not found.\n", argv[0]);
                exit(0);
            }
        }

        if (!bg) {   /* parent waits for fg job to terminate */
            int status;
            if (waitpid(pid, &status, 0) < 0)
                unix_error("waitfg: waitpid error");
        }
        else         /* otherwise, don't wait for bg job */
            printf("%d %s", pid, cmdline);
    }
}
```

Problem with Simple Shell Example

- Shell correctly waits for and reaps foreground jobs.
- But what about background jobs?
  - Will become zombies when they terminate.
  - Will never be reaped because shell (typically) will not terminate.
  - Creates a memory leak that will eventually crash the kernel when it runs out of memory.
- Solution: Reaping background jobs requires a mechanism called a *signal*.

Signals

- A *signal* is a small message that notifies a process that an event of some type has occurred in the system.
  - Kernel abstraction for exceptions and interrupts.
  - Sent from the kernel (sometimes at the request of another process) to a process.
  - Different signals are identified by small integer ID's
  - The only information in a signal is its ID and the fact that it arrived.

Signal Concepts

- Sending a signal
  - Kernel *sends* (delivers) a signal to a *destination process* by updating some state in the context of the destination process.
  - Kernel sends a signal for one of the following reasons:
    - Kernel has detected a system event such as divide-by-zero (SIGFPE) or the termination of a child process (SIGCHLD)
    - Another process has invoked the `kill` system call to explicitly request the kernel to send a signal to the destination process.

Signal Concepts (cont)

- Receiving a signal
  - A destination process *receives* a signal when it is forced by the kernel to react in some way to the delivery of the signal.
  - Three possible ways to react:
    - Ignore the signal (do nothing)
    - Terminate the process.
    - *Catch* the signal by executing a user-level function called a signal handler.
      - Akin to a hardware exception handler being called in response to an asynchronous interrupt.

Signal Concepts (cont)

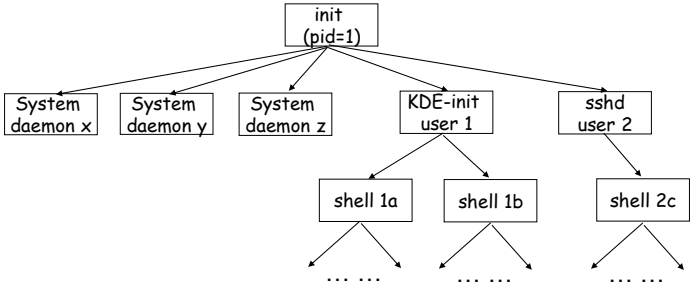
- A signal is *pending* if it has been sent but not yet received
  - There can be at most one pending signal of any particular type
  - Important: Signals are not queued
    - If a process has a pending signal of type k, then subsequent signals of type k that are sent to that process are discarded
- A process can *block* the receipt of certain signals
  - Blocked signals can be delivered, but will not be received until the signal is unblocked
- A pending signal is received at most once

Signal Concepts

- Kernel maintains `pending` and `blocked` bit vectors in the context of each process.
  - `pending` – represents the set of pending signals
    - Kernel sets bit k in `pending` whenever a signal of type k is delivered.
    - Kernel clears bit k in `pending` whenever a signal of type k is received
  - `blocked` – represents the set of blocked signals
    - Can be set and cleared by the application using the `sigprocmask` function.

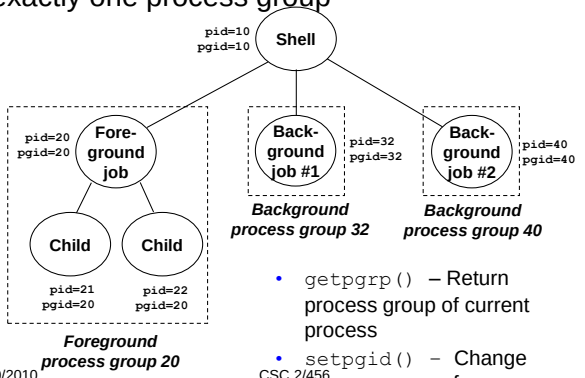
Process Tree on a Linux System

- Parent process creates children processes, which, in turn create other processes, forming a tree of processes.



Process Groups

- Every process belongs to exactly one process group



- `getpgrp()` – Return process group of current process
- `setpgid()` – Change process group of a process

Sending Signals with `kill` Program

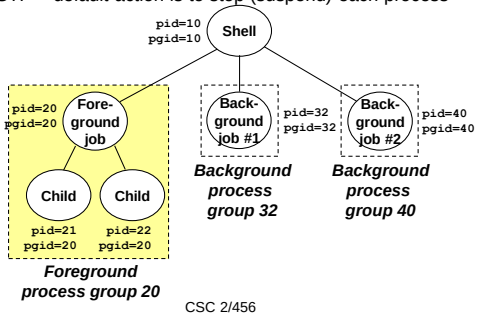
- `kill` program sends arbitrary signal to a process or process group
- Examples
  - `kill -9 24818`
    - Send SIGKILL to process 24818
  - `kill -9 -24817`
    - Send SIGKILL to every process in process group 24817.

```
linux> ./forks 16
linux> Child1: pid=24818 pgrp=24817
Child2: pid=24819 pgrp=24817

linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24818 pts/2    00:00:02 forks
24819 pts/2    00:00:02 forks
24820 pts/2    00:00:00 ps
linux> kill -9 -24817
linux> ps
  PID TTY          TIME CMD
24788 pts/2    00:00:00 tcsh
24823 pts/2    00:00:00 ps
linux>
```


Sending Signals from the Keyboard

- Typing ctrl-c (ctrl-z) sends a SIGINT (SIGTSTP) to every job in the foreground process group.
  - SIGINT – default action is to terminate each process
  - SIGTSTP – default action is to stop (suspend) each process



Example of `ctrl-c` and `ctrl-z`

```
linux> ./forks 17
Child: pid=24868 pgrp=24867
Parent: pid=24867 pgrp=24867
 <typed ctrl-z>
Suspended
linux> ps a
  PID TTY      STAT   TIME COMMAND
24788 pts/2    S      0:00 -usr/local/bin/tcsh -i
24867 pts/2    T      0:01 ./forks 17
24868 pts/2    T      0:01 ./forks 17
24869 pts/2    R      0:00 ps a
bass> fg
./forks 17
<typed ctrl-c>
linux> ps a
  PID TTY      STAT   TIME COMMAND
24788 pts/2    S      0:00 -usr/local/bin/tcsh -i
24870 pts/2    R      0:00 ps a
```

Sending Signals with `kill` Function

```
void fork12()
{
    pid_t pid[N];
    int i, child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            while(1); /* Child infinite loop */

    /* Parent terminates the child processes */
    for (i = 0; i < N; i++) {
        printf("Killing process %d\n", pid[i]);
        kill(pid[i], SIGINT);
    }

    /* Parent reaps terminated children */
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```

Receiving Signals

- Suppose kernel is returning from exception handler and is ready to pass control to process *p*.
- Kernel computes `pnb = pending & ~blocked`
  - The set of pending nonblocked signals for process *p*
- If (`pnb == 0`)
  - Pass control to next instruction in the logical flow for *p*.
- Else
  - Choose least nonzero bit *k* in `pnb` and force process *p* to receive signal *k*.
  - The receipt of the signal triggers some *action* by *p*
  - Repeat for all nonzero *k* in `pnb`.
  - Pass control to next instruction in logical flow for *p*.

Default Actions

- Each signal type has a predefined *default action*, which is one of:
  - The process terminates
  - The process terminates and dumps core.
  - The process stops until restarted by a SIGCONT signal.
  - The process ignores the signal.

Some Common Signals and Their Defaults

ID	Name	Default Action	Corresponding Event
2	`SIGINT`	Terminate	Interrupt from keyboard (`ctl-c`)
9	`SIGKILL`	Terminate	Kill program (cannot override or ignore)
11	`SIGSEGV`	Terminate & Dump	Segmentation violation
14	`SIGALRM`	Terminate	Timer signal
17	`SIGCHLD`	Ignore	Child stopped or terminated

Installing Signal Handlers

- The `signal` function modifies the default action associated with the receipt of signal `signum`:
  - `handler_t *signal(int signum, handler_t *handler)`
- Different values for `handler`:
  - SIG_IGN: ignore signals of type `signum`
  - SIG_DFL: revert to the default action on receipt of signals of type `signum`.
  - Otherwise, handler is the address of a *signal handler*
    - Called when process receives signal of type `signum`
    - Referred to as "*installing*" the handler.
    - Executing the handler is called "*catching*" or "*handling*" the signal.
    - When the handler executes its return statement, control passes back to instruction in the control flow of the process that was interrupted by receipt of the signal.

Signal Handling Example

```
void int_handler(int sig)
{
    printf("Process %d received signal %d\n",
           getpid(), sig);
    exit(0);
}

void fork13()
{
    pid_t pid[N];
    int i, child_status;
    signal(SIGINT, int_handler);

    . . .
}
```

```
linux> ./forks 13
Killing process 24973
Killing process 24974
Killing process 24975
Killing process 24976
Killing process 24977
Process 24977 received signal 2
Child 24977 terminated with exit status 0
Process 24976 received signal 2
Child 24976 terminated with exit status 0
Process 24975 received signal 2
Child 24975 terminated with exit status 0
Process 24974 received signal 2
Child 24974 terminated with exit status 0
Process 24973 received signal 2
Child 24973 terminated with exit status 0
linux>
```

Signal Handler Funkiness

```
int ccount = 0;
void child_handler(int sig)
{
    int child_status;
    pid_t pid = wait(&child_status);
    ccount--;
    printf("Received signal %d from process %d\n",
           sig, pid);
}

void fork14()
{
    pid_t pid[N];
    int i, child_status;
    ccount = N;
    signal(SIGCHLD, child_handler);
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0) {
            /* Child: Exit */
            exit(0);
        }
    while (ccount > 0)
        pause();/* Suspend until signal occurs */
}
```

- Pending signals are not queued
  - For each signal type, just have single bit indicating whether or not signal is pending
  - Even if multiple processes have sent this signal

Living With Nonqueuing Signals

- Must check for all terminated jobs
  - Typically loop with `wait`

```
void child_handler2(int sig)
{
    int child_status;
    pid_t pid;
    while ((pid = wait(&child_status)) > 0) {
       ccount--;
       printf("Received signal %d from process %d\n",
sig, pid);
    }
}

void fork15()
{
    . . .
    signal(SIGCHLD, child_handler2);
    . . .
}
```

A Program That Reacts to Externally Generated Events (ctrl-c)

```
#include <stdlib.h>
#include <stdio.h>
#include <signal.h>

void handler(int sig) {
  printf("You think hitting ctrl-c will stop the bomb?\n");
  sleep(2);
  printf("Well...");
  fflush(stdout);
  sleep(1);
  printf("OK\n");
  exit(0);
}

main() {
  signal(SIGINT, handler); /* installs ctl-c handler */
  while(1) {
  }
}
```

A Program That Reacts to Internally Generated Events

```
#include <stdio.h>
#include <signal.h>

int beeps = 0;

/* SIGALRM handler */
void handler(int sig) {
  printf("BEEP\n");
  fflush(stdout);

  if (++beeps < 5)
    alarm(1);
  else {
    printf("BOOM!\n");
    exit(0);
  }
}
```

```
main() {
  signal(SIGALRM, handler);
  alarm(1); /* send SIGALRM in
               1 second */

  while (1) {
    /* handler returns here */
  }
}
```

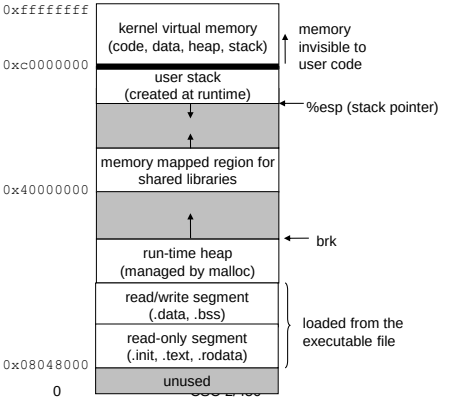
```
linux> a.out
BEEP
BEEP
BEEP
BEEP
BEEP
BOOM!
bass>
```

Process and Its Image

- An operating system executes a variety of programs:
  - A program that browses the Web
  - A program that serves Web requests
- Process – a program in execution.
- A process's state/image in a computer includes:
  - User-mode address space
  - Kernel data structure
  - Registers (including program counter and stack pointer)
- Address space and memory protection
  - Physical memory is divided into user memory and kernel memory
  - Kernel memory can only be accessed when in the kernel mode
  - Each process has its own exclusive address space in the user-mode memory space (sort-of)

Private Address Spaces

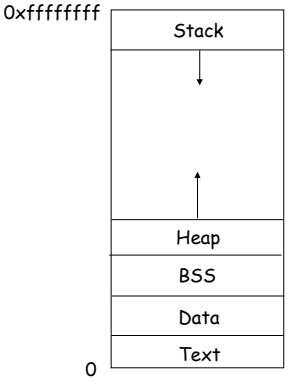
- Each process has its own private address space.



User-mode Address Space

User-mode address space for a process:

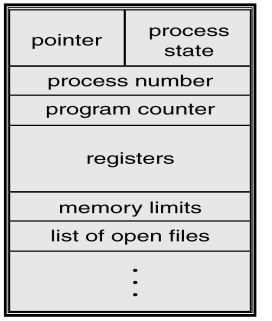
- Text: program code, instructions
- Data: initialized global and static variables (those data whose size is known before the execution)
- BSS (block started by symbol): uninitialized global and static variables
- Heap: dynamic memory (those being malloc-ed)
- Stack: local variables and other stuff for function invocations



Process Control Block (PCB)

OS data structure (in kernel memory) maintaining information associated with each process.

- Process state
- Program counter
- CPU registers
- CPU scheduling information
- Memory-management information
- Accounting information
- Information about open files
- maybe kernel stack?



Process Creation

- When a process (parent) creates a new process (child)
  - Execution sequence?
  - Address space sharing?
  - Open files inheritance?
  - … …
- UNIX examples
  - **fork** system call creates new process with a duplicated copy of everything.
  - **exec** system call used after a **fork** to replace the process' memory space with a new program.
  - child and parent compete for CPU like two normal processes.
- Copy-on-write

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