

CS 318 Principles of Operating Systems

Fall 2018

Lecture 3: Processes

Ryan Huang



JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

Slides adapted from Geoff Voelker's and David Mazières' lectures

Administrivia

- **Homework 1**
- **Lab 0**
 - Due this Thursday
- **Find your project group member soon**
 - Lab 1 starts this Friday
 - Fill out Google form of group info

Recap: Architecture Support for OS

- **Manipulating privileged machine state**

- CPU protection: dual-mode operation, protected instructions
- Memory protection: MMU, virtual address

- **Generating and handling “events”**

- Interrupt, syscall, trap
- Interrupt controller, IVT
- Fix fault vs. notify proceed

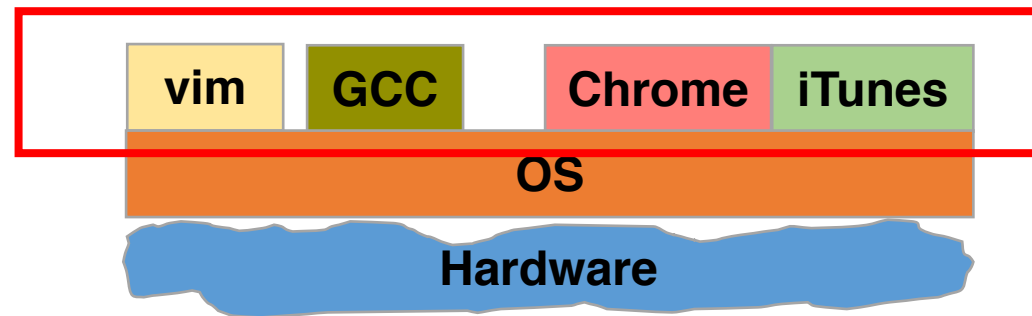
	Unexpected	Deliberate
Exceptions (sync)	fault	syscall trap
Interrupts (async)	interrupt	software interrupt

- **Mechanisms to handle concurrency**

- Interrupts, atomic instructions

Overview

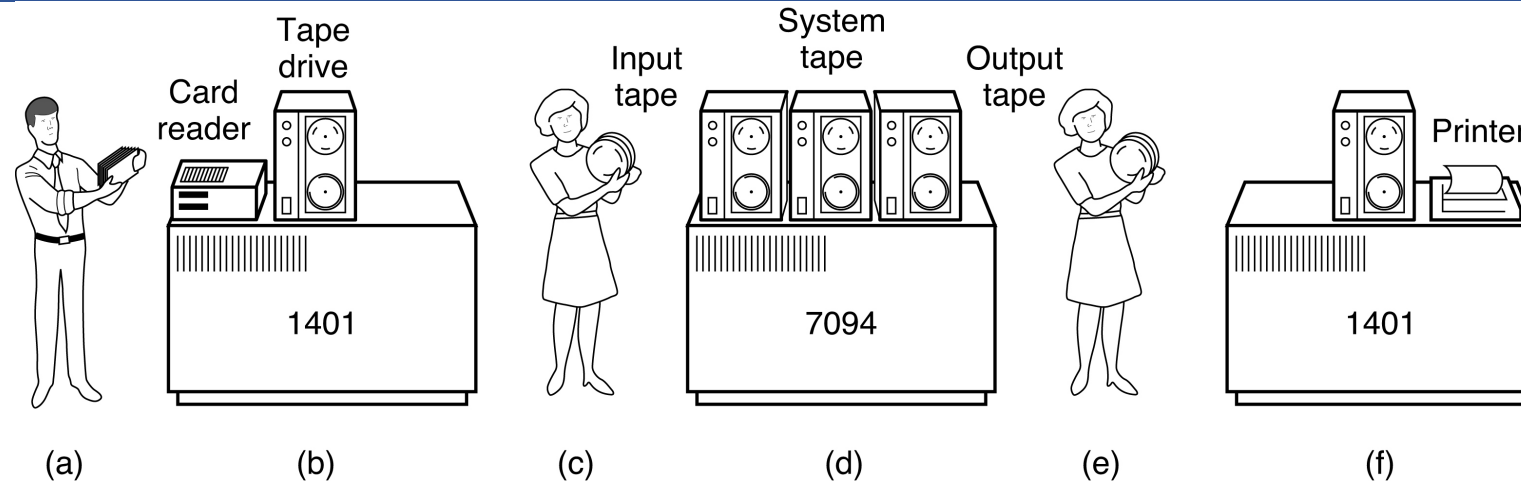
- **Today's topics are processes and process management**
 - What are the units of execution?
 - How are those units of execution represented in the OS?
 - How is work scheduled in the CPU?
 - What are the possible execution states of a process?
 - How does a process move from one state to another?



The Process

- **The process is the OS abstraction for CPU (execution)**
 - It is the unit of execution
 - It is the unit of scheduling
 - It is the dynamic execution context of a program
 - Sometimes also called a **job** or a **task**
- **A process is a program in execution**
 - It defines the sequential, instruction-at-a-time execution of a program
 - Programs are static entities with the **potential** for execution

Simple Process Management: One-at-a-time



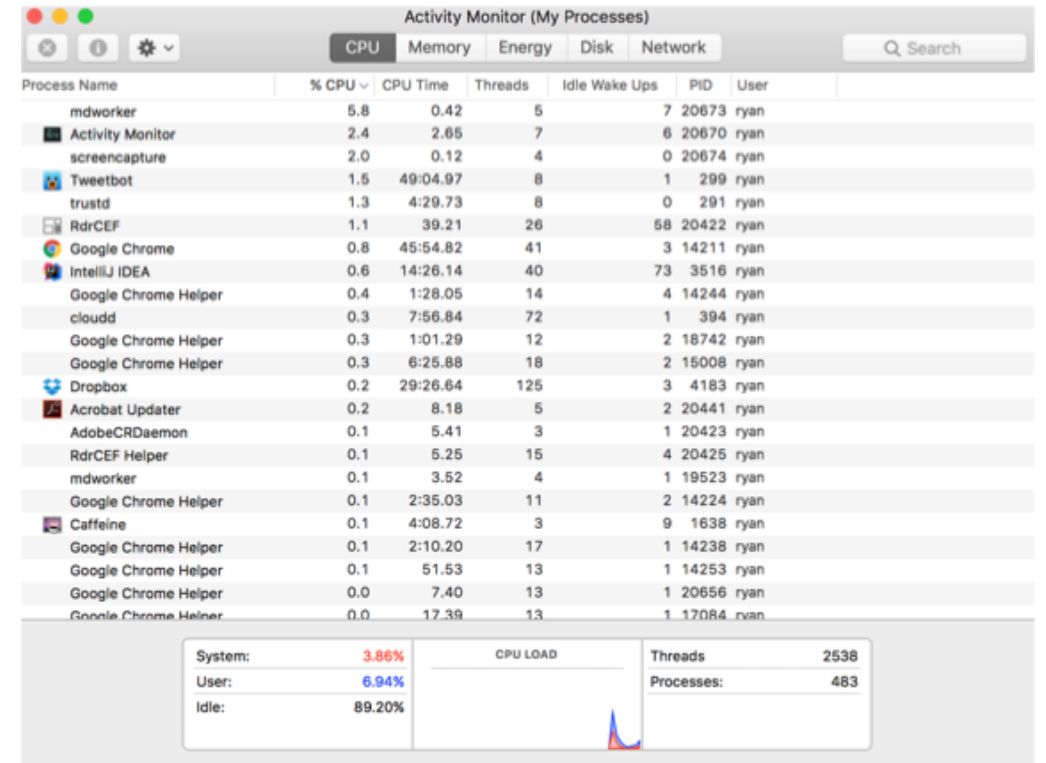
- **Unprogramming: a process runs from start to full completion**
 - What the early batch operating system does
 - Load a job from disk (tape) into memory, execute it, unload the job
 - **Problem: low utilization of hardware**
 - an I/O-intensive process would spend most of its time waiting for punched cards to be read
 - CPU is wasted
 - computers were very expensive back then

Multiple Processes

- Modern OSes run multiple processes simultaneously

```
top - 20:42:55 up 14 days, 15:45, 14 users, load average: 1.27, 0.35, 0.12
Tasks: 145 total, 2 running, 141 sleeping, 2 stopped, 0 zombie
%Cpu(s): 5.6 us, 55.3 sy, 0.0 ni, 0.0 id, 35.6 wa, 0.0 hi, 0.0 si, 3.5 st
KiB Mem : 1016140 total, 72288 free, 858408 used, 85444 buff/cache
KiB Swap: 0 total, 0 free, 0 used. 12892 avail Mem
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
28	root	20	0	0	0	0	R	31.1	0.0	17:11.66	kswapd0
5546	root	20	0	114980	24596	4732	D	26.2	2.4	0:14.53	check-new-relea
5583	ryan	20	0	54544	8820	1752	S	2.3	0.9	0:01.24	mosh-server
14294	tomcat	20	0	2497172	230824	0	S	2.0	22.7	16:04.46	java
5660	ryan	20	0	40536	2172	1488	R	0.7	0.2	0:00.34	top
8370	mysql	20	0	1123396	199620	0	S	0.3	19.6	8:11.12	mysqld
14074	root	20	0	0	0	0	S	0.3	0.0	0:17.19	kworker/0:2
25217	root	20	0	314032	15260	9204	S	0.3	1.5	2:07.55	php-fpm7.0
25274	parsoid	20	0	937076	28144	0	S	0.3	2.8	5:30.90	nodejs
25292	parsoid	20	0	1049820	50772	0	S	0.3	5.0	6:55.52	nodejs
25313	ghost	20	0	1255612	71152	0	S	0.3	7.0	15:16.30	nodejs
1	root	20	0	119628	1796	0	S	0.0	0.2	2:39.46	systemd
2	root	20	0	0	0	0	S	0.0	0.0	0:00.17	kthreadd
3	root	20	0	0	0	0	S	0.0	0.0	0:07.34	ksoftirqd/0
5	root	0	-20	0	0	0	S	0.0	0.0	0:00.00	kworker/0:0H
7	root	20	0	0	0	0	S	0.0	0.0	1:01.94	rcu_sched
8	root	20	0	0	0	0	S	0.0	0.0	0:00.00	rcu_bh
9	root	rt	0	0	0	0	S	0.0	0.0	0:00.00	migration/0



Multiple Processes

- **Modern OSes run multiple processes simultaneously**
- **Examples (can all run simultaneously):**
 - `gcc file_A.c` – compiler running on file A
 - `gcc file_B.c` – compiler running on file B
 - `vim` – text editor
 - `firefox` – web browser
- **Non-examples (implemented as one process):**
 - Multiple `firefox` or `tmux` windows (still one process)

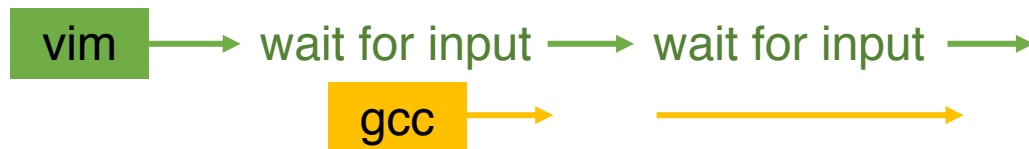
Multiprogramming (Multitasking)

- **Multiprogramming: run more than one process at a time**
 - Multiple processes loaded in memory and available to run
 - If a process is blocked in I/O, select another process to run on CPU
 - Different hardware components utilized by different tasks at the same time
- **Why multiple processes (multiprogramming)?**
 - **Advantages: speed & hardware utilization**
 - higher throughput
 - lower latency

Speed

- **Multiple processes can increase CPU utilization**

- Overlap one process's computation with another's wait

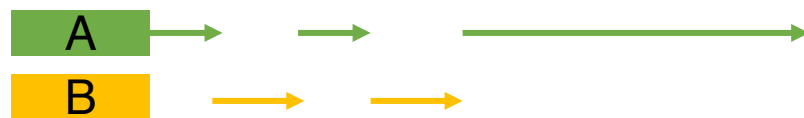


- **Multiple processes can reduce latency**

- Running A then B requires 100 sec for B to complete



- Running A and B concurrently makes B finish faster



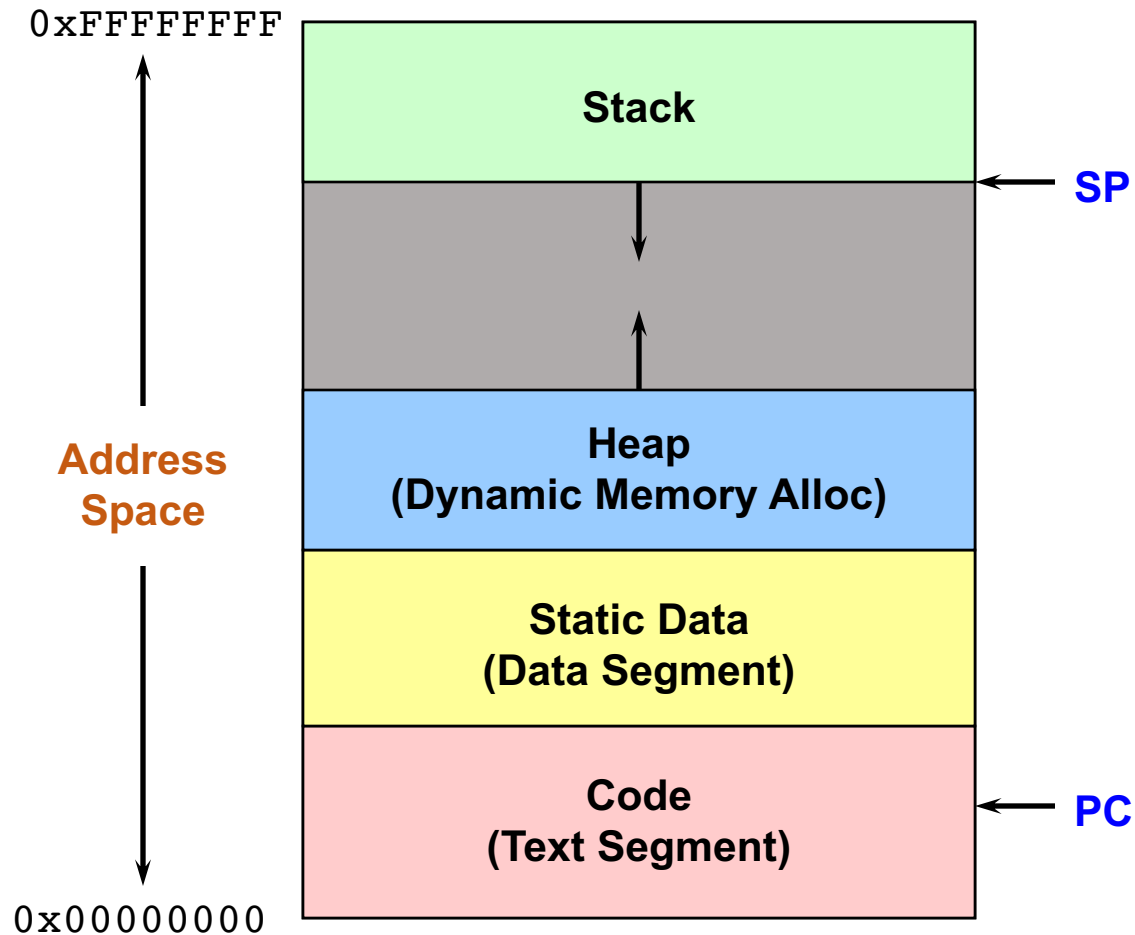
- A is slower than if it had whole machine to itself, but still < 100 sec unless both A and B completely CPU-bound

Kernel's View of Processes

Process Components

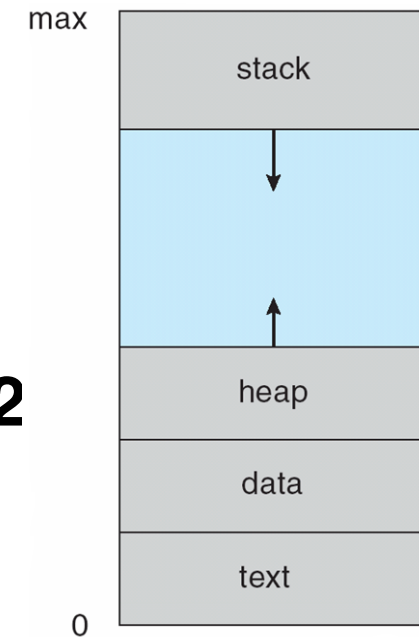
- **A process contains all state for a program in execution**
 - An address space
 - The code for the executing program
 - The data for the executing program
 - An execution stack encapsulating the state of procedure calls
 - The program counter (PC) indicating the next instruction
 - A set of general-purpose registers with current values
 - A set of operating system resources
 - Open files, network connections, etc.

Process Address Space



A Process's View of the World

- **Each process has own view of machine**
 - Its own address space
 - Its own open files
 - Its own virtual CPU (through preemptive multitasking)
- `*(char *)0xc000` means different thing in P1 & P2
- **Simplifies programming model**
 - gcc does not care that `firefox` is running
- **Sometimes want interaction between processes**
 - Simplest is through files: `vim` edits file, `gcc` compiles it
 - More complicated: Shell/command, Window manager/app.



Naming A Process

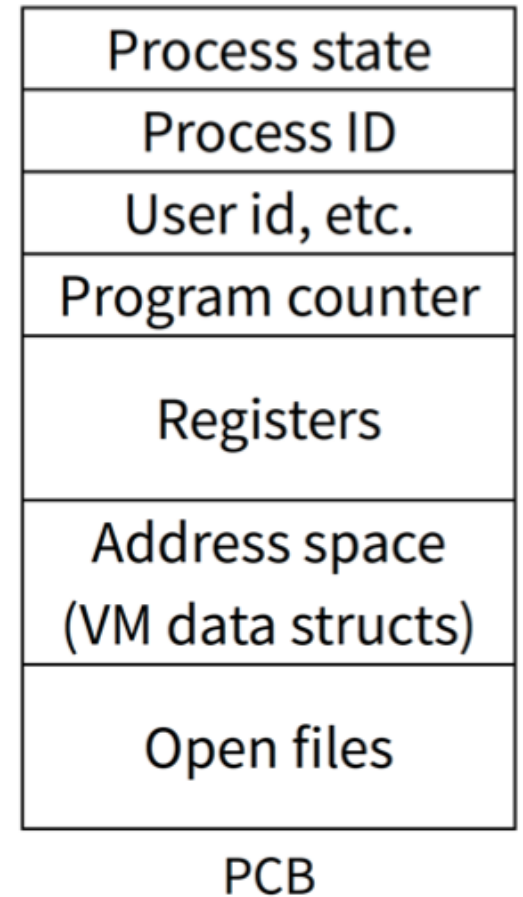
- A process is named using its process ID (PID)

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Implementing Process

- **Keep a data structure for each process**
 - **Process Control Block** (PCB)
 - Contains all of the info about a process
- **Tracks *state* of the process**
 - Running, ready (runnable), waiting, etc.
- **Includes information necessary for execution**
 - Registers, virtual memory mappings, etc.
 - Open files (including memory mapped files)
 - **PCB is also maintained when the process is *not* running**
 - Needed by context switch mechanism
- **Various other data about the process**
 - Credentials (user/group ID), signal mask, priority, accounting, etc.
 - It is a heavyweight abstraction



struct proc (Solaris)

```
/*
 * One structure allocated per active process. It contains all
 * data needed about the process while the process may be swapped
 * out. Other per-process data (user.h) is also inside the proc structure.
 * Lightweight-process data (lwp.h) and the kernel stack may be swapped out.
 */
typedef struct proc {
    /*
     * Fields requiring no explicit locking
     */
    struct vnode *p_exec;          /* pointer to a.out vnode */
    struct as *p_as;              /* process address space pointer */
    struct plock *p_lockp;        /* ptr to proc struct's mutex lock */
    kmutex_t p_crlock;           /* lock for p_cred */
    struct cred *p_cred;          /* process credentials */
    /*
     * Fields protected by pidlock
     */
    int p_swapcnt;               /* number of swapped out lwps */
    char p_stat;                 /* status of process */
    char p_wcode;                /* current wait code */
    ushort_t p_pidflag;          /* flags protected only by pidlock */
    int p_wdata;                 /* current wait return value */
    pid_t p_ppid;                /* process id of parent */
    struct proc *p_link;         /* forward link */
    struct proc *p_parent;       /* ptr to parent process */
    struct proc *p_child;        /* ptr to first child process */
    struct proc *p_sibling;      /* ptr to next sibling proc on chain */
    struct proc *p_psibling;     /* ptr to prev sibling proc on chain */
    struct proc *p_sibling_ns;   /* prt to siblings with new state */
    struct proc *p_child_ns;    /* prt to children with new state */
    struct proc *p_next;         /* active chain link next */
    struct proc *p_prev;         /* active chain link prev */
    struct proc *p_nextofkin;    /* gets accounting info at exit */
    struct proc *p_orphan;
    struct proc *p_nextorph;

    *p_pglink; /* process group hash chain link next */
    struct proc *p_ppglink; /* process group hash chain link prev */
    struct sess *p_sessp; /* session information */
    struct pid *p_pidp; /* process ID info */
    struct pid *p_pgidp; /* process group ID info */
    /*
     * Fields protected by p_lock
     */
    kcondvar_t p_cv; /* proc struct's condition variable */
    kcondvar_t p_flag_cv;
    kcondvar_t p_lwpexit; /* waiting for some lwp to exit */
    kcondvar_t p_holdlwps; /* process is waiting for its lwps */
    /* to to be held. */
    ushort_t p_pad1; /* unused */
    uint_t p_flag; /* protected while set. */

    /* flags defined below */
    clock_t p_utime; /* user time, this process */
    clock_t p_stime; /* system time, this process */
    clock_t p_cutime; /* sum of children's user time */
    clock_t p_cstime; /* sum of children's system time */
    caddr_t *p_segacct; /* segment accounting info */
    caddr_t p_brkbase; /* base address of heap */
    size_t p_brksize; /* heap size in bytes */
    /*
     * Per process signal stuff.
     */
    k_sigset_t p_sig; /* signals pending to this process */
    k_sigset_t p_ignore; /* ignore when generated */
    k_sigset_t p_siginfo; /* gets signal info with signal */
    struct sigqueue *p_sigqueue; /* queued siginfo structures */
    struct sigqhdr *p_sigqhdr; /* hdr to sigqueue structure pool */
    struct sigqhdr *p_sighdr; /* hdr to signotify structure pool */
    uchar_t p_stopsig; /* jobcontrol stop signal */
};
```

struct proc (Solaris) (2)

```
/*
 * Special per-process flag when set will fix misaligned memory
 * references.
 */
char    p_fixalignment;

/*
 * Per process lwp and kernel thread stuff
 */
id_t    p_lwpid;           /* most recently allocated lwpid */
int     p_lwpcnt;         /* number of lwps in this process */
int     p_lwprcnt;        /* number of not stopped lwps */
int     p_lwpwait;        /* number of lwps in lwp_wait() */
int     p_zombcnt;        /* number of zombie lwps */
int     p_zomb_max;       /* number of entries in p_zomb_tid */
id_t    *p_zomb_tid;      /* array of zombie lwpids */
kthread_t *p_tlist;       /* circular list of threads */
/*
 * /proc (process filesystem) debugger interface stuff.
 */
k_sigset_t p_sigmask;     /* mask of traced signals (/proc) */
k_fltset_t p_fltmask;     /* mask of traced faults (/proc) */
struct vnode *p_trace;    /* pointer to primary /proc vnode */
struct vnode *p_plist;    /* list of /proc vnodes for process */
kthread_t *p_agenttp;     /* thread ptr for /proc agent lwp */
struct watched_area *p_warea; /* list of watched areas */
ulong_t p_nwarea;         /* number of watched areas */
struct watched_page *p_wpage; /* remembered watched pages (vfork) */
int     p_nwpage;         /* number of watched pages (vfork) */
int     p_mapcnt;         /* number of active pr_mappage()s */
struct proc *p_rlink;     /* linked list for server */
kcondvar_t p_srchan_cv;
size_t  p_stksize;        /* process stack size in bytes */
```

```
/*
 * Microstate accounting, resource usage, and real-time profiling
 */
hrtime_t p_mstart;        /* hi-res process start time */
hrtime_t p_mterm;         /* hi-res process termination time */
hrtime_t p_mlreal;        /* elapsed time sum over defunct lwps */
hrtime_t p_acct[NMSTATES]; /* microstate sum over defunct lwps */
struct lrusage p_ru;       /* lrusage sum over defunct lwps */
struct itimerval p_rprof_timer; /* ITIMER_REALPROF interval timer */
uintptr_t p_rprof_cyclic; /* ITIMER_REALPROF cyclic */
uint_t    p_defunct;       /* number of defunct lwps */
/*
 * profiling. A lock is used in the event of multiple lwp's
 * using the same profiling base/size.
 */
kmutex_t p_pflock;        /* protects user profile arguments */
struct prof p_prof;       /* profile arguments */

/*
 * The user structure
 */
struct user p_user;        /* (see sys/user.h) */

/*
 * Doors.
 */
kthread_t *p_server_threads;
struct door_node *p_door_list; /* active doors */
struct door_node *p_unref_list;
kcondvar_t p_server_cv;
char p_unref_thread; /* unref thread created */
```

struct proc (Solaris) (3)

```
/*
 * Kernel probes
 */
uchar_t          p_tnf_flags;

/*
 * C2 Security (C2_AUDIT)
 */
caddr_t p_audit_data;      /* per process audit structure */
kthread_t *p_aslwp;      /* thread ptr representing "aslwp" */
#if defined(i386) || defined(__i386) || defined(__ia64)
/*
 * LDT support.
 */
kmutex_t p_ldtlock;      /* protects the following fields */
struct seg_desc *p_ldt;  /* Pointer to private LDT */
struct seg_desc p_ldt_desc; /* segment descriptor for private LDT */
int p_ldtlimit;         /* highest selector used */
#endif
size_t p_swrss;         /* resident set size before last swap */
struct aio *p_aio;      /* pointer to async I/O struct */
struct itimer **p_itimer; /* interval timers */
k_sigset_t p_notifsig; /* signals in notification set */
kcondvar_t p_notifcv; /* notif cv to synchronize with aslwp */
timeout_id_t p_alarmid; /* alarm's timeout id */
uint_t p_sc_unblocked; /* number of unblocked threads */
struct vnode *p_sc_door; /* scheduler activations door */
caddr_t p_usrstack; /* top of the process stack */
uint_t p_stkprot; /* stack memory protection */
model_t p_model; /* data model determined at exec time */
struct lwpchan_data *p_lcp; /* lwpchan cache */

/*
 * protects unmapping and initialization of robust locks.
 */
kmutex_t p_lcp_mutexinitlock;
utraper_handler_t *p_utrap; /* pointer to user trap handlers */
refstr_t *p_corefile; /* pattern for core file */

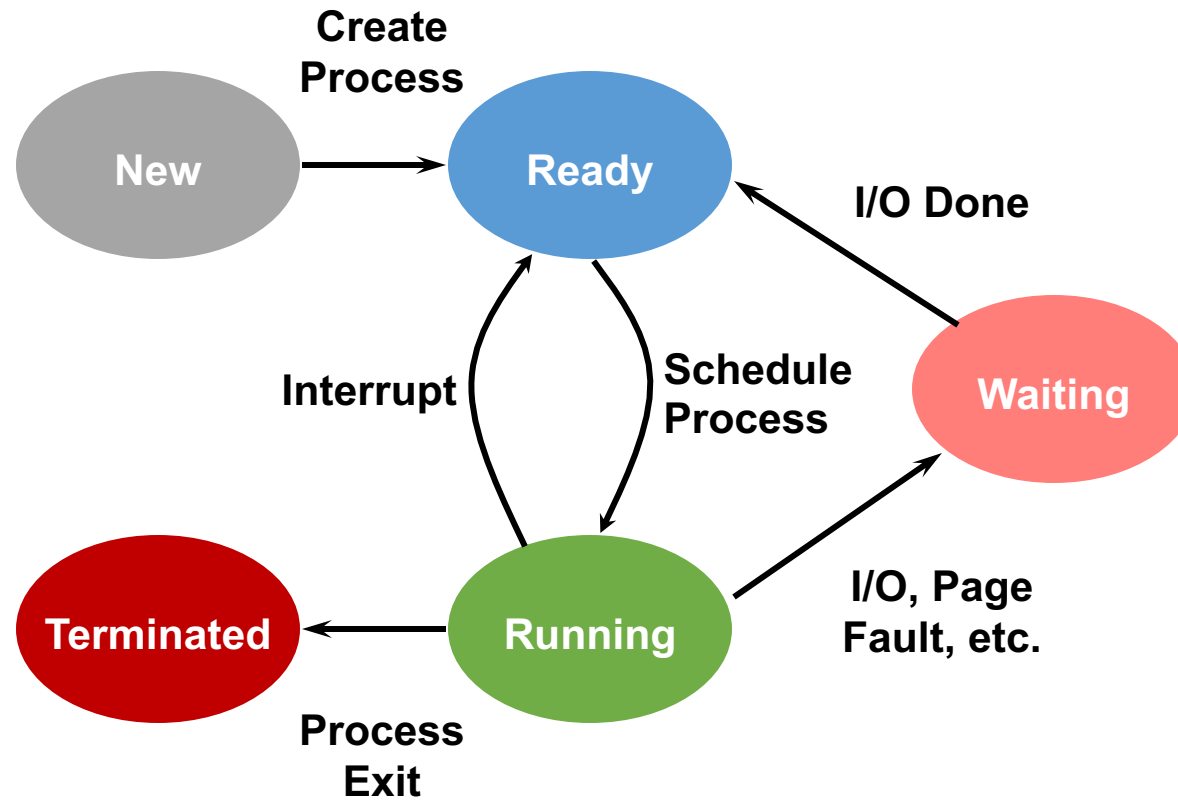
#if defined(__ia64)
caddr_t p_upstack; /* base of the upward-growing stack */
size_t p_upstksize; /* size of that stack, in bytes */
uchar_t p_isa; /* which instruction set is utilized */
#endif

void *p_rce; /* resource control extension data */
struct task *p_task; /* our containing task */
struct proc *p_taskprev; /* ptr to previous process in task */
struct proc *p_tasknext; /* ptr to next process in task */
int p_lwpdaemon; /* number of TP_DAEMON lwps */
int p_lwpdwait; /* number of daemons in lwp_wait() */
kthread_t **p_tidhash; /* tid (lwpid) lookup hash table */
struct sc_data *p_schedctl; /* available schedctl structures */
} proc_t;
```

Process State

- **A process has an **execution state** to indicate what it is doing**
 - **Running**: Executing instructions on the CPU
 - It is the process that has control of the CPU
 - How many processes can be in the running state simultaneously?
 - **Ready**: Waiting to be assigned to the CPU
 - Ready to execute, but another process is executing on the CPU
 - **Waiting**: Waiting for an event, e.g., I/O completion
 - It cannot make progress until event is signaled (disk completes)
- **As a process executes, it moves from state to state**
 - Unix `ps`: `STAT` column indicates execution state
 - What state do you think a process is in most of the time?
 - How many processes can a system support?

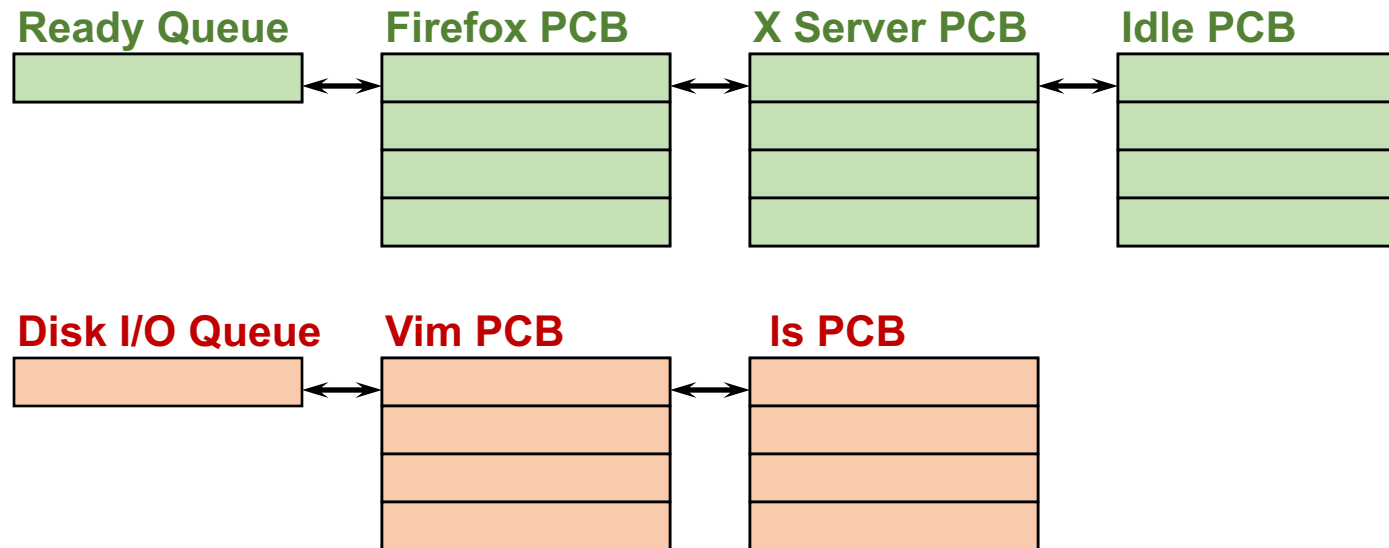
Process State Graph



State Queues

- **How does the OS keep track of processes?**
 - The OS maintains a collection of queues that represent the state of all processes in the system
 - Typically, the OS has one queue for each state
 - Ready, waiting, etc.
 - Each PCB is queued on a state queue according to its current state
 - As a process changes state, its PCB is unlinked from one queue and linked into another

State Queues



Console Queue

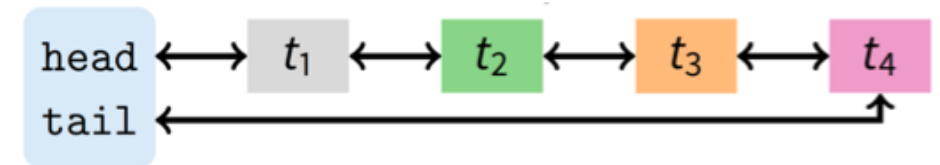
Sleep Queue

- .
- .
- .

There may be many wait queues, one for each type of wait (disk, console, timer, network, etc.)

Scheduling

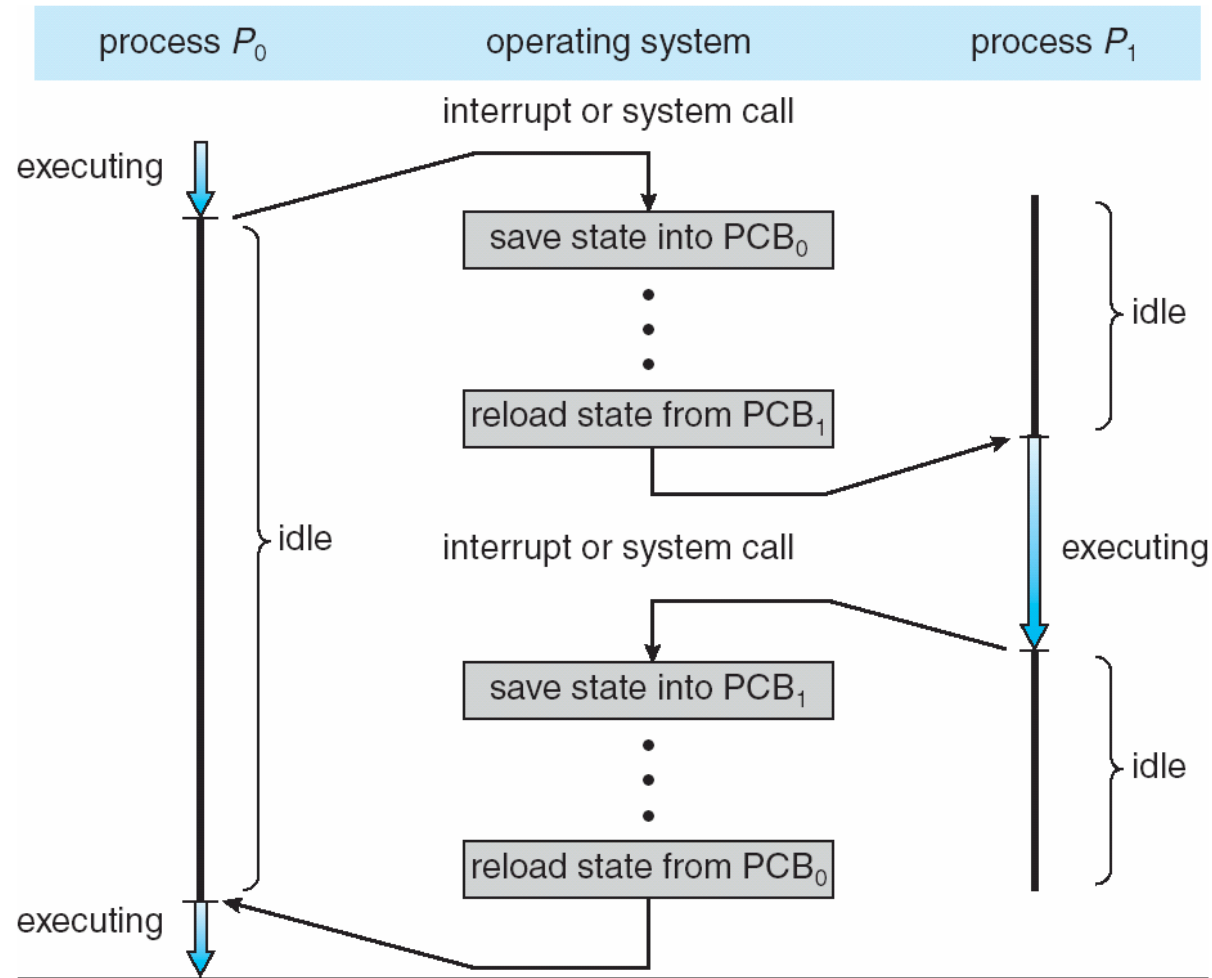
- **Which process should kernel run?**
 - if 0 runnable, run idle loop (or halt CPU), if 1 runnable, run it
 - if >1 runnable, must make scheduling decision
- **Scan process table for first runnable?**
 - Expensive. Weird priorities (small pids do better)
 - Divide into runnable and blocked processes
- **FIFO?**
 - Put threads on back of list, pull them from front:
 - Pintos does this—see `ready_list` in `thread.c`
- **Priority?**
- **Next class discusses in detail**



Preemption

- **When to trigger a process scheduling decision?**
 - Yield control of CPU
 - voluntarily, e.g., `sched_yield`
 - system call, page fault, illegal instruction, etc.
 - Preemption
- **Periodic timer interrupt**
 - If running process used up quantum, schedule another
- **Device interrupt**
 - Disk request completed, or packet arrived on network
 - Previously waiting process becomes runnable
- **Changing running process is called a context switch**
 - CPU hardware state is changed from one to another
 - This can happen 100 or 1000 times a second!

Context Switch



Context Switch Details

- **Very machine dependent. Typical things include:**
 - Save program counter and integer registers (always)
 - Save floating point or other special registers
 - Save condition codes
 - **Change virtual address translations**
- **Non-negligible cost**
 - Save/restore floating point registers expensive
 - Optimization: only save if process used floating point
 - May require flushing TLB (memory translation hardware)
- **Usually causes more cache misses (switch working sets)**

User's (Programmer's) View of Processes

Creating a Process

- **A process is created by another process**
 - Parent is creator, child is created (Unix: ps “PPID” field)
 - What creates the first process (Unix: init (PID 0 or 1))?
- **Parent defines resources and privileges for its children**
 - Unix: Process User ID is inherited – children of your shell execute with your privileges
- **After creating a child**
 - the parent may either wait for it to finish its task or continue in parallel

Process Creation: Windows

- **The system call on Windows for creating a process is called, surprisingly enough, `CreateProcess`:**

```
BOOL CreateProcess(char *prog, char *args) (simplified)
```

- `CreateProcess`
 - Creates and initializes a new PCB
 - Creates and initializes a new address space
 - Loads the program specified by “`prog`” into the address space
 - Copies “`args`” into memory allocated in address space
 - Initializes the saved hardware context to start execution at `main` (or wherever specified in the file)
 - Places the PCB on the ready queue



Windows desktop applications > Develop > Desktop technologies > System Services > Processes and Threads > Process and Thread Reference > Process and Thread Functions > CreateProcess

CreateProcess function

Creates a new process and its primary thread. The new process runs in the security context of the calling process.

If the calling process is impersonating another user, the new process uses the token for the calling process, not the impersonation token. To run the new process in the security context of the user represented by the impersonation token, use the [CreateProcessAsUser](#) or [CreateProcessWithLogonW](#) function.

Syntax

C++

```
BOOL WINAPI CreateProcess(  
    _In_opt_ LPCTSTR lpApplicationName,  
    _Inout_opt_ LPTSTR lpCommandLine,  
    _In_opt_ LPSECURITY_ATTRIBUTES lpProcessAttributes,  
    _In_opt_ LPSECURITY_ATTRIBUTES lpThreadAttributes,  
    _In_ BOOL bInheritHandles,  
    _In_ DWORD dwCreationFlags,  
    _In_opt_ LPVOID lpEnvironment,  
    _In_opt_ LPCTSTR lpCurrentDirectory,  
    _In_ LPSTARTUPINFO lpStartupInfo,  
    _Out_ LPPROCESS_INFORMATION lpProcessInformation  
);
```

Process Creation: Unix

- **In Unix, processes are created using fork()**

```
int fork()
```

- `fork()`
 - Creates and initializes a new PCB
 - Creates a new address space
 - **Initializes the address space with a **copy** of the entire contents of the address space of the parent**
 - Initializes the kernel resources to point to the resources used by parent (e.g., open files)
 - Places the PCB on the ready queue
- **Fork returns **twice****
 - Huh?
 - Returns the child's PID to the parent, "0" to the child



OS X Man Pages

FORK(2)

BSD System Calls Manual

FORK(2)

NAME**fork** -- create a new process**SYNOPSIS****#include** <unistd.h>pid_t**fork**(void);**DESCRIPTION**

Fork() causes creation of a new process. The new process (child process) is an exact copy of the calling process (parent process) except for the following:

- The child process has a unique process ID.
- The child process has a different parent process ID (i.e., the process ID of the parent process).
- The child process has its own copy of the parent's descriptors. These descriptors reference the same underlying objects, so that, for instance, file pointers in file objects are shared between the child and the parent, so that an `lseek(2)` on a descriptor in the child process can affect a subsequent read or write by the parent. This descriptor copying is also used by the shell to establish standard input and output for newly created processes as well as to set up pipes.
- The child processes resource utilizations are set to 0; see `setrlimit(2)`.

RETURN VALUES

Upon successful completion, **fork()** returns a value of 0 to the child process and returns the process ID of the child process to the parent process. Otherwise, a value of -1 is returned to the parent process, no child process is created, and the global variable `errno` is set to indicate the error.

ERRORS

Fork() will fail and no child process will be created if:

- | | |
|----------|---|
| [EAGAIN] | The system-imposed limit on the total number of processes under execution would be exceeded. This limit is configuration-dependent. |
| [EAGAIN] | The system-imposed limit <code>MAXUPRC</code> (< <code>sys/param.h</code> >) on the total number of processes under execution by a single user would be exceeded. |

fork()

```
#include <stdio.h>
#include <unistd.h>
int main(int argc, char *argv[])
{
    char *name = argv[0];
    int child_pid = fork();
    if (child_pid == 0) {
        printf("Child of %s is %d\n", name, getpid());
        return 0;
    } else {
        printf("My child is %d\n", child_pid);
        return 0;
    }
}
```

What does this program print?

Example Output

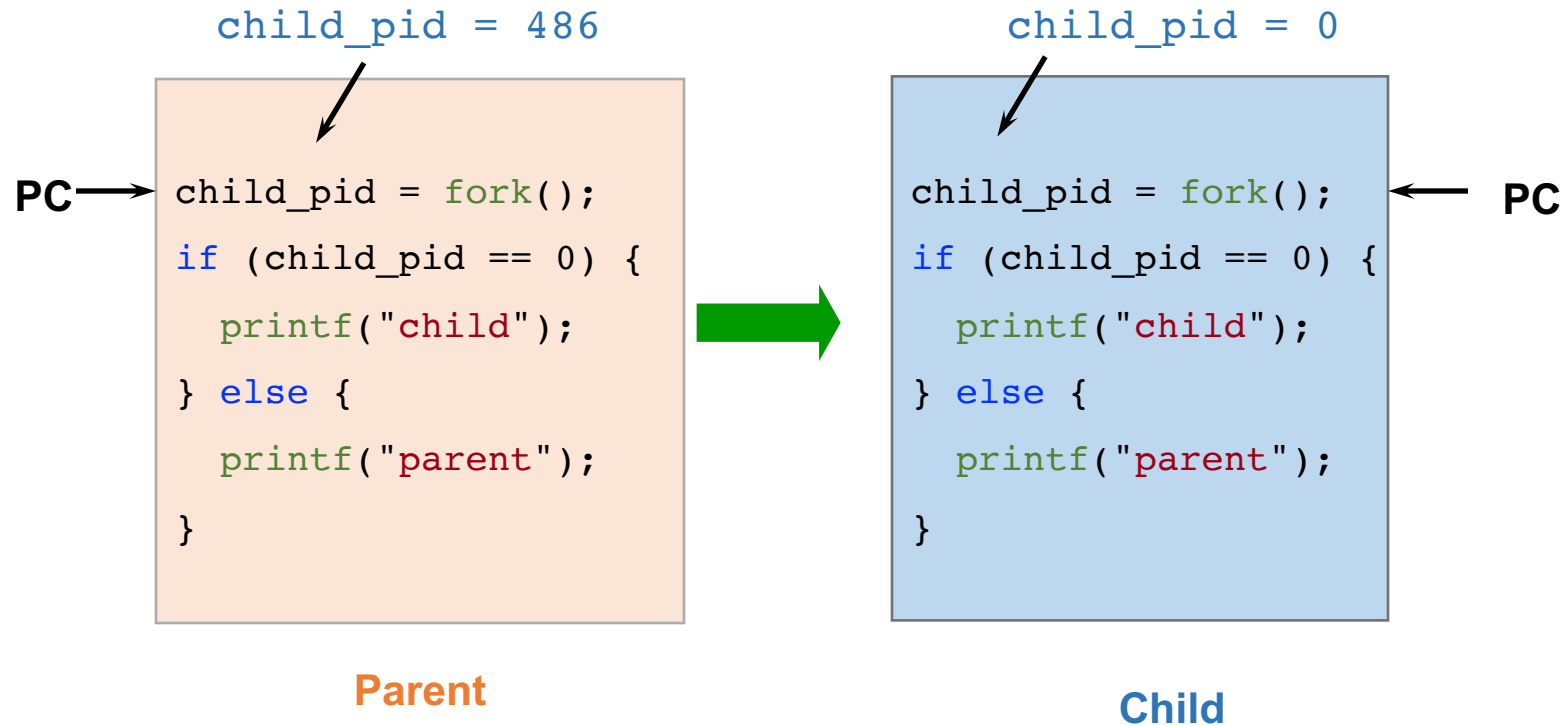
```
$ gcc -o fork fork.c
```

```
$ ./fork
```

My child is 486

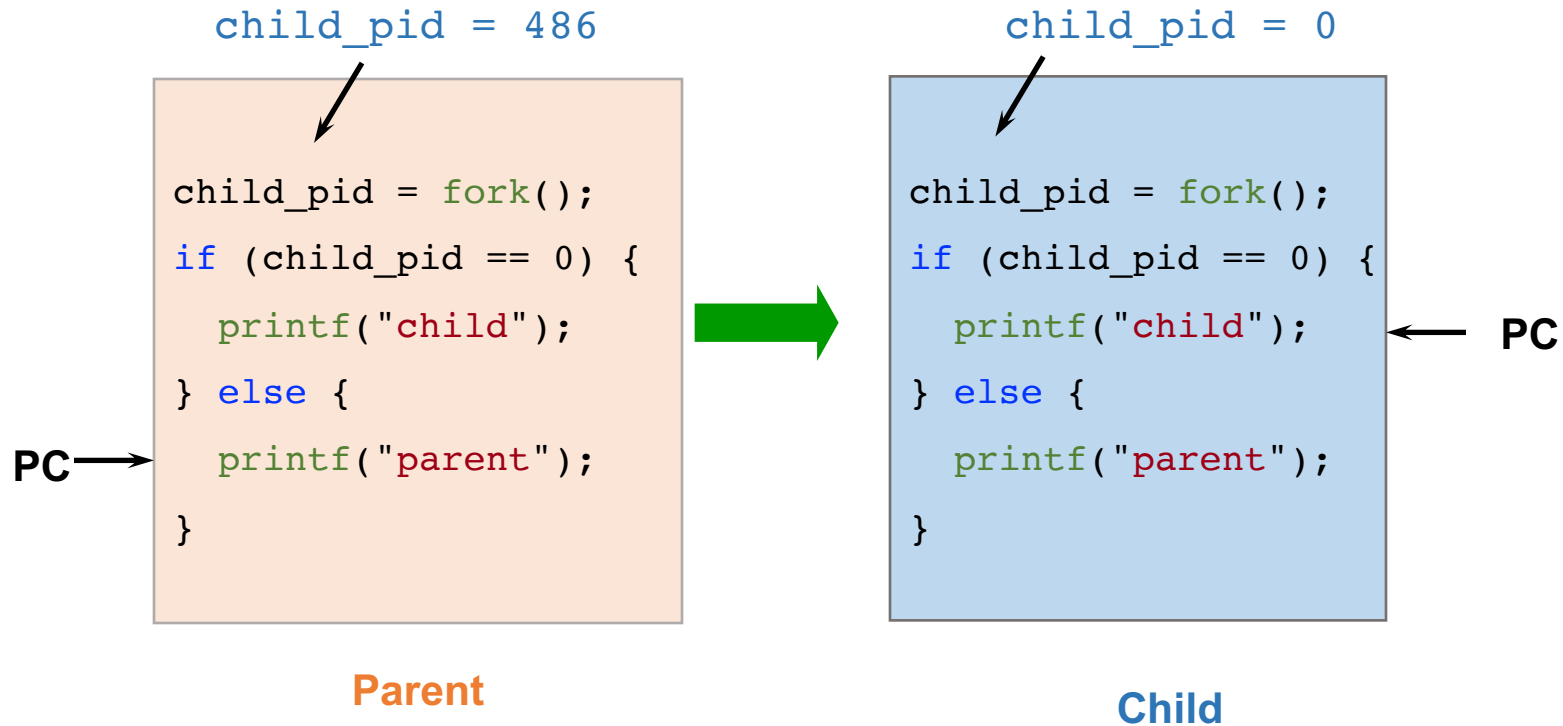
Child of ./fork is 486

Duplicating Address Spaces



The hardware contexts stored in the PCBs of the two processes will be identical, meaning the **EIP** register will point to the same instruction

Divergence



Example Continued

```
$ gcc -o fork fork.c
```

```
$ ./fork
```

My child is 486

Child of ./fork is 486

```
$ ./fork
```

Child of ./fork is 498

My child is 498

Why is the output in a different order?

Process Creation: Unix (2)

- **Wait a second. How do we actually start a new program?**

```
int exec(char *prog, char *argv[])  
int execve(const char *filename, char *const argv[], char *const envp[])
```

- `exec ()`
 - Stops the current process
 - Loads the program “prog” into the process’ address space
 - Initializes hardware context and args for the new program
 - Places the PCB onto the ready queue
 - **Note: It does not create a new process**
- **What does it mean for `exec` to return?**
- **Warning: Pintos `exec` more like combined `fork/exec`**

Manipulating File Descriptors

- `int dup2 (int oldfd, int newfd)`
 - Closes `newfd`, if it was a valid descriptor
 - Makes `newfd` an exact copy of `oldfd`
 - Two file descriptors will share same offset
 - (`lseek` on one will affect both)
- `int fcntl (int fd, F_SETFD, int val)`
 - Sets `close on exec` flag if `val = 1`, clears if `val = 0`
 - Makes file descriptor non-inheritable by spawned programs
- **Example:** `redirsh.c`
 - Loop that reads a command and executes it
 - Recognizes `command < input > output 2> errlog`

redirsh.c²

Example: `command < input > output 2> errlog`

```
void doexec (void) {
    int fd;
    if (infile) {          /* non-NULL for "command < infile" */
        if ((fd = open (infile, O_RDONLY)) < 0) {
            perror (infile);
            exit (1);
        }
        if (fd != 0) {
            dup2 (fd, 0);
            close (fd);
        }
    }
    /* ... do same for outfile→fd 1, errfile→fd 2 ... */
    execvp (av[0], av);
    perror (av[0]);
    exit (1);
}
```

²: <https://www.cs.jhu.edu/~huang/cs318/fall18/code/redirsh.c>

Pipes

- `int pipe (int fds[2])`
 - Returns two file descriptors in `fds[0]` and `fds[1]`
 - Data written to `fds[1]` will be returned by read on `fds[0]`
 - When last copy of `fds[1]` closed, `fds[0]` will return EOF
 - Returns 0 on success, -1 on error
- **Operations on pipes**
 - `read/write/close` – as with files
 - When `fds[1]` closed, `read(fds[0])` returns 0 bytes
 - When `fds[0]` closed, `write(fds[1])`:
 - Kills process with `SIGPIPE`
 - Or if signal ignored, fails with `EPIPE`
- **Example: `pipesh.c`**
 - Sets up pipeline `command1 | command2 | command3 ...`

Why `fork()`?

- **Most calls to `fork` followed by `exec`**
 - could also combine into one `spawn` system call
- **Very useful when the child...**
 - Is cooperating with the parent
 - Relies upon the parent's data to accomplish its task
- **Example: web server**

```
while (1) {  
    int sock = accept();  
    if ((child_pid = fork()) == 0) {  
        // Handle client request  
    } else {  
        // Close socket  
    }  
}
```

Why `fork()`?

- **Most calls to `fork` followed by `exec`**
 - could also combine into one `spawn` system call
- **Very useful when the child...**
 - Is cooperating with the parent
 - Relies upon the parent's data to accomplish its task
- **Example: web server**
- **Example: shell**

minish.c¹ (simplified)

```
pid_t pid; char **av;
void doexec () {
    execvp (av[0], av);
    perror (av[0]);
    exit (1);
}
/* ... main loop: */
for (;;) {
    parse_next_line_of_input (&av, stdin);
    switch (pid = fork ()) {
    case -1:
        perror ("fork"); break;
    case 0:
        doexec ();
    default:
        waitpid (pid, NULL, 0); break;
    }
}
```

¹: <https://www.cs.jhu.edu/~huang/cs318/fall18/code/minish.c>

Why `fork()`?

- **Most calls to `fork` followed by `exec`**
 - could also combine into one `spawn` system call
- **Very useful when the child...**
 - Is cooperating with the parent
 - Relies upon the parent's data to accomplish its task
- **Example: Web server**
- **Real win is simplicity of interface**
 - Tons of things you might want to do to child: manipulate file descriptors, set environment variables, reduce privileges, ...
 - Yet `fork` requires no arguments at all

Spawning a Process Without fork

- **Without fork, needs tons of different options for new process**
 - Example: Windows CreateProcess system call
 - Also CreateProcessAsUser, CreateProcessWithLogonW, CreateProcessWithTokenW, ...

```
BOOL WINAPI CreateProcess(  
    _In_opt_ LPCTSTR lpApplicationName,  
    _Inout_opt_ LPTSTR lpCommandLine,  
    _In_opt_ LPSECURITY_ATTRIBUTES lpProcessAttributes,  
    _In_opt_ LPSECURITY_ATTRIBUTES lpThreadAttributes,  
    _In_ BOOL bInheritHandles,  
    _In_ DWORD dwCreationFlags,  
    _In_opt_ LPVOID lpEnvironment,  
    _In_opt_ LPCTSTR lpCurrentDirectory,  
    _In_ LPSTARTUPINFO lpStartupInfo,  
    _Out_ LPPROCESS_INFORMATION lpProcessInformation  
);
```

Process Creation: Unix (3)

- **Why Windows use `CreateProcess` while Unix uses `fork/exec`?**
- **What happens if you run “`exec csh`” in your shell?**
- **What happens if you run “`exec ls`” in your shell? Try it.**
- **`fork()` can return an error. Why might this happen?**

Process Termination

- **All good processes must come to an end. But how?**
 - Unix: `exit(int status)`, Windows: `ExitProcess(int status)`
- **Essentially, free resources and terminate**
 - Terminate all threads (next lecture)
 - Close open files, network connections
 - Allocated memory (and VM pages out on disk)
 - Remove PCB from kernel data structures, delete
- **Note that a process does not **need** to clean up itself**
 - Why does the OS have to do it?

wait() a second...

- **Often it is convenient to pause until a child process has finished**
 - Think of executing commands in a shell
- **Unix** `wait(int *wstatus)` (**Windows:** `WaitForSingleObject`)
 - Suspends the current process until *any* child process ends
 - `waitpid()` suspends until the specified child process ends
- **Wait has a return value...what is it?**
- **Unix: Every process must be “reaped” by a parent**
 - What happens if a parent process exits before a child?
 - What do you think a “zombie” process is?

Process Summary

- **What are the units of execution?**
 - Processes
- **How are those units of execution represented?**
 - Process Control Blocks (PCBs)
- **How is work scheduled in the CPU?**
 - Process states, process queues, context switches
- **What are the possible execution states of a process?**
 - Running, ready, waiting
- **How does a process move from one state to another?**
 - Scheduling, I/O, creation, termination
- **How are processes created?**
 - CreateProcess (NT), fork/exec (Unix)

Next time...

- **Read Chapters 7, 8**
- **Lab 0 due**
- **Lab 1 starts**