CSE 120
Principles of Operating Systems

Fall 2004

Lecture 4: Processes

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Processes

- This lecture starts a class segment that covers processes, threads, and synchronization
  - These topics are perhaps the most important in this class.
  - You can rest assured that they will be covered in the exams.
- 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?

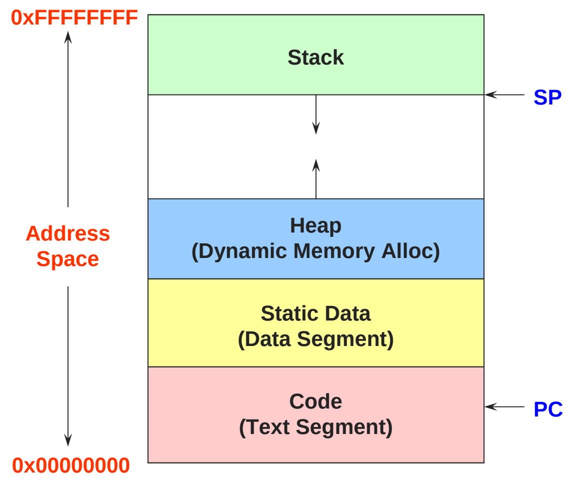
The Process

- The process is the OS abstraction for execution
  - It is the unit of execution
  - It is the unit of scheduling
  - It is the dynamic execution context of a program
- A process is sometimes called a job or a task or a sequential process
- A sequential 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

Process Components

- A process contains all of the 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.
- A process is named using its process ID (PID)

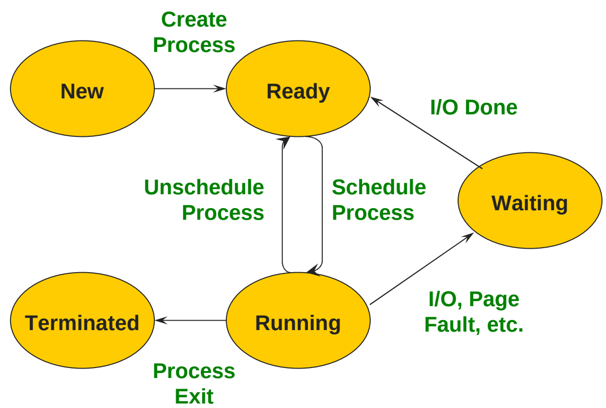
Process Diagram



Process State

- A process has an execution state that indicates what it is currently 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?

Process State Graph



Process Data Structures

How does the OS represent a process in the kernel?

- At any time, there are many processes in the system, each in its particular state
- The OS data structure representing each process is called the Process Control Block (PCB)
- The PCB contains all of the info about a process
- The PCB also is where the OS keeps all of a process' hardware execution state (PC, SP, regs, etc.) when the process is not running
  - This state is everything that is needed to restore the hardware to the same configuration it was in when the process was switched out of the hardware

PCB Data Structure

- The PCB contains a huge amount of information in one large structure
  - » Process ID (PID)
  - » Execution state
  - » Hardware state: PC, SP, regs
  - » Memory management
  - » Scheduling
  - » Accounting
  - » Pointers for state queues
  - » 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_signhdr;      /* 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_srwchan_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 */

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


struct proc (Solaris) (3)

```
        /*
         * C2 Security  (C2_AUDIT)
         */
        caddr_t p_audit_data;          /* per process audit structure */
        kthread_t      *p_aslwptp;     /* 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_notifsigs;    /* 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 initilization of robust locks.
         */
        kmutex_t       p_lcp_mutexinitlock;
        utrap_handler_t *p_utraps;     /* 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;
```

PCBs and Hardware State

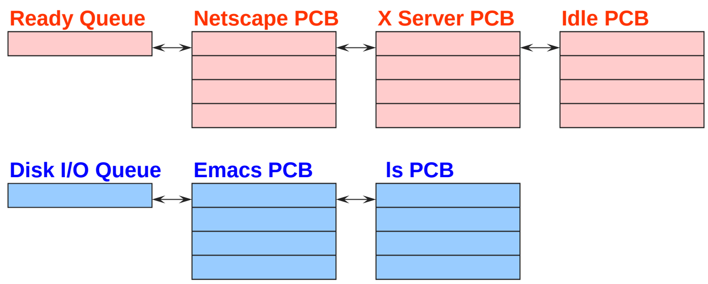
- When a process is running, its hardware state (PC, SP, regs, etc.) is in the CPU
  - The hardware registers contain the current values
- When the OS stops running a process, it saves the current values of the registers into the process' PCB
- When the OS is ready to start executing a new process, it loads the hardware registers from the values stored in that process' PCB
  - What happens to the code that is executing?
- The process of changing the CPU hardware state from one process to another is called a context switch
  - This can happen 100 or 1000 times a second!

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

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

PCBs and State Queues

- PCBs are data structures dynamically allocated in OS memory
- When a process is created, the OS allocates a PCB for it, initialized, and placed on the ready queue
- As the process computes, does I/O, etc., its PCB moves from one queue to another
- When the process terminates, its PCB is deallocated

Process Creation

- 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))?
- In some systems, the parent defines (or donates) 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 (or both)

Process Creation: NT

- The system call on NT 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 hardware context to start execution at main (or wherever specified in the file)
  - Places the PCB on the ready queue

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
  - Returns the child's PID to the parent, "0" to the child
  - Huh?

fork()

```
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

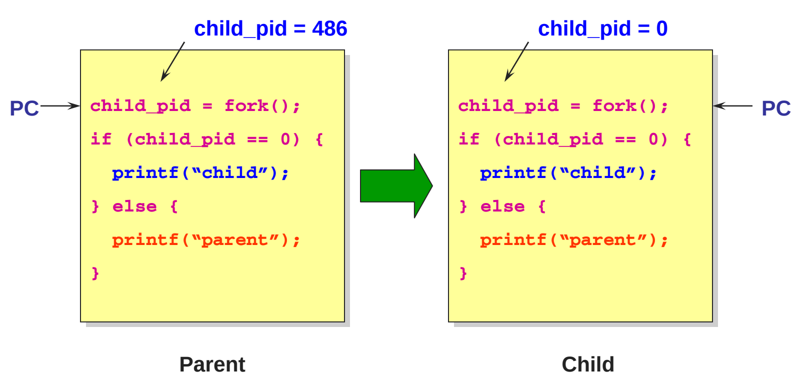
alpenglow (18) ~/tmp> cc t.c

alpenglow (19) ~/tmp> a.out

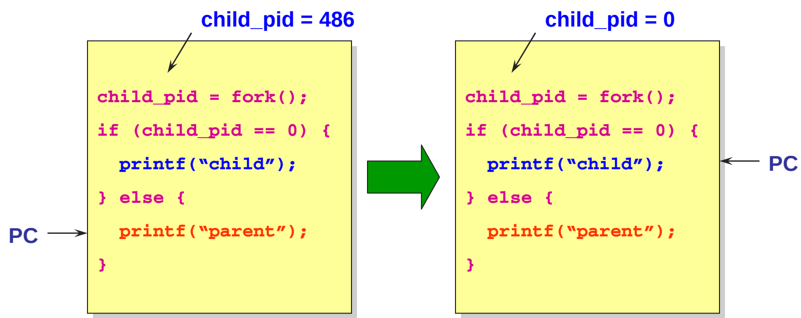
My child is 486

Child of a.out is 486

Duplicating Address Spaces



Divergence



Parent

Child

Example Continued

alpenglow (18) ~/tmp> cc t.c
alpenglow (19) ~/tmp> a.out
My child is 486
Child of a.out is 486
alpenglow (20) ~/tmp> a.out
Child of a.out is 498
My child is 498

Why is the output in a different order?

Why fork()?

- 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
  }
}
```


Process Creation: Unix (2)

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

```
int exec(char *prog, char *argv[])
```

- 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?
- What does it mean for exec to return with an error?

Process Creation: Unix (3)

- fork() is used to create a new process, exec is used to load a program into the address space
  - Why does NT have 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), NT: 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
- Use wait() (WaitForSingleObject)
  - Suspends the current process until a 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?

Unix Shells

```
while (1) {
    char *cmd = read_command();
    int child_pid = fork();
    if (child_pid == 0) {
        Manipulate STDIN/OUT/ERR file descriptors for pipes,
        redirection, etc.
        exec(cmd);
        panic("exec failed");
    } else {
        waitpid(child_pid);
    }
}
```

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 Chapter 5
- Homework #1 due
- Project 0 due