

CSE 120

Principles of Operating Systems

Fall 2023

Lecture 3: 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
- 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 instruction-at-a-time execution of a program
 - ◆ Programs are static entities with the **potential** for execution

Process Components

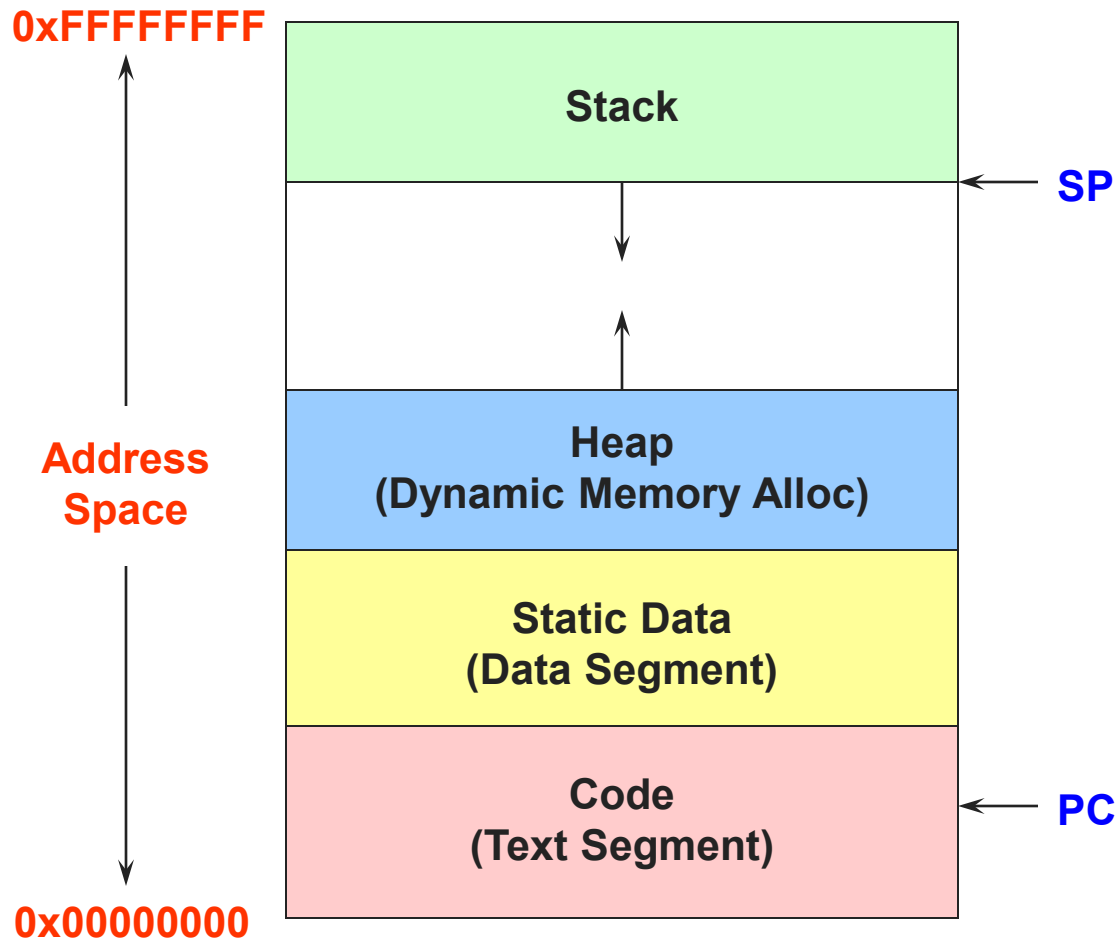
- A process contains all state for a program in execution
 - ◆ An address space
 - ◆ The code for the executing program
 - ◆ The data for the executing program
 - ◆ An execution stack encapsulating the state of procedure calls
 - ◆ The program counter (PC) indicating the next instruction
 - ◆ A set of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

Unix PIDs

```
top - 10:05:04 up 373 days, 1:29, 1 user, load average: 0.00, 0.01, 0.00
Tasks: 206 total, 1 running, 122 sleeping, 1 stopped, 0 zombie
%Cpu(s): 0.0 us, 0.1 sy, 0.0 ni, 99.8 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
KiB Mem : 98967544 total, 72343520 free, 1141584 used, 25482440 buff/cache
KiB Swap: 2097148 total, 2097148 free, 0 used. 96887280 avail Mem
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
27210	voelker	20	0	33536	3692	3160	R	0.3	0.0	0:00.05	top
27211	root	20	0	66208	5360	4664	S	0.3	0.0	0:00.01	sshd
27877	root	20	0	0	0	0	I	0.3	0.0	0:05.72	kworker/0:2
1	root	20	0	225572	9432	6796	S	0.0	0.0	19:46.34	systemd
2	root	20	0	0	0	0	S	0.0	0.0	0:07.77	kthreadd
4	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	kworker/0:+
6	root	20	0	0	0	0	I	0.0	0.0	0:57.38	kworker/u1+
7	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	mm_percpu_+
8	root	20	0	0	0	0	S	0.0	0.0	0:17.02	ksoftirqd/0
9	root	20	0	0	0	0	I	0.0	0.0	191:58.78	rcu_sched
10	root	20	0	0	0	0	I	0.0	0.0	0:00.00	rcu_bh
11	root	rt	0	0	0	0	S	0.0	0.0	0:02.67	migration/0
12	root	rt	0	0	0	0	S	0.0	0.0	0:57.85	watchdog/0
13	root	20	0	0	0	0	S	0.0	0.0	0:00.00	cpuhp/0
14	root	20	0	0	0	0	S	0.0	0.0	0:00.00	cpuhp/1
15	root	rt	0	0	0	0	S	0.0	0.0	0:55.63	watchdog/1
16	root	rt	0	0	0	0	S	0.0	0.0	0:03.08	migration/1

Basic Process Address Space



Process State

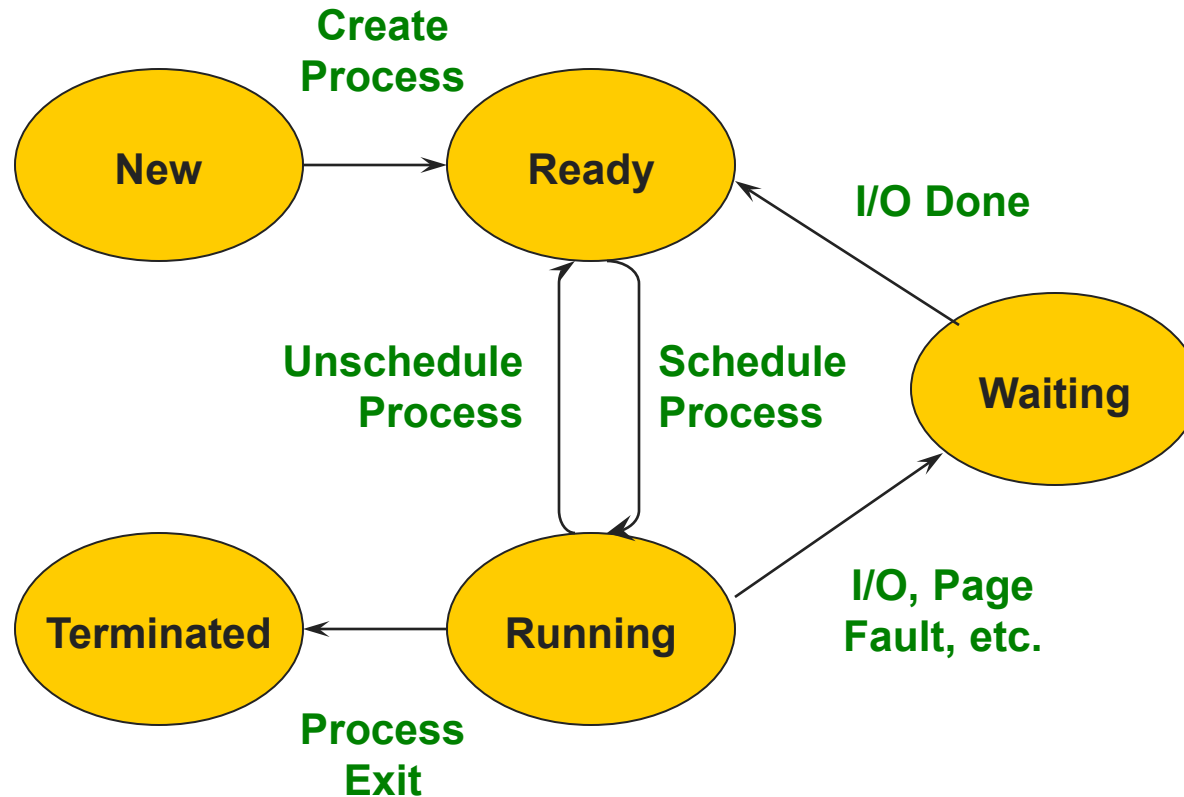
- A process has an **execution state** that indicates what it is currently doing
 - ♦ **Running**: Executing instructions on the CPU
 - » It is the process that has control of the CPU
 - » **How many processes can be in the running state simultaneously?**
 - ♦ **Ready**: Waiting to be assigned to the 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/S** column indicates execution state
 - ♦ **What state do you think a process is in most of the time?**
 - ♦ **How many processes can a system support?**

Unix Process States

```
top - 10:05:04 up 373 days, 1:29, 1 user, load average: 0.00, 0.01, 0.00
Tasks: 206 total, 1 running, 122 sleeping, 1 stopped, 0 zombie
%Cpu(s): 0.0 us, 0.1 sy, 0.0 ni, 99.8 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
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6	root	20	0	0	0	0	I	0.0	0.0	0:57.38	kworker/u1+
7	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	mm_percpu_+
8	root	20	0	0	0	0	S	0.0	0.0	0:17.02	ksoftirqd/0
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13	root	20	0	0	0	0	S	0.0	0.0	0:00.00	cpuhp/0
14	root	20	0	0	0	0	S	0.0	0.0	0:00.00	cpuhp/1
15	root	rt	0	0	0	0	S	0.0	0.0	0:55.63	watchdog/1
16	root	rt	0	0	0	0	S	0.0	0.0	0:03.08	migration/1

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 a particular state
- The OS data structure representing each process is called the **Process Control Block (PCB)**
- The PCB contains all the info about a process
- The PCB also is where the OS keeps all its 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_pgldp;   /* process group ID info */
    /*
     * Fields protected by p_lock
     */
    kcondvar_t p_cv;       /* proc struct's condition variable */
    kcondvar_t p_flag_cv;  /* waiting for some lwp to exit */
    kcondvar_t p_lwpexit;  /* 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_filtset_t p_filtmask; /* 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_srwhchan_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_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_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 initialization 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 PCB
- When the OS is ready to start executing a new process, it loads the hardware registers from the values stored in the 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

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))?
- The parent defines (or donates) resources and privileges for its children
 - ◆ 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

CreateProcessA function (processthreadsapi.h)

Article • 09/23/2022 • 13 minutes to read



☰ In this article

[Syntax](#)[Parameters](#)[Return value](#)[Remarks](#)

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 CreateProcessA(  
    [in, optional] LPCSTR lpApplicationName,  
    [in, out, optional] LPSTR lpCommandLine,  
    [in, optional] LPSECURITY_ATTRIBUTES lpProcessAttributes,  
    [in, optional] LPSECURITY_ATTRIBUTES lpThreadAttributes,  
    [in] BOOL bInheritHandles,  
    [in] DWORD dwCreationFlags,  
    [in, optional] LPVOID lpEnvironment,  
    [in, optional] LPCSTR lpCurrentDirectory,  
    [in] LPSTARTUPINFOA lpStartupInfo,  
    [out] LPPROCESS_INFORMATION lpProcessInformation  
);
```

Parameters

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



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.

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

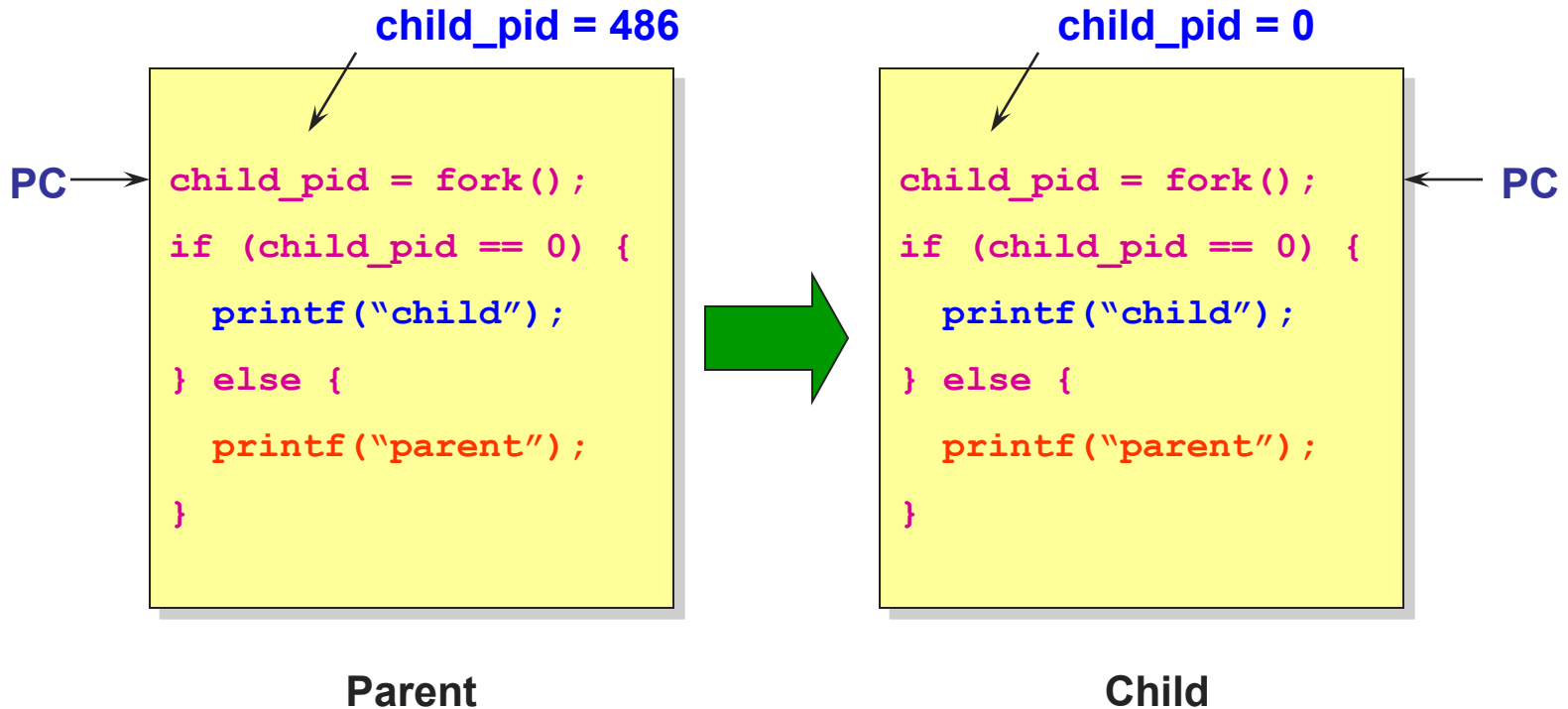
alpenglow (18) ~/tmp> cc t.c

alpenglow (19) ~/tmp> a.out

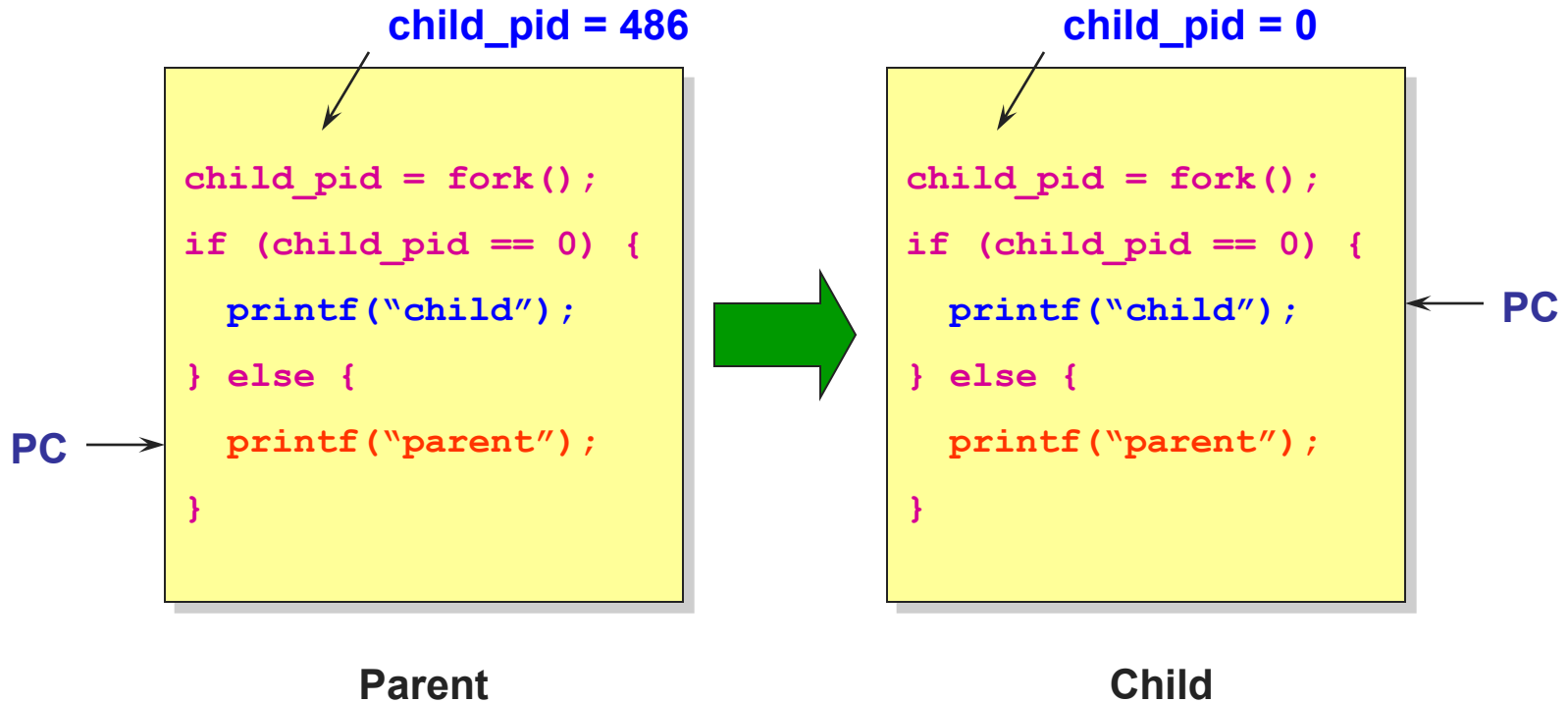
My child is 486

Child of a.out is 486

Duplicating Address Spaces



Divergence



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 and exit  
    } else {  
        Close socket  
    }  
}
```

New Programs: Unix

- Then...how do we 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**

- Can exec ever return?

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()` (Windows: `WaitForSingleObject`)
 - ◆ Suspends the current process until any child process ends
 - ◆ `waitpid()` suspends until the specified child process ends
- Wait returns a status 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 for pipes, redirection, etc.
        exec(cmd);
        panic("exec failed");
    } else {
        waitpid(child_pid);
    }
}
```

Fun With Exec (Extra)

- `fork()` is used to create a new process, `exec` is used to load a program into the address space
- What happens if you run “`exec bash`” 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 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 (Win), fork/exec (Unix)

Next time...

- Read Chapters 26, 27