CSCI3150 Introduction to Operating Systems

Lecture 2: Architectural Support

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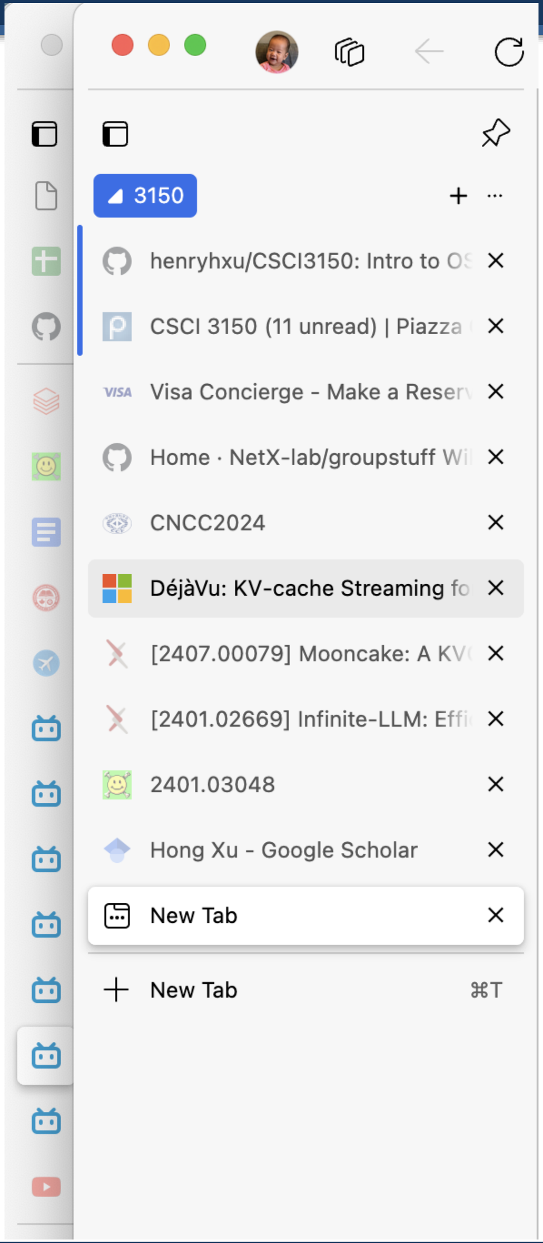
https://github.com/henryhxu/CSCI3150

Processes

- This lecture starts a class segment that covers processes, threads, and synchronization
  - These topics are perhaps the most important in this course
  - You can rest assured that they will be covered in the exams
- Today's topics are <u>processes</u> and <u>process management</u>
  - What are the units of execution?
  - How are those units of execution represented in the OS?
  - What are the possible execution states of a process?
  - How does a process move from one state to another?

Users, Programs

- Users have accounts on the system
- Users launch programs
  - Many users may launch the same program
  - One user may launch many instances of the same program
- Then what is a process?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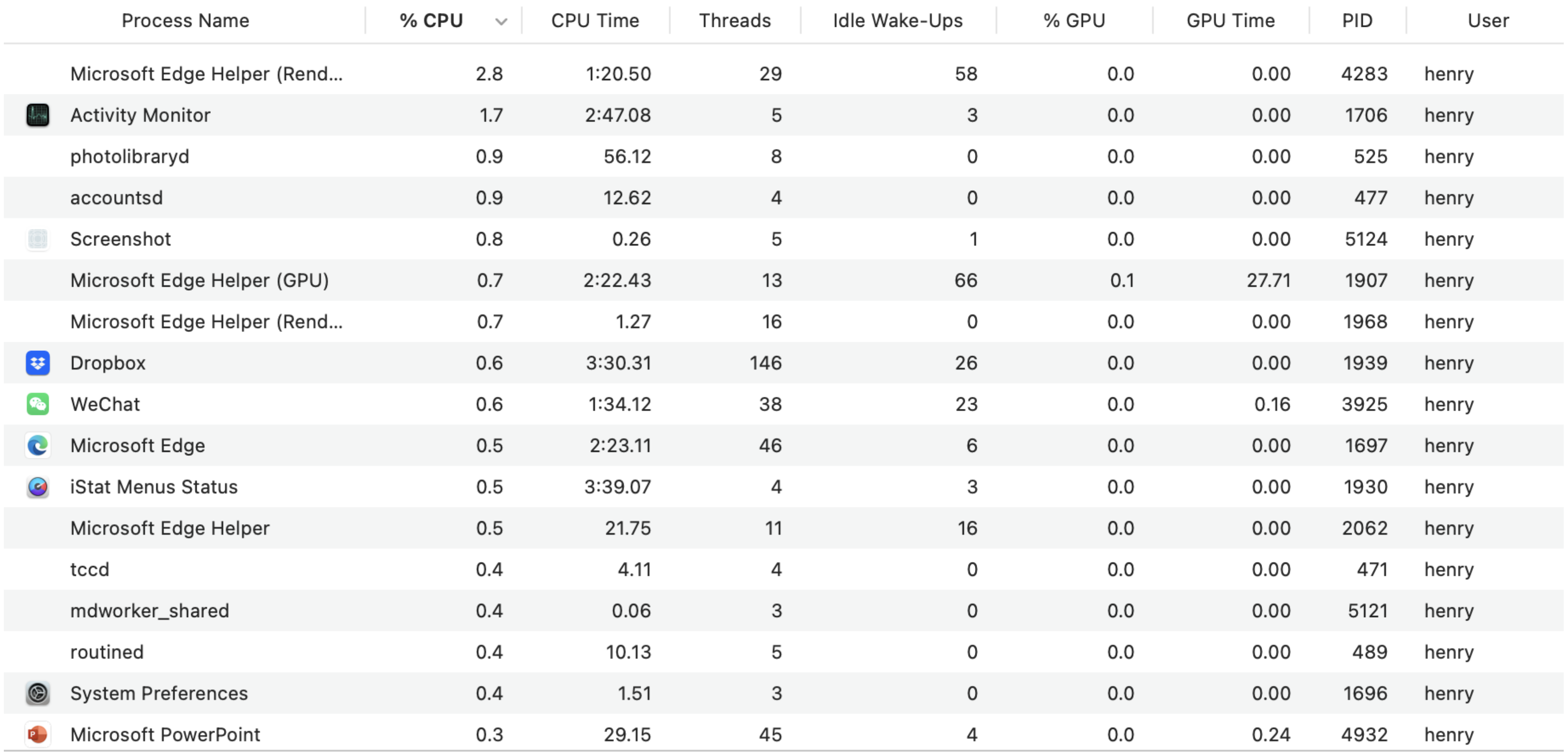
The Process

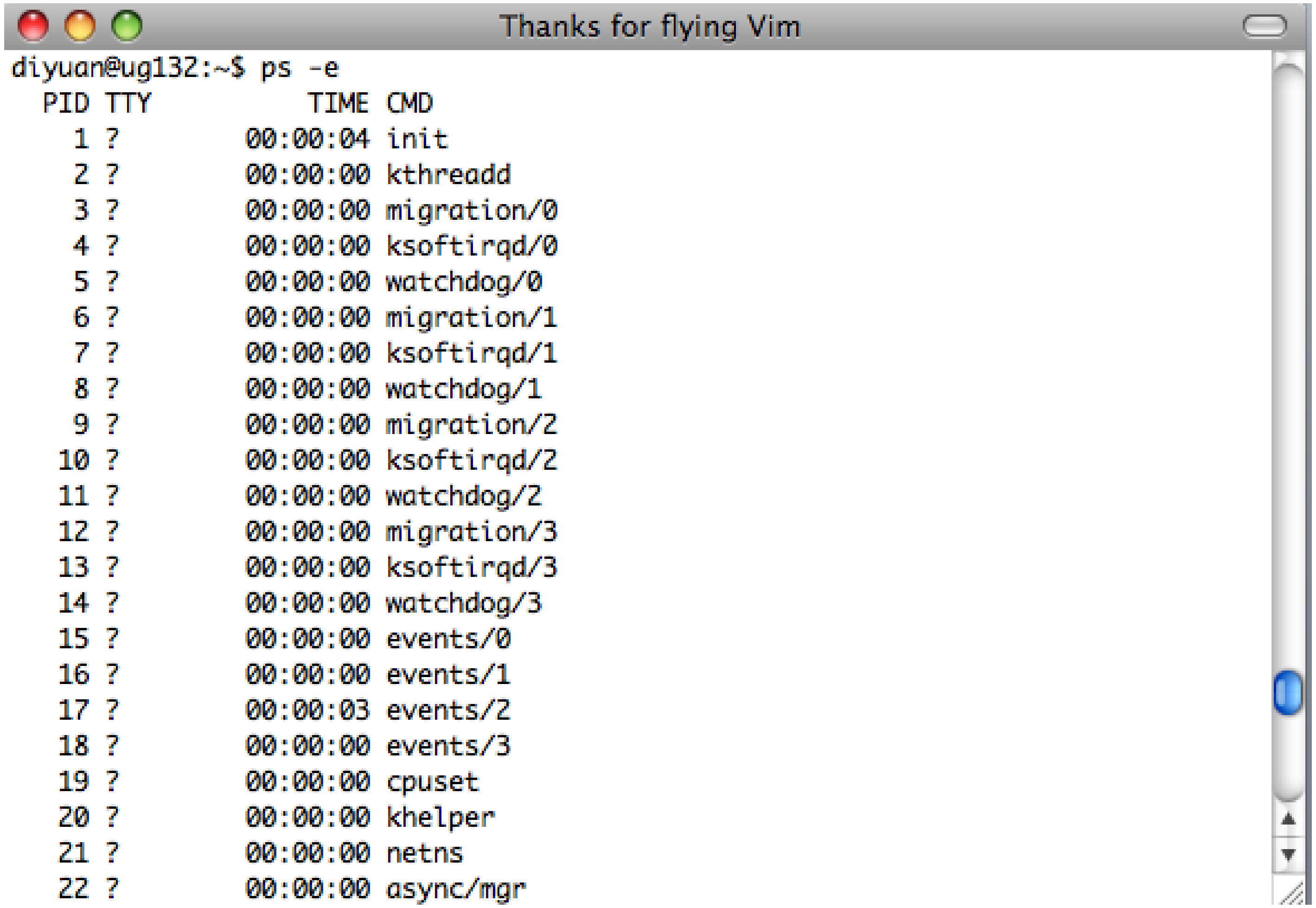
- The process is the OS's abstraction for execution
  - It is the unit of execution
  - It is the unit of scheduling
  - It is the dynamic execution context of a program, a concrete instantiation of the program
- A process is sometimes called a job or a task

MacOS example: Activity monitor



Process Name	% CPU	CPU Time	Threads	Idle Wake-Ups	% GPU	GPU Time	PID	User
Microsoft Edge Helper (Rend...	2.8	1:20.50	29	58	0.0	0.00	4283	henry
Activity Monitor	1.7	2:47.08	5	3	0.0	0.00	1706	henry
photolibraryd	0.9	56.12	8	0	0.0	0.00	525	henry
accountsd	0.9	12.62	4	0	0.0	0.00	477	henry
Screenshot	0.8	0.26	5	1	0.0	0.00	5124	henry
Microsoft Edge Helper (GPU)	0.7	2:22.43	13	66	0.1	27.71	1907	henry
Microsoft Edge Helper (Rend...	0.7	1.27	16	0	0.0	0.00	1968	henry
Dropbox	0.6	3:30.31	146	26	0.0	0.00	1939	henry
WeChat	0.6	1:34.12	38	23	0.0	0.16	3925	henry
Microsoft Edge	0.5	2:23.11	46	6	0.0	0.00	1697	henry
iStat Menus Status	0.5	3:39.07	4	3	0.0	0.00	1930	henry
Microsoft Edge Helper	0.5	21.75	11	16	0.0	0.00	2062	henry
tccd	0.4	4.11	4	0	0.0	0.00	471	henry
mdworker_shared	0.4	0.06	3	0	0.0	0.00	5121	henry
routined	0.4	10.13	5	0	0.0	0.00	489	henry
System Preferences	0.4	1.51	3	0	0.0	0.00	1696	henry
Microsoft PowerPoint	0.3	29.15	45	4	0.0	0.24	4932	henry

Linux example: ps



```
diyuan@ug132:~$ ps -e
  PID TTY          TIME CMD
    1 ?        00:00:04 init
    2 ?        00:00:00 kthreadd
    3 ?        00:00:00 migration/0
    4 ?        00:00:00 ksoftirqd/0
    5 ?        00:00:00 watchdog/0
    6 ?        00:00:00 migration/1
    7 ?        00:00:00 ksoftirqd/1
    8 ?        00:00:00 watchdog/1
    9 ?        00:00:00 migration/2
   10 ?        00:00:00 ksoftirqd/2
   11 ?        00:00:00 watchdog/2
   12 ?        00:00:00 migration/3
   13 ?        00:00:00 ksoftirqd/3
   14 ?        00:00:00 watchdog/3
   15 ?        00:00:00 events/0
   16 ?        00:00:00 events/1
   17 ?        00:00:03 events/2
   18 ?        00:00:00 events/3
   19 ?        00:00:00 cpuset
   20 ?        00:00:00 khelper
   21 ?        00:00:00 netns
   22 ?        00:00:00 async/mgr
```

So what is a process?

- A process is a program in execution
- It is one executing instance of a program
- It is separated from other instances

- It can start ("launch") other processes
- It can be launched by them

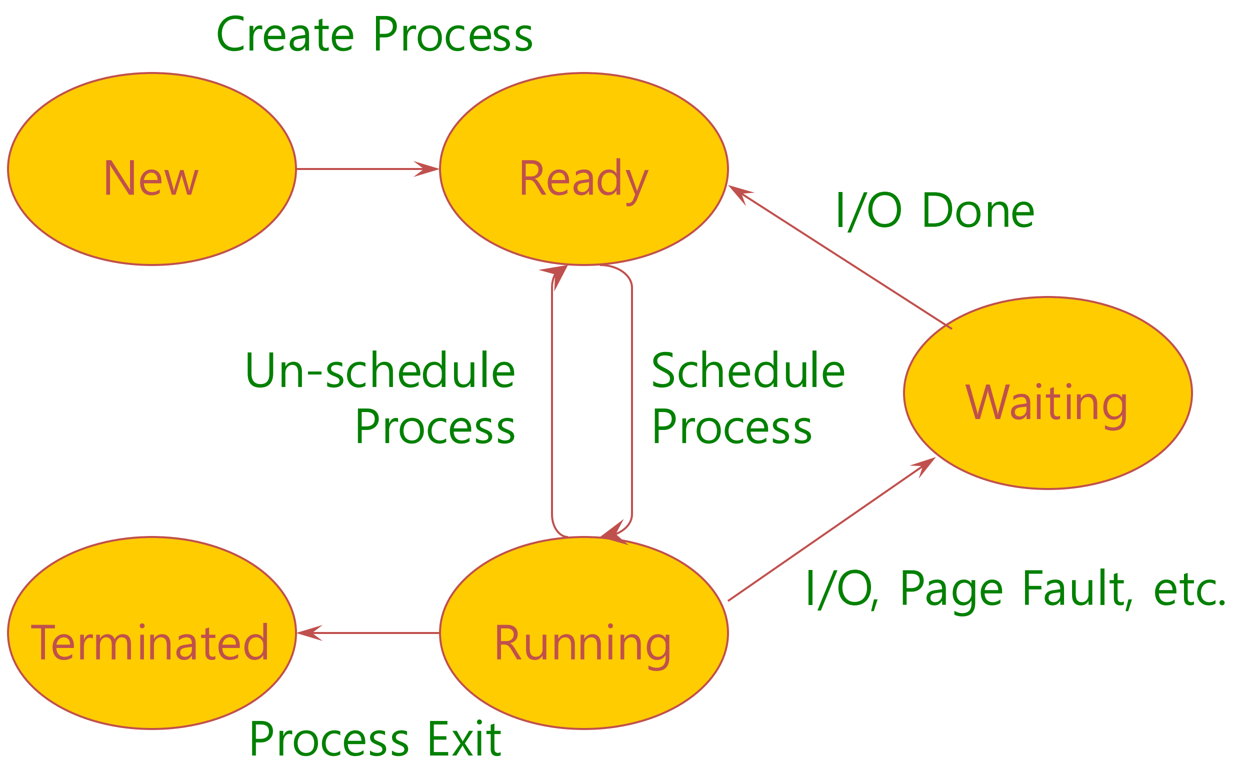
Process State

- A process has an execution state that indicates 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

Questions

- What state do you think a process is in most of the time?
- For a uni-processor machine, how many processes can be in running state?
- Benefit of multi-core?

Process State Graph



Process Components

- Process State
  - new, ready, running, waiting, terminated, …
- Program Counter
  - the address of the next instruction to be executed for this process;
- CPU Registers
  - index registers, stack pointers, general purpose registers;
- CPU Scheduling Information
  - process priority;

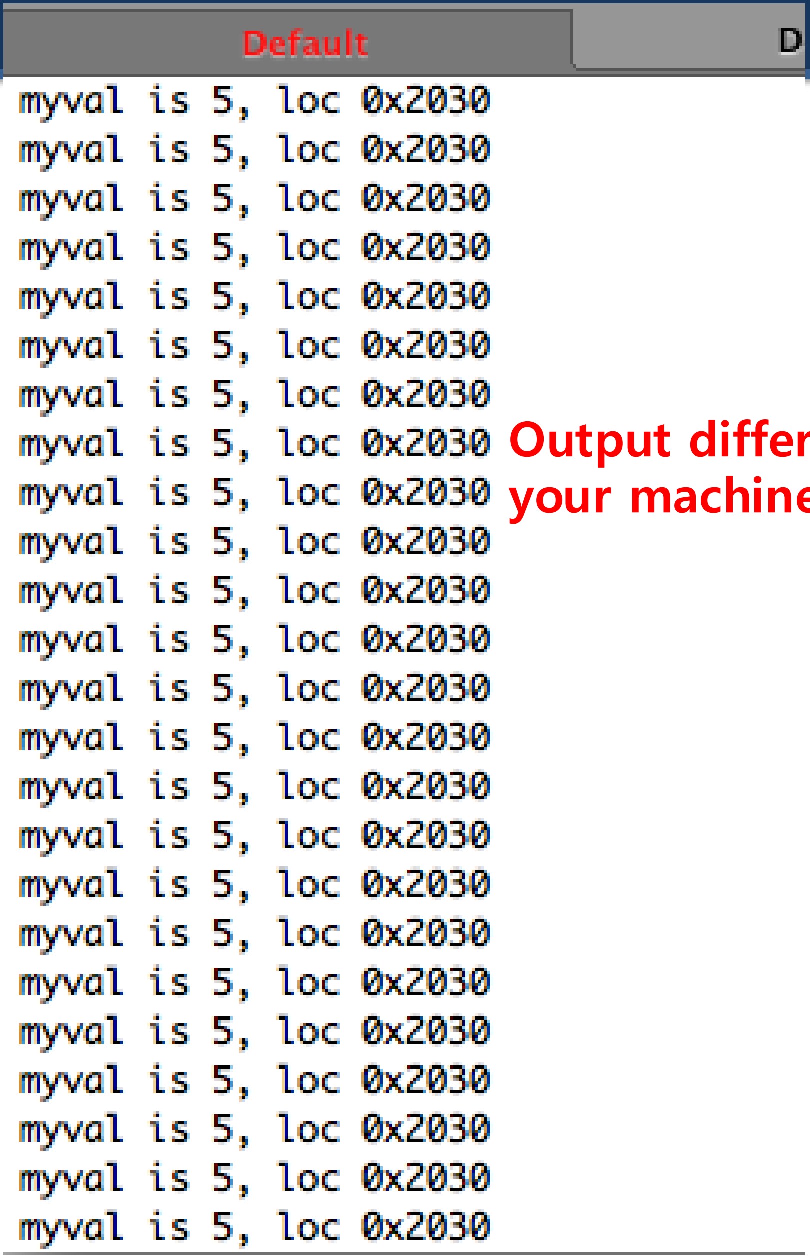
Process Components (cont.)

- Memory Management Information
  - base/limit information, virtual->physical mapping, etc
- Accounting Information
  - time limits, process number; owner
- I/O Status Information
  - list of I/O devices allocated to the process;
- An Address Space
  - memory space visible to one process

Now how about this?

```
int myval;
int main(int argc, char *argv[])
{
  myval = atoi(argv[1]);
  while (1)
   printf("myval is %d, loc 0x%lx\n", myval, (long) &myval);
}
```

- Now *simultaneously* start two instances of this program
  - Myval 5
  - Myval 6
  - What will the outputs be?



```
myval is 5, loc 0x2030
myval is 5, loc 0x2030
myval is 5, loc 0x2030
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myval is 5, loc 0x2030
myval is 5, loc 0x2030
myval is 5, loc 0x2030
myval is 5, loc 0x2030
```
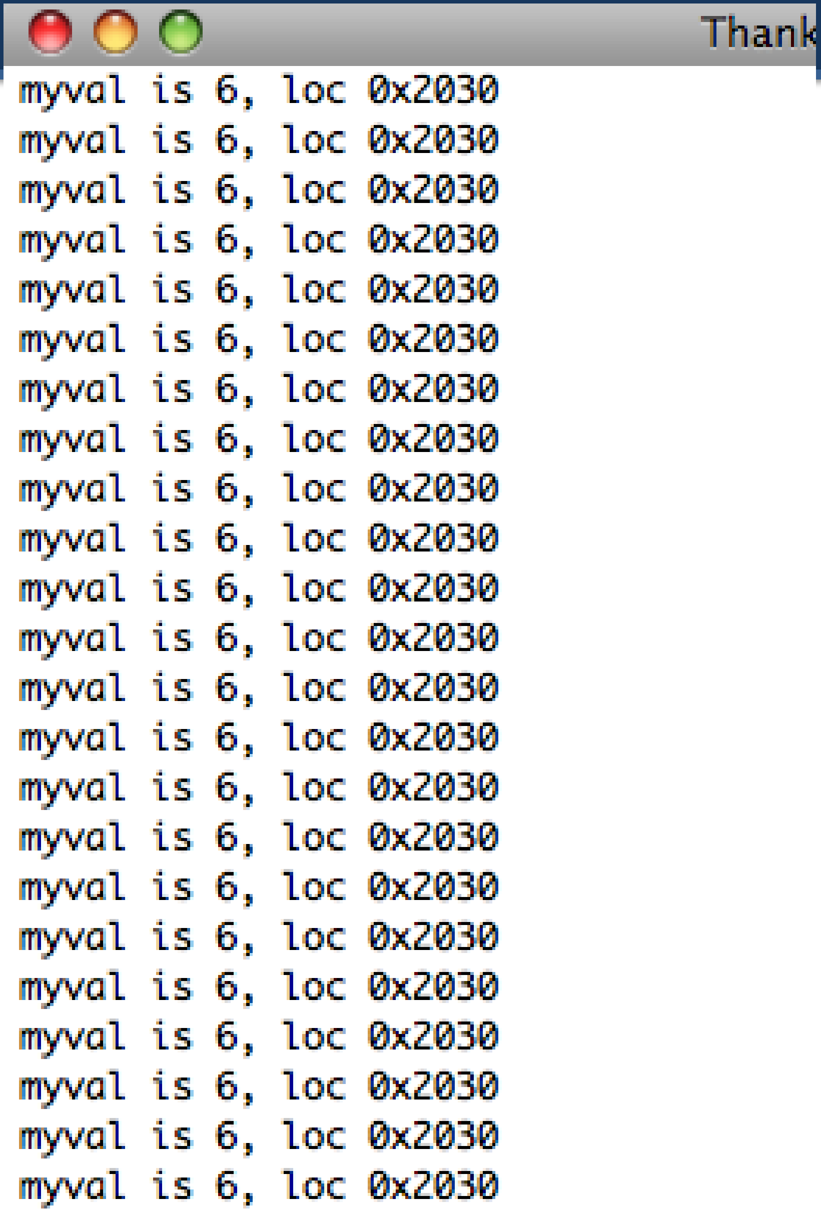

Output differs on your machine!



```
myval is 6, loc 0x2030
myval is 6, loc 0x2030
myval is 6, loc 0x2030
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myval is 6, loc 0x2030
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myval is 6, loc 0x2030
myval is 6, loc 0x2030
myval is 6, loc 0x2030
```
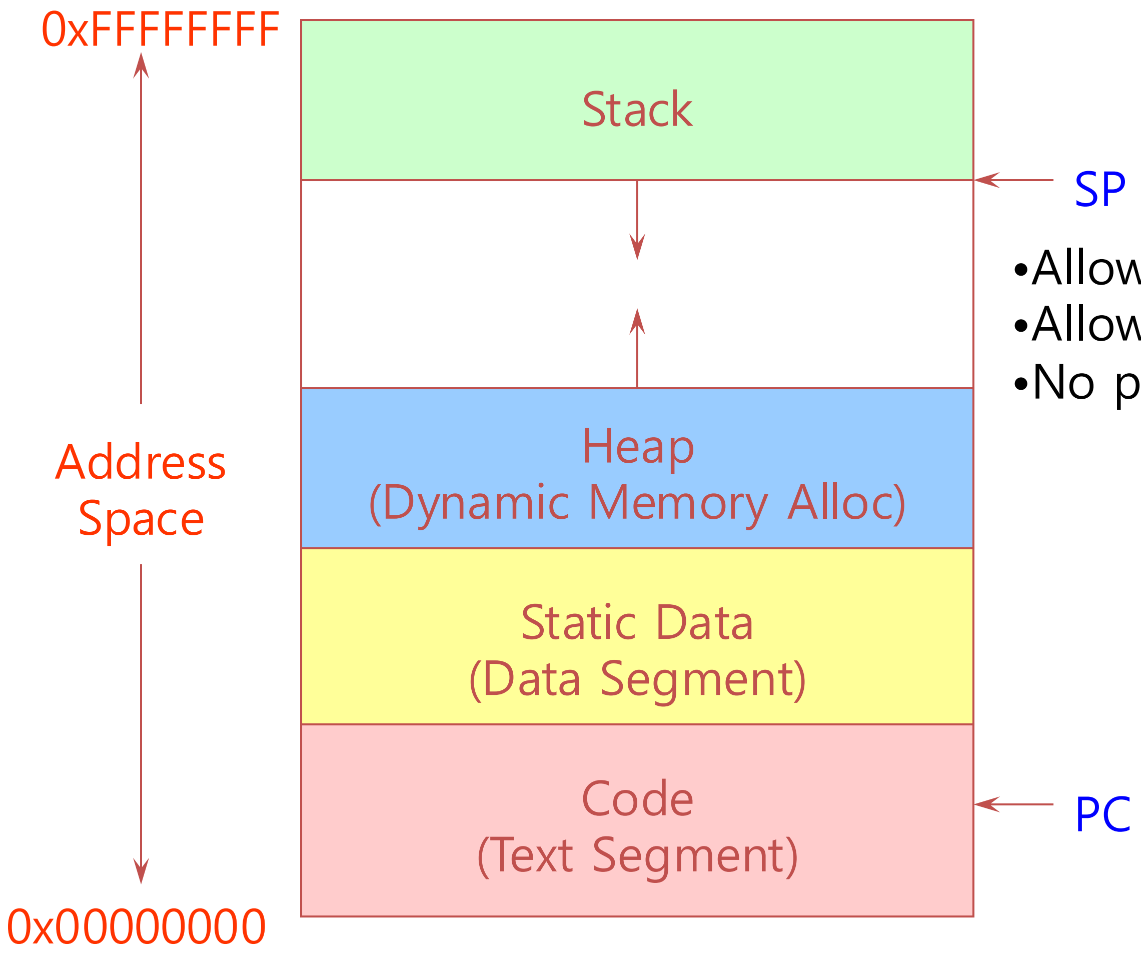

Address in a Process

- The address was always the same
  - But the values were different
- Implications?
  - The programs aren't seeing each other
  - But they think they're using the same address
- Conclusion: addresses here are not w.r.t. the physical memory
- How?
  - Memory mapping
- What is the benefit?

A Process's Address Space



- Allows stack growth
- Allows heap growth
- No predetermined division

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 own state
- The data structure representing each process is called the Process Control Block (PCB)
- The PCB contains all info about a process
- The PCB also is where the OS keeps a process' hardware execution state (PC, SP, regs, etc.) when the process is not running
    - This state is everything needed to restore the hardware to the same state it was in when the process was switched out of the hardware

PCB Data Structure

- PCB contains a huge amount of information in one big structure
    - Process ID (PID)
    - Execution state
    - Hardware state: PC, SP, regs
    - Memory management
    - Scheduling
    - Pointers for state queues
    - etc.

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 mem
ory
        * 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_t
id */
       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 vnod
e */
       struct  vnode *p_plist;          /* list of /proc vnodes for proces
s */
       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 pa
ges (vfork) */
       int      p_nwpage;               /* number of watched pages (vfor
k) */
       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 profi
ling
        */
       hrtime_t p_mstart;                /* hi-res process start time */
       hrtime_t p_mterm;                  /* hi-res process termination tim
e */
```

```
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;
```

Context switching

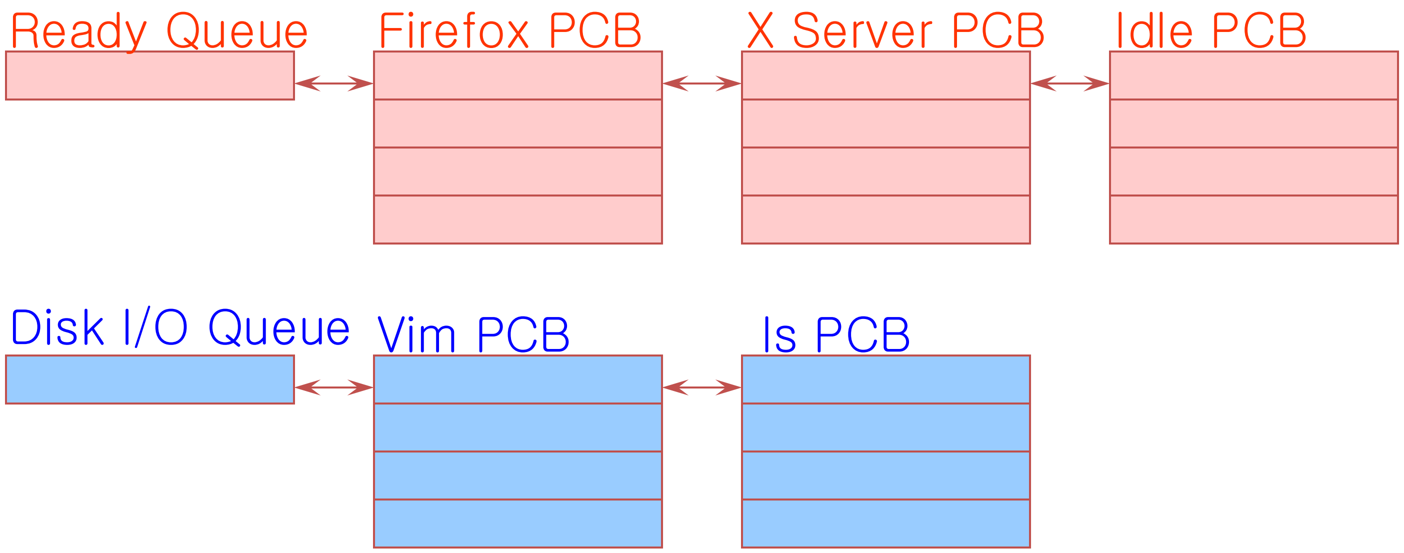
- When a process is running, its hardware state is in the CPU
  - The hardware registers contain the current values
- When the OS stops running a process, it saves the current values of the registers into the process' PCB
- When the OS is ready to start executing a new process, it loads the hardware registers from the values stored in that process's PCB
- 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

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, initializes it, and places it 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 (userspace) process? (Unix: init (PID 1))
- In some OSes, 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: Windows

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

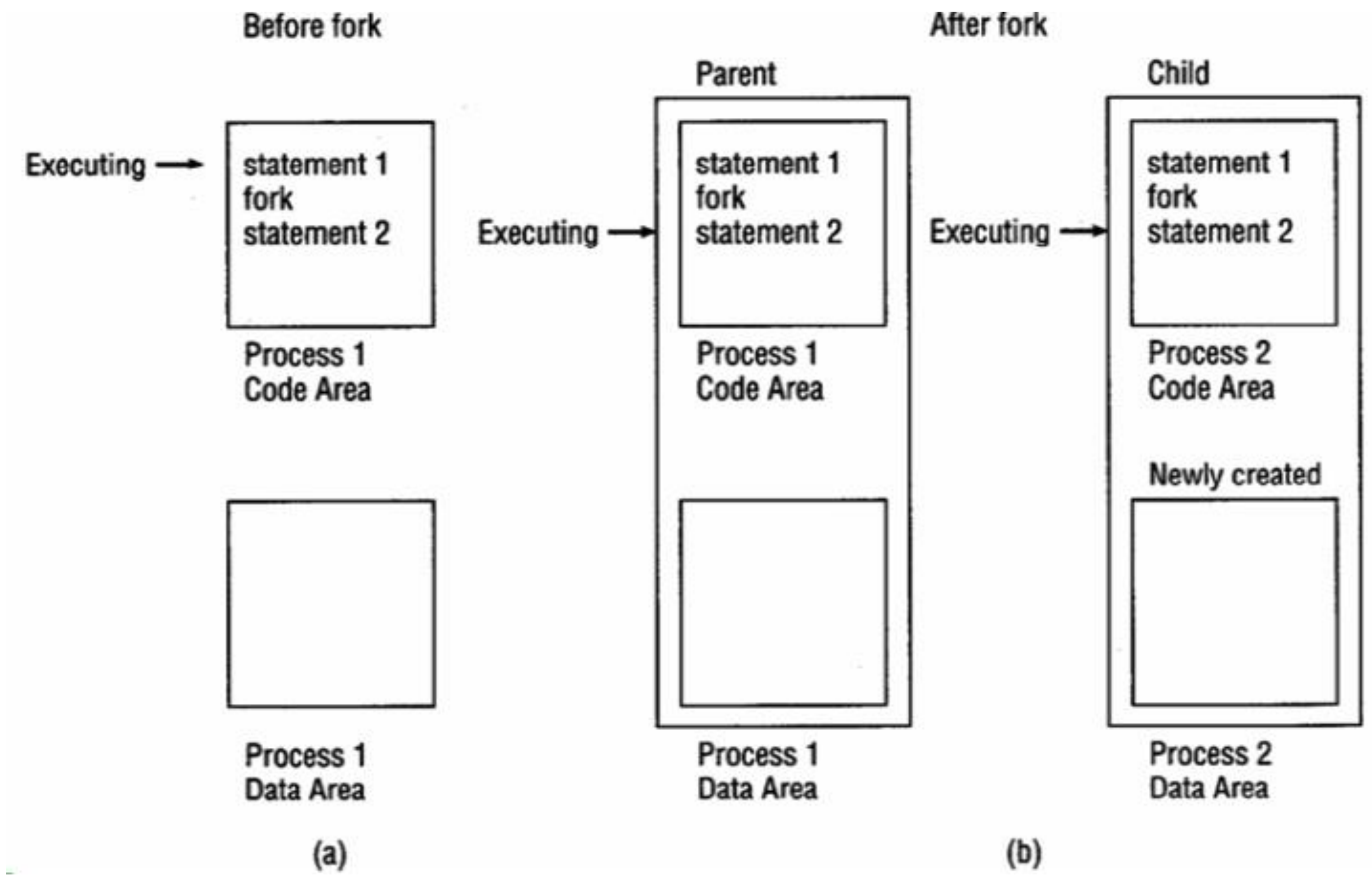
  `BOOL CreateProcess(char *prog, ....)` (simplified)

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

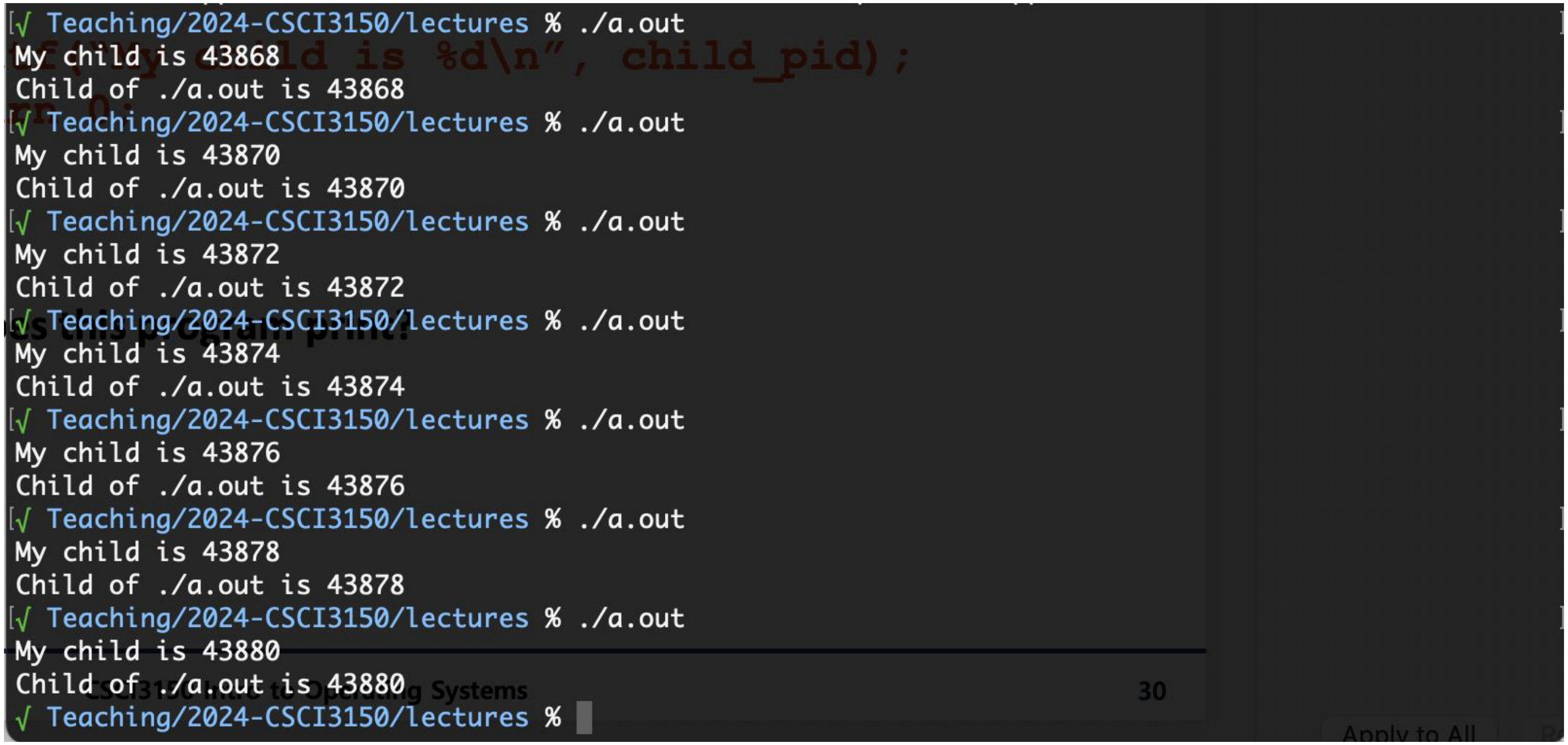
fork() semantics



fork()

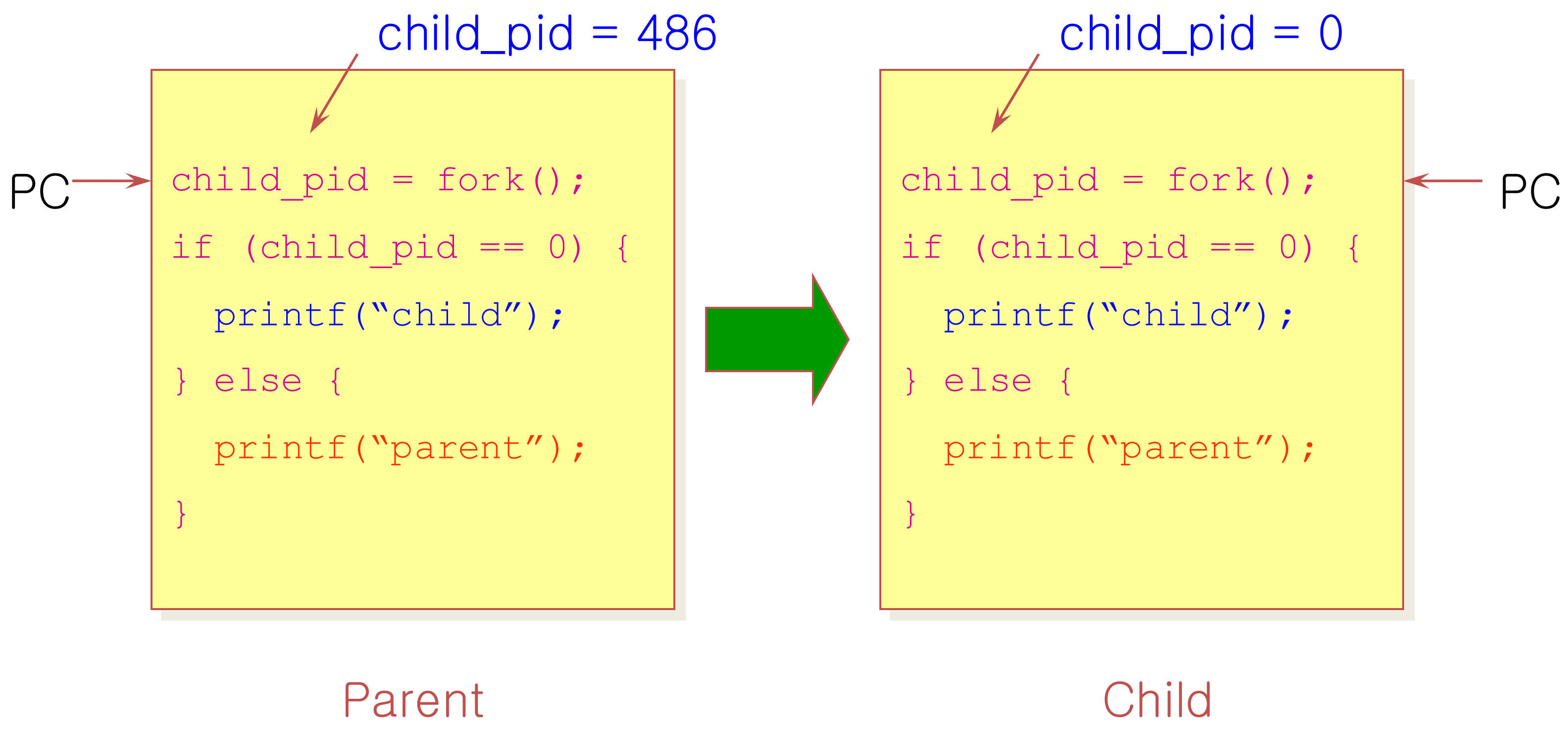
```
int main(int argc, char *argv[])
{
        char *name = argv[0];
        int child_pid = fork();
        if (child_pid == 0) {
                printf("Child of %s is %d\n", name, getpid());
                return 0;
        } else {
                printf("My child is %d\n", child_pid);
        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

What does this program print?



```
√ Teaching/2024-CSCI3150/lectures % ./a.out
My child is 43868
Child of ./a.out is 43868
√ Teaching/2024-CSCI3150/lectures % ./a.out
My child is 43870
Child of ./a.out is 43870
√ Teaching/2024-CSCI3150/lectures % ./a.out
My child is 43872
Child of ./a.out is 43872
√ Teaching/2024-CSCI3150/lectures % ./a.out
My child is 43874
Child of ./a.out is 43874
√ Teaching/2024-CSCI3150/lectures % ./a.out
My child is 43876
Child of ./a.out is 43876
√ Teaching/2024-CSCI3150/lectures % ./a.out
My child is 43878
Child of ./a.out is 43878
√ Teaching/2024-CSCI3150/lectures % ./a.out
My child is 43880
Child of ./a.out is 43880
√ Teaching/2024-CSCI3150/lectures %
```

Duplicating Address Spaces



```
child_pid = fork();
if (child_pid == 0) {
  printf("child");
} else {
  printf("parent");
}
```

```
child_pid = fork();
if (child_pid == 0) {
  printf("child");
} else {
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}
```
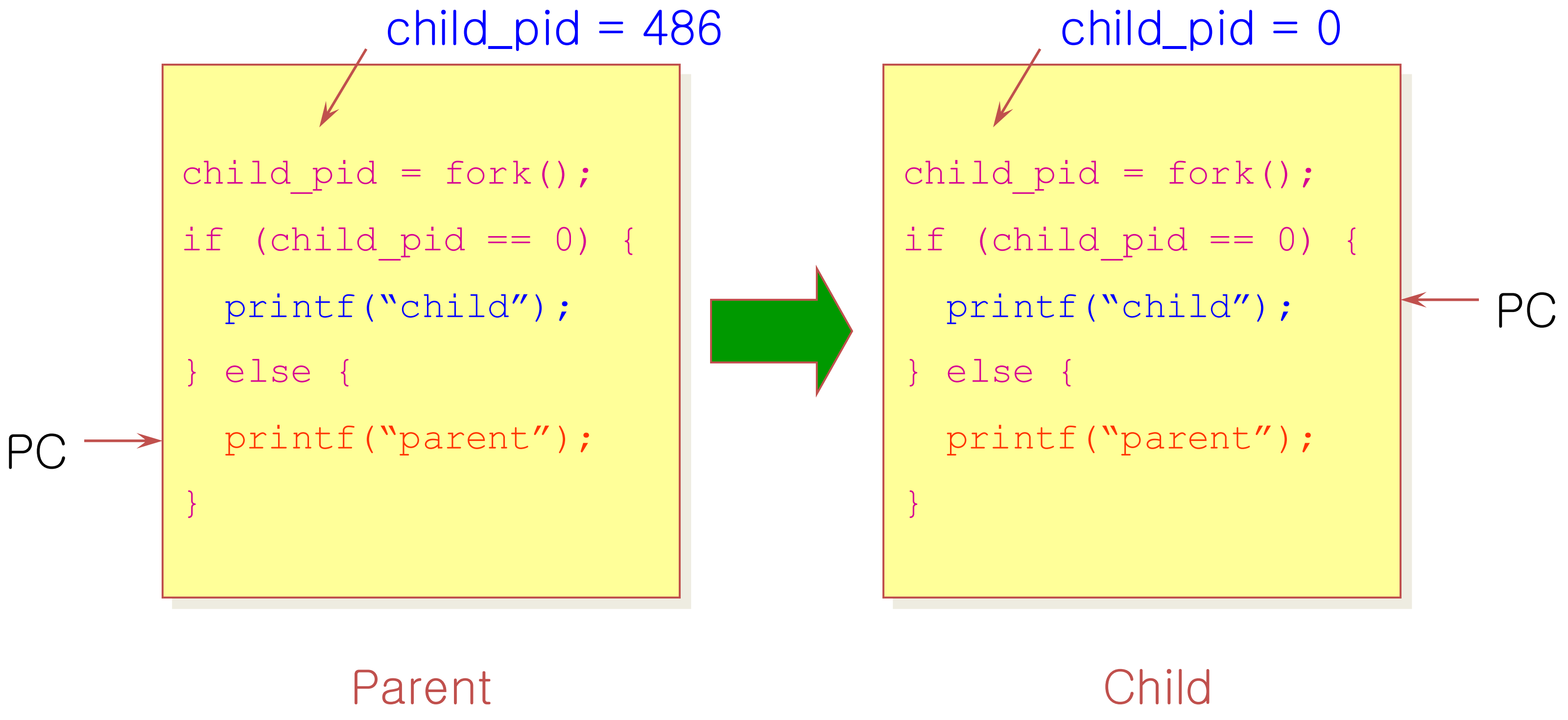

Divergence



```
child_pid = fork();
if (child_pid == 0) {
  printf("child");
} else {
  printf("parent");
}
```

```
child_pid = fork();
if (child_pid == 0) {
  printf("child");
} else {
  printf("parent");
}
```

Example Continued

```
> a.out
My child is 486
Child of a.out is 486
> 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
  }
}
```

How can fork return differently?

- A: Return values are passed through registers
  - Integer return values use EAX for 32-bit architecture
- B: PCB stores the states of all registers
- Thus, can do the following trick:

```
child->PCB[return_value_register] = 0;
parent->PCB[return_value_register] = child_pid;
```

https://stackoverflow.com/questions/8857830/fork-implementation
https://en.wikipedia.org/wiki/X86_calling_conventions

Process Creation: Unix (2)

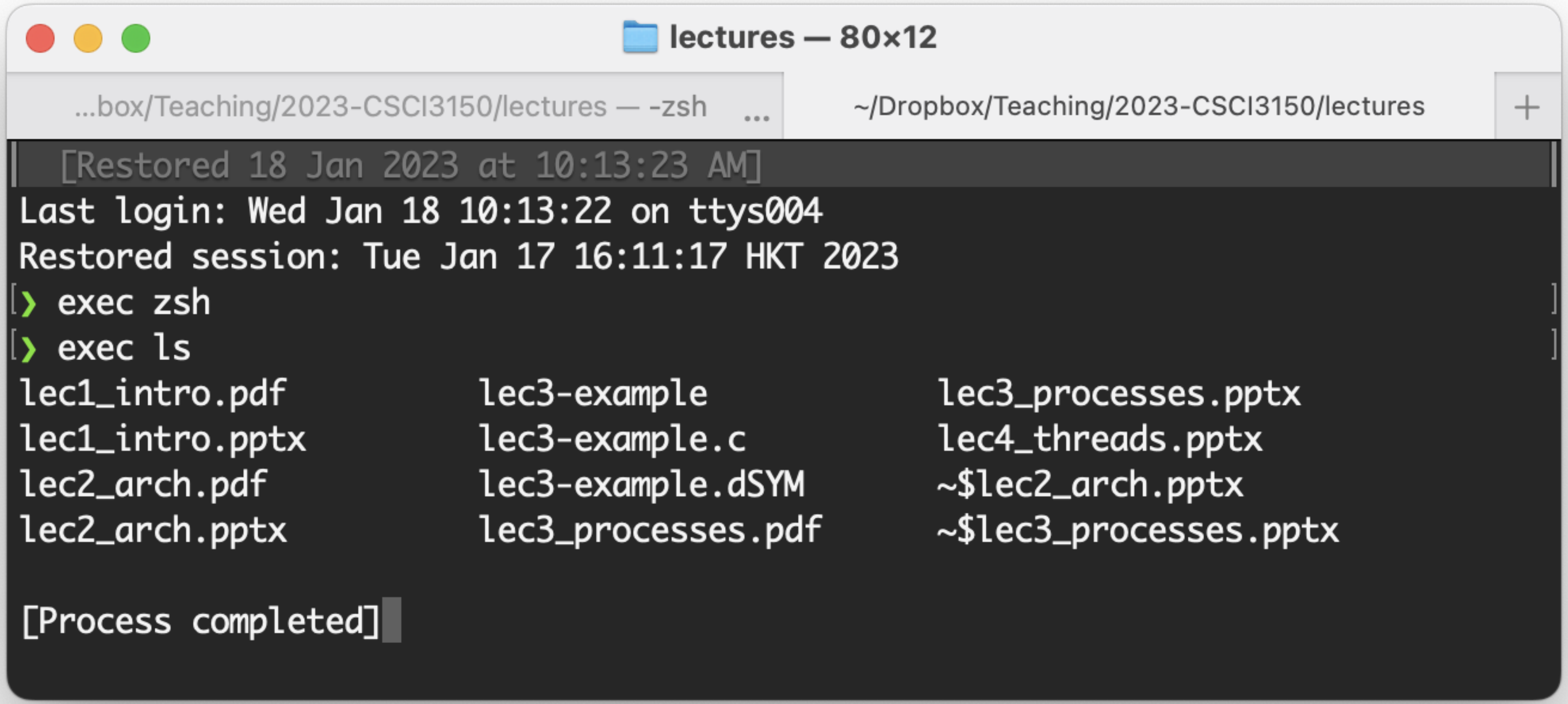
- Wait a second. How do we actually start a new program?

  ```
  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, no new PID
- What does it mean for exec to return?

Process Creation: Unix (3)

- 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 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?
  - Cannot create child process (return to parent).

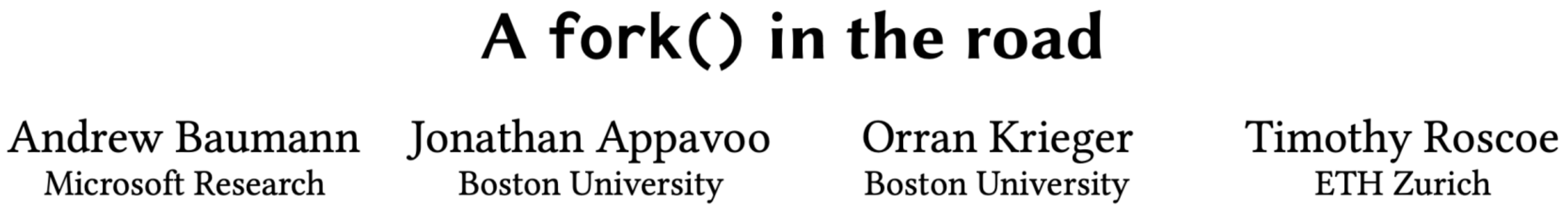

lectures — 80×12
...box/Teaching/2023-CSCI3150/lectures — -zsh
~/Dropbox/Teaching/2023-CSCI3150/lectures

```
  [Restored 18 Jan 2023 at 10:13:23 AM]
Last login: Wed Jan 18 10:13:22 on ttys004
Restored session: Tue Jan 17 16:11:17 HKT 2023
❯ exec zsh
❯ exec ls
lec1_intro.pdf          lec3-example            lec3_processes.pptx
lec1_intro.pptx         lec3-example.c          lec4_threads.pptx
lec2_arch.pdf           lec3-example.dSYM       ~$lec2_arch.pptx
lec2_arch.pptx          lec3_processes.pdf      ~$lec3_processes.pptx

[Process completed]
```

exec() overrides the current process completely
→ If it runs successfully, it never returns!

Process Creation: fork or not?

- Why does Windows have CreateProcess while Unix uses fork/exec?
  - Comparing fork() and CreateProcess()?
  - Which is more convenient to use?
  - Which is more efficient?



A fork() in the road

Andrew Baumann, Microsoft Research; Jonathan Appavoo, Boston University; Orran Krieger, Boston University; Timothy Roscoe, ETH Zurich

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?

Process Termination

- When exit() is called on Unix:
  - Threads are terminated (next lecture)
  - Open files, network connections are closed; address space is de-allocated
  - But the PCB still remains in the process table
    - To allow the parent to check for its exit status using a wait() variant
- Only a parent can remove the PCB
  - and completely terminate the process, called reap
    - By calling wait()
- Died but not yet reaped process is called a zombie

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
- 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);
        }
}
```

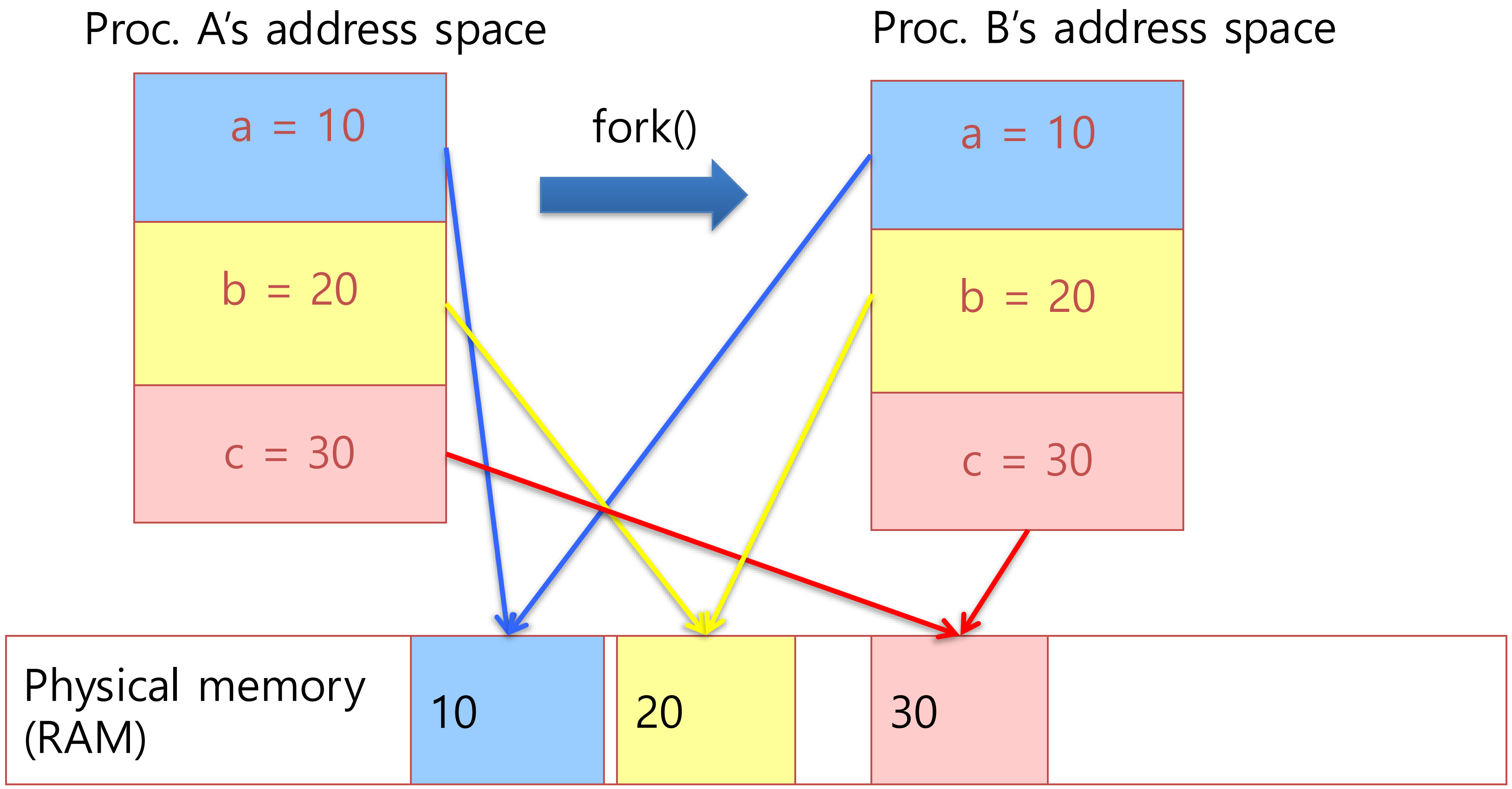
The evolution of the Unix time-sharing system, Dennis M. Ritchie
https://www.bell-labs.com/usr/dmr/www/hist.html

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 (Windows), fork/exec (Unix)

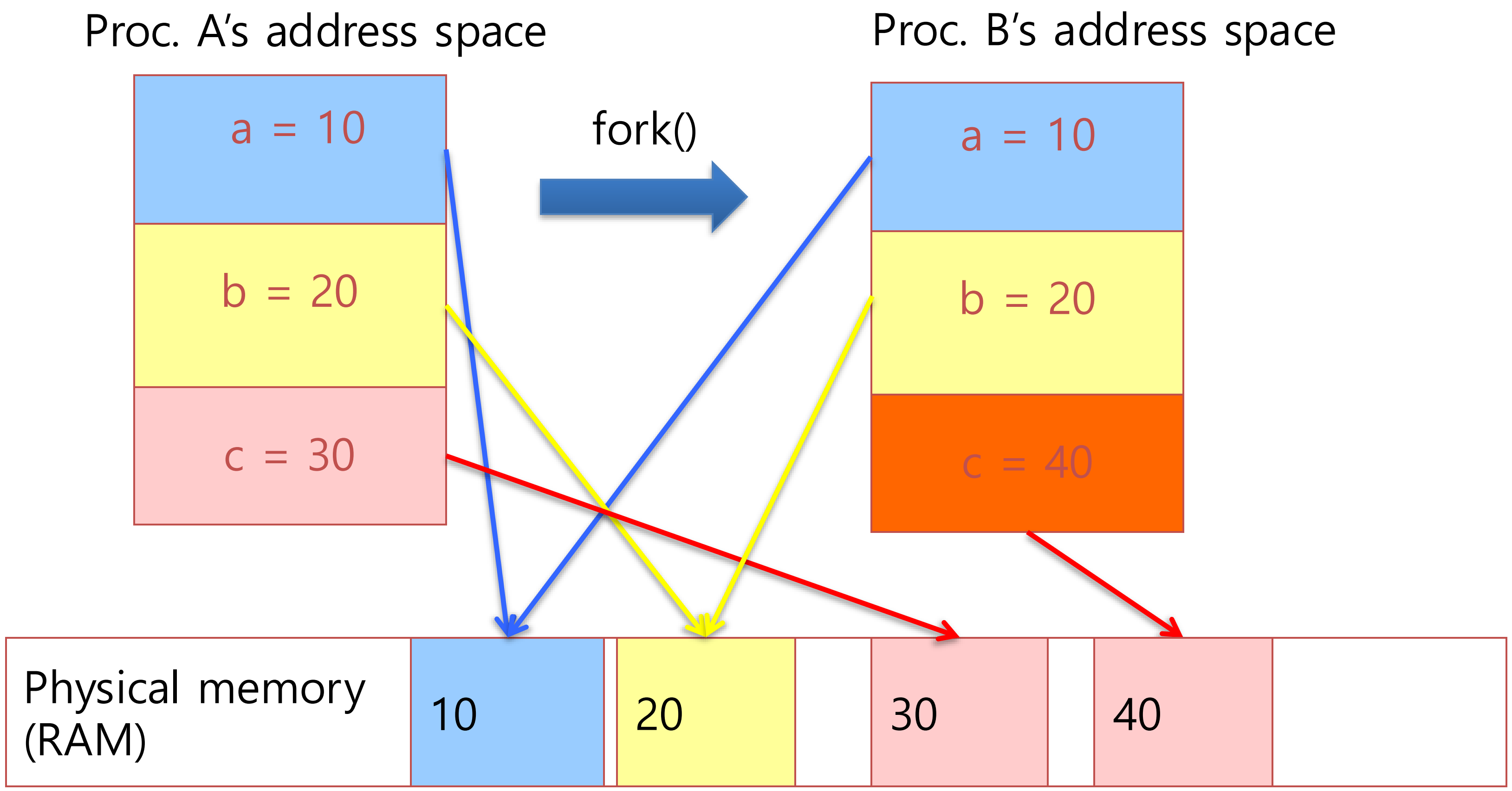
Copy-On-Write

- *Lazy* copy



Copy-On-Write

- *Lazy* copy


Proc. A's address space
a = 10
b = 20
c = 30
fork()
Proc. B's address space
a = 10
b = 20
c = 40
Physical memory (RAM)
10
20
30
40