Processes
(part 1)

M1 MOSIG – Operating System Design

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Acknowledgments

- Many ideas and slides in these lectures were inspired by or even borrowed from the work of others:
  - Arnaud Legrand, Noël De Palma, Sacha Krakowiak
  - David Mazières (Stanford)
    - (many slides/figures directly adapted from those of the CS140 class)
  - Remzi and Andrea Arpaci-Dusseau (U. Wisconsin)
  - Randall Bryant, David O'Hallaron, Gregory Kesden, Markus Püschel (Carnegie Mellon University)
    - Textbook: Computer Systems: A Programmer's Perspective (2nd Edition) a.k.a. "CSAPP"
    - CS 15-213/18-243 classes (many slides/figures directly adapted from these classes)
  - Textbooks (Silberschatz et al., Tanenbaum)

Outline

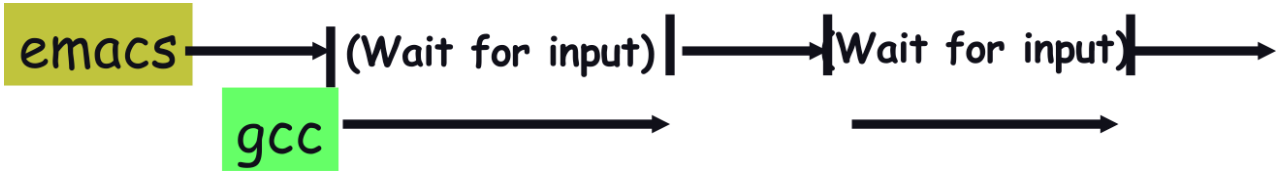
- Introduction
- Basic process management interface from the user-level
- Kernel-level process management

Processes

- A process is an instance of a running program
- Modern OSes run multiple programs simultaneously
- Examples (can all run simultaneously)
  - **`gcc file1.c`** – compiler running on file 1
  - **`gcc file2.c`** – compiler running on file 2
  - **`emacs`** – text editor
  - **`firefox`** – web browser
- Non-examples (implemented as one process):
  - Multiple **`firefox`** windows or **`emacs`** frames (still one process)
- Why processes?
  - Simplicity of programming
  - Higher CPU throughput, lower latency (details on next slide)

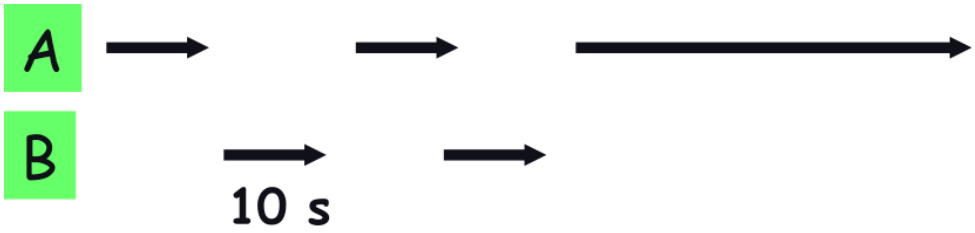
Speed

- Multiple processes can increase CPU utilization
  - Overlap one process 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 process's view of the world

- Each process has is own view of the machine
  - Its own address space
  - Its own open files
  - Its own virtual CPU (through preemptive multitasking)

- A given (virtual) address has a different "meaning" for two distinct processes

- This greatly simplifies the application programming model
  - **`gcc`** does not care that **`firefox`** is running

- Sometimes interaction between processes is necessary
  - Simplest is through files: **`emacs`** edits file, **`gcc`** compiles it
  - More complicated: Shell/command, Window manager/application

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- Kernel-level process management

Creating a new process

- **`pid_t fork(void)`**
  - Creates a new process (child process) that is identical to the calling process (parent process)
  - Returns 0 to the child process
  - Returns the child's pid to the parent process

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

  - **`fork`** is interesting (and often confusing) because it is called once but returns twice

Understanding fork

Process n

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

pid = m

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

Child Process m

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

pid = 0

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

```
pid_t pid = fork();
if (pid == 0) {
   printf("hello from child\n");
} else {
   printf("hello from parent\n");
}
```

`hello from parent` ***Which one is first?*** `hello from child`

Fork: additional details

- Parent and child both run the same code
  - Distinguish parent from child by return value from **`fork`**
- Start with the same state, but each has private copy
  - Memory address space
  - Environment variables
  - List of currently open files
  - Signal handlers, signal mask and list of pending signals
- Scheduling non-determinism
  - Who runs first after a fork? Parent? Child? (Both?)
  - No order imposed/specified

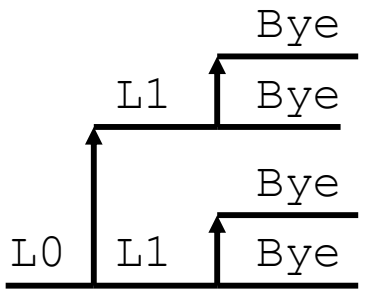
Fork Example #1

```
void fork1()
{
    int x = 1;
    pid_t pid = fork();
    if (pid == 0) {
        printf("Child has x = %d\n", ++x);
    } else {
        printf("Parent has x = %d\n", --x);
    }
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

Fork Example #2

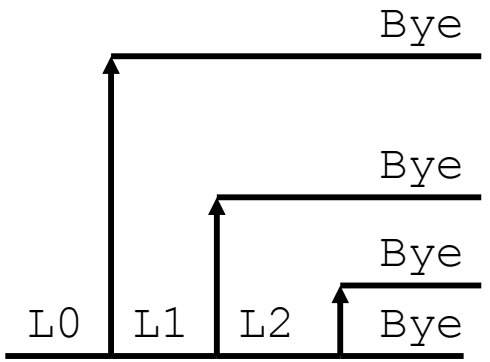
- Both parent and child can continue forking

```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



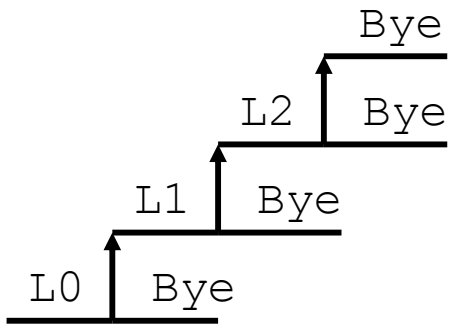
Fork example #3

```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
       printf("L1\n");
       if (fork() != 0) {
           printf("L2\n");
           fork();
       }
    }
    printf("Bye\n");
}
```



Fork example #4

```
void fork5()
{
    printf("L0\n");
    if (fork() == 0) {
       printf("L1\n");
       if (fork() == 0) {
           printf("L2\n");
           fork();
       }
    }
    printf("Bye\n");
}
```



Ending a process

- **`void exit(int status)`**
  - Exits a process (current process ceases to exist)
    - By convention, status of 0 is success (non-zero means error)
  - **`atexit()`** allows programmer to register function to be executed upon exit

```
void cleanup(void) {
   printf("cleaning up\n");
   ... // clean things up
   printf("done\n");
}

int main() {
   atexit(cleanup);
   ... // do useful things
   exit(0);
}
```

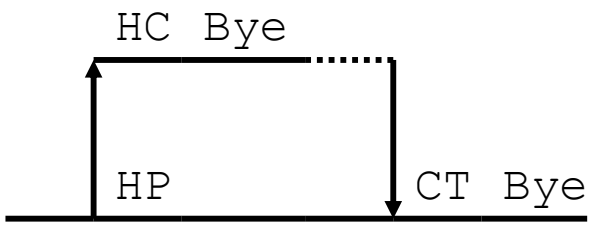
Synchronizing with child processes

- **`int wait(int *child_status)`**
  - suspends current process until one of its children terminates
  - return value is the **`pid`** of the child process that terminated
  - if **`child_status != NULL`**, then the variable it points to will be set to a status indicating why the child process terminated

Synchronizing with child processes
`wait`: example #1

```
int main() {
   int child_status;

   if (fork() == 0) {
      printf("HC: hello from child\n");
   }
   else {
      printf("HP: hello from parent\n");
      wait(&child_status);
      printf("CT: child has terminated\n");
   }
   printf("Bye\n");
   exit();
}
```



Synchronizing with child processes
`wait`: details and example #2

- If multiple children completed, will take in arbitrary order
- Can use macros **`WIFEXITED`** and **`WEXITSTATUS`** to get information about exit status (see **`man 2 wait`** for details)

```
int main()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++)
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    for (i = 0; i < N; i++) {
        pid_t wpid = wait(&child_status);
        if (WIFEXITED(child_status))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```

Synchronizing with child processes
Waiting for a specific process

- **`waitpid(pid, &status, options)`**
  - suspends current process until specific process terminates
  - various options – see man page for details

```
int main()
{
    pid_t pid[N];
    int i;
    int child_status;
    for (i = 0; i < N; i++) {
        if ((pid[i] = fork()) == 0)
            exit(100+i); /* Child */
    }
    for (i = 0; i < N; i++) {
        pid_t wpid = waitpid(pid[i], &child_status, 0);
        if (WIFEXITED(child_status)) /* Child terminated due to call to exit */
            printf("Child %d terminated with exit status %d\n",
                    wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
}
```

Zombies

- Idea
  - When a process terminates, it still consumes system resources
    - Various tables maintained by OS
  - Called a “zombie”
    - Living corpse, half alive and half dead
- Reaping
  - Performed by parent on terminated child via **`wait`** or **`waitpid`**
  - Parent is given exit status information
  - Kernel discards process
- What if parent doesn’t reap?
  - If any parent terminates without reaping a child, then child will be reaped by a special OS process (often called **`init`**)
  - So, we only need explicit reaping in long-running processes
    - e.g., shells and servers

Zombies – Example

```
int main()
{
    if (fork() == 0) {
        /* Child */
        printf("Terminating Child, PID = %d\n",
               getpid());
        exit(0);
    } else {
        printf("Running Parent, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    }
}
```

```
linux> ./forks &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

- **`ps`** shows child process as “defunct”
- Killing parent allows child to be reaped by **`init`**

Loading and running programs

- **`int execve(char *filename, char *argv[], char *envp);`**

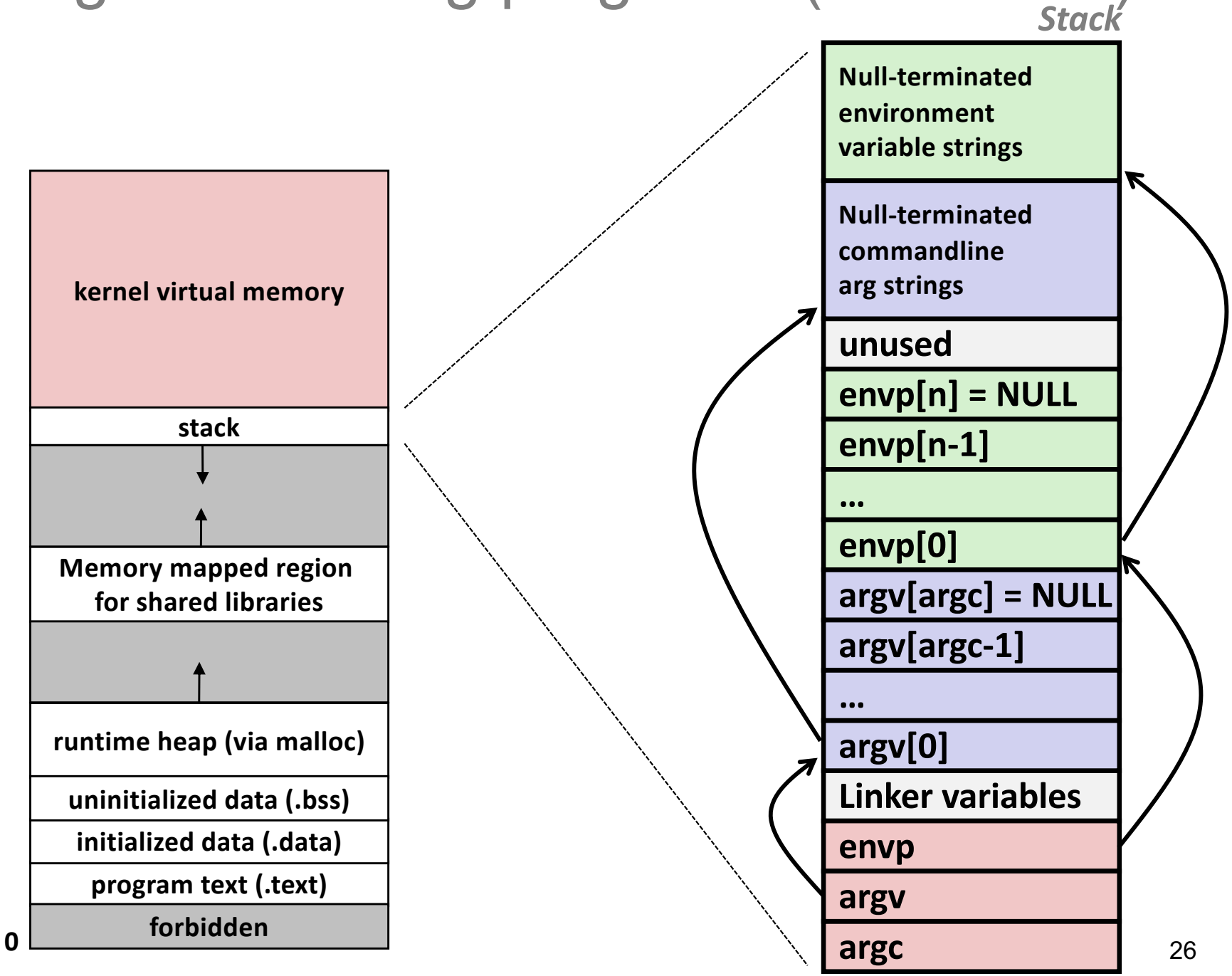
- Completly reconfigures the image of the calling process

- Loads and runs
  - Executable **`filename`**
  - With argument list **`argv`** (NULL terminated)
  - By convention, **`argv0`** should be the name of the executable file
  - And environment variable list **`envp`**
- **Does not return!** (unless error)

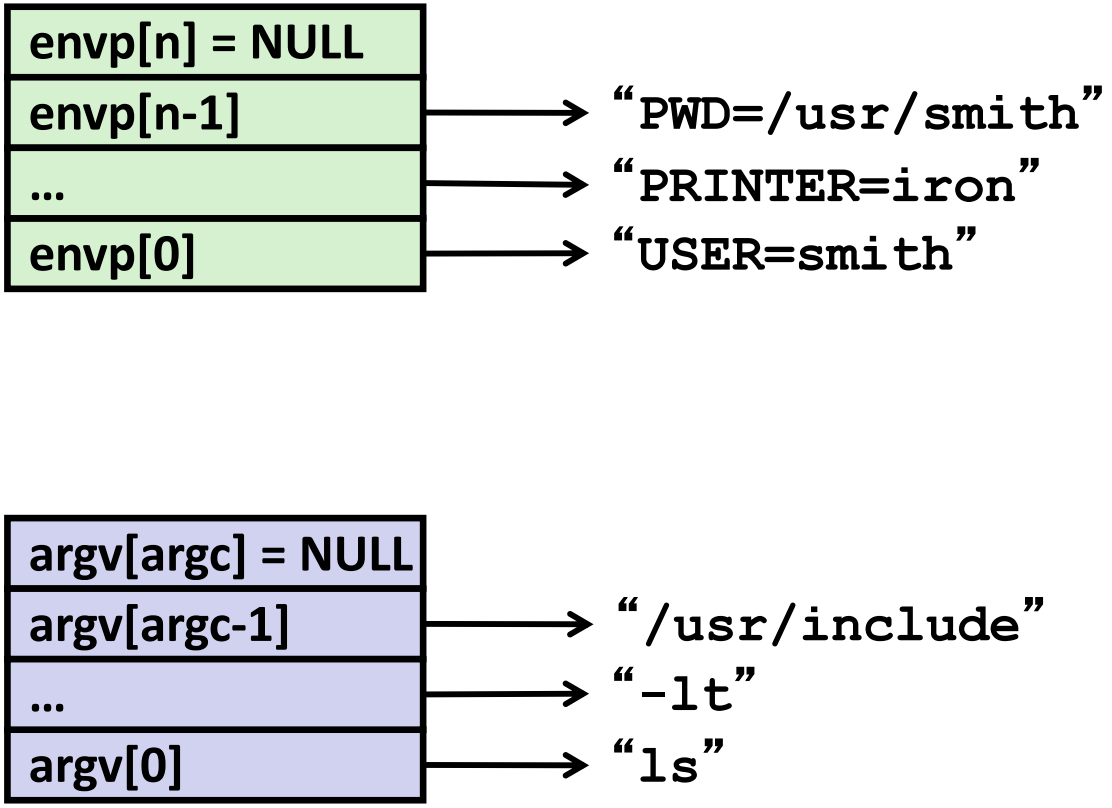
- Overwrites process memory address space, keeps pid

- Environment variables
  - “name=value” strings

Loading and running programs (continued)



`Execve` arguments: example



`execl` and `exec` family

- `int execl(char *path, char *arg0, char *arg1, ..., (char*)NULL)`

- Loads and runs executable at path with args **`arg0`**, **`arg1`**, ...)
  - **`path`** is the complete path of an executable object file
  - By convention, **`arg0`** is the executable object file
  - "Real" arguments to the program start with **`arg1`**, etc.
  - **List of args is terminated by a `(char*)NULL` argument**
  - Environment (implicitly) taken from **`char **environ`** (an automatically defined global variable), which points to an array of "name=value" strings

`execl` and `exec` family (continued)

- Family of functions includes **`execv, execve, execvp, execl, execle, execlp`**
- **These functions only differ in terms of interface; their purpose is the same (loading and running a new process, in the context of the current process)**
- Usually, **`execve`** is the only system call
  - The other functions are implemented as library wrappers

- **Semantics of the suffixes**
  - **`v`** (vector): pass arguments as (**`NULL`**-terminated) array of pointers
  - **`l`** (list): pass arguments as (**`NULL`**-terminated) list of pointers (i.e., the function has a variable number of arguments)
  - **`p`** (path): search executable file name in the **`PATH`** (otherwise, full path must be provided)
  - **`e`** (environment): explicitly provide new environment (otherwise, use the current environment pointed by **`environ`**)

`execl`: example

```
int main() {
   int res;
   if (fork() == 0) {
      res = execl("/usr/bin/cp", "cp",
                  "foo", "bar", (char*)NULL);
      if (res < 0) {
          printf("error: execl failed\n");
          exit(-1);
      }
   }
   wait(&res);
   if (WIFEXITED(res) && (WEXITSTATUS(res) == 0)) {
      printf("copy completed successfully\n");
   } else {
      printf("copy failed\n");
   }
   exit(0);
}
```

Wrap-up: mini-shell example

- A *shell* is an application program that runs programs on behalf of the user
  - Interpreted shell scripts (not detailed here)
  - Built-in commands (e.g., **cd**)
  - External binary programs
- Examples: tcsh, bash

```
int main()
{
    char cmdline[MAXLINE];

    while (1) {
        /* read */
        printf("myshell> ");
        Fgets(cmdline, MAXLINE, stdin);
        if (feof(stdin))
            exit(0);

        /* evaluate */
        eval(cmdline);
    }
}
```

Execution is a sequence of read/evaluate steps

Wrap-up: mini-shell example (continued)

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

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

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

What is a “background job”?

- Users generally run one command at a time
  - Type command, read output, type another command

- Some programs run “for a long time”
  - Example: “delete this file in two hours”

```
% sleep 7200; rm /tmp/junk  # shell stuck for 2 hours
```

- A “background” job is a process we don't want to wait for

```
% (sleep 7200 ; rm /tmp/junk) &
[1] 907
% # ready for next command
```

Problem with mini-shell example

- Shell correctly waits for and reaps foreground jobs

- But what about background jobs?
  - Will become zombies when they terminate
  - Will never be reaped because shell (typically) will not terminate
  - Will create a memory leak that could theoretically run the kernel out of memory
  - Modern Unix: once you exceed your process quota, your shell can't run any new commands for you: **`fork()`** returns -1

- Solution: asynchronously notify the shell when a child process terminates
  - Using “Unix signals” (details on this mechanism soon)

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Implementing processes

- The OS kernel keeps a data structure for each process
  - Generic name: Process control block (PCB)
  - Sometimes named differently, e.g., **`task_struct`** in Linux
- Tracks states of the process
  - Running, ready (runnable), blocked, etc.
- Includes information necessary to run
  - Saved context (registers ...)
  - Information about virtual memory (memory region descriptors, pointer to page tables ...)
  - Information about open files and memory-mapped files
- Various other data about the process
  - Credentials (user/group ID), signal mask, controlling terminal, priority, accounting statistics, whether being debugged, ...

Fork revisited – How does it work internally?

- **Create and initialize kernel data structures about the new process**, such as:
  - Process control block (PCB) and corresponding pid
  - Open file descriptors and memory mapped files
    - Inherited from parent – each process can close them independently

- **Create and initialize virtual memory address space**
  - For efficiency, the whole address space of the parent process is not copied
  - Instead, only copy memory region descriptors and page tables
  - Then, **use Copy-on-Write (CoW)** to track and support changes between parent and child address spaces
    - Mark PTEs of writeable regions as read-only
    - Flag region descriptors for these areas as private “copy-on-write”
    - Writes by either process to these pages will cause page faults
    - Fault handler recognizes copy-on-write, makes a copy of the page, and restores write permissions

Fork revisited – How does it work internally? (continued)

- Conclusion
  - Thanks to CoW, copies of memory pages are deferred until absolutely necessary (i.e., when one of the processes tries to modify a shared page)
  - Important optimization, especially given the fact that **`fork`** is often followed by a call to **`exec`**, which completely reconfigures the contents of the virtual memory address space

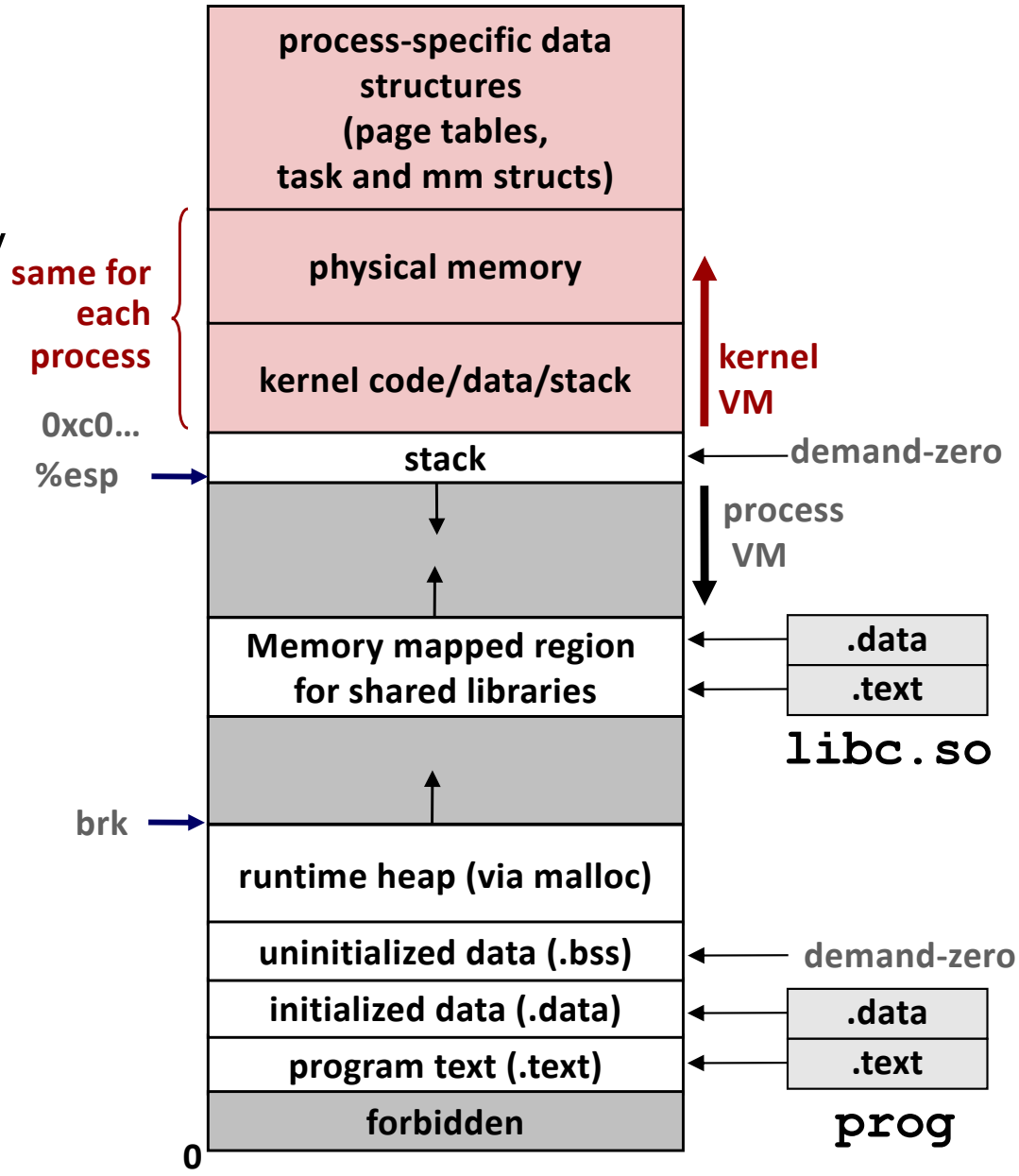
`exec` revisited

To run a new program **`prog`** in the current process using **`exec()`**:

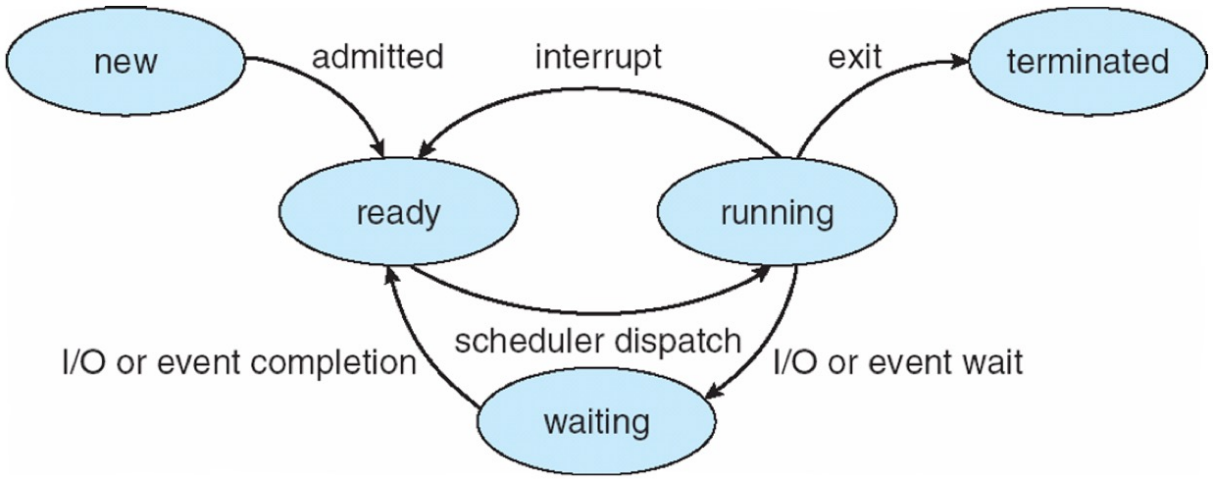
- **Free the region descriptors and page tables** for the existing memory regions

- **Create new region descriptors and page tables** according to the contents of the new executable file
  - Stack, BSS, data, text, shared libs.
  - Text and data backed by ELF executable object file
  - BSS and stack initialized to zero
  - Shared libraries (e.g., **`libc`**)

- **Set PC to entry point**: main function in **`.text`**
  - The kernel will fault in code, data pages as needed



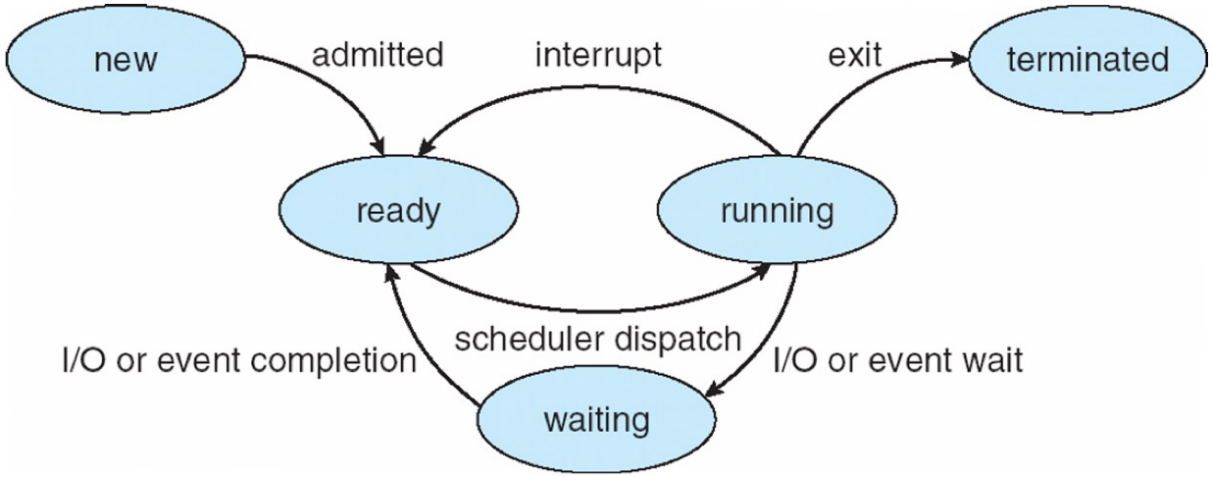
Process states



- A process can be in one of several states
  - New/terminated: at beginning/end of life
  - Running – currently executing (or will execute on kernel return)
  - Ready – can run, but kernel has chosen different process to run
  - Waiting – needs external event (e.g., end of disk operation) to proceed

- Which process should the kernel run?
  - If non runnable, run idle loop, if a single process runnable, run this one
  - If more than one runnable process, must make scheduling decision

CPU scheduling



- Scheduling decisions may take place when a process:
  1. Switches from running to waiting state
  2. Switches from running to ready state
  3. Switches from new/waiting to ready
  4. Exits

- Non-preemptive schedules use only 1 & 4
- Preemptive schedulers run at all four points

Scheduling criteria

- A few important criteria
  - **Throughput**: Number of processes that complete per time unit (higher is better)
  - **Turnaround time**: Time for each process to complete (lower is better)
  - **Response time**: time from request to first response (e.g., key press to character echo) (lower is better)

- The above criteria are affected by secondary criteria
  - **CPU utilization**: fraction of time that the CPU spends doing productive work (i.e., not idle)
  - **Waiting time**: time that each process spends waiting in ready queue

Scheduling

- How to pick which process to run?

- Scan process table for first runnable?
  - Expensive. Weird priorities (small pids better)
  - Divide into runnable and blocked processes

- FIFO?
  - Put process on back of list, pull them off from front

- Priority?
  - Give some processes a better shot at the CPU

Scheduling policy

- Want to balance multiple goals. For example:
  - *Fairness*: don't starve processes
  - *Priority*: reflect relative importance of processes
  - *Deadlines*: must do x (e.g., play audio) by certain time
  - *Reactivity*: minimize response time
  - *Throughput* : want good overall performance (e.g., number of processes completed per time unit)
  - *Efficiency*: minimize overhead of scheduler itself

- No universal policy
  - Many objectives – cannot optimize for all
  - Conflicting goals (e.g., throughput or priority versus fairness)

Preemption

- **A process can be preempted when kernel gets control – There are several such opportunities:**
- **A running process can transfer control to kernel through a trap**
  - System call (including **`exit`**), page fault, illegal instruction, etc.
  - May put current process to sleep – e.g., read from disk
  - May make other process runnable – e.g., **`fork`**, write to pipe
  - (May destroy current process)
- **Periodic timer interrupt**
  - If running process used up time quantum, schedule another
- **Device interrupt**
  - E.g., disk request completed, or packet arrived on network
  - A previously waiting process becomes runnable
  - Schedule if higher priority than current running process

- Recall that changing the running process is called a **context switch**

Context switch details

- Implementation is very machine (processor) dependent. Typical things include:
  - Save/restore general registers
  - Save/restore floating point or other special registers
  - Switch virtual address translations (e.g., pointer to root of paging structure)
  - Save/restore condition codes (flags)
  - Save/restore program counter

- Non-negligible cost
  - Save/restore of floating point registers is expensive
    - Optimization: only saved if process used floating point operations
  - May require flushing TLB (memory translation hardware)
    - Optimization: do not flush the kernel's own (global) data from the TLB
  - Usually causes L1/L2/L3 cache misses (switches working sets)