HARVARD
School of Engineering and Applied Sciences

UNIX Systems Programming 2: Processes and signals

CS61, Lecture 16

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October 26, 2010

Announcements

- In-class **midterm exam**, Thursday 28 Oct
  - Open book, closed note
  - No computers, no smartphones, no internet access
  - Practice exam and quiz solutions on iSite website (accessible only to enrollees)

- Mid-course evaluations
  - Please take the mid-course survey on the course's iSite (linked to from cs61.seas) by end of today.

Topics for today

- The UNIX process abstraction
- Process lifecycle
  - Creating processes: forking
  - Running new programs within a process
  - Terminating and reaping processes
- Signaling processes
- Interprocess communication: pipes

What is a process?

- A **process** is the OS's abstraction for **execution**
  - A process is *an instance of a program in execution*.
  - i.e., each process is running a program; there may be many processes running the same program
- A process provides
  - Private address space
    - Through the mechanism of virtual memory!
  - Illusion of exclusive use of processor

Process context

- Process **context** is the state that the operating system needs to run a process
  - 1) **Address space**
    - The memory that the process can access
    - Consists of various pieces: the program code, static variables, heap, stack, etc.
  - 2) **Processor state**
    - The CPU registers associated with the running process
    - Includes general purpose registers, program counter, stack pointer, etc.
  - 3) **OS resources**
    - Various OS state associated with the process
    - Examples: page table, file table, network sockets, etc.

Context switches

- Multiple processes can run simultaneously.
  - On a single CPU system, only one process is running on the CPU at a time.
  - On a multi-CPU (or multi-core) system, multiple processes really can run concurrently.
  - The OS will timeshare each CPU/core, rapidly switching processes across them all.
- Switching a CPU from running one process to another is called a **context switch**.
  - (1) Save the context of the currently running process,
  - (2) Restore the context of some previously preempted process
  - (3) Resume execution of the newly restored process
- Deciding when to preempt current process and restart previously preempted process is known as **scheduling**
  - Performed by part of the OS called a **scheduler**

Process IDs

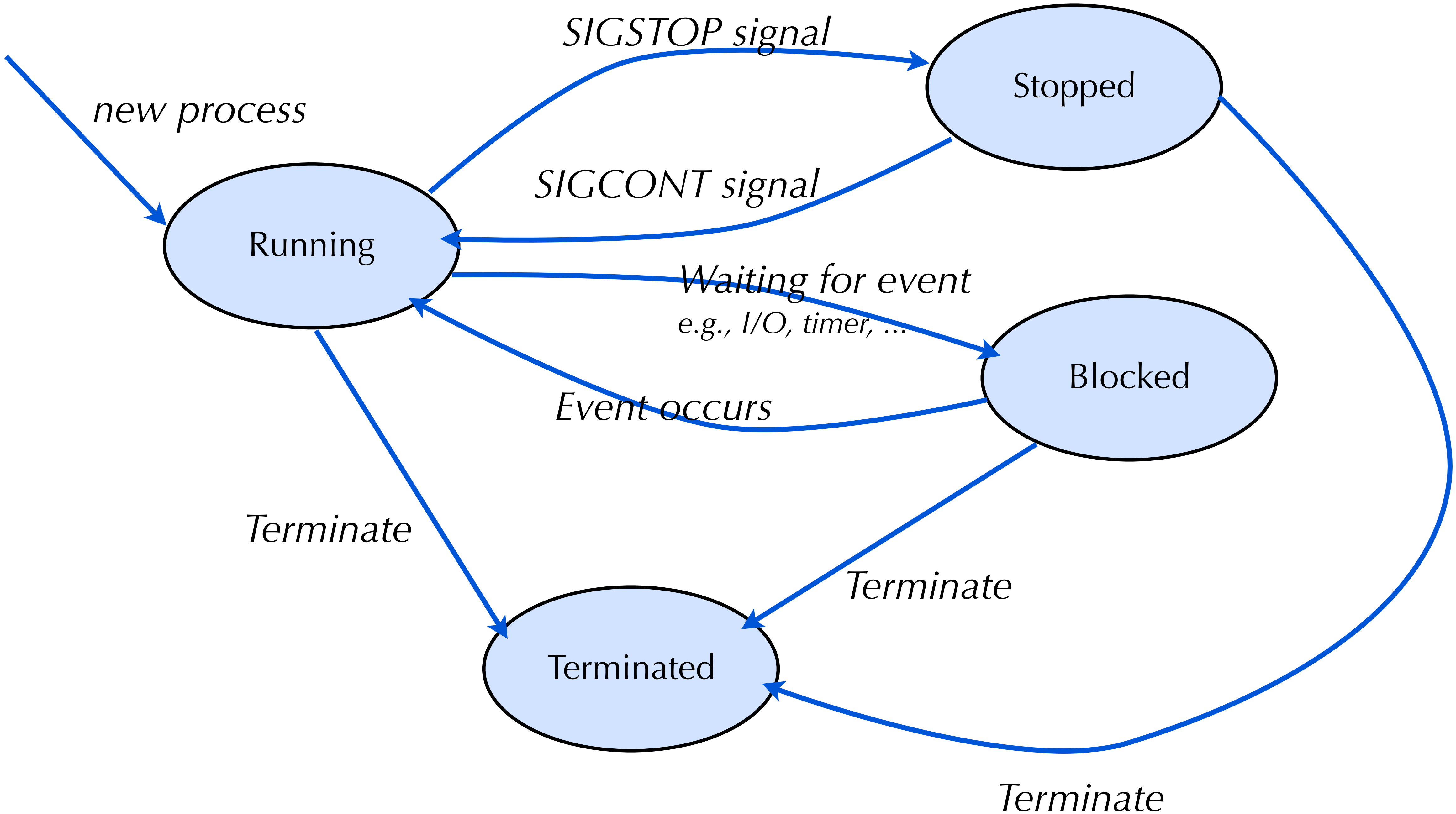
- Each process has a unique positive **process ID (PID)**
- `getpid` returns current process's PID
- `getppid` returns PID of parent of current process

```
pid_t getpid(void);
pid_t getppid(void);
```

Process states

- At any moment, a process is in one of several states:
  - **Running**:
    - Process is executing on a CPU, or waiting to be executed
  - **Stopped**:
    - Process is *suspended* (due to receiving a certain **signal**) and will not be scheduled
    - More on signals soon...
  - **Waiting** (or **sleeping** or **blocked**):
    - Process is waiting for an event to occur, such as completion of I/O, timer, etc.
    - Why is this different than "ready" ?
  - **Terminated:**
    - Process is stopped permanently, e.g., by returning from `main`, or by calling `exit`
- As the process executes, it moves between these states
  - What state is the process in most of the time?

Process lifecycle



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How are processes created?

- Typically, new process is created when user runs a program
  - E.g., Double-click an application, or type a command at the shell
- In UNIX, starting a new program is done by **some other process**
  - The shell is a process itself!
  - So are the Dock and Finder in MacOS (a variant of UNIX)
- One process (e.g., the shell) is creating another process (the command you want to run)
  - This is called **forking**
  - Every process has a **parent process**
- Chicken-and-egg problem: How does first process get created?
  - At boot time, the OS creates the first process, called `init`, which is responsible for starting up many other processes

`fork`: Creating New Processes

- `int fork(void)`
  - creates a new process (**child process**) that is **identical** to the calling process (**parent process**)
  - returns 0 to the child process
  - returns child's process ID (pid) to the parent process

```
if (fork() == 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

Fork Example #1

- Parent and child process both run the same program.
  - Only difference is the return value from `fork()`
- Child's address space starts as an **exact copy** of parent's
  - They do not share the memory – instead they each have a private copy.
  - Also have the same open files with the same offsets into the files.
    - Includes stdin, stdout, and stderr

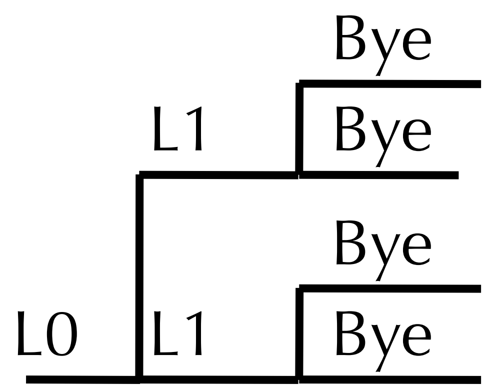
```
void fork1()
{
    int x = 1;
    pid_t pid = fork();
    if (pid == 0) {
        printf("Child has x = %d\n", ++x);
    } else {
        printf("Parent has x = %d\n", --x);
    }
    printf("Bye from process %d with x = %d\n", getpid(), x);
}
```

```
Parent has x = 0
Bye from process 9991 with x = 0
Child has x = 2
Bye from process 9992 with x = 2
```

Fork Example #2

- Key Points
  - Both parent and child can continue forking

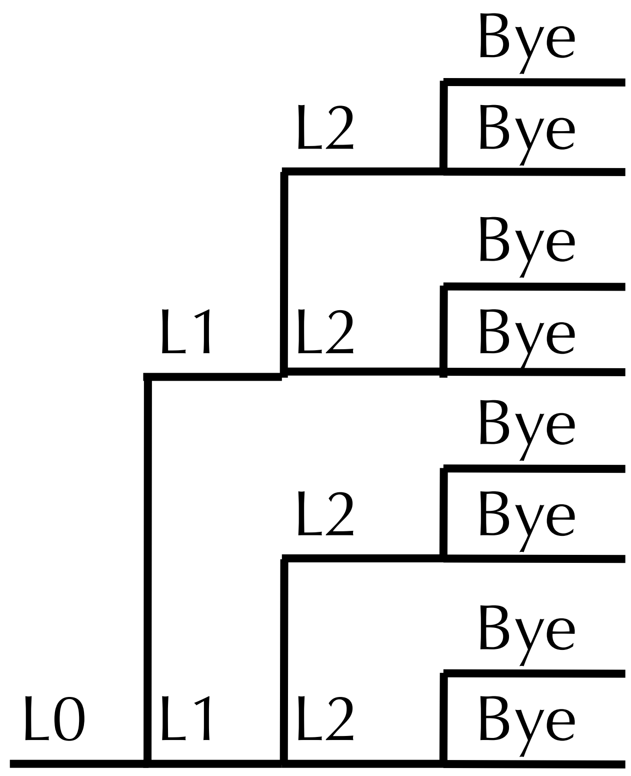
```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #3

- Key Points
  - Both parent and child can continue forking

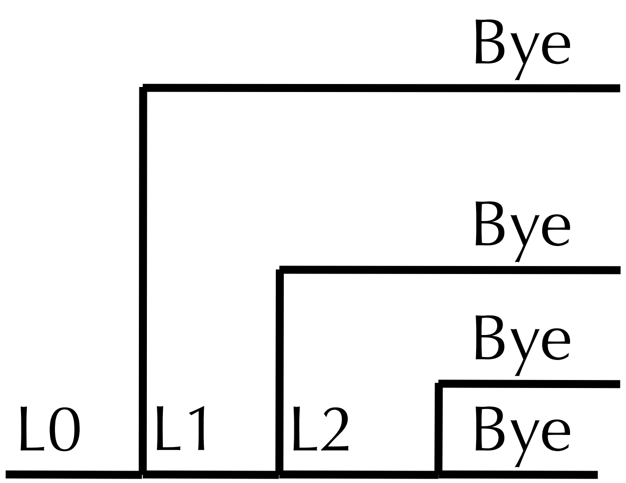
```
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #4

- Key Points
  - Both parent and child can continue forking

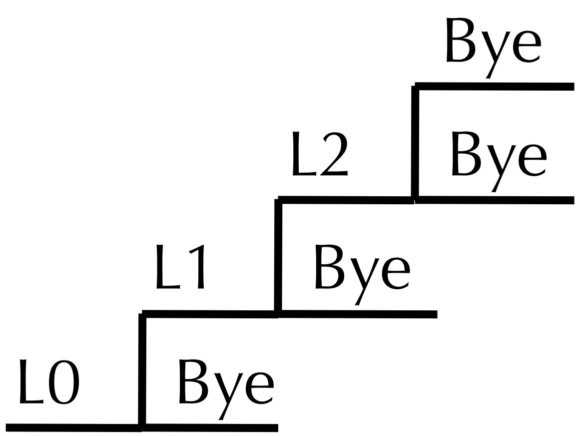
```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
        printf("L1\n");
        if (fork() != 0) {
            printf("L2\n");
            fork();
        }
    }
    printf("Bye\n");
}
```



Fork Example #5

- Key Points
  - Both parent and child can continue forking

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



Starting new programs

- How do we start a new program, instead of copying the parent?
- Use the UNIX `execve()` system call
- ```
  int  execve(const  char  *filename,
               char  *const  argv [],
               char *const envp[]);
  ```
    - `filename`: name of executable file to run
    - `argv`: Command line arguments
    - `envp`: environment variable settings (e.g., $PATH, $HOME, etc.)
  ```

Starting new programs

- `execve()` does not fork a new process!
  - Rather, it replaces the address space and CPU state of the current process
  - Loads the new address space from the executable file and starts it from `main()`
  - So, to start a new program, use `fork()` followed by `execve()`

Using fork and exec

```
int main(int argc, char **argv) {
    int rv;
    if (fork() == 0)  {   /* Child process */
        char *newargs[3];
        printf("Hello, I am the child process.\n");
        newargs[0] = "/bin/echo"; /* Convention! Not required!! */
        newargs[1] = "some random string";
        newargs[2] = NULL;     /* Indicate end of args array */
        if (execv("/bin/echo", newargs)) {
            printf("warning: execve returned an error.\n");
            exit(-1);
        }
        printf("Child process should never get here\n");
        exit(42);
    }
}
```

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Terminating a process

- A process terminates for one of 3 reasons:
  - (1) return from the `main()` procedure
  - (2) call to the `exit()` function
  - (3) receive a signal whose default action is to terminate

`exit`: Destroying Process

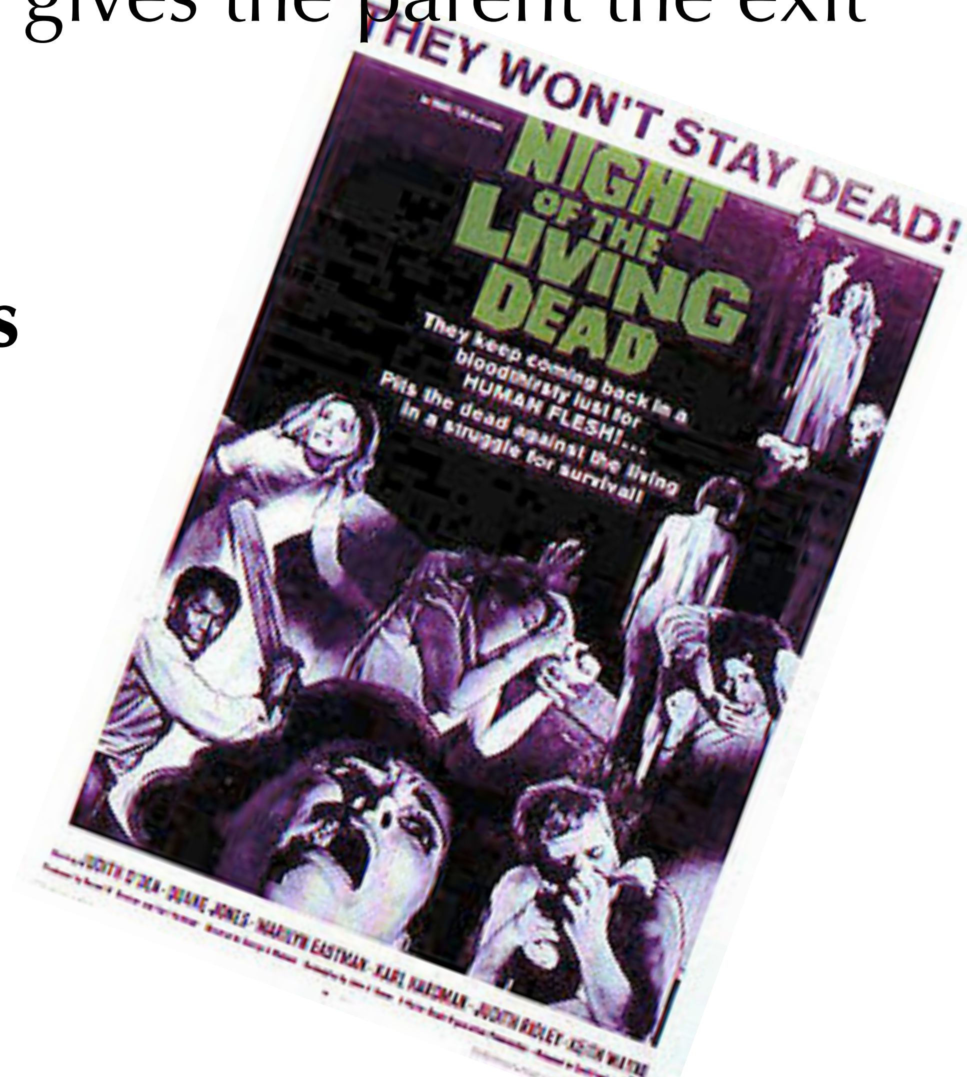
- `void exit(int exit_status)`
  - Exits a process with specified exit status.
  - By convention, status of 0 is a "normal" exit, non-zero indicates an error of some kind.
  - `atexit()` registers functions to be executed upon exit.

```
void cleanup(void) {
   printf("cleaning up\n");
}

void fork6() {
   atexit(cleanup);
   fork();
   exit(0);
}
```

Zombies

- When a process terminates (for whatever reason) OS does not remove it from system immediately
- Process stays until it is **reaped** by parent
  - When parent reaps a child process, OS gives the parent the exit status of child, and cleans up child
  - A terminated process that has not been reaped is called a **zombie process**



- How do you reap a child process?

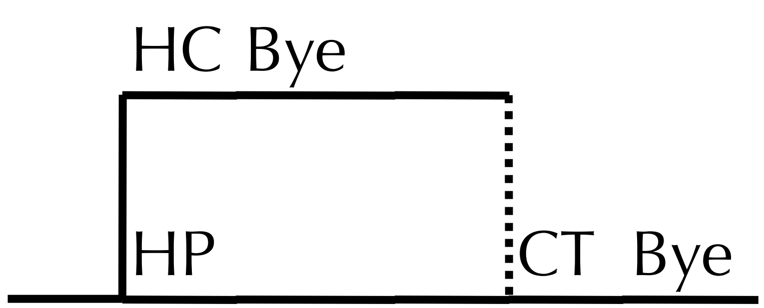
`wait`: Synchronizing with Children

- `int wait(int *child_status)`
  - Suspends parent process until one of its children terminates
  - Return value is the pid of the child process that terminated
  - if `child_status != NULL`, it will point to the child's return status
- `child_status` can be accessed using several macros:
  - `WIFEXITED(child_status) == 1` if child exited due to call to `exit()`
  - `WEXITSTATUS(child_status)` gives the return code passed to `exit()`
  - `WCOREDUMP(child_status) == 1` if child dumped core.
  - And others (see “`man 2 wait`”)

`wait`: Synchronizing with Children

```c
void fork9() {
   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();
}
```



What if multiple child processes exit?

- `wait()` returns status of exited children in arbitrary order.

```
void fork10()
{
    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 terminate abnormally\n", wpid);
    }
}
```

`waitpid()`: Waiting for a specific process

- ```
  pid_t waitpid(pid_t child_pid,
                int *status,
                int options)
  ```
  - Causes parent to wait for a **specific** child process to exit.
- Most general form of wait
  - `child_pid > 0`: wait for specific child to exit
  - `child_pid = -1`: wait for any child to exit
  - return value is PID of child process
  - `options` can be used to specify if call should return immediately (with return value of 0) if no terminated children, and also whether we are interested in stopped processes
  - `status` encodes information about how child exited (or was stopped)
  ```

waitpid(): Waiting for a specific process

- `pid_t waitpid(pid_t child_pid, int *status, int options)`

```
void fork11()
{
    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))
            printf("Child %d terminated with exit status %d\n",
                   wpid, WEXITSTATUS(child_status));
        else
            printf("Child %d terminated abnormally\n", wpid);
    }
```

Back to the zombies...

- Zombie example

```
void zombie()
{
    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> ./zombie &
[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 zombie
 6640 ttyp9    00:00:00 zombie <defunct>
 6641 ttyp9    00:00:00 ps
linux>
```

- ps shows child process as “defunct”

Orphans

- So bad things happen if the parent does not wait for the child...
- If the child exits first, child becomes a zombie
- If the parent exits first, the child becomes an **orphan**.
  - Problem: All processes (except for init) need a parent process.
  - Orphan processes “adopted” by `init` (PID 1 on most UNIX systems)
  - If child subsequently terminates, it will be reaped by `init`
    - `init` reaps zombie orphans...

Nonterminating Child Example

```
void fork8()
{
    if (fork() == 0) {
        /* Child */
        printf("Running Child, PID = %d\n",
               getpid());
        while (1)
            ; /* Infinite loop */
    } else {
        printf("Terminating Parent, PID = %d\n",
               getpid());
        exit(0);
    }
}
```

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

- Child process still active even though parent has terminated
- Must kill explicitly, or else will keep running indefinitely

Zombie orphan

- Zombie example

```
void zombie()
{
    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> ./zombie &
[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 zombie
 6640 ttyp9    00:00:00 zombie <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

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Signals

- Unix provides a mechanism to allow processes and OS to interrupt other processes
- A signal is small message to notify a process of some system event
  - These messages not normally visible to program
  - e.g.,

ID	Name	Default Action	Corresponding Event
2	SIGINT	Terminate	Interrupt (e.g., ctl-c from keyboard)
9	SIGKILL	Terminate	Kill program (cannot override or ignore)
11	SIGSEGV	Terminate & Dump	Segmentation violation
14	SIGALRM	Terminate	Timer signal
17	SIGCHLD	Ignore	Child stopped or terminated

Signal concepts

- Two distinct steps to transfer a signal:
  - (1) OS **sends** (**delivers**) signal to destination process
    - either because of some system event, or because explicitly requested via `kill` function
  - (2) Process **receives** signal (i.e., forced by OS to react to signal in some way)
    - Process can react in one of three ways:
      - ignore signal (i.e., do nothing)
      - terminate (maybe dumping core)
      - **catch** a signal with a **signal handler** function

Signal concepts

- Signal sent but not yet received is **pending**
  - At most one signal of each type is pending
  - Signals are not queued!
    - If process has pending signal of type *k*, then subsequent signals of type *k* are discarded
- Process can **block** receipt of certain signals.
  - Blocked signals will be delivered but not received until process unblocks
- Any signal received at most once

Pending and blocking signals

- OS maintains `pending` and `blocked` bit vectors for each process
  - `pending` represents set of pending signals
    - OS sets bit *k* of pending when signal of type *k* is delivered
    - OS clears bit *k* of pending when signal of type *k* is received
  - `blocked` represents set of signals process has blocked
    - Can be set and cleared using `sigprocmask` function
- For a process, OS computes `pnb = pending & ~blocked`
  - If `pnb == 0` then no signals to be received
  - If `pnb != 0` then OS chooses a signal to be received, and triggers some action by process

Sending signals with kill

- kill programs sends an arbitrary signal to a process
  - E.g., `kill -9 24818` sends SIGKILL to process 24818
- Also a function: `kill(pid_t p, int signal)`

- Can send a signal to a specific process, or all processes in a **process group**
  - Every process belongs to a process group
  - Read textbook for more info

Default actions

- Each signal type has a predefined **default action**
- One of
  - The process terminates
  - The process terminates and dumps core
  - The process stops (until restarted by a SIGCONT signal)
  - The process ignores the action

Signal handlers

- `signal(int signum, handler_t *handler)`
  - Overrides default action for signals of kind `signum`
- Different values for `handler`
  - SIG_IGN: ignore signals of type `signum`
  - SIG_DFL: revert to the default action for signals of type `signum`
  - Otherwise, it is a function pointer for a **signal handler**
    - Function will be called on receipt of signal of type `signum`
    - Referred to as **installing** handler
    - Handler execution is called **handling** or **catching** signal
    - When handler returns, control flow of interrupted process continues

Signal handler example

```
void int_handler(int sig) {
    printf("Process %d received signal %d\n",
            getpid(), sig);
}

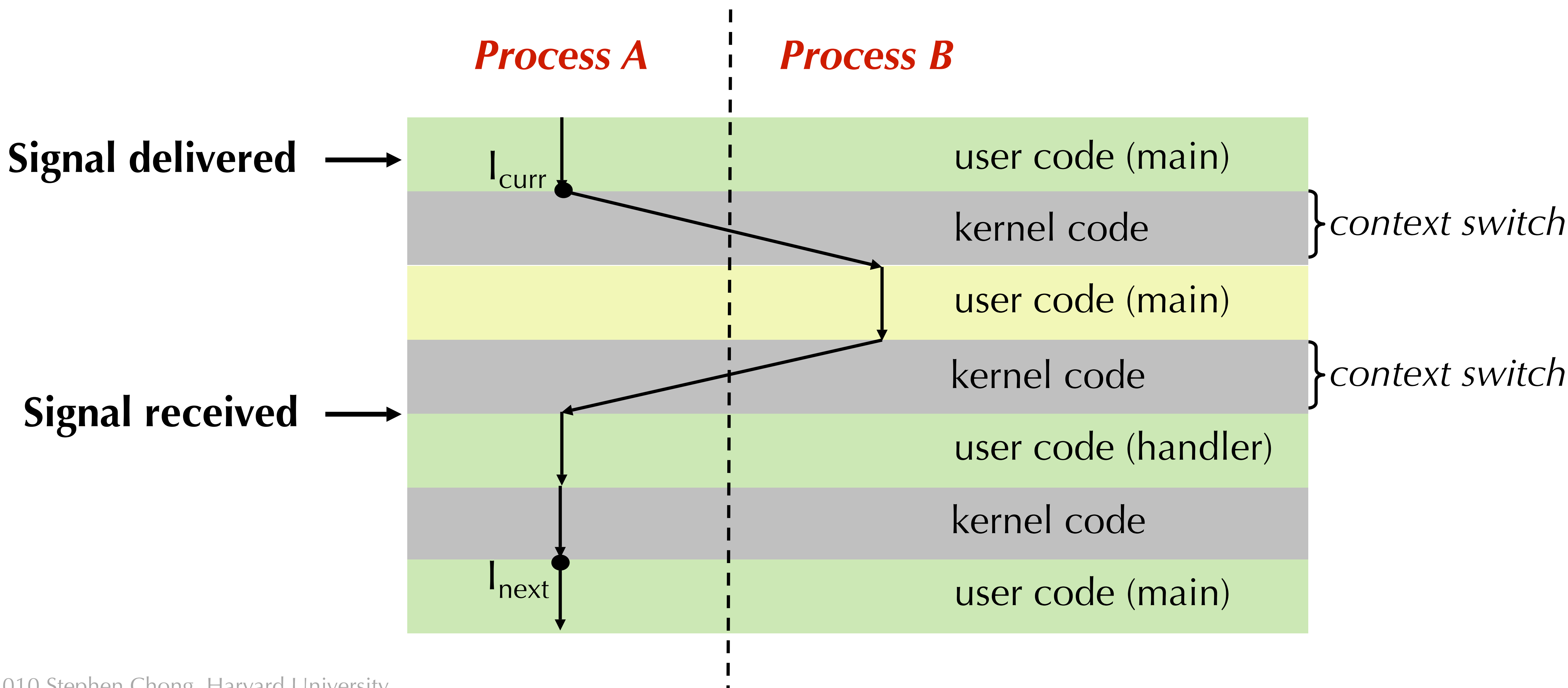
int main() {
    signal(SIGINT, int_handler);
    while (1)
        ;
}
```

```
$ ./signaleg
^C
Process 319 received signal 2
^C
Process 319 received signal 2
^C
Process 319 received signal 2
Killed
```

```
$ kill -9 319
```

Signal handlers as concurrent flows

- Signal handlers run **concurrently** with main program
  - Signal handler is not a separate process
  - Concurrent here means “non-sequential”, as opposed to “parallel”



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Communication between processes

- UNIX provides several mechanisms for inter-process communication (IPC)
  - Shared memory regions
  - Sockets (also used for communication over a network).
  - Pipes
- A **pipe** is a pair of file descriptors for communication between two processes.
  - One process can write data to one "end" of the pipe
  - The other process can read data from the other "end" of the pipe.
- `int pipe(int filedes[2]);`
  - `filedes[1]` is the write end of the pipe; `filedes[0]` is the read end of the pipe.

Using pipes

- But how do we get two processes to use a pipe?
- Idea: Parent process first creates the pipe, then forks the child
    - Since parent and child share open files, they can communicate.
- This is exactly what the UNIX shell does for you when you "pipe" the output of one command into another.

```
$ ./myprog | grep 'somestring'
```

- Shell creates the pipe, forks both "myprog" and "grep", and uses dup2() to wire the ends of the pipe into stdout and stdin of each process.
- Somewhat more complex example:

```
$ ./myprog | grep 'somestring' | sort | uniq | more
```

Pipe example

```
main() {
   char inbuf[BUFSIZE];
   int p[2], j, pid;

   /* open pipe */
   if(pipe(p) == -1)
   {    perror("pipe call error");
        exit(1);
   }

   switch(pid = fork()){
   case -1: perror("error: fork failed");
            exit(2);

   case 0:  /* if child then write down pipe */
         close(p[0]);  /* first close the read end of the pipe */
         write(p[1], “Hello there.”, 12);
         write(p[1], “This is a message.”, 18);
            write(p[1], “How are you?”, 12);
         break;
   default:   /* parent reads pipe */
         close(p[1]);  /* first close the write end of the pipe */
         read(p[0], inbuf, BUFSIZE);  /* What is wrong here?? */
         printf("Parent read: %s\n", inbuf);
         wait(NULL);
   }
   exit(0);
}
```

Next lecture

- Midterm exam!
- (And then network programming)