

Exceptional Control Flow

15-213: Introduction to Computer Systems

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Ian Hartwig

Section E

Agenda

- Midterm Wrap-Up
- Exceptional Control Flow
- Processes
- Process Examples
- Signals
- Shell lab

Midterm Wrap-Up

- Midterms are viewable now; see your email for details.

Exceptional Control Flow

- Up to now: two mechanisms for changing control flow:

- Jumps and branches
- Call and return

Both react to changes in *program state*

- Insufficient for a useful system:

Difficult to react to changes in *system state*

- data arrives from a disk or a network adapter
- instruction divides by zero
- user hits Ctrl-C at the keyboard
- System timer expires

- System needs mechanisms for “exceptional control flow”

Exceptional Control Flow

- What are the different types of ECF?
 - Exceptions
 - Process Context Switch
 - Signals
 - Nonlocal jumps

Exceptional Control Flow

- Exceptions are either synchronous or asynchronous:
- Asynchronous
 - I/O interrupts
 - Reset interrupts
- Synchronous
 - Traps
 - Faults
 - Aborts

Asynchronous Exceptions (Interrupts)

- Caused by events external to the processor
 - Indicated by setting the processor's interrupt pin
 - Handler returns to "next" instruction

- Examples:
 - I/O interrupts
 - hitting Ctrl-C at the keyboard
 - arrival of a packet from a network
 - arrival of data from a disk
 - Hard reset interrupt
 - hitting the reset button
 - Soft reset interrupt
 - hitting Ctrl-Alt-Delete on a PC

Synchronous Exceptions

- Caused by events that occur as a result of executing an instruction:
 - **Traps**
 - Intentional
 - Examples: **system calls**, breakpoint traps, special instructions
 - Returns control to “next” instruction
 - **Faults**
 - Unintentional but possibly recoverable
 - Examples: page faults (recoverable), protection faults (unrecoverable), floating point exceptions
 - Either re-executes faulting (“current”) instruction or aborts
 - **Aborts**
 - unintentional and unrecoverable
 - Examples: parity error, machine check
 - Aborts current program

Agenda

- Exceptional Control Flow
- **Processes and Signals**
- Shell lab

Processes

- What is a *program*?
 - A bunch of data and instructions stored in an executable binary file
 - Written according to a specification that tells users what it is supposed to do
 - Stateless since binary file is static

Processes

- Definition: A *process* is an instance of a running program.
- Process provides each program with two key abstractions:
 - Logical control flow
 - Each program seems to have exclusive use of the CPU
 - Private virtual address space
 - Each program seems to have exclusive use of main memory
 - Gives the running program a *state*
- How are these Illusions maintained?
 - Process executions interleaved (multitasking) or run on separate cores
 - Address spaces managed by virtual memory system
 - Just know that this exists for now; we'll talk about it soon

Processes

- Four basic States
 - Running
 - Executing instructions on the CPU
 - Number bounded by number of CPU cores
 - Runnable
 - Waiting to be running
 - Blocked
 - Waiting for an event, maybe input from STDIN
 - Not runnable
 - Zombie
 - Terminated, not yet reaped

Processes

- Four basic process control function families:
 - `fork()`
 - `exec()`
 - And other variants such as `execve()`
 - `exit()`
 - `wait()`
 - And variants like `waitpid()`
- Standard on all UNIX-based systems
- Don't be confused:
Fork(), Exit(), Wait() are all wrappers provided by CS:APP

Processes

■ `int fork(void)`

- creates a new process (child process) that is identical to the calling process (parent process)
- OS creates an exact duplicate of parent's state:
 - Virtual address space (memory), including heap and stack
 - Registers, except for the return value (%eax/%rax)
 - File descriptors but files are shared
- **Result → Equal but separate state**
- Fork is interesting (and often confusing) because it is called *once* but returns *twice*

Processes

■ `int fork(void)`

- returns 0 to the child process
- returns child's **pid** (process id) to the parent process
- Usually used like:

```
pid_t pid = fork();

if (pid == 0) {
    // pid is 0 so we can detect child
    printf("hello from child\n");
}

else {
    // pid = child's assigned pid
    printf("hello from parent\n");
}
```

Processes

- `int exec()`
 - Replaces the current process's state and context
 - But keeps PID, open files, and signal context
 - Provides a way to load and run **another** program
 - Replaces the current running memory image with that of new program
 - Set up stack with arguments and environment variables
 - Start execution at the entry point
 - Never returns on successful execution
 - The newly loaded program's perspective: as if the previous program has not been run before
 - More useful variant is `int execve()`
 - More information? `man 3 exec`

Processes

- `void exit(int status)`
 - Normally return with status 0 (other numbers indicate an error)
 - Terminates the current process
 - OS frees resources such as heap memory and open file descriptors and so on...
 - Reduce to a zombie state
 - Must wait to be reaped by the parent process (or the init process if the parent died)
 - Signal is sent to the parent process notifying of death
 - Reaper can inspect the exit status

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
 - When wait returns a pid > 0, child process has been reaped
 - All child resources freed
 - if `child_status != NULL`, then the object it points to will be set to a status indicating why the child process terminated
 - More useful variant is `int waitpid()`
 - For details: `man 2 wait`

Process Examples

```
pid_t child_pid = fork();

if (child_pid == 0){
    /* only child comes here */

    printf("Child!\n");

    exit(0);
}
else{

    printf("Parent!\n");
}
```

- What are the possible output (assuming fork succeeds) ?
 - Child!
Parent!
 - Parent!
Child!
- How to get the child to always print first?


Process Examples

```
int status;
pid_t child_pid = fork();

if (child_pid == 0){
    /* only child comes here */

    printf("Child!\n");

    exit(0);
}
else{
    waitpid(child_pid, &status, 0);
    printf("Parent!\n");
}
```



- Waits til the child has terminated.
 - Parent can inspect exit status of child using 'status'
 - WEXITSTATUS(status)
- Output always:
Child!
Parent!

Process Examples

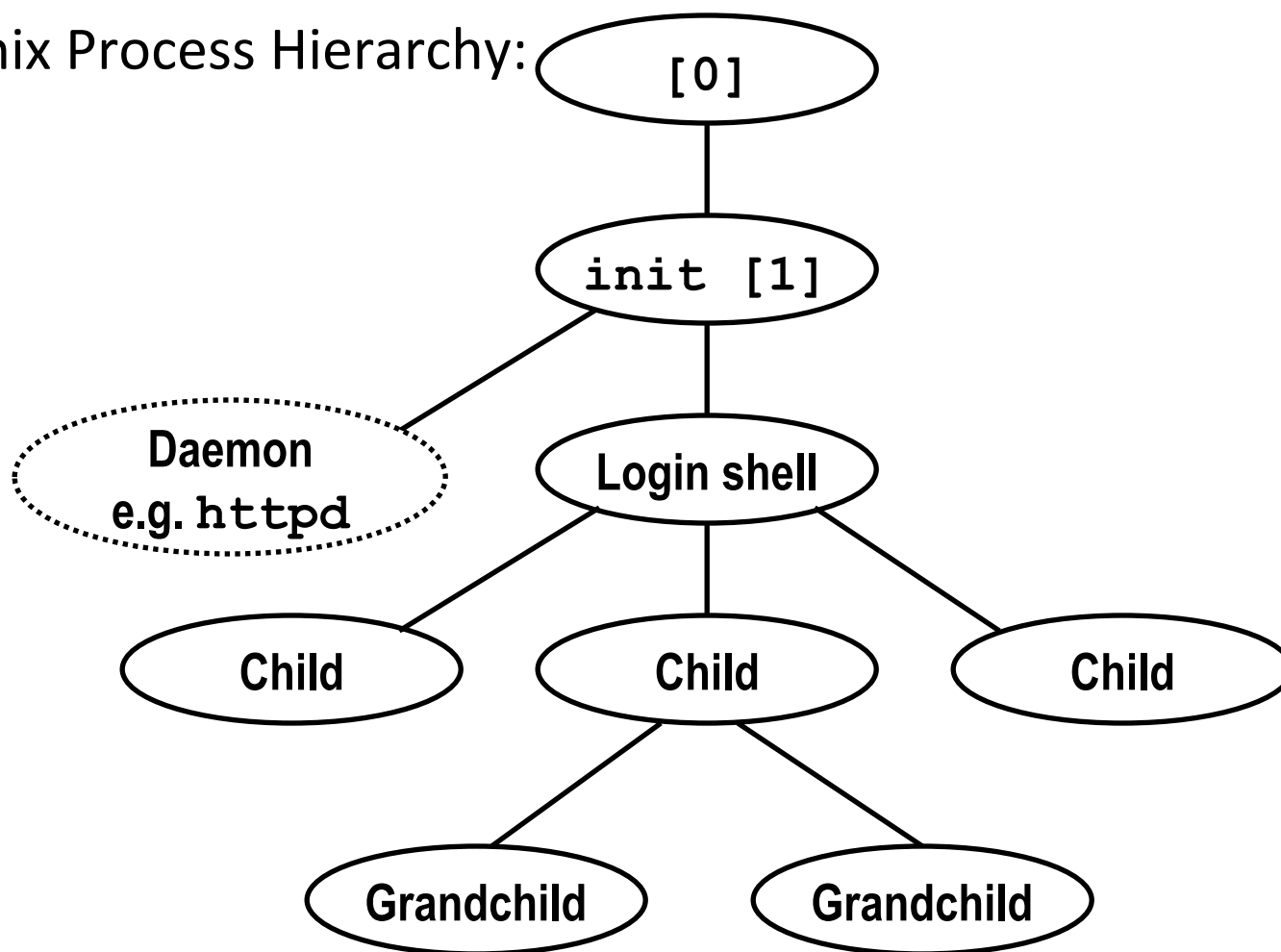
```
int status;  
pid_t child_pid = fork();  
char* argv[] = {"/bin/ls", "-l", NULL};  
char* env[] = {..., NULL};
```

```
if (child_pid == 0){  
    /* only child comes here */  
  
    execve("/bin/ls", argv, env);  
  
    /* will child reach here? */  
}  
else{  
    waitpid(child_pid, &status, 0);  
  
    ... parent continue execution...  
}
```

- An example of something useful.
- Why is the first arg `"/bin/ls"`?
- Will child reach here?

Process Examples

■ Unix Process Hierarchy:



Signals

- A *signal* is a small message that notifies a process that an event of some type has occurred in the system
 - akin to exceptions and interrupts (asynchronous)
 - sent from the kernel (sometimes at the request of another process) to a process
 - signal type is identified by small integer ID's (1-30)
 - only information in a signal is its ID and the fact that it arrived

<i>ID</i>	<i>Name</i>	<i>Default Action</i>	<i>Corresponding Event</i>
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

Signals

- Kernel *sends* (delivers) a signal to a *destination process* by updating some state in the context of the destination process

- Kernel sends a signal for one of the following reasons:
 - Kernel has detected a system event such as Ctrl-C (SIGINT), divide-by-zero (SIGFPE), or the termination of a child process (SIGCHLD)
 - Another program called the `kill()` function
 - The user used a `kill` utility

Signals

- A destination process *receives* a signal when it is forced by the kernel to react in some way to the delivery of the signal
- Receiving a signal is non-queuing
 - There is only one bit in the context per signal
 - Receiving 1 or 300 SIGINTs looks the same to the process
- Signals are received at a context switch
- Three possible ways to react:
 - *Ignore* the signal (do nothing)
 - *Terminate* the process (with optional core dump)
 - *Catch* the signal by executing a user-level function called *signal handler*
 - Akin to a hardware exception handler being called in response to an asynchronous interrupt

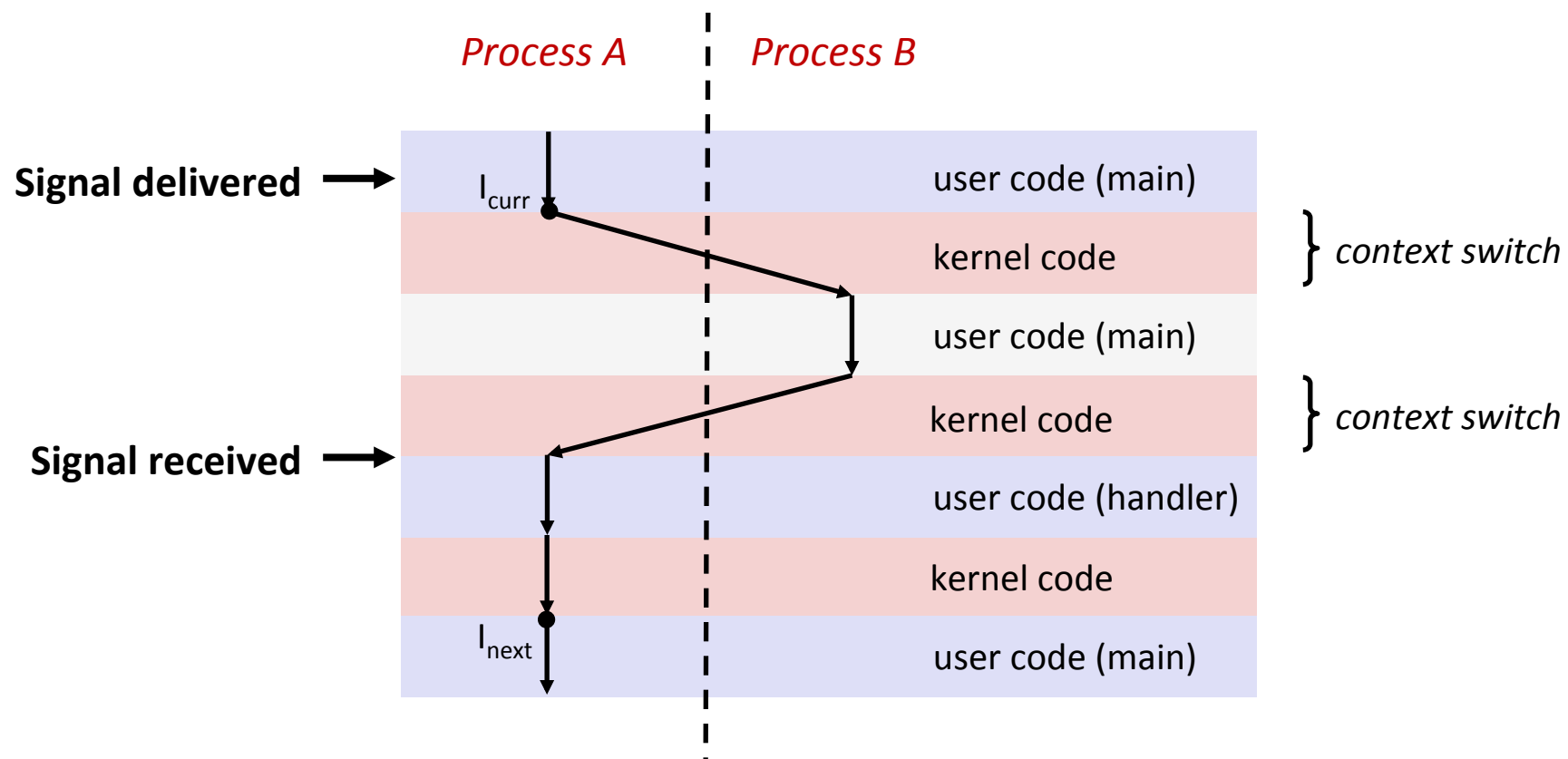
Signals

- A destination process *receives* a signal when it is forced by the kernel to react in some way to the delivery of the signal
- Blocking signals
 - Sometimes code needs to run through a section that can't be interrupted
 - Implemented with `sigprocmask()`
- Waiting for signals
 - Sometimes, we want to pause execution until we get a specific signal
 - Implemented with `sigsuspend()`
- Can't modify behavior of SIGKILL and SIGSTOP

Signals

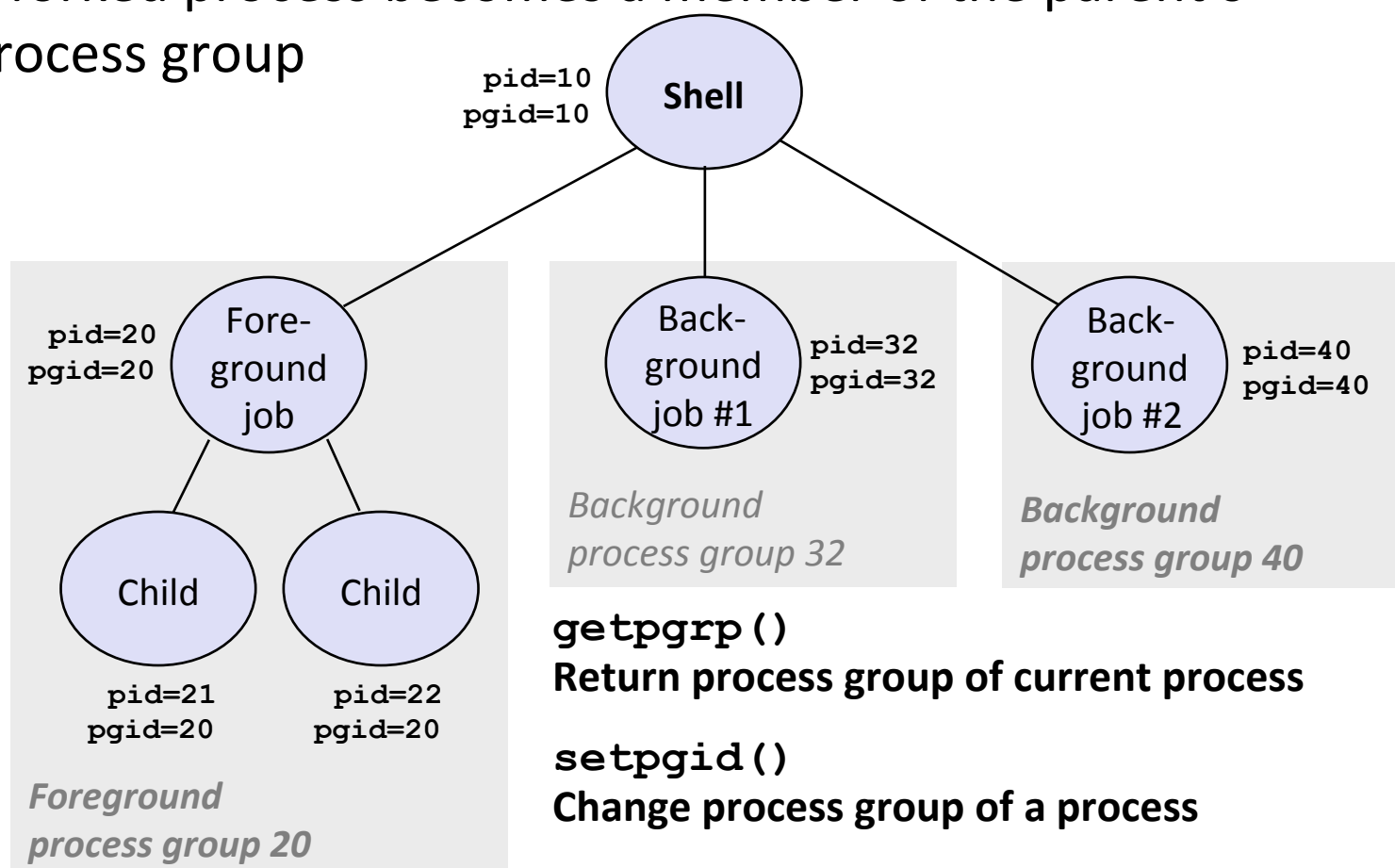
- Signal handlers
 - Can be installed to run when a signal is received
 - The form is `void handler(int signum){ ... }`
 - **Separate** flow of control in the same process
 - Resumes normal flow of control upon returning
 - Can be called **anytime** when the appropriate signal is fired

Signal Examples



Signal Examples

- Every process belongs to exactly one process group
- Process groups can be used to distribute signals easily
- A forked process becomes a member of the parent's process group



Signal Examples

```
// sigchld handler installed

pid_t child_pid = fork();

if (child_pid == 0){
    /* child comes here */

    execve(.....);
}
else{

    add_job(child_pid);

}
```

```
void sigchld_handler(int signum)
{
    int status;

    pid_t child_pid =
        waitpid(-1, &status, WNOHANG);

    if (WIFEXITED(status))
        remove_job(child_pid);
}
```

- Does add_job or remove_job() come first?
- Where can we block signals in this code to guarantee correct execution?

Signal Examples

```
// sigchld handler installed
void sigchld_handler(int signum)
{
    int status;

    pid_t child_pid =
        waitpid(-1, &status, WNOHANG);

    if (WIFEXITED(status))
        remove_job(child_pid);
}

pid_t child_pid = fork();

if (child_pid == 0){
    /* child comes here */
    execve(.....);
}
else{
    add_job(child_pid, ...);
}
```

Block SIGCHLD

Unblock SIGCHLD

Unblock SIGCHLD

- Does `add_job` or `remove_job()` come first?
- Where can we block signals in this code to guarantee correct execution?

Shell Lab

- Read the code we've given you
 - There's a lot of stuff you don't need to write yourself; we gave you quite a few helper functions
 - It's a good example of the code we expect from you!
- Don't be afraid to write your own helper functions; this is not a simple assignment

Shell Lab

- Read man pages. You may find the following functions helpful:
 - `sigemptyset()`
 - `sigaddset()`
 - `sigprocmask()`
 - `sigsuspend()`
 - `waitpid()`
 - `open()`
 - `dup2()`
 - `setpgid()`
 - `kill()`
- Please do not use `sleep()` to solve synchronization issues.

Shell lab

■ Hazards

- Race conditions
 - Hard to debug so start early (and think carefully)
- Reaping zombies
 - Race conditions
 - Handling signals correctly
- Waiting for foreground job
 - Think carefully about what the right way to do this is

Q & A

- For your listening enjoyment:

http://www.monzy.com/intro/killdashnine_lyrics.html