Exceptional Control Flow

15-213: Introduction to Computer Systems
Recitation 9: Monday, October 26th, 2015

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Adapted from slides by Ian Hartwig

Agenda

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

Midterm Wrap-Up

- Midterms scores are on Autolab
- View exams during OH in 5207
- Regrade requests – in writing (hardcopy only)

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”

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

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(), **E**xit(), **W**ait() 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!

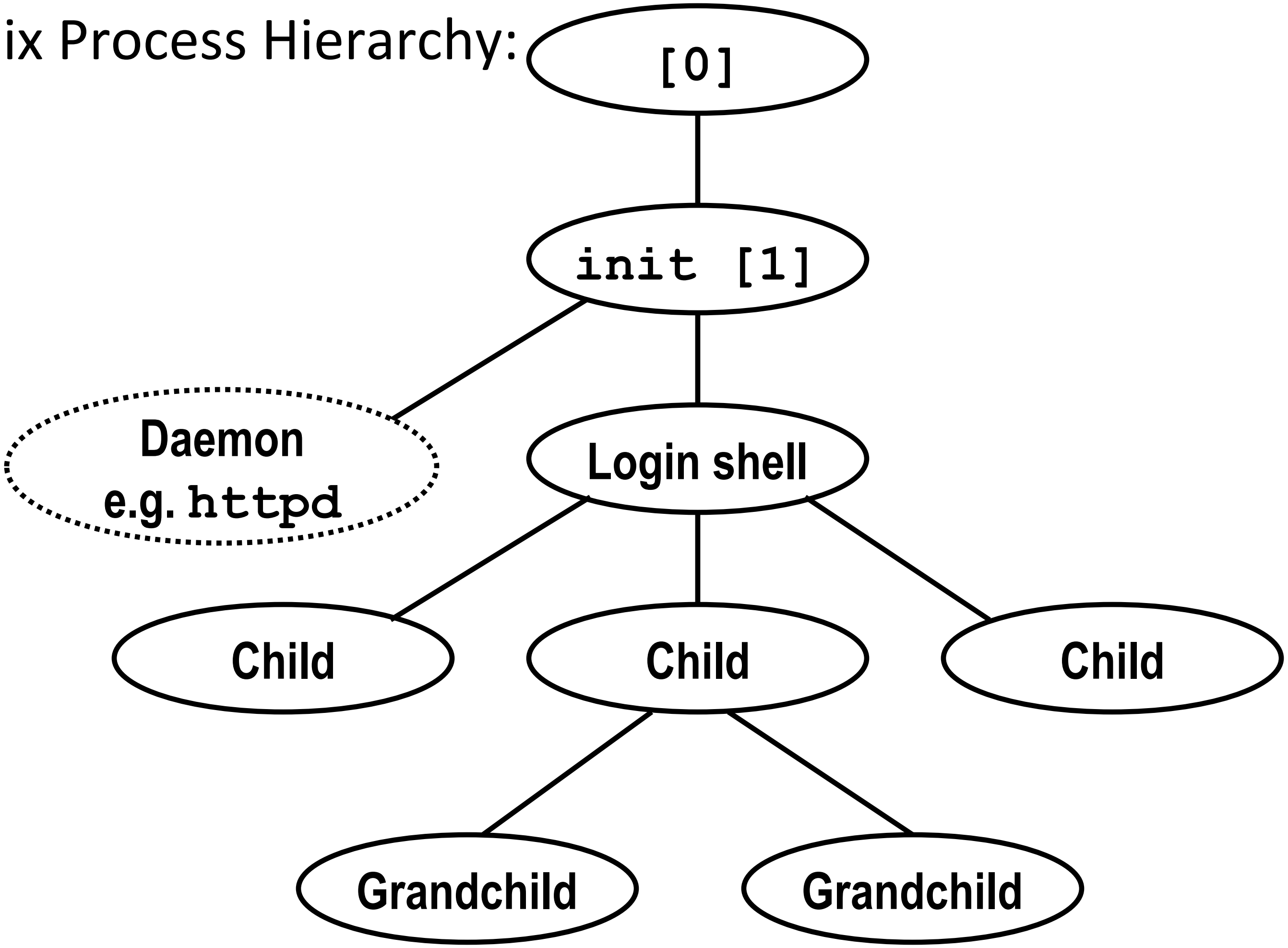
Process Examples

```
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

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

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

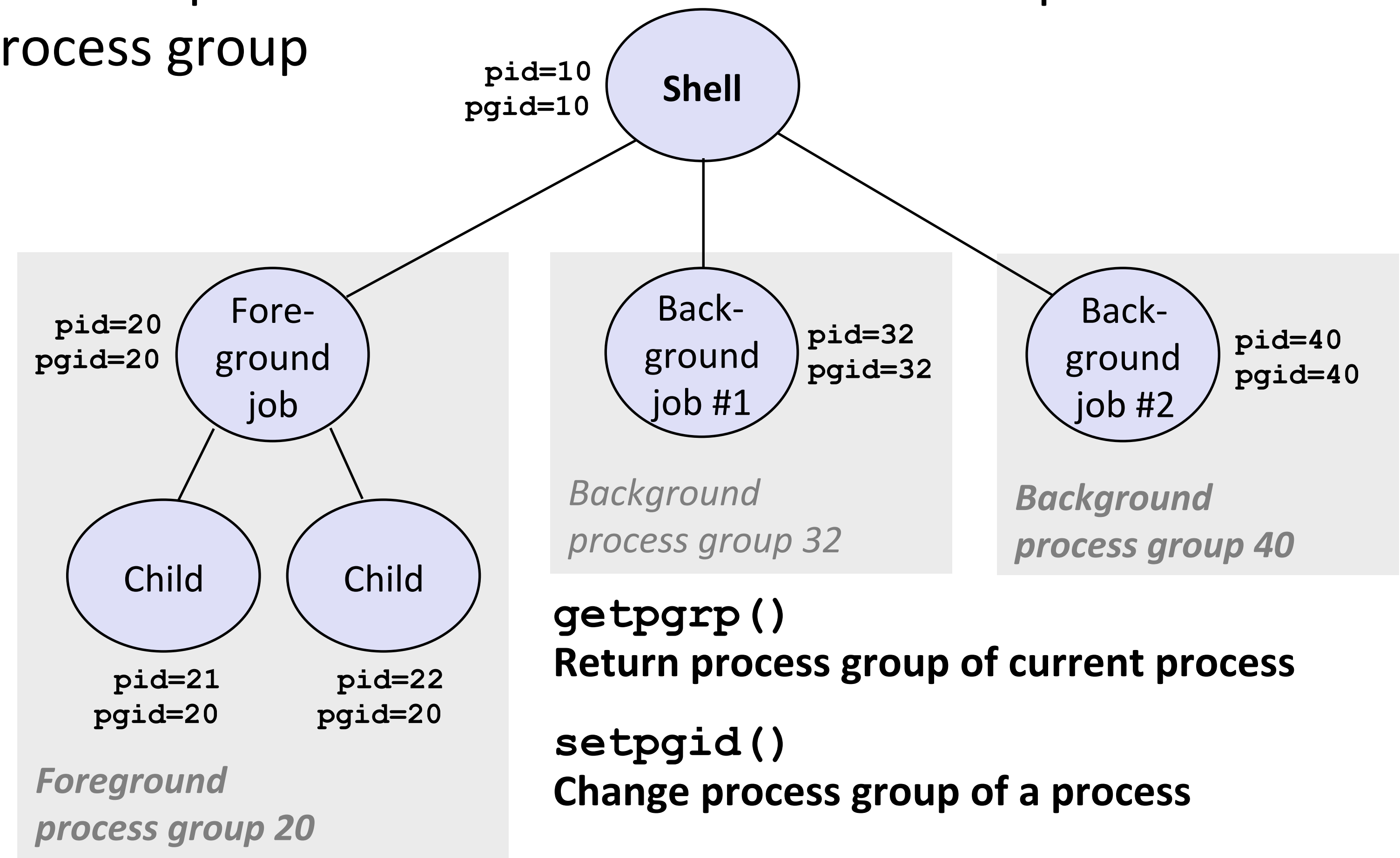
- Signal handlers
  - Can be installed to run when a signal is received
  - The form is `void handler(int signum){ … }`
  - **Separate** flow of control in the same process
  - Resumes normal flow of control upon returning
  - Can be called **anytime** when the appropriate signal is fired

Signals

- `int sigsuspend(const sigset_t *mask)`
  - Can't use wait() twice – use sigsuspend!
  - Temporarily replaces the signal mask of the calling process with the mask given
  - Suspends the process until delivery of a signal whose action is to invoke a signal handler or terminate a process
  - Returns if the signal is caught
    - Signal mask restored to the previous state
  - Use sigaddset(), sigemptyset(), etc. to create the mask

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



`getpgrp()`
Return process group of current process

`setpgid()`
Change process group of a process

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

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);
}
```

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

- Shell Lab is out!
- Due Tuesday, November 3rd at 11:59pm
- 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

Shell Lab Testing

- Run your shell
  - This is the fun part!
- tshref
  - How should the shell behave?
- runtrace
  - Each trace tests one feature.