Exceptional Control Flow: Exceptions and Processes

15-213 / 18-213: Introduction to Computer Systems
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Today

- The Process Abstraction
- Exceptional Control Flow
- Process Details
Processes

Definition: A *process* is an instance of a running program.
- One of the most profound ideas in computer science
- Not the same as “program” or “processor”

Process provides each program with two key abstractions:
- Logical control flow
  - Each program seems to have exclusive use of the CPU
- Private copy of program state
  - Register values (PC, stack pointer, general registers, condition codes)
  - Private virtual address space
    - Program has exclusive access to main memory
    - Including stack
Multiprocessing: The Illusion

- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, ...
  - Background tasks
    - Monitoring network & I/O devices
**Multiprocessing Example**

- **Running program “top” on Mac**
  - System has 123 processes, 5 of which are active
  - Identified by Process ID (PID)
Multiprocessing: The (Traditional) Reality

- Single Processor Executes Multiple Processes Concurrently
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system
    - we’ll talk about this in a couple of weeks
  - Register values for nonexecuting processes saved in memory
Multiprocessing: The (New) Reality

- **Multicore processors**
  - Multiple CPUs on single chip
  - Share main memory (and some of the caches)
  - Each can execute a separate process
    - Scheduling of processors onto cores done by OS
Multithreading: The Illusion

- Single process runs multiple *threads* concurrently
- Each has own control flow and runtime state
  - But view memory as shared among all threads
  - One thread can read/write the state of another
- We will talk about this later in the term
  - For today, just consider one thread / process executing on single core
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Control Flow

- Processors do only one thing:
  - From startup to shutdown, a CPU simply reads and executes (interprets) a sequence of instructions, one at a time
  - This sequence is the CPU’s control flow (or flow of control)

**Physical control flow**

\[
\begin{align*}
\text{<startup>} & \quad \text{inst}_1 \\
\text{inst}_2 & \quad \text{inst}_3 \\
\cdots & \\
\text{inst}_n & \quad \text{<shutdown>}
\end{align*}
\]
Altering the 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

- Exists at all levels of a computer system
- Low level mechanisms
  - Exceptions
    - change in control flow in response to a system event (i.e., change in system state)
  - Combination of hardware and OS software
- Higher level mechanisms
  - Process context switch
  - Signals
  - Nonlocal jumps: setjmp()/longjmp()
  - Implemented by either:
    - OS software (context switch and signals)
    - C language runtime library (nonlocal jumps)
Exceptions

- An *exception* is a transfer of control to the OS in response to some *event* (i.e., change in processor state)

![Diagram]

- Examples:
  - div by 0, arithmetic overflow, page fault, I/O request completes, Ctrl-C
**Exception Tables**

- Each type of event has a unique exception number $k$
- $k = \text{index into exception table (a.k.a. interrupt vector)}$
- Handler $k$ is called each time exception $k$ occurs
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 power 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
Trap Example: Opening File

- User calls: `open(filename, options)`
- Function `open` executes system call instruction `int`

```
0804d070 <__libc_open>:
  . . .
804d082:     cd 80                   int  $0x80
804d084:     5b                     pop  %ebx
. . .
```

- OS must find or create file, get it ready for reading or writing
- Returns integer file descriptor
Fault Example: Page Fault

- User writes to memory location
- That portion (page) of user’s memory is currently on disk

```c
int a[1000];
main ()
{
    a[500] = 13;
}
```

Exception: page fault

Create page and load into memory

- Page handler must load page into physical memory
- Returns to faulting instruction
- Successful on second try
Fault Example: Invalid Memory Reference

```c
int a[1000];
main ()
{
    a[5000] = 13;
}
```

80483b7:  c7 05 60 e3 04 08 0d  movl   $0xd,0x804e360

**User Process**

- Page handler detects invalid address
- Sends **SIGSEGV** signal to user process
- User process exits with “segmentation fault”
### Exception Table IA32 (Excerpt)

<table>
<thead>
<tr>
<th>Exception Number</th>
<th>Description</th>
<th>Exception Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Divide error</td>
<td>Fault</td>
</tr>
<tr>
<td>13</td>
<td>General protection fault</td>
<td>Fault</td>
</tr>
<tr>
<td>14</td>
<td>Page fault</td>
<td>Fault</td>
</tr>
<tr>
<td>18</td>
<td>Machine check</td>
<td>Abort</td>
</tr>
<tr>
<td>32-127</td>
<td>OS-defined</td>
<td>Interrupt or trap</td>
</tr>
<tr>
<td>128 (0x80)</td>
<td>System call</td>
<td>Trap</td>
</tr>
<tr>
<td>129-255</td>
<td>OS-defined</td>
<td>Interrupt or trap</td>
</tr>
</tbody>
</table>

Check Table 6-1: [http://download.intel.com/design/processor/manuals/253665.pdf](http://download.intel.com/design/processor/manuals/253665.pdf)
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**Concurrent Processes**

- Two processes *run concurrently* (*are concurrent*) if their flows overlap in time
- Otherwise, they are *sequential*
- Examples (running on single core):
  - Concurrent: A & B, A & C
  - Sequential: B & C
User View of Concurrent Processes

- Control flows for concurrent processes are physically disjoint in time

- However, we can think of concurrent processes as running in parallel with each other
Context Switching

- Processes are managed by a shared chunk of OS code called the *kernel*
  - Important: the kernel is not a separate process, but rather runs as part of some user process

- Control flow passes from one process to another via a *context switch*
**fork: Creating New Processes**

- `int fork(void)`
  - creates a new process (child process) that is identical to the calling process (parent process)
  - (Appears to) create complete new copy of program state
  - Child & parent then execute as independent processes
    - Writes by one don’t affect reads by other
    - But … share any open files

![Diagram showing memory, CPU, and registers before and after the fork](image)
fork: Details

- 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 pid (process id) to the parent process

```c
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");
}
```

**Child Process 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");
}
```

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

```
pid_t pid = fork();
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}
```

```
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");
}
```

**Which one is first?**

hello from parent  Which one is first?  hello from child
Fork Example #1

- Parent and child both run same code
  - Distinguish parent from child by return value from `fork`
- Start with same state, but each has private copy
  - Including shared output file descriptor
  - Relative ordering of their print statements undefined

```c
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

- Two consecutive forks

```c
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```
Fork Example #3

- Three consecutive forks

```c
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```
Fork Example #4

- Nested forks in parent

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

Diagram:

```
L0 ----> Bye
   |
   v
L1 ----> Bye
   |
   v
L2 ----> Bye
   |
   v
Bye
```
Fork Example #5

- Nested forks in children

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

```plaintext
L0 Bye
L1 Bye
Bye
Bye
Bye
L2
Bye
L1
Bye
L0
Bye
```
exit: Ending a process

- **void exit(int status)**
  - exits a process
    - Normally return with status 0
  - **atexit()** registers functions to be executed upon exit

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

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

- **Idea**
  - When process terminates, 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 (using `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 `init` process (pid == 1)
  - So, only need explicit reaping in long-running processes
    - e.g., shells and servers
Zombie Example

```c
void fork7()
{
    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 */
    }
}
```

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

```c
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);
    }
}
```

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

- Parent reaps child by calling the `wait` function

```c
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 object it points to will be set to a status indicating why the child process terminated
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();
}
**wait() Example**

- If multiple children completed, will take in arbitrary order
- Can use macros WIFEXITED and WEXITSTATUS to get information about exit status

```c
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

- `waitpid(pid, &status, options)`
  - suspends current process until specific process terminates
  - various options (see textbook)

```c
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 = N-1; i >= 0; 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);
    }
}
```
execve: Loading and Running Programs

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

- **Loads and runs in current process:**
  - Executable `filename`
  - With argument list `argv`
  - And environment variable list `envp`

- **Does not return** (unless error)

- **Overwrites code, data, and stack**
  - keeps pid, open files and signal context

- **Environment variables:**
  - “name=value” strings
  - `getenv` and `putenv`
execve Example

```c
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);
  }
}
```

- `argv[argc] = NULL`
- `argv[argc-1]` → `/usr/include`
- `...` → `-lt`
- `argv[0]` → `ls`

- `environ[0]` → `USER=droh`
- `environ[n-1]` → `PRINTER=iron`
- `...` → `PWD=/usr/droh`
Summary

- **Exceptions**
  - Events that require nonstandard control flow
  - Generated externally (interrupts) or internally (traps and faults)

- **Processes**
  - At any given time, system has multiple active processes
  - Only one can execute at a time on a single core, though
  - Each process appears to have total control of processor + private memory space
Summary (cont.)

- **Spawning processes**
  - Call `fork`
  - One call, two returns

- **Process completion**
  - Call `exit`
  - One call, no return

- **Reaping and waiting for processes**
  - Call `wait` or `waitpid`

- **Loading and running programs**
  - Call `execve` (or variant)
  - One call, (normally) no return