Exceptions and Processes

The material for this lecture is drawn from
Computer Systems: A Programmer’s Perspective (Bryant & O’Hallaron) Chapter 8

Goals of this Lecture

• Help you learn about:
  • Exceptions
  • The process concept
    … and thereby…
  • How operating systems work
  • How application programs interact with operating systems and hardware

The process concept is one of the most important concepts in systems programming
Context of this Lecture

Second half of the course

Previously
- C Language
- Assembly Language
- Machine Language

language levels tour

Starting Now
- Application Program
- Operating System
- Hardware

service levels tour

Application programs, OS, and hardware interact
via exceptions

Motivation

Question:
- Executing program thinks it has exclusive control of the CPU
- But multiple executing programs must share one CPU (or a few CPUs)
- How is that illusion implemented?

Question:
- Executing program thinks it has exclusive use of all of memory
- But multiple executing programs must share one memory
- How is that illusion implemented?

Answers: Exceptions and Processes
Exceptions

• **Exception**
  • An abrupt change in control flow in response to a change in processor state

• **Examples:**
  • Application program:
    • Requests I/O
    • Requests more heap memory
    • Attempts integer division by 0
    • Attempts to access privileged memory
    • Accesses variable that is not in real memory (see upcoming “Virtual Memory” lecture)
  • User presses key on keyboard
  • Disk controller finishes reading data

Exceptions Note

• **Note:**
  Exceptions in OS ≠ exceptions in Java
  
  Implemented using `try/catch` and `throw` statements
Exception Control Flow

Exceptions vs. Function Calls

- Exceptions are similar to function calls
  - Control transfers from original code to other code
  - Other code executes
  - Control returns to original code

- Exceptions are different from function calls
  - Processor pushes additional state onto stack
    - E.g. values of all registers
  - Processor pushes data onto OS’s stack, not application pgm’s stack
  - Handler runs in privileged mode, not in user mode
    - Handler can execute all instructions and access all memory
  - Control might return to next instruction
    - Control sometimes returns to current instruction
    - Control sometimes does not return at all
Classes of Exceptions

• There are 4 classes of exceptions…

(1) Interrupts

Cause: Signal from I/O device
Examples:
  User presses key
  Disk controller finishes reading/writing data

<table>
<thead>
<tr>
<th>Application program</th>
<th>Exception handler</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) CPU interrupt pin goes high</td>
<td>(2) After current instr finishes, control passes to handler</td>
</tr>
<tr>
<td></td>
<td>(3) Handler runs</td>
</tr>
<tr>
<td></td>
<td>(4) Handler returns control to next instr</td>
</tr>
</tbody>
</table>
(2) Traps

**Cause:** Intentional (application program requests OS service)

**Examples:**
- Application program requests more heap memory
- Application program requests I/O

Traps provide a function-call-like interface between application and OS

![Diagram showing the flow of control between application program and exception handler for traps.](image)

(1) Application program traps

(2) Control passes to handler

(3) Handler runs

(4) Handler returns control to next instr

(3) Faults

**Cause:** Application program causes (possibly) recoverable error

**Examples:**
- Application program accesses privileged memory (seg fault)
- Application accesses data that is not in real memory (page fault)

![Diagram showing the flow of control between application program and exception handler for faults.](image)

(1) Current instr causes a fault

(2) Control passes to handler

(3) Handler runs

(4) Handler returns control to current instr, or aborts
(4) Aborts

**Cause:** Non-recoverable error

**Example:**
Parity check indicates corruption of memory bit (overheating, cosmic ray, etc.)

- **Application program**
  - (1) Fatal hardware error occurs

- **Exception handler**
  - (2) Control passes to handler
  - (3) Handler runs
  - (4) Handler aborts execution

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**Summary of Exception Classes**

<table>
<thead>
<tr>
<th>Class</th>
<th>Cause</th>
<th>Asynch/Synch</th>
<th>Return Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interrupt</strong></td>
<td>Signal from I/O device</td>
<td>Asynch</td>
<td>Return to next instr</td>
</tr>
<tr>
<td><strong>Trap</strong></td>
<td>Intentional</td>
<td>Sync</td>
<td>Return to next instr</td>
</tr>
<tr>
<td><strong>Fault</strong></td>
<td>(Maybe) recoverable error</td>
<td>Sync</td>
<td>(Maybe) return to current instr</td>
</tr>
<tr>
<td><strong>Abort</strong></td>
<td>Non-recoverable error</td>
<td>Sync</td>
<td>Do not return</td>
</tr>
</tbody>
</table>
Exceptions in Intel Processors

Each exception has a number
Some exceptions in Intel processors:

<table>
<thead>
<tr>
<th>Exception #</th>
<th>Exception</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Fault: Divide error</td>
</tr>
<tr>
<td>13</td>
<td>Fault: Segmentation fault</td>
</tr>
<tr>
<td>14</td>
<td>Fault: Page fault (see “Virtual Memory” lecture)</td>
</tr>
<tr>
<td>18</td>
<td>Abort: Machine check</td>
</tr>
<tr>
<td>32-127</td>
<td>Interrupt or trap (OS-defined)</td>
</tr>
<tr>
<td>128</td>
<td>Trap</td>
</tr>
<tr>
<td>129-255</td>
<td>Interrupt or trap (OS-defined)</td>
</tr>
</tbody>
</table>

Traps in Intel Processors

- To execute a trap, application program should:
  - Place number in EAX register indicating desired functionality
  - Place parameters in EBX, ECX, EDX registers
  - Execute assembly language instruction “int 128”

- Example: To request more heap memory...

```assembly
movl $45, %eax  
movl $1024, %ebx  
int $128
```

In Linux, 45 indicates request for more heap memory

Causes trap

Request is for 1024 bytes
System-Level Functions

- For convenience, traps are wrapped in **system-level functions**

- Example: To request more heap memory...

```
/* unistd.h */
void *sbrk(intptr_t increment);
...

/* unistd.s */
Defines sbrk() in assembly lang
Executes int instruction
...

/* client.c */
sbrk(1024);
...
```

`sbrk()` is a system-level function

A call of a system-level function, that is, a **system call**

See Appendix for list of some Linux system-level functions

Processes

- **Program**
  - Executable code

- **Process**
  - An instance of a program in execution

- **Every program runs in the context of some process**

- **Context** consists of:
  - Process ID
  - Address space
    - TEXT, RODATA, DATA, BSS, HEAP, and STACK
  - Processor state
    - EIP, EFLAGS, EAX, EBX, etc. registers
  - Etc.
Significance of Processes

- **Process** is a key abstraction in computer science
- The process abstraction provides application programs with two key illusions:
  - Private control flow
  - Private address space

Private Control Flow: Illusion

Hardware and OS give each application process the illusion that it is the only process running on the CPU. Multiple processes appear to run “at the same time.”
**Private Control Flow: Reality**

All application processes -- and the OS process -- share the same CPU(s)
Only one process can run on the CPU at any instant

**Context Switches**

- **Context switch**
  - The activity whereby the OS assigns the CPU to a different process
  - Occurs during exception handling, at discretion of OS

- **Exceptions can be caused**:
  - Synchronously, by application pgm (trap, fault, abort)
  - Asynchronously, by external event (interrupt)
  - **Asynchronously, by hardware timer**
    - So no process can dominate the CPUs

- **Exceptions and context switches are mechanisms that enable the illusion of private control flow**
Context Switch Details

- **Context**
  - State the OS needs to restart a preempted process

- **Context switch**
  - Save the context of current process
  - Restore the saved context of some previously preempted process
  - Pass control to this newly restored process

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When Should OS Do Context Switch?

- **When a process is stalled waiting for I/O**
  - Better utilize the CPU, e.g., while waiting for disk access
  
  1: CPU I/O CPU I/O CPU I/O
  2: CPU I/O CPU I/O CPU I/O

- **When a process has been running for a while**
  - Sharing on a fine time scale to give each process the illusion of running on its own machine
  - Trade-off efficiency for a finer granularity of fairness
Life Cycle of a Process

- **Running**: instructions are being executed
- **Waiting**: waiting for some event (e.g., I/O finish)
- **Ready**: ready to be assigned to a processor

Context Details

- What does the OS need to save/restore during a context switch?
  - Process state
    - New, ready, waiting, terminated
  - CPU registers
    - EIP, EFLAGS, EAX, EBX, …
  - I/O status information
    - Open files, I/O requests, …
  - Memory management information
    - Page tables (see “Virtual Memory” lecture)
  - Accounting information
    - Time limits, group ID, …
  - CPU scheduling information
    - Priority, queues
Private Address Space: Illusion

- Hardware and OS give each application process the illusion that it is the only process using memory.
- Addresses start at 0 and go to FFFFFFFF…

Private Address Space: Reality

- All processes use the same physical memory.
- A given physical address can’t hold data for multiple processes.
- Hardware and OS provide application programs with a virtual view of memory, i.e., virtual memory (VM).
Private Address Space Details

- Exceptions (specifically, page faults) are the mechanism that enables the illusion of private address spaces

- See the Virtual Memory lecture for details

Summary

- **Exception**: an abrupt change in control flow
- **Interrupts**: asynchronous; e.g. I/O completion, hardware timer
- **Traps**: synchronous; e.g. app pgm requests more heap memory, I/O
- **Faults**: synchronous; e.g. seg fault
- **Aborts**: synchronous; e.g. parity error

- **Process**: An instance of a program in execution
  - Hardware and OS use exceptions to give each process the illusion of:
    - Private control flow (reality: context switches)
    - Private address space (reality: virtual memory)
### Appendix: System-Level Functions

**Linux system-level functions for I/O management**

<table>
<thead>
<tr>
<th>Number</th>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td><code>read()</code></td>
<td>Read data from file descriptor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Called by <code>getchar()</code>, <code>scanf()</code>, etc.</td>
</tr>
<tr>
<td>4</td>
<td><code>write()</code></td>
<td>Write data to file descriptor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Called by <code>putchar()</code>, <code>printf()</code>, etc.</td>
</tr>
<tr>
<td>5</td>
<td><code>open()</code></td>
<td>Open file or device</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Called by <code>fopen()</code></td>
</tr>
<tr>
<td>6</td>
<td><code>close()</code></td>
<td>Close file descriptor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Called by <code>fclose()</code></td>
</tr>
<tr>
<td>8</td>
<td><code>creat()</code></td>
<td>Open file or device for writing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Called by <code>fopen(…, &quot;w&quot;)</code></td>
</tr>
</tbody>
</table>

Described in *I/O Management* lecture

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### Appendix: System-Level Functions

**Linux system-level functions for process management**

<table>
<thead>
<tr>
<th>Number</th>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><code>exit()</code></td>
<td>Terminate the process</td>
</tr>
<tr>
<td>2</td>
<td><code>fork()</code></td>
<td>Create a child process</td>
</tr>
<tr>
<td>7</td>
<td><code>waitpid()</code></td>
<td>Wait for process termination</td>
</tr>
<tr>
<td>7</td>
<td><code>wait()</code></td>
<td>(Variant of previous)</td>
</tr>
<tr>
<td>11</td>
<td><code>exec()</code></td>
<td>Execute a program in current process</td>
</tr>
<tr>
<td>20</td>
<td><code>getpid()</code></td>
<td>Get process id</td>
</tr>
</tbody>
</table>

Described in *Process Management* lecture
## Appendix: System-Level Functions

### Linux system-level functions for I/O redirection and inter-process communication

<table>
<thead>
<tr>
<th>Number</th>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>41</td>
<td><code>dup()</code></td>
<td>Duplicate an open file descriptor</td>
</tr>
<tr>
<td>42</td>
<td><code>pipe()</code></td>
<td>Create a channel of communication between processes</td>
</tr>
<tr>
<td>63</td>
<td><code>dup2()</code></td>
<td>Close an open file descriptor, and duplicate an open file descriptor</td>
</tr>
</tbody>
</table>

Described in *Process Management* lecture

### Linux system-level functions for dynamic memory management

<table>
<thead>
<tr>
<th>Number</th>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td><code>brk()</code></td>
<td>Move the program break, thus changing the amount of memory allocated to the HEAP</td>
</tr>
<tr>
<td>45</td>
<td><code>sbrk()</code></td>
<td>(Variant of previous)</td>
</tr>
<tr>
<td>90</td>
<td><code>mmap()</code></td>
<td>Map a virtual memory page</td>
</tr>
<tr>
<td>91</td>
<td><code>munmap()</code></td>
<td>Unmap a virtual memory page</td>
</tr>
</tbody>
</table>

Described in *Dynamic Memory Management* lectures
## Appendix: System-Level Functions

### Linux system-level functions for signal handling

<table>
<thead>
<tr>
<th>Number</th>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td><code>alarm()</code></td>
<td>Deliver a signal to a process after a specified amount of wall-clock time</td>
</tr>
<tr>
<td>37</td>
<td><code>kill()</code></td>
<td>Send signal to a process</td>
</tr>
<tr>
<td>67</td>
<td><code>sigaction()</code></td>
<td>Install a signal handler</td>
</tr>
<tr>
<td>104</td>
<td><code>setitimer()</code></td>
<td>Deliver a signal to a process after a specified amount of CPU time</td>
</tr>
<tr>
<td>126</td>
<td><code>sigprocmask()</code></td>
<td>Block/unblock signals</td>
</tr>
</tbody>
</table>

Described in **Signals** lecture