Exceptions and Processes

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April 18, 2017

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

Time

<startup>
$inst_1$
$inst_2$
$inst_3$
…
$inst_n$
<shutdown>

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Altering the Control Flow

- Up to now: two mechanisms for changing control flow:
  - Jumps and branches
  - Call and return

  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"

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Exceptional Control Flow

- Exists at all levels of a computer system
- Low level mechanisms
  - 1. **Exceptions**
    - Change in control flow in response to a system event (i.e., change in system state)
    - Implemented using combination of hardware and OS software
- Higher level mechanisms
  - 2. **Process context switch**
    - Implemented by OS software and hardware timer
    - Overlaps execution with useful work from other process
  - 3. **Signals**
    - Implemented by OS software

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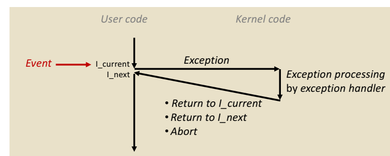
Today

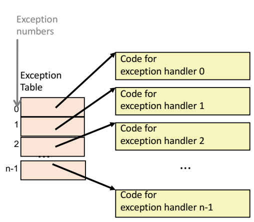
- Exceptional Control Flow
- Exceptions
- Processes
- Process Control

Exceptions

- An *exception* is a transfer of control to the OS *kernel* in response to some *event* (i.e., change in processor state)
  - Kernel is the memory-resident part of the OS
  - Examples of events: Divide by 0, arithmetic overflow, page fault, I/O request completes, typing Ctrl-C



Exception Tables

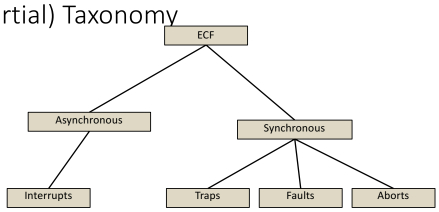


- Each type of event has a unique exception number k
- k = index into exception table (a.k.a. interrupt vector)
- Handler k is called each time exception k occurs

Running the Exception Handler

- Hardware saves the old program counter
- Identifies location of exception handler via table
- Then jumps to that location
- OS code can save registers, etc.

(partial) Taxonomy



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Asynchronous Exceptions (Interrupts)

- Caused by events external to the processor
  - Indicated by setting the processor's *interrupt pin*
  - Handler returns to "next" instruction
- Examples:
  - Timer interrupt
    - Every few ms, an external timer chip triggers an interrupt
    - Used by the kernel to take back control from user programs
  - I/O interrupt from external device
    - Hitting Ctrl-C at the keyboard
    - Arrival of a packet from a network
    - Arrival of data from a disk

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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: illegal instruction, parity error, machine check
    - Aborts current program

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Note on Terminology

- Real world does not use consistent terms for exceptions
- We will follow textbook's terms in this course
- However, in real world:
  - 'interrupt' meaning what we call 'exception' (x86)
  - 'exception' meaning what we call 'fault'
  - 'fault' meaning what we call 'fault' or 'abort' (ARM)
  - … and more

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System Calls

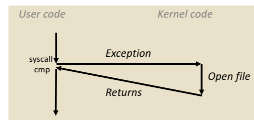
- **Each x86-64 system call has a unique ID number**
- **Examples:**

Number	*Name*	*Description*
0	`read`	Read file
1	`write`	Write file
2	`open`	Open file
3	`close`	Close file
4	`stat`	Get info about file
57	`fork`	Create process
59	`execve`	Execute a program
60	`_exit`	Terminate process
62	`kill`	Send signal to process

System Call Example: Opening File

- User calls: `open(filename, options)`
- Calls `__open` function, which invokes system call instruction `syscall`

```
00000000000e5d70 <__open>:
...
e5d79:   b8 02 00 00 00      mov  $0x2,%eax  # open is syscall #2
e5d7e:   0f 05               syscall         # Return value in %rax
e5d80:   48 3d 01 f0 ff ff   cmp  $0xfffffffffffff001,%rax
...
e5dfa:   c3                  retq
```



- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

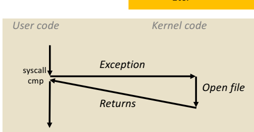
System Call

- User calls: `open(fi`
- Calls `__open` functic

```
00000000000e5d70 <
...
e5d79:   b8 02 00
e5d7e:   0f 05
e5d80:   48 3d 01
...
e5dfa:   c3
```

Almost like a function call
- Transfer of control
- On return, executes next instruction
- Passes arguments using calling convention
- Gets result in `%rax`

One Important exception!
- Executed by Kernel
- Different set of privileges
- And other differences:
  - E.g., "address" of "function" is in `%rax`
  - Uses `errno`
  - Etc.



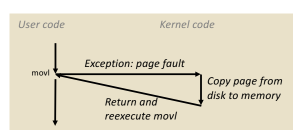
- `%rax` contains syscall number
- Other arguments in `%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9`
- Return value in `%rax`
- Negative value is an error corresponding to negative `errno`

Fault Example: Page Fault

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

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

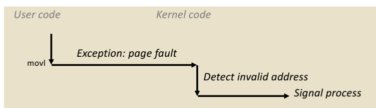
```
80483b7:      c7 05 10 9d 04 08 0d   movl   $0xd,0x8049d10
```



Fault Example: Invalid Memory Reference

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

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



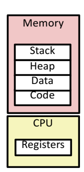
- Sends `SIGSEGV` signal to user process
- User process exits with "segmentation fault"

Today

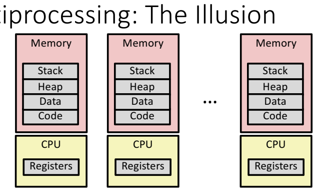
- Exceptional Control Flow
- Exceptions
- Processes
- Process Control

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
    - Provided by kernel mechanism called *context switching*
  - ***Private address space***
    - Each program seems to have exclusive use of main memory.
    - Provided by kernel mechanism called *virtual memory*

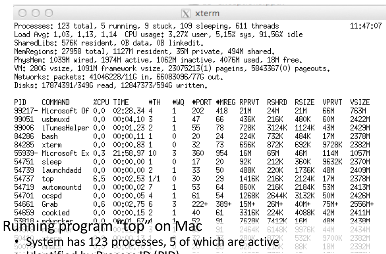


Multiprocessing: The Illusion



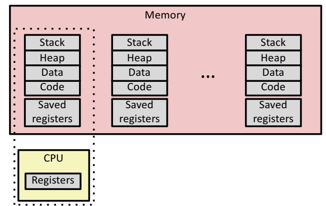
- Computer runs many processes simultaneously
  - Applications for one or more users
    - Web browsers, email clients, editors, …
  - Background tasks
    - Monitoring network & I/O devices

Multiprocessing Example



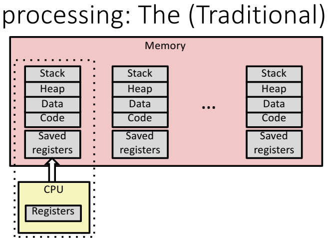
- Running program "top" on Mac
  - System has 123 processes, 5 of which are active
  - Identified by Process ID (PID)

Multiprocessing: The (Traditional) Reality



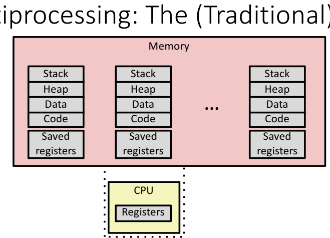
- Single processor executes multiple processes concurrently
  - Process executions interleaved (multitasking)
  - Address spaces managed by virtual memory system (later in course)
  - Register values for nonexecuting processes saved in memory

Multiprocessing: The (Traditional) Reality



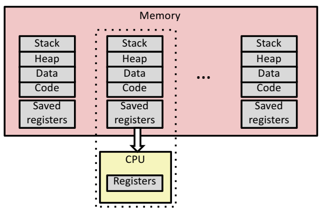
- Save current registers in memory

Multiprocessing: The (Traditional) Reality



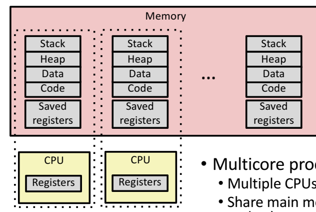
- Schedule next process for execution

Multiprocessing: The (Traditional) Reality



- Load saved registers and switch address space (context switch)

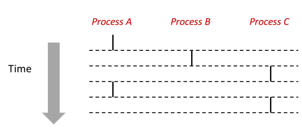
Multiprocessing: The (Modern) Reality



- Multicore processors
  - Multiple CPUs on single chip
  - Share main memory (and some caches)
  - Each can execute a separate process
    - Scheduling of processors onto cores done by kernel

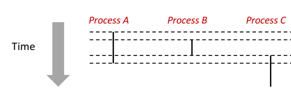
Concurrent Processes

- Each process is a logical control flow.
- 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



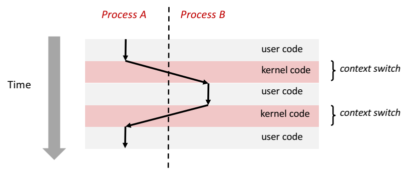
User View of Concurrent Processes

- 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

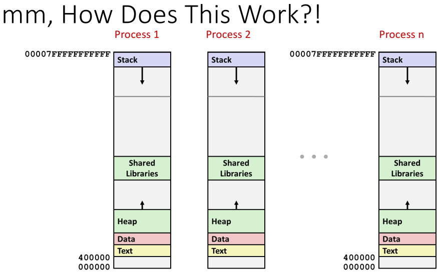
- Processes are managed by a shared chunk of memory-resident OS code called the *kernel*
  - Important: the kernel is not a separate process, but rather runs as part of some existing process.
- Control flow passes from one process to another via a *context switch*



Context

- all registers values
- %rax %rbx, …, %rsp, …
- condition codes
- program counter
- i.e. all visible state in your CPU except memory

Hmmm, How Does This Work?!



Solution: Virtual Memory (next lecture)

Context

- all registers values
- %rax %rbx, …, %rsp, …
- condition codes
- program counter
- address space: map from program to real addresses

Today

- Exceptional Control Flow
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System Call Error Handling

- On error, Linux system-level functions typically return -1 and set global variable `errno` to indicate cause.
- Hard and fast rule:
  - You must check the return status of every system-level function
  - Only exception is the handful of functions that return `void`
- Example:

```
if ((pid = fork()) < 0) {
    fprintf(stderr, "fork error: %s\n", strerror(errno));
    exit(-1);
}
```


Error-reporting functions

- Can simplify somewhat using an *error-reporting function*:

```
void unix_error(char *msg) /* Unix-style error */
{
    fprintf(stderr, "%s: %s\n", msg, strerror(errno));
    exit(-1);
}
```

```
if ((pid = fork()) < 0)
    unix_error("fork error");
```


Error-handling Wrappers

- We simplify the code we present to you even further by using error-handling wrappers:

```
pid_t Fork(void)
{
    pid_t pid;

    if ((pid = fork()) < 0)
        unix_error("Fork error");
    return pid;
}
```

```
pid = Fork();
```

- NOT what you generally want to do in a real application

Creating and Terminating Processes

From a programmer's perspective, we can think of a process as being in one of three states

- Running
  - Process is either executing, or waiting to be executed and will eventually be *scheduled* (i.e., chosen to execute) by the kernel
- Stopped
  - Process execution is *suspended* and will not be scheduled until further notice (next lecture when we study signals)
- Terminated
  - Process is stopped permanently

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Terminating Processes

- Process becomes terminated for one of three reasons:
  - Receiving a signal whose default action is to terminate (next lecture)
  - Returning from the **`main`** routine
  - Calling the **`exit`** function
- `void exit(int status)`
  - Terminates with an *exit status* of **`status`**
  - Convention: normal return status is 0, nonzero on error
  - Another way to explicitly set the exit status is to return an integer value from the main routine
- `exit` is called once but never returns.

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Creating Processes

- *Parent process* creates a new running *child process* by calling `fork`
- `int fork(void)`
  - Returns 0 to the child process, child's PID to parent process
  - Child is *almost* identical to parent:
    - Child get an identical (but separate) copy of the parent's virtual address space.
    - Child has a different PID than the parent
- `fork` is interesting (and often confusing) because it is called *once* but returns *twice*

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`fork` Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    return 0;
}
```

fork.c

- **Call once, return twice**
- **Concurrent execution**
  - Can't predict execution order of parent and child

```
linux> ./fork
parent: x=0
child : x=2
```

```
linux> ./fork
child : x=2
parent: x=0
```

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fork Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    printf("parent: x=%d\n", --x);
    return 0;
}
```

```
linux> ./fork
parent: x=0
child : x=2
parent: x=-1
child : x=3
```

- **Call once, return twice**
- **Concurrent execution**
  - Can't predict execution order of parent and child
- **Duplicate but separate address space**
  - x has a value of 1 when fork returns in parent and child
  - Subsequent changes to x are independent

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fork Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    return 0;
}
                                    fork.c
```

```
linux> ./fork
parent: x=0
child : x=2
```

- **Call once, return twice**
- **Concurrent execution**
  - Can't predict execution order of parent and child
- **Duplicate but separate address space**
  - x has a value of 1 when fork returns in parent and child
  - Subsequent changes to x are independent
  - stdout is the same in both parent and child

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Modeling fork with Process Graphs

- A *process graph* is a useful tool for capturing the partial ordering of statements in a concurrent program:
  - Each vertex is the execution of a statement
  - a -> b means a happens before b
  - Edges can be labeled with current value of variables

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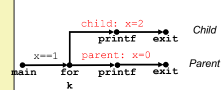
Process Graph Example

```
int main(int argc, char** argv)
{
    pid_t pid;
    int x = 1;

    pid = Fork();
    if (pid == 0) {  /* Child */
        printf("child : x=%d\n", ++x);
        return 0;
    }

    /* Parent */
    printf("parent: x=%d\n", --x);
    return 0;
}
                                    fork.c
```



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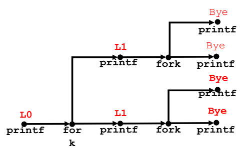
fork Example: Two consecutive forks

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



Feasible output:	Infeasible output:
L0	L0
L1	Bye
Bye	L1
Bye	Bye
L1	L1
Bye	Bye
Bye	Bye

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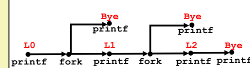
fork Example: Nested forks in parent

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



Feasible output:	Infeasible output:
L0	L0
L1	Bye
Bye	L1
Bye	Bye
L2	Bye
Bye	L2

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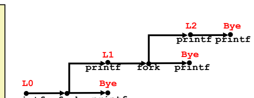
fork Example: Nested forks in children

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



Feasible output:	Infeasible output:
L0	L0
Bye	Bye
L1	L1
L2	Bye
Bye	Bye
Bye	L2

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execve: Loading and Running Programs

- `int execve(char *filename, char *argv[], char *envp[])`
- Loads and runs in the current process:
  - Executable file **`filename`**
    - Can be object file or script file (e.g., `#!/bin/bash`)
  - ...with argument list **`argv`**
    - By convention **`argv[0]==filename`**
  - ...and environment variable list **`envp`**
    - "name=value" strings (e.g., `USER=droh`)
- Overwrites code, data, and stack
  - Retains PID, open files and signal context
- Called once and never returns
  - ...except if there is an error

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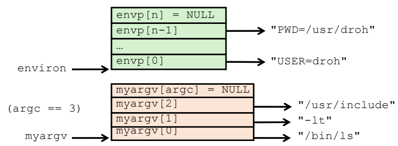
`execve` Example

- Execute "`/bin/ls -lt /usr/include`" in child process using current environment:




```
if ((pid = Fork()) == 0) {   /* Child runs program */
    if (execve(myargv[0], myargv, environ) < 0) {
        printf("%s: Command not found.\n", myargv[0]);
        exit(1);
    }
}
```

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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 any single core
  - Each process appears to have total control of processor + private memory space

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Summary (cont.)

- Spawning processes
  - Call `fork`
  - One call, two returns
- Process completion
  - Call `exit`
  - One call, no return
- Loading and running programs
  - Call `execve` (or variant)
  - One call, (normally) no return

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Exceptions and Processes

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April 18, 2017