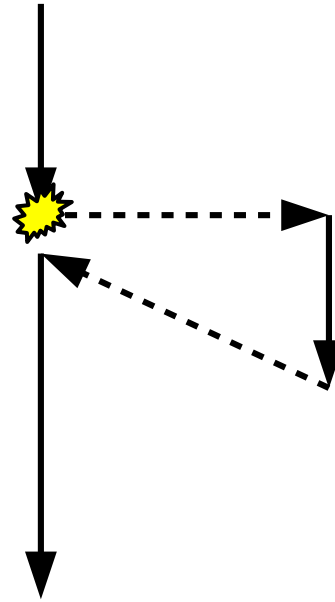


CS 261 Fall 2023

Mike Lam, Professor



Exceptional Control Flow and Processes

Exceptional control flow

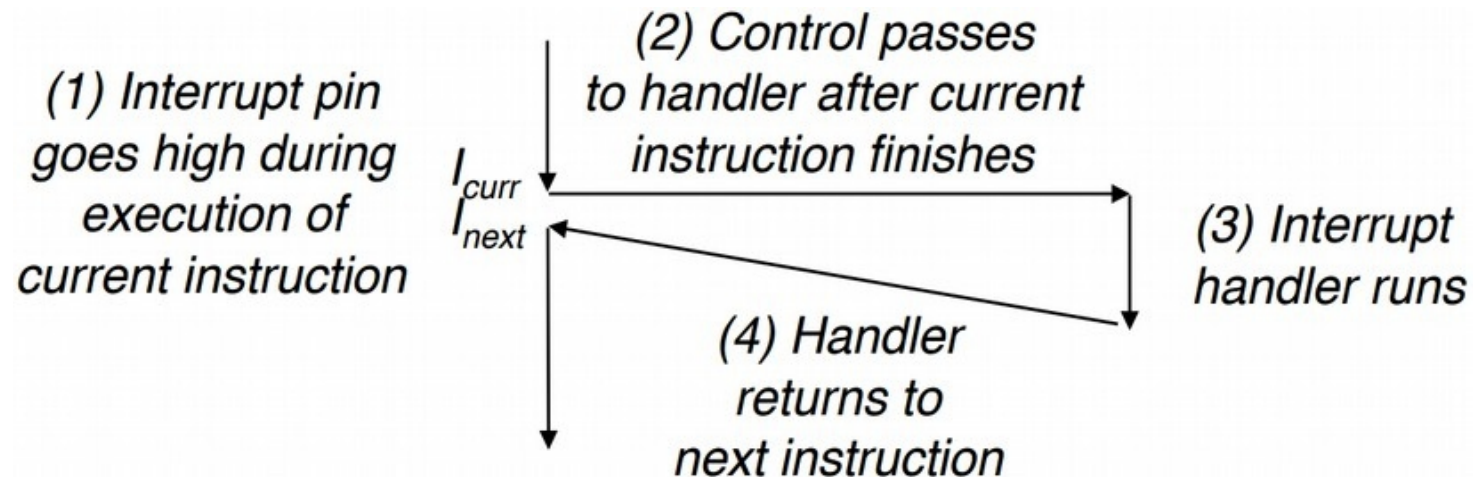
- Most control flow is sequential
 - Minor exceptions: jumps and procedure calls
 - Caused by changes in internal program state (and thus predictable)
 - However, we have also seen violations of this rule
 - Control flow changes in response to external factors
 - (e.g., exceptions in Java or segfaults in C)

Exceptional control flow

- **Exceptions** violate sequential control flow
 - Unconditional transfer to another location in code
 - Partially implemented in hardware, partially in software
 - Often the result of an error condition
 - But not necessarily – we can also use exceptions for time-sharing!
 - Categorized as **asynchronous** vs. **synchronous**
 - Whether it happens as a result of an external source or not
 - Categorized by **recovery** possibility
 - Always returns, sometimes returns, or never returns
 - If recovery is possible, further categorized by **recovery location**
 - Same instruction vs. next instruction

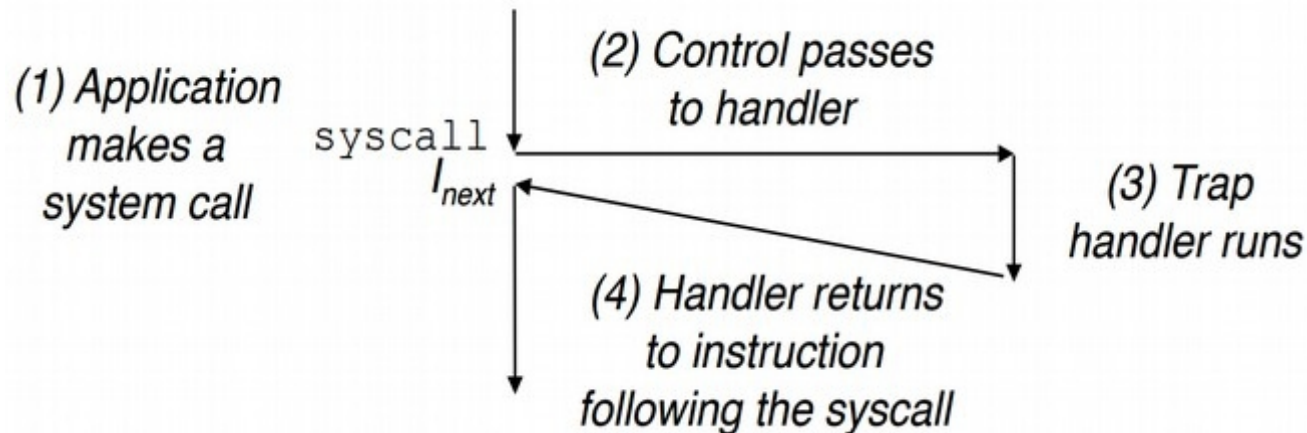
Interrupts

- **Interrupt**: communication mechanism
 - Asynchronous, always returns to next instruction
 - “Interrupts” execution as the result of an outside event
 - Example: an I/O operation has finished
 - Example: a process has finished its time slice



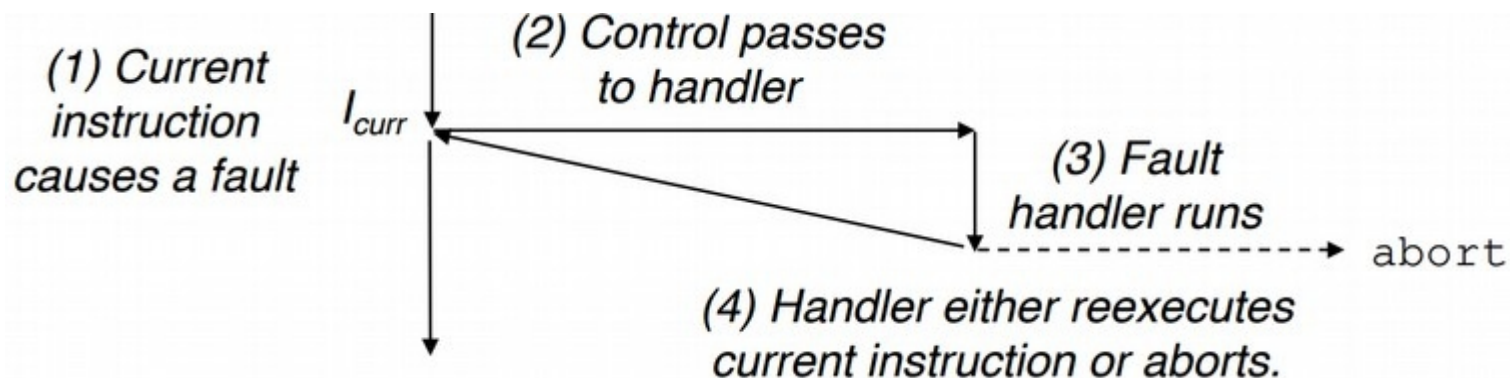
Traps

- **Trap**: intentional control transfer to kernel
 - Synchronous, (almost) always returns to next instruction
 - Like a function call, except the target runs in kernel mode
 - Also referred to as **system calls**
 - x86-64 instruction “`syscall`” w/ ID in `%rax`
 - Parameters are passed in `%rdi-%r9`; return value stored in `%rax`
 - Well-known standards (e.g., POSIX)



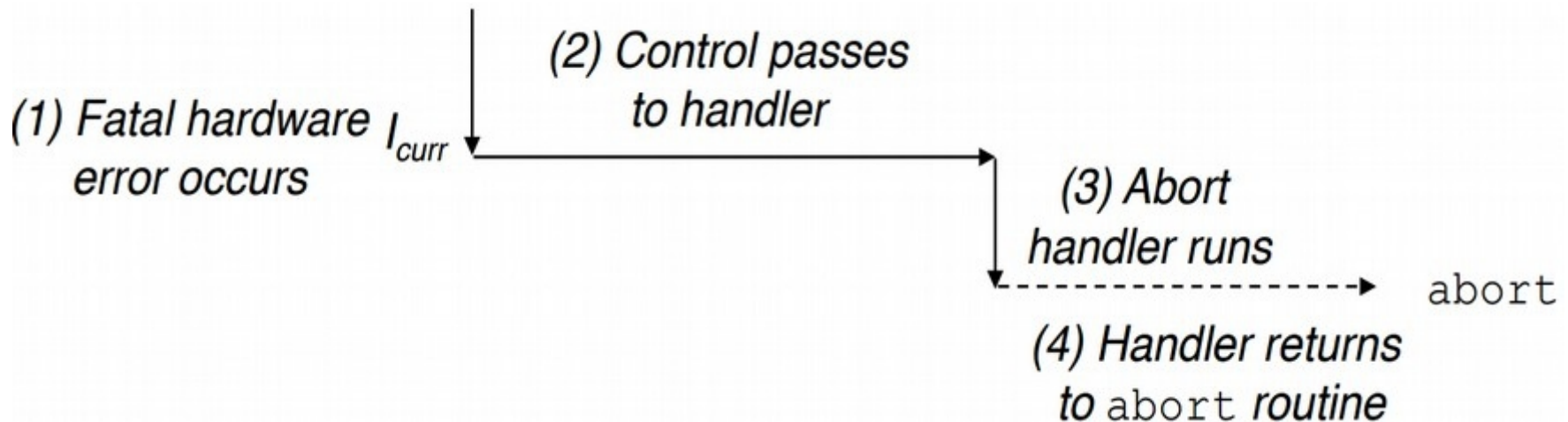
Faults

- **Fault**: error that is potentially correctable
 - Synchronous, sometimes returns to same instruction
 - **Page fault** (#14): virtual memory cache miss
 - Recoverable – read the required page from slower memory
 - **Segmentation fault** (#13): invalid memory access
 - Not recoverable – undefined behavior
 - **Divide-by-zero** error (#0)
 - Not recoverable – undefined result



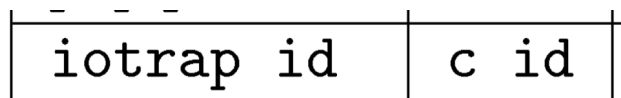
Aborts

- **Abort**: unrecoverable error
 - Synchronous, never returns
 - Machine check (#18): fatal hardware error



System calls

- In P4: `iotrap` instruction is a system call
 - Performs I/O operations using `stdin` and `stdout`
 - Input: single character or decimal integer
 - Destination memory address in `%rdi`
 - Output: single character, decimal integer, or string
 - Source memory address in `%rsi`



In P4, you'll simulate these system calls using standard C functions like `printf` and `scanf`

| Trap IDs: | |
|----------------------|---|
| <code>charout</code> | 0 |
| <code>charin</code> | 1 |
| <code>decout</code> | 2 |
| <code>decin</code> | 3 |
| <code>strout</code> | 4 |
| <code>flush</code> | 5 |

System calls

- Some of the functions we've been using in C are actually wrappers for a system call (or multiple system calls)
 - `fopen`, `fread`, `malloc`
 - System calls: `open` (id=2), `read` (id=0), `mmap` (id=9)
 - System call interfaces are defined by standards
 - `SysV` vs. `POSIX` (IEEE standard: <http://pubs.opengroup.org/onLinepubs/9699919799/>)
 - In general, system call wrappers are called **system-level functions**
 - It is important to check for errors after calling these functions
 - Textbook uses wrapper functions (e.g., "Open") for this

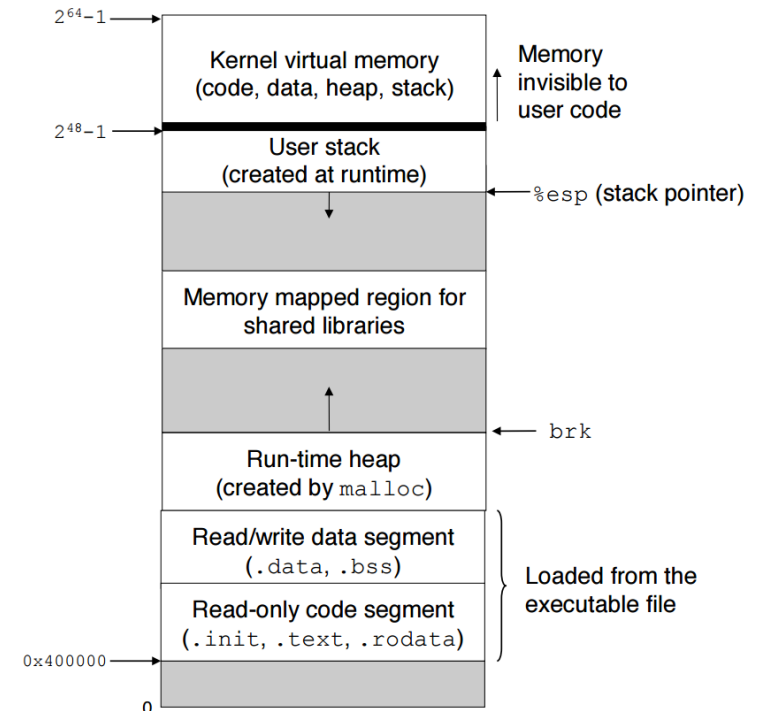
```
int fd = open("file.txt", O_RDONLY);
if (fd < 0) {
    fprintf(stderr, "Error opening file: %s\n", strerror(errno));
    exit(EXIT_FAILURE);
}
```

Textbook notes

- Error handling is important!
 - Textbook provides error-handling wrappers; this is good practice
 - However, we'll omit error handling to simplify examples
- `envp` parameter to `main()` is not standard
 - `getenv()` is the only environmental mechanism defined by the POSIX C99 standard

Processes

- Exceptions enable **processes**
 - **Process**: a running program
 - One program, (possibly) many processes
 - Abstraction provided by OS kernel
 - One kernel, many user processes
 - Shared portion of virtual address space
 - Kernel memory (above stack)
 - This region is not visible to user programs
 - Toggle control (kernel and processes)
 - **Interrupts** – cycle through processes ("**round robin**")
 - **Traps** – function call from processes into kernel ("**syscalls**")
 - **Faults** – software error (recover or abort)
 - **Aborts** – stop process without taking down the machine

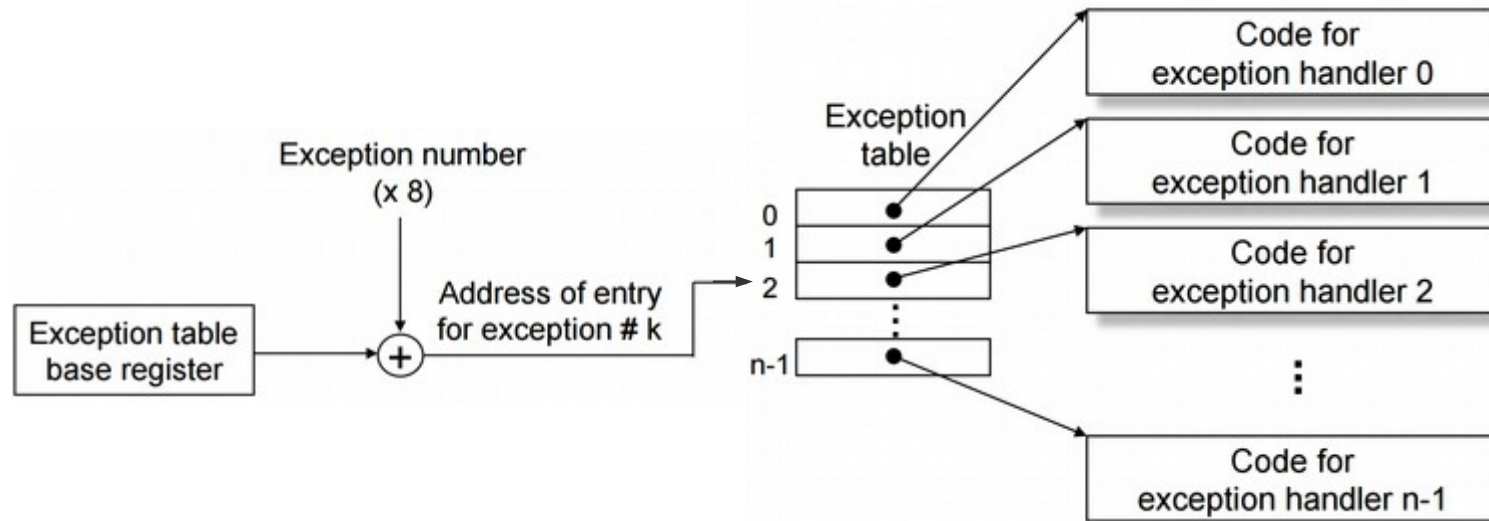


Implementing processes

- Processes are implemented by the OS kernel
 - Kernel maintains data structure w/ process information
 - Including an ID for each process (**pid**)
 - Multitasking via exceptional control flow
 - Periodic interrupt to switch processes
 - Called **round-robin** switching
 - **Context switch**: swapping current process
 - Save context of old process
 - Restore context of new process
 - Pass control to the restored process

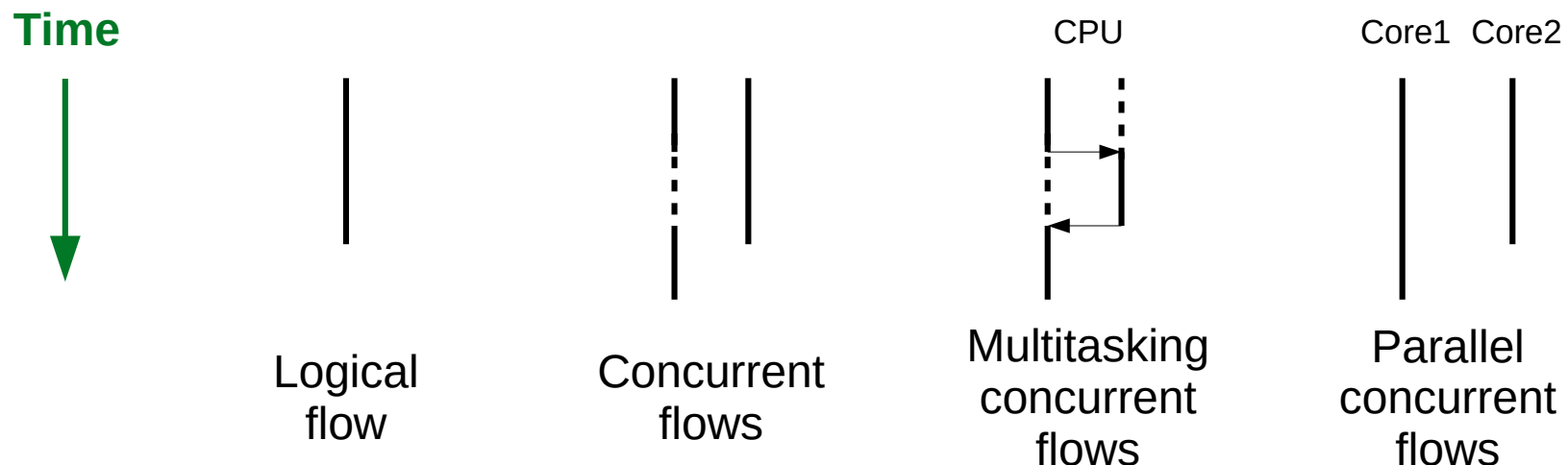
Exception implementation

- Kernel **exception table**
 - Every exception is assigned a unique ID
 - Table translates exception ID to handler address



Processes

- **Process**: instance of an executing program
 - Independent single logical flow and private virtual address space
- **Logical flow**: sequence of executed instructions
- **Concurrency**: overlapping logical flows
- **Multitasking**: processes take turns
- **Parallelism**: concurrent flows on separate CPUs/cores

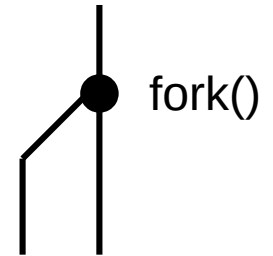


Process creation

- The `fork()` syscall creates a new process
 - Initializes new entry in the kernel data structures
 - **To user code, the function call returns twice**
 - Once for original process (**parent**) and once for new process (**child**)
 - Returns 0 in child process
 - Returns child pid in parent process
 - Both processes will continue executing concurrently
 - Parent and child have separate address spaces
 - Child's space is a duplicate of parent's at the time of the fork
 - They will diverge after the fork!
 - Child inherits parent's environment and open files

Process creation example

- Fork returns twice!



```
int main ()
{
    printf("Before fork\n");

    pid_t pid = fork();

    printf("After fork: pid=%d\n", pid);

    return 0;
}
```


Process creation example

- What does this code do?

```
int main ()
{
    printf("Before fork\n");

    pid_t pid1 = fork();

    printf("After fork: pid1=%d\n", pid1);

    pid_t pid2 = fork();

    printf("After second fork: pid1=%d pid2=%d\n", pid1, pid2);

    return 0;
}
```

Process creation example

- Fork returns twice! (every time)
 - Beware of non-determinism and I/O interleaving

```
int main ()
{
    printf("Before fork\n");

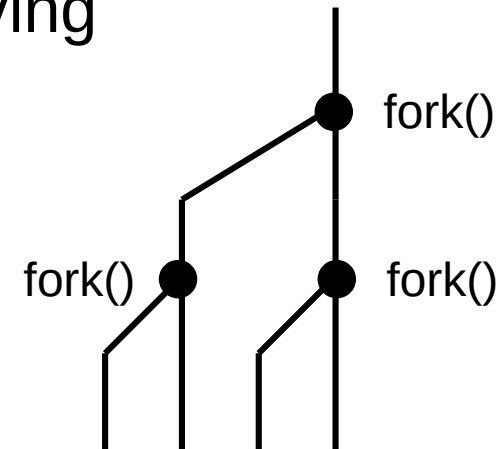
    pid_t pid1 = fork();

    printf("After fork: pid1=%d\n", pid1);

    pid_t pid2 = fork();

    printf("After second fork: pid1=%d pid2=%d\n", pid1, pid2);

    return 0;
}
```



Exercise: Modify this program to fork a total of **three** processes

Parent/child process example

- Parents can wait for children to finish

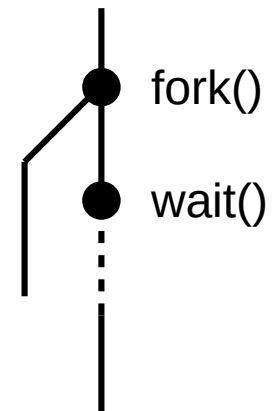
```
int main ()
{
    printf("Before fork\n");

    pid_t pid = fork();

    if (pid != 0) {        // parent
        wait(NULL);
        printf("Child has terminated.\n");
    } else {              // child
        printf("Child is running.\n");
    }

    printf("After fork: pid=%d\n", pid);

    return 0;
}
```



Process control syscalls

- **#include <stdlib.h>**
 - `getenv`: get environment variable value
 - `setenv`: change environment variable value
- **#include <sys/types.h>**
 - `pid_t`: new type for PID value
- **#include <unistd.h>**
 - `fork`: create a new process
 - `getpid`: return current process id (pid)
 - `getppid`: return parent's process id (pid)
 - `exit`: terminate current process
 - `execve`: load and run another program in the current process
 - `sleep`: suspend process for specified time period
- **#include <sys/wait.h>**
 - `waitpid`: wait for a particular child process to terminate (requires child's PID)
 - `wait`: wait for any child process to terminate

Processes and shells

- A **shell** is an interactive application-level program that launches other programs (called **jobs** or **process groups**)
 - All spawned as a result of the same command
- **Foreground** vs. **background** jobs
 - A single foreground job (interactive I/O)
 - Zero or more background jobs
 - Use '&' to start something in the background
 - Ex: `./my_prog &`
 - Use **CTRL-Z** to send foreground job to background
 - Use **CTRL-C** to interrupt the foreground job
 - **fg**: promote background job to foreground

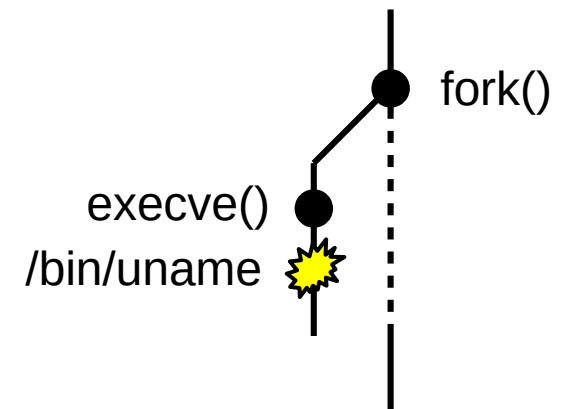
Fork/execve example

- Shells use `fork()` and `execve()` to run commands

```
int main ()
{
    printf("Before fork\n");
    pid_t pid = fork();

    if (pid != 0) {        // parent
        wait(NULL);
        printf("Child has terminated.\n");
    } else {              // child
        printf("Child is running.\n");
        char *cmd = "/bin/uname";
        char *args[] = { "uname", "-a", NULL };
        char *env[] = { NULL };
        execve(cmd, args, env);
        printf("This won't print unless an error occurs.\n");
    }

    printf("After fork: pid=%d\n", pid);
    return 0;
}
```



Linux process tools

- `ps` – list processes
 - "`ps -fe`" to see all processes on the system
 - "`ps -fu <username>`" to see your processes
- `top` – list processes, ordered by current CPU
 - Auto-updates
- `/proc` – virtual filesystem exposing kernel data structures
- `pmap` – display memory map of a process
- `strace` – prints a list of system calls from a process
 - Compile with "`-static`" to get cleaner traces