CS 261
Fall 2021

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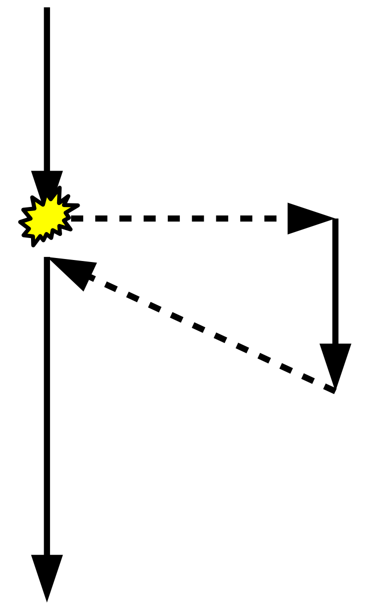


Exceptional Control Flow
and Processes

Exceptional control flow

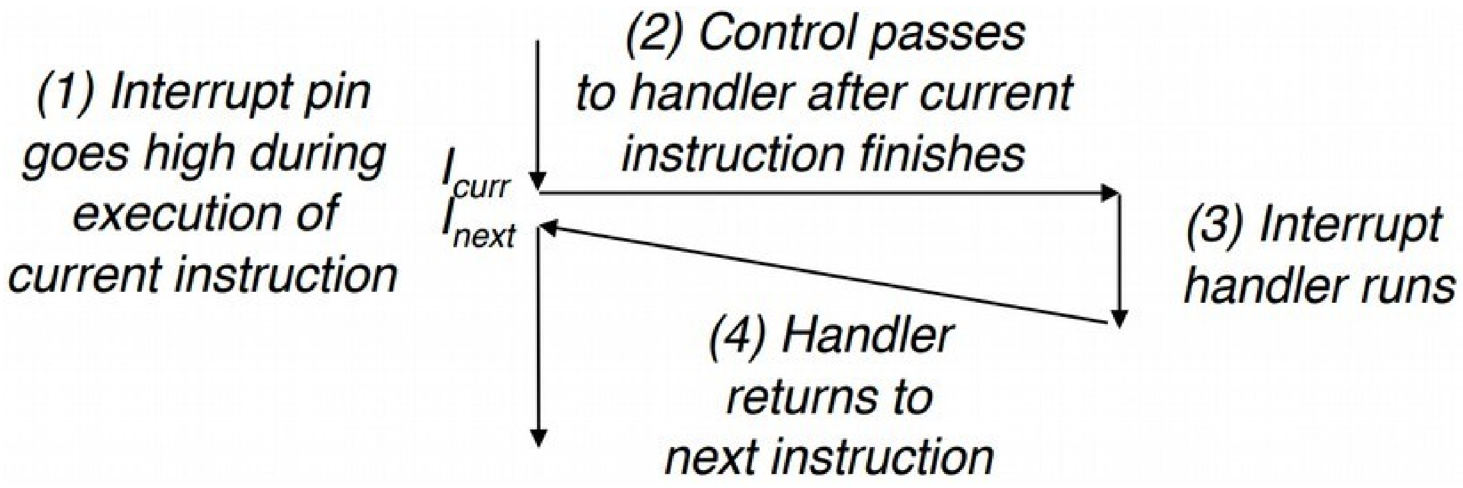
- Most control flow is sequential
  - Minor exceptions: jumps and procedure calls
    - Caused by changes in internal program state (and thus predictable)
  - However, we have also seen violations of this rule
    - Control flow changes in response to external factors
    - (e.g., exceptions in Java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

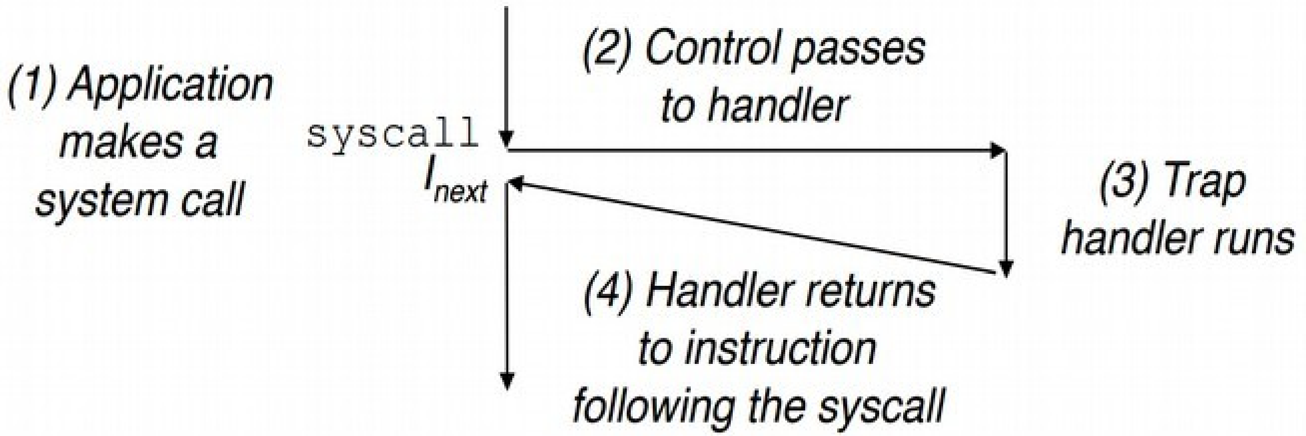
Interrupts

- 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



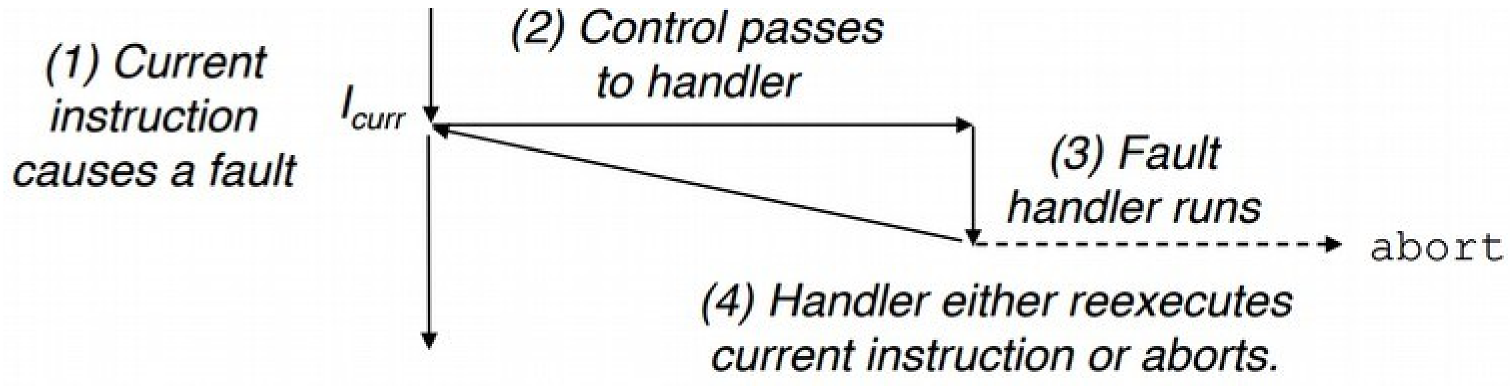
Traps

- 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)



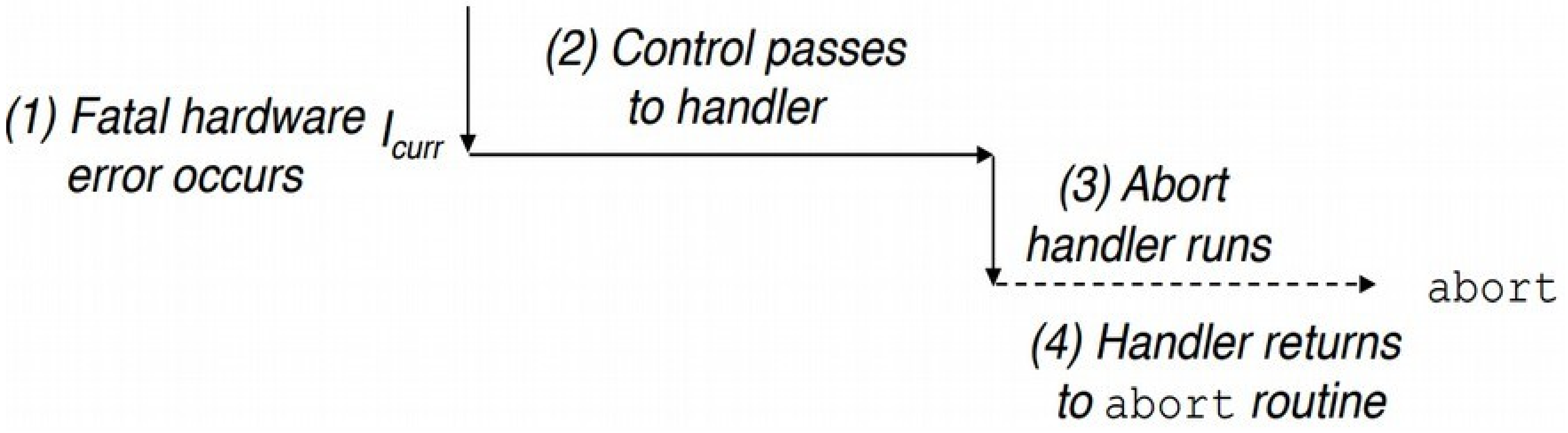
Faults

- 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`

iotrap id	c id

Trap IDs:	
charout	0
charin	1
decout	2
decin	3
strout	4
flush	5

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

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);
}
```

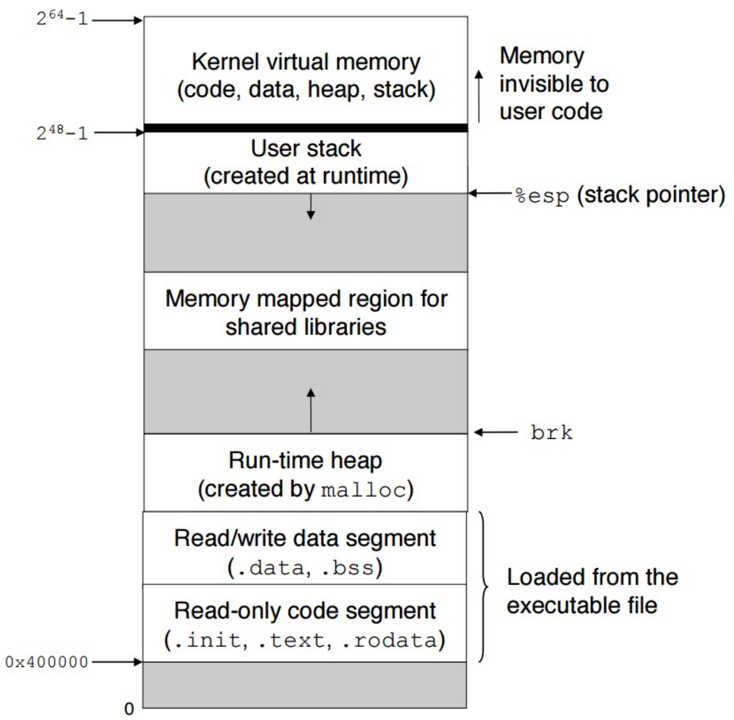
Textbook notes

- 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

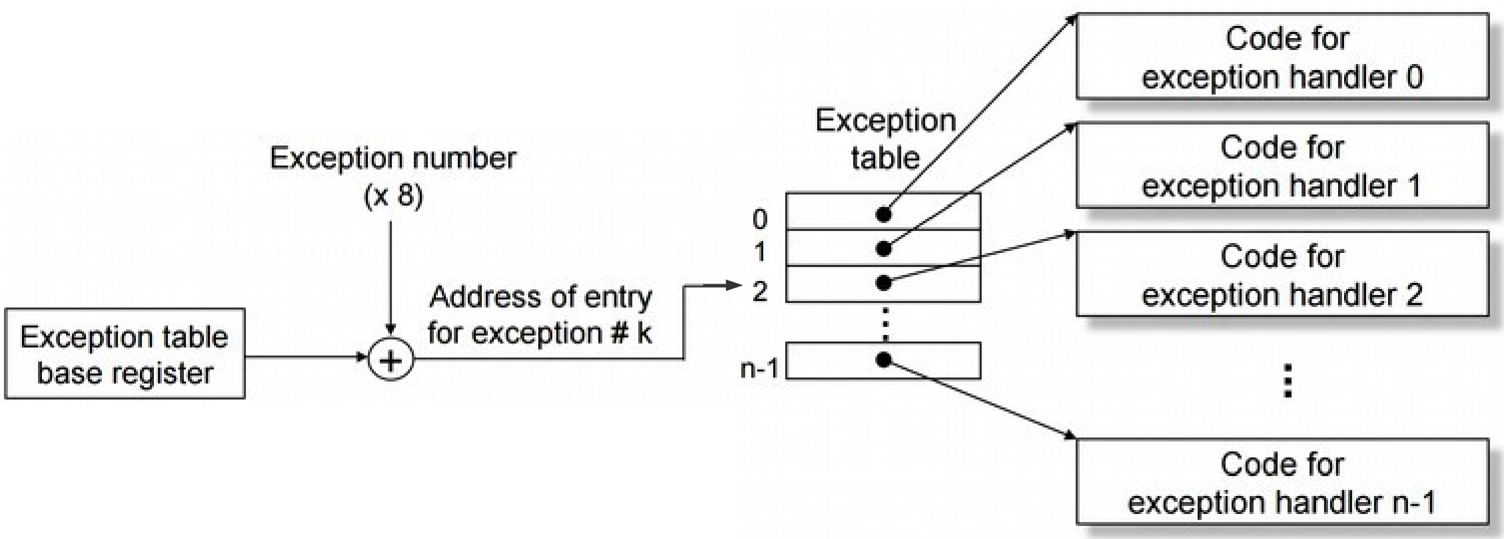


Implementing processes

- 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

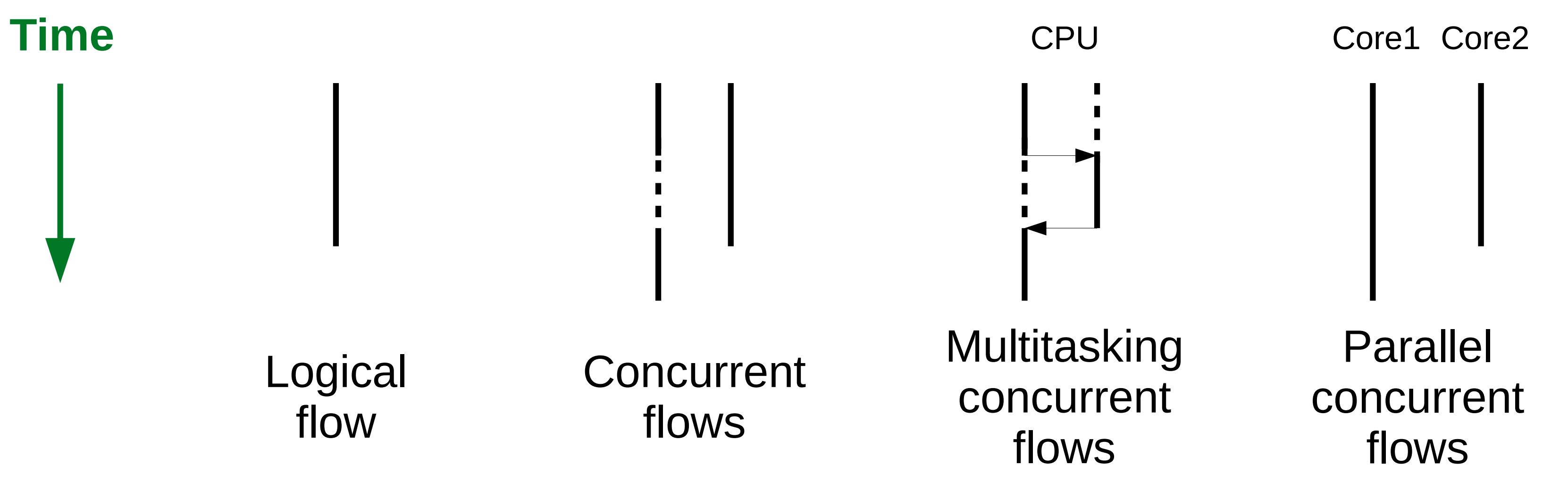
Exception implementation

- 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

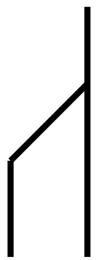


Process creation

- 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;
}
```

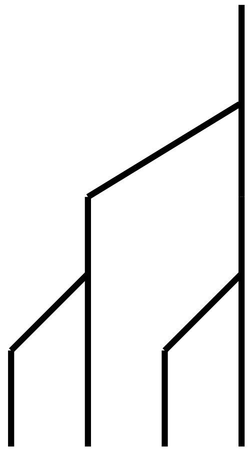
Process creation example

- 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

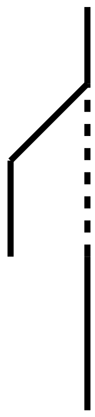


```
int main ()
{
    printf("Before fork\n");

    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

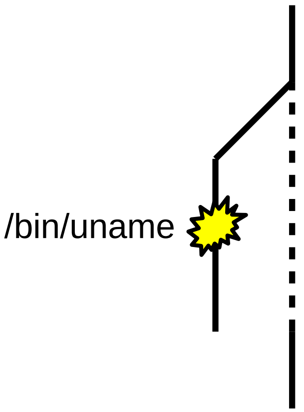
Processes and shells

- 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