Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

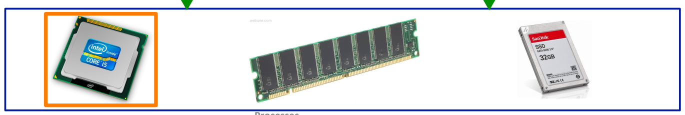
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Computer system:



- Data & addressing
- Integers & floats
- Machine code & C
- x86 assembly
- Procedures & stacks
- Arrays & structs
- Memory & caches
- **Processes**
- Virtual memory
- Memory allocation
- Java vs. C

Processes – another important abstraction

- **First some preliminaries**
  - Control flow
  - Exceptional control flow
  - Asynchronous exceptions (interrupts)
- **Processes**
  - Creating new processes
  - Fork and wait
  - Zombies

Control Flow

- So far, we've seen how the flow of control changes as a single program executes
- A CPU executes more than one program at a time though – we also need to understand how control flows across the many components of the system

- ***Exceptional* control flow is the basic mechanism used for:**
  - Transferring control between processes and OS
  - Handling I/O and virtual memory within the OS
  - Implementing multi-process applications like shells and web servers
  - Implementing concurrency

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>

Altering the Control Flow

- **Up to now: two ways to change control flow:**
  - Jumps (conditional and unconditional)
  - Call and return

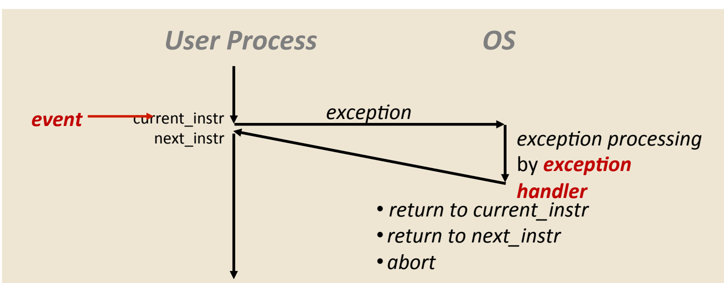
  Both react to changes in ***program state***
- **Processor also needs to react to changes in *system state***
  - user hits "Ctrl-C" at the keyboard
  - user clicks on a different application's window on the screen
  - data arrives from a disk or a network adapter
  - instruction divides by zero
  - system timer expires
- **Can jumps and procedure calls achieve this?**
  - Jumps and calls are not sufficient – the system needs mechanisms for "*exceptional*" control flow!

Exceptional Control Flow

- **Exists at all levels of a computer system**
- **Low level mechanisms**
  - Exceptions
    - change processor's in control flow in response to a system event (i.e., change in system state, user-generated interrupt)
  - Combination of hardware and OS software
- **Higher level mechanisms**
  - Process context switch
  - Signals – you'll hear about these in CSE451 and CSE466
  - Implemented by either:
    - OS software
    - C language runtime library

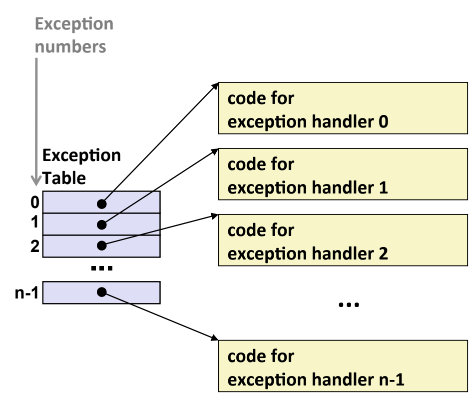
Exceptions

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



- **Examples:**
  div by 0, page fault, I/O request completes, Ctrl-C
- *How does the system know where to jump to in the OS?*

Interrupt Vectors



- **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**

basically a jump table for exceptions…

Asynchronous Exceptions (Interrupts)

- **Caused by events external to the processor**
  - Indicated by setting the processor's interrupt pin(s) (wire into CPU)
  - Handler returns to "next" instruction
- **Examples:**
  - I/O interrupts
    - hitting Ctrl-C on the keyboard
    - clicking a mouse button or tapping a touchscreen
    - arrival of a packet from a network
    - arrival of data from a disk
  - Hard reset interrupt
    - hitting the reset button on front panel
  - Soft reset interrupt
    - hitting Ctrl-Alt-Delete on a PC

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Synchronous Exceptions

- **Caused by events that occur as a result of executing an instruction:**
  - ***Traps***
    - Intentional: transfer control to OS to perform some function
    - Examples: ***system calls***, breakpoint traps, special instructions
    - Returns control to "next" instruction
  - ***Faults***
    - Unintentional but possibly recoverable
    - Examples: page faults (recoverable), segment protection faults (unrecoverable), integer divide-by-zero exceptions (unrecoverable)
    - Either re-executes faulting ("current") instruction or aborts
  - ***Aborts***
    - Unintentional and unrecoverable
    - Examples: parity error, machine check (hardware failure detected)
    - Aborts current program

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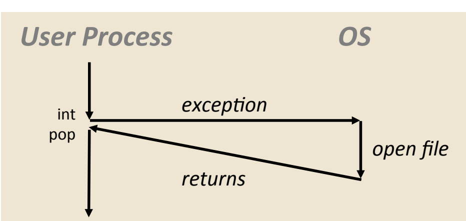
Trap Example: Opening File

- 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

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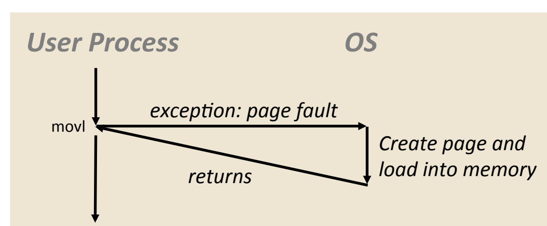
Fault Example: Page Fault

- 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
```

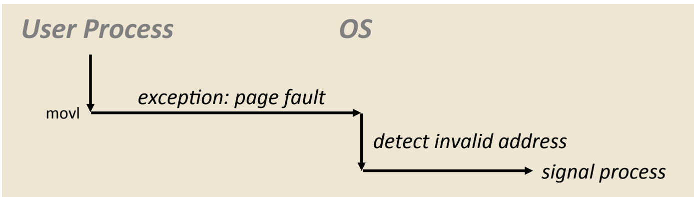


- Page handler must load page into physical memory
- Returns to faulting instruction: `mov` is executed again!
- Successful on second try

Fault Example: Invalid Memory Reference

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

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



- Page handler detects invalid address
- Sends **SIGSEGV** signal to user process
- User process exits with "segmentation fault"

Exception Table IA32 (Excerpt)

Exception Number	*Description*	*Exception Class*
0	Divide error	Fault
13	General protection fault	Fault
14	Page fault	Fault
18	Machine check	Abort
32-127	OS-defined	Interrupt or trap
128 (0x80)	System call	Trap
129-255	OS-defined	Interrupt or trap

http://download.intel.com/design/processor/manuals/253665.pdf

Summary

- **Exceptions**
  - Events that require non-standard control flow
  - Generated externally (interrupts) or internally (traps and faults)
  - After an exception is handled, one of three things may happen:
    - Re-execute the current instruction
    - Resume execution with the next instruction
    - Abort the process that caused the exception

What is a process?

- What is a program? A processor? A process?

What is a process?

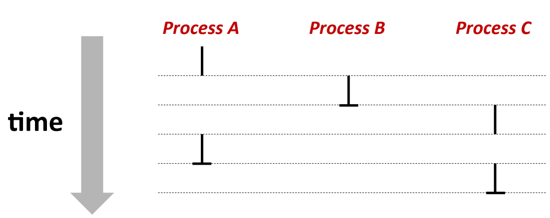
- Why are we learning about processes?
  - Processes are another *abstraction* in our computer system – the process abstraction provides an *interface* between the program and the underlying CPU + memory.
- What do processes have to do with exceptional control flow (previous lecture)?
  - Exceptional control flow is the mechanism that the OS uses to enable multiple processes to run on the same system.

Processes

- **Definition: A *process* is an instance of a running program**
  - One of the most important ideas in computer science
  - Not the same as “program” or “processor”
- **Process provides each program with two key abstractions:**
  - Logical control flow
    - Each process seems to have exclusive use of the CPU
  - Private virtual address space
    - Each process seems to have exclusive use of main memory
- **Why are these illusions important?**
- **How are these illusions maintained?**
  - Process executions interleaved (multi-tasking)
  - Address spaces managed by virtual memory system – next course topic

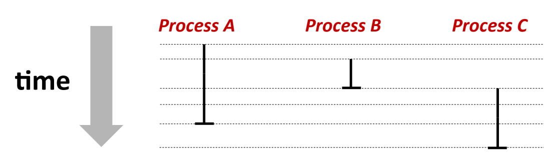
Concurrent Processes

- **Two processes *run concurrently* (are concurrent) if their instruction executions (flows) overlap in time**
- **Otherwise, they are *sequential***
- **Examples:**
  - Concurrent: A & B, A & C
  - Sequential: B & C



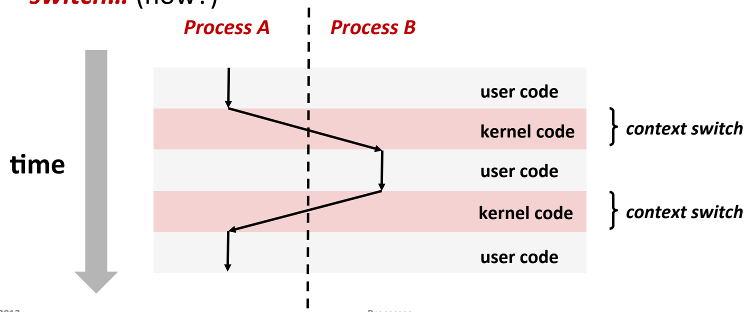
User View of Concurrent Processes

- **Control flows for concurrent processes are physically disjoint in time**
  - CPU only executes instructions for one process at a time
- **However, we can think of concurrent processes as executing in parallel**



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 a user process
- **Control flow passes from one process to another via a *context switch…*** (how?)



Creating New Processes & Programs

- **fork-exec model:**
  - **`fork()`** creates a copy of the current process
  - **`execve()`** replaces the current process' code & address space with the code for a different program
- **`fork()` and `execve()` are *system calls***
  - Note: process creation in Windows is slightly different from Linux's fork-exec model
- **Other system calls for process management:**
  - **`getpid()`**
  - **`exit()`**
  - **`wait()` / `waitpid()`**

`fork`: Creating New Processes

- **`pid_t fork(void)`**
  - creates a new process (child process) that is identical to the calling process (parent process), including all state (memory, registers, etc.)
  - returns 0 to the child process
  - returns child's process ID (`pid`) to the parent process

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

- **`fork` is unique (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");
}
```

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");
}
```


Understanding fork

Process n

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

pid = m

```
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 = 0

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


Understanding fork

Process n

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

pid = 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");
}
```

Child Process m

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

pid = 0

```
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");
}
```

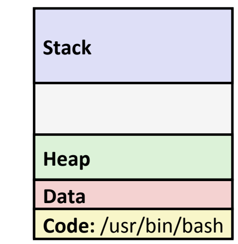
`hello from parent` ***Which one is first?*** `hello from child`

Fork Example

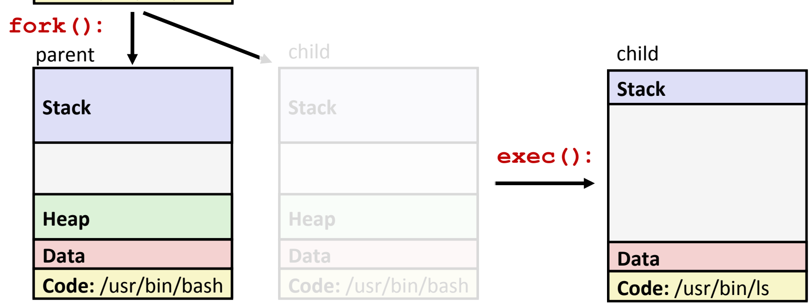
- **Parent and child both run the same code**
  - Distinguish parent from child by return value from **`fork()`**
  - Which runs first after the **`fork()`** is undefined
- **Start with same state, but each has a *private* copy**
  - Same variables, same call stack, same file descriptors, same register contents, **same program counter**…

```
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);
}
```

Exec-ing a new program

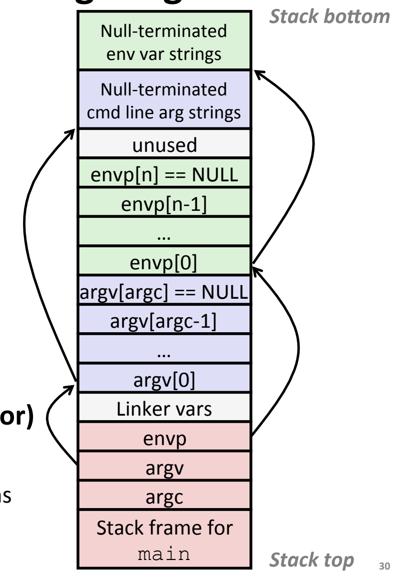


Very high-level diagram of what happens when you run the command "**ls**" in a Linux shell:

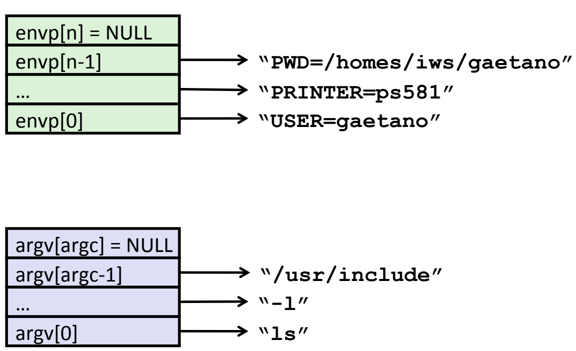


execve: Loading and Running Programs

- `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**
    - Env. vars: "name=value" strings (e.g. "PWD=/homes/iws/bpw")
- **execve** ***does not return*** **(unless error)**
- **Overwrites code, data, and stack**
  - Keeps pid, open files, a few other items



execve: Example



exit: Ending a process

- `void exit(int status)`
  - Exits a process
    - Status code: 0 is used for a normal exit, nonzero for abnormal exit
  - **atexit()** registers functions to be executed upon exit

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

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

function pointer

Zombies

- **Idea**
  - When process terminates, it still consumes system resources
    - Various tables maintained by OS
  - Called a "zombie"
    - A living corpse, half alive and half dead
- **Reaping**
  - Performed by parent on terminated child
  - 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)
  - But in long-running processes we need *explicit* reaping
    - e.g., shells and servers

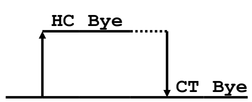
`wait`: Synchronizing with Children

- `int wait(int *child_status)`
  - Suspends current process (i.e. the parent) until one of its children terminates
  - Return value is the `pid` of the child process that terminated
    - On successful return, the child process is reaped
  - If `child_status != NULL`, then the int that it points to will be set to a status indicating why the child process terminated
    - NULL is a macro for address 0, the null pointer
    - There are special macros for interpreting this status – see **wait(2)**
- If parent process has multiple children, `wait()` will return when *any* of the children terminates
  - `waitpid()` can be used to wait on a specific child process

`wait` Example

```
void fork_wait() {
   int child_status;
   pid_t child_pid;

   if (fork() == 0) {
      printf("HC: hello from child\n");
   } else {
      child_pid = wait(&child_status);
      printf("CT: child %d has terminated\n",
          child_pid);
   }
   printf("Bye\n");
   exit(0);
}
```



Process management summary

- **`fork` gets us two copies of the same process (but `fork()` returns different values to the two processes)**
- **`execve` has a new process substitute itself for the one that called it**
  - Two-process program:
    - First `fork()`
    - if (pid == 0) { /* child code */ } else { /* parent code */ }
  - Two different programs:
    - First `fork()`
    - if (pid == 0) { `execve()` } else { /* parent code */ }
    - Now running two completely different programs
- **`wait` / `waitpid` used to synchronize parent/child execution and to reap child process**

Summary

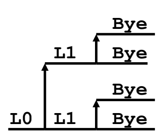
- **Processes**
  - At any given time, system has multiple active processes
  - Only one can execute at a time, but each process appears to have total control of the processor
  - OS periodically "context switches" between active processes
    - Implemented using *exceptional control flow*
- **Process management**
  - `fork`: one call, two returns
  - `exec`: one call, usually no return
  - `wait` or `waitpid`: synchronization
  - `exit`: one call, no return

Detailed examples

Fork Example #2

- **Both parent and child can continue forking**

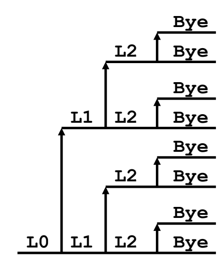
```
void fork2()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #3

- **Both parent and child can continue forking**

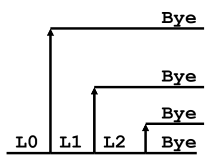
```
void fork3()
{
    printf("L0\n");
    fork();
    printf("L1\n");
    fork();
    printf("L2\n");
    fork();
    printf("Bye\n");
}
```



Fork Example #4

- Both parent and child can continue forking

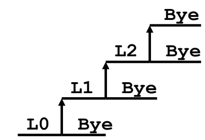
```
void fork4()
{
    printf("L0\n");
    if (fork() != 0) {
       printf("L1\n");
       if (fork() != 0) {
           printf("L2\n");
           fork();
       }
    }
    printf("Bye\n");
}
```



Fork Example #5

- Both parent and child can continue forking

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



Zombie Example

```
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 */
    }
}
```

```
linux> ./forks 7 &
[1] 6639
Running Parent, PID = 6639
Terminating Child, PID = 6640
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6639 ttyp9    00:00:03 forks
 6640 ttyp9    00:00:00 forks <defunct>
 6641 ttyp9    00:00:00 ps
linux> kill 6639
[1]    Terminated
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6642 ttyp9    00:00:00 ps
```

- **ps** shows child process as "defunct"
- Killing parent allows child to be reaped by **init**

Non-terminating Child Example

```
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);
    }
}
```

```
linux> ./forks 8
Terminating Parent, PID = 6675
Running Child, PID = 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6676 ttyp9    00:00:06 forks
 6677 ttyp9    00:00:00 ps
linux> kill 6676
linux> ps
  PID TTY          TIME CMD
 6585 ttyp9    00:00:00 tcsh
 6678 ttyp9    00:00:00 ps
```

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

`wait()` Example

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

```
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 terminated abnormally\n", wpid);
    }
}
```


`waitpid()`: Waiting for a Specific Process

- **`waitpid(pid, &status, options)`**
  - suspends current process until specific process terminates
  - various options (that we won't talk about)

```
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 = 0; i < N; 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);
    }
```