Processes (ch. 4+5)

Operating Systems
Based on: Three Easy Pieces by Arpaci-Dusseaux

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The Process

A **running program**

- Lots of processes seemingly running at the same time
- The challenge:
    - Few physical CPUs, illusion of many CPUs

The Process

- **Virtualizing** the CPU
  - Running one process, stopping it, running another, and so forth
  - **Time sharing** of the CPU
  - Illusion that many virtual CPUs exist

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  - Running one process, stopping it, running another, and so forth
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- **Context switch**
  - Low-level mechanism
  - Stop running one program and start running another
- **Scheduling policy**
  - Algorithm to decide which process should run next
  - By history, workload, performance

Context switch example (xv6-riscv64)

```
swtch:
        sd ra, 0(a0)
        sd sp, 8(a0)
        sd s0, 16(a0)
        sd s1, 24(a0)
        sd s2, 32(a0)
        sd s3, 40(a0)
        sd s4, 48(a0)
        sd s5, 56(a0)
        sd s6, 64(a0)
        sd s7, 72(a0)
        sd s8, 80(a0)
        sd s9, 88(a0)
        sd s10, 96(a0)
        sd s11, 104(a0)
```

```
        ld ra, 0(a1)
        ld sp, 8(a1)
        ld s0, 16(a1)
        ld s1, 24(a1)
        ld s2, 32(a1)
        ld s3, 40(a1)
        ld s4, 48(a1)
        ld s5, 56(a1)
        ld s6, 64(a1)
        ld s7, 72(a1)
        ld s8, 80(a1)
        ld s9, 88(a1)
        ld s10, 96(a1)
        ld s11, 104(a1)

        ret
```

Time and Space Sharing

- **Time sharing**
  - Resource used for a little while by one entity, then a little while by another, and so forth
  - e.g., CPU
- **Space sharing**
  - Resource is divided (in space) among those who wish to use it
  - e.g., memory, disk

Process vs. Program

- **Program**: static code and static data
- **Process**: dynamic instance of the program

- Multiple processes of the same program can exist

What constitutes a process?

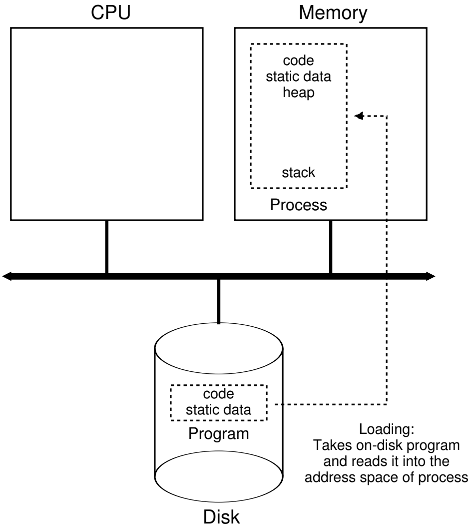
- Memory (**address space**)
  - Instructions (program code)
  - Data (static and dynamic)
  - `cat /proc/<PID>/maps`
- Registers
  - Program counter (PC)
  - Stack pointer
  - etc.
- I/O information
  - e.g., open files
  - `cat /proc/<PID>/fdinfo/*`

Process Creation

- Unix likes OSes: A process is a replica of a currently existing process.
    - There is a way to load an executable file into an existing process.
- Non-Unix like OSes: A process is created with information from an exe file.

Either way, the first process is created by the OS on initialization.

Executable Loading



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- **Load** code and static data into memory
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  - Used for dynamically-allocated data
  - Request space by calling `malloc`, free it by `free`

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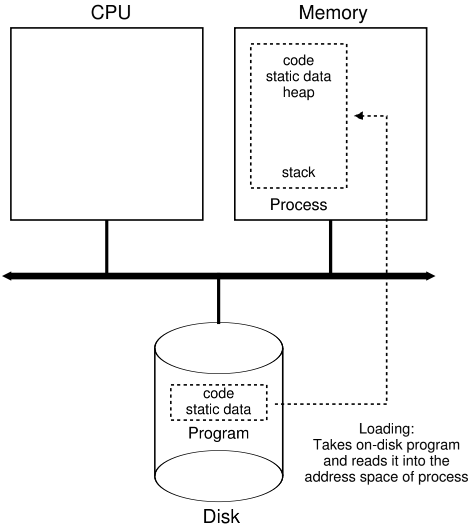
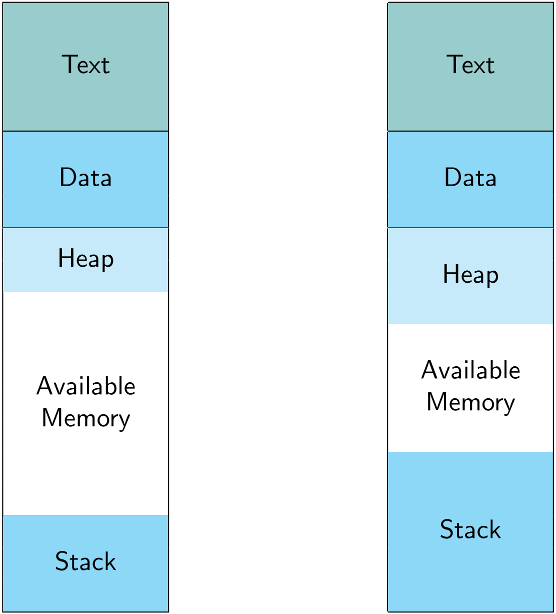
  - Initialized with `main` arguments: `argc`, `argv`
- Allocate the **heap**
  - Used for dynamically-allocated data
  - Request space by calling `malloc`, free it by `free`
- Start program at entry point (NOT necessarily `main()`)
  - Transfer control of CPU to the newly-created process

Executable loading



Two Processes for One Program (Virt Mem View)



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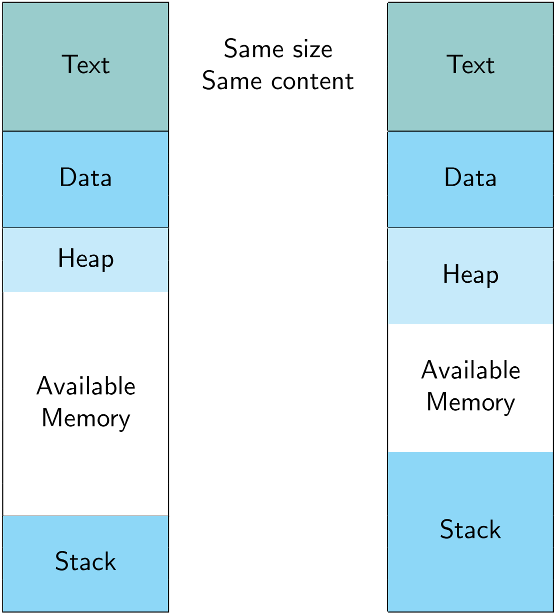

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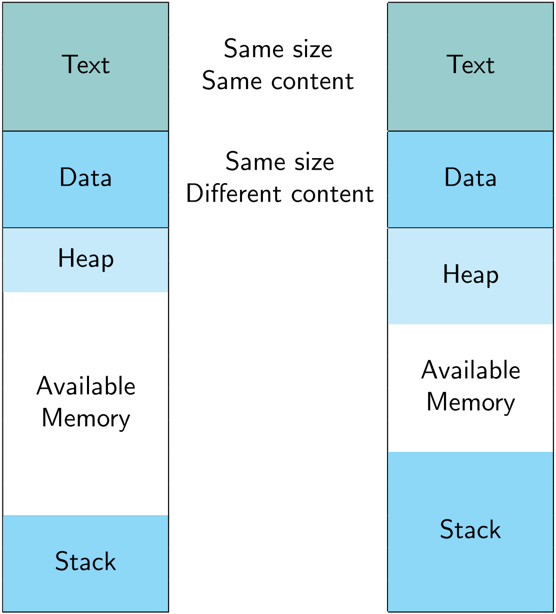

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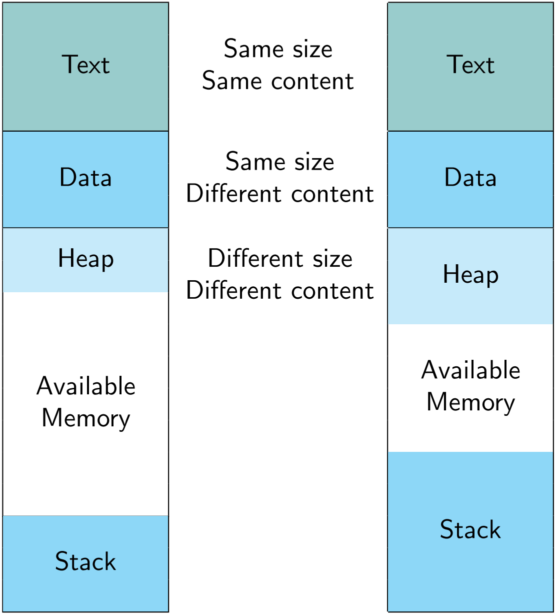

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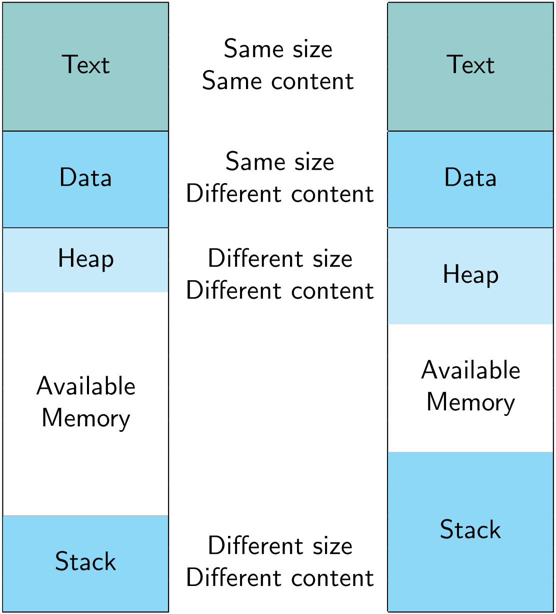

Process Life Cycle

- A process can be in a finite number of **states**
- Events cause **transitions** between states

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  - Only one process at a time
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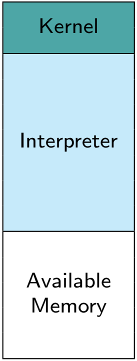

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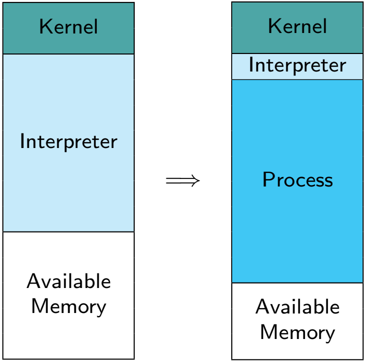

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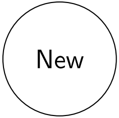

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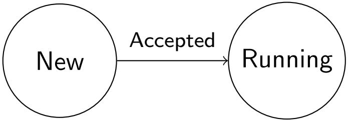

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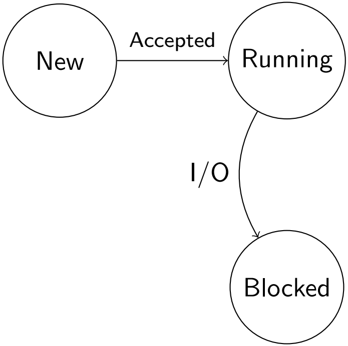

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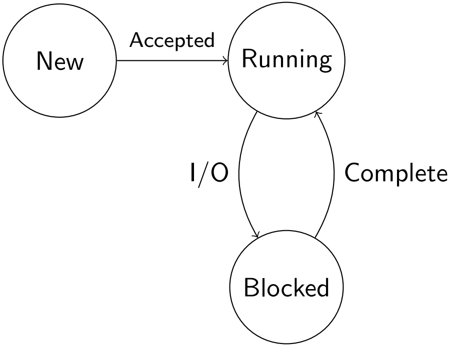

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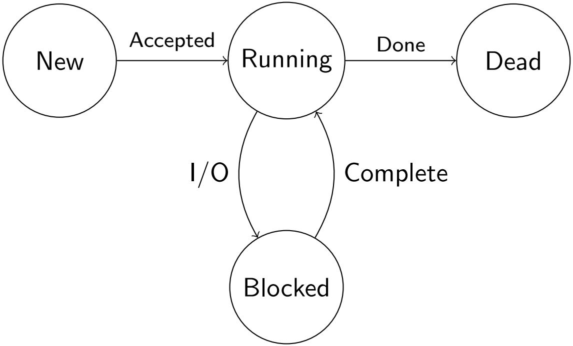


Process Life Cycle

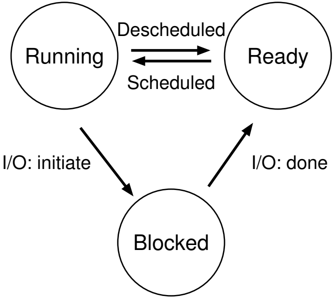
- Modern operating systems: **multi-tasking**
  - Multiple processes co-exist
  - **Cooperative** multi-tasking: `yield`
  - **Preemptive** multi-tasking: **interrupts**

Process Life Cycle

- Modern operating systems: **multi-tasking**
  - Multiple processes co-exist
  - **Cooperative** multi-tasking: `yield`
  - **Preemptive** multi-tasking: **interrupts**
- A process can be **ready** to run, but not running
  - OS schedules a process to run for a while, then deschedules it and picks another process, and so forth
  - A new state: **ready**

Process States

- **Running**: executing on CPU
- **Ready**: ready to run, waiting to be scheduled
- **Blocked**: suspended, waiting for some event



Process States - Example I

Time	Process 0	Process 1	Notes
1	Running	Ready	
2	Running	Ready	
3	Running	Ready	
4	Running	Ready	Process 0 done
5	-	Running	
6	-	Running	
7	-	Running	
8	-	Running	Process 1 done

Process States - Example II

Time	Process 0	Process 1	Notes
1	Running	Ready	
2	Running	Ready	
3	Running	Ready	0 initiates I/O
4	Blocked	Running	0 is blocked
5	Blocked	Running	so 1 runs
6	Blocked	Running	
7	Ready	Running	I/O done
8	Ready	Running	Process 1 done
9	Running	-	
10	Running	-	Process 0 done

Data Structures

- OS maintains a data structure of active processes
  - The **process table**
  - Limited size - `cat /proc/sys/kernel/threads-max`

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  - The **process table**
  - Limited size - `cat /proc/sys/kernel/threads-max`
- Process Control Block (**PCB**):
  - Process identifier (**PID**)
  - State
  - Related processes (parent)
  - CPU context, e.g., registers (saved when suspended)
  - Memory locations
  - Open files

Summary (Process Abstraction)

- **Process**: OS abstraction of a running program
- Can be described by:
  - **Address space**
  - CPU registers (inc. **program counter** & **stack pointer**)
  - I/O information (e.g., open files)
- **Process state**: running, ready to run, blocked.
  - transition by different events
- **Process list**: information about all processes in the system
  - **Process control block**: a structure with information about a specific process

Process API

- API: Application Programming Interface
- The API of the OS: **system calls**
  - Function call into OS code
  - Higher privilege level, for sensitive operations (e.g., hardware)

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- Rewrite code for each OS?
  - **POSIX API**: standard set for each POSIX-compliant OS
    `write`)

POSIX hides details

fork xv6-x86

```
movl      $1, %eax
int       $64
```

fork Linux-x86

```
movl      $2, %eax
int       $128
```

close xv6-x86

```
    pushl    fd
    subl     $4,%esp
    movl     $21,%eax
    int      $64
    addl     $4,%esp
```

close Linux-x86

```
    movl     fd,%ebx
    movl     $6,%eax
    int      $127
```

Posix Process API

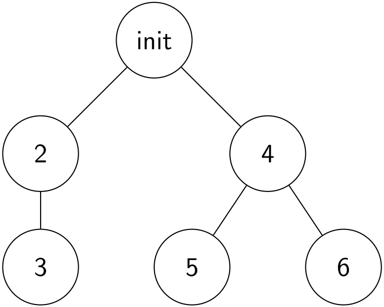
- `fork()`: create a new process
- `wait()`: block until a child process terminates
- `exec()`: make the process execute a given program

Process Tree

- Start with one process: `init` (PID 1)
- A process can create processes
  - Process A creates B: A is the **parent** of B, B is the **child** of A
  - Can create many children, only one parent
  - Parent can **wait** for child process to finish
- Process ID (**PID**): increasing identifier
  - Get PID: `getpid()`
  - Get parent PID: `getppid()`

Process Tree

- Processes form a tree:



- `ps --forest -eaf`
- `pstree`

`fork()`

- `fork()`: creates a new process
  - Wrapper for `clone` (in Linux)
- New process: almost exact copy of parent
  - Same: memory, execution point, open files
  - Different: PID, return value
  - **Copy-on-write** (Optimization)

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- Parent: `fork()` returns an integer:
  - If successful returns the **PID** of created child process
  - If fails negative number for erro code
- Child process:
  - Begins to run at the point after the fork.
  - 'return value' is zero.

`fork` in details

```c
pid = fork();
```

```
        movl    $1,%eax
        int     $64
        movl    %eax,pid
```

<table>
<tr><th>Parent</th><th>Child</th></tr>
<tr><td><pre>movl $1,%eax
int $64</pre></td><td></td></tr>
<tr><td><pre>movl   %eax,pid</pre></td><td><pre>movl   %eax,pid</pre></td></tr>
</table>

fork()

Typical usage example (fork.c):

```
printf("hello world (pid:%d)\n", getpid());
int rc = fork();
if (rc < 0) {
    fprintf(stderr, "fork failed\n");
    exit(1);
}
else if (rc == 0) {
    // child (new process)
    // sleep(5);   // Try with and without
    printf("I am child of %d (pid:%d)\n", getppid(), getpid());
}
else {
    // parent
    printf("I am parent of %d (pid:%d)\n", rc, getpid());
}
```

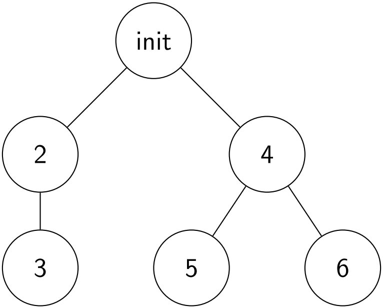
fork()

Output:

```
prompt> gcc -o fork fork.c -Wall
prompt> ./fork
hello world (pid:1300)
I am parent of 1301 (pid:1300)
I am child of 1 (pid:1301)
prompt>
```

- Child of **1**??

fork()



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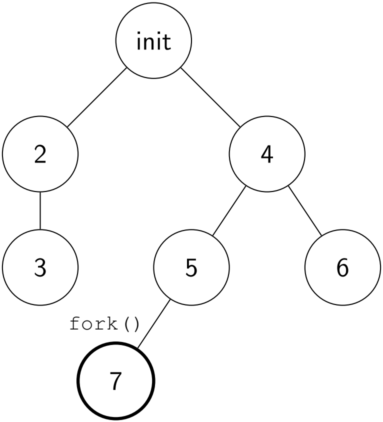

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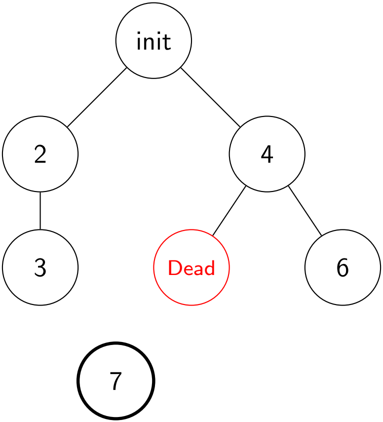

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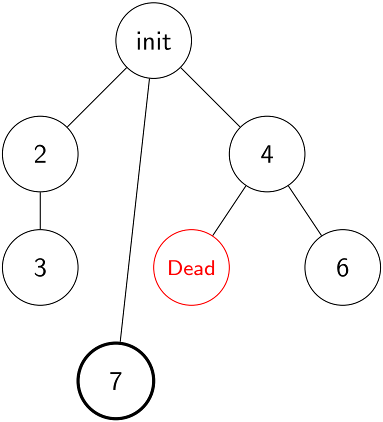

fork()

peculiar1.c:

```c
int main(int argc, char *argv[])
{
    fork();
    fork();
    printf("hello there\n");
}
```

What is the output?

fork()

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```

What is the output?

```
hello there
hello there
hello there
hello there
```

fork()

peculiar2.c:

```c
int main(int argc, char *argv[])
{
    int pid = fork();
    if (pid)
        fork();
    fork();
    printf("hello there\n");
}
```

What is the output?

fork()

peculiar2.c:

```c
int main(int argc, char *argv[])
{
    int pid = fork();
    if (pid)
        fork();
    fork();
    printf("hello there\n");
}
```

What is the output?

fork()

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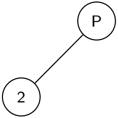

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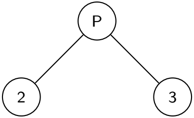

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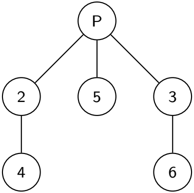

fork()

peculiar3.c:

```
int main(int argc, char *argv[])
{
    fork();
    printf("hello\n");
}
```

Can this print “hehellollo”?

fork()

peculiar3.c:

```
int main(int argc, char *argv[])
{
    fork();
    printf("hello\n");
}
```

Can this print "hehellollo"?

- No! Due to how `printf` works
- But... very important to consider these cases
- More on this in the future (**concurrency**)

fork()

peculiar4.c:

```
int main(int argc, char *argv[])
{
    int x = 0;
    if (fork()) {
        sleep(5); // BLOCKED state for 5 seconds
        printf("%d\n", x);
    }
    else {
        x += 3;
    }
}
```

What is the output?

fork()

peculiar4.c:

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    }
}
```

What is the output? **0**

- Why?

fork()

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    int x = 0;
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    }
    else {
        x += 3;
    }
}
```

What is the output? **0**

- Why? Child's memory is a **copy**

fork()

peculiar5.c:

```
fork();
if (fork()) {
    fork();
}
fork();
```

How many processes does this code create?

fork()

peculiar5.c:

```c
fork();
if (fork()) {
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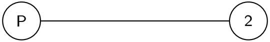

fork()

`peculiar5.c`:

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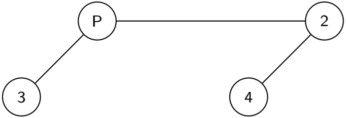

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}
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```

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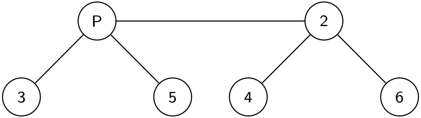

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}
fork();
```

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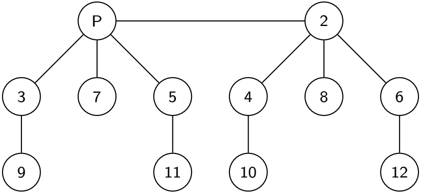

fork()

peculiar6.c:

```
int main(int argc, char *argv[])
{
    int x = 0;
    if (fork()) {
        sleep(5); // BLOCKED state for 5 seconds
    }
    else {
        x += 3;
    }
    printf(%d\n", x);
}
```

Last one - what is the output?

fork()

peculiar6.c:

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int main(int argc, char *argv[])
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        x += 3;
    }
    printf(%d\n", x);
}
```

Last one - what is the output? **30** or **03**

- Depends on scheduling

fork()

peculiar6.c:

```
int main(int argc, char *argv[])
{
    int x = 0;
    if (fork()) {
        sleep(5); // BLOCKED state for 5 seconds
    }
    else {
        x += 3;
    }
    printf(%d\n", x);
}
```

Last one - what is the output? **30** or **03**

- Depends on scheduling
- Can we make it deterministic?

`wait()`

- `wait()`: waits for a child process to finish
  - Any child process (if several exist)
  - Returns PID of terminated child process (-1 on error)
  - `waitpid()`: waits for a specific child process (by PID)
- To wait for all child processes to end:
  - `while (wait(NULL) != -1);`

wait()

wait.c:

```c
int main(int argc, char *argv[])
{
    int x = 0;
    int rc = fork();
    if (rc) {
        wait(NULL); // BLOCKED until child terminates
        // equivalent here: waitpid(rc, NULL, 0);
    }
    else {
        x += 3;
    }
    printf("%d\n", x);
}
```

Output is always **30**

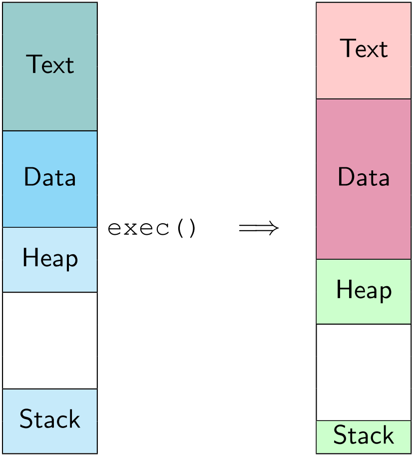
`exec()`

- After `fork()`, parent and child execute same code
    - What if we want to run a different program?
    - `exec()` does just that
- Six variants of `exec()`: `execl`, `execlp`, `execle`, `execv`, `execvp`, `execvpe`. Read `man` for details

`exec()`

- After `fork()`, parent and child execute same code
  - What if we want to run a different program?
  - `exec()` does just that
- Six variants of `exec()`: `execl`, `execlp`, `execle`, `execv`, `execvp`, `execvpe`. Read `man` for details
- `exec()`: transform current program into a different program
  - Receives program name and arguments (`argv`)
  - Overwrites and re-initializes process memory
  - A successful `exec()` never returns!

exec()



exec()

exec.c:

```
int main(int argc, char *argv[])
{
    int rc = fork();
    if (rc < 0) {
        fprintf(stderr, "fork failed\n");
        exit(1);
    }
    else if (rc == 0) {
        char* args[4] = { "wc", "-l", "exec.c", NULL };
        execvp(args[0], args);
        printf("this shouldn't print out\n");
    }
    else {
        int rc_wait = wait(NULL); // or waitpid(rc,NULL,0)
        printf("I am parent of %d (rc_wait:%d) (pid:%d)\n",
            rc, rc_wait, getpid());
    }
}
```

The Living Dead

- When a process terminates, it remains in the process list as a **zombie**
  - Parent process may want to know its status
- Zombie remains until it is reaped (or its parent terminates)
  - Process 1 adpots orphans (zombied or live)

- A program should not leave zombies!

The Living Dead

- How to avoid zombies?
  - `wait()`: blocks until a child completes & reaps it
  - `waitpid()`: blocks until a <u>specific</u> child completes & reaps it
- Not enough
  - The terminal (shell) executes processes in the background, wants to continue accepting user input
  - It is possible to `wait()` without blocking, but very inconvenient
- What can we do?

Signals

- **Software interrupts**
  - Asynchronous notification of an event
  - Inter-process communication (**IPC**) or messages from OS

Signals

- **Software interrupts**
  - Asynchronous notification of an event
  - Inter-process communication (**IPC**) or messages from OS
- Various signals exist:
  - ˆC in the terminal sends `SIGINT` ("interrupt from keyboard")
  - Invalid memory reference causes `SIGSEGV`
  - A process can send `SIGKILL` to another process
  - Child process terminated - **SIGCHLD**

Signal Handlers

- Some signals are handled automatically by the OS
  - `SIGKILL`, `SIGSTOP`
- Others are handled by a **signal handler**
  - Each signal has a default behavior, e.g., `SIGINT` causes the process to terminate
  - Can override default with `sigaction()`
- Let's write our own **signal handler**!

Signal Handlers

`signal1.c`:

```
int main(int argc, char *argv[])
{
    struct sigaction act;
    sigemptyset(&act.sa_mask);
    act.sa_handler = SIG_IGN;
    act.sa_flags = 0;

    if (sigaction(SIGINT, &act, NULL) == -1) {
        fprintf(stderr, "sigaction failed\n");
        exit(1);
    }
    while (1);
}
```

Signal Handlers

`signal2.c`:

```
void signal_handler(int signal) {
    if (signal == SIGCHLD) {
        int rc = wait(NULL);
        printf("child terminated %d (pid:%d)\n", rc, getpid());
    }
}
int main(int argc, char *argv[])
{
    struct sigaction act;
    sigemptyset (&act.sa_mask);
    act.sa_handler = signal_handler;
    act.sa_flags = 0;

    sigaction(SIGCHLD, &act, NULL);
    if (fork()) {
        while (1);
    }
}
```

No zombies!

`kill()`

- `kill()`: send a signal to another process
  - `kill(pid_t` *pid*`, int` *sig*`)`
  - *pid*: process id to send signal to
  - *sig*: signal to send
- Name is misleading
  - Can send any signal

Case Study

- How does a shell work?
  - Reads user command
  - Forks a child
  - Sets up process (e.g., redirection)
  - Execs the relevant program
  - Waits for it to finish (if not background)
  - Reads next command

Summary (Process API)

- `fork()`: create a new process (clone current)
- `wait()`: waits for a child process to finish
  - Also `waitpid()`
- `exec()`: transform program into a different program
  - Successful `exec()` never returns
- Terminated process remains as a **zombie**, to avoid:
  - Parent terminates
  - `wait()` or `waitpid()` by parent
- **Signals** are software interrupts
  - Can write our own **signal handlers**
  - Also helps with zombies
- `kill()`: send a signal to another process