Chapter II
Processes

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Chapter Overview

- Processes
- States of a process
- Operations on processes
  - `fork()`, `exec()`, `kill()`, `signal()`
- Threads and lightweight processes
  - POSIX threads

Processes

Definition

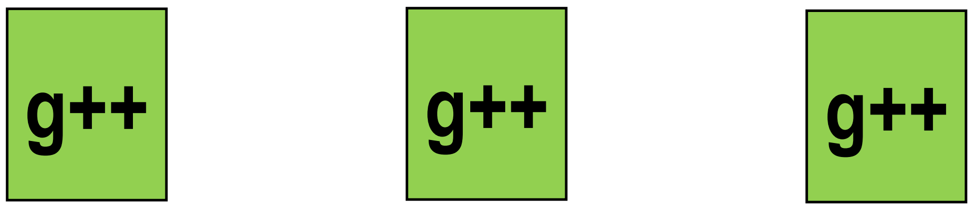
- A process is a ***program*** executing a given ***sequential computation***.
  - An ***active entity*** unlike a program
  - *Think of the difference between a recipe in a cookbook and the activity of a cook preparing a dish according to the recipe!*

Processes and programs (I)

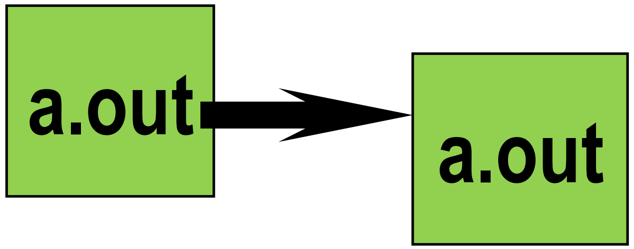
- Can have one program and many processes
  - When several users execute the same program (text editor, compiler, and so forth) at the same time, each execution of the program constitutes a ***separate process***
  - A program that ***forks*** another sequential computation gives birth to a new process.

Examples

- Several executions of same program



- A program forking a child

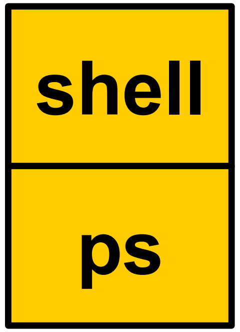


Processes and programs (II)

- Can have one process and two—or more—programs
  - A process that performs an **`exec()`** call replaces the program it was executing

Examples

- One process executing two programs
  - Typical of Unix/Linux processes



The UNIX shell

- Program that
  - Reads input from the keyboard
  - Creates the process that will execute the command.
  - Wait for the completion of the process it has created unless it was specified otherwise
- *User-level program that you and I could write*

Yes, we can

```
#!/usr/bin/python3
"""  A very very basic shell in Python 3
      Check https://www.python-course.eu/forking.php
"""
import os
def changeDirectory(argc, argv) :
    if argc ==  2 :
        try :
            os.chdir(argv[1])
        except Exception :
            print("Pshell: " + argv[0] +
                   ": no such file or directory")
    elif argc == 1 :
        os.chdir(os.environ['HOME'])
    else :
        print("Pshell: cd: too many arguments")
def vanillaCase(argc, argv) :
    kidpid = os.fork()
    if kidpid == 0 :
        try :
            os.execvp(argv[0], argv)
        except Exception :
            print(argv[0]+": program not found")
    else :
        os.wait()
```

```
while (1) :
    argline = input("Pshell: ")
    argline.strip()
    argv = argline.split() # Break at spaces
    argc = len(argv)
    if argc == 0 :
        continue
    if argv[0] == 'exit' : # Exiting Pshell
        break
    elif argv[0] == 'cd' :
        # Changing current directory
        changeDirectory(argc, argv)
    else :
        vanillaCase(argc, argv)
```

A very basic UNIX shell

```
for (;;) {
    parse_input_line(arg_vector);
    if built_in_command(arg_vector[0]) {
        do_it(arg_vector);
        continue;
    } // built-in command
    pathname = find_path(arg_vector[0]);
    create_process(pathname, arg_vector);
    if (interactive())
        wait_for_this_child();
} // for loop
```

Notes

- All functions in italics are templates yet to be written
- Real shells do more:
  - I/O redirection
  - Pipes (as in **ls -alg | more**)
  - Command aliasing,
  - Wildcard characters (as" *****")
  - …

Importance of processes

- Processes are the ***basic entities*** managed by the operating system
  - OS provides to each process the illusion it has the whole machine for itself
  - Each process has a dedicated ***address space***

The process address space

- Set of main memory locations allocated to the process
  - Other processes cannot access them
  - Process cannot access address spaces of other processes
- A process address space is the ***playpen*** or the ***sandbox*** of its owner

A last word

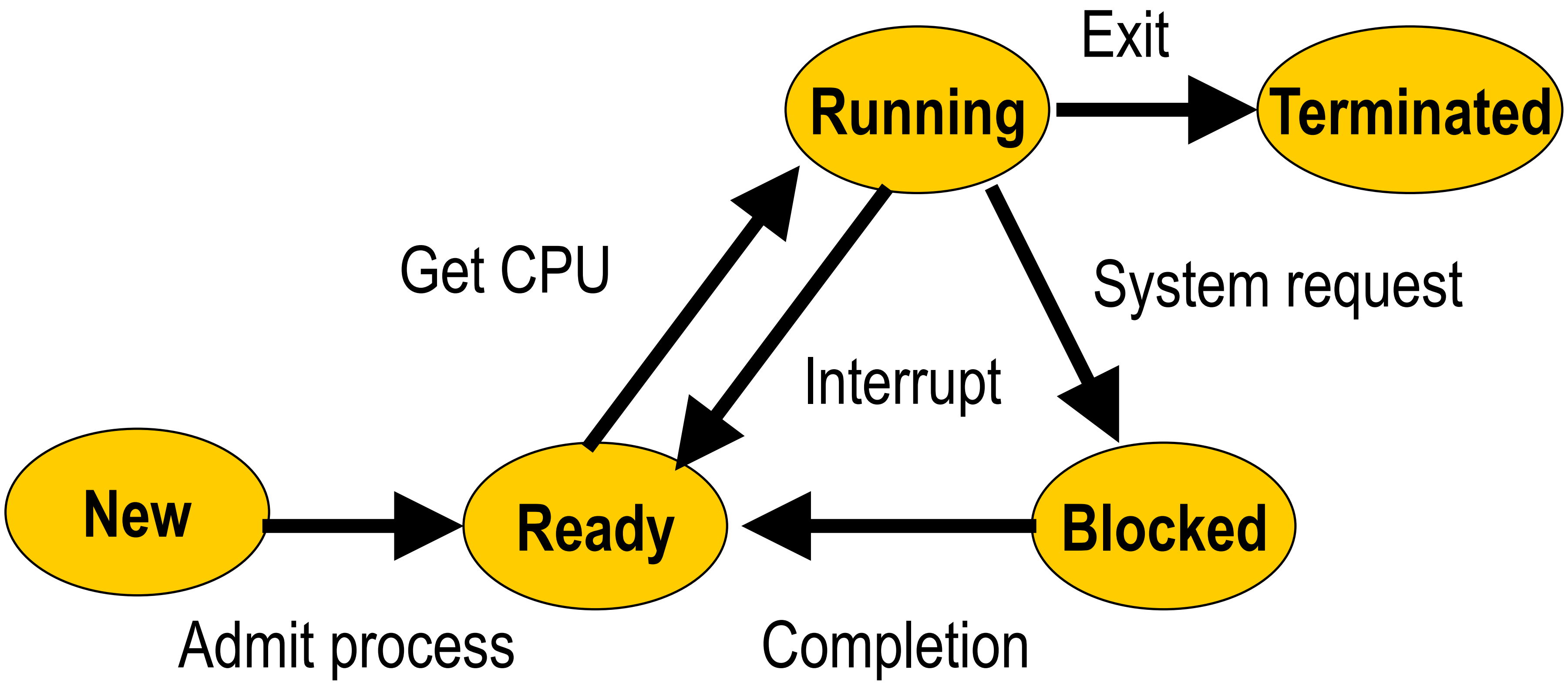
- There are many *quasi-synonyms* for process:
  - Job (very old programmers still use it)
  - Task
  - Program (strongly deprecated)

Process states

The five basic process states

- Processes go repeatedly through several stages during their execution
  - Waiting to get into main memory
  - Waiting for the CPU
  - Running
  - Blocked while waiting for the completion of a system call

The big diagram



This is fundamental material

Process arrival

- New process
  - Starts in NEW state
  - Gets allocated a Process Control Block (PCB) and main memory
  - Is put in the READY state waiting for CPU time

The ready state

- AKA the ***ready queue***
- Contains all processes waiting for the CPU
- Organized as a ***priority queue***
- Processes leave the priority queue when they get some CPU time
  - Move then to the RUNNING state

The running state (I)

- A process in the running state has exclusive use of the CPU until
  - It ***terminates*** and goes to the ***TERMINATED*** state
  - It does a ***system call*** and goes to the ***BLOCKED*** state
  - It is ***interrupted*** and returns to the ***READY*** state

The running state (II)

- Processes are forced to relinquish the CPU and return to the ***READY*** state when
  - A ***higher-priority process*** arrives in the ready queue and ***preempts*** the running process
    - *Get out, I'm more urgent than you!*
  - A ***timer interrupt*** indicates that the process has exceeded its time slice of CPU time

The blocked state (I)

- Contains all processes waiting for the completion of a system request:
  - I/O operation
  - Any other system call
- Process is said to be
  - ***blocked*** (Arpaci-Dusseau & Arpaci-Dusseau)
  - ***waiting***
  - ***sleeping*** (UNIX)

The blocked state (II)

- A system call that does not require callers to wait until its completion is said to be ***non-blocking***
  - Calling processes are immediately returned to the ***READY*** state
- The blocked state is organized as a ***set of queues***
  - One queue per device, OS resource

The process control block (I)

- Contains all the information associated with a specific process:
  - ***Process identification*** (pid), *argument vector*, ...
    - UNIX pids are unique integers
  - ***Process state*** (new, ready, running, …),
  - ***CPU scheduling information***
    - Process priority, processors on which the process can run, …,

The process control block (II)

- ***Program counter*** and other CPU registers
  - Including the ***Program Status Word*** (PSW),
- ***Memory management information***
  - Very system specific,
- ***Accounting information***
  - CPU time used, system time used, ...
- ***I/O status information***
  - List of opened files, allocated devices, …

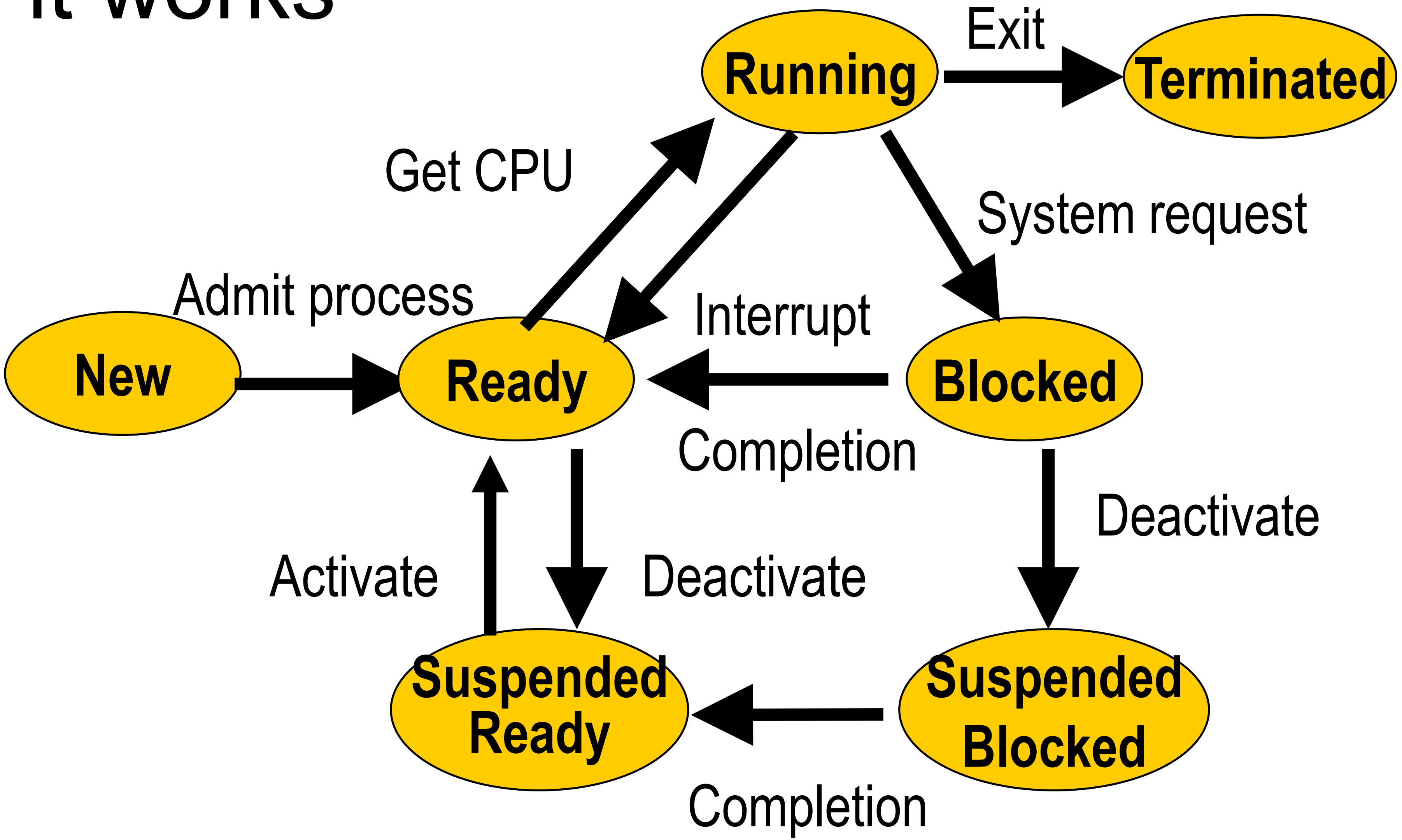
The process table

- System-wide table containing
  - ***Process identification*** (pid), *argument vector*, ...
  - ***Process current state***
  - ***Process priority and other CPU scheduling information***
  - A ***pointer*** to the remaining information.

Swapping

- Whenever the system is very loaded, we might want to expel from main memory or ***swap out***
  - Low priority processes
  - Processes that have been waiting for a long time for an external event
    - *User is out of the office*
- These processes are said to be ***swapped out*** or ***suspended*.**

How it works


Running
Exit
Terminated
Get CPU
System request
Admit process
Interrupt
New
Ready
Blocked
Completion
Deactivate
Activate
Deactivate
Suspended Ready
Suspended Blocked
Completion

Suspended processes

- Suspended processes
  - Do not reside in main memory
  - Continue to be included in the process table
- Can distinguish between two types of suspended processes:
  - Waiting for the completion of some request (***blocked_suspended***)
  - Ready to run (***ready_suspended***).

A warning

- A system should ***not*** swap out ready processes unless their priority is ***very low***
- Otherwise swapping out ready processes can only be a ***desperate measure***

Operations on processes

Process creation, deletion, …

The six essential operations

- Process creation
  - `fork()`
  - `exec()`
- Process synchronization
  - `wait()`
- Process termination
  - `_exit()`
  - `kill()`
  - `signal()`

Process creation

- Two basic system calls
  - **`fork()`** creates a carbon-copy of calling process sharing its opened files
  - **`execv()`** overwrites the contents of the process address space with the contents of an executable file

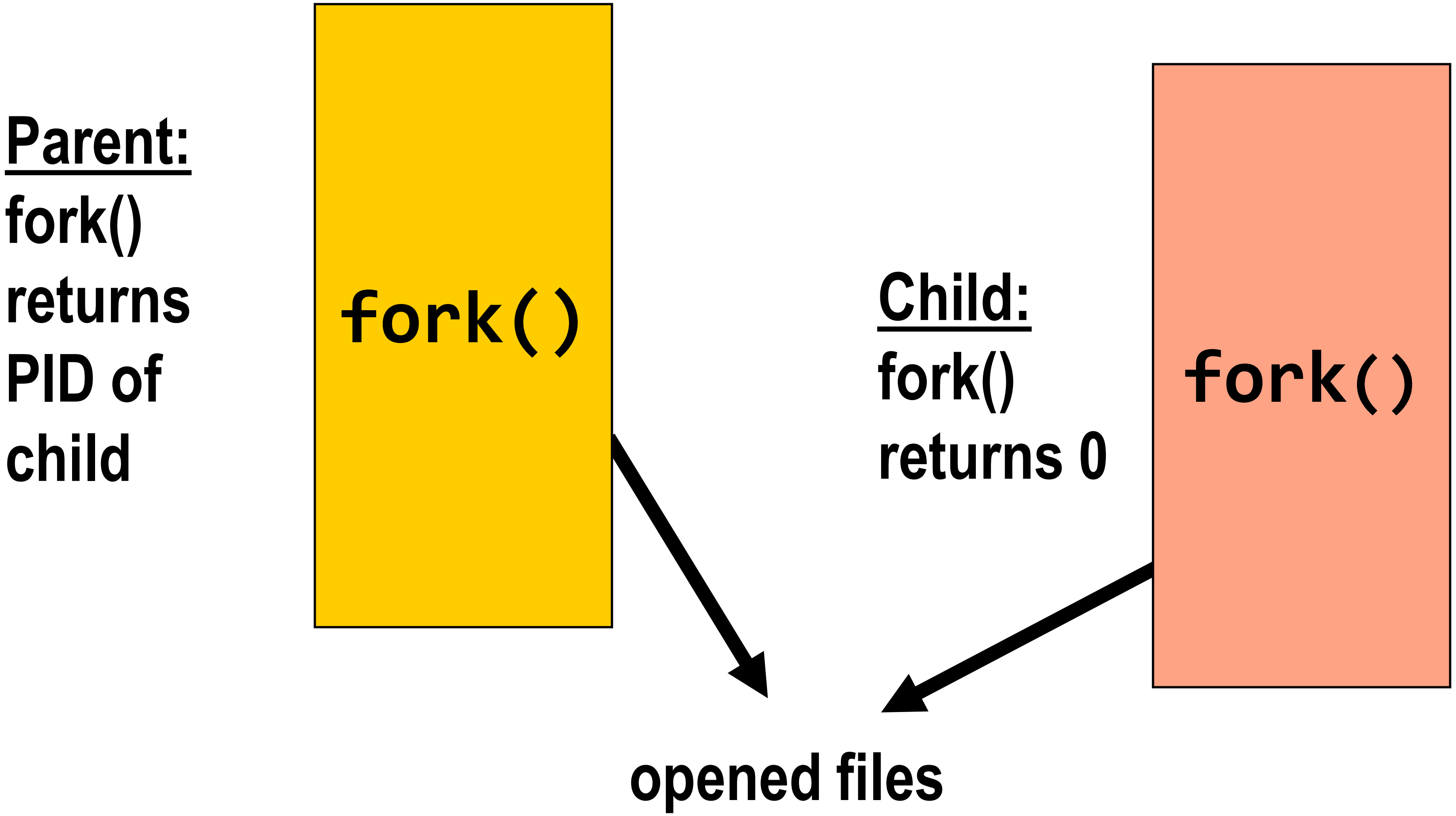
fork() (I)

- First process of a system is created when the system is booted
- All other processes are forked by another process
  - Their ***parent process***
  - Said to be ***children*** of that process

fork() (II)

- When a process forks, OS creates an ***identical copy*** of forking process with
  - A ***new address space***
  - A ***new PCB***
- The ***only*** resources shared by the parent and the child process are the ***opened files***

fork() (III)

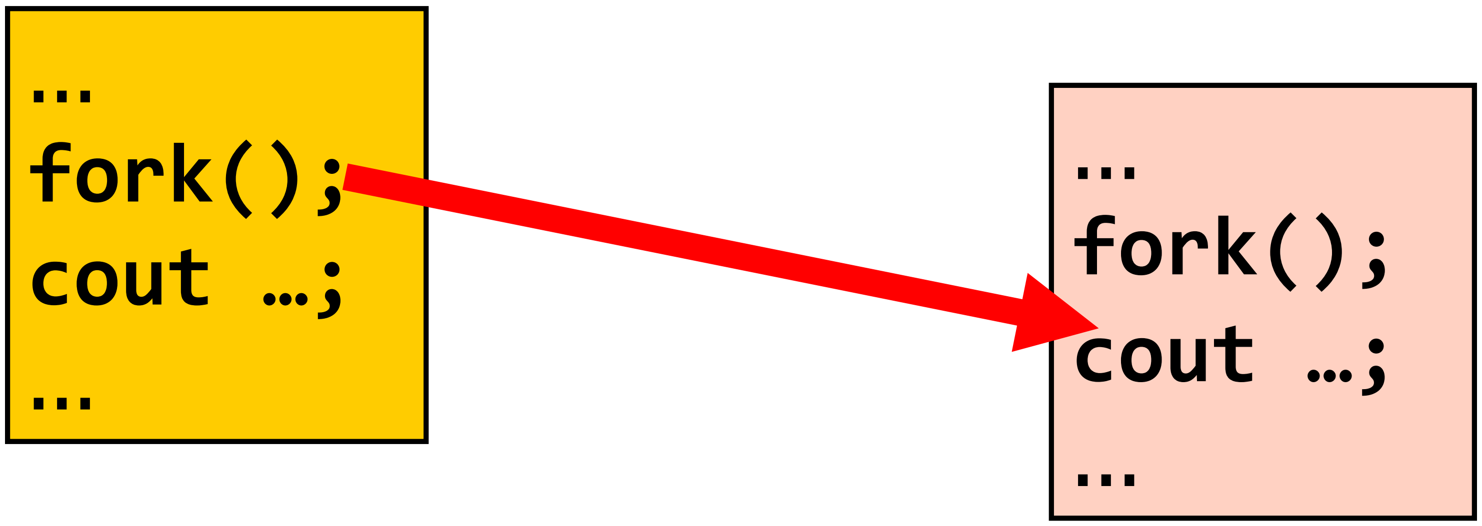

Parent:
fork()
returns
PID of
child
fork()
Child:
fork()
returns 0
fork()
opened files

First example

```
#include <iostream>
using namespace std;
main() {
    fork();
    cout << "Hello" << endl;
} // main
```

will print two lines as **`cout`** will be executed by ***both*** the parent and the child

How it works

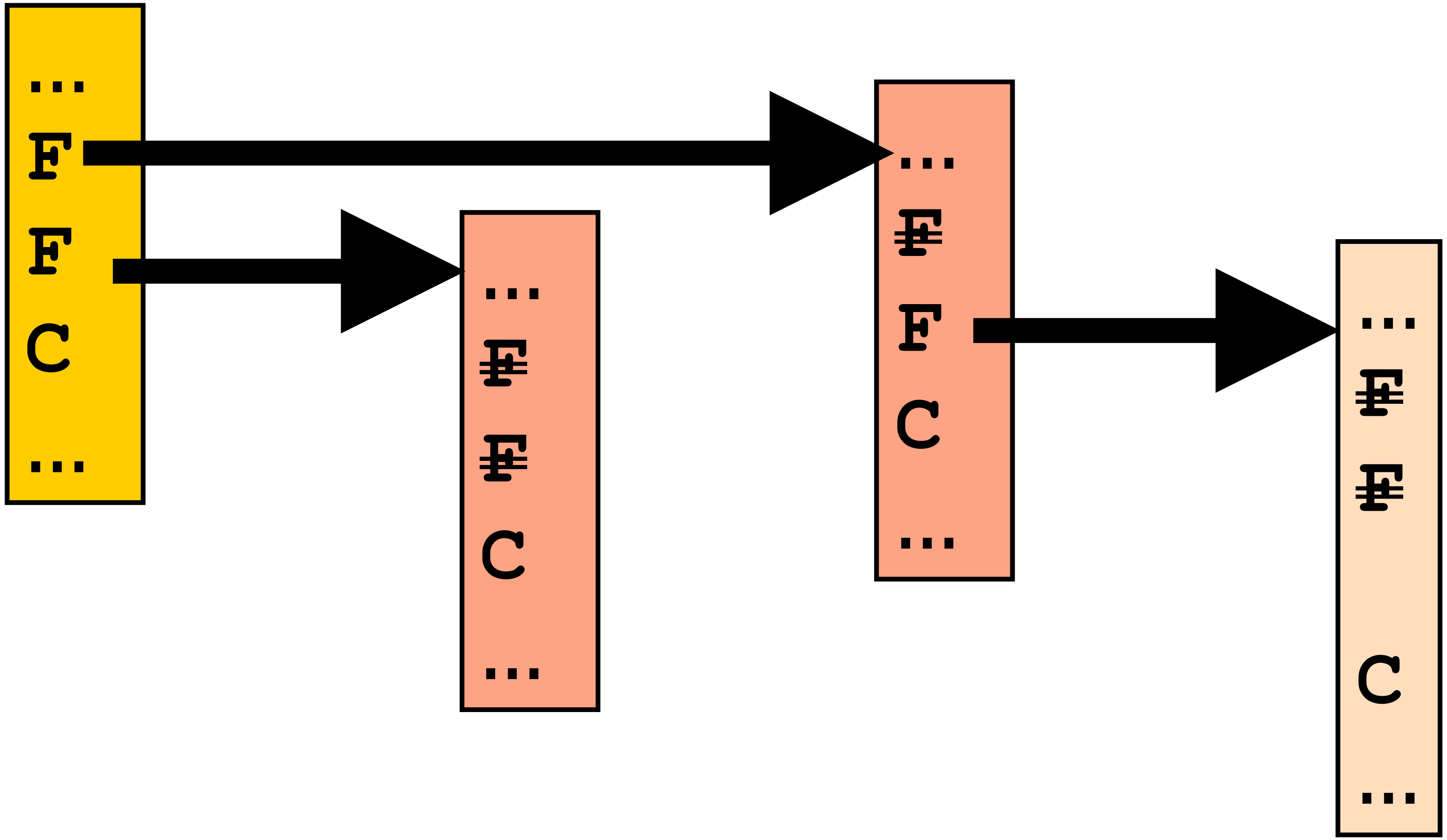


Second example

```
main() {
   fork();
   fork();
     cout << "Hello" << endl;
 } // main
```

will print four lines as **`cout`** will be executed by the parent, its two children and its grandchild

How it works



Something smarter

```
int pid;
pid = fork();
if (pid == 0) {
      // child process
      ...
} else {
      // parent process
      ...
}
```

First simplification

```
int pid;
pid = fork();
if (pid == 0) {
     // child process
     ...
     _exit(0); // normal exit
} // if
// parent process continues
     ...
```

Second simplification

```
int pid;
if ((pid = fork()) == 0) {
     // child process
     ...
     _exit(0); // normal exit
} // if
// parent process continues
     ...
```

Waiting for child completion

- `wait(0)`
  - Waits for the completion of any child
  - No wait if any child has already completed
- `while (wait(0) != kidpid)`
  - Waits for the completion of a specific child identified by its ***pid***

An example (I)

```
#include <iostream>
#include <sys/types.h>
#include <sys/wait.h>
using namespace std;
```

An example (II)

```
main() {
        int pid;
        if((pid = fork()) == 0)  {
                cout << "Hello !" << endl;
                 _exit(0);
        } // child
        wait(0);
        cout << "Goodbye!" << endl;
} // main
```

Why we needs loop

- UNIX keeps in its process table all processes that have terminated but their parents have not yet waited for their termination
  - They are called ***zombie processes***
- The statement

```
while (kidpid != wait(0));
```

is a loop with an ***empty body***

Putting everything together (I)

```
int kidpid;
if ((kidpid = fork()) == 0) {
        // child process
        ...
        _exit(0); // normal exit
} // if
// parent waits for child
while (wait(0) != kidpid);
        ...
```

Must use the while loop if the process has already forked other children

exec

- Whole set of exec() system calls
- Most interesting are
  - **`execv(pathname, argv)`**
  - **`execve(pathname, argv, envp)`**
  - **`execvp(filename, argv)`**
- All **`exec()`** calls perform the same two tasks
  - Erase current address space of process
  - Load specified executable

execv

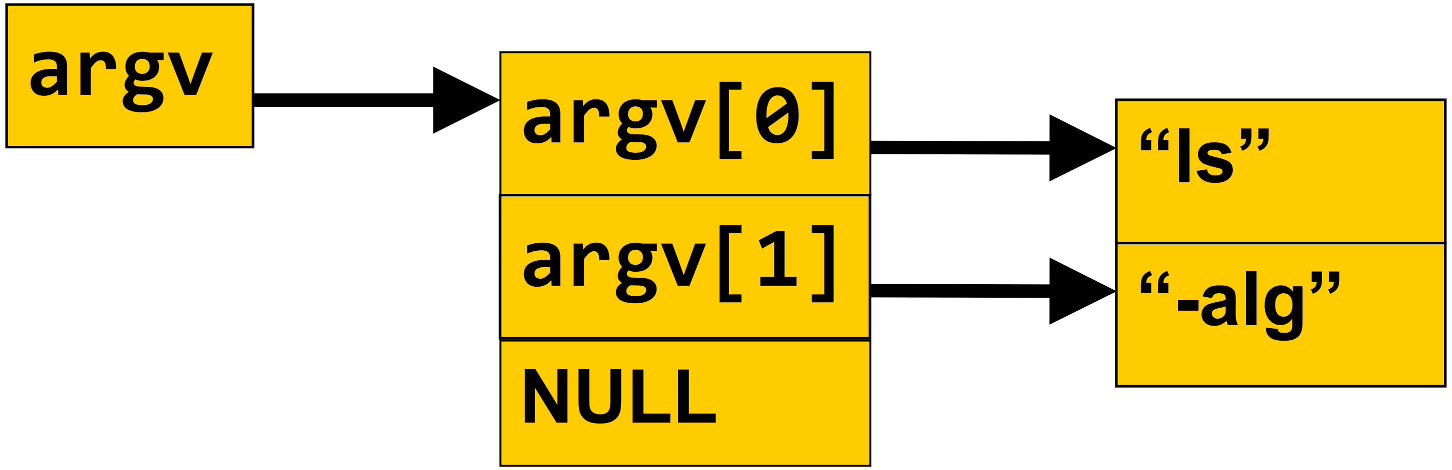
- `execv(pathname, argv)`
  - `char pathname[]`
    - ***full pathname*** of file to be loaded:
      `/bin/ls` instead of `ls`
  - `char argv[][]`
    - the ***argument vector***:
      passed to the program to be loaded

Argument vector (I)

- An array of pointers to the individual argument strings
  - **`arg_vector[0]`** contains the name of the program *as it appears in the command line*
  - Other entries are parameters
  - End of the array is indicated by a **NULL** pointer

Argument vector (II)

- `char argv[][];`
- `char **argv;`



execve() and execvp()

- **`execve(pathname, argv, envp)`**
  - Third argument points to a list of environment variables
- **`execvp(argv[0], argv)`**
  - Lets user specify a command name instead of a full pathname
  - Looks for **`argv[0]`** in list of directories specified in environment variable **`PATH`**

Putting everything together (II)

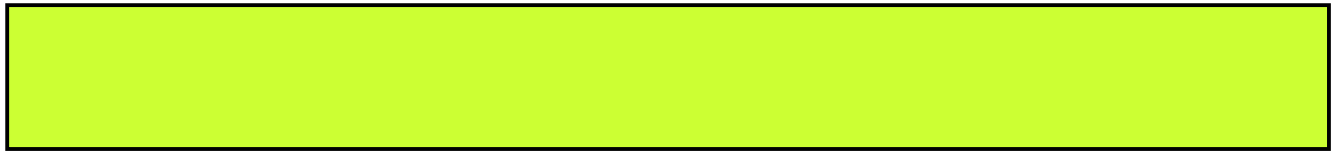
```
int pid
if ((pid = fork()) == 0) {
   // child process
   ...
   execvp(filename, argv);
   _exit(1); // exec failed
 }  // if
 while (pid != wait(0));
 // parent waits
  ...
```

Observations (I)

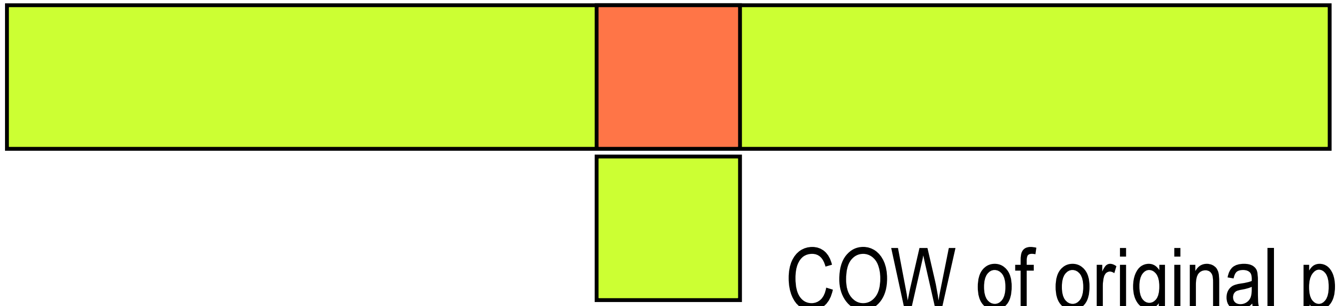
- Not cheap
  - `fork()` makes a ***complete copy*** of parent address space
    - ***Very costly*** in a virtual memory system
  - `exec()` thrashes that address space
- Best solution is copy-on-write (COW)

Copy-on-write

Parent and child share same address space



When either of them modifies a page,
other gets its ***own copy*** of original page



COW of original page

Copy-on-write as a lazy approach

- Copy-on-write postpones address space copying until it is actually needed
  - Do the strict minimum
- ***Lazy approach***
  - Betting that very little copying will be actually needed
    - An **`execv()`** will quickly follow
- Opposite is ***eager approach***

Observations (II)

- Neither **`fork()`** nor **`exec()`** affect opened file descriptors
  - They remain unchanged
- Important for UNIX I/O redirection mechanism

How this happened

- Fork was not that expensive on a minicomputer with a 16-bit address space
  - Never had to copy more than 64KB
- Using a fork/exec allowed a very easy implementation of I/O redirection
  - After the **`fork()`** thus in the child
  - Before the **`exec()`** while parent is still in control

A very basic shell (I)

```
for (;;) {
    parse_input_line(argv);
    if built_in(argv[0]) {
        do_it(arg_vector);
        continue;
     } //built_in command
     path = find_path(argv[0]);
```

A very basic shell (II)

```
        if ((pid = fork()) == 0) {
            // put here I/O
            // redirection code
            execv(path, argv);
            _exit(1); // execv failed
        } //child process
        if (interactive())
            while (wait(0) != pid);
} // main for loop
```

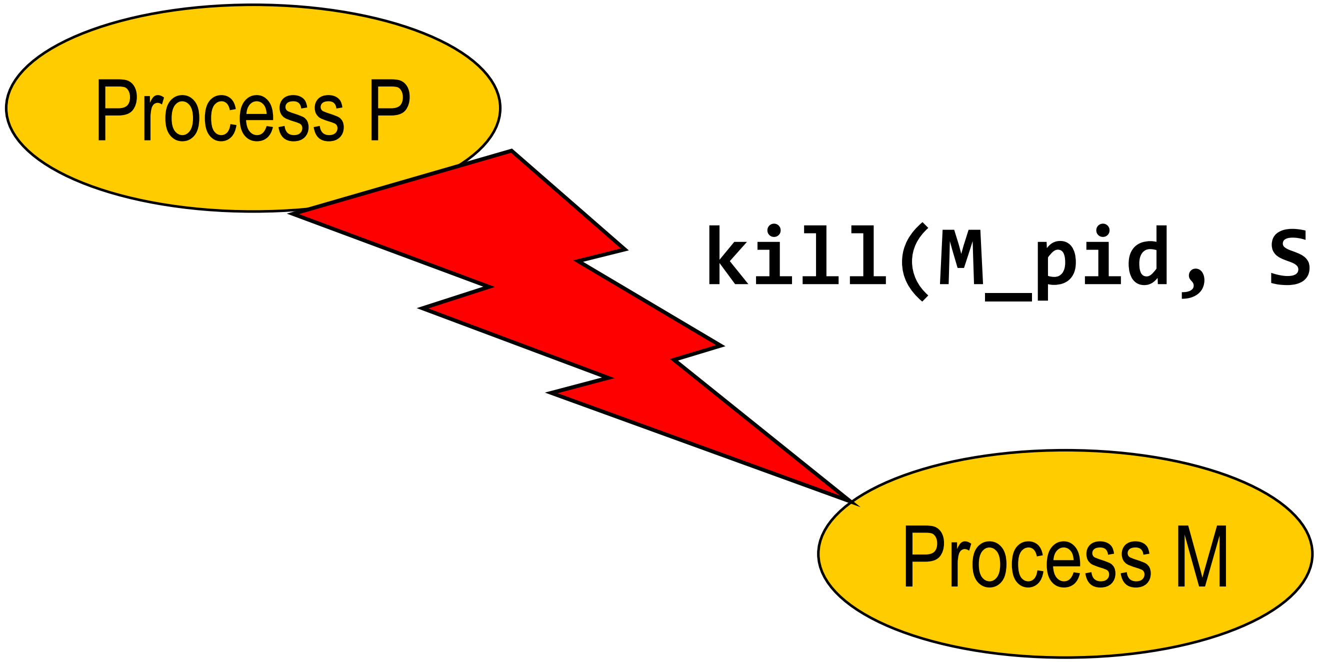
Comments

- Shell built-in commands include
  - `exit`
    terminates the shell
  - `cd`
    changes current directory
- Commands are assumed to be interactive
  - ***Non-interactive*** commands end with an "&"

Terminating a process (I)

- Sending a signal:
  - `kill()` has two arguments
    - The ***process id*** of the receiving process
    - A ***signal name*** or a ***signal number***
- ```
  #include <signal.h>
  kill(this_pid, this_signal);
  ```
- Process receiving the signal will ***terminate***
  ```

Terminating a process (II)



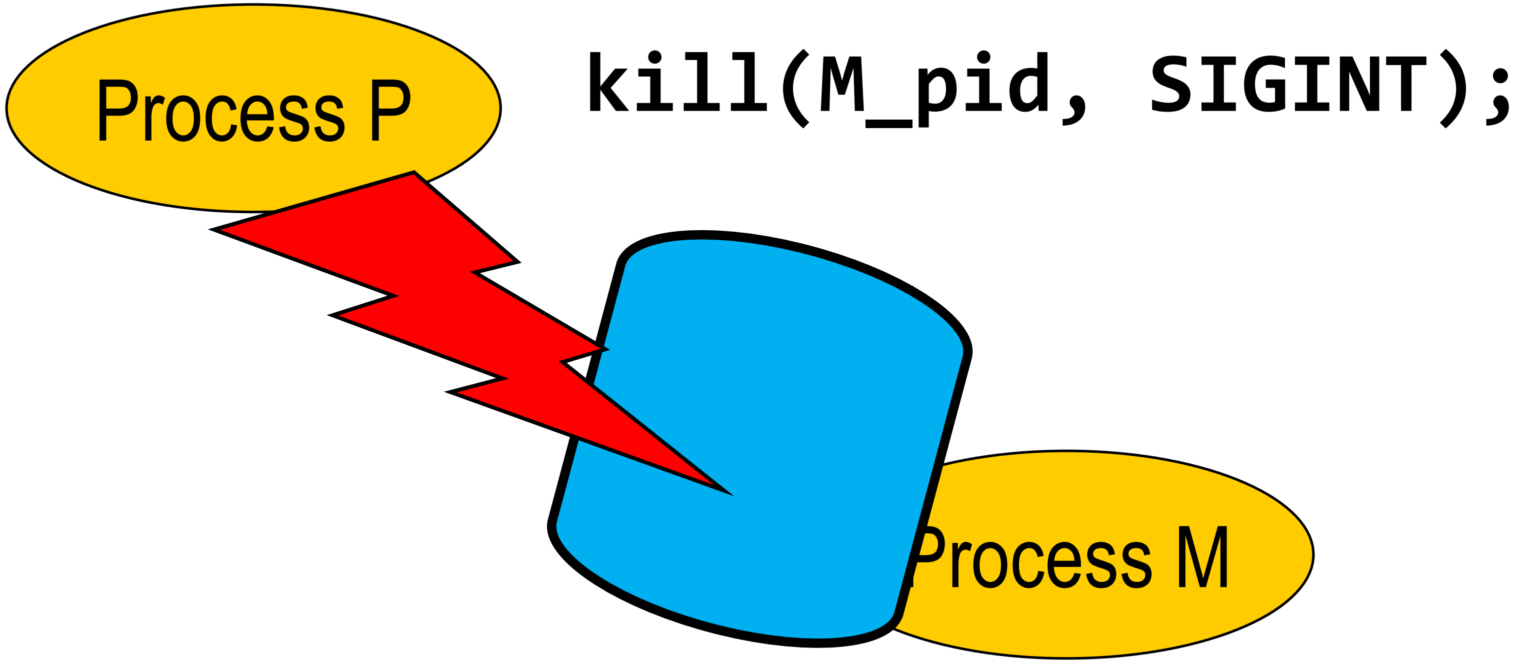
`kill(M_pid, SIGINT);`

What should I do? **AARGH!**

Catching a signal (I)

- The process receiving signal can ***catch*** it by using **`signal()`**
  - Will not terminate
- **`signal(a_signal, catch_it);`**
  - where **`catch_it`** points to a function that will be called whenever signal **`a_signal`** signal is received.
- The ninth signal, **`SIGKIL`**, cannot be caught.

Catching a signal (II)



Process is now **shielded** by **`signal()`** call

Lightweight processes/threads

Kernel supported threads, user-level threads, POSIX threads (pthreads)

Limitations of processes

- Single threaded server:
  - Processes one request at a time

```
for (;;) {
    receive(&client, request);
    process_request(...);
    send(client, reply);
} // for
```

A basic question

- ***What does a server do when it does not process client requests?***

Three good answers

- Nothing
- It waits for client requests
- It “sleeps”
  - ***Blocked state*** *is sometimes called the* ***sleep state***

The problem

- Most client requests involve disk accesses
  - File servers
  - Authentications servers
- When this happens, the server remains in the BLOCKED state
  - Cannot handle other customers' requests
- Could end doing nothing most of the time
- ***Poor throughput (and long delays)***

An analogy

- *In most fast-food restaurants, counter employees process customer orders one order at a time.*
- *Not be possible in a traditional restaurant*
  - *A server that would only be able to wait on one table at a time would be idle most of the time.*

A first solution

```
int pid;
for (;;) {
   receive(&client, request);
   if ((pid = fork())== 0) {
       process_request(...);
       send(client, reply);
       _exit(0); // done
   } // if
} // for
```

The good and the bad news

- ***The good news:***
  - Server can now handle several user requests in parallel
- ***The bad news:***
  - `fork()` is a ***very expensive*** system call
    - Has to create a new address space

A better solution

- Provide a faster mechanism for creating cheaper processes:
  - ***Lightweight processes***
  - ***Threads***

How?

- Lightweight processes and threads ***share the address space of their parent***
  - ***No need to create a new address space***
    - Most expensive step of **`fork()`** system call

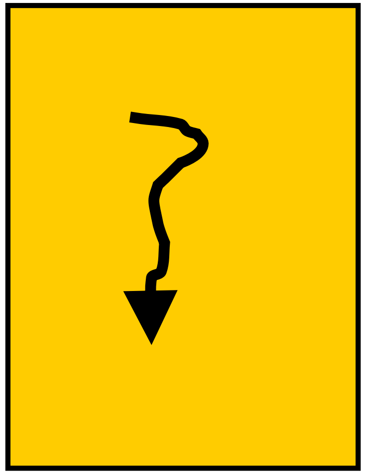
Is it not dangerous?

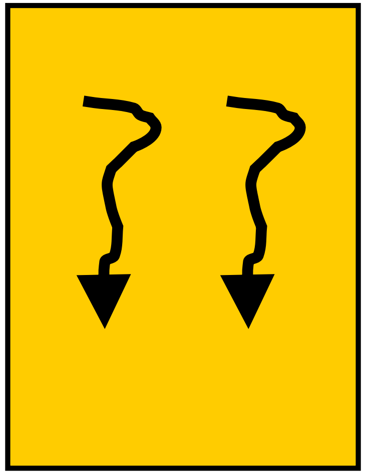
- ***To some extent because***
  - No memory protection inside an address space
  - Lightweight processes can now interfere with each other
- ***But***
  - All lightweight process code is written by the same team

General Concept (I)

- A ***thread*** or *l**ightweight process***
  - Does ***not*** have its ***own address space***
  - Shares it with its parent and other peer threads in the same address space (***task***)
- Each thread has a ***program counter***, a ***set of registers*** and its ***own stack***.
  - *Everything else is shared*

General Concept (II)





- A regular process (single-threaded)
- A process containing several threads

Implementation

- Threads and LWPs can either be
  - ***Kernel supported:***
    - Mach, Linux, Windows NT and after
  - ***User-level:***
    - Pthread library, …

Kernel-Supported Threads (I)

- Managed by the kernel through system calls
- One process table entry per thread
- This is the best solution for *multiprocessor architectures*
  - Kernel can allocate ***several processors*** to a ***single multithreaded task***

Kernel-Supported Threads (II)

- Supported by Mach, Linux, Windows NT and more recent systems
- ***Performance Issue:***
  - Switching between two threads in the same task involves a system call
  - Results in ***two context switches***

Linux Threads

FYI

- `clone (fn, stack, flags)`

  where
  - `fn` specifies function to be executed by new thread or process
  - `stack` points to the stack it will use
  - `flags` is a set of flags specifying various options
    - `CLONE_VM` for threads
    - Regular process if `CLONE_VM` is missing

User-Level Threads (I)

- User-level threads are managed by procedures **within** the task address space
  - The ***thread library***
- One process table entry per task/address space
  - Kernel is not even aware that process is multithreaded

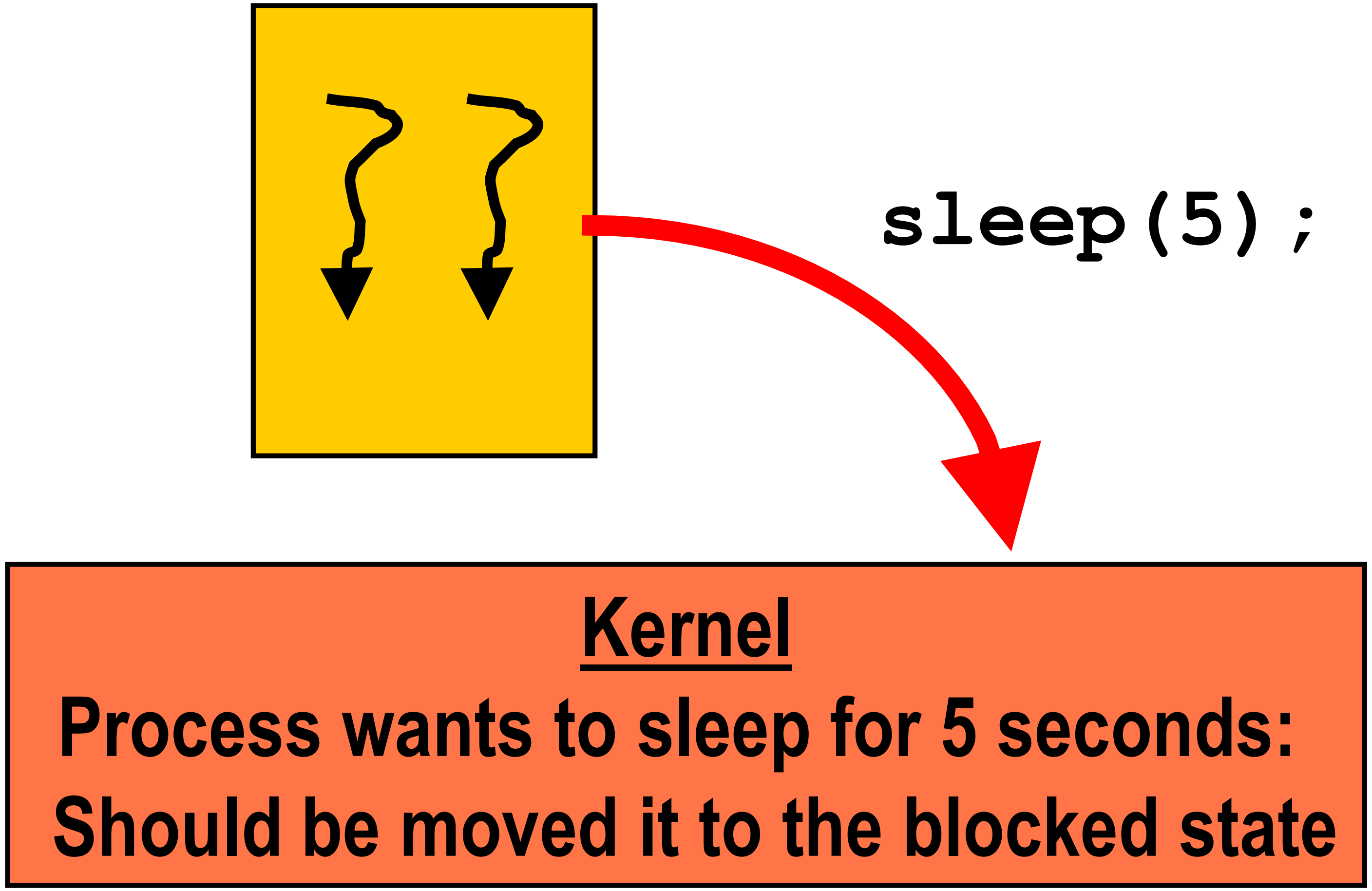
User-Level Threads (II)

- Can be retrofitted into an OS lacking thread support
  - Portable thread libraries
- ***No performance penalty:***
  - Switching between two threads of the same task is done cheaply within the task
  - Same cost as a procedure call

User-Level Threads (III)

- ***Programming issue:***
  - Each time a thread does a ***blocking system call***, kernel will move the ***whole process*** to the ***blocked state***
    - It does not know better
  - Must then use ***non-blocking*** system calls
    - *Complicates programmer's task*

User-Level Threads (IV)



POSIX Threads

- POSIX threads, or ***pthreads***, started as pure user-level threads managed by the POSIX thread library
  - Gained later ***some kernel support***
- Ported to various Unix and Windows systems (***Pthreads-win32***).
- Function names start with **`pthread_`**
- Calls tend to have a complex syntax

An Example (I)

FYI

```
#include <pthread.h>
static int count[2];
```

Static variables are shared by all threads

Other variables are stored on the private stack of each thread.

An Example (II)

FYI

```
void *child(void *arg) {
    int index;
    index = (int) arg;  // required
    for(;;) {
        printf("Child count: %d\n",
             ++count[index]);
      sleep(1); // one second delay
     } // for loop
} // child
```

An Example (III)

FYI

```
int main() {
    thread_t tid; // thread id
    int i = 0;
    pthread_create(&tid, NULL,
                   child, (void *) i);
    // pthread will execute
    // "child" function
```

NULL *stack address specifies a new stack "anywhere"*

An Example (IV)

FYI

```
    i++; // now i == 1
    while (count[i] < 12) {
        printf("Parent count: %d\n", ++count[i]);
        sleep(1); // one second delay
    } // while loop
    return 0;
} // main
```

Understanding pthread_create()

FYI

- **`pthread_create()`** has four arguments
  - **`&tid`**
    - Placeholder for **`thread_id`**
  - **`NULL`**
    - Stack address of new stack
    - **`NULL`** means can be put “anywhere”
  - **`start_function`**
    - Void pointer to a function
  - **`(void *) arg`**
    - Sole argument passed to **`start_function`**

Comparing the approaches

Feature	***Kernel threads***	***User-level threads***
Portability		
Multiprocessing		
Performance		
Ease of use		

Which approach is the most portable?

Feature	***Kernel threads***	***User-level threads***
Portability		☑
Multiprocessing		
Overhead		
Ease of use		

Which approach handles best multicores?

Feature	***Kernel threads***	***User-level threads***
Portability		☑
Multiprocessing	☑	
Overhead		
Ease of use		

Which approach has the lowest overhead

Feature	***Kernel threads***	***User-level threads***
Portability		☑
Multiprocessing	☑	
Overhead		☑
Ease of use		

Which approach is easier to use?

Feature	***Kernel threads***	***User-level threads***
Portability		☑
Multiprocessing	☑	
Overhead		☑
Ease of use	☑	

Conclusion

- No clear winner between kernel-supported and user-level threads
- Solaris (from Sun, now taken over by Oracle)
  - Supports both ***user-level threads*** and ***kernel threads***
  - Lets programmers combine them as they need