Chapter II
Processes

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Chapter Overview

- Processes
- States of a process
- Operations on processes
  - `fork()`, `exec()`, `kill()`, `signal()`
- Cooperating Processes
- Threads and lightweight processes
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
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
A very basic UNIX shell

```c
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

- Processes go repeatedly through several stages during their execution
  - Waiting to get into main memory
  - Waiting for the CPU
  - Running
  - 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
- These processes are said to be *swapped out* or *suspended*. 
How it works

- **New** → **Ready**
  - Admit process
  - Get CPU
- **Ready** → **Running**
  - Interrupt
  - Completion
- **Running** → **Terminated**
  - Exit
- **Ready** → **Blocked**
  - Deactivate
- **Blocked** → **Suspended**
  - Deactivate
- **Suspended** → **Blocked**
  - Completion
- **Suspended** → **Ready**
  - Activate
- **Ready** → **Suspended**
  - Deactivate
  - 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 is a **desperate measure**
OPERATIONS ON PROCESSES

- Process creation
  - fork()
  - exec()
  - The argument vector

- Process deletion
  - 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)

- The first process of a system is created when the system is booted.
- All other processes are forked by another process (**parent process**) (children).
  - They are said to be **children** of the process that created them.
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

Child:
fork()
returns 0

opened files
First example

```cpp
#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

```c
... fork();
cout ...;
...
```

```c
cout ...;
...
```
Second example

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

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

```c
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
```
Notes

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

  is a loop with an **empty body**
Putting everything together

```c
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;`

```
argv
argv[0]
argv[1]
NULL
```

```
“ls”
“-alg”
```
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

```c
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
  - \texttt{fork()} makes a \textit{complete copy} of parent address space
  - \textbf{Very costly} in a virtual memory system
  - \texttt{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
  - Bets 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>`
    ```c
    kill(this_pid, this_signal);
    ```
- Process receiving the signal will *terminate*
Terminating a process (II)

```
kil(Q_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)

```c
kill(Q_pid, SIGINT);
```

Process is now *shielded* by `signal()` call
Limitations of processes

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

```c
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
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 waitperson that would only be able to wait on one table at a time would be idle most of the time.
A first solution

```c
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 lightweight 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

- Thread 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 (I)

- Created through:
  
  \[ \text{clone (fn, stack, flags)} \]

  where

  - `fn` specifies function to be executed by the 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)
Linux Threads (II)

- If the `CLONE_VM` flag is missing, Linux creates a regular process with its own address space.
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
    - *Can be nasty*
User-Level Threads (IV)

Kernel

Process wants to sleep for 5 seconds:
Should be moved it to the blocked state

sleep(5);
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)

#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.
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)

```c
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)

```c
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()

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

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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