

# Systems and Networking I

Applied Computer Science and Artificial Intelligence  
2025-2026



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# OS Process Management So Far...

- How the OS abstracts processes from physical memory
  - Virtual Address Space (VAS)
- In which state a process can be while it is managed by the OS
- What data structure the OS uses to keep track of each process info
  - Process Control Block (PCB)

# Outline

- Process creation
- Process termination
- Process scheduling
- Process communication

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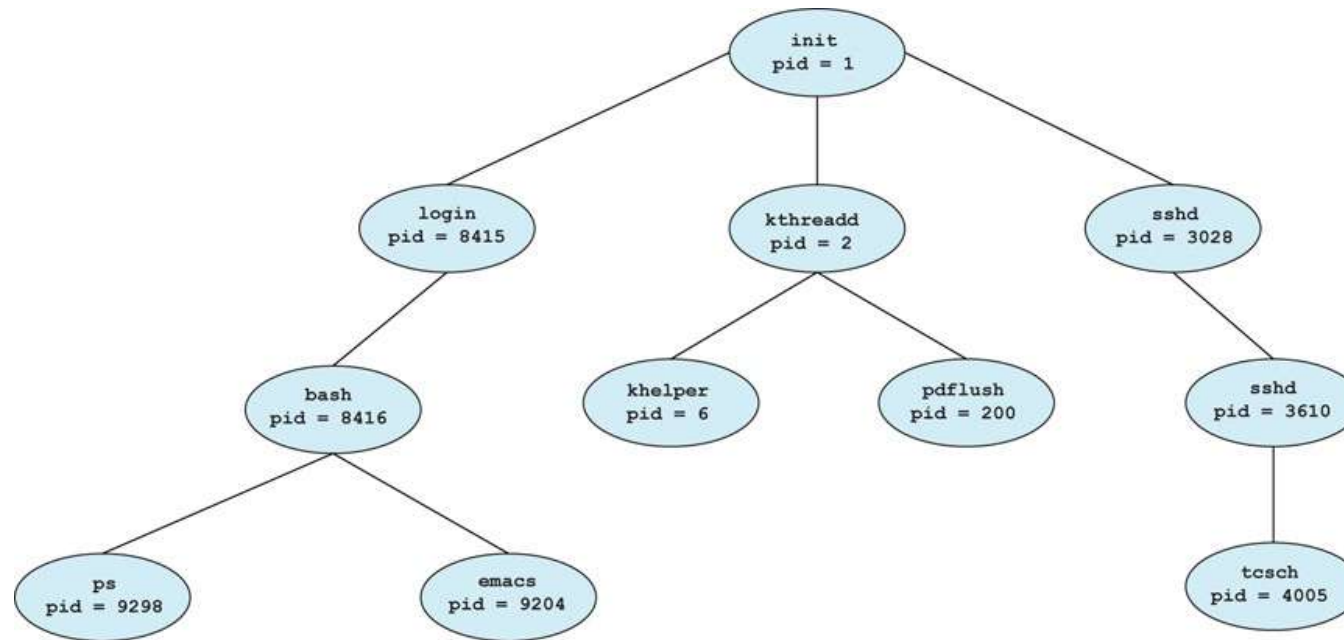
# Process Creation

- Processes may create other processes through specific system calls
  - The creator process is called **parent** of the new process, which is called **child**
  - The parent shares resources and privileges to its children
  - A parent can either wait for a child to complete, or continue in parallel
- Each process is given an integer **identifier** (a.k.a. process identifier or PID) and a parent ID (PPID)

# Process Creation: UNIX/Linux

- On typical UNIX systems the process scheduler is named **sched**, and is given PID 0
- The first thing it does at system startup time is to launch **init**, which gives that process PID 1
- **init** then launches all system daemons and user logins, and becomes the ultimate parent of all other processes
- Processes are created through the **fork()** system call

# Process Creation: UNIX/Linux



# Process Creation: Parent vs. Child Resources

- Relatively to the parent, the address space of the child process can be:
  - **Duplicated** (UNIX/Linux `fork()`)
  - **Brand New** (Windows `spawn()`)

# Process Creation: Parent vs. Child Resources

- When the child is an exact **duplicate of the parent**
  - It shares the same program and data segments in memory
  - Still, each process will have its own PCB, including program counter, registers, and PID

# Process Creation: Parent vs. Child Resources

- When the child contains an **brand new program**
  - Its address space has new code and data segments
  - UNIX systems implement this as a second step, using the **exec** system call

# Process Creation: Parent vs. Child Execution

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  1. Wait for the child to terminate before proceeding



# Process Creation: Parent vs. Child Execution

- **2 options** for the parent after creating the child:
  1. Wait for the child to terminate before proceeding
    - The parent makes a `wait()` system call, for either a specific child or for any child
    - This causes the parent process to block until the `wait()` returns
    - Usual behavior of UNIX shell that normally waits for their children to complete before issuing a new prompt ">"

# Process Creation: Parent vs. Child Execution

- **2 options** for the parent after creating the child:
  2. Run concurrently with the child, continuing to process without waiting (and blocking)
    - This is the operation seen when a UNIX shell runs a process as a background task "&"
    - The parent may also run for a while, and then wait for the child later, which might occur in a sort of a parallel processing operation

# Process Creation: UNIX/Linux Code

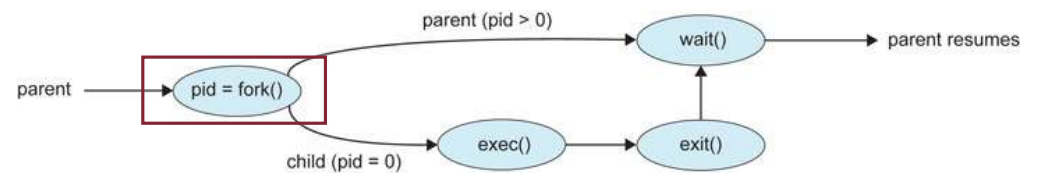
```
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>

int main()
{
    pid_t pid;

    /* fork a child process */
    pid = fork();

    if (pid < 0) { /* error occurred */
        fprintf(stderr, "Fork Failed");
        exit(-1);
    }
    else if (pid == 0) { /* child process */
        execlp("/bin/ls", "ls", NULL);
    }
    else { /* parent process */
        /* parent will wait for the child to complete */
        wait(NULL);
        printf("Child Complete");
        exit(0);
    }
}
```

Figure 3.10 C program forking a separate process.



# Process Creation: UNIX/Linux Code

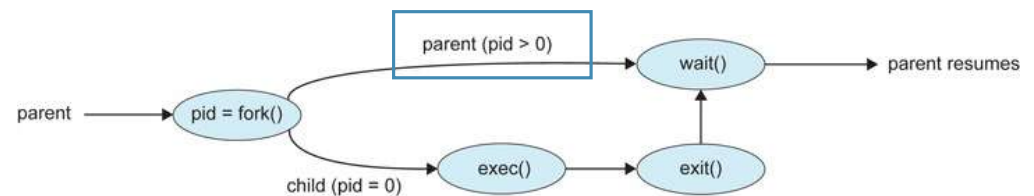
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        printf("Child Complete");
        exit(0);
    }
}
```

Figure 3.10 C program forking a separate process.



In the parent process, **fork()** returns the PID of the child

# Process Creation: UNIX/Linux Code

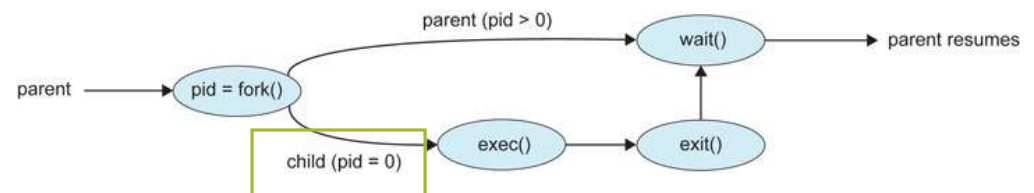
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#include <stdio.h>
#include <unistd.h>

int main()
{
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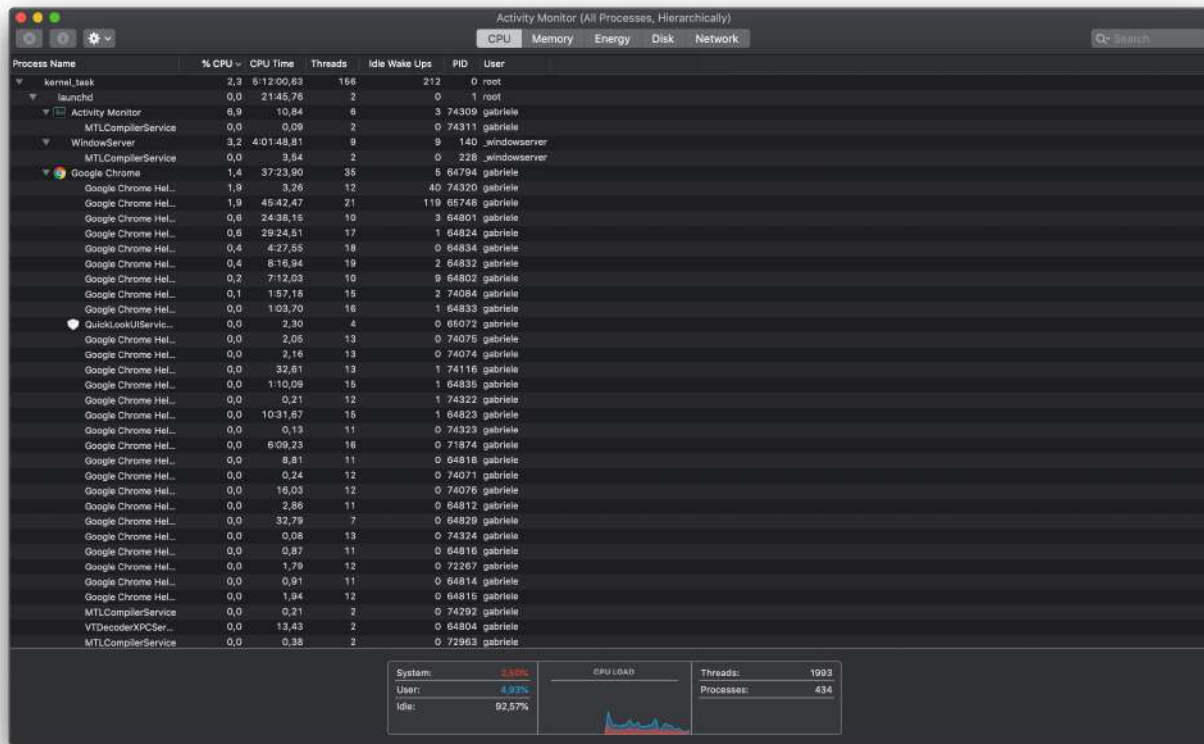
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    }
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    }
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Figure 3.10 C program forking a separate process.



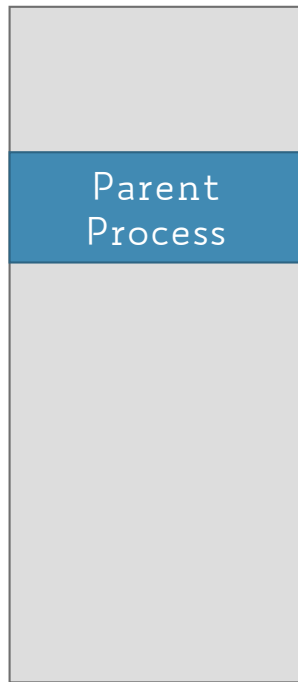
In the child process, it returns 0

# Process Creation: Activity Monitor



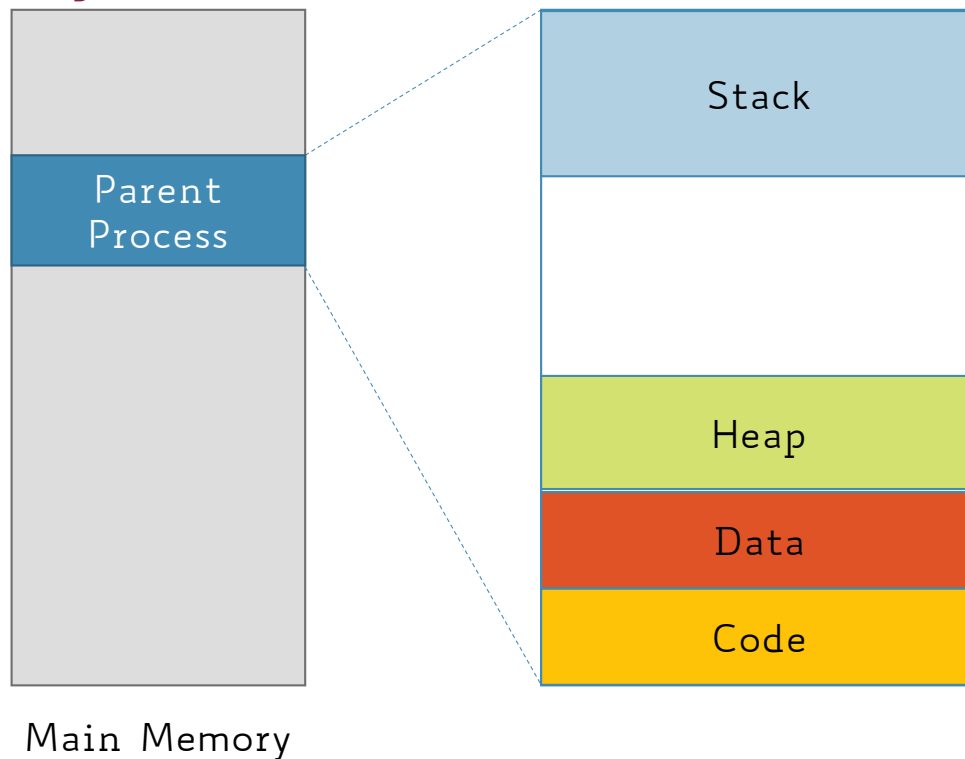
Hierarchy of  
Processes  
(i.e., process tree)

# Process Creation: Parent vs. Child Layout



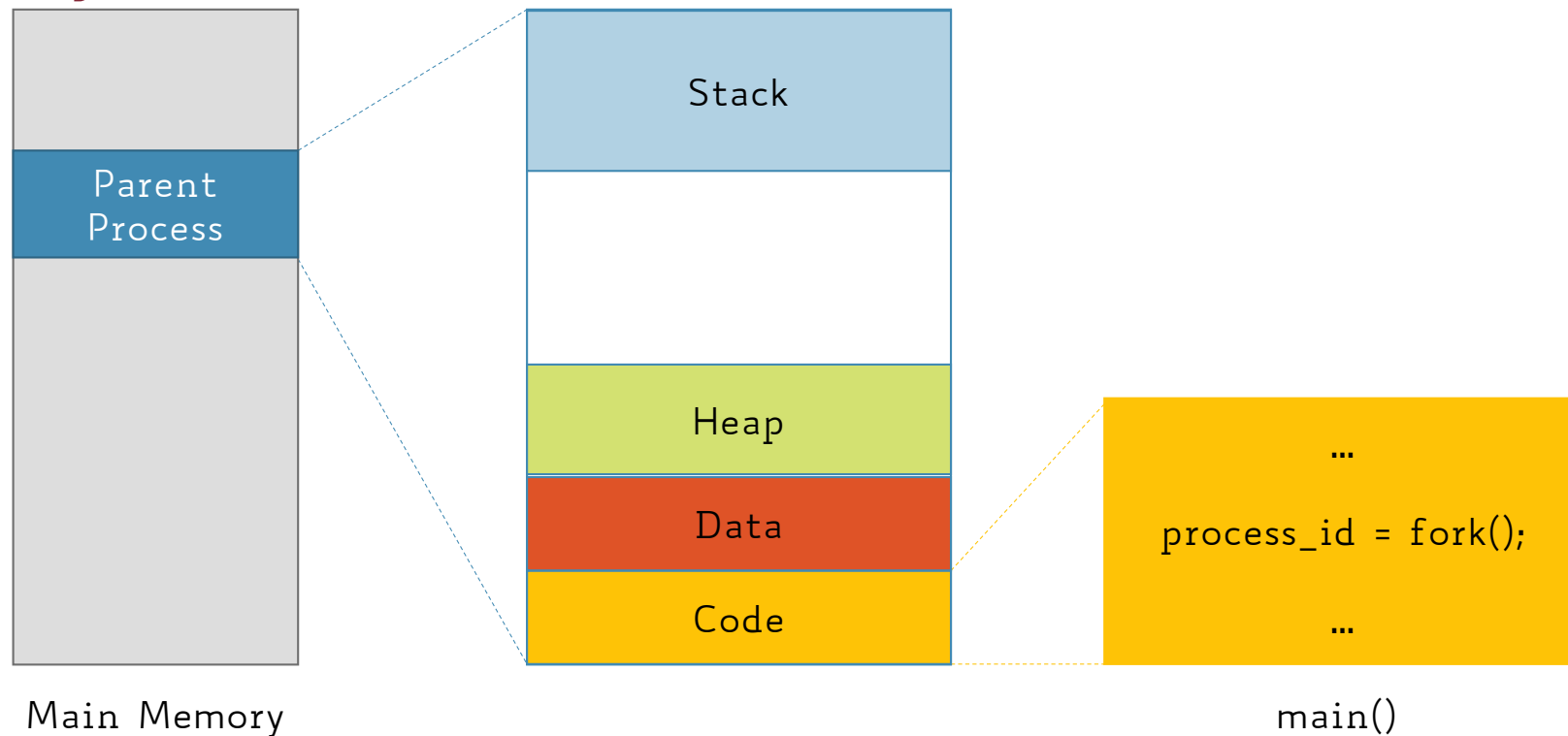
Main Memory

# Process Creation: Parent vs. Child Layout

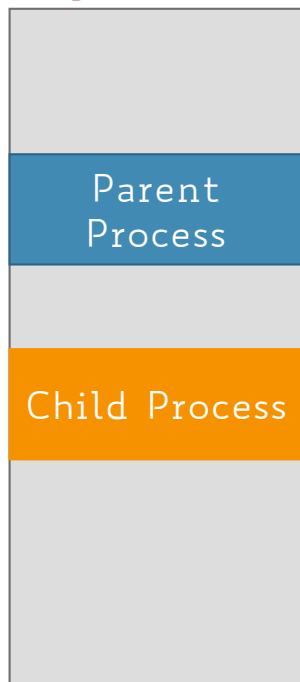




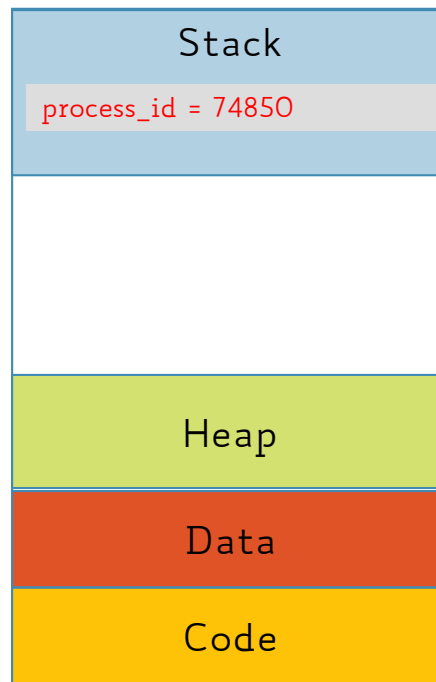
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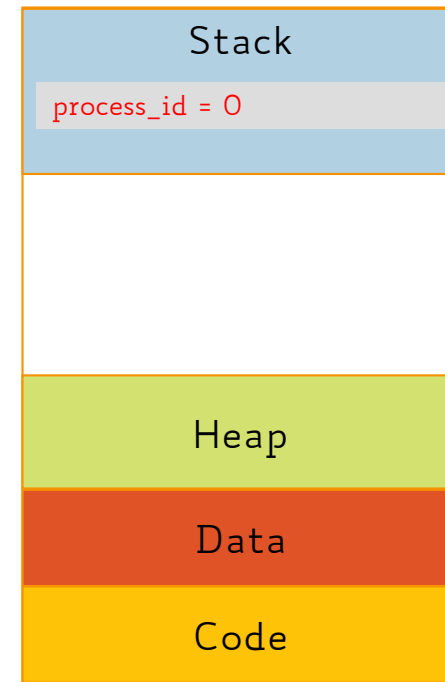
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Main Memory

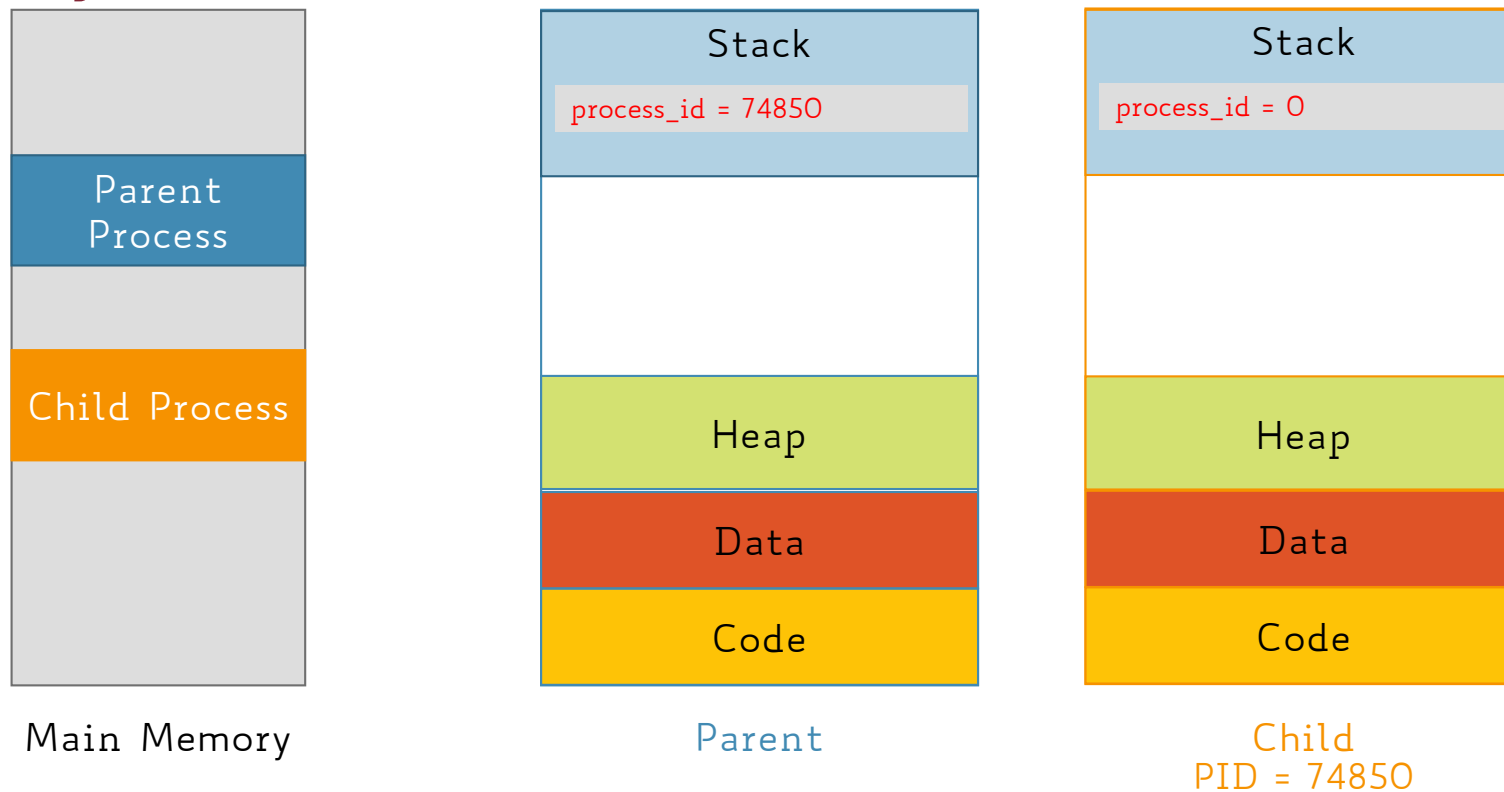


Parent



Child

# Process Creation: Parent vs. Child Layout

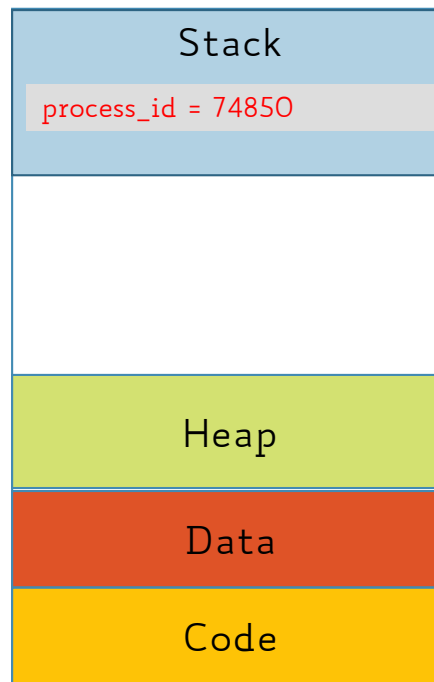


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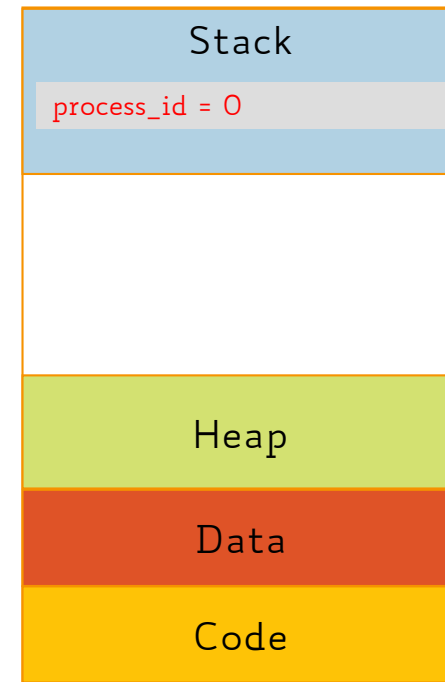
Main Memory

02/10/2025



Parent

PID = 74849



Child

PID = 74850

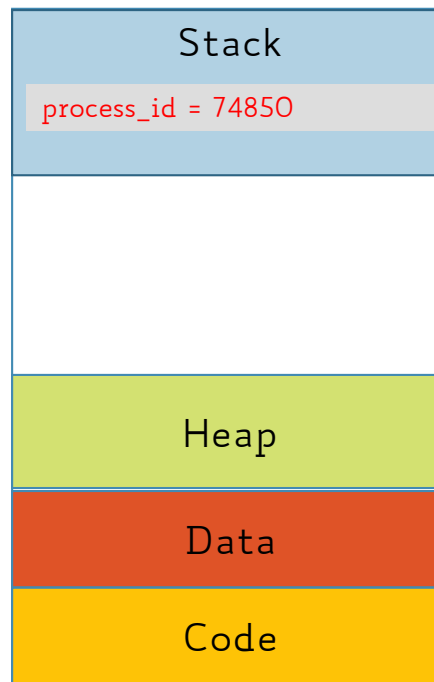
parentID = 74849

# Process Creation: Parent vs. Child Layout



Main Memory

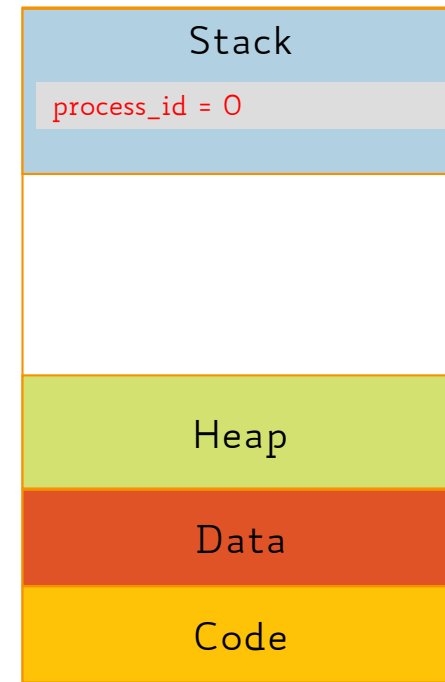
02/10/2025



Parent

PID = 74849

parentID = 65784



Child

PID = 74850

parentID = 74849

29

# Process Creation: Code Example

```
1  #include <iostream>
2  #include <unistd.h>
3
4  using namespace std;
5
6  int main() {
7
8      cout << "Current process ID is: " << getpid() << endl;
9      cout << "\nCurrent parent's process ID is: " << getppid() << endl;
10
11     int pid;
12     pid = fork();
13     // once the fork() system call returns,
14     // both the parent and the child processes will resume from this point onward
15
16     if (pid == 0) { // child
17         cout << "\nThis is the child process with process ID = "
18             << getpid() << endl;
19         cout << "\nThis is the child process with parent's process ID = "
20             << getppid() << endl;
21     }
22     else { // parent
23         sleep(1); // to ensure the child process finishes before the parent
24
25         cout << "\nThis is the parent process with process ID = "
26             << getpid() << endl;
27         cout << "\nThis is the parent process with parent's process ID = "
28             << getppid() << endl;
29     }
30
31     return 0;
32 }
```

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32 }
```

What happens if the child sleeps rather than the parent?

# Process Creation: What's Next?

- So far, we have seen how `fork` system call is able to make a complete copy of an existing process
- However, this ability alone is not that useful, right?
- Our ultimate goal is to create new yet different processes, not just copies of a single one!



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  - the former duplicates process, whilst the latter execute the new process
  - e.g., try typing emacs on your shell

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  - the former duplicates process, whilst the latter execute the new process
  - e.g., try typing emacs on your shell
- **NOTE:** adding "&" at the end of the command will run the child process in parallel with the parent shell (background)

# Process Creation and Execution: Example

```
1 #include <iostream>
2 #include <unistd.h>
3 #include <sys/wait.h>
4 #include <stdio.h>
5 #include <string.h>
6
7 using namespace std;
8
9 int main() {
10
11     int current_pid = getpid();
12     cout << "Current process ID is: " << current_pid << endl;
13
14     string progStr;
15     // read the name of the program we want to start
16     getline(cin, progStr);
17     const char *prog = progStr.c_str();
18
19     int pid = fork();
20
21     if (pid == 0) { // child
22         execlp(prog, prog, 0); // load the program
23         // if prog can actually be started, we will never get to the
24         // following statement, as the child process will be replaced by prog!
25         printf("Can't load the program %s\n", prog);
26     }
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29         waitpid(pid, 0, 0); // wait for child process to terminate
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`execlp` loads the program  
whose name is read from  
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int execlp(const char *file, const char *arg, ...);
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```

path to executable

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```

argv[0]

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```

`waitpid` allows the parent  
to wait for a child  
process to finish

```
pid_t waitpid(pid_t pid, int *status, int options);
```



# Process Creation and Execution: Exercise

How do we create the following process hierarchy using `fork` and possibly `exec`?



# Process Creation and Execution: Exercise

How do we create the following process hierarchy using fork and possibly exec?



```
int pid = fork();
if(pid == 0) { // A's child (B)
    pid = fork();
    if(pid == 0) { // B's child (C)
        ...
        execlp(...);
    }
    else { // B
        ...
    }
}
else { // A
    ...
}
```

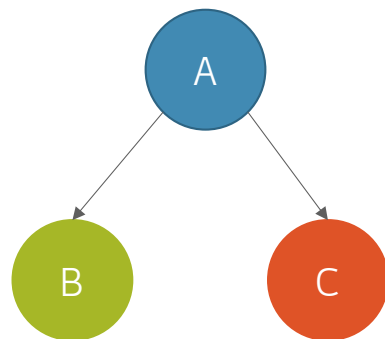
# Process Creation and Execution: Exercise

More generally, we will need  $n-1$  `fork` and `if-else`  
if we want to create a sequence of  $n$  processes



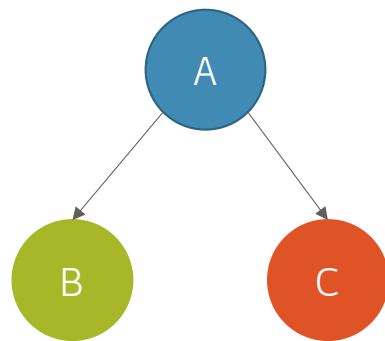
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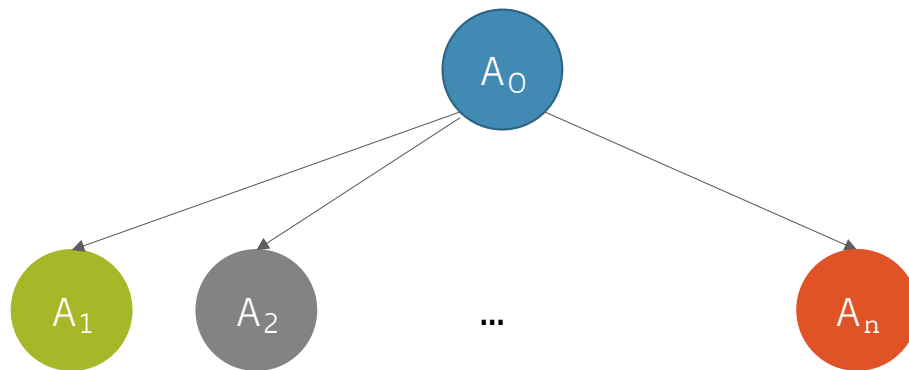


Left-to-Right (by convention)

```
int pid = fork();  
if(pid == 0) { // A's child (B)  
    ...  
    execlp(...);  
}  
else { // A  
    pid = fork();  
    if(pid == 0) { // A's child (C)  
        ...  
        execlp(...);  
    }  
}
```

# Process Creation and Execution: Exercise

More generally, if we want to create  $n$  child processes all having the same parent



```
for(int i=0;i<n;i++) {  
    if(fork() == 0) { // A0's child  
        ...  
        execlp(...);  
    }  
    // else we are in the parent: keep forking  
}  
// back in the parent A0  
  
// wait for all children to terminate  
for(int i=0;i<n;i++) {  
    wait(NULL);  
}
```

# Process Creation and Execution: Be Careful!

What will happen if we do the following?

```
while(1) {  
    fork();  
}
```

# Process Creation and Execution: Be Careful!

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```

Infinite number of child processes  
growing with an exponential rate



# Recap of System Calls Seen So Far

- `fork` → spawn a new child process as an exact copy of the parent

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# Recap of System Calls Seen So Far

- `fork` → spawn a new child process as an exact copy of the parent
- `execlp` → replaces the program of the current process with the input named program
- `sleep` → suspends the execution for a certain amount of seconds
- `wait/waitpid` → wait for any/a specific process to finish execution

# Outline

- Process creation
- **Process termination**
- Process scheduling
- Process communication

# Process Termination

- Processes may request **their own** termination by making the **exit** system call, typically returning an int
- This int is passed along to the parent if it is doing a **wait**
- It is usually 0 on successful completion and some non-zero in the event of problems

# Process Termination

- Processes may also be terminated by the system for a variety of reasons:
  - The inability of the system to deliver necessary system resources
  - In response to a `kill` command, or other un handled process interrupt

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  - The inability of the system to deliver necessary system resources
  - In response to a `kill` command, or other un handled process interrupt
- A parent may kill its children if the task assigned to them is no longer needed



# Process Termination

- If the parent exits, the system may or may not allow the child to continue without a parent

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- On UNIX systems, **orphaned** processes are generally inherited by **init**, which then proceeds to kill them

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- The process termination status and execution times are returned to the parent if this is waiting for the child to terminate
- Or eventually to `init` if the process becomes an **orphan**

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- Processes which are trying to terminate but cannot because their parent is not waiting for them are called **zombies**

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- Eventually inherited by **init** as orphans and killed

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# Process Scheduling

- **2 main goals** of the process scheduling system:
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- **2 main goals** of the process scheduling system:
  - i. keep the CPU busy at all times
  - ii. deliver "acceptable" response times for all programs, particularly for interactive ones

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- The process scheduler must meet these objectives by implementing suitable policies for swapping processes in and out of the CPU

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- The process scheduler must meet these objectives by implementing suitable policies for swapping processes in and out of the CPU
- Note that these objectives can be conflicting!
  - Every time the OS steps in to swap processes it takes up time on the CPU to do so, which is thereby "lost" from doing any useful productive work

# Process State Queues

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- The OS maintains the PCBs of all the processes in state queues
- There is one queue for each of the **5 states** a process can be in
- There is typically one queue for each I/O device (where processes wait for sending/receiving data to/from a device)

# Process State Queues

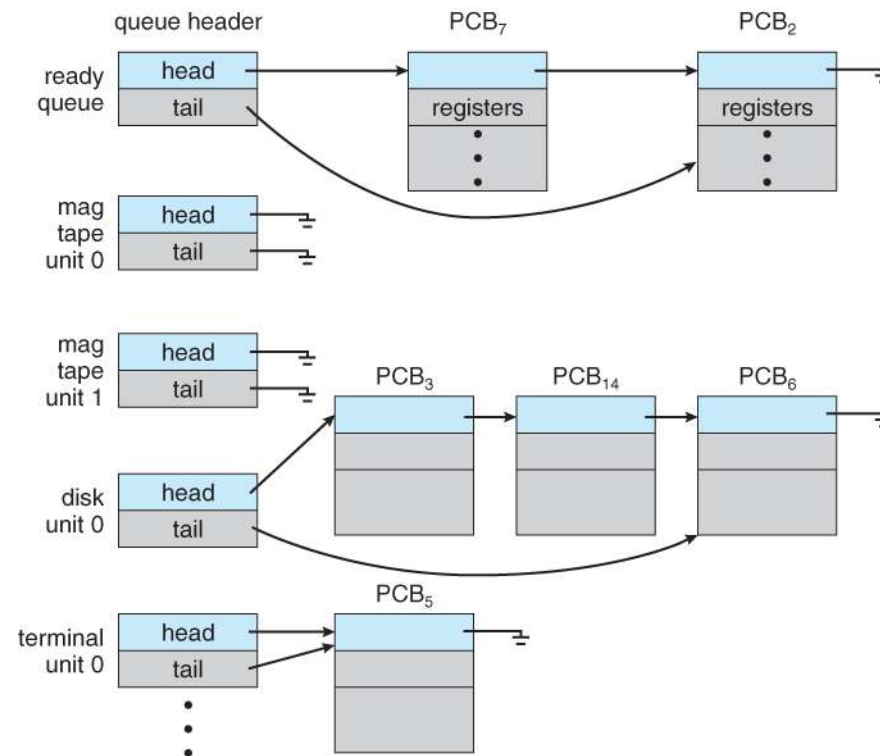
- The OS maintains the PCBs of all the processes in state queues
- There is one queue for each of the **5 states** a process can be in
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- The OS may use different policies to manage each state queue

# Process State Queues: Example



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  - The Running Queue is bound by the number of cores available on the system
  - At each time, only one process can be executed on a CPU
- What about the other queues?
  - They are basically unbounded as there is no theoretical limit on the number processes in new/ready/waiting/terminated states

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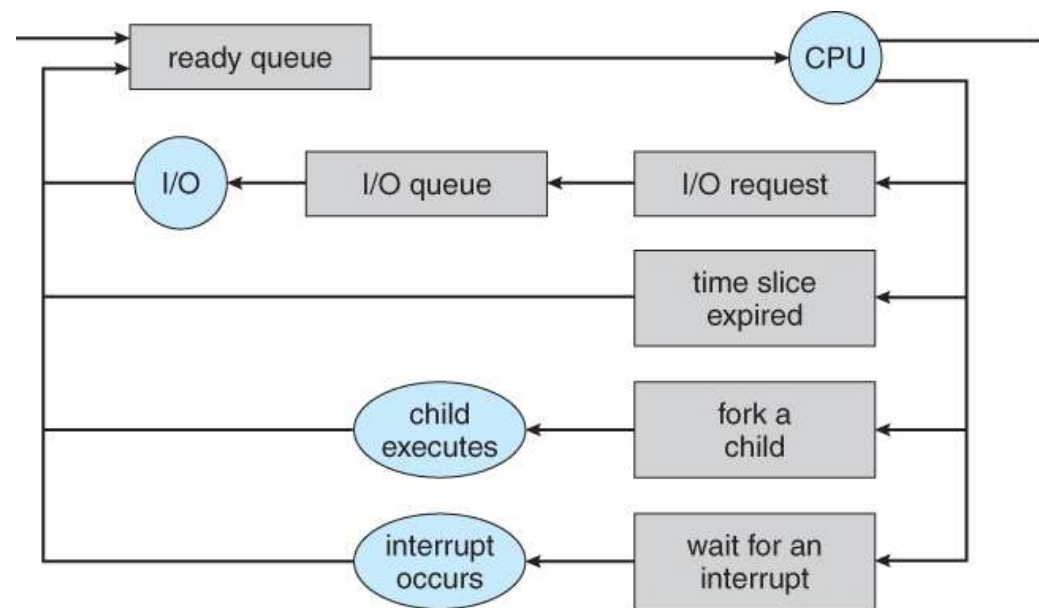
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- When system loads get high, a medium-term scheduler allows smaller faster jobs to finish up quickly and clear the system
- An efficient scheduling system will select a good mix of CPU-bound processes and I/O bound processes

# Schedulers: Queuing Diagram



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- It is a highly costly operation because:
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- A context switch occurs due to any incoming trap
  - system calls, exceptions, or HW interrupts
- Whenever a trap arrives, the CPU must:
  - perform a state-save of the currently running process
  - switch into kernel mode to handle the interrupt
  - perform a state-restore of the interrupted process



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- I/O-bound processes eventually get switched due to I/O requests
- CPU-bound processes, instead, could theoretically never issue any I/O requests
- To avoid CPU-bound processes hog the CPU, context switch is also triggered via HW timer interrupts (**time quantum** or **slice**)

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- To ensure that at least a context switch occurs every, say, 50 ms
- In practice, it can happen more frequently than that (e.g., due to I/O requests)

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- Can be easily implemented in HW through timer interrupt
- Mechanism used by modern time-sharing multi-tasking OSs to increase system responsiveness (**pseudo-parallelism**)



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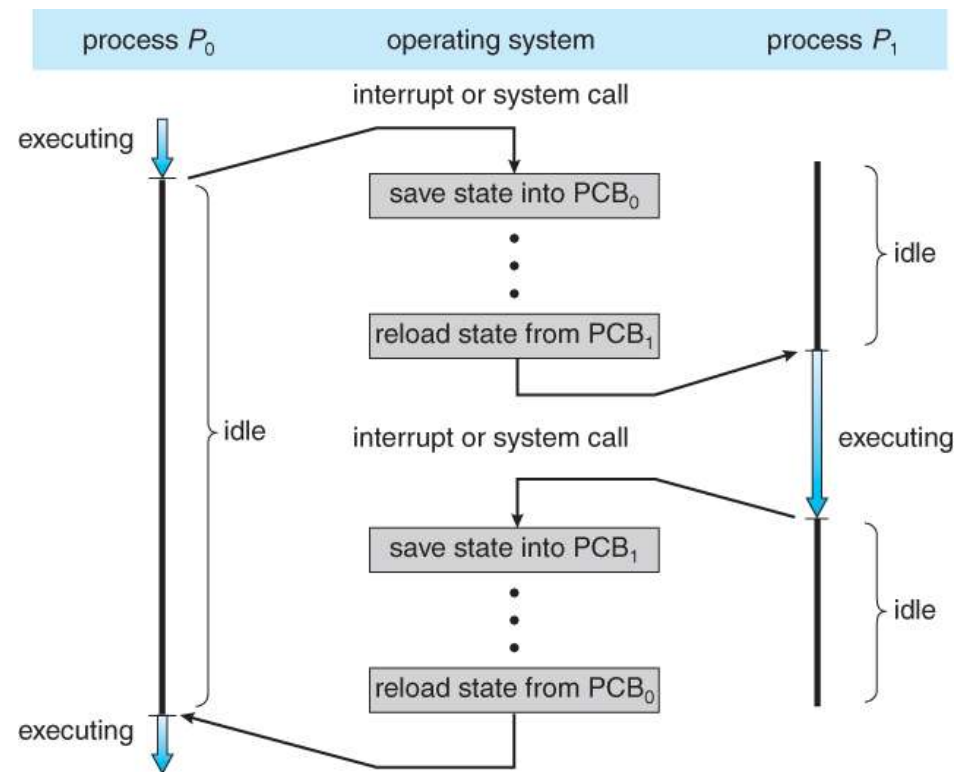
## Trade-off

- A smaller time slice results in more frequent context switches
  - **maximizing responsiveness**
- A larger time slice results in less frequent context switches
  - minimizing wasted CPU time, therefore **maximizing CPU utilization**

# Context Switch: A Few Numbers

- Typical values of time slice range between 10 and 100 ms
- Context switch takes around 10  $\mu$ s, so the overhead is small relative to time slice
- $10^{-2}$  to  $10^{-1}$  vs.  $10^{-8}$  seconds

# Context Switch: Example



# Outline

- Process creation
- Process termination
- Process scheduling
- **Process communication**

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- Processes can be either **independent** or **cooperating**
- **Independent processes** → operate concurrently on a system and can neither affect or be affected by other processes
- **Cooperating processes** → can affect or be affected by other processes in order to achieve a common task

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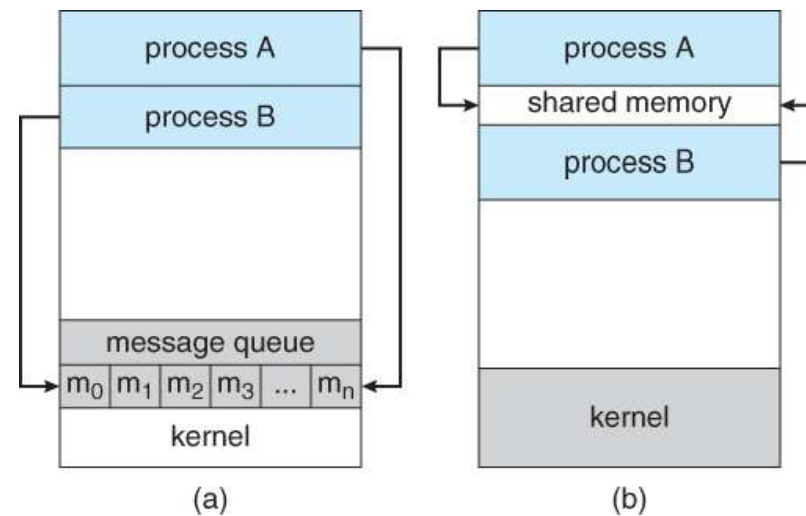
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# Cooperating Processes: Why?

- **Information sharing** → There may be several processes which need access to the same file (e.g., pipelines)
- **Computation speedup** → A problem can be solved faster if it can be broken down into sub-tasks to be solved simultaneously
- **Modularity** → The most efficient architecture may be to break a system down into cooperating modules
- **Convenience** → Even a single user may be multi-tasking, such as editing, compiling, printing, and running the same code in different windows

# Cooperating Processes: Communication

- 2 possible ways for cooperating processes to communicate:



Message Passing

Shared Memory

# Shared Memory vs. Message Passing

- **Shared Memory**

- Faster once it is set up, as no system calls are needed
- More complicated to set up, and doesn't work as well across multiple computers
- Preferable when (large amount of) information must be shared on the same computer



# Shared Memory vs. Message Passing

- Message Passing

- Slower as it requires system calls for every message transfer
- Simpler to set up and works well across multiple computers
- Preferable when the amount and/or frequency of data transfers is small, or when multiple computers are involved

# Shared Memory Systems

- The memory to be shared is initially within the address space of a particular process
- This needs to make system calls in order to make that memory publicly available to other processes
- Other processes must make their own system calls to attach the shared memory onto their address space

# Message Passing Systems

- Must support at least system calls for sending and receiving messages
- A communication link must be established between the cooperating processes before messages can be sent
- **3 key issues** to be solved:
  - **Naming** → Does the sender talk directly to a process, or indirectly via mailbox/queue?
  - **Timing** → Do send/receive block (synchronous) or not (asynchronous)?
  - **Storage** → Who provides buffering (automatic/system vs. explicit/programmer), and how much? (zero, bounded, unbounded)

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- Scheduling policies to maximize CPU utilization for process execution
- **Context switch** to intertwine the execution of multiple processes
- Process communication either via **shared memory** or **message passing**