Systems and Networking I

Applied Computer Science and Artificial Intelligence

2023-2024

Gabriele Tolomei

Dipartimento di Informatica

Sapienza Università di Roma

tolomei@di.uniroma1.it

SAPIENZA
UNIVERSITÀ DI ROMA

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

Outline

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

Process Creation

- Processes may create other processes through specific system calls

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**

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

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

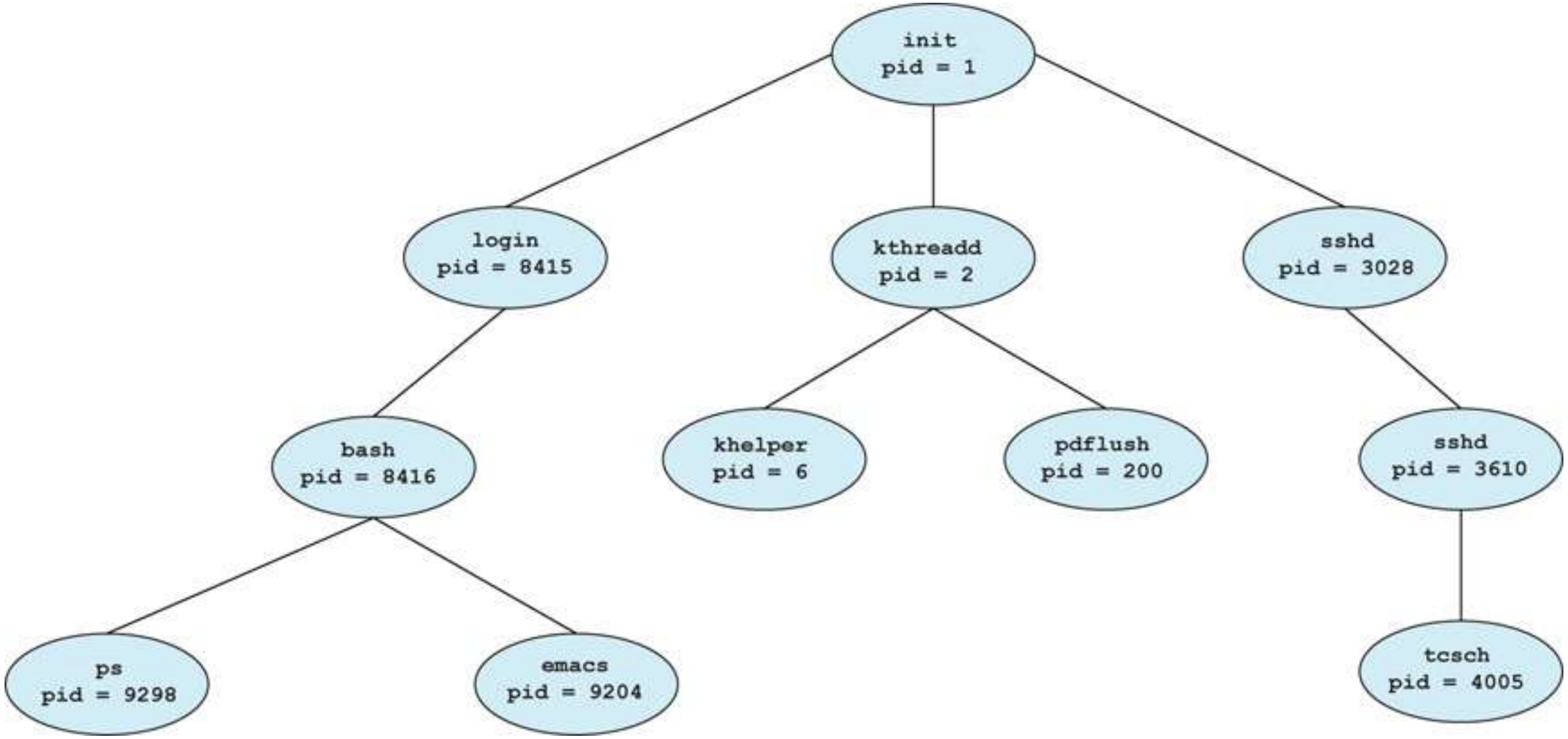
Process Creation

- 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

- 2 options for the parent after creating the child:

Process Creation: Parent vs. Child Execution

- 2 options for the parent after creating the child:
  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 ">"

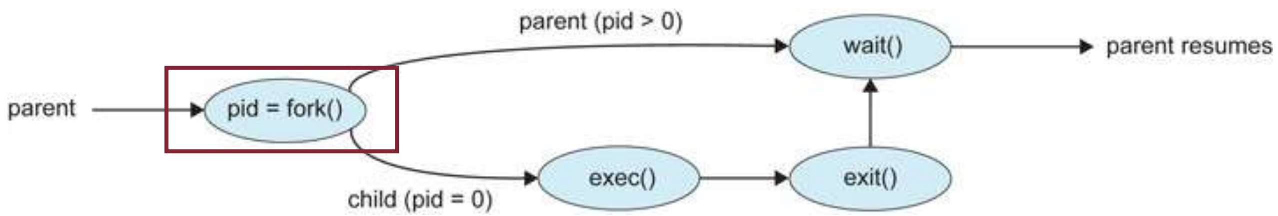
Process Creation: Parent vs. Child Execution

- 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

```c
#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);
   }
}
```

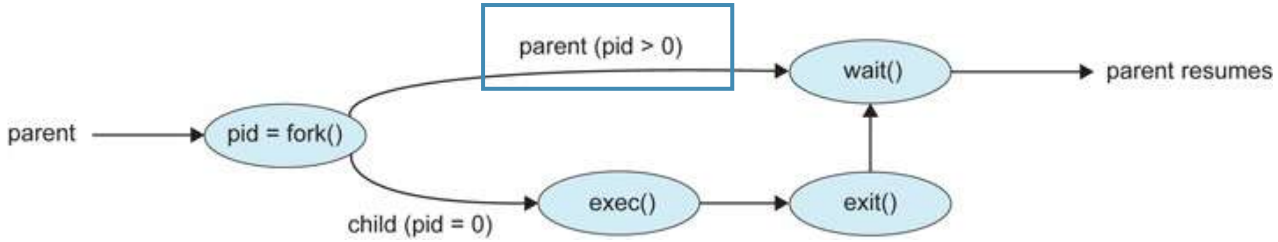
Figure 3.10 C program forking a separate process.



Process Creation: UNIX/Linux Code

```c
#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.

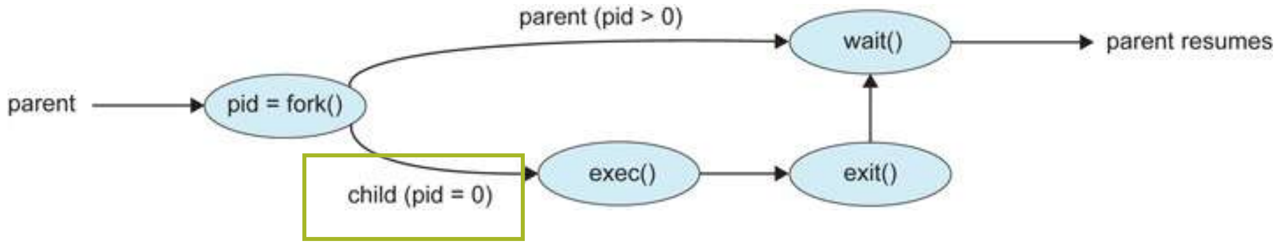


In the parent process, fork() returns the PID of the child

Process Creation: UNIX/Linux Code

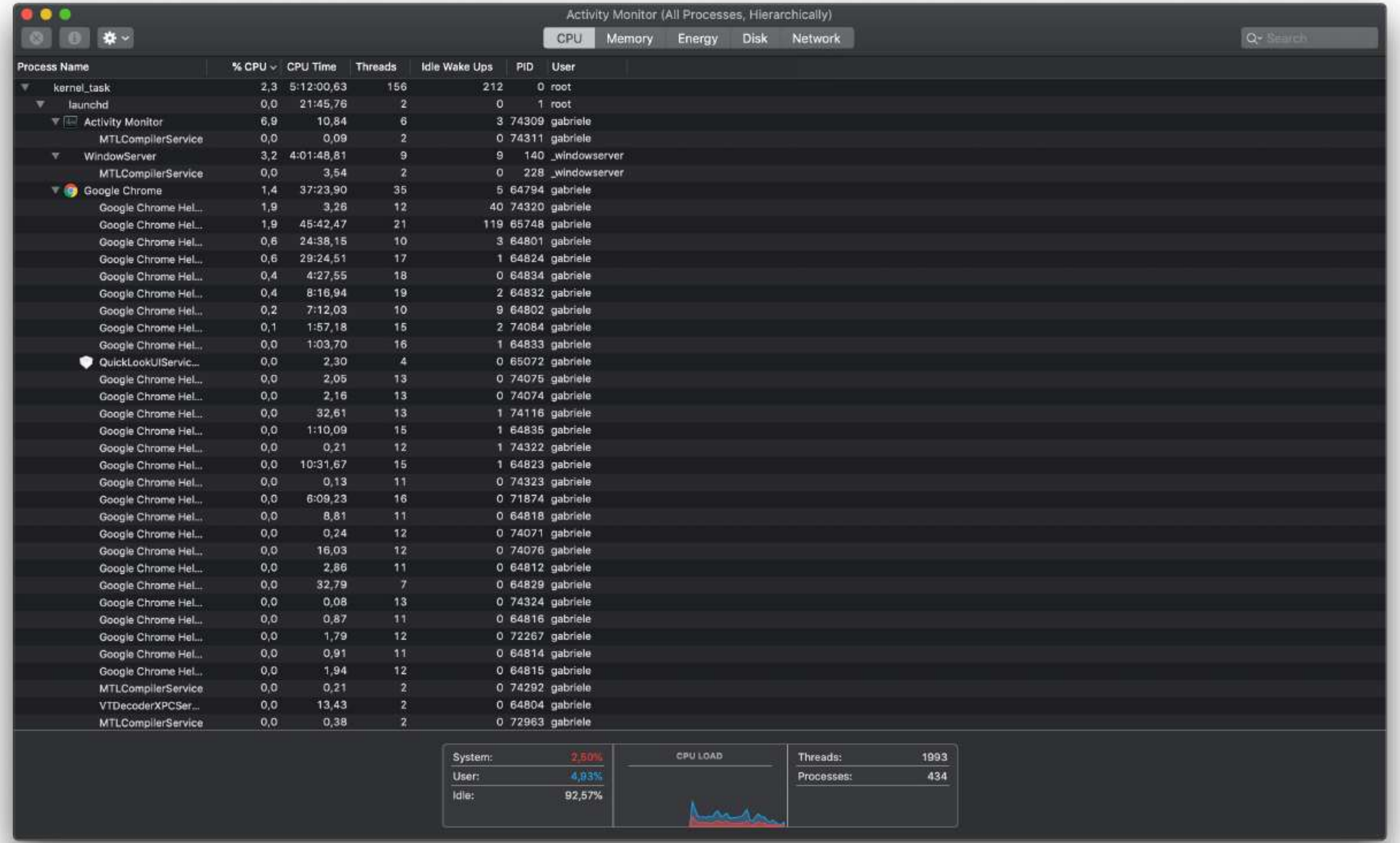
```c
#include <sys/types.h>
#include <stdio.h>
#include <unistd.h>

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.



In the child process, it returns 0

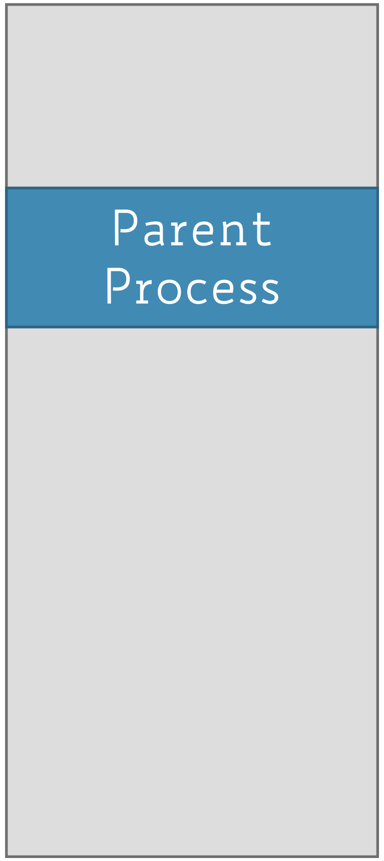
Process Creation: Activity Monitor



Process Name	% CPU	CPU Time	Threads	Idle Wake Ups	PID	User
kernel_task	2,3	5:12:00,63	156	212	0	root
launchd	0,0	21:45,76	2	0	1	root
Activity Monitor	6,9	10,84	6	3	74309	gabriele
MTLCompilerService	0,0	0,09	2	0	74311	gabriele
WindowServer	3,2	4:01:48,81	9	9	140	_windowserver
MTLCompilerService	0,0	3,54	2	0	228	_windowserver
Google Chrome	1,4	37:23,90	35	5	64794	gabriele
Google Chrome Hel...	1,9	3,26	12	40	74320	gabriele
Google Chrome Hel...	1,9	45:42,47	21	119	65748	gabriele
Google Chrome Hel...	0,6	24:38,15	10	3	64801	gabriele
Google Chrome Hel...	0,6	29:24,51	17	1	64824	gabriele
Google Chrome Hel...	0,4	4:27,55	18	0	64834	gabriele
Google Chrome Hel...	0,4	8:16,94	19	2	64832	gabriele
Google Chrome Hel...	0,2	7:12,03	10	9	64802	gabriele
Google Chrome Hel...	0,1	1:57,18	15	2	74084	gabriele
Google Chrome Hel...	0,0	1:03,70	16	1	64833	gabriele
QuickLookUIServic...	0,0	2,30	4	0	65072	gabriele
Google Chrome Hel...	0,0	2,05	13	0	74075	gabriele
Google Chrome Hel...	0,0	2,16	13	0	74074	gabriele
Google Chrome Hel...	0,0	32,61	13	1	74116	gabriele
Google Chrome Hel...	0,0	1:10,09	15	1	64835	gabriele
Google Chrome Hel...	0,0	0,21	12	1	74322	gabriele
Google Chrome Hel...	0,0	10:31,67	15	1	64823	gabriele
Google Chrome Hel...	0,0	0,13	11	0	74323	gabriele
Google Chrome Hel...	0,0	6:09,23	16	0	71874	gabriele
Google Chrome Hel...	0,0	8,81	11	0	64818	gabriele
Google Chrome Hel...	0,0	0,24	12	0	74071	gabriele
Google Chrome Hel...	0,0	16,03	12	0	74076	gabriele
Google Chrome Hel...	0,0	2,86	11	0	64812	gabriele
Google Chrome Hel...	0,0	32,79	7	0	64829	gabriele
Google Chrome Hel...	0,0	0,08	13	0	74324	gabriele
Google Chrome Hel...	0,0	0,87	11	0	64816	gabriele
Google Chrome Hel...	0,0	1,79	12	0	72267	gabriele
Google Chrome Hel...	0,0	0,91	11	0	64814	gabriele
Google Chrome Hel...	0,0	1,94	12	0	64815	gabriele
MTLCompilerService	0,0	0,21	2	0	74292	gabriele
VTDecoderXPCSer...	0,0	13,43	2	0	64804	gabriele
MTLCompilerService	0,0	0,38	2	0	72963	gabriele

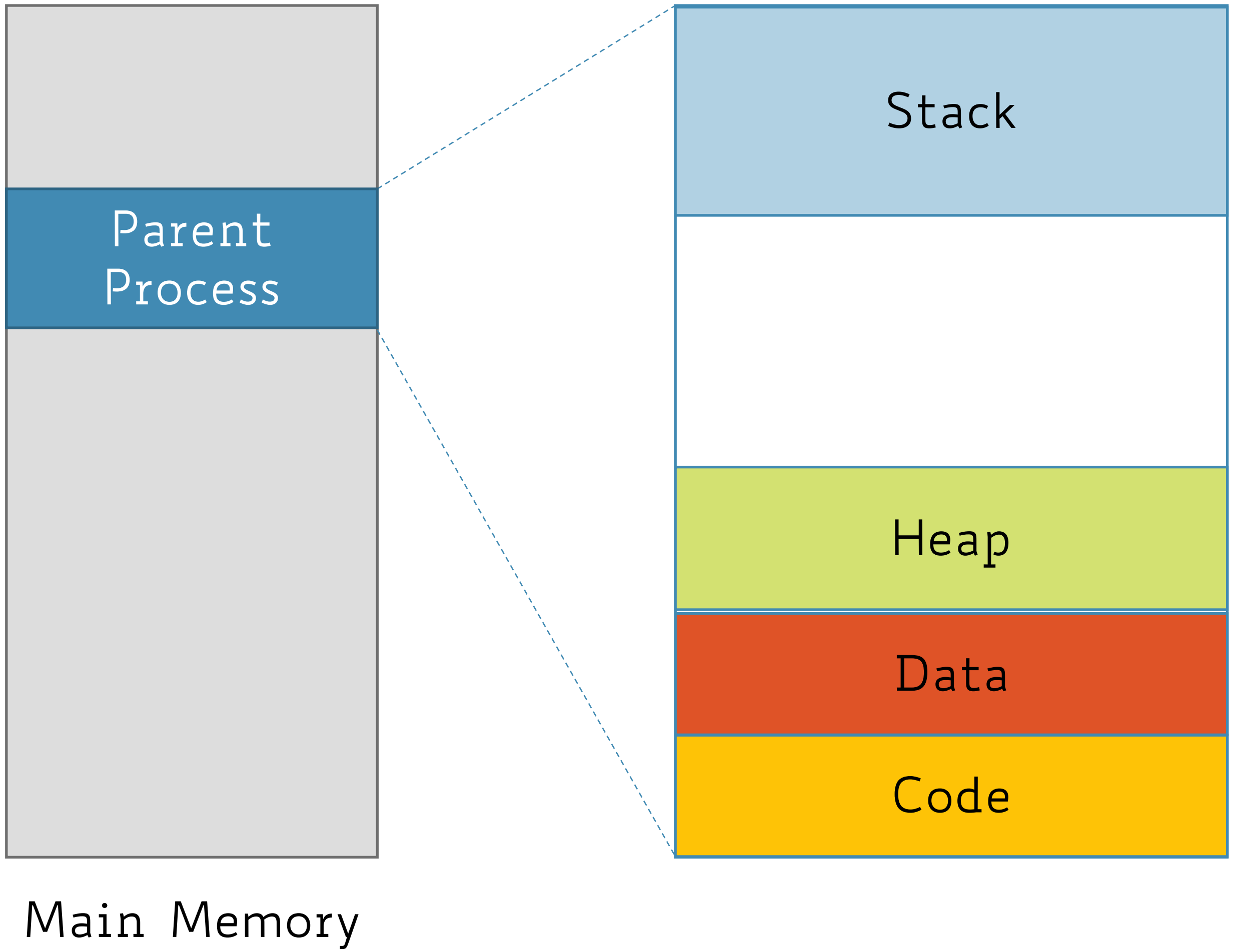
Hierarchy of Processes
(i.e., process tree)

Process Creation: Parent vs. Child Layout

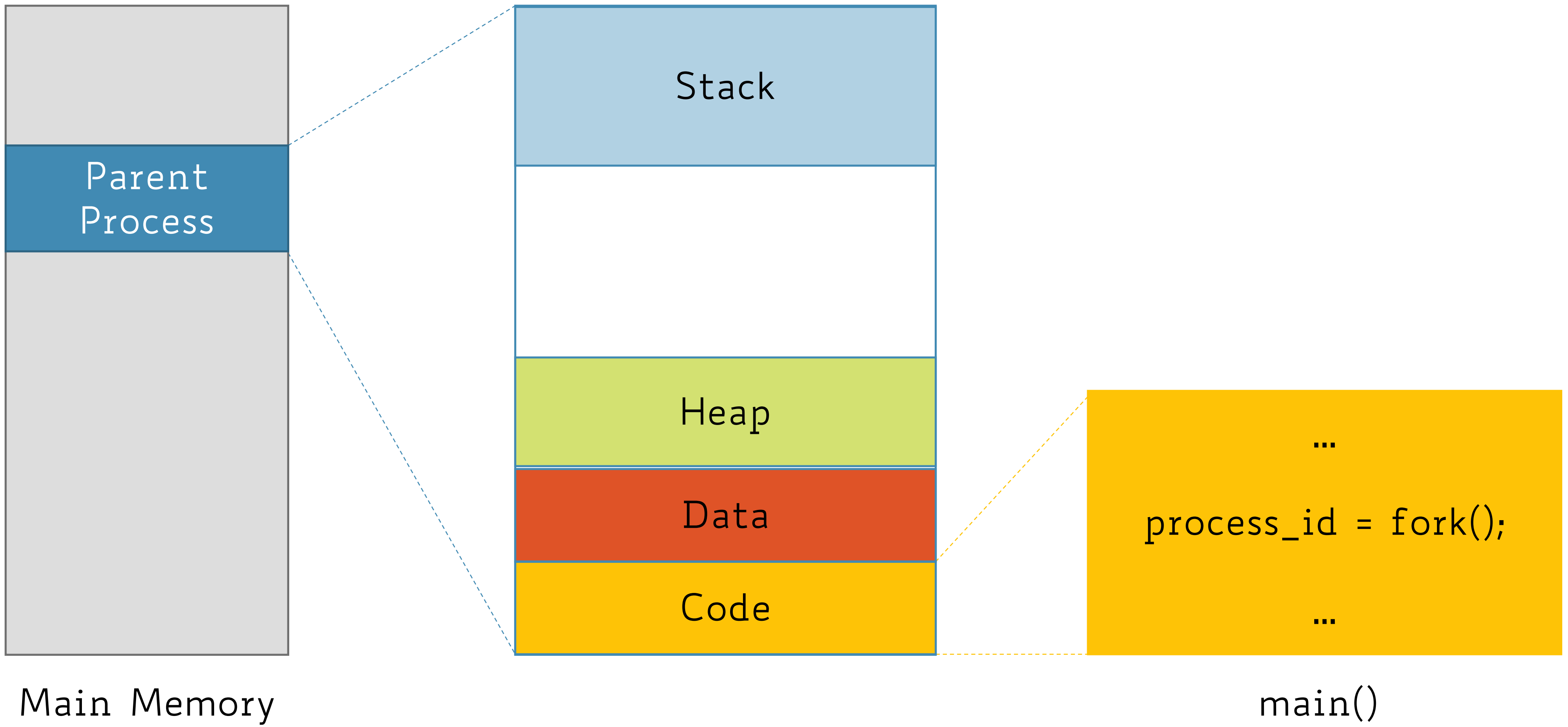


Main Memory

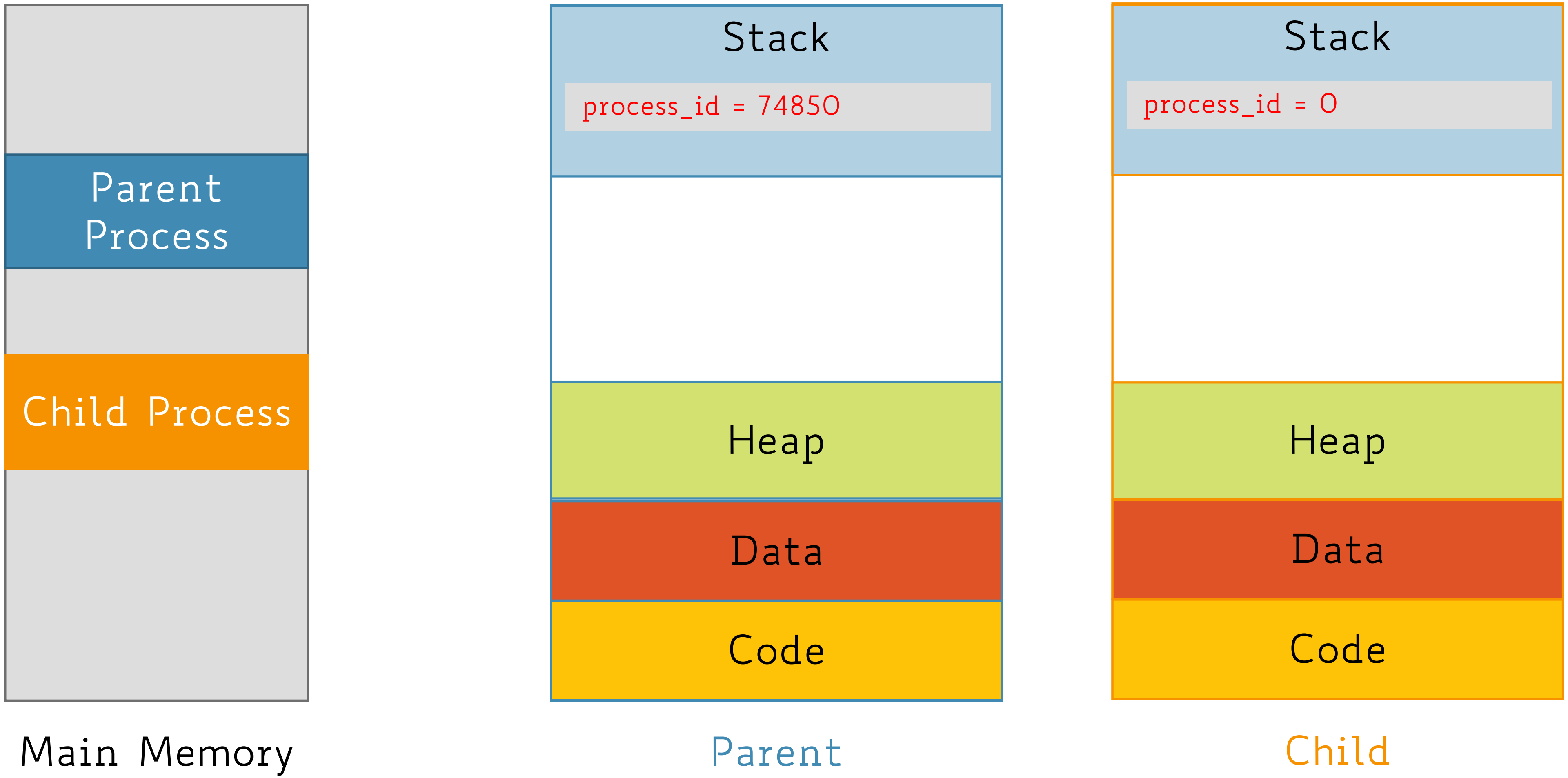
Process Creation: Parent vs. Child Layout



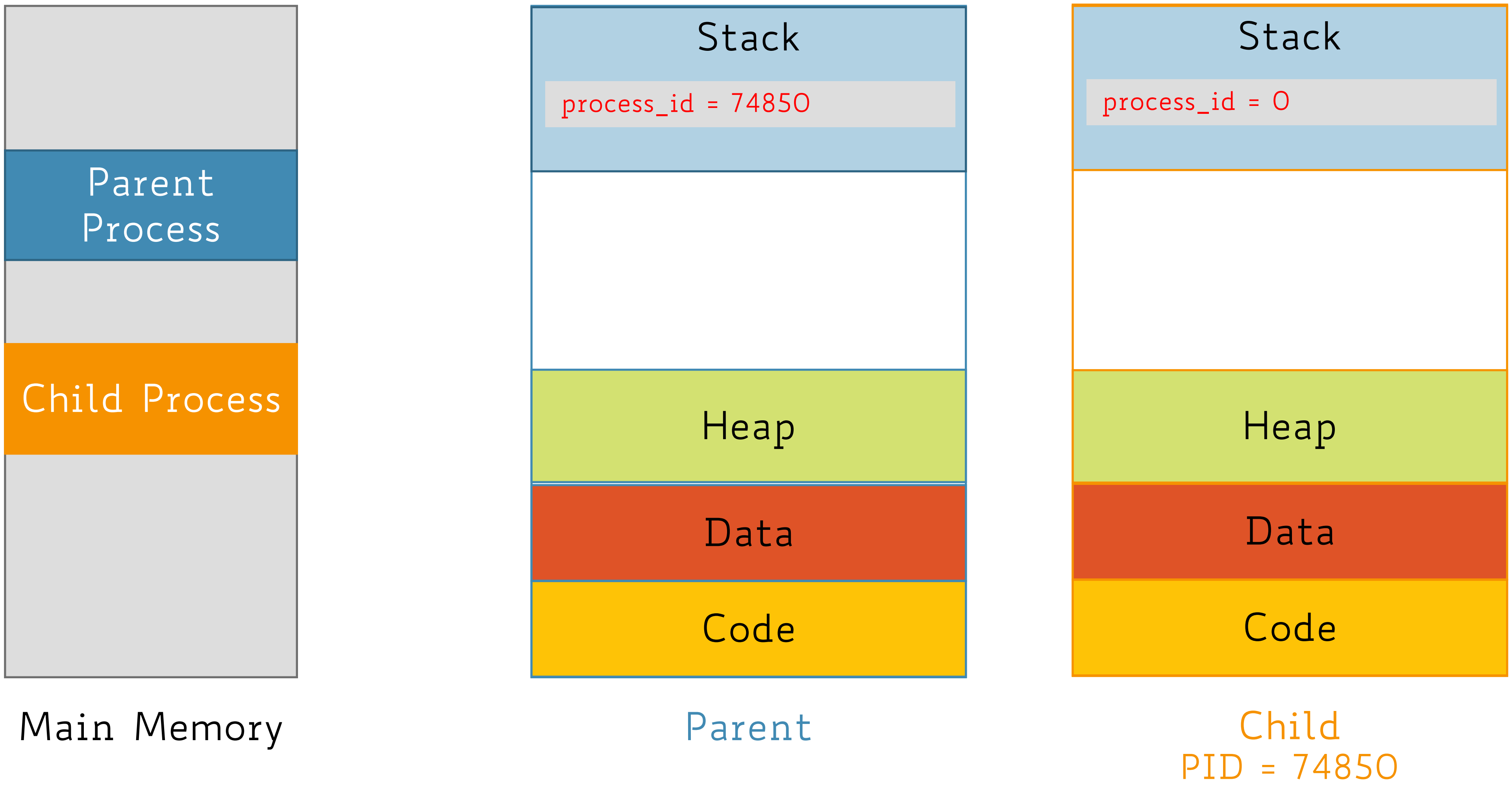
Process Creation: Parent vs. Child Layout



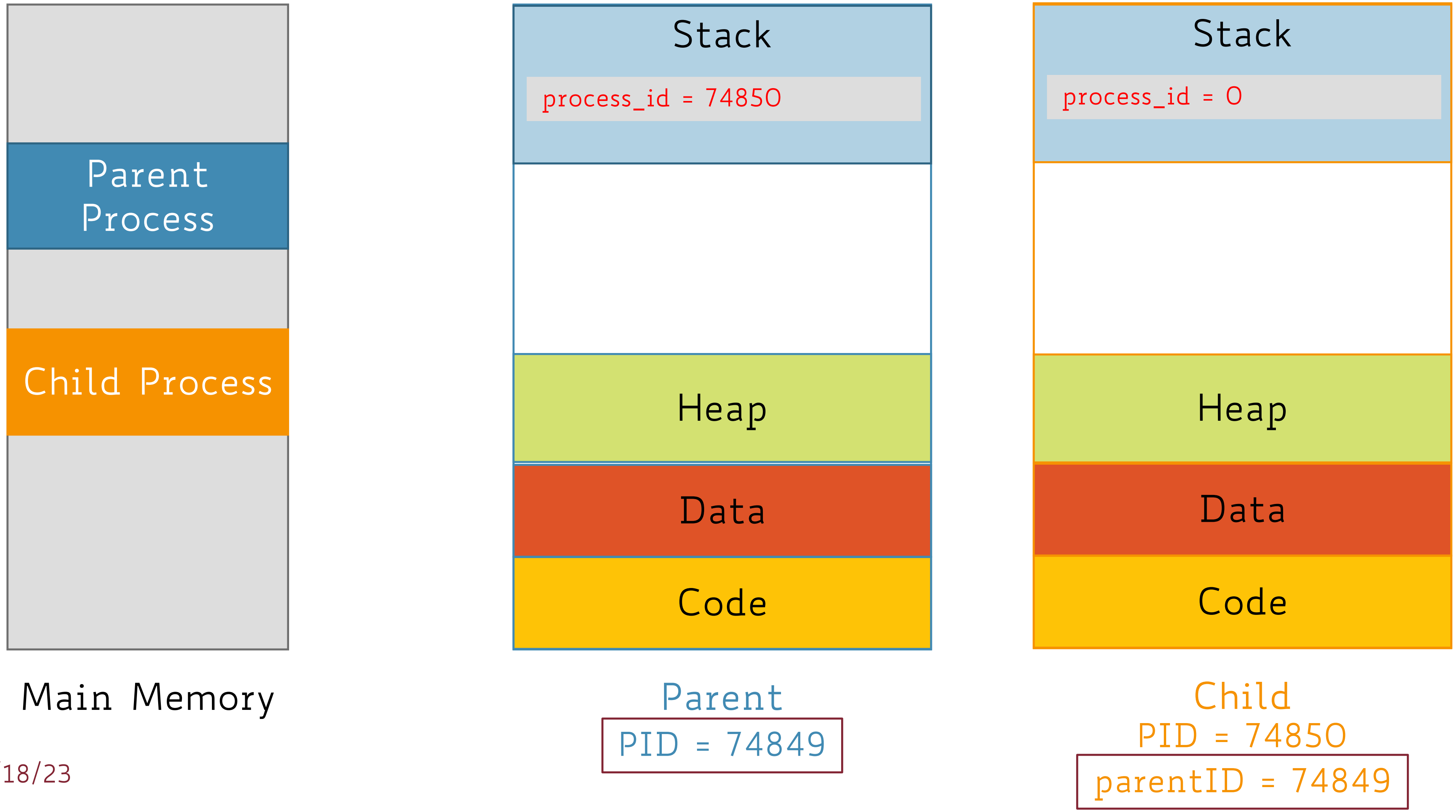
Process Creation: Parent vs. Child Layout



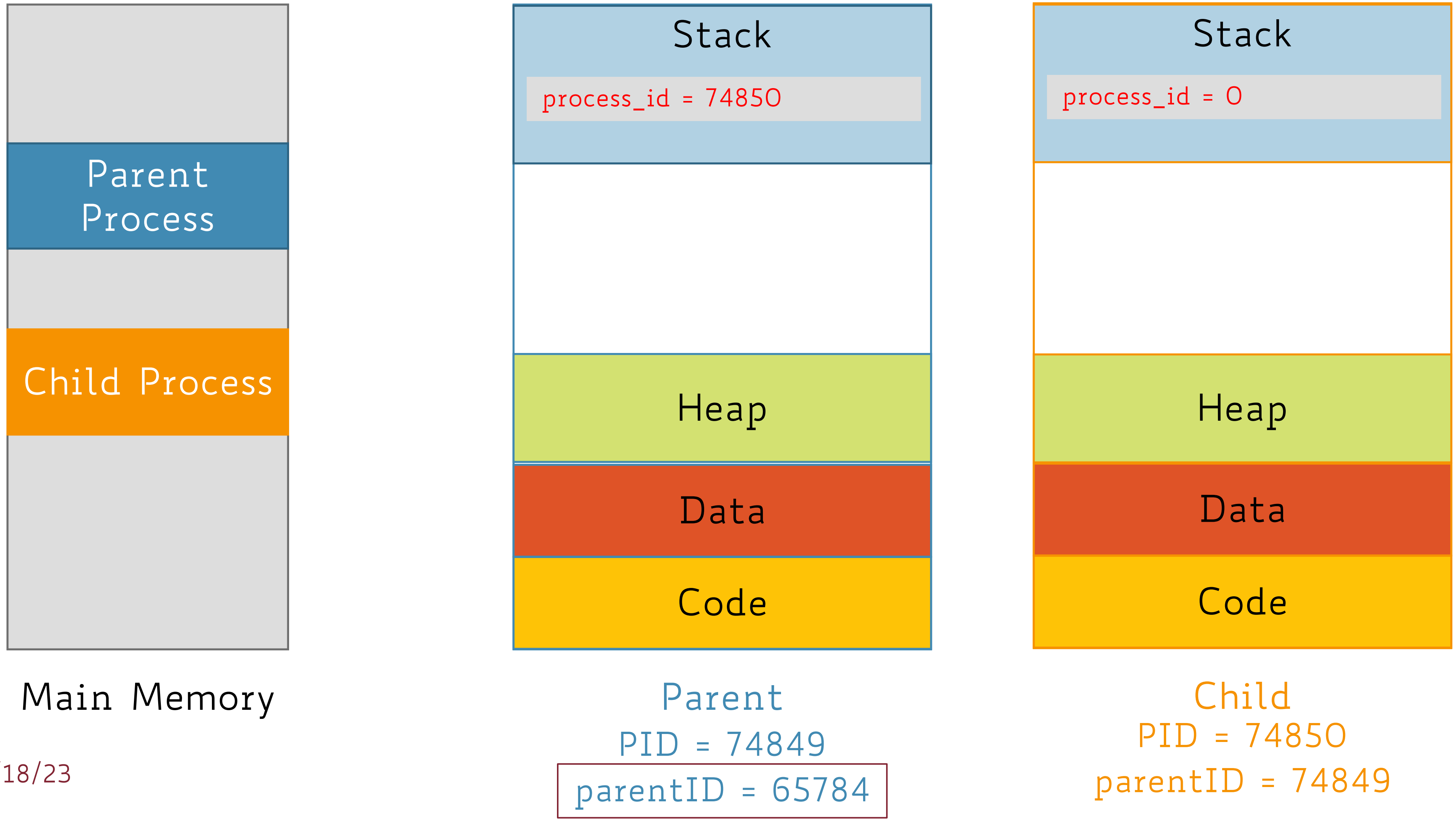
Process Creation: Parent vs. Child Layout



Process Creation: Parent vs. Child Layout



Process Creation: Parent vs. Child Layout



Process Creation: Code Example

```cpp
#include <iostream>
#include <unistd.h>

using namespace std;

int main() {

    cout << "Current process ID is: " << getpid() << endl;
    cout << "\nCurrent parent's process ID is: " << getppid() << endl;

    int pid;
    pid = fork();
    // once the fork() system call returns,
    // both the parent and the child processes will resume from this point onward

    if (pid == 0) { // child
        cout << "\nThis is the child process with process ID = "
             << getpid() << endl;
        cout << "\nThis is the child process with parent's process ID = "
             << getppid() << endl;
    }
    else { // parent
        sleep(1); // to ensure the child process finishes before the parent

        cout << "\nThis is the parent process with process ID = "
             << getpid() << endl;
        cout << "\nThis is the parent process with parent's process ID = "
             << getppid() << endl;

    }
    return 0;
}
```

Process Creation: Code Example

```
#include <iostream>
#include <unistd.h>

using namespace std;

int main() {

    cout << "Current process ID is: " << getpid() << endl;
    cout << "\nCurrent parent's process ID is: " << getppid() << endl;

    int pid;
    pid = fork();
    // once the fork() system call returns,
    // both the parent and the child processes will resume from this point onward

    if (pid == 0) { // child
        cout << "\nThis is the child process with process ID = "
             << getpid() << endl;
        cout << "\nThis is the child process with parent's process ID = "
             << getppid() << endl;
    }
    else { // parent
        sleep(1); // to ensure the child process finishes before the parent

        cout << "\nThis is the parent process with process ID = "
             << getpid() << endl;
        cout << "\nThis is the parent process with parent's process ID = "
             << getppid() << endl;

    }
    return 0;
}
```

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!

Process Creation: The Example of UNIX Shell

- When we log in to a UNIX machine a shell process is started

Process Creation: The Example of UNIX Shell

- When we log in to a UNIX machine a shell process is started
- Every command we type into the shell creates a new child process whose parent is the shell itself

Process Creation: The Example of UNIX Shell

- When we log in to a UNIX machine a shell process is started
- Every command we type into the shell creates a new child process whose parent is the shell itself
- Implicitly, **2 system calls** take place: fork and exec
  - the former duplicates process, whilst the latter execute the new process
  - e.g., try typing emacs on your shell

Process Creation: The Example of UNIX Shell

- When we log in to a UNIX machine a shell process is started
- Every command we type into the shell creates a new child process whose parent is the shell itself
- Implicitly, **2 system calls** take place: fork and exec
  - 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

```
#include <iostream>
#include <unistd.h>
#include <sys/wait.h>
#include <stdio.h>
#include <string.h>

using namespace std;

int main() {

    int current_pid = getpid();
    cout << "Current process ID is: " << current_pid << endl;

    string progStr;
    // read the name of the program we want to start
    getline(cin, progStr);
    const char *prog = progStr.c_str();

    int pid = fork();

    if (pid == 0) { // child
        execlp(prog, prog, 0); // load the program
        // if prog can actually be started, we will never get to the
        // following statement, as the child process will be replaced by prog!
        printf("Can't load the program %s\n", prog);
    }
    else { // parent
        sleep(1); // give some time to the child process to starting up
        waitpid(pid, 0, 0); // wait for child process to terminate
        printf("Program %s finished!\n", prog);
    }
    return 0;
}
```

execlp loads the program whose name is read from stdin

```
int execlp(const char *file, const char *arg, ...);
```

Process Creation and Execution: Example

```
#include <iostream>
#include <unistd.h>
#include <sys/wait.h>
#include <stdio.h>
#include <string.h>

using namespace std;

int main() {

    int current_pid = getpid();
    cout << "Current process ID is: " << current_pid << endl;

    string progStr;
    // read the name of the program we want to start
    getline(cin, progStr);
    const char *prog = progStr.c_str();

    int pid = fork();

    if (pid == 0) { // child
        execlp(prog, prog, 0); // load the program
        // if prog can actually be started, we will never get to the
        // following statement, as the child process will be replaced by prog!
        printf("Can't load the program %s\n", prog);
    }
    else { // parent
        sleep(1); // give some time to the child process to starting up
        waitpid(pid, 0, 0); // wait for child process to terminate
        printf("Program %s finished!\n", prog);
    }
    return 0;
}
```

execlp loads the program whose name is read from stdin

```
int execlp(const char *file, const char *arg, ...);
```

path to executable

Process Creation and Execution: Example

```cpp
#include <iostream>
#include <unistd.h>
#include <sys/wait.h>
#include <stdio.h>
#include <string.h>

using namespace std;

int main() {

    int current_pid = getpid();
    cout << "Current process ID is: " << current_pid << endl;

    string progStr;
    // read the name of the program we want to start
    getline(cin, progStr);
    const char *prog = progStr.c_str();

    int pid = fork();

    if (pid == 0) { // child
        execlp(prog, prog, 0); // load the program
        // if prog can actually be started, we will never get to the
        // following statement, as the child process will be replaced by prog!
        printf("Can't load the program %s\n", prog);
    }
    else { // parent
        sleep(1); // give some time to the child process to starting up
        waitpid(pid, 0, 0); // wait for child process to terminate
        printf("Program %s finished!\n", prog);
    }
    return 0;
}
```

execlp loads the program whose name is read from stdin

```c
int execlp(const char *file, const char *arg, ...);
```

argv[0]

Process Creation and Execution: Example

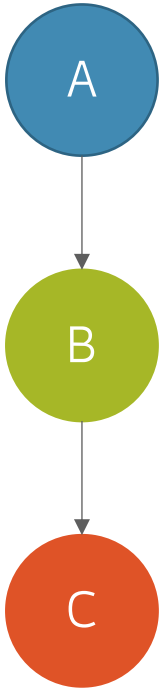
```cpp
#include <iostream>
#include <unistd.h>
#include <sys/wait.h>
#include <stdio.h>
#include <string.h>

using namespace std;

int main() {

    int current_pid = getpid();
    cout << "Current process ID is: " << current_pid << endl;

    string progStr;
    // read the name of the program we want to start
    getline(cin, progStr);
    const char *prog = progStr.c_str();

    int pid = fork();

    if (pid == 0) { // child
        execlp(prog, prog, 0); // load the program
        // if prog can actually be started, we will never get to the
        // following statement, as the child process will be replaced by prog!
        printf("Can't load the program %s\n", prog);
    }
    else { // parent
        sleep(1); // give some time to the child process to starting up
        waitpid(pid, 0, 0); // wait for child process to terminate
        printf("Program %s finished!\n", prog);
    }
    return 0;
}
```

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

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

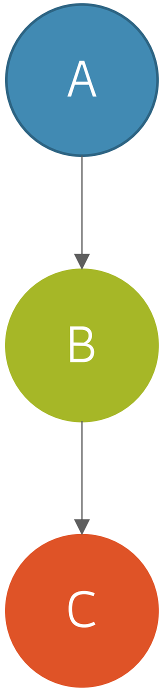
Process Creation and Execution: Exercise

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?

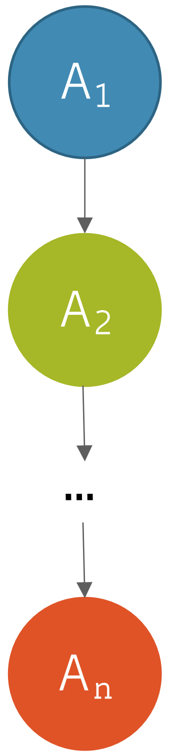



```
int pid = fork();

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

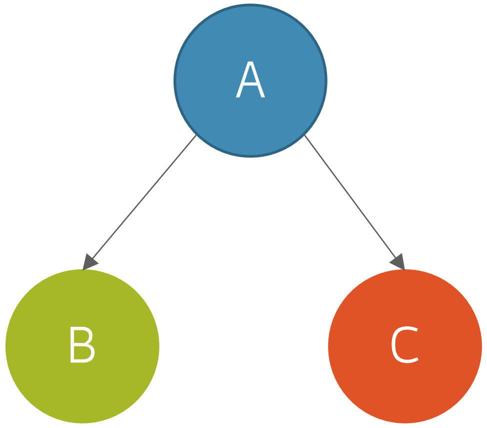
More generally, we will need *n-1* fork and if-else

if we want to create a sequence of *n* processes



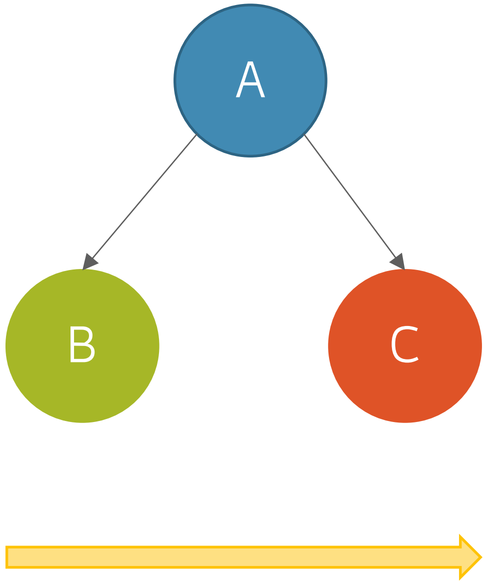
Process Creation and Execution: Exercise

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?

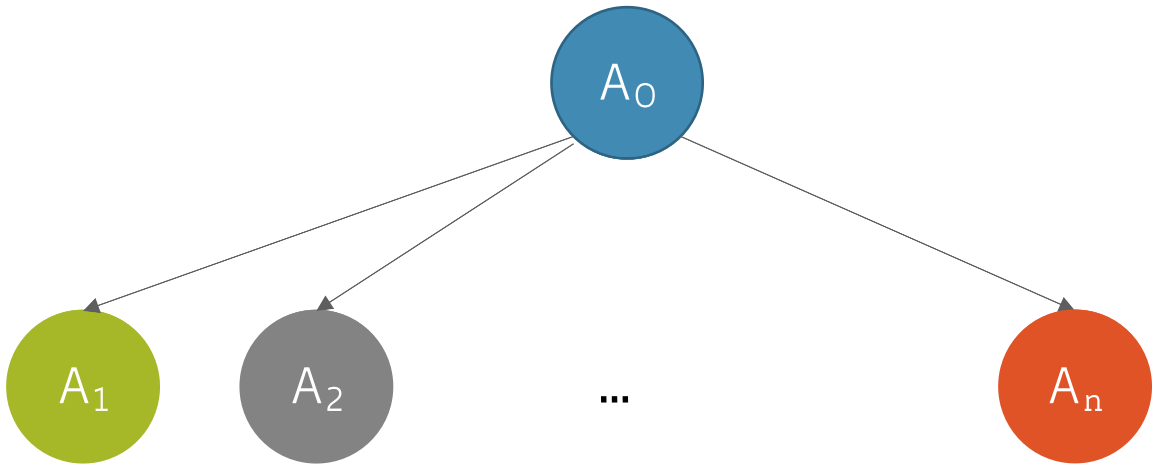


Left-to-Right (by convention)

```
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!

What will happen if we do the following?

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

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

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

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

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

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
- 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

Process Termination

- If the parent exits, the system may or may not allow the child to continue without a parent
- On UNIX systems, **orphaned** processes are generally inherited by `init`, which then proceeds to kill them

Process Termination

- When a process terminates, all its system resources are freed up, open files flushed and closed, etc.

Process Termination

- When a process terminates, all its system resources are freed up, open files flushed and closed, etc.
- The process termination status and execution times are returned to the parent if this is waiting for the child to terminate

Process Termination

- When a process terminates, all its system resources are freed up, open files flushed and closed, etc.
- 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**

Process Termination

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

Process Termination

- Processes which are trying to terminate but cannot because their parent is not waiting for them are called **zombies**
- Eventually inherited by `init` as orphans and killed

Outline

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

Process Scheduling

- 2 **main goals** of the process scheduling system:
    i. keep the CPU busy at all times

Process Scheduling

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

Process Scheduling

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

Process Scheduling

- 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

- The OS mantains the PCBs of all the processes in state queues

Process State Queues

- The OS mantains the PCBs of all the processes in state queues
- There is one queue for each of the **5 states** a process can be in

Process State Queues

- The OS mantains 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)

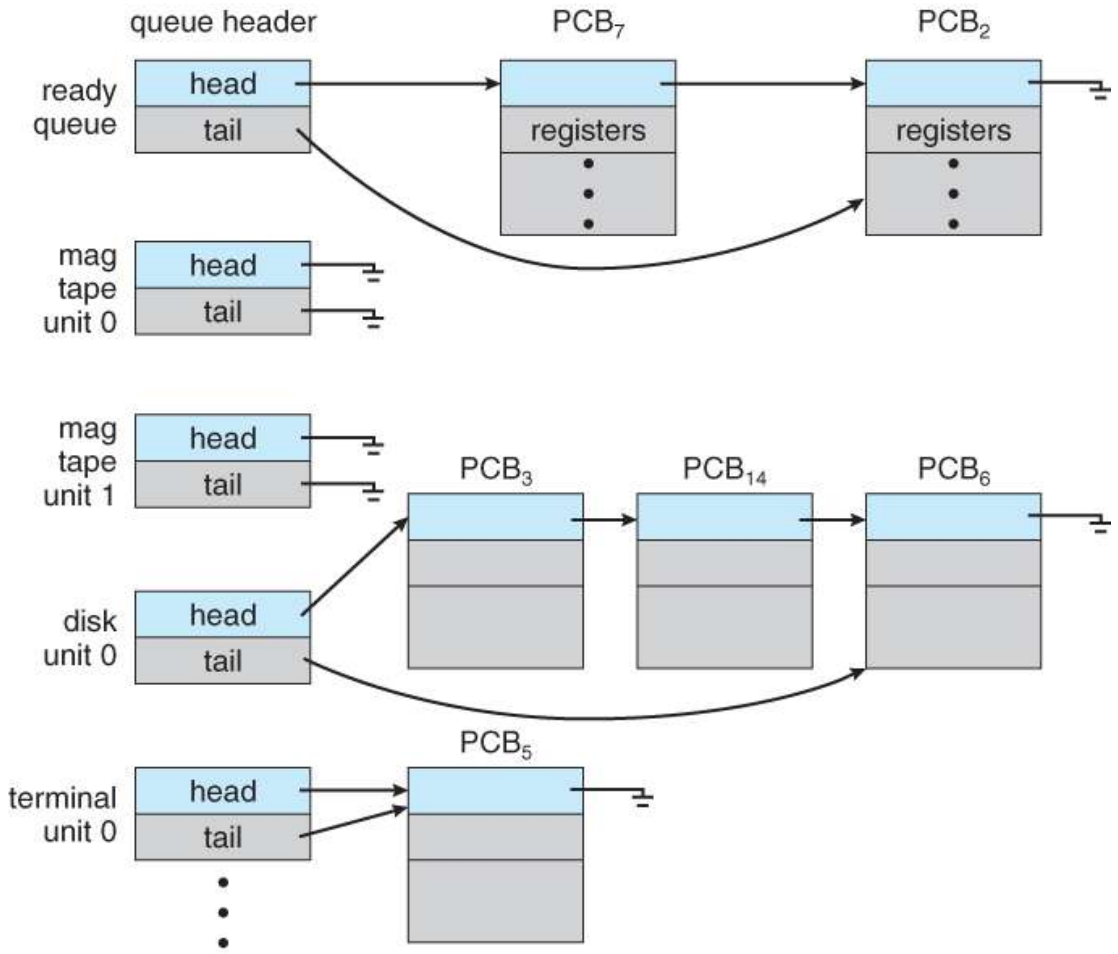
Process State Queues

- The OS mantains 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)
- When the OS changes the status of a process (e.g., from ready to running) the PCB is unlinked from one queue and moved to appropriate one

Process State Queues

- The OS mantains 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)
- When the OS changes the status of a process (e.g., from ready to running) the PCB is unlinked from one queue and moved to appropriate one
- The OS may use different policies to manage each state queue

Process State Queues: Example



Process State Queues: Considerations

- How many PCBs can be in the Running Queue?

Process State Queues: Considerations

- How many PCBs can be in the Running Queue?
  - 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

Process State Queues: Considerations

- How many PCBs can be in the Running Queue?
  - 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?

Process State Queues: Considerations

- How many PCBs can be in the Running Queue?
  - 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

Schedulers

- A **long-term scheduler** runs infrequently and is typical of a batch system or a very heavily loaded system

Schedulers

- A **long-term scheduler** runs infrequently and is typical of a batch system or a very heavily loaded system
- A **short-term scheduler** runs very frequently (about every 100 milliseconds) and must very quickly swap one process out of the CPU and swap in another one

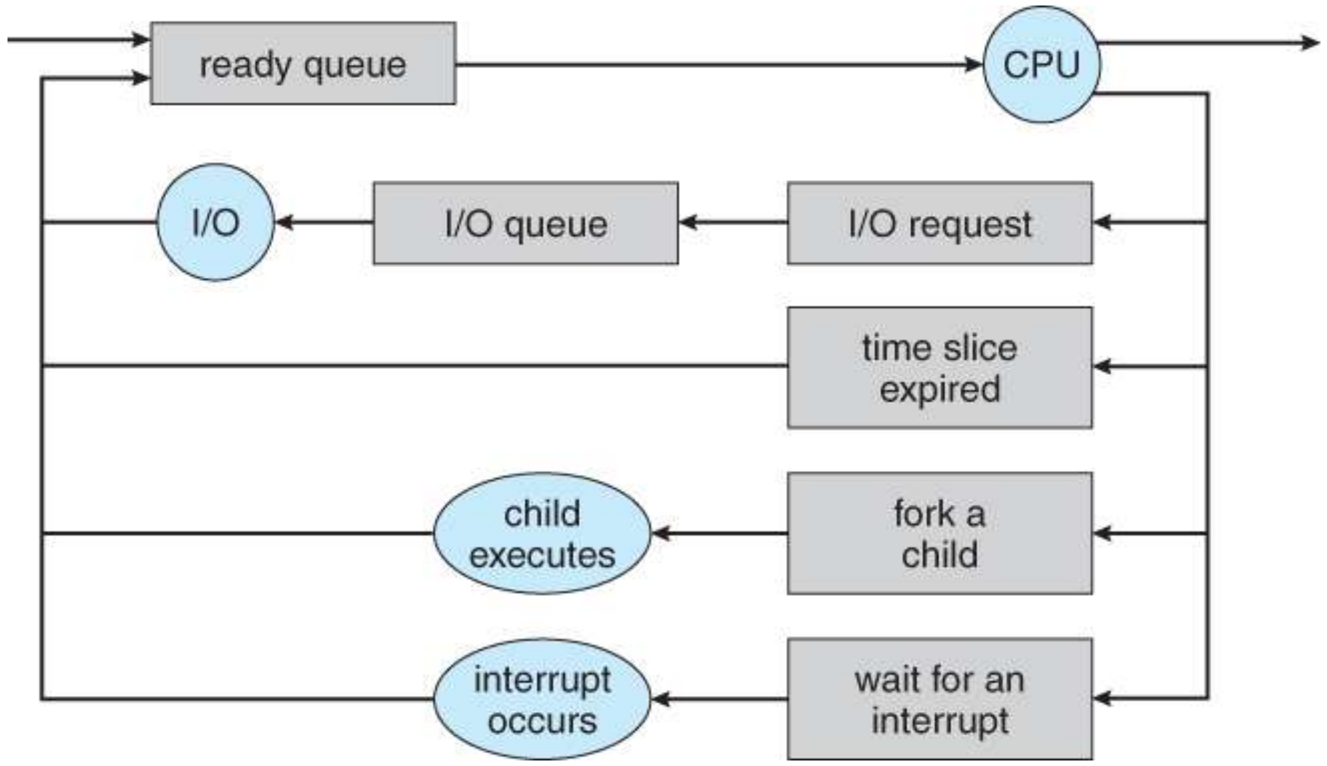
Schedulers

- A **long-term scheduler** runs infrequently and is typical of a batch system or a very heavily loaded system
- A **short-term scheduler** runs very frequently (about every 100 milliseconds) and must very quickly swap one process out of the CPU and swap in another one
- When system loads get high, a medium-term scheduler allows smaller faster jobs to finish up quickly and clear the system

Schedulers

- A **long-term scheduler** runs infrequently and is typical of a batch system or a very heavily loaded system
- A **short-term scheduler** runs very frequently (about every 100 milliseconds) and must very quickly swap one process out of the CPU and swap in another one
- 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



Context Switch: What?

- It is the procedure used by the CPU to suspend the currently executing process in order to run a ready one

Context Switch: What?

- It is the procedure used by the CPU to suspend the currently executing process in order to run a ready one
- It is a highly costly operation because:
  - stopping the current process involves saving all of its internal state (PC, SP, other registers, etc.) to its PCB

Context Switch: What?

- It is the procedure used by the CPU to suspend the currently executing process in order to run a ready one
- It is a highly costly operation because:
  - stopping the current process involves saving all of its internal state (PC, SP, other registers, etc.) to its PCB
  - starting a ready process consists of loading all of its internal state (PC, SP, other registers, etc.) from its PCB

Context Switch: When?

- A context switch occurs due to any incoming trap
  - system calls, exceptions, or HW interrupts

Context Switch: When?

- 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

Context Switch: Fairness

- I/O-bound processes eventually get switched due to I/O requests

Context Switch: Fairness

- I/O-bound processes eventually get switched due to I/O requests
- CPU-bound processes, instead, could theoretically never issue any I/O requests

Context Switch: Fairness

- 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**)

Context Switch: Time Slice

- The maximum amount of time between two context switches

Context Switch: Time Slice

- The maximum amount of time between two context switches
- To ensure that at least a context switch occurs every, say, 50 ms

Context Switch: Time Slice

- The maximum amount of time between two context switches
- 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)

Context Switch: Time Slice

- Can be easily implemented in HW through timer interrupt

Context Switch: Time Slice

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

Context Switch: How Often?

- The time taken to complete a context switch is just wasted CPU time

Context Switch: How Often?

- The time taken to complete a context switch is just wasted CPU time
- A smaller time slice results in more frequent context switches
  - **maximizing responsiveness**

Context Switch: How Often?

- The time taken to complete a context switch is just wasted CPU time
- 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: How Often?

- The time taken to complete a context switch is just wasted CPU time

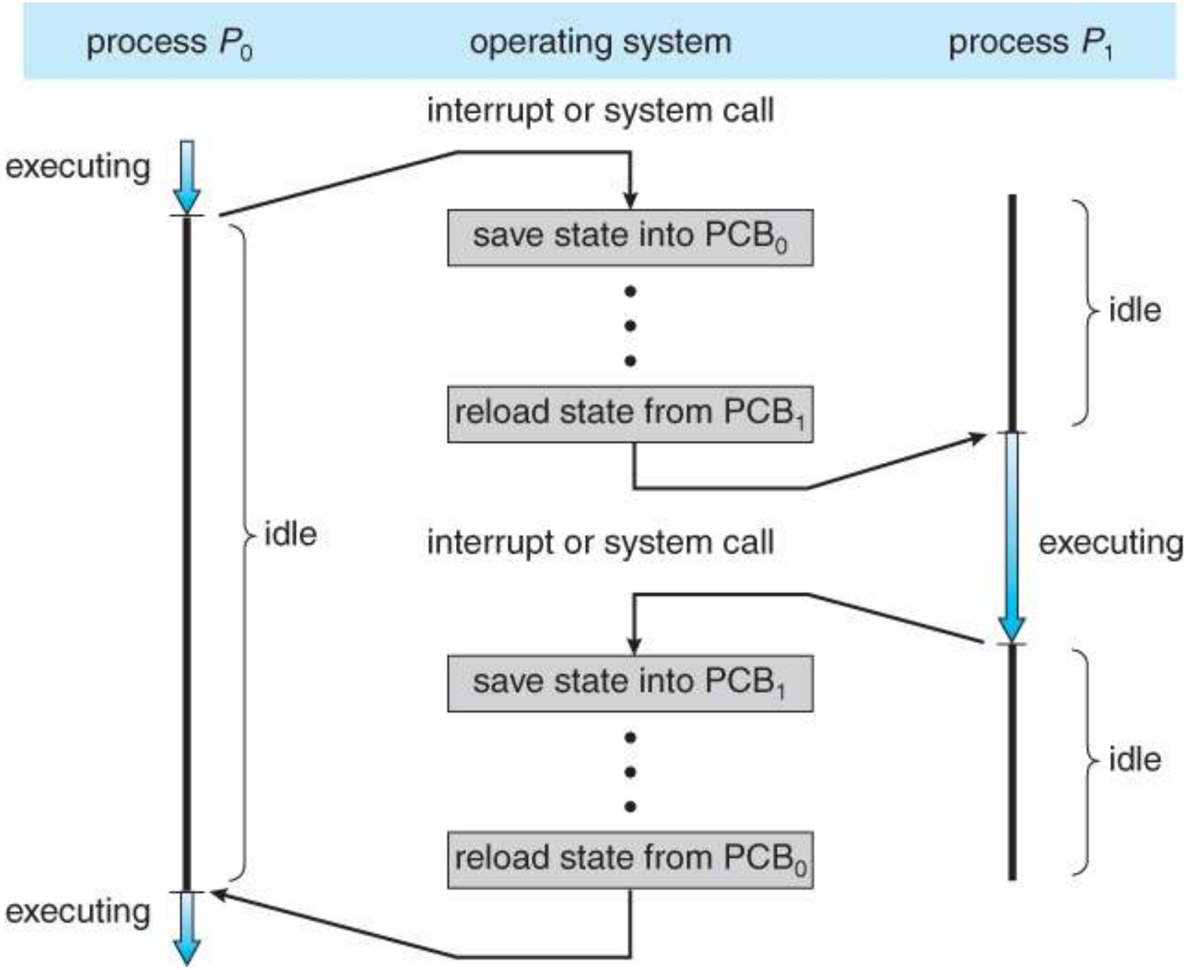
Trade-off

- 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 μs, so the overhead is small relative to time slice
- $10^{-2} \div 10^{-1}$ vs. 10^{-8} seconds

Context Switch: Example



Outline

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

Interprocess Communication

- Processes can be either **independent** or **cooperating**

Interprocess Communication

- Processes can be either **independent** or **cooperating**
- **Independent processes** → operate concurrently on a system and can neither affect or be affected by other processes

Interprocess Communication

- 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

Cooperating Processes: Why?

- **Information sharing** → There may be several processes which need access to the same file (e.g., pipelines)

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

Cooperating Processes: Why?

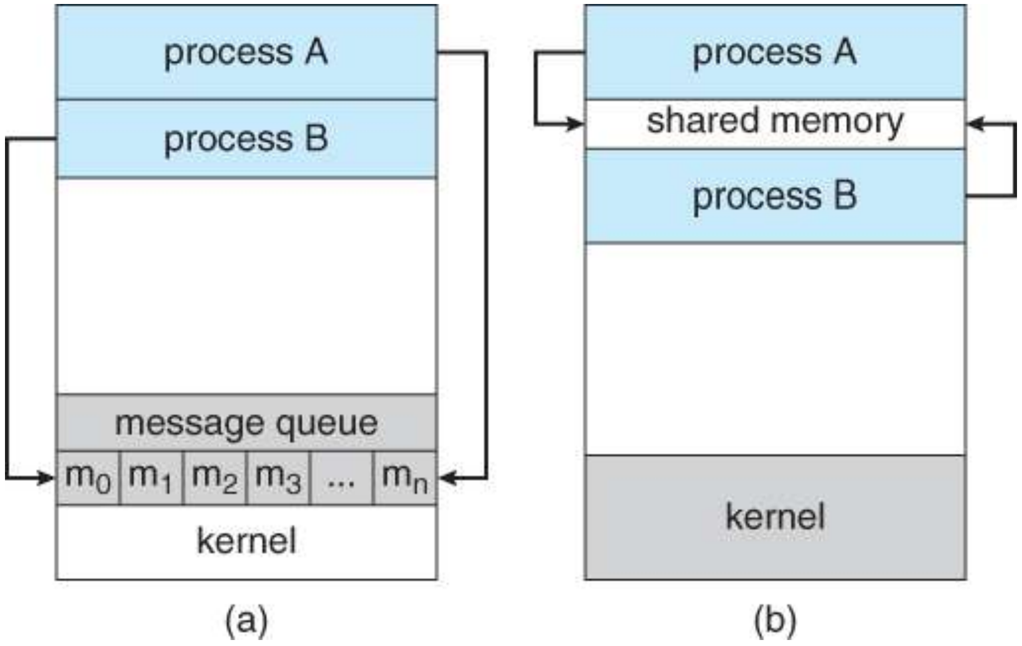
- **Information sharing** → There may be several processes which need access to the same file (e.g., pipelines)
- **Computation speedup** → A problem can be solved faster if it can be broken down into sub-tasks to be solved simultaneously
- **Modularity** → The most efficient architecture may be to break a system down into cooperating modules

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:
  - direct or indirect communication (i.e., naming)
  - synchronous or asynchronous communication
  - automatic or explicit buffering

Message Passing Systems: Naming

- **Direct communication** → the sender must know the name of the receiver to which it wishes to send a message
  - one-to-one link between every sender-receiver pair
  - for symmetric communication, the receiver must also know the name of the sender

Message Passing Systems: Naming

- **Direct communication** → the sender must know the name of the receiver to which it wishes to send a message
  - one-to-one link between every sender-receiver pair
  - for symmetric communication, the receiver must also know the name of the sender
- **Indirect communication** → uses shared mailboxes or ports
  - multiple processes can share the same mailbox or port
  - only one process can read any given message in a mailbox
  - the OS must provide system calls to create and delete mailboxes, and to send and receive messages to/from mailboxes

Message Passing Systems: Buffering and Synchronization

- **Zero capacity** → Messages cannot be stored in the queue, so senders must block until receivers accept the messages

Message Passing Systems: Buffering and Synchronization

- **Zero capacity** → Messages cannot be stored in the queue, so senders must block until receivers accept the messages
- **Bounded capacity** → There is a pre-determined finite capacity in the queue, so senders must block if the queue is full, otherwise may be either blocking or non-blocking

Message Passing Systems: Buffering and Synchronization

- **Zero capacity** → Messages cannot be stored in the queue, so senders must block until receivers accept the messages
- **Bounded capacity** → There is a pre-determined finite capacity in the queue, so senders must block if the queue is full, otherwise may be either blocking or non-blocking
- **Unbounded capacity** → The queue has a theoretical infinite capacity, so senders are never forced to block

Summary

- Process are created programmatically via system calls (e.g., `fork`/`exec`)

Summary

- Process are created programmatically via system calls (e.g., fork/exec)
- Scheduling policies to maximize CPU utilization for process execution

Summary

- Process are created programmatically via system calls (e.g., fork/exec)
- Scheduling policies to maximize CPU utilization for process execution
- **Context switch** to intertwine the execution of multiple processes

Summary

- Process are created programmatically via system calls (e.g., fork/exec)
- 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**