OPERATING SYSTEMS

Processes

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AGENDA

- Process Management
- Process State Models
- Create and Erase Processes
- Structure of a UNIX Process in Memory

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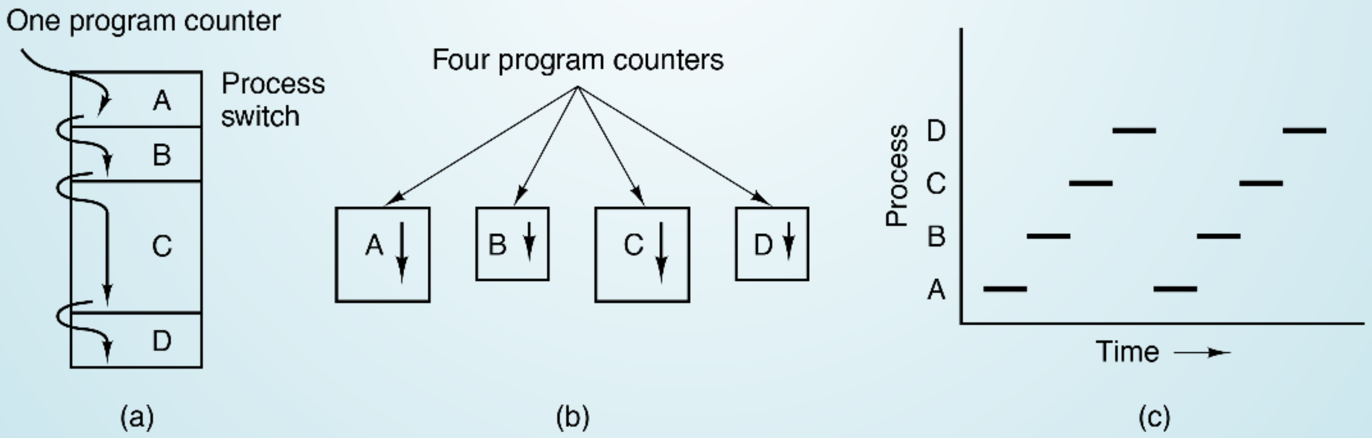
What is a process?

PROCESS MANAGEMENT

PROCESS

Definition: Process

- A process (lat. *procedere* = proceed, move forward) is an instance of a *program*
- A program in execution
- Dynamic objects which represent sequential activities in a computer system
- While running every computer always run (at least) one process
- Each process has assigned resources
- A process can run in *user* or *kernel mode*



PROCESS RESOURCES

Which resources are associated to a process?

PROCESS CONTEXT

- The **resources** associated with a process managed by the OS are called the process context
- The operating system manages three types of context information:
  - User context
    - Content of the allocated address space ($\longrightarrow$ **virtual memory**)
  - Hardware context
    - CPU registers
  - System context
    - Information, which stores the operating system about a process
- Typically information about the **hardware** and **system context** are stored in the process control block (PCB)

RECAP: REGISTERS

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- What is a register?
- Which registers do you remember?

HARDWARE CONTEXT

Definition: Hardware Context

The hardware context describes the content of the CPU registers during process execution.

- The following registers may need to be backed up when switching to another process ($\longrightarrow$ context switch):
  - Program Counter (Instruction Pointer) – stores the memory address of the next instruction to be executed
  - Stack pointer – stores the address at the current end of the stack
  - Base pointer – points to an address in the stack
  - Instruction register – stores the instruction, which is currently executed
  - Accumulator – stores operands for the ALU and their results
  - Page-table base Register – stores the address of the page table of the running process
  - Page-table length register – stores the length of the page table of the running process

SYSTEM CONTEXT

Definition: System Context

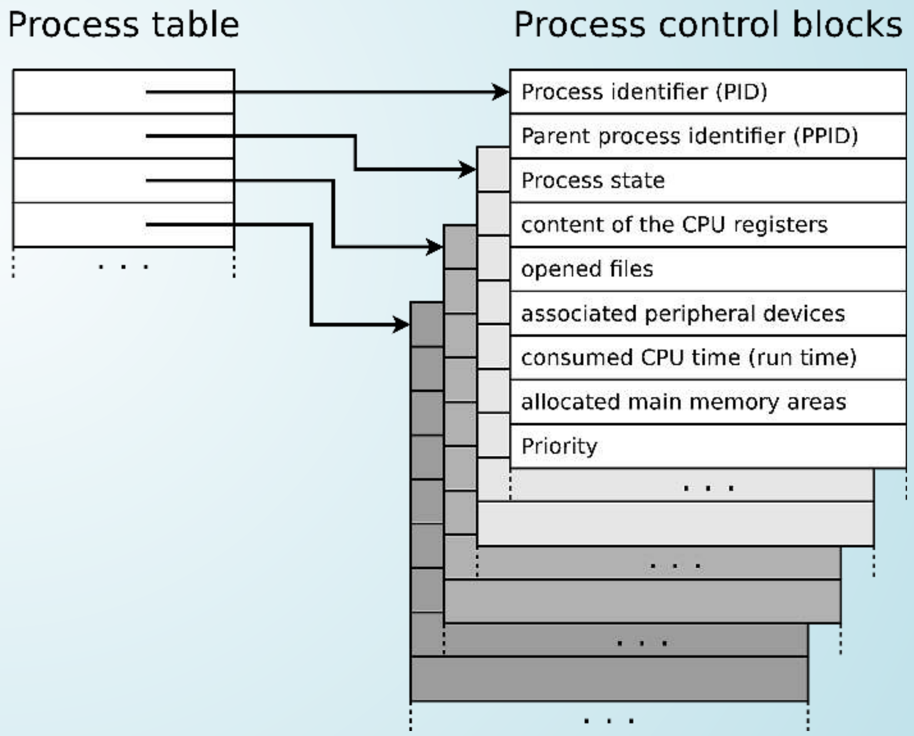
The information the operating system stores about a process is called the system context. Each process can be uniquely identified by a subset of this information.

- **Examples**:
  - Record in the process table,
  - Identifier ($\rightarrow$ Process ID (PID)),
  - $\longrightarrow$ State,
  - Information about parent or child processes,
  - Priority,
  - Identifiers - access credentials to resources,
  - Quotas (allowed usage quantity of individual resources),
  - Runtime,
  - Opened files, or
  - Assigned devices.

PROCESS TABLE AND PROCESS CONTROL BLOCKS

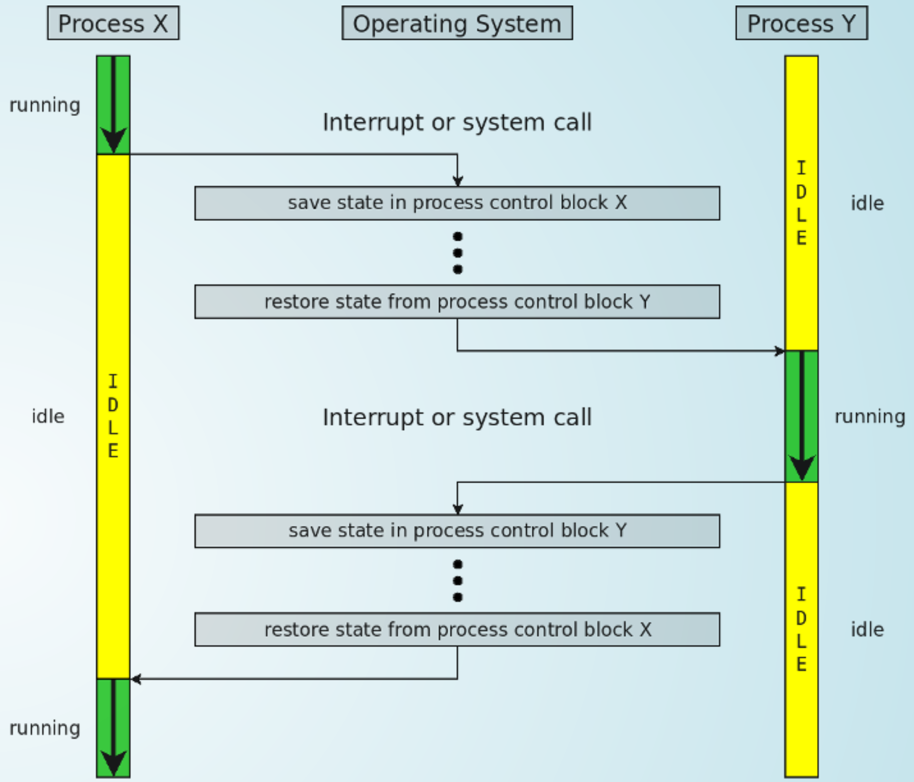
- Each process has its own process context, which is independent of the contexts of other processes

- For managing the processes, the operating system implements the process table
  - It is a list of all existing processes.
  - It contains for each process a record which is called **process control block (PCB)**



CONTEXT SWITCHING

- In order to switch from one process to another, the OS stores the context ($\longrightarrow$ CPU register content) of the former one in the **process control block**
- The context of the latter one is restored from the content of its **process control block**



- Each process is at any moment in a particular state
$\longrightarrow$ Process state models

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PROCESS STATE MODELS

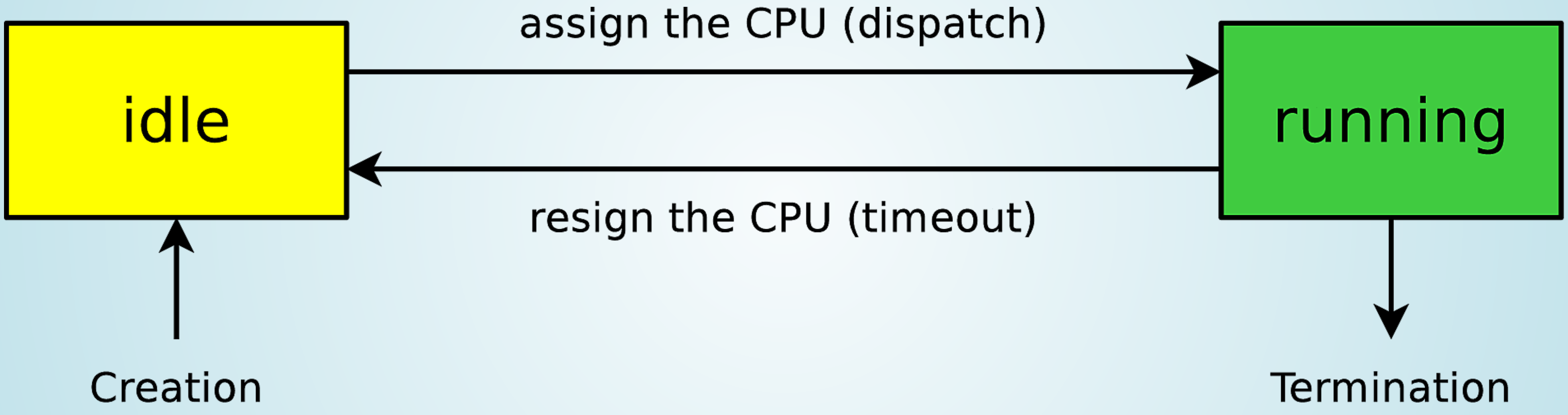
PROCESS STATES

- The number of different states depends on the **process state model** of the operating system used

How many process states must a process model contain at least?

PROCESS STATE MODEL WITH 2 STATES

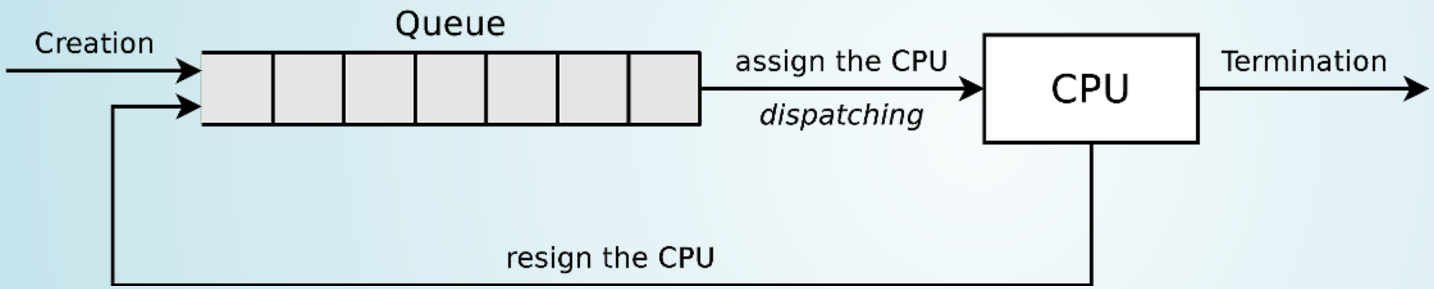
- In principle two process states are enough:
  - running: The CPU is allocated to a process
  - idle: The processes waits for the allocation of CPU



Source: Prof. Christian Baun

PROCESS STATE MODEL WITH 2 STATES (IMPLEMENTATION)

- Processes in state idle are stored in a queue ($\longrightarrow$ the **runqueue**), in which they wait for execution
  - The list can be sorted according to the process priority or waiting time



Source: Prof. Christian Baun

- This model also shows the working method of the **dispatcher**
  - The job of the dispatcher is to carry out the state transitions
- The execution order of the processes is specified by the **scheduler**, which uses a **scheduling algorithm**

PROCESS PRIORITIES

- The priority of a process is proportional to its CPU time
- The process priority is typically expressed as an integer value
  - A lower value represents a higher priority
- For **Linux** systems:
  - Priorities between `-20` and `+19` are available
  - `-20` is the highest priority and `+19` is the lowest priority.
  - The default priority is `0`
  - Normal users can assign priorities from `0` to `19`
  - The super user (`root`) can assign negative values too
- For **RIOT** systems:
  - Priorities between `0` and `15` are available
  - `0` is the highest priority and `15` is the lowest priority.
  - The default priority is `7`
  - Priorities are typically fixed at process creation

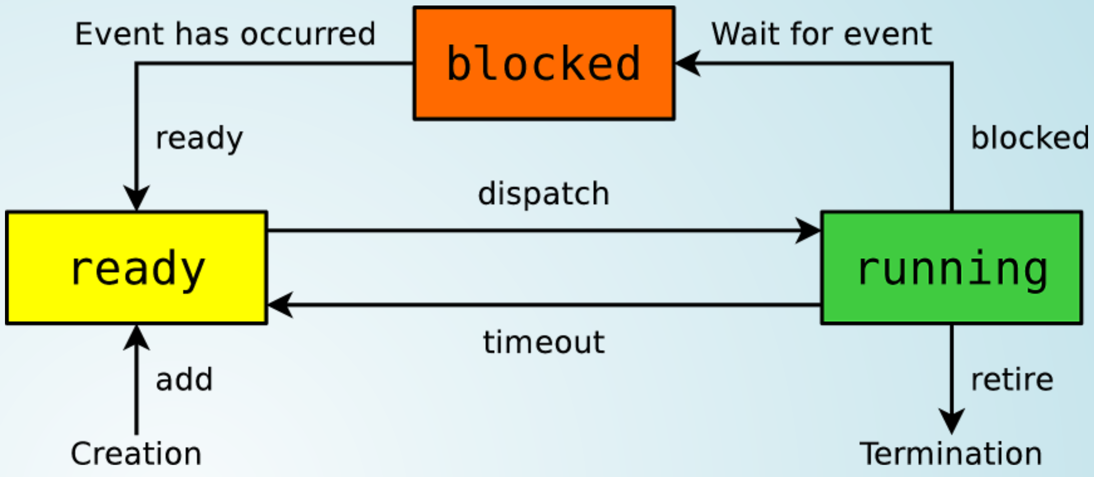
TWO STATES DO NOT SUFFICE IN PRACTICE

- The process state model with 2 states assumes that all processes are ready to run at any time
  - This is unrealistic!
- In almost any system processes become blocked at some point
  - Possible reasons:
    - They wait for an I/O device
    - They wait for the result of another process
    - They wait for a user input
- **Solution:** Split the idle state into two:
  - ready state
  - blocked state

$\Longrightarrow$ Process state model with 3 states

PROCESS STATE MODEL WITH 3 STATES

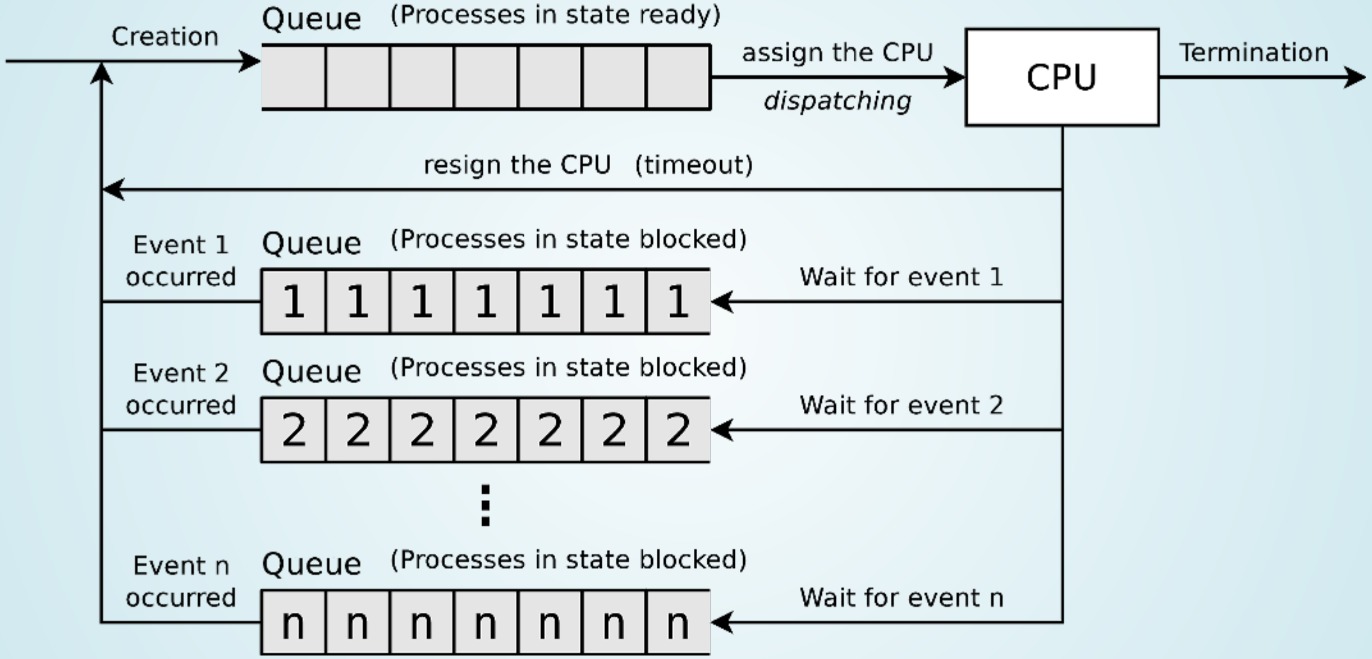
- Each process is in one of the following states:
- running:
  - The CPU is assigned to the process and executes its instructions



- ready:
  - The process is ready to run and is currently waiting for the allocation of the CPU
  - This state is sometimes also called pending
- blocked:
  - The process can currently not be executed and is waiting for the occurrence of an event or the satisfaction of a condition
  - This may be e.g., a message of another process or of an I/O device or the occurrence of a synchronization event

PROCESS STATE MODEL WITH 3 STATES – IMPLEMENTATION

- In practice, operating systems (e.g., Linux or RIOT) implement multiple queues for processes **blocked** state

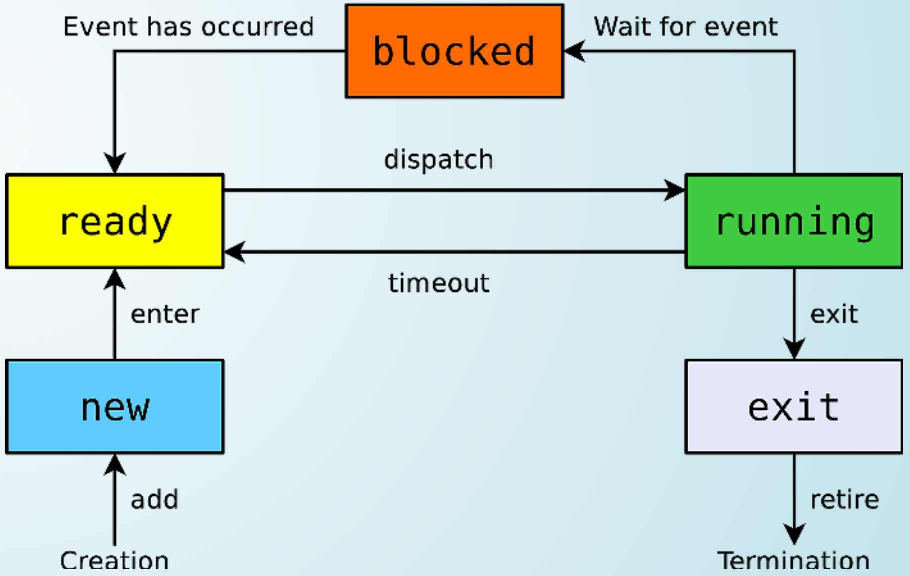


- State transition: When a process state is changed, the corresponding entry is removed from one queue and inserted into another one
- No separate list exists for processes in running state

PROCESS STATE MODEL WITH 5 STATES

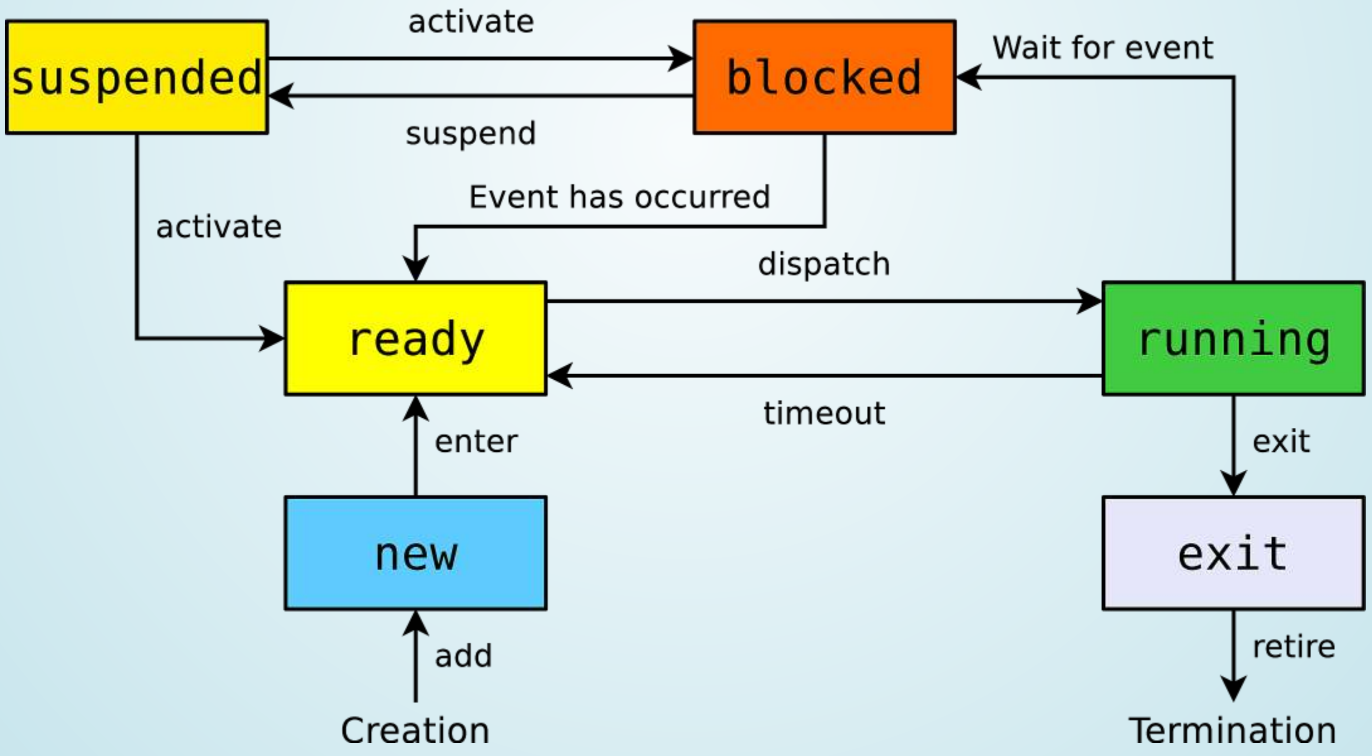
- For many implementations the introduction of two additional states is useful:
  - new: The process (process control block) has been created by the OS but not yet in **ready** state
  - exit: The execution of the process has finished or was terminated but the process control block still exists

- Reason for the existence of the process states **new** and **exit**:
  - The number of executable processes may be limited in order to save memory and to specify the degree of multitasking



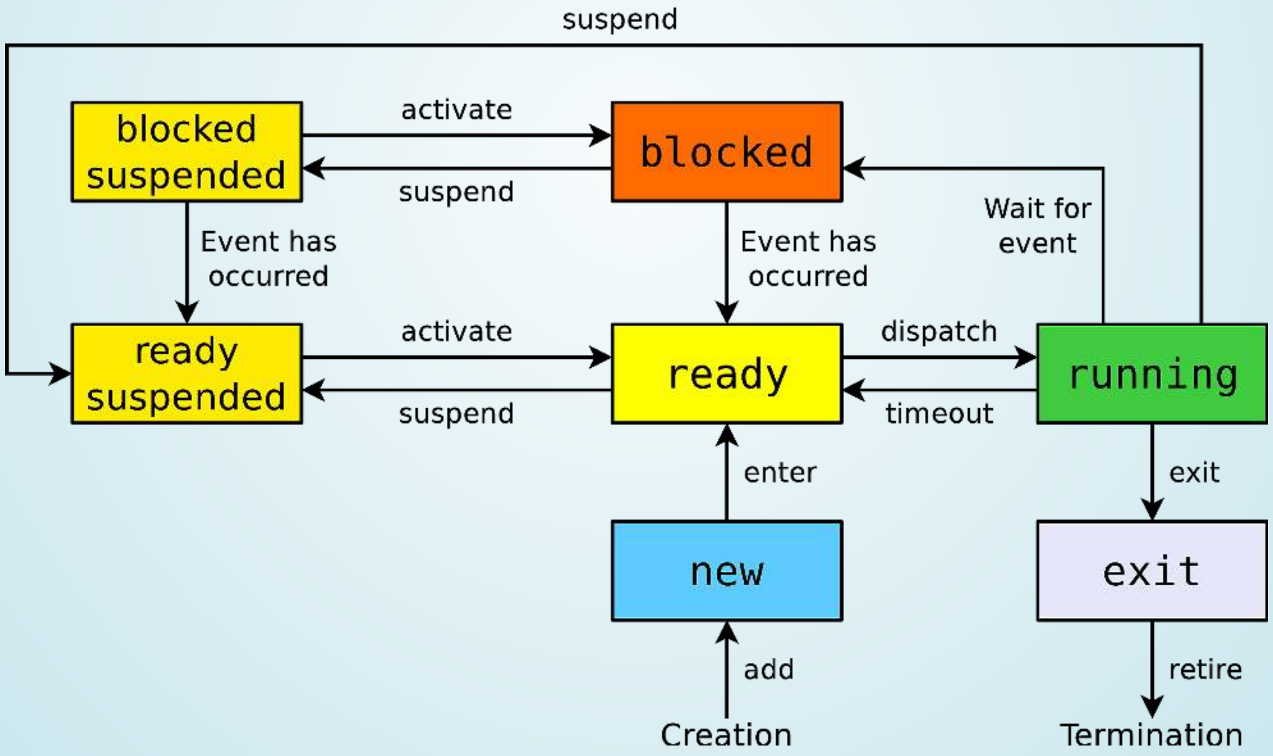
PROCESS STATE MODEL WITH 6 STATES

- The sum of all processes may exceed the amount of physical main memory $\Rightarrow$ memory belonging to currently not running processes is swapped out
  $\Longrightarrow$ swapping
- The OS outsources processes which are in blocked state



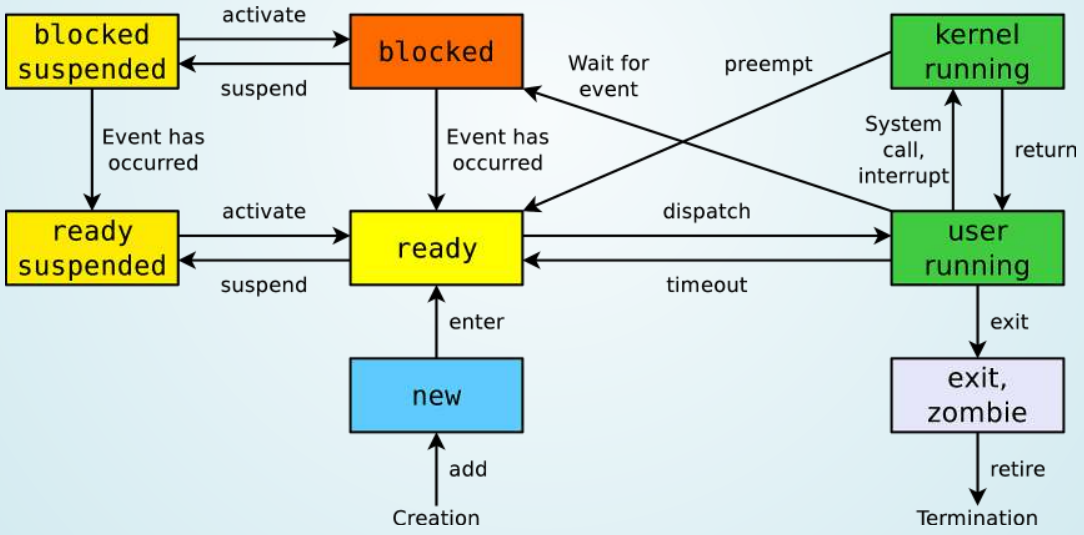
PROCESS STATE MODEL WITH 7 STATES

- For more efficient use of available memory or in order to reduce waiting time, processes in suspended state may be distinguished into
  - blocked suspended state
  - ready suspended state



PROCESS STATE MODEL OF LINUX/UNIX (SOMEWHAT SIMPLIFIED)

- The state running is split into the states…
  - user running for user mode processes
  - kernel running for kernel mode processes



A zombie process has completed execution (via the system call `exit`) but its entry in the process table exists until the parent process has fetched (via the system call `wait`) the exit status (return code)

RECAP

What do you already know? Let's go to the survey again: https://fra-uas.particifyapp.net/p/66824346

- Which cache write policy yields the best performance?
- Which types of context information does the OS store per process?
- To which states are there valid transitions from the ready state in a Linux system?

CREATE AND ERASE PROCESSES

WRITING PORTABLE CODE

What does one need to do in order to implement an application that can be run on a variety of computers?

POSIX

- POSIX (Portable Operating System Interface) is a family of IEEE standards for operating systems
- Aims for portability and compatibility of applications between different operating systems
- Defines user and system level **APIs (application programming interfaces)**
- Additionally it defines command line **shells** and utility interfaces
- It is based on UNIX
- There are few POSIX-certified OS (e.g., macOS, VxWorks, or AIX)
- Many OS (like Linux, FreeBSD, or Minix) are mostly POSIX compliant

POSIX PROCESS CREATION VIA fork

- In a POSIX system the **system call** `fork()` is the only way to create a new process
- If a process calls `fork()`, an identical copy is started as a new process
  - The calling process is called **parent process**
  - The new process is called **child process**
- Child process and parent process both have their own process context, but ...
- all assigned resources (like opened files and memory areas) of the parent process are copied for the child process and are independent from the parent process
- The child process after creation runs the exactly same code
  - Since the program counters are identical as well both processes refer to the same line of code

CODE EXAMPLE FOR fork ON LINUX

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- If a process calls **fork()**, an exact copy is created
  - The processes differ only in the return values of fork()

```c
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
void main(void) {
    int return_value = fork();
    if (return_value < 0) {
        // If fork() returns -1, an error happened.
        // Memory or processes table have no more free capacity.
        ...
    }
    if (return_value > 0) {
        // If fork() returns a positive number, we are in the parent process.
        // The return value is the PID of the newly created child process.
        ...
    }
    if (return_value == 0) {
        // If fork() returns 0, we are in the child process.
        ...
    }
}
```

PROCESS HIERARCHY OF A POSIX SYSTEM

- All processes on a POSIX system are spawned via `fork()`
- All processes are part of the same hierarchy

But which process forms the root of this hierarchy?

`init` or `systemd` (PID 1) is the first process in Linux/UNIX

All running processes originate from `init` $\rightarrow$ init (or systemd) = parent of all processes

PROCESS TREE

- Processes in a system form a tree of processes ($\longrightarrow$ process hierarchy) based on the **parent-child** relationship

The commands `pstree` and `ps f` return an overview about the processes, running in Linux/UNIX, as a tree according to their parent/child relationships

```
$ ps fax
 1   ?        Ss     0:01 /usr/lib/systemd/systemd --switched-root --system
...
1211 ?        Ss     0:00 dhcpcd: [manager] [ip4] [ip6]
1214 ?        S      0:00  \_ dhcpcd: [privileged proxy]
7775 ?        S      0:00  |   \_ dhcpcd: [BPF ARP] enp0s31f6 10.2.0.190
7778 ?        S      0:00  |   \_ dhcpcd: [BPF ARP] wlan0 10.51.134.219
1215 ?        S      0:00  \_ dhcpcd: [network proxy]
1216 ?        S      0:00  \_ dhcpcd: [control proxy]
1339 ?        Ss     0:00 /usr/lib/systemd/systemd --user
1340 ?        S      0:00  \_ (sd-pam)
1465 ?        Ss     0:00  \_ /usr/bin/dbus-daemon --session --nofork
1511 ?        Ssl    0:00  \_ /usr/lib/at-spi-bus-launcher
1519 ?        S      0:00  |   \_ /usr/bin/dbus-daemon --address=unix:path=/run/user/1000/at-spi/bus
```

INFORMATION ABOUT PROCESSES IN LINUX/UNIX

```
$ ps -eFw
UID       PID  PPID  C    SZ   RSS PSR STIME TTY          TIME CMD
root        1     0  0  5456 12860   2 12:06 ?        00:00:01 /usr/lib/systemd/systemd
root     1311     1  0  1998  4992   4 12:06 ?        00:00:00 login -- oleg
oleg     1339     1  0  5110 11828   4 12:07 ?        00:00:00 /usr/lib/systemd/systemd --user
oleg     1347  1311  0 1122763 171300 0 12:07 tty1 00:00:51 sway
oleg     8031     1  0 285131 31908  3 13:16 ?        00:00:02 foot
oleg     8033  8031  0  4948 15160   7 13:16 pts/2 00:00:02 /usr/bin/zsh
oleg 14043     1  3 949647 569960 4 13:26 ?        00:01:33 /usr/lib/firefox/firefox
oleg 14077     1  0 261432 165640 2 13:26 tty1  00:00:06 Xwayland :0 -rootless -core
oleg 22367     1  0 285340 35712  3 13:54 ?        00:00:01 foot
oleg 22369 22367  0  3710  9548   2 13:54 pts/1 00:00:00 /usr/bin/zsh
root 25003     2  0     0     0   6 14:05 ?        00:00:00 [kworker/6:2-events]
root 25097     2  0     0     0   0 14:05 ?        00:00:00 [kworker/0:2-i915-unordered]
oleg 25202 22369  0  3187  4564   3 14:05 pts/1 00:00:00 ps -eFw
```

- C (CPU) = CPU utilization of the process in percent
- SZ (Size) = virtual process size = Text segment, heap and stack (see $\longrightarrow$ slide)
- RSS (Resident Set Size) = Occupied physical memory (without swap) in kB
- PSR = CPU core assigned to the process
- STIME = start time of the process
- TTY (Teletypewriter) = control terminal.
  Usually a virtual device: pts (pseudo terminal slave)
- TIME = consumed CPU time of the process (HH:MM:SS)

PARENT AND CHILD PROCESSES

- The example demonstrates that parent and child processes operate independently of each other and have different memory areas

```c
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
int main(void) {
    int i;
    if (fork())
    // Parent process source code
        for (i = 0; i < 5000000; i++)
            printf("\n Parent: \%i", i);
    else
    // Child process source code
        for (i = 0; i < 5000000; i++)
            printf("\n Child : \%i", i);
    return 0;
}
```

```
Child : 0
Child : 1
...
Child : 21019
Parent: 0
...
Parent: 50148
Child : 21020
...
Child : 129645
Parent: 50149
...
Parent: 855006
Child : 129646
...
```

- The output demonstrates the switches between the processes
- The value of the loop variable `i` proves that parent and child processes are independent of each other

The result of execution can not be reproduced!

THE PID NUMBERS OF PARENT AND CHILD PROCESS (1/2)

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```c
#include <stdio.h>
#include <unistd.h>
#include <stdlib.h>
void main(void) {
    int pid_of_child;
    pid_of_child = fork();
    // An error occured --> program abort
    if (pid_of_child < 0) {
        perror("\n fork() caused an error!");
        exit(1);
    }
    // Parent process
    if (pid_of_child > 0) {
        printf("\n Parent: PID: %i", getpid());
        printf("\n Parent: PPID: %i", getppid());
    }
    // Child process
    if (pid_of_child == 0) {
        printf("\n Child:  PID: %i", getpid());
        printf("\n Child:  PPID: %i", getppid());
    }
}
```

- This example creates a child process
- Child process and parent process both print:
    - Own PID
    - PID of parent process (PPID)

THE PID NUMBERS OF PARENT AND CHILD PROCESS (2/2)

- The output is usually similar to this one:

```
Parent: PID: 20835
Parent: PPID: 3904
Child:  PID: 20836
Child:  PPID: 20835
```

- This result can be observed sometimes:

```
Parent: PID: 20837
Parent: PPID: 3904
Child:  PID: 20838
Child:  PPID: 1
```

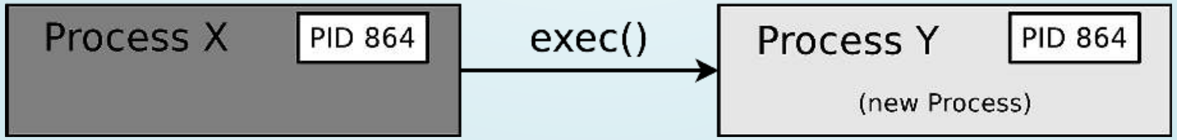
- The parent process was terminated before the child process
  - If a parent process terminates before the child process, it gets `init` as the new parent process assigned
  - Orphaned processes are always adopted by `init`

REPLACING PROCESSES VIA exec

- The system call exec() replaces a process with another one
  - The new process gets the PID of the calling process
- To start a new process, one need to …
  - call fork(), and then
  - call exec()

If no new process is created with fork() before exec() is called, the parent process is replaced

- Steps of a program execution from a **shell**:
  - The shell creates with fork() an identical copy of itself
  - In the new process, the actual program is stared with exec()



Source: Prof. Christian Baun

EXEC EXAMPLE

```
$ ps -f
UID         PID  PPID  C STIME TTY          TIME CMD
user       1772  1727  0 May18 pts/2    00:00:00 bash
user      12750  1772  0 11:26 pts/2    00:00:00 ps -f
$ bash
$ ps -f
UID         PID  PPID  C STIME TTY          TIME CMD
user       1772  1727  0 May18 pts/2    00:00:00 bash
user      12751  1772 12 11:26 pts/2    00:00:00 bash
user      12769 12751  0 11:26 pts/2    00:00:00 ps -f
$ exec ps -f
UID         PID  PPID  C STIME TTY          TIME CMD
user       1772  1727  0 May18 pts/2    00:00:00 bash
user      12751  1772  4 11:26 pts/2    00:00:00 ps -f
$ ps -f
UID         PID  PPID  C STIME TTY          TIME CMD
user       1772  1727  0 May18 pts/2    00:00:00 bash
user      12770  1772  0 11:27 pts/2    00:00:00 ps -f
```

- Because of the `exec`, the `ps -f` command replaced the bash and got its PID (12751) and PPID (1772)

ANOTHER exec EXAMPLE

```c
#include <stdio.h>
#include <unistd.h>
int main(void) {
    int pid;
    pid = fork();
    // If PID!=0 --> Parent process
    if (pid) {
        printf("...Parent process...\n");
        printf("[Parent] Own PID:           %d\n", getpid());
        printf("[Parent] PID of the child:  %d\n", pid);
    }
    // If PID=0 --> Child process
    else {
        printf("...Child process...\n");
        printf("[Child]  Own PID:           %d\n", getpid());
        printf("[Child]  PID of the parent: %d\n", getppid());
        // Current program is replaced by "date"
        // "date" will be the process name in the process table
        execl("/bin/date", "date", "-u", NULL);
    }
    printf("[%d ]Program abort\n", getpid());
    return 0;
}
```

- The system call `exec()` does not exist as wrapper function
- But multiple variants of the `exec()` function exist
- One of these variants is `execl()`

Helpful overview about the different variants of the `exec()` function:
http://www.cs.uregina.ca/Links/class-info/330/Fork/fork.html

EXPLANATION OF THE exec EXAMPLE

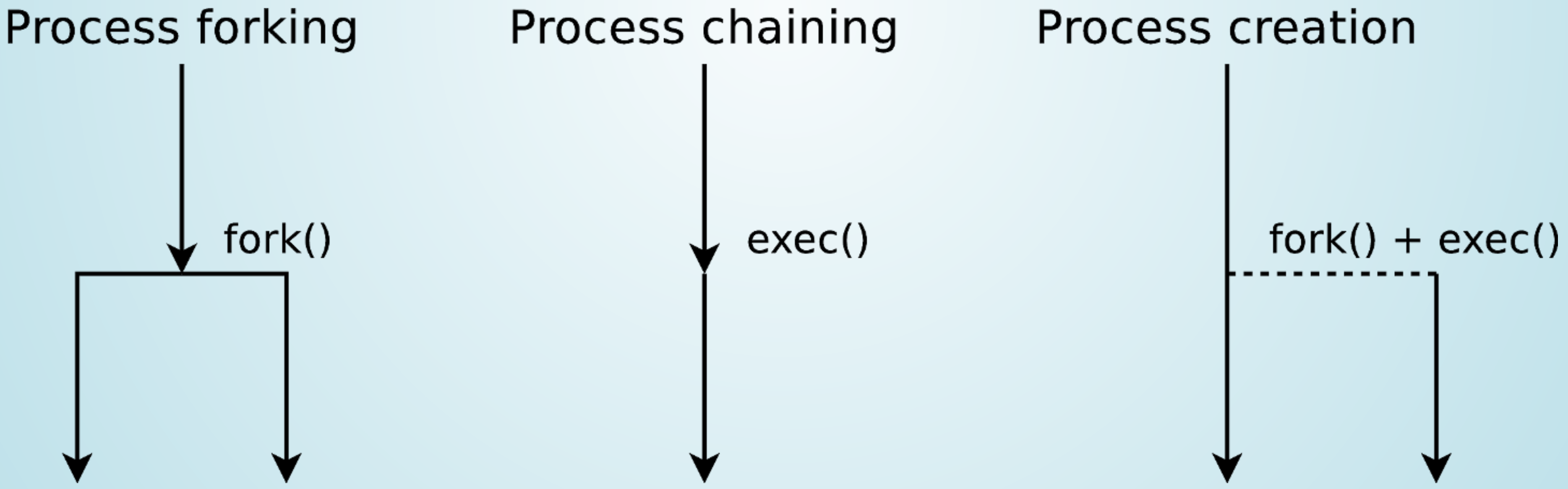

```
$ ./exec_example
...Parent process...
[Parent] Own PID:           25646
[Parent] PID of the child:  25647
[25646 ]Program abort
...Child process...
[Child]  Own PID:           25647
[Child]  PID of the parent: 25646
Di 24. Mai 17:25:31 CEST 2016
$ ./exec_example
...Parent process...
[Parent] Own PID:           25660
[Parent] PID of the child:  25661
[25660 ]Program abort
...Child process...
[Child]  Own PID:           25661
[Child]  PID of the parent: 1
Di 24. Mai 17:26:12 CEST 2016
```

- After printing its PID via `getpid()` and the PID of its parent process via `getppid()`, the child process is replaced via `date`
- If the parent process of a process terminates before the child process, the child process gets `init` as new parent process assigned :::

Since Linux Kernel 3.4 (2012) and Dragonfly BSD 4.2 (2015), it is also possible that other processes than PID=1 become the new parent process of an orphaned process http://unix.stackexchange.com/questions/149319/new-parent-process-when-the-parent-process-dies/177361#177361

3 POSSIBLE WAYS TO CREATE A NEW PROCESS

- Process forking: A running process creates with `fork()` a new, identical process
- Process chaining: A running process creates with `exec()` a new process and terminates itself this way because it gets replaced by the new process
- Process creation: A running process creates with `fork()` a new, identical process, which replaces itself via `exec()` by a new process



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HAVE FUN WITH FORK BOMBS

- A fork bomb is a program, which calls the `fork()` system call in an infinite loop
- **Objective**: Create copies of the process until there is no more free memory
  - The system becomes unusable
- Only protection option: Limit the maximum number of processes and the maximum memory usage per user

Python code

```python
import os

while True:
    os.fork()
```

C code

```c
#include <unistd.h>

int main(void)
{
    while(1)
    fork();
}
```

PHP code

```php
<?php
  while(true)
    pcntl_fork();
?>
```

STRUCTURE OF A UNIX PROCESS IN MEMORY

PROCESS' DATA

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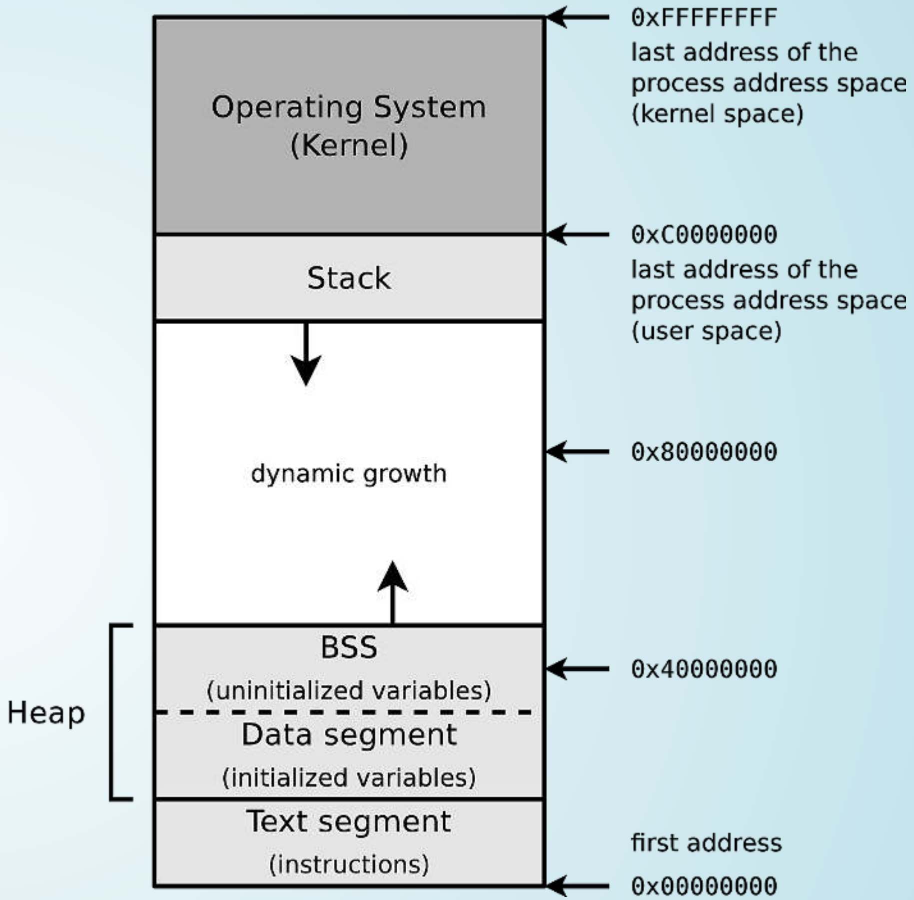
What types of data are being accessed by a process?

MEMORY LAYOUT OF A UNIX PROCESS

- The command **size** returns the size (in bytes) of the text segment, data segment, and BSS of program files
  - The contents of the text segment and data segment are included in the program files
  - All contents in the BSS are set to value `0` at process creation

```
$ size /bin/c*
text    data    bss     dec     hex filename
46480    620    1480    48580    bdc4 /bin/cat
7619    420      32    8071    1f87 /bin/chacl
55211    592     464    56267    dbcb /bin/chgrp
51614    568     464    52646    cda6 /bin/chmod
57349    600     464    58413    e42d /bin/chown
120319    868    2696  123883    1e3eb /bin/cp
131911    2672    1736  136319    2147f /bin/cpio
```



Sources UNIX-Systemprogrammierung, *Helmut Herold*, Addison-Wesley (1996), P.345-347
Betriebssysteme, *Carsten Vogt*, Spektrum (2001), P.58-60
Moderne Betriebssysteme, *Andrew S. Tanenbaum*, Pearson (2009), P.874-877

SUMMARY

You should now be able to answer the following questions:

- What is a process?
- Which information does the hardware and the system context provide?
- What happens when the OS switches from one process to another?
- Which states can a process have?
- How can a new process be started?
- How can a user mode process execute a higher privileged task?