Operating Systems

Introduction, Processes, Threads

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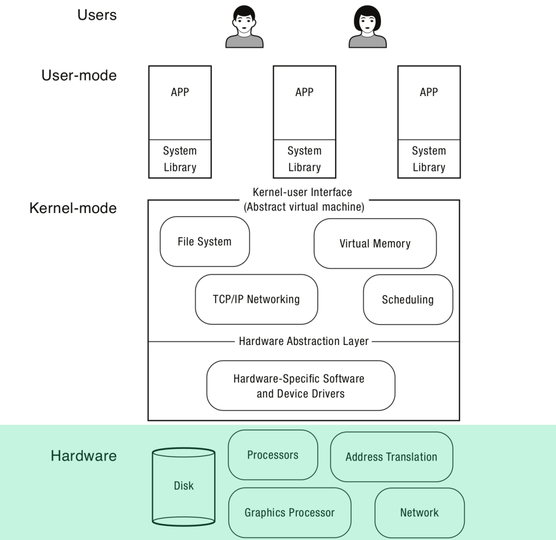
Basics

What is an Operating System



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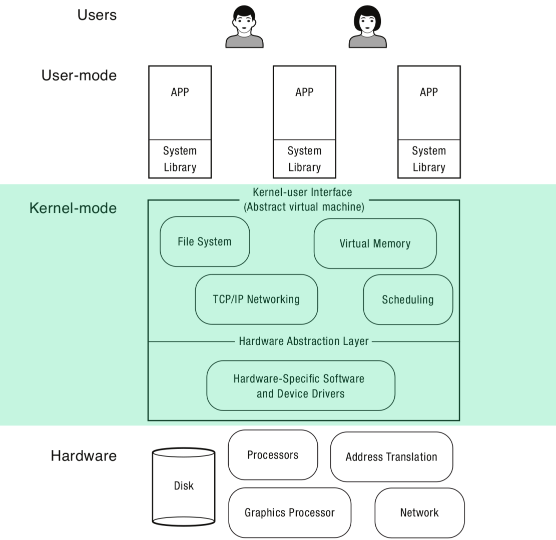

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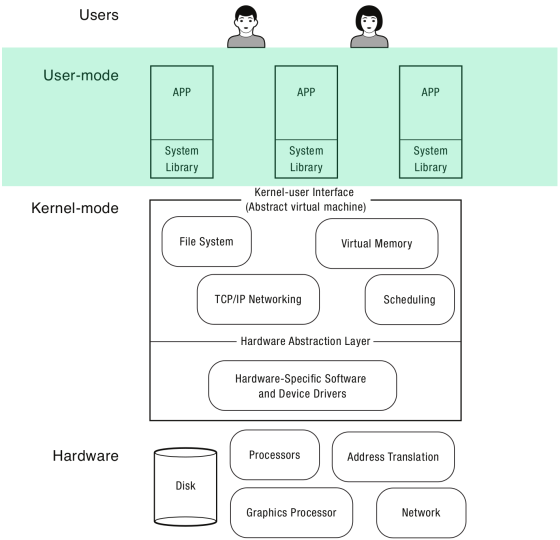

What is an Operating System

- Run on all sorts of devices:
    - Servers, Desktops, Notebooks
    - Tablets, Smartphones
    - Routers, Switches, Displays
    - Door Locks, Washing Machines, Toasters
    - Cars, Airplanes
    - ....
- We focus on general purpose operating systems

Operating System Roles

- Referee
- Illusionist
- Glue

OS Design Patterns I

- OS challenges are not unique - apply to many different computing domains
- many complex software systems
  - have multiple users
  - run programs written by third-party developers
  - need to coordinate simultaneous activities

Challenges:

- resource allocation
- fault isolation
- communication
- abstraction
- how to provide a set of common services

Design Criteria for Operating Systems

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- Reliability and Availability

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- Security
- Portability
- Performance
- Adoption

The first computers were so called “mainframes” that had no operating systems.

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  - *automate some of the reconfiguration performed by human operators*

UNIX et al.

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- by programmers - for programmers
- originally in assembly language
- rewritten in C
- portable operating system!

Evolution of Operating Systems

Phase	Idea
Open shop	operating systems
Batch processing	tape batching, first-in/first -out scheduling
Multiprogramming	processor multiplexing, atomic operations, demand paging, I/O spooling, priority scheduling, remote job entry
Timesharing	simultaneous user interactions, on-line file systems
Concurrent programming	hierarchical systems, extensible kernels, parallel programming
Personal Computing	graphical user interface
Distributed Systems	remote servers

Personal Computing

1968: First devices named "personal computer" (actually a calculator)

1973: Xerox Alto, first computer with mouse, desktop, and GUI

PC Operating Systems

- Different requirements: only one user
- CP/M, DOS, Apple-DOS
- Windows
- OS-2, Windows-XP, OS-X, Linux....

Process and Thread Fundamentals

Program, Process, Thread

- A program: a binary file containing code and data

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Abstractions

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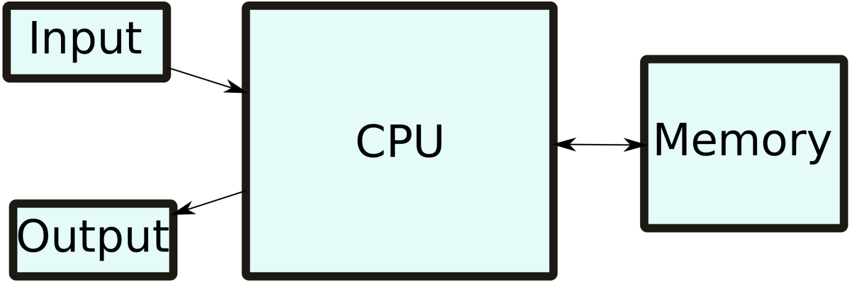
→ Abstractions hide many details but provide the required capabilities

CPU vs. Process



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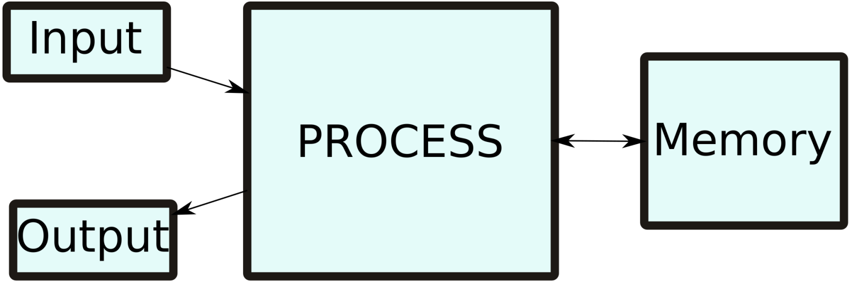
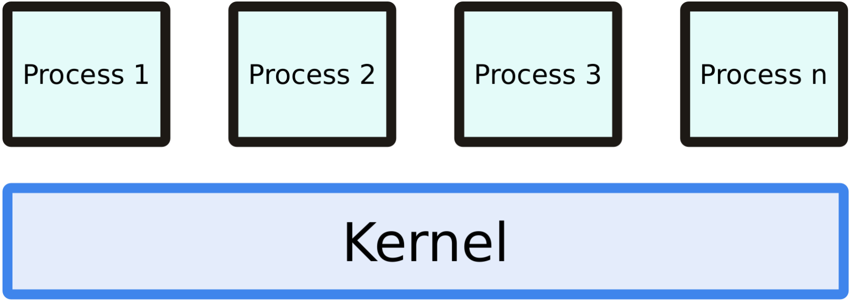


Processes

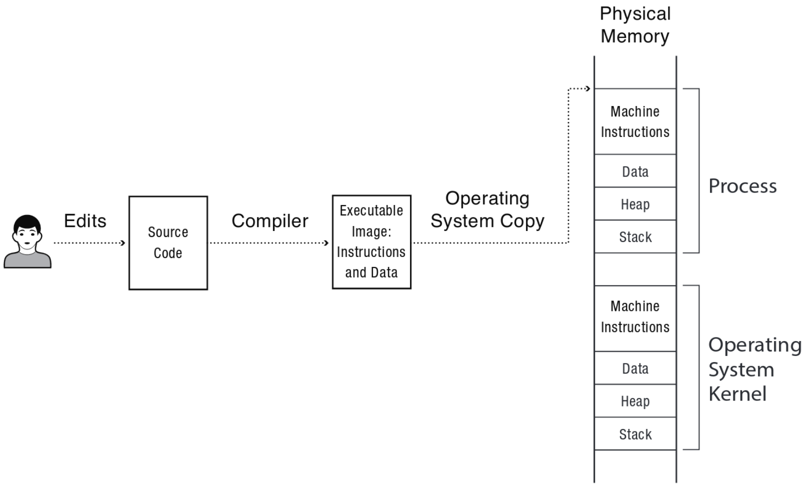
Implemented by the kernel



Implementation?

- We have “one hardware”
- We have many “processes”
- How do we solve this?

The Process Abstraction



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- Must be able to switch from one process to another
- OS keeps a list of process data structure (aka the "PCB")

Process List (aka PCB)

Process list stores

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- own stack

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Process can have multiple threads

- same program code and data
- own stack
- own registers (including instruction pointer)

Process Protection Mechanisms

How can it be safe to run untrusted software on your hardware?

Challenges:

- Threads of a process run code

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- Maybe buggy? Malicious?
- We want to give the program restricted privileges
- How can we do that?

Privileged and unprivileged instructions

- Most instructions cannot do any harm

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- Some instructions can

Privileged and unprivileged instructions

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```
asm("cli");
asm("hlt");
```

Examples for Privileged Instructions (Intel)

- `LGDT`: Load GDT register
- `LLDT`: Load LDT register
- `LTR`: Load task register
- `LIDT`: Load IDT register
- `MOV (control registers)`: Load and store control registers
- `LMSW`: Load machine status word
- `CLTS`: Clear task-switched flag in register CR0
- `MOV (debug registers)`: Load and store debug registers
- `INVD`: Invalidate cache, without writeback
- `WBINVD`: Invalidate cache, with writeback
- `INVLPG`: Invalidate TLB entry
- `HLT`: Halt processor
- `RDMSR`: Read Model-Specific Registers

Dual-mode operation

- User-mode: limited privileges
- Kernel-mode: complete privileges

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Recall: DPL defined in segment descriptor

- User-mode: $DPL = 3$
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$\rightarrow$ hardware-assisted control mechanisms

Hardware Support: Dual-Mode

Kernel Mode:

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Hardware Support: Dual-Mode

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- OS runs in kernel mode

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Hardware Support: Dual-Mode

Kernel Mode:

- OS runs in kernel mode
- Full privileges for hardware accesses
- Read/write to any memory

User Mode:

- User programs run in user mode
- Limited privileges
- Some instructions and memory regions are not accessible

Hardware Support: Dual-Mode

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- OS runs in kernel mode
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- Access to any I/O-device

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- If tried anyway: exception is raised by the CPU.

Hardware Support: Dual-Mode

Kernel Mode:

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  $\rightarrow$ ask operating system for help

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→ system call

Hardware Support: Dual-Mode Implementation

- mode stored in EFLAGS register
- segment descriptors
- paging structures
- ...

IA-32 Ring Structure

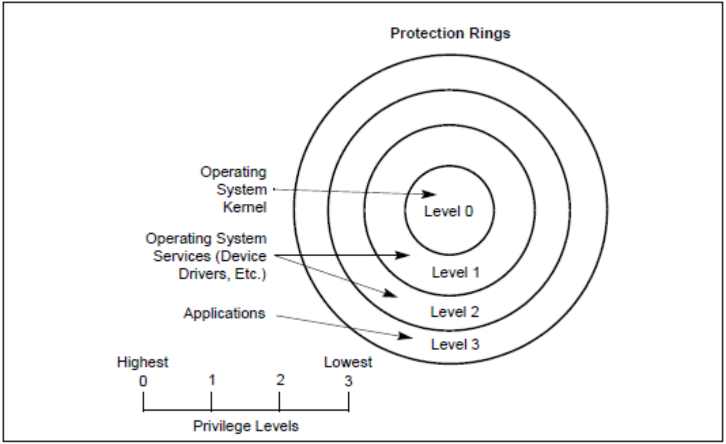

Figure 6-3. Protection Rings

How to change from ring to ring . . .

- change from kernel mode (lower level ring) to user mode (higher level ring) not a problem

How to change from ring to ring . . .

- change from kernel mode (lower level ring) to user mode (higher level ring) not a problem
- change from user mode (higher level ring) to kernel mode (lower level ring) must be a controlled procedure

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→ Otherwise there would be no protection

How to change from ring to ring . . .

- change from ring 0 to ring 3 not a problem
- change from user mode (higher level ring) to kernel mode (lower level ring) must be a controlled procedure

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How to change from ring to ring . . .

- change from ring 0 to ring 3 not a problem
- change from ring 3 to ring 0 through controlled procedure

→ Otherwise there would be no protection

How to change from ring to ring ...

- change from ring 0 to ring 3 through special return instruction (`iret`)
- change from ring 3 to ring 0 through controlled procedure

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How to change from ring to ring . . .

- change from ring 0 to ring 3 through special return instruction (`iret`)
- change from ring 3 to ring 0 through int 0x80, sysenter, or syscall

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  - timer
  - I/O-devices
  - exceptions (divide-by-zero, page fault, etc.)

Interrupts and Stacks

- Interrupts switch stack to a kernel stack

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- Why?

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  - Maybe SP points to illegal address
  - Would raises an page fault exception (in the kernel)
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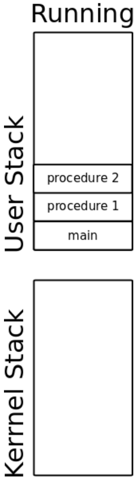
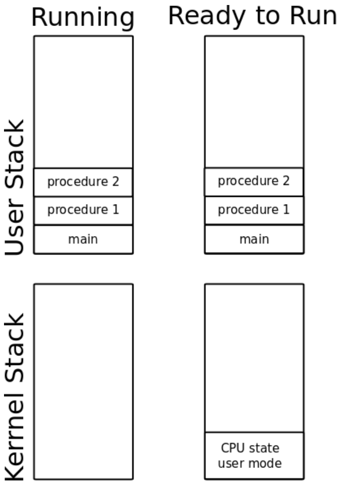
- How many stacks do we actually need?
- Do we need multiple stacks for the kernel?

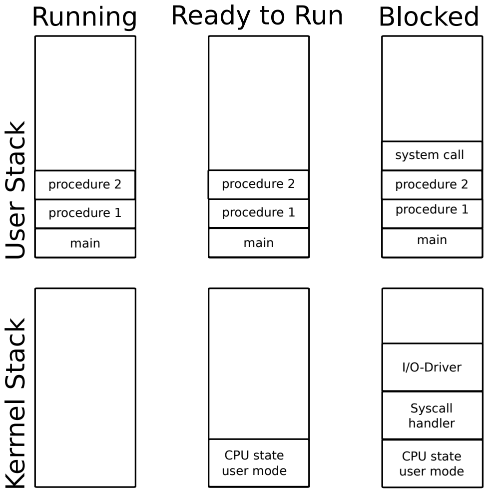
Stacks


Running
User Stack
procedure 2
procedure 1
main
Kernel Stack

Stacks


Running
Ready to Run
User Stack
procedure 2
procedure 1
main
procedure 2
procedure 1
main
Kernel Stack
CPU state
user mode

Stacks


Running
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User Stack
Kernel Stack
procedure 2
procedure 1
main
procedure 2
procedure 1
main
system call
procedure 2
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main
CPU state
user mode
I/O-Driver
Syscall
handler
CPU state
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Context Switches

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Threads. Multiple Threads.

Changing the instruction pointer

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asm("jmp *%[other_thread_function]"
    :
    : [other_thread_function]"r"(other_thread_function));
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Changing the instruction pointer

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```

does this work?

Changing the instruction pointer

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Context Switch: Old Thread → New Thread

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2. Pop all CPU register values into a struct
3. Set `currentThreadInfo`, etc. to kernel thread

currentThreadRegisters

```
struct ArchThreadRegisters
{
  uint64  rip;        //   0
  uint64  cs;         //   8
  uint64  rflags;     //  16
  uint64  rax;        //  24
  uint64  rcx;        //  32
  uint64  rdx;        //  40
  uint64  rbx;        //  48
  uint64  rsp;        //  56
  uint64  rbp;        //  64
  uint64  rsi;        //  72
  uint64  rdi;        //  80
  uint64  r8;         //  88
  uint64  r9;         //  96
  uint64  r10;        // 104
  uint64  r11;        // 112
  uint64  r12;        // 120
  uint64  r13;        // 128
  uint64  r14;        // 136
  uint64  r15;        // 144
  uint64  ds;         // 152
  uint64  es;         // 160
  uint64  fs;         // 168
  uint64  gs;         // 176
  uint64  ss;         // 184
  uint64  dpl;        // 192
  uint64  rsp0;       // 200
  uint64  ss0;        // 208
  uint64  cr3;        // 216
  uint32  fpu[28];    // 224
};
```

Context Switch: Old Thread → New Thread

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1. "Restore" CPU register values

Context Switch: Old Thread → New Thread

1. "Restore" CPU register values
    1.1 `iretq` (interrupt return) expects `ss`, `rsp`, `rflags`, `cs`, `rip` on the stack
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Context Switch

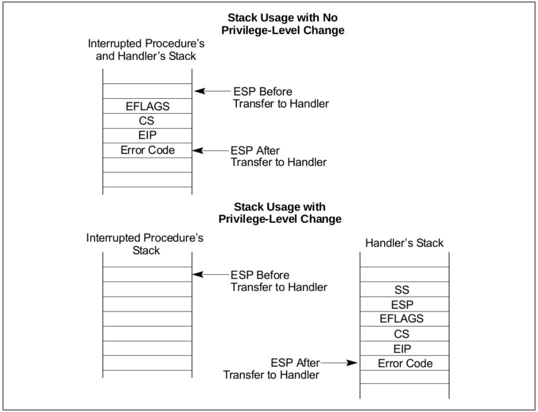

Figure 6-4. Stack Usage on Transfers to Interrupt and Exception-Handling Routines

Looks identical for 64 bits

Context Switch: New Thread/First Thread

Context Switch: New Thread/First Thread

Act as if:

- Thread was running already
- We are returning from an interrupt

Context Switch: New Thread/First Thread

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- clock
- device
- system call (`syscall` / `sysenter` / `int 0x80`)
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  - executing privileged instruction
  - divide by 0
  - integer overflow
  - bad memory access

Process and Thread Organization

Program, Process, Thread

- **Program**: a binary file containing code and data

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  - a mold for a process

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A process is a container.

- Process ID

Process Resources

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- A user stack
- A kernel stack (for syscalls)
- A second set of register values for the kernel (for syscalls)

Process and Thread Interaction

Load program, create process, . . .

Process and Thread Interaction

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- 1 initial thread

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Process and Thread Interaction

Load program, create process, . . .

- 1 initial thread
- executes the `main()`-function
- it's not a "main"-thread
- process may start further threads if required (how?)

Threads

- "There is no such thing as a thread" at the CPU-level

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- Threads can be implemented with and without support of the operating system
  - Pure Userspace Threading: lightweight, but many drawbacks
- Threads can be implemented with and without support of the CPU (`int 0x80` vs. `sysenter/syscall`)

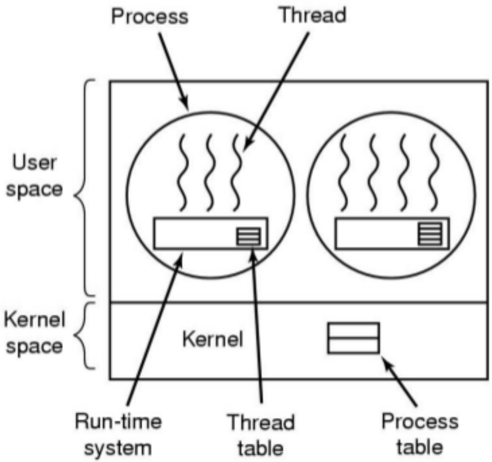
Pure Userspace Threads

- Kernel has no concept of threads and no idea they might exist

Pure Userspace Threads

- Kernel has no concept of threads and no idea they might exist (that's how it started)
- Implement threads in userspace as library
- can be implemented in all operating systems

Userspace Threads



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    - change stack pointer and instruction pointer (this time `jmp`)

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- Sometimes not
  - Page faults
  - if page not in memory, process will block
  - if thread has an endless loop and does not free CPU...

Implementation

Two and a half options:

- Userspace
- Kernelspace
- Mixed

kernel mode threads

- No runtime system needed

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  - less code the user can break

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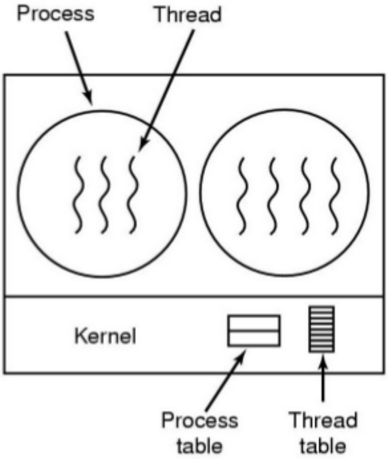
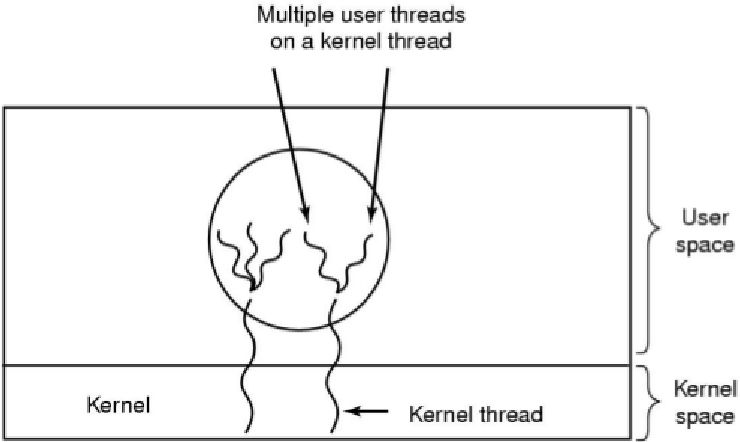
- thread creation and management via syscall
  - takes longer than before
  - thread-recycling

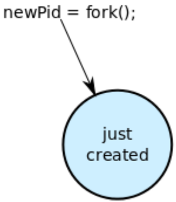
Kernel mode threads



Hybrid solution



Thread states



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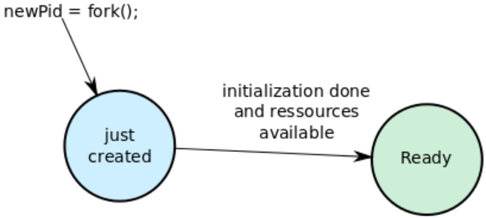

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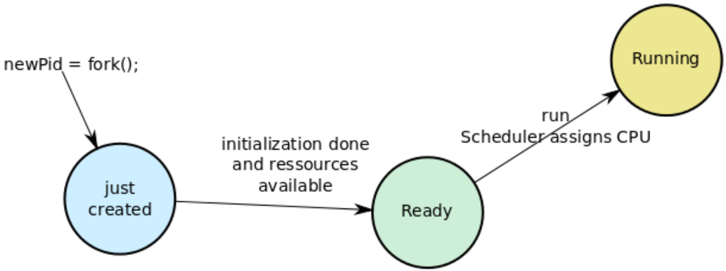

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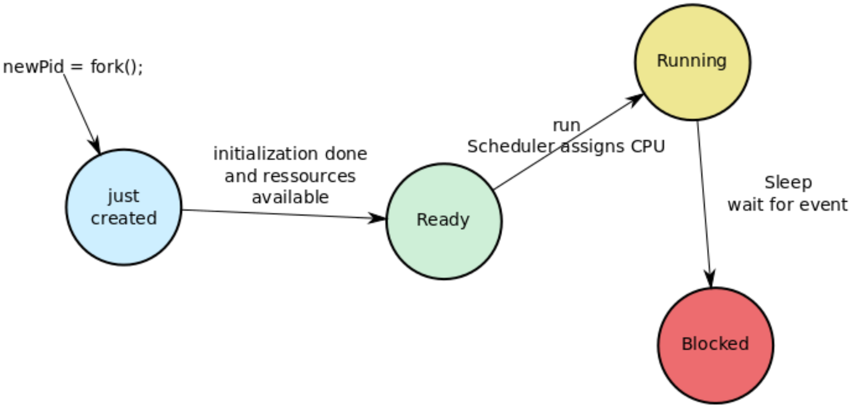

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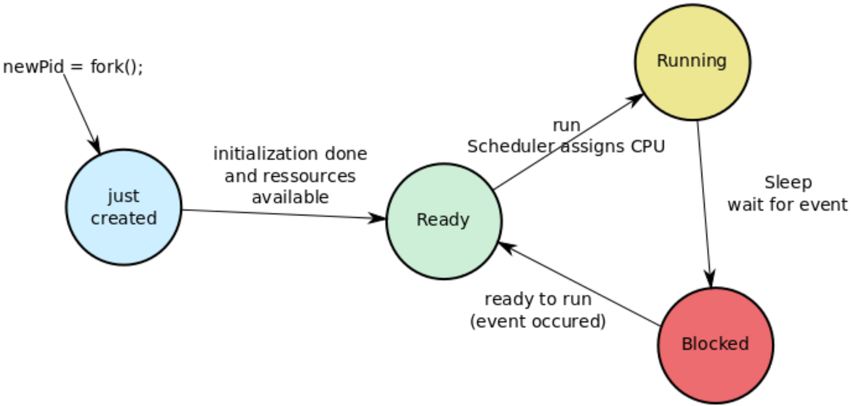

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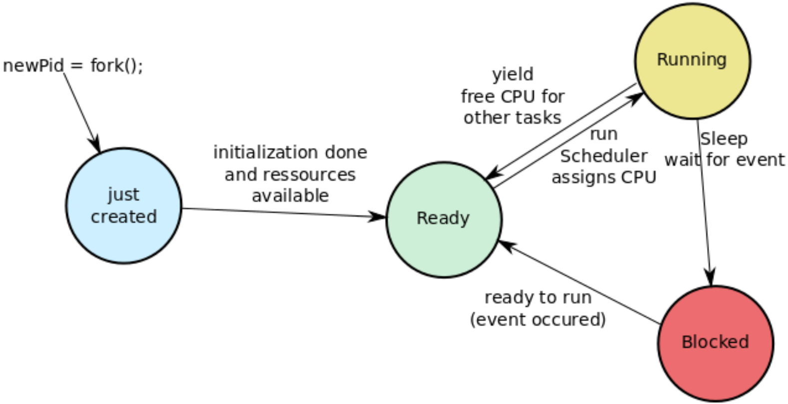

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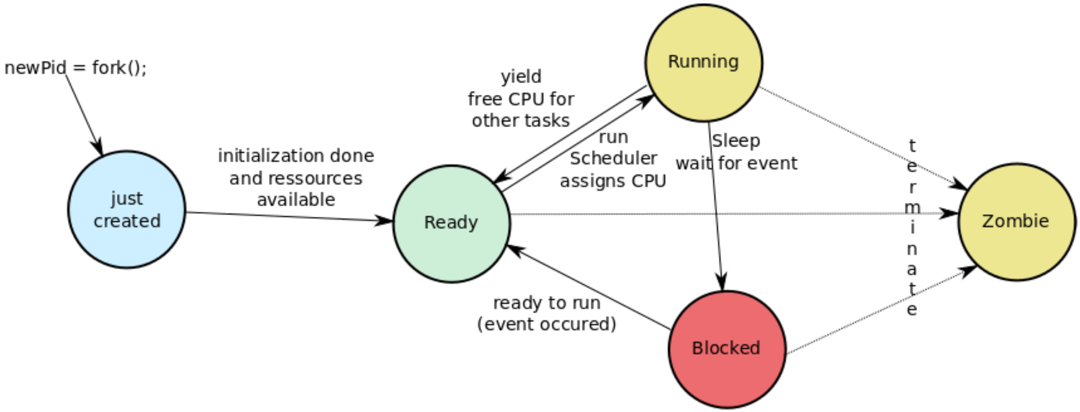
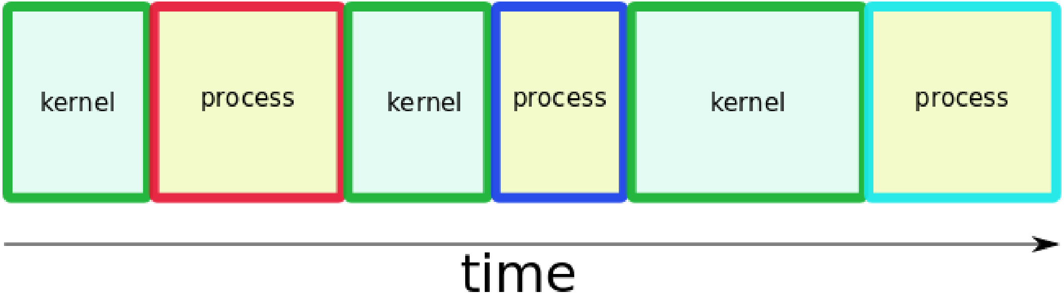


Context Switching



Process Creation

- at boot time (kernel threads, init processes)

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- at boot time (kernel threads, init processes)
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    - also: start of a scheduled batch job (cronjob, how?)

Process Creation at request of a user

via Syscall!

- UNIX/Linux: `fork` (exact copy)

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- Windows: `CreateProcess` (new image)

Process Creation at request of a user

via Syscall!

- UNIX/Linux: `fork` (exact copy)
- Windows: `CreateProcess` (new image)
- SWEB: `fork` (as soon as you have implemented it)

What does the fork do?

Check http://pubs.opengroup.org/onlinepubs/9699919799/functions/fork.html!!

Process Creation via fork (on Unix / Linux / SWEB)

http://pubs.opengroup.org/onlinepubs/9699919799/functions/fork.html:

```
pid_t fork(void);
```

The fork() function shall create a new process. The new process (child process) shall be an **exact copy** of the calling process (parent process) **except** as detailed below:

- unique PID
- copy of file descriptors
- semaphore state is copied
- shall be created with a single thread. If a multi-threaded process calls fork(), the new process shall contain a replica of the calling thread and its entire address space, possibly including the states of mutexes and other resources.
- parent and the child processes shall be capable of executing independently before either one terminates.

fork/exec Return Value

http://pubs.opengroup.org/onlinepubs/9699919799/functions/fork.html:

```
pid_t fork(void);
```

Upon successful completion, fork() shall return 0 to the child process and shall return the process ID of the child process to the parent process. Both processes shall continue to execute from the fork() function. Otherwise, -1 shall be returned to the parent process, no child process shall be created, and errno shall be set to indicate the error.

Fork

```
pid_t child_pid;
child_pid = fork();
if (child_pid == -1) {
        printf("fork failed\n");
} else if (child_pid == 0) {
        printf("i'm the child\n");
} else {
        printf("i'm the parent\n");
        waitpid(child_pid,0,0); //
            wait for child to die
}
```

- child does not know the parent

Fork

```
pid_t child_pid;
child_pid = fork();
if (child_pid == -1) {
        printf("fork failed\n");
} else if (child_pid == 0) {
        printf("i'm the child\n");
} else {
        printf("i'm the parent\n");
        waitpid(child_pid,0,0); //
            wait for child to die
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```

- child does not know the parent
- parent knows the child

Fork

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- child does not know the parent
- parent knows the child
- parent waits for child to die (`waitpid`)

Process Termination

- Normal exit (return value: zero)

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- Normal exit (return value: zero)
- Error exit (return value: non-zero)
- Fatal error (e.g. segmentation fault)
- Killed by another process

Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking

Implicit parent-child hierarchy on Unix/Linux:

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Process Hierarchies

Some operating systems have hierarchies:

- implicit hierarchy from forking
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- doesn't exist in Windows

Implicit parent-child hierarchy on Unix/Linux:

- when parent dies, all children, grand-children, grand-grand-children, . . . , die aswell
- UNIX/Linux also cheats a bit: parent process typically inherits a processes' children, etc.

Process/Thread State

```
git grep TODO | sort
```

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git grep TODO | sort
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- sort has to wait for input
- what does the sort do in the meantime?
    - loop and check (busy wait)
    - sleep and get woken up
- blocking the process makes sense
- do we actually block the process?

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Take Aways

- Processes divide resources amongst themselves (except processor time)
- Threads divide processor time amongst themselves (and a few resources)
- Building block of modern multi-threading are context switches
- Operating system creates illusions
  - for the hardware: there is only 1 thread and a lot of interrupts
  - for the userspace: we can have an arbitrary number of threads