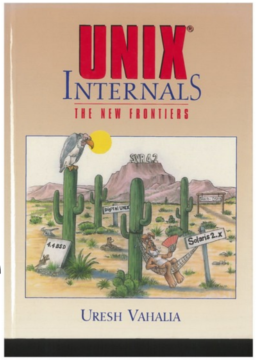
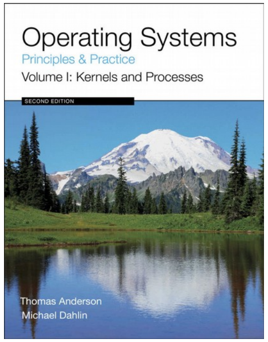
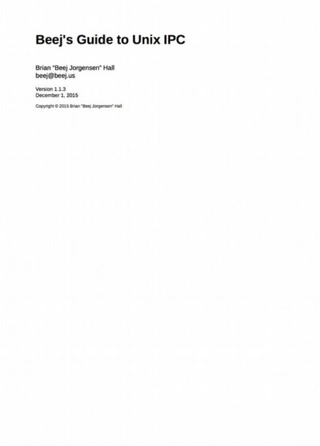
Kernel and processes

- Unix Internals
  - Chapter 2
- Operating Systems Principles & Practice
  - Volume I: Kernels and Processes
    - Chapter 2
    - Chapter 3
- Beej's Guide to Unix IPC
  - Chapter 2





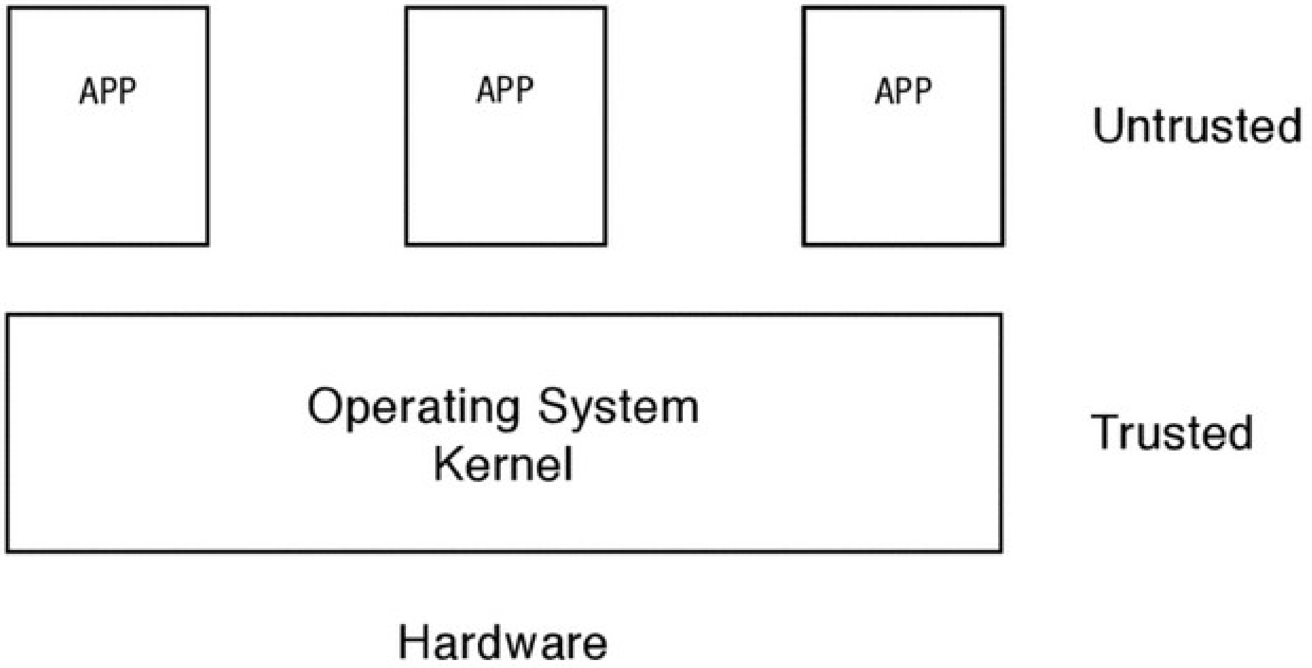


Protection

- OS central role
  - isolation of misbehaving applications
- Fundamental to other OS goals
  - Reliability
  - Security
  - Privacy
  - fairness
- OS kernel
  - implements protection
  - lowest level SW running on the system
-

(Un)trusted code

- Applications
  - untrusted



- Process
  - execution of application program with restricted rights
  - Needs permission
    - from OS kernel
    - to access resources (memory from other processes, I/O. ...)

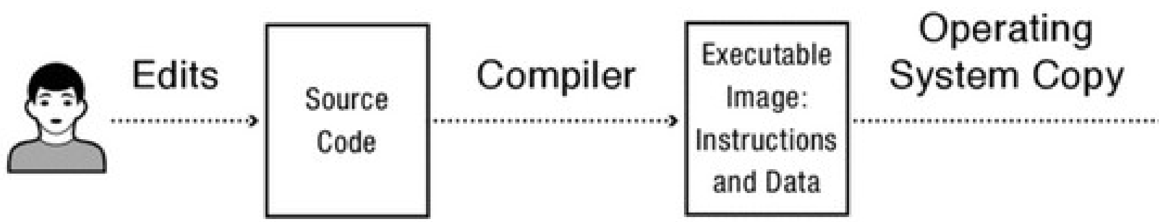
Challenge: Protection

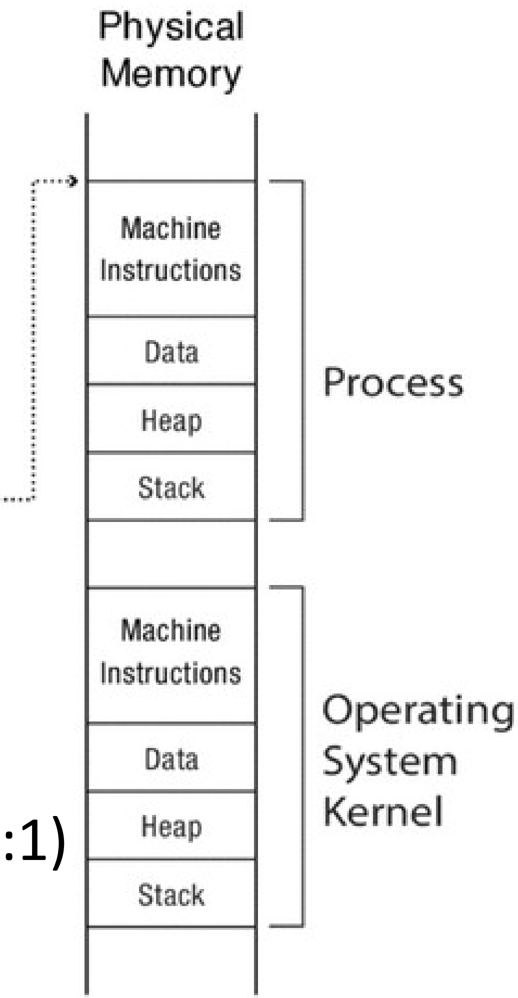
- How do we execute code with restricted privileges?
  - because the code is buggy
  - because it might be malicious

- Some examples:
  - A script running in a web browser
  - A program you just downloaded off the Internet
  - A program you just wrote that you haven't tested yet

Process Abstraction

- Process: an *instance* of a program, running with limited rights





  – Thread: a sequence of instructions within a process
    - Potentially many threads per process (for now 1:1)
  – Address space: set of rights of a process
    - Memory that the process can access
    - Other permissions the process has (e.g., which system calls it can make, what files it can access)

Hardware Support

- Privileged instructions
  - Available to kernel
  - Not available to user code
- Limits on memory accesses
  - To prevent user code from overwriting the kernel
- Timer
  - To regain control from a user program in a loop
- Safe way to change context
- Safe way to switch from user mode to kernel mode, and vice versa

How to guarantee protection?

- How can we implement execution with limited privilege?
  - Execute each program instruction in a simulator
  - If the instruction is permitted, do the instruction
  - Otherwise, stop the process
  - Basic model in Javascript and other interpreted languages
- How do we go faster?
  - Run the unprivileged code directly on the CPU
  - control privileged code
  - limit privileged code

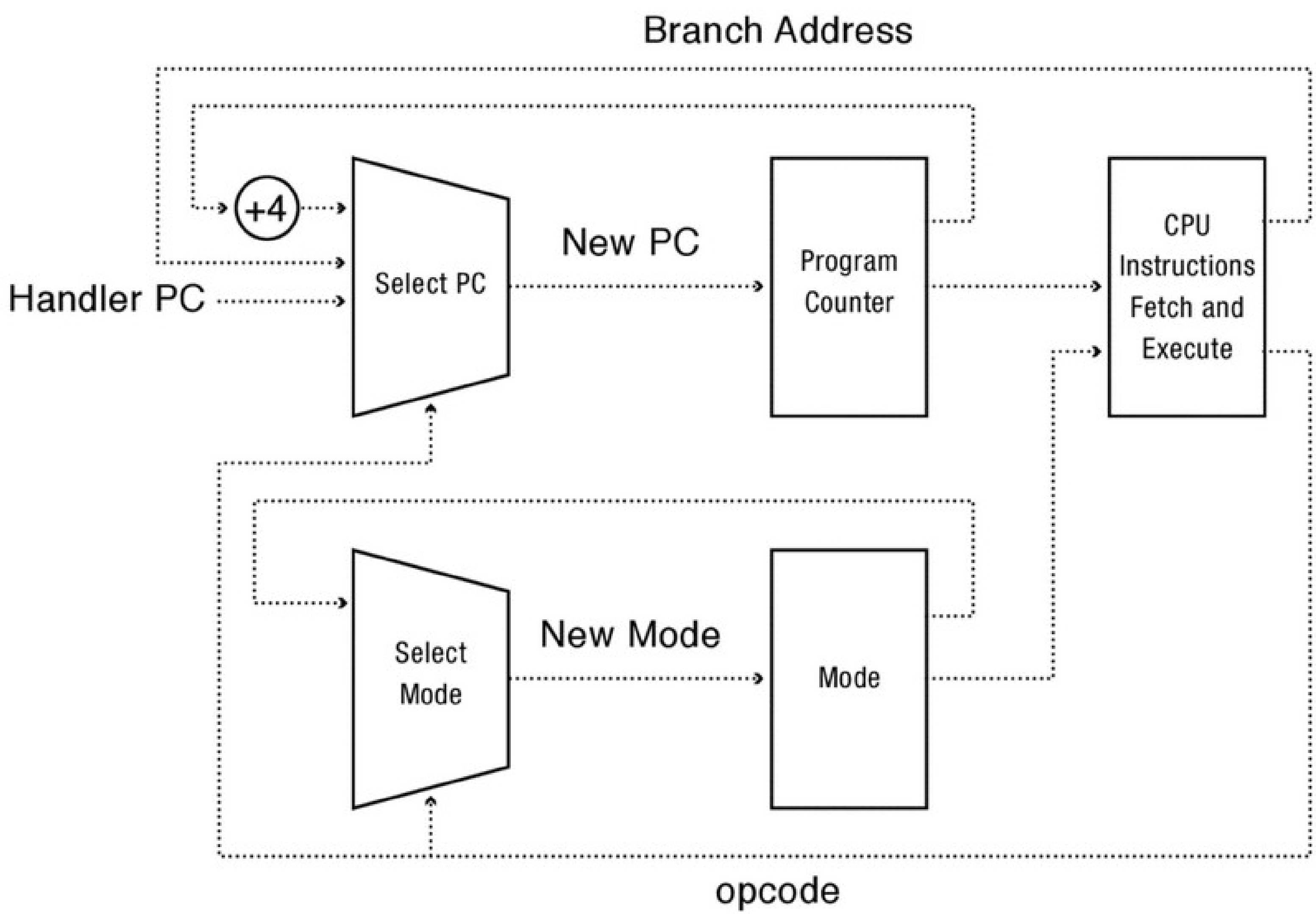
Hardware Support: Dual-Mode Operation

- Kernel mode
  - Execution with the full privileges of the hardware
  - Read/write to any memory, access any I/O device, read/write any disk sector, send/read any packet
- User mode
  - Limited privileges
  - Only those granted by the operating system kernel

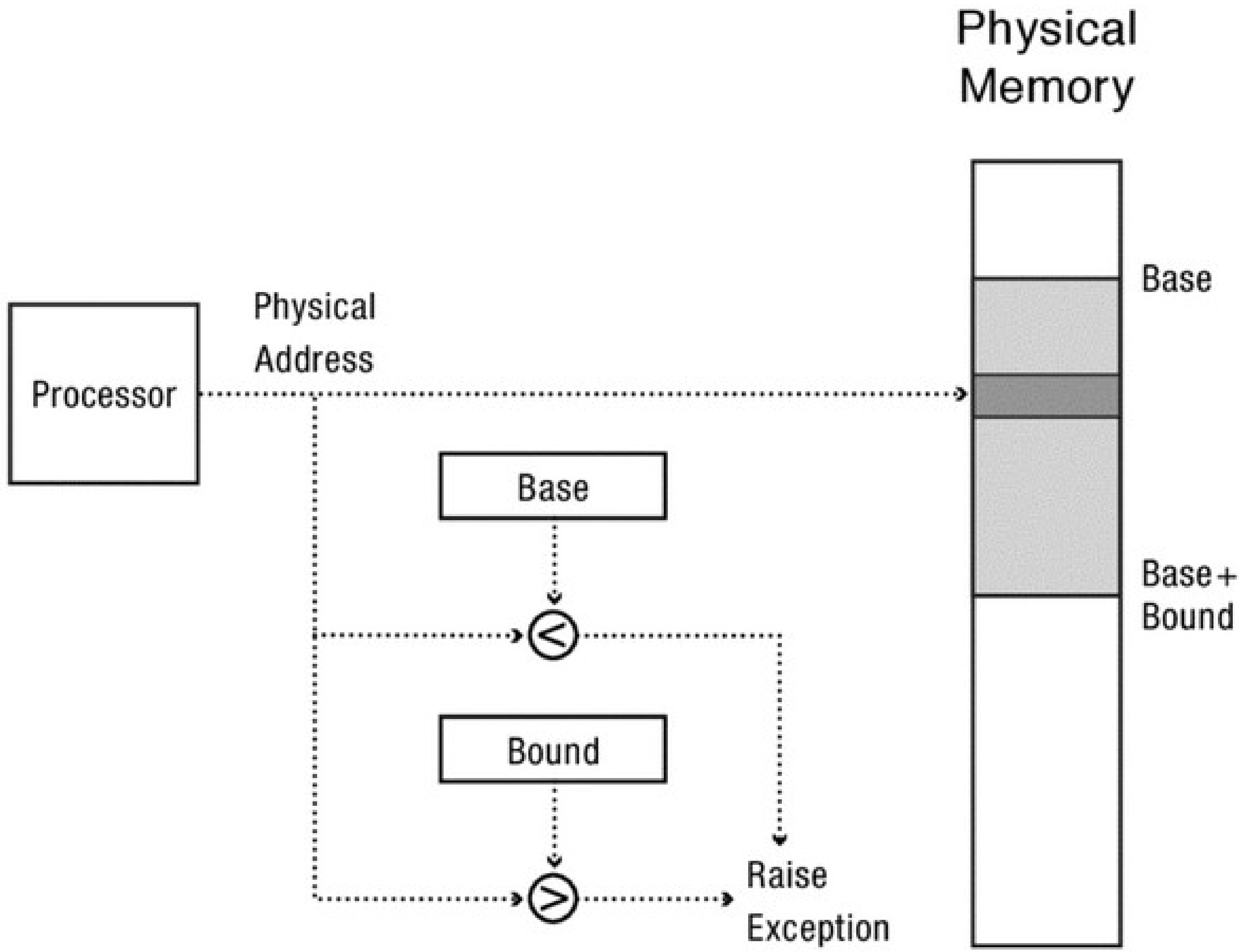
Hardware Support: Dual-Mode Operation

- On the x86, mode stored in EFLAGS register
- On the MIPS, mode in the status register
-
- Safe control transfer
  - How do we switch from one mode to the other?

A CPU with Dual-Mode Operation



Simple Memory Protection



Simple Memory Protection

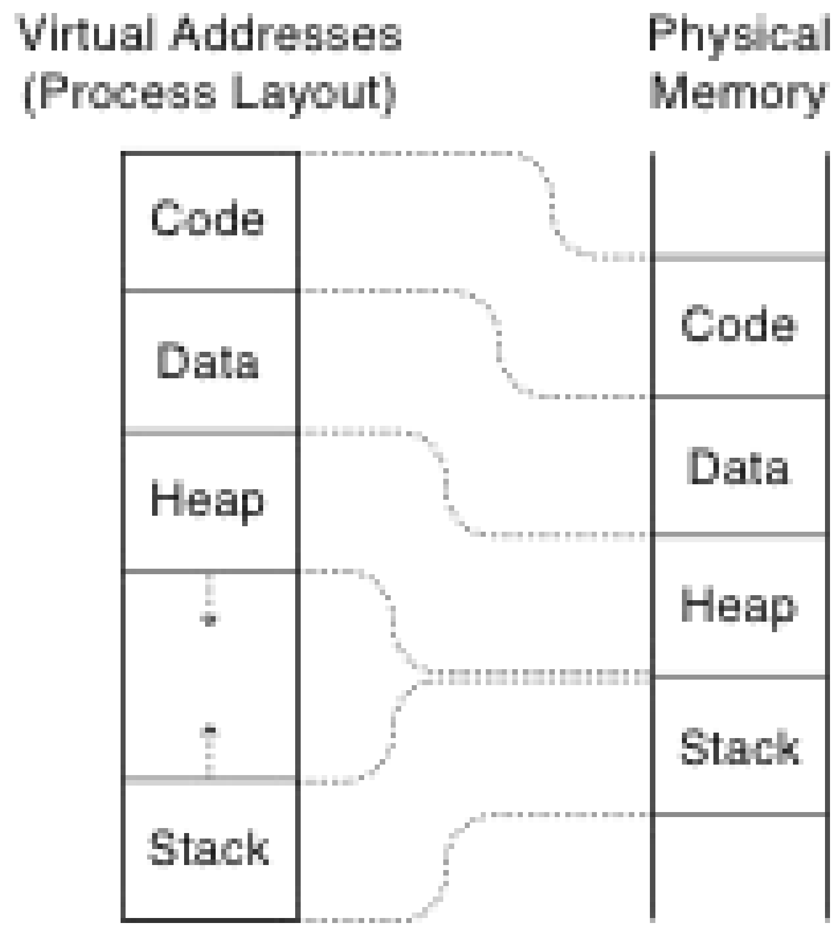
- Kernel
  - executes without base and bound registers
  - full access to all memory
- User level process
  - different base and bound registers
  - disjoint memory areas

Simple Memory Protection

- Expandable heap and stack
- Memory sharing
- Physical memory addresses
- Memory fragmentation
-
- Virtual memory

Virtual Addresses

- Translation done in hardware, using a table
- Table set up by operating system kernel



Example

```
int staticVar = 0;      // a static variable
main() {
   staticVar += 1;
   sleep(10);  // sleep for x seconds
   printf ("static address: %x, value: %d\n", &staticVar,
   staticVar);
}
```

What happens if we run two instances of this program at the same time?

What if we took the address of a procedure local variable in two copies of the same program running at the same time?

Hardware Timer

- Hardware device that periodically interrupts the processor
  - Returns control to the kernel handler
  - Interrupt frequency set by the kernel
    - Not by user code!
  - Interrupts can be temporarily deferred
    - Not by user code!
    - Interrupt deferral crucial for implementing mutual exclusion
- Scheduling/ multiprocessing
  - Assign PCU to processes in round-robin
  - Switch processes at high frequency

Mode Switch

- From user mode to kernel mode
  - Interrupts
    - Triggered by timer and I/O devices
  - Exceptions
    - Triggered by unexpected program behavior
    - Or malicious behavior!
  - System calls (aka protected procedure call)
    - Request by program for kernel to do some operation on its behalf
    - Only limited # of very carefully coded entry points

Mode Switch

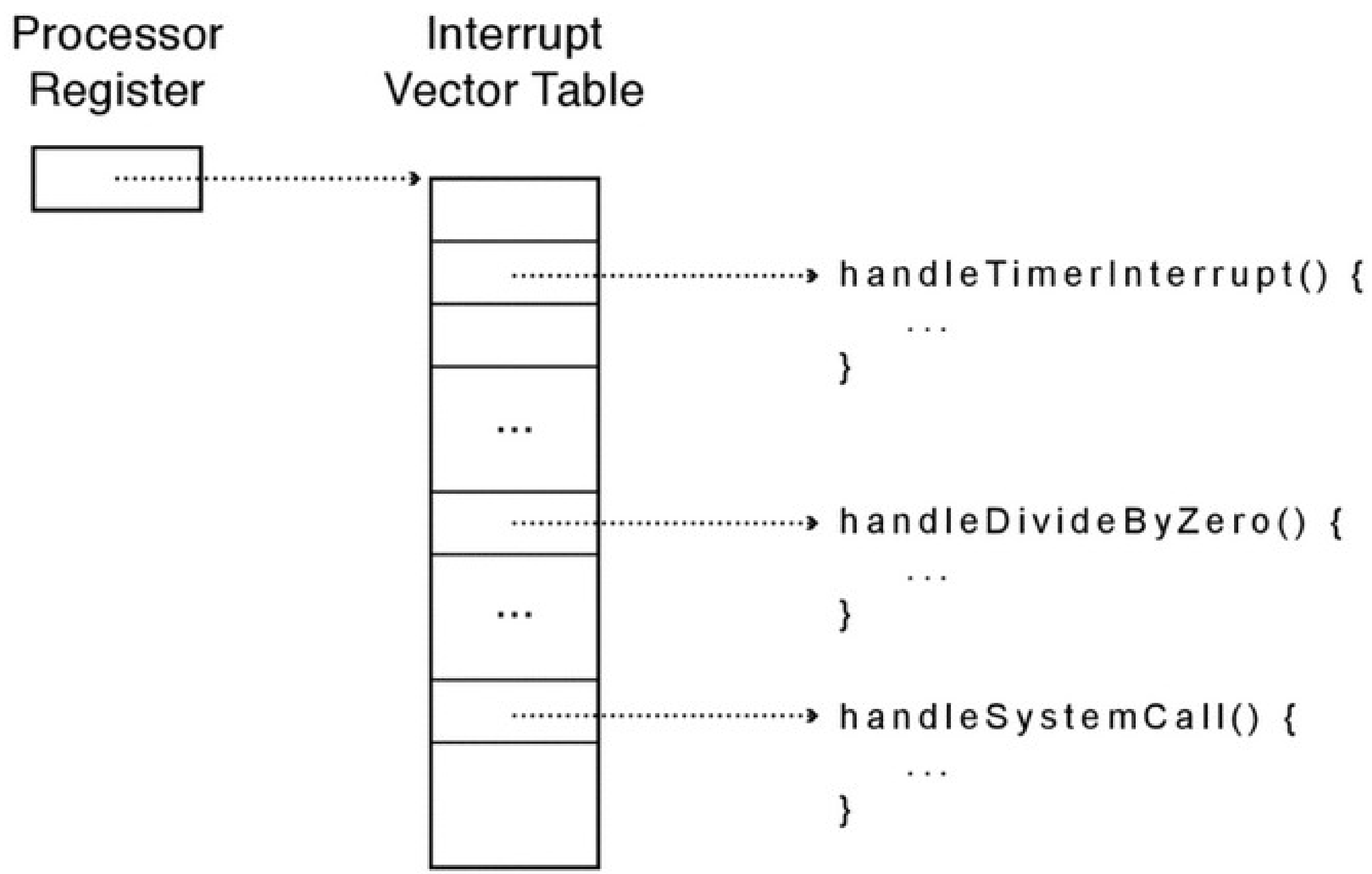
- From kernel mode to user mode
  - After booting
  - Resume after interrupt, process exception, system call
  - New process
  - Switch to a different process
  - User level-upcall

How interrupt safely?

- Interrupt vector
  - Limited number of entry points into kernel
- Atomic transfer of control
  - Single instruction to change:
    - Program counter
    - Stack pointer
    - Memory protection
    - Kernel/user mode
- Transparent restartable execution
  - User program does not know interrupt occurred

Interrupt Vector

- Table set up by OS kernel; pointers to code to run on different events

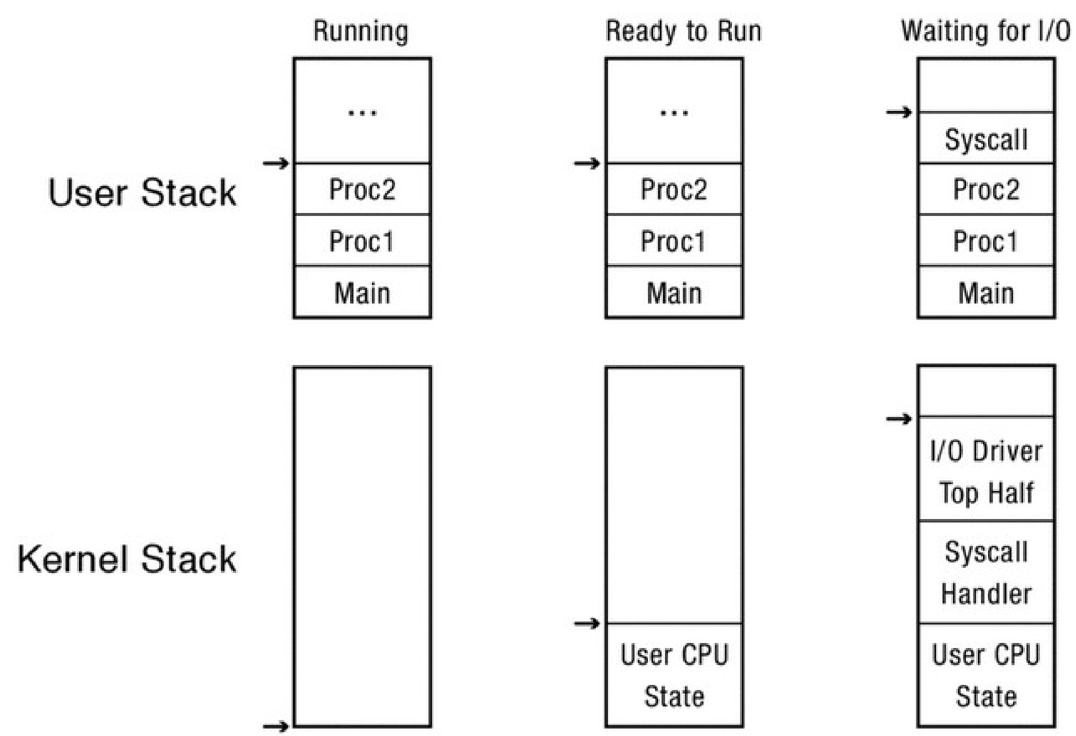


Interrupt Stack

- Per-processor, located in kernel (not user) memory
  - Usually a process/thread has both: kernel and user stack
- Kernel stack
  - reliability /security
    - insecure code should not modify kernel stack (execution)
- Multiprocessors
  - Multiple stacks <= Multiple syscalls

Two stacks per process

- Running process - user mode
  - no kernel stack
- Running process - kernel mode
  - kernel stack
- Ready to running process
  - CPU state in kernel stack
- Waiting for I/)
  - kernel execution state
    - stored in stack



Interrupt Masking

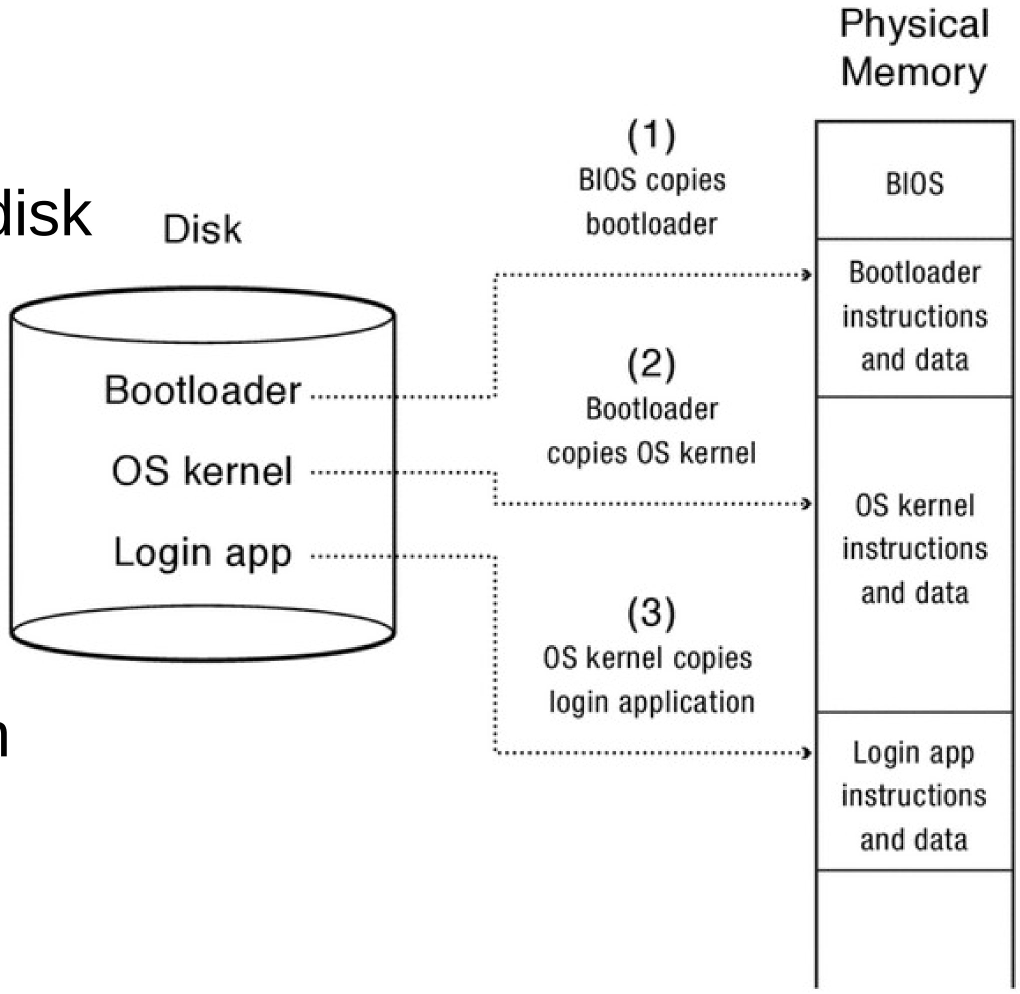
- Interrupt handler runs with interrupts off
  - Re-enabled when interrupt completes
- OS kernel can also turn interrupts off
  - Eg., when determining the next process/thread to run
  - On x86
    - CLI: disable interrrupts
    - STI: enable interrupts
    - Only applies to the current CPU (on a multicore)
- We'll need this to implement synchronization in chapter 5

Interrupt Handlers

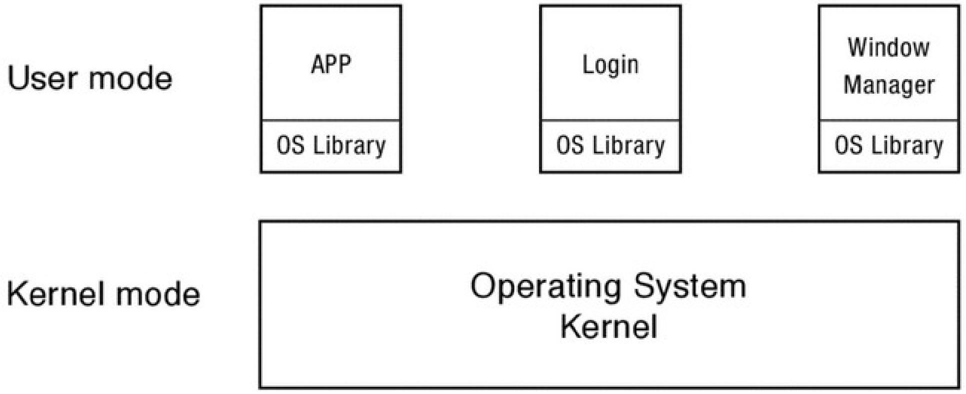
- Non-blocking, run to completion
  - Minimum necessary to allow device to take next interrupt
  - Any waiting must be limited duration
  - Wake up other threads to do any real work
    - Linux: semaphore
- Rest of device driver runs as a kernel thread

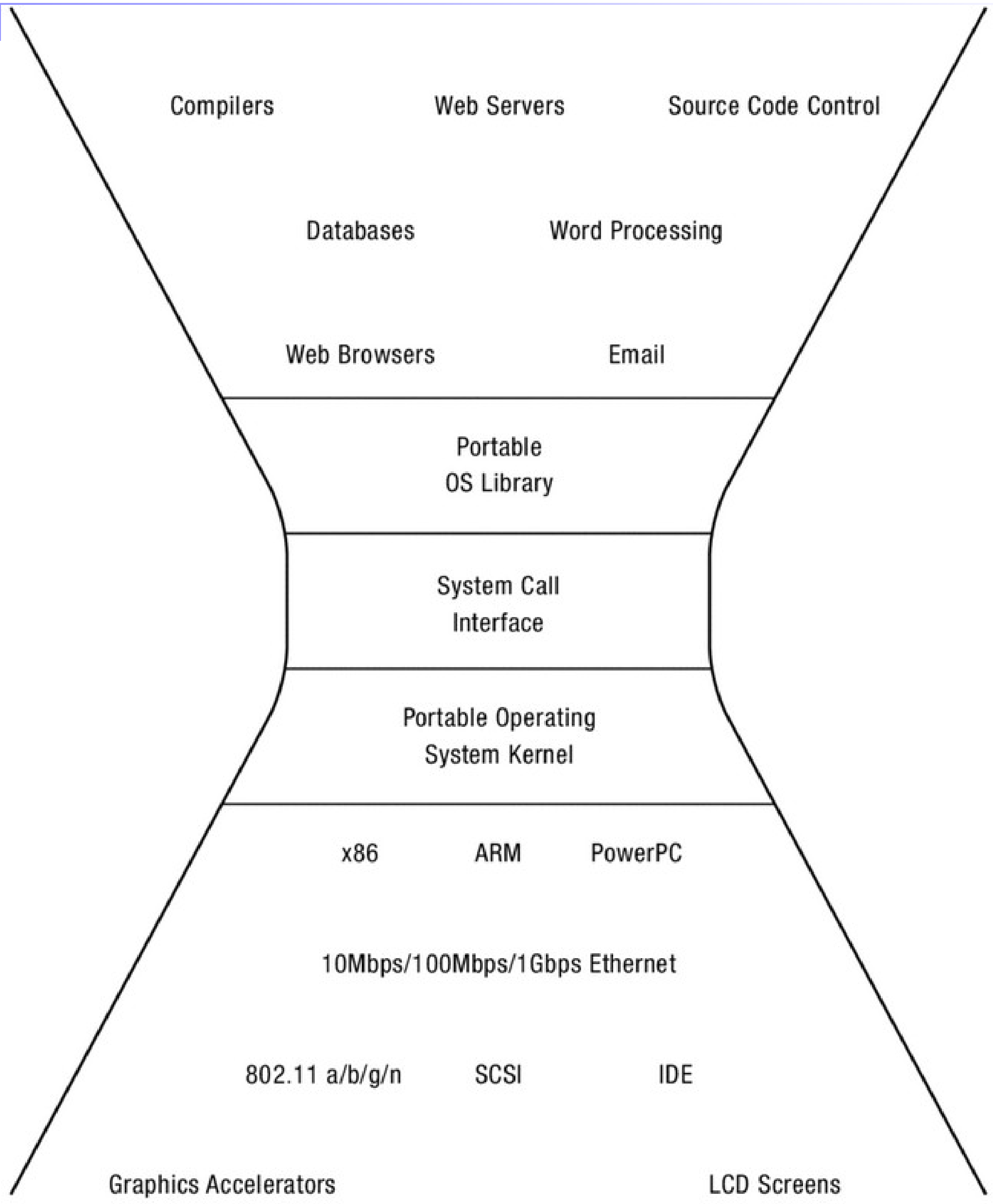
OS boot

- PC is powered on
- BIOS is executed
  - Bios copies bootloader from disk
- Bootloader executes
  - Os kernel is copied
- OS kernel is executed
  - configures INT table
  - configures memory protection
- Executed services
- Executes login app



System calls





System Calls

- Application interact with the OS
  - by system calls
- Some system calls can be invoked by the user from a C program
  - count=read(fd,buffer,nbytes)
- Or from the command line
  - read [-u fd] [-n nbytes] [-a aname] [nome1] …

System Calls

- In Linux system calls are grouped in groups:
  - Process control: fork, execute, wait,…
  - File management: open, read, set,…
  - Device management: request, read, …
  - Information maintenance: date, ps , …
  - Communication: send, …
- First unix version
  - 60 system calls
- Current Linux version
  - more than 300

System Calls

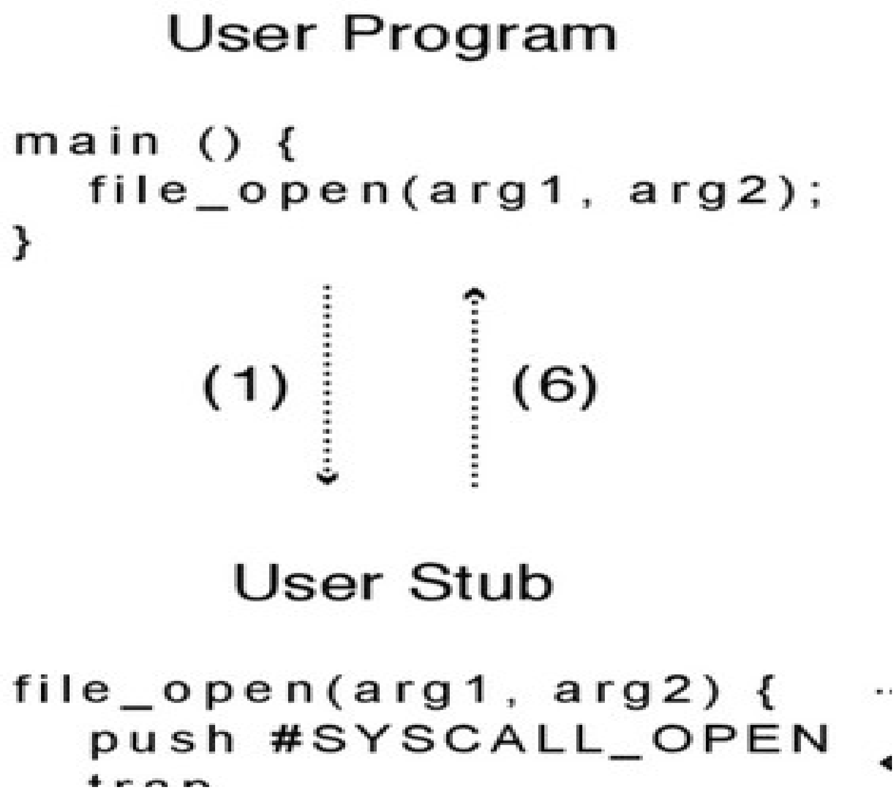
- Microsoft offers the **Windows API** .
- Consists of the following functional categories:
  - Administration and Management
  - Diagnostics
  - Graphics and Multimedia
  - Networking
  - Security
  - **System Services**
  - Windows User Interface
- https://msdn.microsoft.com/en-us/library/aa383723

System call vs Library functions

- System calls are provided by the system and are executed (mostly) in the system kernel.
  - They are entry points into the kernel and are therefore NOT linked into your program.
  - The source code is not portable
  - The API is portable
- Library calls include the ANSI C standard library and are therefore portable.
  - These functions are linked into your program.
- man read
- man fread

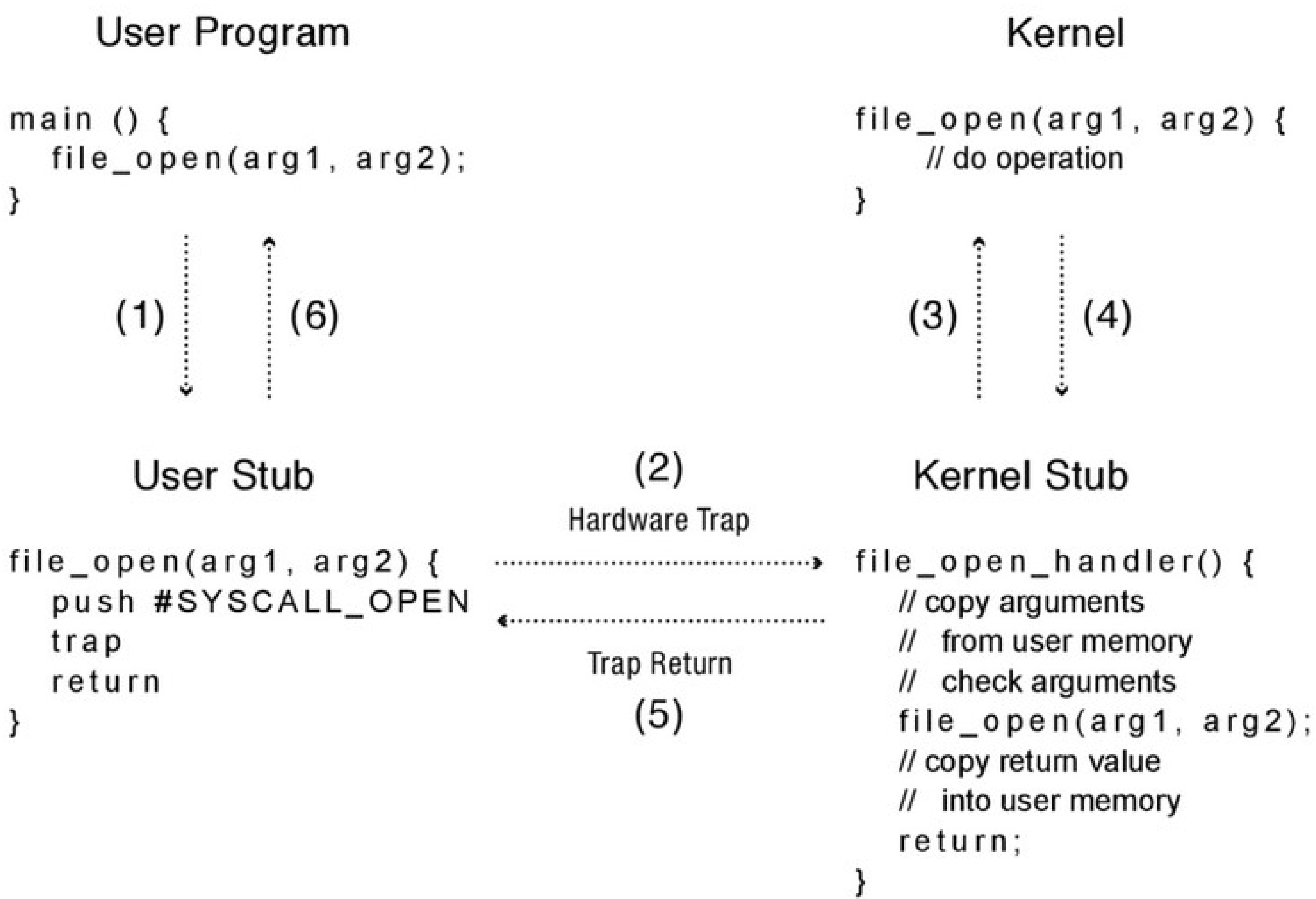
Kernel System Call

- Stub call (regular C)
- Stubb fills “syscall arguments”
- Trap is generated
  - similar in INTR
- Kernel code executed
- handle returns



Kernel System Call Handler

- Kernel stub
  - Locate arguments
    - In registers or on user stack
    - Translate user addresses into kernel addresses
  - Copy arguments
    - From user memory into kernel memory
    - Protect kernel from malicious code evading checks
  - Validate arguments
    - Protect kernel from errors in user code
- Executes handler
- Kernel Stub
  - Copy results back into user memory
  - Translate kernel addresses into user addresses


User Program
Kernel
main () {
file_open(arg1, arg2);
}
file_open(arg1, arg2) {
// do operation
}
(1)
(6)
(3)
(4)
User Stub
(2)
Hardware Trap
Kernel Stub
file_open(arg1, arg2) {
push #SYSCALL_OPEN
trap
return
}
Trap Return
(5)
file_open_handler() {
// copy arguments
// from user memory
// check arguments
file_open(arg1, arg2);
// copy return value
// into user memory
return;
}

Process management

- What
  - Can a program create an instance of another?
  - Wait for its completion?
  - Stop/resume another program?
  - Send asynchronous events?
- Where
  - Everything on the kernel?
    - Batch systems
  - Allow user code to manage processes

User level process management

- Processes can create processes
  - Without kernel recompilation
- Shell command line interpreters
  - User level processes
  - Job control system
    - Creation / killing / suspending resuming
  - Job coordination system
    - Pipe-lining /sequencing

Compiling a program

- cc -c file1.c
  - Creation of a new process
    - Arguments: -c file1.c
  - Cc program reads file and produces output
  - Shell waits for it completion
- cc -c file1.c
  - Creation of a new process
  - Cc program reads file and produces output
  - Shell waits for it completion
- …
- Can be defined in a file
  - Becoming a program

Process creation

- Kernel operations
  - Allocate process data-structures
  - Allocate memory for process
  - Copy program from disk to allocated memory
  - Allocate Stacks
    - User-level for functions
    - Kernel-level for system-calls / interrupts
  - Process startup

Process startup

- Kernel
  - Copy arguments for user memory
    - Argc/argv
  - Copy environment
  - Transfer control to user mode
    - POP + IRET
      - After manipulation of kernel stack

Process termination

- Call of **exit** system call
  - Inserted by compiler
- Executed by kernel
  - Free stacks
  - Free process memory
  - Free kernel datastructures
  - Notify “parent”

Process creation

- In a OS process creation can follow different policies
  - Execution mode
    - Father and son execute in parallel
    - Father blocks till son terminates
  - Memory management
    - Son gets new memory (data and code)
    - Son gets new data
    - Son gets a shared copy of father memory
    - Son gets a NON SHARED copy of father memory
  - Resource sharing (files, ...)
    - Father and son share all resources
    - Father and son share some resourses
      - Open files IPC objects, …)
    - Father and son do not share any resource

Windows process creation

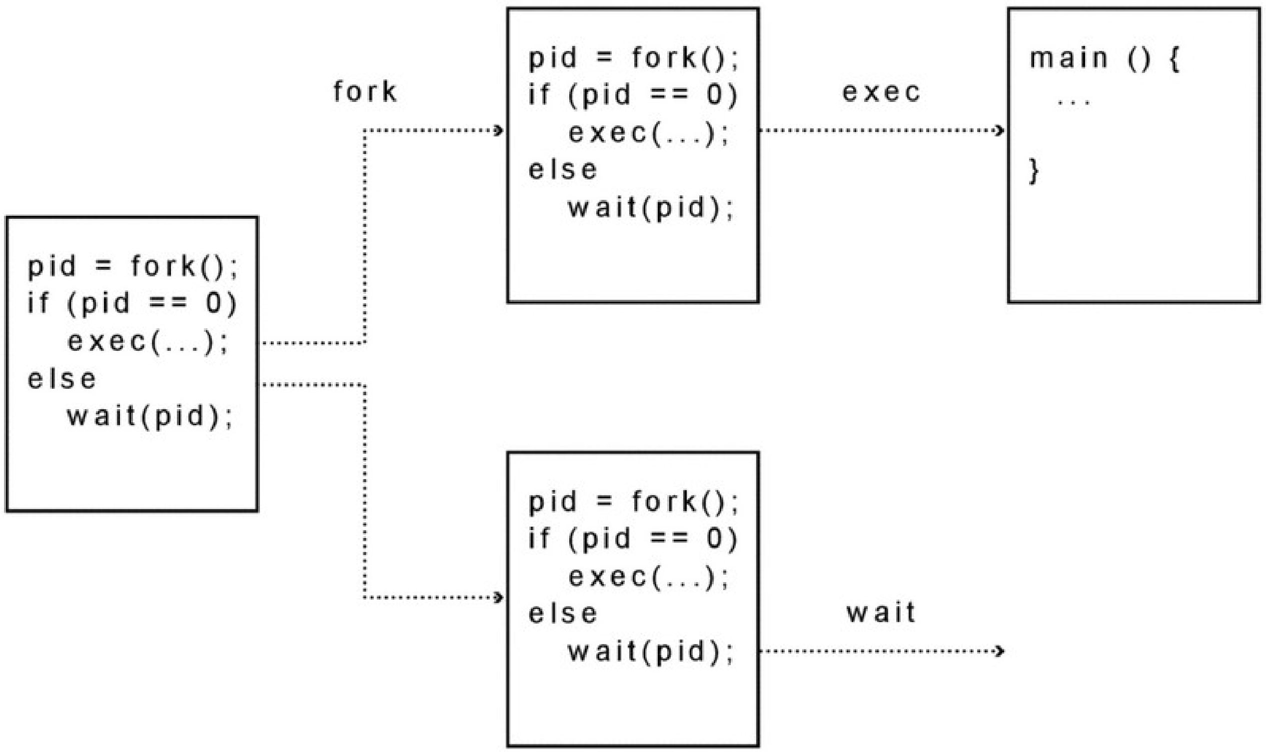
- Boolean Createprocess(char * prog, char * arg)
  - Create and initializae Process Control Block
  - Create and initialize adress space
  - Load program into adress space
  - Copy arguments into process memory
  - Initialize hardware context
  - Inform the nschedule of the new process
- Further security configuration is necessary
  - Limit previleges
  - Change priority

Windows process creation

- BOOL WINAPI CreateProcess(
- _In_opt_ LPCTSTR lpApplicationName,
- _Inout_opt_ LPTSTR lpCommandLine,
- _In_opt_ LPSECURITY_ATTRIBUTES lpProcessAttributes,
- _In_opt_ LPSECURITY_ATTRIBUTES lpThreadAttributes,
- _In_ BOOL bInheritHandles,
- _In_ DWORD dwCreationFlags,
- _In_opt_ LPVOID lpEnvironment,
- _In_opt_ LPCTSTR lpCurrentDirectory,
- _In_ LPSTARTUPINFO lpStartupInfo,
- _Out_ LPPROCESS_INFORMATION lpProcessInformation
-);

Unix process creation

- Two steps
  - Copy of the current process
  - Execution of a different program



UNIX Process Management

- UNIX fork – system call to create a copy of the current process, and start it running
  - No arguments!
- UNIX exec – system call to change the program being run by the current process
- UNIX wait – system call to wait for a process to finish
- UNIX signal – system call to send a notification to another process

How fork returns two values?

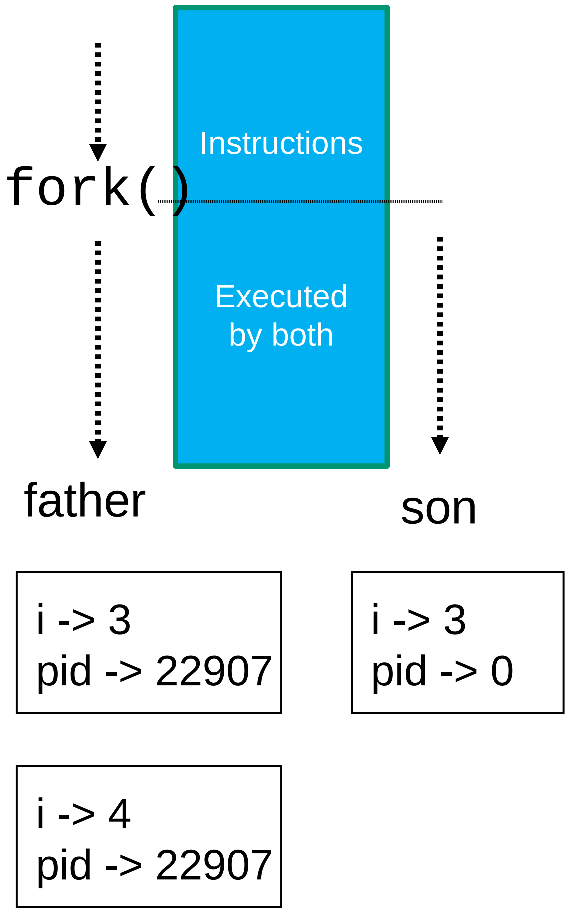
```
int child_pid = fork();
if (child_pid == 0) {          // I'm the child process
    printf("I am process #%d\n", getpid());
    return 0;
} else {                       // I'm the parent process
    printf("I am parent of process #%d\n", child_pid);
    return 0;
}
```

Process creation

- To start a new process call:
  - `#include <unistd.h>`
  - `pid_t fork();`
- A new process is created
- The new instruction to be executed is the one following the fork
  - On the fater and son !!!!
- All variables are duplicated with the same value
  - After the fork all changes in values are local to each process.
- Fork is a system call that return two different values:
  - In the son return 0
  - In the father return the son PID

Process creation

- Process creation pattern
  - pid_t pid;
  - int i=3;
  - pid = fork();
  - if (pid==0) {
  -   /* processo son */
  - }else {
  -   /* processo father */
  -   i++;
  - }
  - /* bothe processes */



New processes

- Inherit most of information
  - Memory space (variables allocated memory)
  - Code
  - Opened files (pipes, fifos, sockets)
- How to execute different programs?
  - Replace code after fork

Implementing UNIX fork

Steps to implement UNIX fork

- Create and initialize the process control block (PCB) in the kernel
- Create a new address space
- Initialize the address space with a copy of the entire contents of the address space of the parent
- Inherit the execution context of the parent (e.g., any open files)
- Inform the scheduler that the new process is ready to run

Execve

- execve() executes the program pointed to by filename.
  - int execve(const char *filename, char *const argv[],
  - char *const envp[]);
    - Filename – program
    - Argv – program arguments
    - Envp – environment variables
    - Empty argv/ envp → array[0] = NULL !!!!
  - Only returns on error :/
- Replaces process image
  - Code, data, files, pipes, socket, mqueus, mmap, timers, signals, ...
  - All previous state is lost

Implementing UNIX exec

- Steps to implement UNIX fork
  - Load the program into the current address space
  - Copy arguments into memory in the address space
  - Initialize the hardware context to start execution at ``start''

Questions

- Can UNIX fork() return an error? Why?

- Can UNIX exec() return an error? Why?

- Can UNIX wait() ever return immediately? Why?

System

- Some times it is necessary to execute other program
  - Without loosing everything (execve)
- Solution:
  - if(fork() ==0)
  - execve(program, …, …);
  - else
  - Wait for children termination();
- Other solution
  - int system(const char *command);

System

- Man system
  - int system(const char *command);
- Launches a process and waits for its termination
- The system function executes the following system calls:
- Forks a new process
- The child replaces the program (with execve)
- The parent process waits for the child termination
- System retunrs the child exit code

Command line

- How processes are started on the command line?
  - The program file is read from the keyboard
  - The command interpreter looks for the program in the PATH
  - A new process is created
  - The new process replaces himself by the selected program
  - The parent process (command line) blocks waiting for thew termination of the child
- The wait can be done in the background if
  - The user terminated the command with &
  - The notification of conclusion is printed on the screen

Process termination

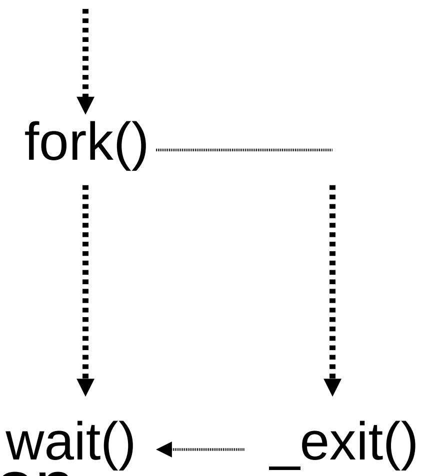
- When a process executes the exit(int) function:
  - The calling process is terminated "immediately".
  - Any open file descriptors belonging to the process are closed;
  - any children of the process are inherited by process 1,
  - init, and the process's parent is sent a SIGCHLD signal.
  - Man 2 exit / man 3 exit
- What happens to the return code?

Process termination

- When a process terminates UNIX maintain some information regarding the process
  - Until the parent is notified of its dead
  - During this period the process is considered “zombie”.
- A process return code is to be received by the parent
  - Child → parent communication
  - This reception can be done asynchronously
- The OS should mainaint some information regarding
  - the process that terminated
  - Its return code
  - The id of the parent that should receive the retunr code

Reception of return code

- If parent need the child return code:
  - It must wait for its dead:
  - Call wait/waitpid function



- pid_t waitpid(pid_t pid, int *status, int options);
  - Process waits for a specifi child temrination.
    - 1st argument – ID of child (-1 any process)
    - 2nd argument – child status
    - 3rd argument
      - WNOHANG: return immediately if no child has exited
      - WUNTRACED: also return if a child has stopped

Reception of return code

- pid_t wait(int *);
  - Process waits for any child
  - 1^{st} argument status code
- wait(&status) <=> waitpid(-1, &status, 0)

- wait():
  - on success, returns the process ID of the terminated child
  - error, -1 is returned.
- waitpid():
  - on success, returns the process ID of the child whose state has changed;
  - if WNOHANG was specified and one or more child(ren) specified by pid exist, but have not yet changed state,
    - then 0 is returned.
  - On error, -1 is returned.

Reception of return code

- WIFEXITED(status)
  - returns true if the child terminated normally, that is, by call ing exit(3) or _exit(2), or by returning from main().
- WEXITSTATUS(status)
  - returns the exit status of the child. This consists of the least significant 8 bits of the status argument that the child specified in a call to exit(3) or _exit(2) or as the argument for a return statement in main().
  - This macro should be employed only if WIFEXITED returned true.
- WIFSIGNALED(status)
  - returns true if the child process was terminated by a signal.
  - WTERMSIG(status)
    - returns the number of the signal that caused the child process to terminate.
    - This macro should be employed only if WIFSIGNALED returned true.
- WIFSTOPPED(status)
  - returns true if the child process was stopped by delivery of a signal; this is possible only if the call was done using WUN-TRACED or when the child is being traced (see ptrace(2)).
  - WSTOPSIG(status)
    - returns the number of the signal which caused the child to stop.
    - This macro should be employed only if WIFSTOPPED returned true.

Killing processes

- A process running in the command line can be killed:
  - Issuing the CTRL-C command
  - Executing the command **`kill [-s signal] PID`**
    - If PID equals 0 all process from the groups are killed
- CTRL-Z stops (suspends a process)
  - The user can then issue:
    - **`bg`**: the suspended process resumes in the “background”
    - **`fg`** : the suspended process resumes in the ”forground”
    - **`kill %`**: the process is killed

Killing processes

- int kill(pid_t pid, int sig)
  - send signal to a process
  - 1st argument – PID of the process
    - 0 → all processes from the groups are signaled
  - 2nd argument the signal identifyer
    - SIGTERM – same as the CTRL-C
    - SIGKILL – Kills the process
    - SIGTERM - same as the CTRL-Z
    - SIGCONT – same as fg or bg

Zombies

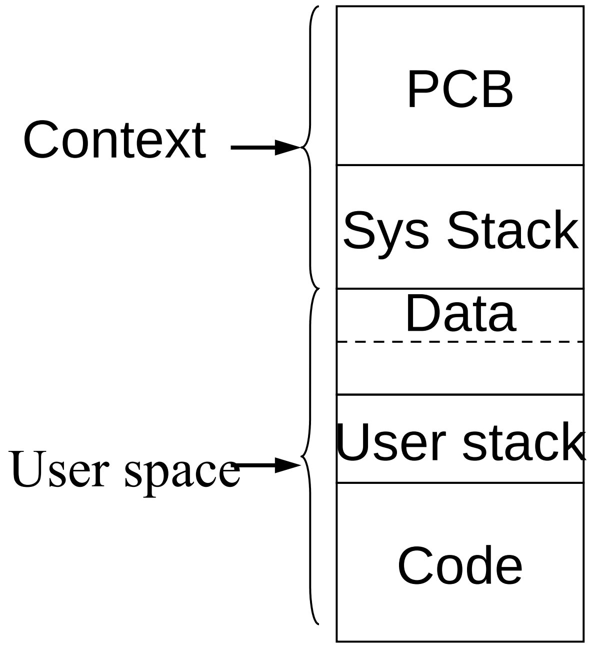
- When a process exits, it remains in **zombie** state until cleaned up by its parent.
- In this state, the only resource it holds is a **proc** structure,
  - Contains its exit status and resource usage information
  - This information may be important to its parent.
- The parent retrieves this information by calling **wait**, which also frees the **proc** structure.
- If the parent dies before the child, the **init** process inherits the child.
- When the child dies, init calls wait to release the child’s proc structure.

Zombies

- A problem may arise if a process dies before it´s parent,
  - and the parent does not call wait.
- The child's **proc** structure is never released
  - the child remains in the zombie state until the system is rebooted.
- This situation is rare, since the shells are written carefully to avoid this problem.
- It may happen, however, if a carelessly written application does not wait for all child processes.
  - This is an annoyance, because such zombies are visible in the output of **ps**
  - And users are vexed to find that they cannot be killed (they are already dead).
  - furthermore, they use up a **proc** structure, (reducing the available number of processes)
- Some newer UNIX allow a process to specify that it wiil not wait for its children.
  - For instance, in SVR4, a process may specify the SA_NOCLDWAIT flag to the sigaction system call to specify the action for SIGCH LD signals.
    - This asks the kemel not to create zombies when the caller's children terminate.

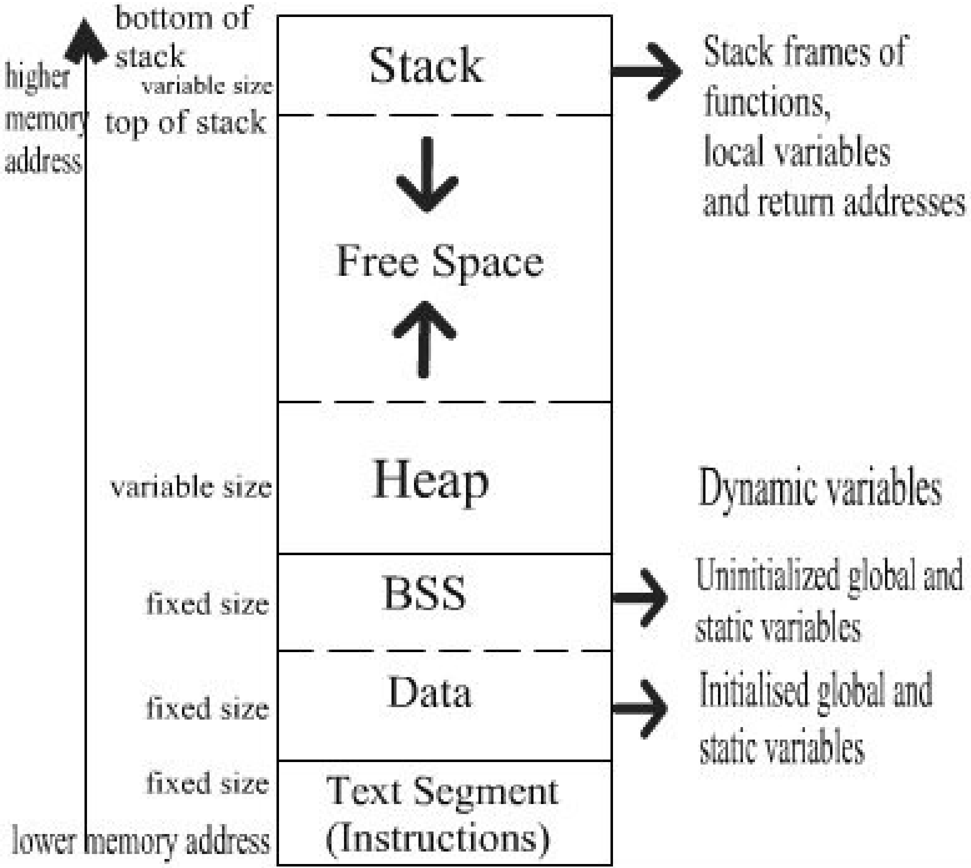
Processes

- PID / Process ID
  - Number that identifies each process
  - PID is of type pid_t (tipicamente int).
- The maximum value is usually 32768 (short),
  - /proc/sys/kernetl/pid_max
- Each p4roces has 2 parts
  - User space
  - Context.



Process

- User addressable space contains
  - Program data
    - User stack
      - local variables and parameters
    - Heap
      - mallocs
    - Shared memory
      - mmap
    - Global variables.
  - Program code
- size
  - Returns program size
- Top
  - Show process size



Process context

- Stored in kernel memory
- Kernel stack
  - Needed by system calls
- PCB“Process Control Block
  - Information needed for process management
    - Multiprocessing
    - Memory/devices management
  - An entry in a kernel table
  - Contains everything a process needs to run.
  - Stores process state between times it is running
  - PCB is reflected in the pseudo-filesystem /proc

Process context

- PCB - Process Control Block
  - Process identification data
    - Process ID, ID of parent procees, user ID of owner
  - Processor state data
    - Program counter
    - Registers
  - Process control data
    - Process state
    - Priority
    - Execution times (since last contect switch)
    - memory map information
    - Open I/O devices and files
    - Events waiting for processing

Management

- Fork
  - creates a new process
- Exec
  - Replaces execution by a new program
- wait / waitpid
  - blocks process until child exits
- exit()
  - terminates program execution
- kill
  - sends signal to process
- getpid
  - returns process identifier

Processes organization

- In unix the first process to be created is called init/systemd/launchd
  - Its PID is 1
- This process is responsible for the unix initialization
  - It executes the /etc/rc.* files to start services
- When a user logins
  - A hierarchy of processes is created
  - Last one to be created is bash
    - less /proc/2571/status
    - less /proc/2563/status
    - less /proc/1/status
- In unix all processes are created by another one
  - Not exactly :)
- There is a tree hierarchy that starts in init/systemd/launchd

Process identification

- All processes are identified by its PID
  - ps / top /proc/...
- To know is identifier a process can call the
  - getpid system call
- To know the identification of its parent
  - getppid
- Man getpid
  - #include <sys/types.h>
  - #include <unistd.h>
  - pid_t getpid(void);
  - pid_t getppid(void);