Course Title: Linux System Programming

Faculty: Rajesh Sola, Srinivas.K & Bharath.G

L&T Technology Services

LTTS
GLOBAL ENGINEERING ACADEMY

Content

Linux OS Architecture & Kernel

Operating system

- Operating System is an interface between the user and the system hardware

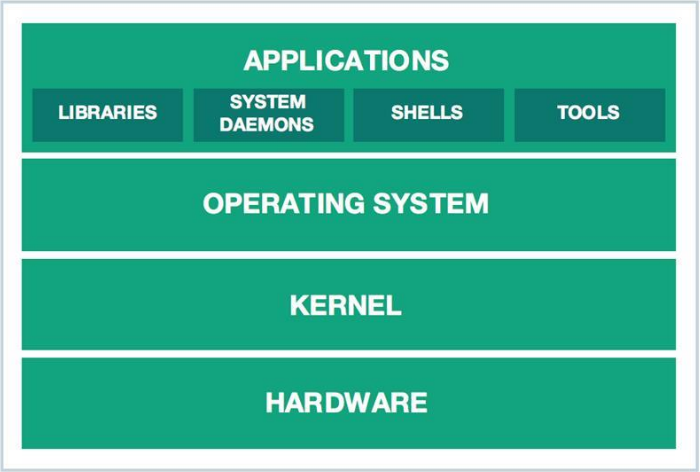
Types of Operating system

- Batch OS
- Time-sharing OS (Linux)
- Distributed OS
- Network OS
- Real-time OS

For more info Refer : https://www.tutorialspoint.com/operating_system/os_types.htm

Linux OS Architecture

- Kernel
  - Core of OS, responsible for all major OS activities, interacts with hardware, provides abstraction to hardware from system / application programs
- Drivers
  - Used for interaction for additional hardware & I/O
- System Libraries
  - Special programs used by system / application programs access kernel's features, implement most of the functionalities of OS
  - Multimedia library, Network library
- System Utilities
  - Used to do specialized, individual level tasks
  - Shell, Terminal



Kernel

- Mandate component of Operating System
- Resides in memory all the time, rest all depending on kernel
- Provides basic services including memory management, IO management & other management services
- Provides services to application and libraries in the form of SYSTEM CALLS
- Detailed Info: https://en.wikipedia.org/wiki/Linux_kernel

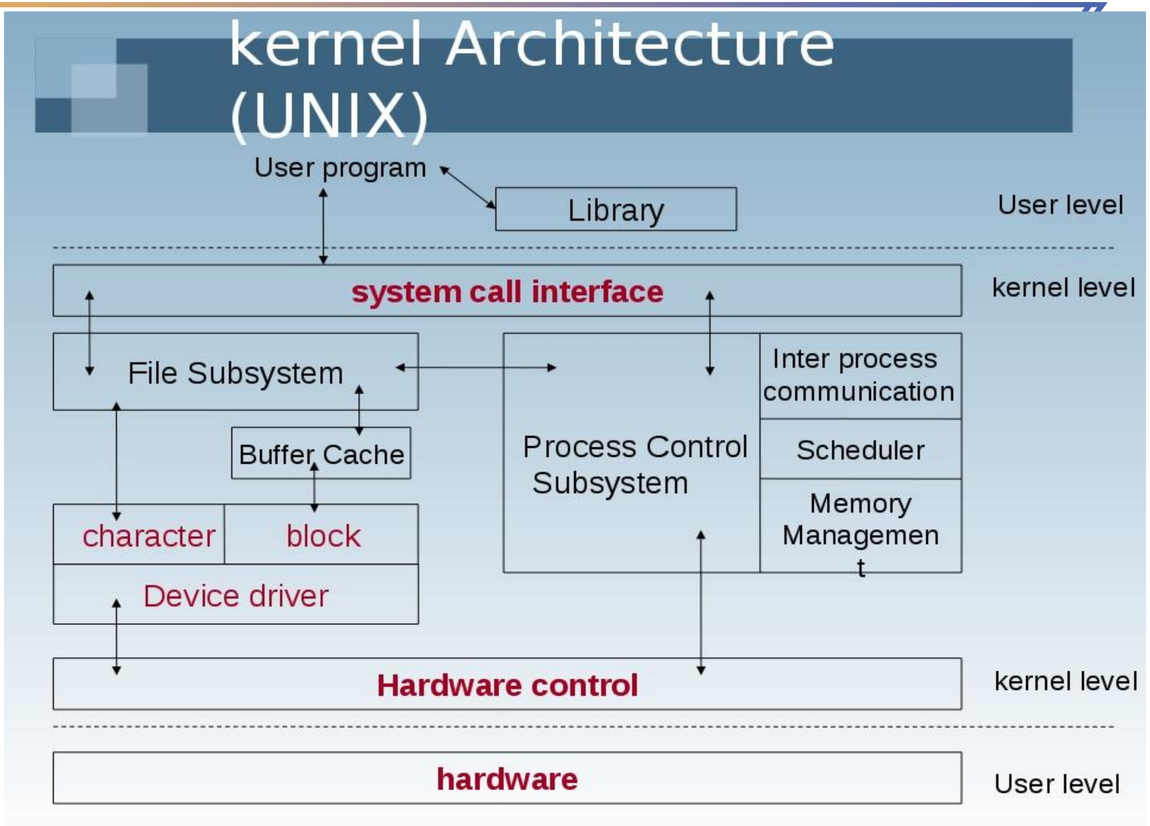


Image Source: The Design of the Unix Operating System, Maurice Bach

Types of Kernel

Micro

CPU, memory and IPC in kernel mode, everything else is accessory and runs in user mode.

Advantages

- Portability, Small install footprint
- Small memory footprint, Security

Disadvantages

- Hardware is more abstracted through drivers, may react slower because drivers are in user mode
- Processes have to wait in a queue to get information, can't get access to other processes without waiting

Monolithic

CPU, memory, IPC + device drivers, file system management, and system server calls in kernel mode

Advantages

- More direct access to hardware for programs
- Easier for processes to communicate between each other
- If your device is supported, it should work with no additional installations
- Processes react faster because there isn't a queue for processor time

Disadvantages

- Large install footprint
- Large memory footprint
- Less secure because everything runs in supervisor mode

Modular

Linux is modular kernel type is combination of both monolithic & micro kernel

Advantages

- Has collection of both statically loaded & dynamically loadable modules
- No need to load everything on boot, less boot time, less size, new need to recompile to add new module

Disadvantages

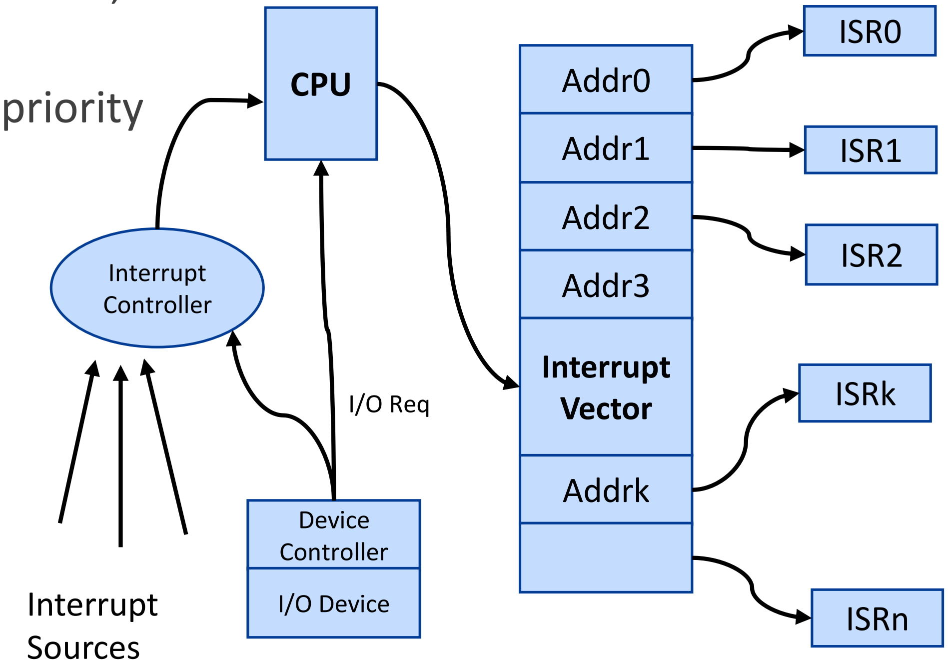
- Chances of losing stability
- Security Compromise with modules
- Coding can be difficult

Linux OS Kernel

- Compressed Kernel is stored at /boot/vmlinu*
- Dynamic modules of kernel /lib/modules
- uname –r
  - 5.4.0-33-generic
    (major.minor.release-tagname)
- Versions of kernel
  - 2.x, 2.4, 2.5, 2.6, 3.x, 4.x, 5.x
  - 5.x is current version

Interrupts

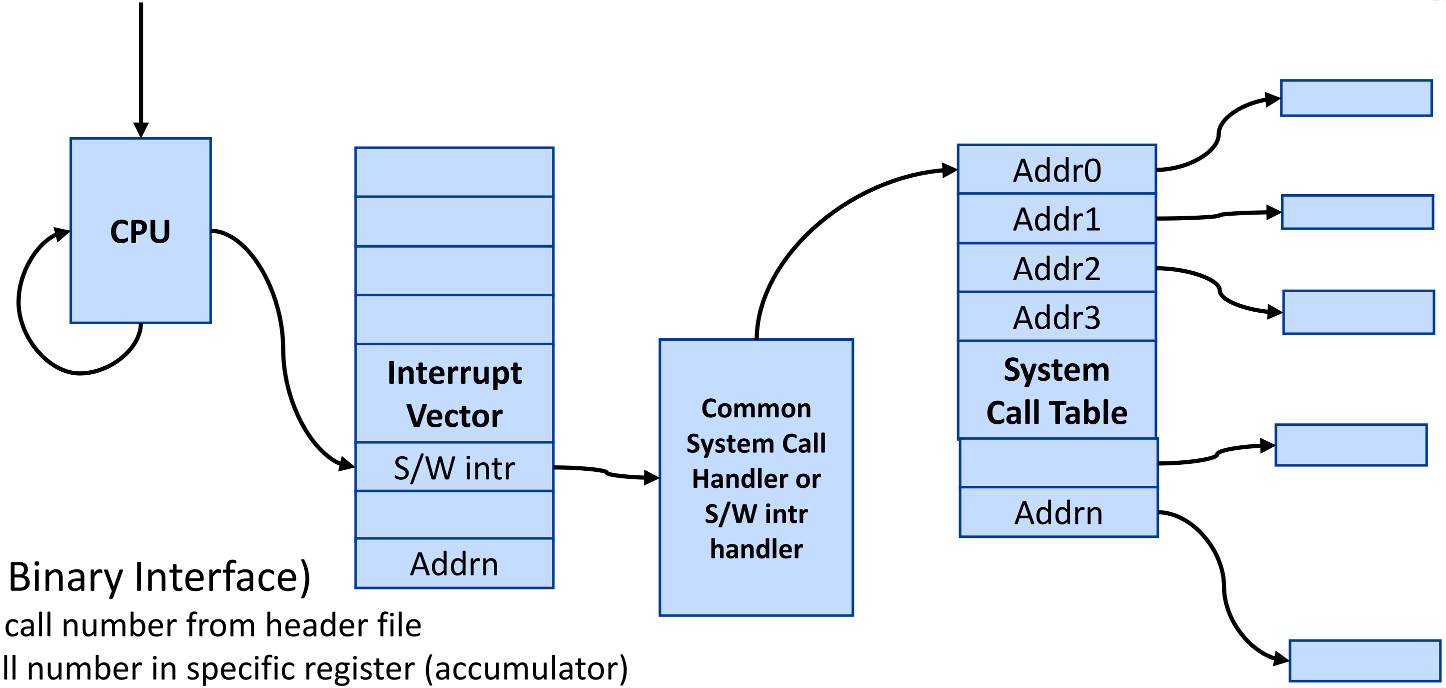
- Asynchronous events
- IRQ (Interrupt Request), Interrupt Vector Table, ISR (Interrupt Service Routine)
- Interrupts must be serviced with utmost priority
- ISR should be as short as possible with no/minimal blocking calls
- Maskable & Non-maskable Interrupts
- Types
  - Hardware Interrupts
  - Software Interrupts



System calls

- Interface to OS Services, Communication between Kernel mode and User mode.
- System calls initiated by user space, executed by kernel space
- System calls are also referred as software interrupts
- Identified by Unique Number
- Written in C or Assemble within Kernel space
- System call offers the services of the operating system to the user programs via API (Application Programming Interface)
- Follows “standard protocol” for parameter flow and return values
  - No common memory between user space and kernel space, hence system calls use REGISTERS for communications
  - If arguments are more than available registers, then arguments are packed in structures or blocks and address is passed in register
- man syscall → details of registers

System Calls



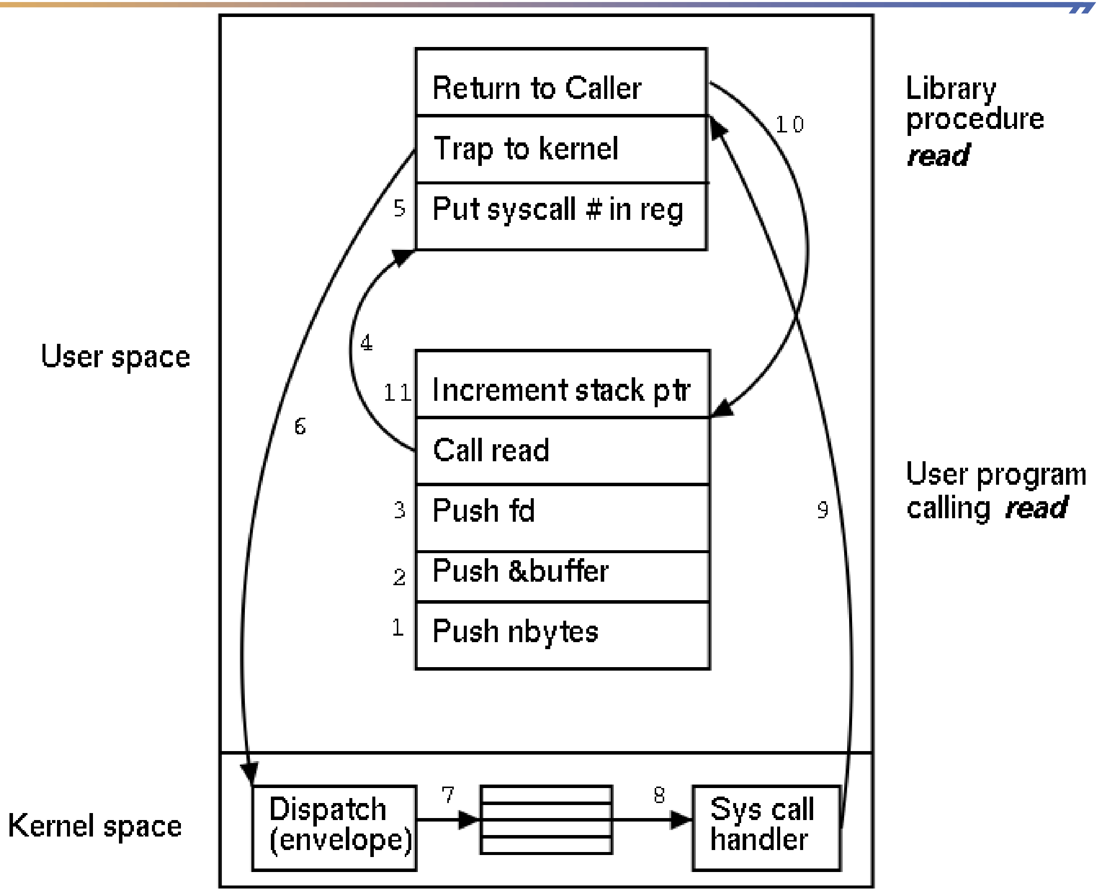
- ABI (Application Binary Interface)
  - Identify system call number from header file
  - Store system call number in specific register (accumulator)
  - Store parameters in other registers
  - Initiate TRAP instruction
- On execution, system call always returns 0 or positive for SUCCESS & negative for FAIL

System calls

Types of System calls

- Process Control
- File Management
- Device Management
- Information Maintenance
- Communications
- Protection

- Write system call:
  - printf in C, echo in shell, cout in C++
- Read system call:
  - scanf in C, cin in C++
- Trace the system calls:
  - strace man, echo, cp, cat
  - man strace
- list of system call numbers
  - /usr/include/asm*/unistd.h



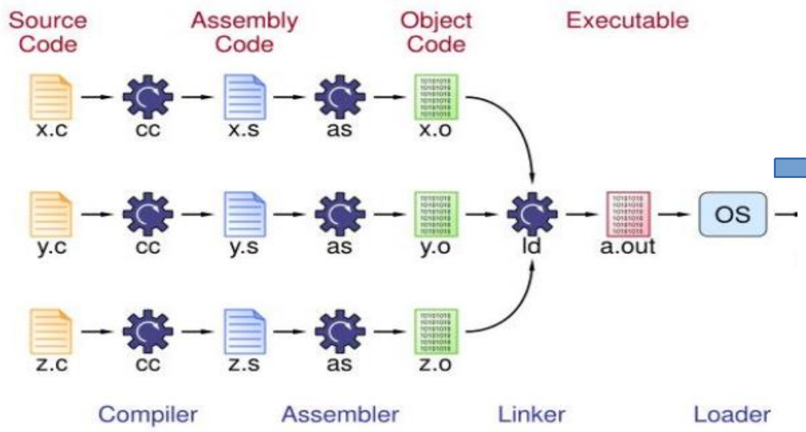
System calls

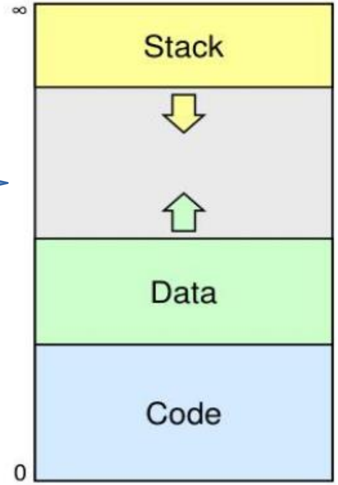
- Example folder **“Intro”**
- Standard file descriptors used by any process
  - fd = 0 (stdin) (read)
  - fd = 1 (stdout) (write)
  - fd = 2 (stderr)
- “perror” – always appends error message based on return value of system call

Process management

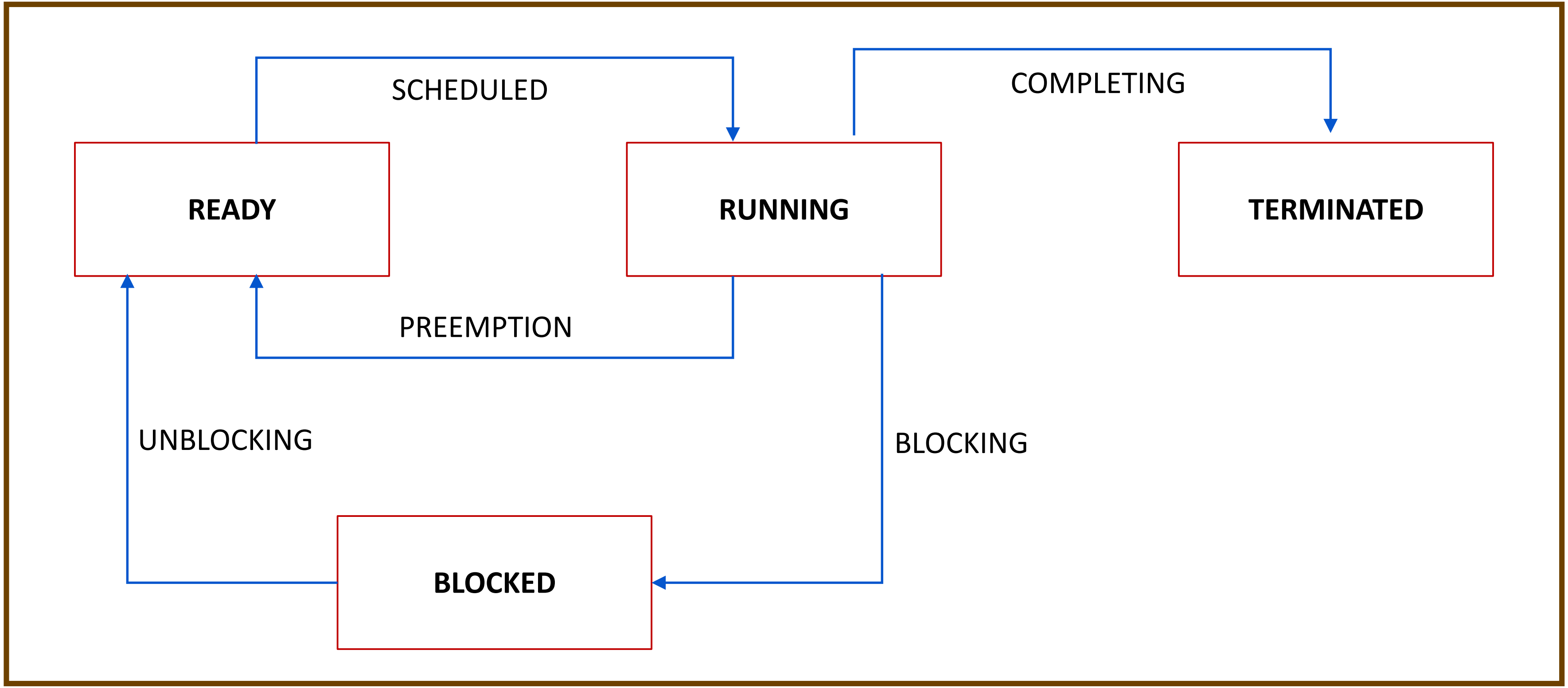
Process

- **Process is a Program under execution**
- Program is passive entity and process is active entity
- Every process has its own independent stack
- Kernel maintains process list table in the form of doubly linked list
- Each process has a unique id (pid)



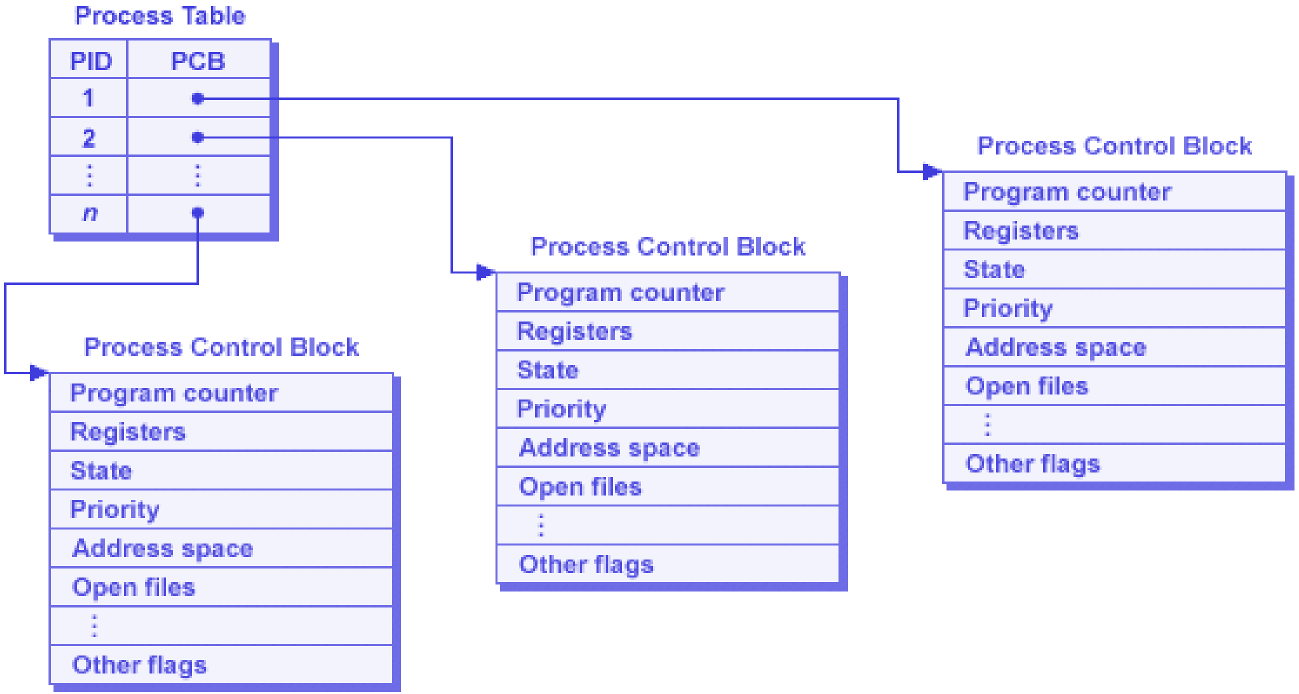


Process Life Cycle



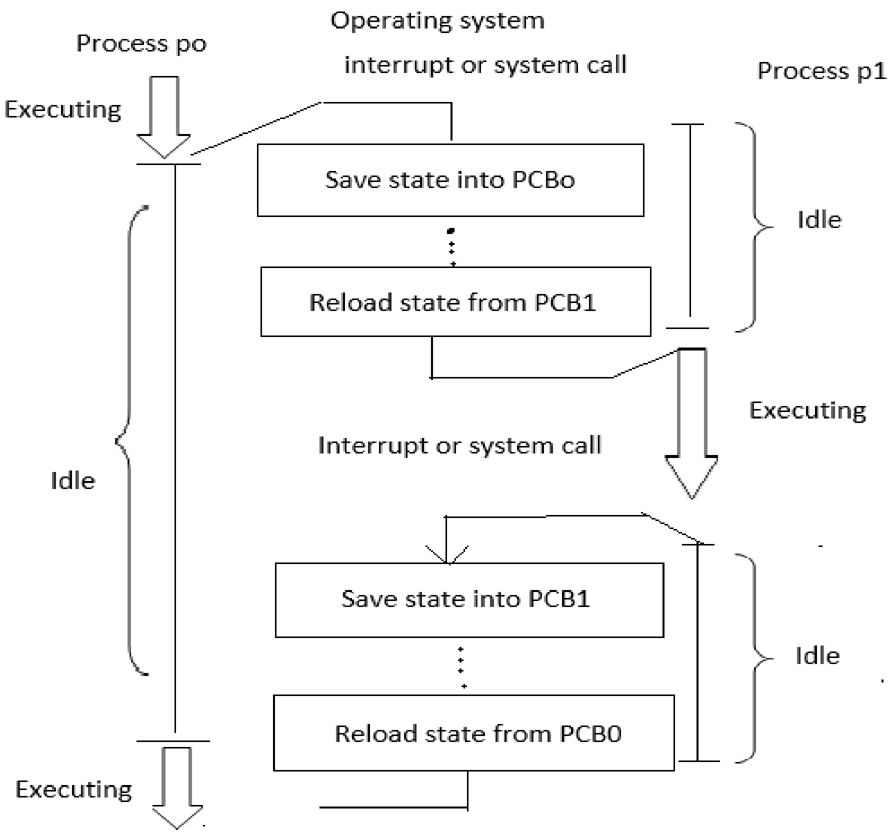
Process Table and Process Control Block

- **Process table is maintained by kernel**
- **Process Control Block**



Context Switch

- **Context saving**
  - Copy data from CPU to SAVE AREA
- **Context loading**
  - Copy data from SAVE AREA to CPU
- **Context switching**
  - combination of context saving and context loading
  - Switching CPU from one Process to other
  - Occurs on Interrupt or system call or pre-emption
- Every process has individual process stack in user space and kernel space to store register values on context switching



Process

- To start a process in Background use **&** symbol in command
  - cat file.txt &
  - jobs
- Lis the running processes
  - ps , ps –f
- Stop a process
  - kill -9, pkill
- Parent and Child
  - Each Process(PID) has a parent (PPID)
- Zombie and Orphan Process
  - Orphan process is one whose parent is killed/terminated before itself.
  - Processes which completed the execution but still have entry in process table.
- Daemon Processes
  - Processes that run in background

Process Hierarchy

- Every process has parent process
- a.out → shell → terminal → .. → init with PID = 1
- init is considered as the ORIGIN of linux process hierarchy
- Commonly used commands
  - pstree, pstree –np
  - top
  - ps, ps –el, ps aux, ps –e –o pid,ppid,stat,cmd
  - pgrep
  - kill, killall, kill -9, pkill

New Process Creation

fork

- Creates a new process known as child process
- New pid, process control block (PCB) / process descriptor (PD) will be allocated to child (new entry in process table)
- Duplicates resources from parent to child
- fork returns zero to child, non zero to parent
- Child resumes from next statement after fork
- Parent & child run concurrently based on architecture

Process termination

- exit() function causes normal process termination and the value of status is returned to the parent
- Process normal termination can be
  - success – exit (0)
  - Failure – exit with positive value
- abnormal termination
  - With exceptions

waitpid

- Blocks parent process till completion of child process
- Collect exit status of child
- Cleans some pending resources of child (else child will become Zombie)
- waitpid paramaters
    - 1st param : pid of child process waiting for, -1 means any one child
    - 2nd param : status of terminated child (pass by address)
    - 3rd param : flags
- man waitpid

execl

- Overwrites child address space with resources of specified program
- Process remains same, but program/resources will change
- Any code after execl is redundant, if execl succeeds
- Syntax
  - execl(const char *path, const char *arg, ..., NULL);

  For ex
  - excel("/usr/bin/cal", "cal", "2018", NULL)
- Excel uses absolute path, excelp uses cmd name

Signals

Signals overview

- Signals always operate at process level
- Signals communicate between applications at user level
- Used for communication of abnormal termination, illegal memory access & events that go wrong
- Signals are considered as software interrupts, but there is no interrupt vector table
- Signals between processes
  - SENDER send / triggers signals from one process to other process
  - TARGET will set the corresponding bit based on sender’s signal bit
  - Target will lookup in the signal handler table for handler addresses for each of signal handler
- Process descriptor (PD) / process control block (PCB) has signal related fields
- Most of the default signal handlers will cause abnormal termination

Signals in common actions

Signal Name	Description	Signal Name	Description
SIGINT	User sends INTERRUPT signal (Ctrl + C)	SIGTERM	User sends TERMINATION signal (kill <pid>)
SIGQUIT	User sends QUIT signal (Ctrl + \)	SIGCHLD	Child process stopped
SIGTSTP	User sends SUSPEND signal (Ctrl + z)	SIGFPE	Floating point exceptio

- Commands
  - kill –l, will list all the signals
  - kill –SIGxxxx <pid>
  - kill -<signo> <pid>
  - kill <pid>
  - kill -9 <pid> → terminate is SURE KILL
  - kill (pid, signal number) → system call
  - pkill, killall, pgrep → process kill

Default & Custom handlers

- Signal has default handler
- Custom handler can override the default handler

- APIs – signal, raise, pause, kill, alarm
- Modern APIs – sigaction, sigprocmask, sigsuspend

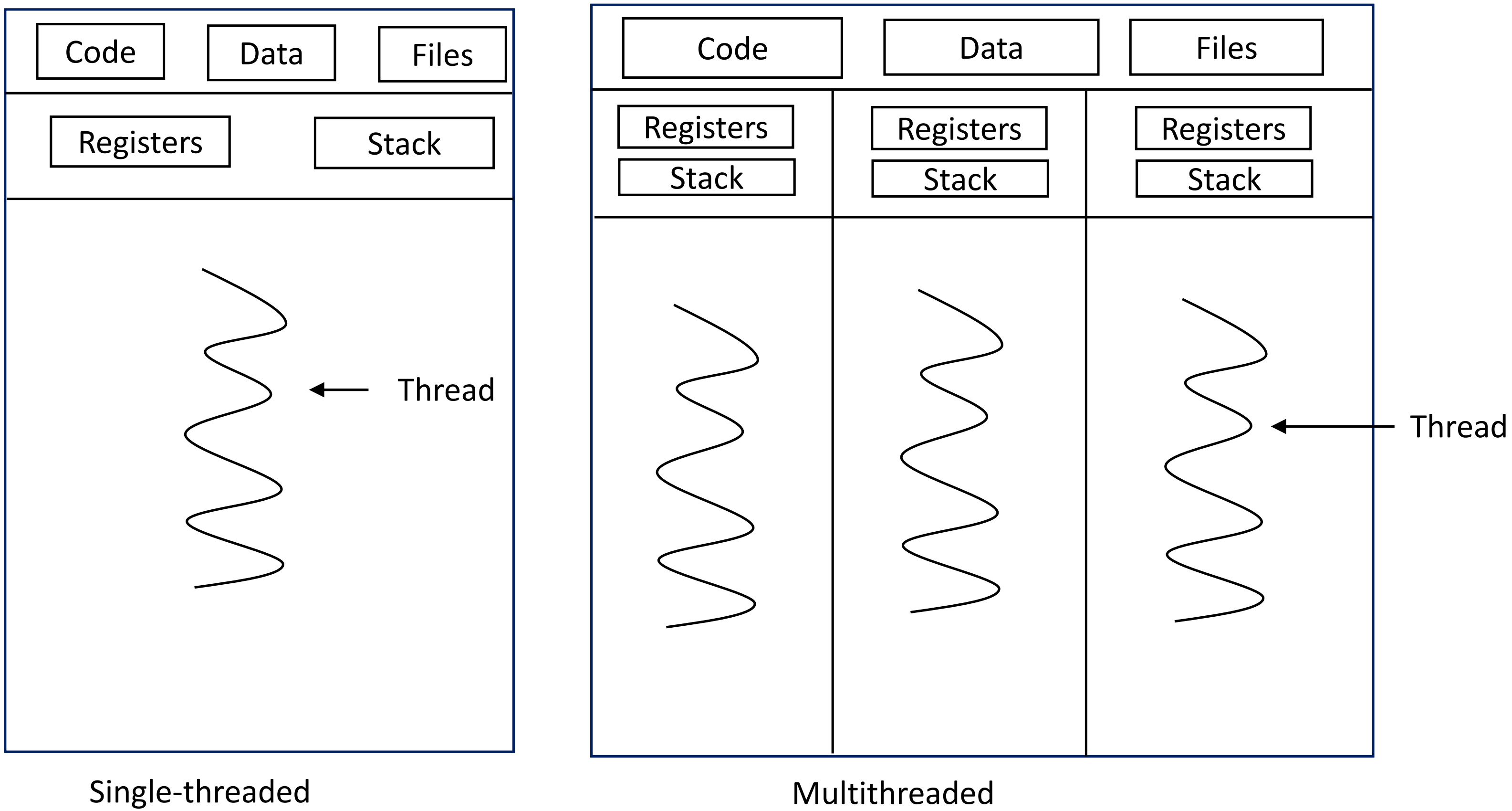
- Non maskable signals
  - Have NO custom handlers
  - SIGKILL, SIGSTOP

Threads

Basics of Threads

- Path of execution within a process
- Various sub-activities within applications are referred as threads
- Referred as Light Weight Process (LWP)
- Significance of threads
  - Concurrent execution (parent – child process / multiple child process)
  - RESOURCE SHARING across threads
- Child process will have own resources, but threads will have shared resources
- Scheduled threads interchangeably use CPU based on time sharing
- Every process is run initially as a single thread, then multiple threads spawn
  - Firefox browser initially will be a single thread, on need basis multiple threads spawn
- Threads are faster than fork
- Common resources during execution run independently

Basics of Threads



Advantage of Thread over Process

- Concurrent execution and faster response, less time for context switch
- Effective use of multiprocessor system
- Resource sharing: code, global data, files can be shared among threads
  - PC, Stack and Registers is separate for each thread
  - Private / local data is not shared
- Easier communication between threads
- Enhanced throughput of the system
  - Number of jobs completed per unit time

Note:

If one thread makes a blocking call, whole process gets blocked.

Thread Models

- Types of threads
  - User threads
    - Threads used by application programmers, are above kernel and without kernel support
  - Kernel threads
    - Supported within kernel, perform multiple simultaneous tasks to serve multiple kernel system calls
- Models
  - Used to map user threads to kernel threads
  - Many to One model
    - Many user-level threads are mapped to single kernel thread, thread management is handled by thread library in user space
  - One to One model
    - Separate kernel thread is created to handle each and every thread, limitation is the count of threads that can be created
  - Many to Many
    - Many user-level threads are mapped to multiple kernel level threads

Commands

- ps –e –L –o pid,ppid,lwp,nlwp,stat,cmd
- ps –eLf

- To create threads, POSIX thread library is used
  - pthread_create
  - pthread_join
  - pthread_self
  - pthread_equal
  - pthread_yield
  - pthread_cancel

- gcc psample.c -lpthread

Inter process communication (IPC)

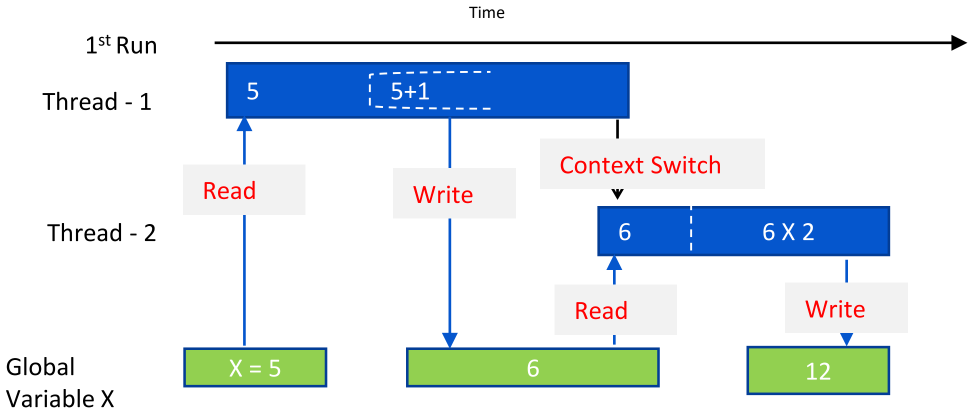
IPC

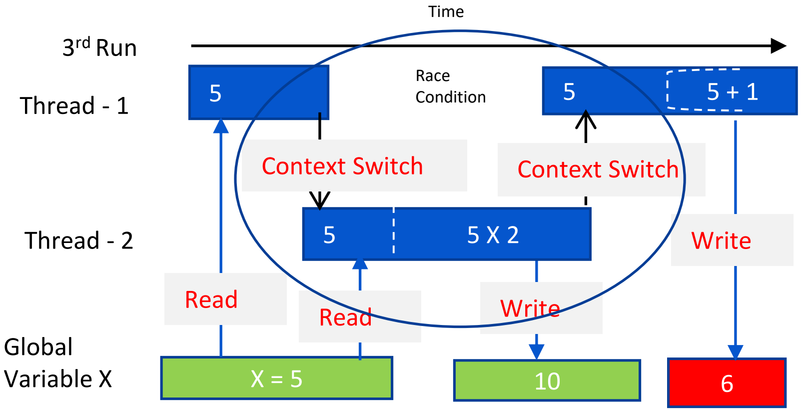
Requirement of IPC

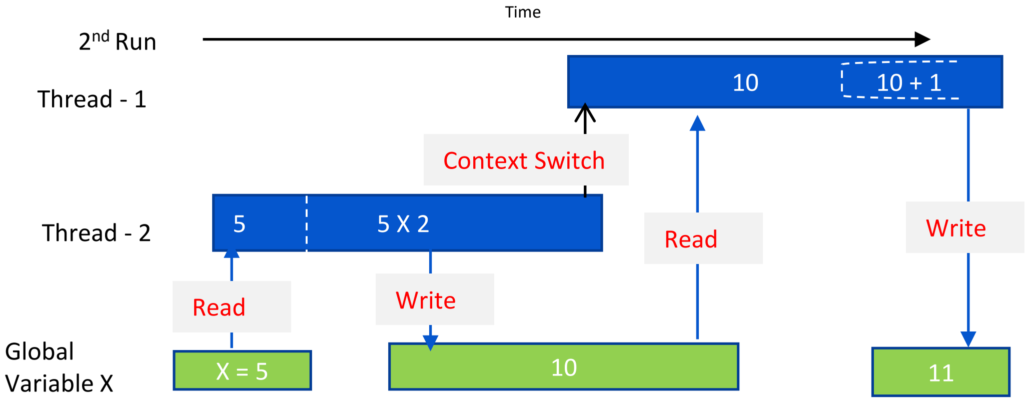
- Data exchange
- Synchronization
  - Dependency / Sequencing
  - Mutual Exclusion
- Data exchange → shared memory, message queues, FIFOs/pipes
- Mutual exclusion → semaphore, mutex, spinlocks
- Dependency →semaphores, condition variables / event flags

Process that writes/updates data is **PRODUCER** and process that reads is **CONSUMER**

Race conditions







- More than one process accessing same resource will cause resource to be corrupted
- Resources accessed by more than one Process/Thread will cause race condition

Process switching scenarios under consideration

- Switching between instructions
- Switching before/after instructions

Critical section & Mutual Exclusion

Critical Section: Code/Instructions in a Process/Thread using shared resources

- During process execution in critical section, no switching should be allowed
- Only one Process/Thread can be in a related critical section at any given time.
- Should be as short as possible & no blocking calls

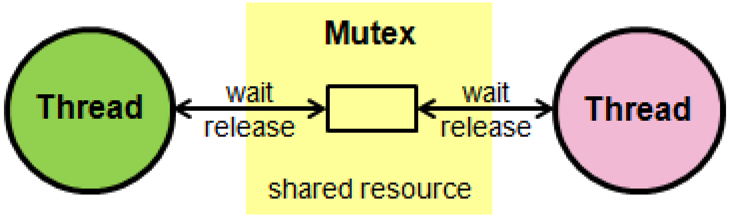
Mutual exclusion: Preventing simultaneous access to shared resources

- Disable interrupts (for very shorter duration)
    - - User space cannot have access
    - - For longer duration, inconsistency occurs
    - - Other CPU can access the resources
- Hardware support instructions
  - Atomic operation: Programming operations independent of other processes
    - - Resources can't be accessed by other process
  - Data bus locking techniques: CPU level bus locking techniques
- Above techniques have limitations and not scalable
- Software level solution for Mutual exclusion is semaphore & mutex

Semaphore & Mutex

Mutex

- Mutual Exclusion
- Only locked Process(es)/Threads can unlock the resources
- Any other Process/Threads trying to unlock is referred as “unauthorized operation”
- Unlocking twice or unlocking before locking is not allowed
- Strictly lock & unlock in the same thread only
- Mutex will have "ownership" as compared to semaphore



Mutex API’s

- #include <pthread.h>
- pthread_mutex_t m1=PTHREAD_MUTEX_INITIALIZER (declare & initialize)
- pthread_mutex_init(&m1)
- pthread_mutex_lock(&m1) (lock)
- pthread_mutex_unlock(&m1) (unlock)
- pthread_mutex_destroy (&m1) (destroy)

Always check return value for Success or Failure

Semaphores

- Sequencing, Signaling mechanism, used for process/thread synchronization
- Manage and protect access to shared resources
- Kernel level data structure

Types of usage

- Binary Semaphore
  - Value of semaphore ranges between 0 & 1
  - Mutual Exclusion / Access to a single resource
- Counting Semaphore
  - Value of semaphore can be 0 (zero) & any positive value
  - Accessing/sharing multiple similar resources

Two (2) varieties of semaphores

- Traditional System V semaphores
- POSIX semaphores.

Two (2) types of POSIX semaphores

- Named
- Unnamed

Named Semaphore

Name is given to semaphore and can be access by parent & child or different processes

- Uses internal shared memory for resources access

POSIX API's

#include <semaphore.h>

#include <errno.h>

- sem_t *ps; (declare a semaphore variable)
- ps = sem_open("/s1", O-CREAT, 0666, 1) (internal shared memory)
- sem_wait(ps) (lock the semaphore)
- sem_post(ps) (unlock the semaphore)
- sem_close(ps) (close semaphore from process)
- sem_unlink(ps) (remove named semaphore)

All calls return 0 on success, -1 on error and '**errno**' variable is set to error number

Unnamed Semaphores

No name is given to the Semaphore.

- Memory is allocated in the program address space

POSIX Unnamed Semaphore API's

#include <semaphore.h>

#include <errno.h>

- sem_init(sem_t *sem, int pshared, unsigned int value) (Initialize unnamed semaphore)
- sem_wait(sem_t *sem) (Lock the semaphore)
  - Check sem_trywait & sem_timedwait
- sem_post(sem_t *sem) (Unlock the semaphore)
- sem_destroy(sem_t *sem) (Destroy the semaphore)

All calls return 0 on success, -1 on error and '**errno'** variable is set to error number

Produce and Consumer Problem

Producer and Consumer scenario

- A Process/Thread will add data – Producer
- A Process/Thread will remove data – Consumer
- Common Buffer/Data Source
- Either Producer or Consumer only can access common data at a time (Shared resource)
- Consumer should block if buffer empty
- Producer should block if Buffer full

Deadlock

Two or more processes infinitely blocked (forever) due to circular dependency of resources

- Digital Copy – Printer(s1), Scanner(s2) Problem
- Arbitrary locking of multiple semaphores
- Parent & child - unlocking semaphore after waitpid
- Producer consumer problem - order of locking

Avoid deadlock

- If multiple locks are required, lock all of them at once (atomic locking)
- Don't apply mutual exclusion, before resolving dependency

Limitations of Semaphore and Mutex as a method of IPC

- Semaphores & Mutex can never carry data
- Processes / threads need to carry data or exchange the data

Data Exchange

Limitations of Semaphore and Mutex as a method of IPC

- Semaphores & Mutex can never carry data
- Processes / threads need to carry data or exchange the data

Need for other IPC Mechanisms

- Pipes/FIFO
- Message Queue
- Shared Memory

FIFO/Pipes

FIFO/Pipes

Pipe is a connection between two related processes

- Pipe is one-way communication only
- If a process tries to read before something is written to the pipe, the process is suspended until something is written.
- For two way communication using pipes, two pipes should be used.
  - Process-1 writes to Pipe-1 & reads from Pipe-2
  - Process-2 reads from Pipe-1 & writes to Pipe-2

Named Pipe/ FIFO

- Connection between two unrelated processes

  int mkfifo(const char *pathname, mode_t mode)

- mkfifo mypipe, tail -f mypipe

Example

Pipes

System Calls related to pipe

#include <unistd.h>

- int pipe(int pipedes[2]) (Create unnamed pipe)
- ssize_t write(int fd, void *buf, size_t count) (Write to pipe)
- ssize_t read(int fd, void *buf, size_t count) (Read from pipe)
- int close(int fd) (Close pipe)

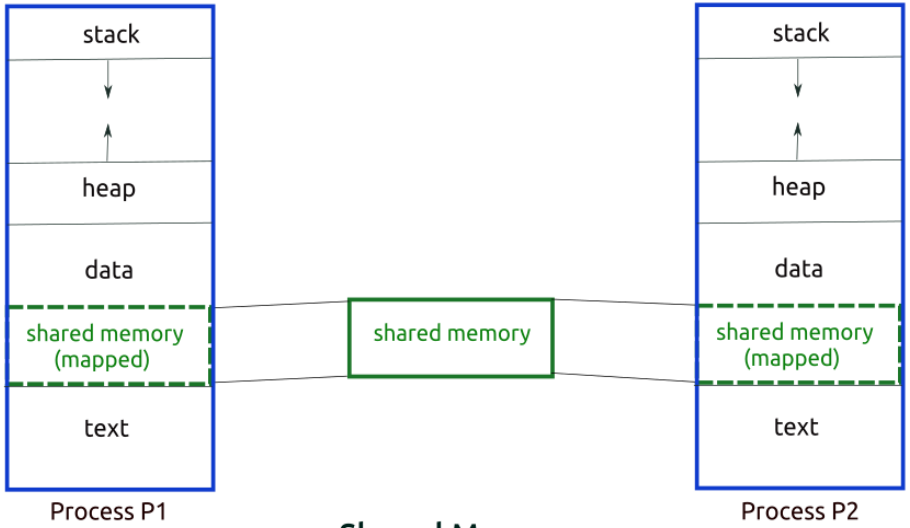
- Advantages and Disadvantages

Shared Memory

Shared Memory

Memory Segment is created by the kernel and mapped to the data segment of the address space of a requesting process

Can be used like a global variable in address space



Shared Memory

Shared Memory

- int shm_open (const char *name, int oflag, mode_t mode);

Create, or gain access to, a shared memory object.

- void *mmap (void *addr, size_t length, int prot, int flags, int fd, off_t offset);

Map a shared memory object into its address space.

Do operations on shared memory (read, write, update).

- int munmap (void *addr, size_t length);

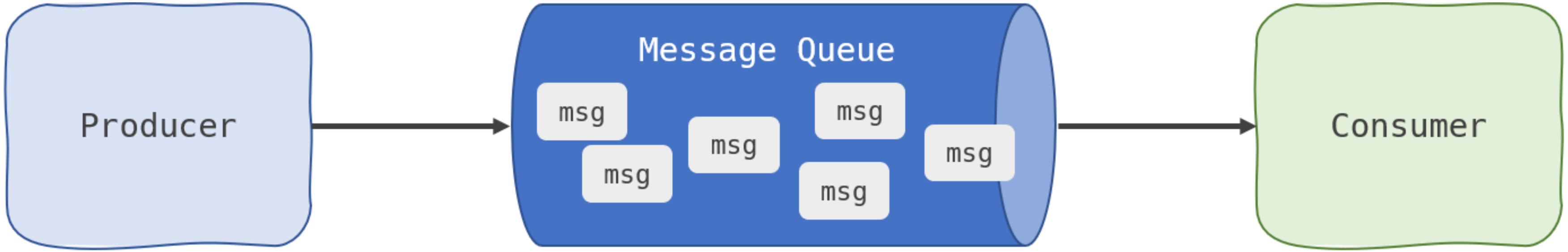
Delete mappings of the shared memory object.

- int shm_unlink (const char *name);

Destroy a shared memory object when no references to it remain open.

Message queues

Message Queues



The messages from Producer are stored on queue & provided on-demand to Consumer

- Typically FIFO based, can also be priority based
- Messages with same priority are read in FIFO order

Synchronization

- On read, if queue is empty, the receiver is blocked
- On write, if the queue is full, sender will be blocked
- Messages are discrete

Message Queues

#include <fcntl.h> /* For O_* constants */

#include <sys/stat.h> /* For mode constants */

#include <mqueue.h>

- mqd_t mq_open(const char *name, int oflag)
- mqd_t mq_open(const char *name, int oflag, mode_t mode, struct mq_attr *attr)
- int mq_send(mqd_t mqdes, const char *msg_ptr, size_t msg_len, unsigned int msg_prio)
- ssize_t mq_receive(mqd_t mqdes, char *msg_ptr, size_t msg_len, unsigned int *msg_prio)
- int mq_close(mqd_t mqdes)
- int mq_unlink(const char *name)

Link with -lrt

Queries?

Thank You !

L&T Technology Services