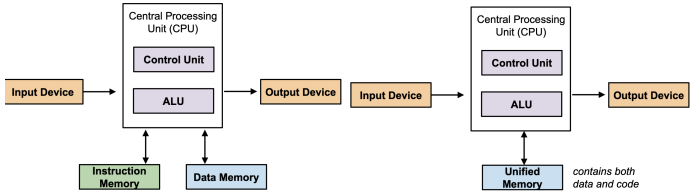
CS2106
AY22/23 Sem 2
github.com/securespider

01. Introduction
OS - Program that acts as an intermediary between user and hardware

Different architectures


Difference Separate vs common storage pathway for code and data

Why do we need OS?
- Should not have bugs
- Treat process as malicious

Mainframe
Old analog "computers" using physical cards for programming

Improvements
- Problem: Batch processing inefficient
- Solution: Multiprogramming
  - Loading multiple jobs that runs while other jobs using I/O
  - Overlapping computation with I/O
- Problem: Only one user
- Solution: Time sharing OS
  - Multiple concurrent users using terminals
  - User job scheduling
  - Memory management
  - **Hardware virtualization** - Each program executes as if it had all resources

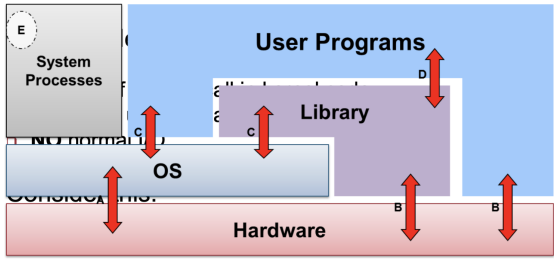
Motivation
1. Abstraction
   - Hide low level details and present common, high-level functionality to users
2. Resource allocation
   - Allow concurrent usage of resource and execute programs simultaneously
   - Arbitrate conflicting request fairly and efficiently
3. Control programs
   - Restrict resource allocation
   - Security, protection and error prevention (Defensive)
   - Ensure proper use of device

Advantage
- Portable and flexible
- Use computer resources efficiently

Disadvantage
- Significant overhead

OS vs User Program
Similarities
- Both softwares

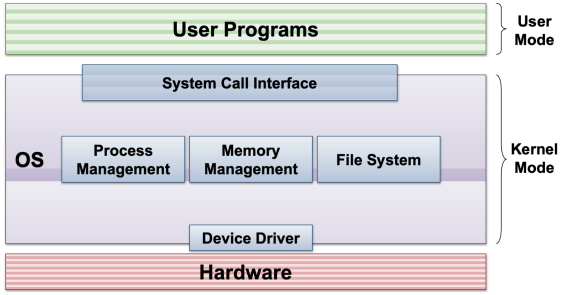
Difference
- OS runs in **kernel mode** - Access to all hardware resources
- User programs run in **User mode** - Limited access
- User programs use syscalls to communicate with OS for hardware processes
- User - Full virtual address space for code but cannot write outside of virtual address space
- Kernel - All code share same address space



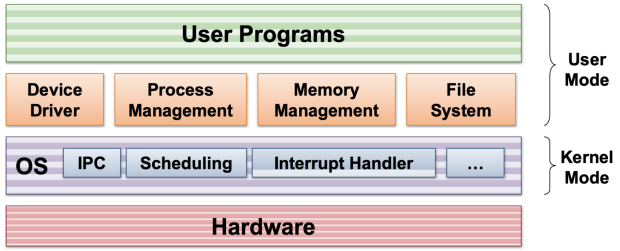
A OS executes machine instructions
B Normal machine instructions executed
C Calling OS using **syscall interface**
D User programs call library code
E System processes providing high level services

Why OS dont occupy entire hardware layer
- Slow to have all operations pass through intermediary
- User programs can have direct interaction with hardware (eg. Arithmetic) during low risk operations

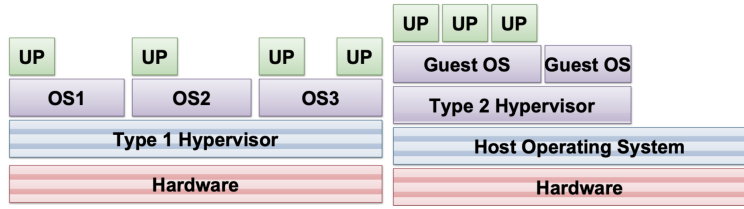
OS structure
Monolithic OS
- One big kernel program
- Well understood and has good performance
- Highly **coupled** - internal structure interconnected that unintentionally affect each other



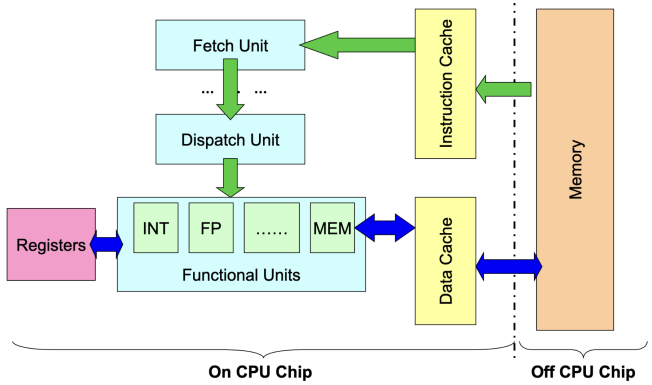
Microkernel
- Small clean
- Basic and essential facilities
- IPC communication OR run external programs outside OS
- Robust and more **modular** - Extendible and maintainable
- Better isolation btw kernel and services
- Lower performance
- Unix is monolithic kernel, Windows is hybrid



Virtual Machines
- Software emulation of hardware
- Virtualization of underlying hardware to run additional operating systems concurrently



02. Process abstraction
Motivation
- Allow concurrent usage of hardware
- Multiple programs sharing the same processors/IO

Computer organisation


Memory

- Storage for instruction and data
- Managed by the OS
- Normally accessed via load/store instructions

Cache

- Fast and invisible to software
- Duplicate part of the memory for faster access
- Usually split into instruction and data cache

Fetch

- Load instructions from memory
- Location indicated by **Program Counter**

Functional units

- Carry out instruction execution
- Dedicated to specific instruction type

Registers

- Internal storage for fastest access speed

Information needed

- Memory context
  - Code
  - Data
- Hardware context
  - Register
  - PC value
  - Frame Pointer
- OS context
  - Process properties
  - Resources used
  - Files

Function calls

Suppose a function f() calls g()

- f is caller and g is callee

Steps of control flow

1. Setup parameters
2. Trf ctrl to callee
3. Setup local var
   - Remember the initial variables especially if registers are to be reverted back when jumping back to caller
   - Callee does not know the registers callers used, so prevent accidental overwrite of content to registers caller use
4. Store any results
5. Return ctrl to caller

Issues

Control Flow

- Need to jump to functional body when callee called
- Need to resume to next instruction in caller after done

Data storage

- Need to pass parameters to function
- Need to capture return result
- May have local variables

Additional

- May lead to overriding of data in caller by callee (interference)
- Calling g() multiple times may lead to insufficient space and overriding

Stack memory

Memory to store function invocation

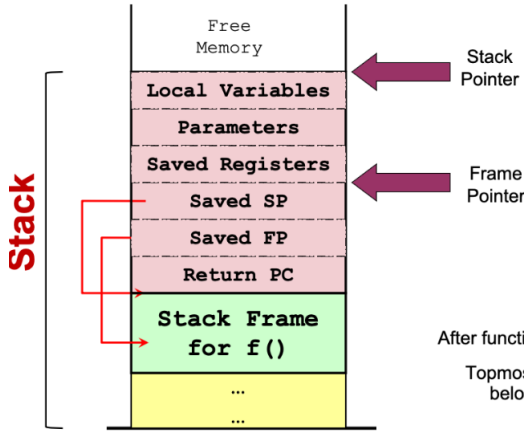
Stack Pointer - Indicates the first free location in the stack region

Frame Pointer - Points to the frame and is used for traversing around the stack easily

- On executing function call:
  - **Caller**: Pass arguments with registers and/or stack
  - **Caller**: Save Return PC on stack
  - **Transfer control from caller to callee**
  - **Callee**: Save registers used by callee. Save old FP, SP
  - **Callee**: Allocate space for local variables of callee on stack
  - **Callee**: Adjust SP to point to new stack top
- On returning from function call:
  - **Callee**: Restore saved registers, FP, SP
  - Transfer control from callee to caller using saved PC
  - **Caller**: Continues execution in caller

Information needed for function invocation - Stack frame

- Return address of caller
- Arguments for the function
- Local variables
- Stack and frame pointer of caller
- GPR values (register spilling)



Callee stack frame will be on top of the caller

Dynamic memory (Heap)

Memory that the program/user specifies manually (eg. malloc, new)

Problems:

- Allocated only at runtime
  - Size not known at program compilation time
  - Cannot specify a region in data
- No definite dellocation timing
  - Must be freed explicitly by the program
  - Cannot place in stack region

Solution:

Add a region "Heap for dynamic allocation

Problems with heap memory:

- Generation of holes in between data due to variable deallocation timing

OS context

Process identification

Features:

- Distinguish processes from each other (Unique)
- Communicated to the hardware

Process state

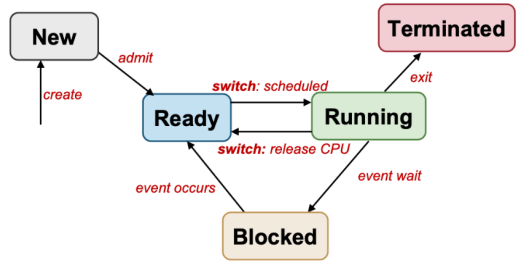
New New process that may still be under initialization (not schedulable)

Ready

Running Executed on CPU

Blocked Sleeping/waiting for event - cannot execute until event available

Terminated Finished execution and requires OS cleanup



Process control block

Table representing all processes containing entire execution context stored in OS memory

- PC, FP, SP and other GPR (only updated when swapped out)
- Memory region info (Text, data, heap and stack)
  - It is a "point" to real memory space **NOT actual memory space used by process**
- PID and process state

Context switching

1. Interrupt or syscalls
2. Save state of old process into PCB
3. Reload state of new process from PCB

- Involves a change to kernel mode and back

Exceptions and interrupts

Exceptions

- Synchronous (due to program execution)
- Machine level instructions arise errors
- Exception handler executed automatically in software (can be handled by programmer)
- Handled by OS which sends a signal to application to implement try-catch mechanism

Interrupts

- Asynchronous (Can happen anytime)
- External events that cause execution to fail (hardware related errors)
- Program execution suspended and **interrupt handler** executed automatically

Instruction execution

1. Read byte from PC and decode instruction
2. Read 2 bytes to get the address/operands
3. Perform ALU operations
4. Store result into destination
5. Check if any interruptions

Interrupts can happen at anytime, and will remain pending until step 5 where it is handled

Interruption handling

1. Push PC and status register into hardware
2. Disable interrupts
3. Read **Interrupt Vector Table** - Table where the OS stores address of all interrupt handlers
4. Switch to kernel mode
5. Set PC to handler address and execute the instructions

- OS populates the IVT table with address of interrupt routines
- Hardware reads IVT to locate the handler

System calls

Application Program Interface - Provides way of calling facilities/services in kernel
Synchronous function only done in kernel mode providing system services
Typically more expensive than library calls due to context switching
OS dependent anc cannot be avoided by any application

Functions

Process control Direct processes like creating, terminating or synchronisation

File/device manipulation

Information maintenance Get system data, time, etc

Communication Create, delete connections and send/receive messages

Method (Programming language specific)

- Library version with the same name and same arguments
- User friendly library version
- Using func $long\ syscall(long\ number);$

Mechanism

1. User invoke library call
2. Place call number in the designated location
3. Library call executes a special instruction (**TRAP/syscall**) to change user to kernel mode
4. (in kernel) syscall handler is determined (by a **dispatcher**)
5. syscall handler is executed
6. Syscall handler ends and control returned to the library call
7. Return to user mode and continue normal function mechanism

03. Process abstraction in Unix

Process information

Pid

Proc state Running, sleeping, stopped, zombie

Parent pid

Cumulative CPU time For scheduling

fork()

Process creation

Package unistd.h and sys/types.h

return PID of newly created process(parent) and 0 (child process)

Behaviour

- Creates a child process
  - **Copy** data of parent (Independent memory space)
  - Unless explicitly modifying value at address, parent and child variables are distinct
  - Sane code, same address space
  - Differs by pid, ppid and fork() return value

Implementation

Clone the parent process

1. Create address space of child process
2. allocate new pid to child and pass to parent
3. Create kernel process data structures
4. Copy kernel environment of parent process
5. Initialize child process context (pid, ppid, cpu_time = 0)
6. Copy memory regions from parent
   - Very expensive operation
   - Code, data, stack
7. Acquire shared resources
8. Initialize hardware context for child process (copy parent registers)

Problem: Memcopy is very expensive operation
Solution: Copy on write

- Only duplicate a memory location when it is written to

exec(@param)

Replace current executing process image

- Code and data replaced
- PID/PPID intact
- If fail, program just continues to run the next instruction

Format

param char *path, char *arg0...

- Note that last term MUST be **NULL** indicating end of argument list

header unistd.h

exit(status)

return Does not return anything

param int status - returned to the wait call

- Most system resource used by process are released on exit
- return from main() implicitly calls exit(0)
- Basic processes are not releasable
  - Pid and status
  - Process accounting info

wait(&status)

Parent child synchronisation

param &status - address to put return value

header sys/types.h and sys/wait.h

return pid of terminated process

- Call is blocking - suspend operation until at least one child terminates
- Cleans up remainder of child system resources (PID, status)
- waitpid - used for waiting for specific child process

Orphan and zombie process

Zombie - **All** processes that has exited but parent did not call wait
Orphan - Child process whose parent has been terminated

- Parenthood will be propagated up to init which may use wait() to clean up

04. Inter Process Communication

Mechanism

- Shared memory
- Message passing
  - Pipes
  - Signal

Shared memory

Communication through read/write to shared memory
Advantages

Efficient Only require OS to setup shared region once

Ease of use Simple reads and write to memory

- Implicit communication
- Can store any type of information

Disadvantages

Limited to single machines Less efficient over different system

Need Sync Might have data races without synchronisation

Race condition - System behaviour is dependent on the context/interleaving of process → unpredictable outcome

Steps

1. Create/locate a shared memory region M
2. Attach M to process memory space
3. Read from/write to M
4. Detach M from memory space after use
5. Destroy M
   - Only one process need to do this
   - Can only destroy if M is not attached to any process

Message Passing

Explicit communication through exchange of message

Naming Have to identify the parties in the communication

Synchronisation Behaviour of sending/receiving operations

- Messages have to be stored in kernel memory space
- All sending/receiving operations have to be done through syscalls

Direct communication

Sender/receiver explicitly name parties in communication

- One link per pair of communicating processes
- Need to know identity of other party

Indirect communication

Message storage (**Mailbox/Port**)

- Can be shared among a number of processes

Synchronisation behaviour

Blocking

- send and receive is blocked until a message has received/sent (other party is ready)

Non-blocking (asynchronous)

- execute immediately and sends information to somebody OR returns empty handed

Typically, receive is synchronous and send is asynchronous
BUT send just buffers the message and only sends the message when the receiver is receiving (no loss)
Message buffers

- Under OS control
- Decouples sender and receiver - less sensitive to variation in execution
- Mailbox capacity declaration in advance

Rendezvous

- Synchronous message passing
- Sender is blocked until receiver sends matching receive
- No buffering needed

Pros

- Applicable beyond a single machine
- **Portable** - Easily implemented on many platforms and processing environments
- Easier synchronisation
  - Implicit via send/receive behaviour
  - Communication and synchronisation is done simultaneously

Cons

Inefficient Usually requires OS intervention every operation

Difficult to use Requires information packing into specific format

Unix Pipes

3 different communication channels to user

1. stdin - standard in bounded to keyboard input
2. stderr - used for error messages
3. stdout - linked to screen

"|" symbol for linking input/output channels of each process to each other
Create communication channel with 2 ends (one reading, one writing)

- Producer-consumer relationship
- Like anonymous file reading information FIFO

Synchronisation

- Circular bounded byte buffer with implicit synchronization
- Writer wait when buffer is full
- Reader wait when buffer is empty
- Unidirectional (one write one read exclusively) vs bidirectional (any end for reading and writing)

pipe(@param)

param array of file descriptors

return 0 for success, != for errors

Unix signals

Asynchronous notification about an event sent to process/threads

- Handle signal via default or user defined/supplied handlers(not all signals)
- Can only call async safe functions within handler (signal/wait cannot be called in POSIX)
- eg. Kill, stop, continue, error

Standard signals

First the signals described in the original POSIX.1-1990 standard.

Signal	Value	Action	Comment
SIGHUP	1	Term	Hangup detected on controlling terminal or death of controlling process
SIGINT	2	Term	Interrupt from keyboard
SIGQUIT	3	Core	Quit from keyboard
SIGILL	4	Core	Illegal Instruction
SIGABRT	6	Core	Abort signal from abort(3)
SIGFPE	8	Core	Floating point exception
SIGKILL	9	Term	Kill signal
SIGSEGV	11	Core	Invalid memory reference
SIGPIPE	13	Term	Broken pipe: write to pipe with no readers
SIGALRM	14	Term	Timer signal from alarm(2)
SIGTERM	15	Term	Termination signal
SIGUSR1	30,10,16	Term	User-defined signal 1
SIGUSR2	31,12,17	Term	User-defined signal 2
SIGCHLD	20,17,18	Ign	Child stopped or terminated
SIGCONT	19,18,25	Cont	Continue if stopped
SIGSTOP	17,19,23	Stop	Stop process
SIGTSTP	18,20,24	Stop	Stop typed at terminal
SIGTTIN	21,21,26	Stop	Terminal input for background process
SIGTTOU	22,22,27	Stop	Terminal output for background process

05.Process scheduling

Concurrency

- Multiple process progress at the same time
- Virtual parallelism (threading, context switching)
- Physical parallelism (multicore, multi CPU)

Scheduling

More ready processes vs limited CPU

- Each process diff CPU usage
- **Scheduling algorithms** - Deciding the process to run based on environment and process behaviour
- Processes have phases of io-bound and cpu intensive activities

Processing environment (sorted by increasing user interaction and response times):

1. Batch
2. Interactive
3. Real time

Objectives

Fairness Should get fair share of CPU time n prevent **starvation** - processes never have access to CPU

Utilization Hardware is used all the time

non-preemptive - Process gives up resources voluntarily **preemptive** - Process given a fixed quota to run and is suspended for other processes

Timeline

1. Scheduler is triggered (OS take over)
2. Context switching can happen and current process information stored and placed back in queue
3. Pick process to run using algorithm and setup its context

Batch

Non-preemptive used dominantly cos minimal user interaction needed

Objectives

Turnaround time Total time till finish running **including waiting** (finish time - arrival time)

Throughput Rate of task completion

Makespan Total time to complete **ALL** tasks

CPU utilization Percentage of **time** CPU is used

Algorithms

1. First Come First Serve (FCFS)
   - Scheduled using FIFO queue based on arrival time (bad turnaround time)
   - Guarantee no starvation - number of tasks in front of task is strictly decreasing
   - Reordering can reduce waiting time
   - **Convoy Effect** - Not all hardware resources are used concurrently because a process blocks it
2. Shortest Job First (SJF)
   - Choose tasks with smallest total CPU time
   - Estimate CPU time for tasks in advance using the previous CPU-bound phases
   - $Estimated_{n+1} = \alpha Actual_n + (1-\alpha) Predicted_n$
   - Starvation is possible as long tasks end up continuously waiting
3. Shortest Remaining Time (SRT)

Interactive system

Objectives

Response time Time between request and response by system

Predictability Decreased variation in response time

Premptive scheduling

- Periodic scheduler with time interrupts
- **Time quantum** - Execution duration given to a process
  - Constant(regardless whether the process has given up processing halfway) OR Variable(full time quantum given to a process)
  -

Algorithms

1. Round Robin (RR)
   - Store tasks in FIFO queue and pick tasks to run until
     (a) Fixed time slice elapsed
     (b) Task gives up CPU voluntarily
     (c) Task blocks
   - Task placed at end of queue to wait for next turn
   - Response time guaranteed bounded by num task time quantum
   - Timer interrupt needed
   - Choice of time quantum duration is important
     - Longer quantum: Better utilization but greater wait time
     - Shorter quantum: Bigger overhead/ lower utilization but shorter wait time
   - Poor performance when there are many jobs all exceeding time quantum - high overhead from context switching
2. Priority scheduling
   - Assign tasks processes priorities based on impt and select them
   - Starvation for low priority tasks
     - Solution:
     - Lower priority every time the process have executed
     - Give processes a time quantum
   - **Priority Inversion** - Lower priority tasks locks the resources used by a higher priority task leading to deadlock OR allowing lower priority tasks to run before
     - Solution:
     - Temporarily increase priority of tasks that lock resources until it unlocks
     - Low priority task inherit the priority of high priority tasks which is restored once unlocked
3. Multi-level Feedback Queue (MLFQ)
   - Runs processes with higher priorities but lower priority when the job fully utilise its time quantum
   - Processes that voluntarily gives up/blocks before time quantum retains its priority
   - New processes have highest priority
   - Processes with same priority run in RR
   - Long CPU processes are starved as its priority becomes very low and cannot complete
     - Solution: Occassionally reset tasks to full priority
   - Processes can exploit and voluntarily give up to retain its priority
     - Solution: Peg priority based on total CPU usage instead
4. Lottery scheduling

- Give out tickets to processes for various system resources and randomly pick winners to be granted the resources
- **Responsive** - Newly created processes can immediately join the lottery
- Good control - Process can be assigned quantity of tickets and resources which can be shared among its children/threads
- Simple implementation

06.Synchronisation primitives

Race condition

- Execution of sequential processes should be **deterministic** - Repeated execution returns the same result... however,
- Process sharing modifiable resources AND execute concurrently by interleaving may cause synchronization problems - non deterministic outcomes
- Order determines the execution outcome

Critical section

Region where unsynchronised access could lead to incorrectly interleaving scenarios
Only **ONE** process should be in the critical section at one time

Properties

Mutual exclusion/Mutex All other processes should be blocked from entering critical section if occupied

Progress If no process occupying section, waiting process should be granted access

Bounded wait Upper bound on number of times other processes can enter critical section before a waiting process

Independence Process not in critical section should not block other process

Incorrect synchronization

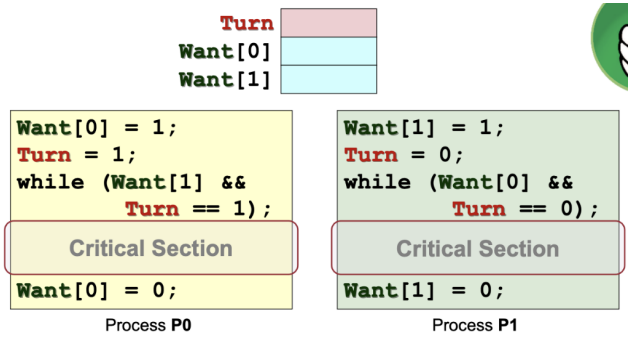
Deadlock All processes blocked

Livelock Processes keep changing states to avoid deadlock resulting in no progress (Deadlock avoidance mechanism)

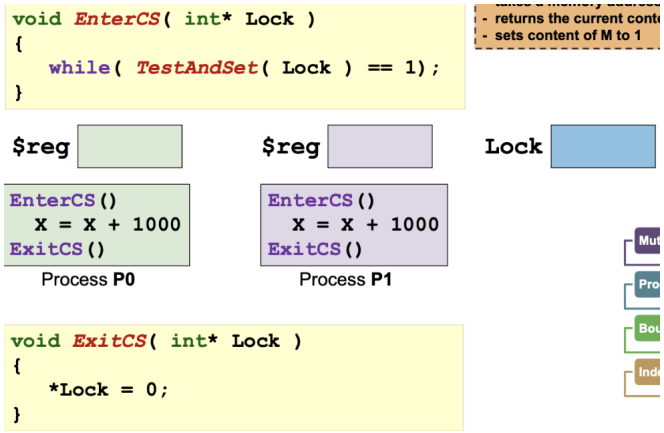
Starvation

Implementations

- High level language implementation (Peterson Algorithm)
  - Busy waiting - Repeatedly tests while-loop condition instead of going into blocked state (Wastes CPU power)
  - Low level - Error prone and complicated
  - Not general - cannot extend to allowing multiple access instead of Mutex



- Assembly implementation
  - Atomic instruction to load value and replace value in memory location (**TestAndSet**)
  - **Atomicity** - Prevents race condition of process viewing and upon modification, the value changes
  - No bounded wait unless fair scheduling algorithm employed
  - Employs busy waiting still



- High level synchronization mechanism (Semaphore)
  - Generalised mechanism to block a number of processes (sleeping), S, and unblock sleeping processes
  - **wait()** - Blocks if $S \leq 0$, decrement S
  - **signal()** - Increment S, wake up sleeping processes, operation **never** blocks
  - **Invariant** - $S_{current} = S_{initial} + N_{signal} - N_{wait}$

Conditional variables

- Tasks wait for certain events to happen
- Event completion/begin is broadcasted

POSIX semaphore

header semaphore.h

wait pthread_mutex_unlock

signal pthread_mutex_lock

Midterm

- **Tail-call optimization** - Stack frame can be replaced in iterative recursion since all information is retained in the 'return' function call at every iteration

07.Threads

Motivation

- Processes are expensive
  - Process creation via fork() duplicates memory space and process context
  - Requires context switching and saving/restoring process information repeatedly
- Hard to communicate with each other
  - Independent memory space (IPC communication only)
- Need easy way to execute some instructions simultaneously (more threads of control to same process)

Features

- **Multithreaded process** - Single process with multiple threads
- Threads share the same **Memory context**(Text, data, heap) and **OS context**(PID)
- Contains unique information
  - Identification (thread id)
  - Registers (GPR and special)
  - Stack

Benefits

Economy Less resources to manage

Resource sharing

Responsiveness

Scalability Can take advantage of multiple CPUs

Problems

- Syscall concurrency
  - Parallel execution of threads may result in parallel syscalls
- Process behaviour
  - Unable to impact process operations

Thread implementation

1. User thread
   - Implemented as a user library - More flexible and configurable
   - Runs on any OS
   - Kernel unaware of threads in process (scheduling at process level)
   - If process is blocked, all the threads in the process cannot run
2. Kernel thread
   - Implemented in the OS through syscalls (slower and more resource intensive)
   - Scheduling among threads instead of via process
   - Use threads in kernel operations
   - Less flexible
     - Used by all multithreaded programs so kernel must cater to all
     - Balance btw many and less features
3. Hybrid thread
   - OS schedules on kernel threads
   - User threads can be bound to kernel threads
   - If the user thread is blocked, the kernel thread that it is assigned to is blocked and the OS will execute another kernel thread
   - Lead to greater flexibility

Posix Threads (pthreads)

pthread_create

param tid, attributes, &function, function_params

return 0 success, != 0 fail

pthread_exit

Automatically called after function finishes

param exit_value

behaviour return value of function will be the "exit value"

pthread_join

param tid, **&status** - Exit value returned by target pthread

08.Synchronization classics

Use cases of synchronisation (mutexes)

Producer Consumer

- Processes share a bounded biffer of size K
  - Producers produce items to insert in buffer when not full
  - Consumers remove items from buffer when non-empty
- Busy waiting vs blocking version and message passing

```
while (TRUE) {
        Produce Item;

        wait( notFull );
        wait( mutex );
        buffer[in] = item;
        in = (in+1) % K;
        //count++;
        signal( mutex );
        signal( notEmpty );
}
```
Producer Process

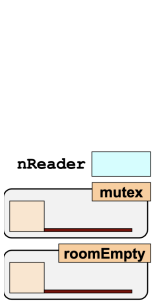
```
while (TRUE) {

        wait( notEmpty );
        wait( mutex );
        item = buffer[out];
        out = (out+1) % K;
        //count--;
        signal( mutex );
        signal( notFull );

        Consume Item;
}
```
Consumer Process

Initial Values:

- `in = out = 0`
- `mutex = S(1), notFull = S(K), notEmpty = S(0)`

Reader writer

- Processes share data structure D
  - Reader retrieves information from D (multiple concurrent accesses)
  - Writer modifies information from D exclusively
- Starvation of the writer as readers can continue to occupy the resource continuously

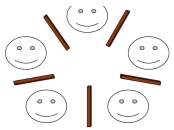



```
while (TRUE) {
    wait( roomEmpty );

    Modifies data

    signal( roomEmpty );
}
```
Writer

```
while (TRUE) {

    wait( mutex );
    nReader++;
    if (nReader == 1)
        wait( roomEmpty );
    signal( mutex );

    Reads data

    wait( mutex );
    nReader--;
    if (nReader == 0)
        signal( roomEmpty);
    signal( mutex );

}
```
Reader

Initial Values: `roomEmpty = S(1), mutex = S(1), nReader = 0`

Dining philosophers



- Single chopsticks between philosophers sitting around a table
- Philosophers need pair to eat without deadlocks and starvation
- Philosophers makes the same decision (takes the same side of chopsticks everytime)

Livelock

- To prevent deadlock, philosophers put down chopstick if cannot get the other side
- Livelock because all philosophers take chopstick, put down ....

Limited eater

- One of the philosophers delay their eating temporarily until either side finishes
- All philosophers can complete their execution pigeonhole theorum (more chopsticks than philos)
- Not fair to the philosopher not eating (How to decide who stops operation?)

Tanenbaum Solution

- Randomly decide which side chopstick the philosophers take first