CS2106
AY22/23 Sem 2
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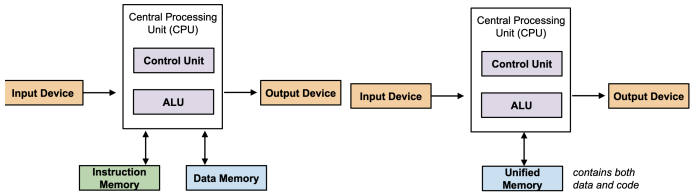
01. Introduction
OS - Program that acts as an intermediary between user and hardware

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

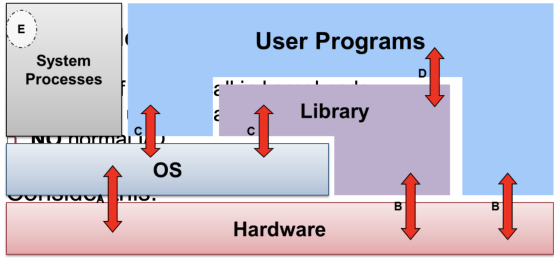
Motivation
1. Abstraction
   - Hide low level details and present common, high-level functionality to users
2. Resource allocation
   - Allow concurrent usage of resource and execute programs simultaneously
   - Arbitrate conflicting request fairly and efficiently
3. Control programs
   - Restrict resource 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

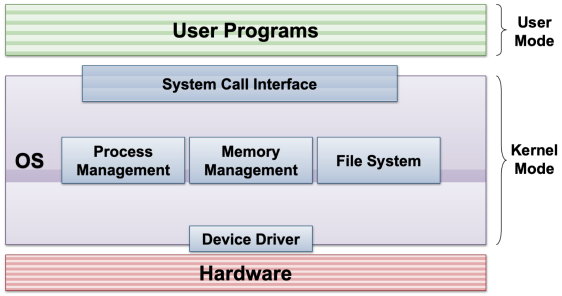
Difference
- OS runs in **kernel mode** - Access to all hardware resources
- User programs run in **User mode** - Limited access
- User programs use syscalls to communicate with OS for hardware processes
- User - Full virtual address space for code but cannot write outside of virtual address space
-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



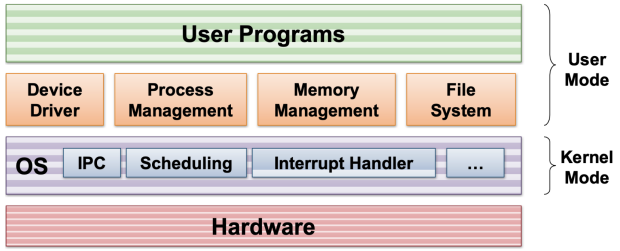
A OS executes machine instructions
B Normal machine instructions executed
C Calling OS using **syscall interface**
D User programs call library code
E System processes providing high level services

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

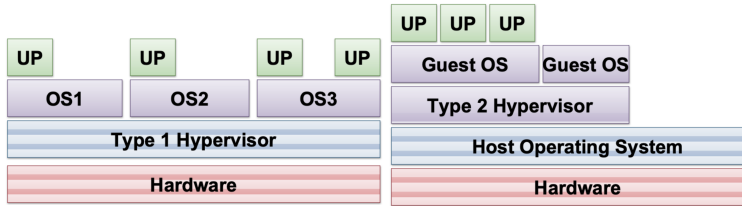
OS structure
Monolithic OS
- One big kernel program
- Well understood and has good performance
- Highly **coupled** - internal structure interconnected that unintentionally affect each other



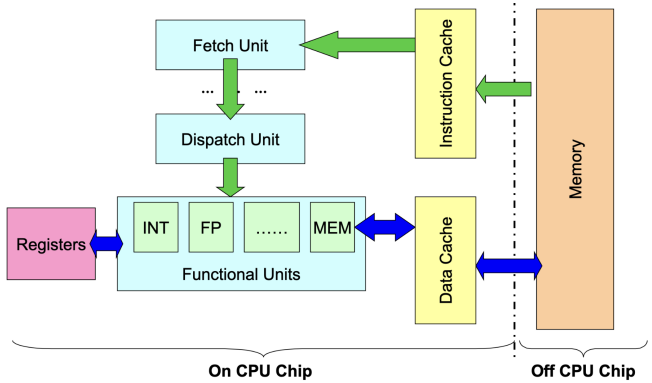
Microkernel
- Small clean
- Basic and essential facilities
- IPC communication OR run external programs outside OS
- Robust and more **modular** - Extendible and maintainable
- Better isolation btw kernel and services
- Lower performance
- Unix is monolithic kernel, Windows is hybrid



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

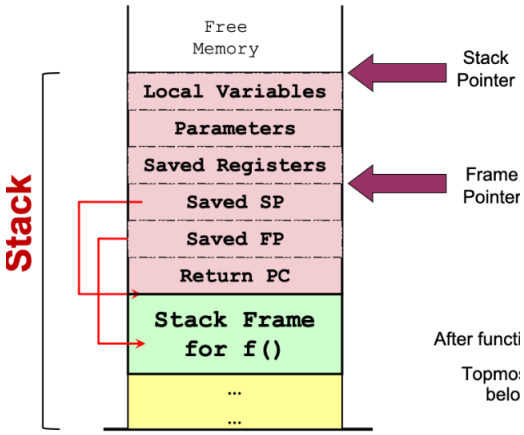
Stack Pointer - Indicates the first free location in the stack region

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

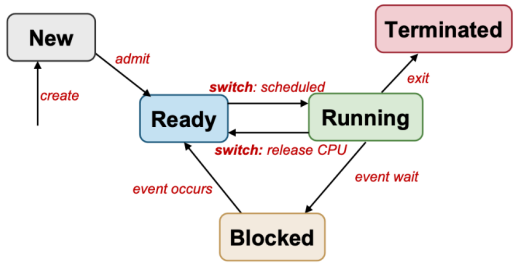
New New process that may still be under initialization (not schedulable)

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

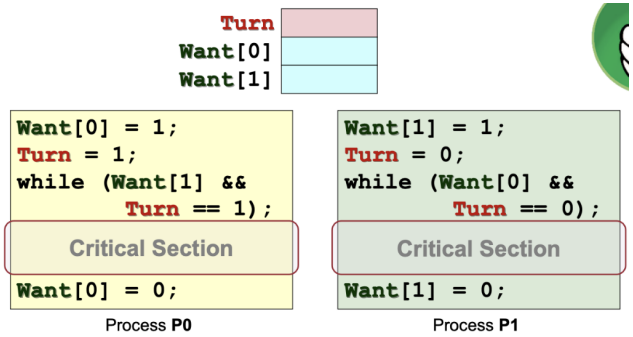
Deadlock All processes blocked

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

```
void EnterCS( int* Lock )
{
   while( TestAndSet( Lock ) == 1);
}
```

- returns the current cont
- sets content of M to 1

$reg $reg Lock

```
EnterCS()
  X = X + 1000
ExitCS()
```
Process P0

```
EnterCS()
  X = X + 1000
ExitCS()
```
Process P1

```
void ExitCS( int* Lock )
{
   *Lock = 0;
}
```

- 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. Classic synchronisation problems

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

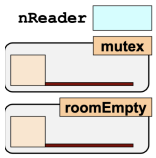
Initial Values:

- `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

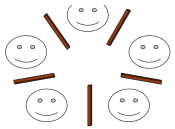
```
while (TRUE) {

    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

09. Memory abstraction

Hardware

- uses Random Access Memory
  - Access latency approximately constant regardless of location
- Can be treated as a 1D array of **AU** - Addressable unit
- **Contiguous** - Consecutive memory address with unique index (physical address)

Content

- Text (for instructions), Data (global variables), Heap (dynamic allocation)
- Stack (for function invocation)
- Btw heap and stack is region of unallocated memory

Memory usage of process

Types of data

1. **Transient data** - Valid only for a specific duration (parameters, local var)
2. **Persistent data** - Valid for complete duration of prgm until explicitly deallocated

Role of OS

1. Allocate and manage memory space for each process
2. Protect memory space of distinct processes
3. Provide memory-related system calls
4. Manage memory space for internal OS use

Memory abstractions

Motivation

- Processes assume memory starts at 0 and occupy the same memory location
- Difficult to protect memory space

Solutions (?)

- Address reallocation
  - Offset all memory references when process is loaded to actual memory address
  - Problems: Slow runtime because have to run through all the instructions
  - Difficulty in distinguishing memory references
- Base and limit registers
  - All memory references compiled as offset from base register
  - When loading, base register initialised to starting address of process memory space
  - Limit register as the range of memory space of current process (protect memory space integrity)
  - Memory access checked against limit

Logical address

- How each process views its memory space
- Mapping between physical and logical address needed
- Each process has a self contained, independent logical memory space

Contiguous Memory allocation

Assumptions

- Processes occupies contiguous memory region
- Physical memory must accommodate 1..* processes with complete memory space

Multitasking/context switching

- Multiple concurrent processes in memory
- Free memory via removing terminated processes/swapping to secondary storage

Fixed size partitions

- Fixed number of partitions of equal size
- Larger min addressable units of partition
- **Internal fragmentation** - More memory allocated to program than used
- Pros: Easy to manage and fast to allocate
- Cons: Partition size need to be large enough to contain the largest process

Variable size partitions

External fragmentation - Unallocated contiguous memory surrounding partitions insufficient to satisfy memory request of process

- Pros: Flexible, no internal fragmentation
- Cons: Need more info in OS and takes longer time to locate appropriate region

Allocation algorithms

- First fit
  - Take the first hole large enough
  - Fastest runtime (don't have to iterate through all the free partitions)
  - May be inefficient (high external fragmentation)
- Best fit
  - Choose the smallest partition that fits the information
  - Slower runtime but more efficient
- Worst fit
  - Choose the largest partition
  - Try to ensure that there is enough free space in the large partition for other process

Merging and Compaction

Merging Freed partitions can join surrounding holes

Compaction Mv occupied partitions to create bigger consolidated holes

- Time consuming (can be amortised)

Multiple free lists

- Dictionary of list of free holes
  - Key = size, value = addresses
- Find smallest hole that accommodates req size
- Partition size increases exponentially
- Faster allocation (vs iterating all holes)

Buddy system

- Free block split into half repeatedly to meet request size
- Merge buddy blocks when both free
- Efficient partition splitting and dealloc
- Locate good match for holes

Allocation algorithm

- Free block split half repeatedly to meet req size
- Buddy block pair merge when free

N = req size, 2^K = largest allocable block size
A[J] = linked list of free blocks with size 2^J

1. Find smallest s such that $2^s \geq N$
2. Access A[S] for free block
   (a) Free block exists
   - Remove block from free block list

   (b) Find smallest R from S+1 - K such that A[R] has a free block B
   (c) Split B and restart from step 2

Deallocation algorithm

1. Check if buddy (sizeof=2^S) is free in A[S]
   (a) If buddy is free
   - Remove both blocks from list
   - Add merged block, B' to A[S+1]
   - Repeat steps for B'

2 blocks B and C of size 2^S are buddies if

- Right S bits (0..S-1) of B and C are identical
- S+1th bit of B and C is different

10. Disjoint memory schemes

- Processes informations can be split into disjoint physical memory chunks

Paging scheme

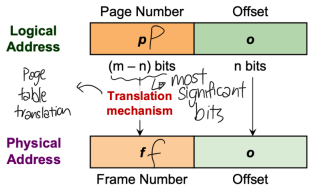
- **Physical frames** - Phy mem split into regions of fixed size
- Frames sizes are decided by hardware
  – Reduce number of access to memory
  – Dedicated component to support paging by speeding address translation
- **Logical page** - Logical mem split into regions of same size
- Pages of process loaded into any available mem frame at execution time
- Logical mem remains contiguous

Page table - Lookup mechanism

- Map logical pages to physical frames
- Frame sizes should be power of 2

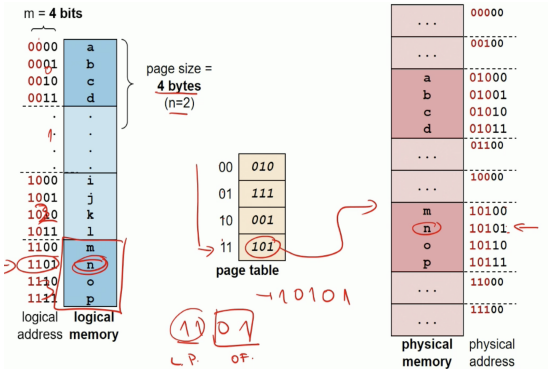
Translation

PA = **F x sizeof(physical_frame) + offset**



Benefits

- No external fragmentation
  – Every single free frame can be used
- Insignificant internal fragmentation
- Separation of logical and physical address
  – Greater flexibility
  – Simple translation



Implementation

1. Pure software solution
2. Page table info in Process Control Block (PCB)
   - 2 mem access per reference
     (a) Read the indexed page table entry to get the frame number
     (b) Access the actual memory item
   - Memory context of process includes page table/pointers to it
3. Hardware support
   - Contain **Translation Look-aside Buffer** - Specialized on-chip component to cache page table entries
   - Use page numbers to search TLB associatively
   - Possible to have multiple TLB per core
     TLB-hit Frame number retrieved to generate physical address
     TLB-miss Memory access to page table → frame number used to generate physical address and update TLB
   - Very small and fast (reducing Average Memory Access Time)
     – AMAT = $P(TLB\ hit) * latency(TLB\ hit) + P(TLB\ miss) * latency(TLB\ miss)$
     – Latency of filling in TLB hidden by hardware
   - Part of hardware context, so entries will be flushed when context switch occurs
     – Save pointer to prev process' page table in PCB
     – Ensure process does not get incorrect translation

Protection

- Access-right bits
  – Enforce protection like read, write execute permissions
  – Memory access checked against access-right bits in hardware
- Valid Bit
  – Exclude pages that are out-of-range for particular process from mapping
  – Check against bits in hardware whether the page can be accessed by process

Page sharing

- Several processes' logical pages mapped to same physical frame
  – Used in shared code pages - code used by many processes
  – Implementing copy on write - pages shared until child changes its value

Segmentation scheme

Motivation

- Process contains different types of memory regions (data, text, heap, stack)
  – Order of memory regions does not matter
- Regions are variable sized and grow/shrink at execution time
  – Gaps btw regions shld be provisioned early
  – Difficult to check the permissions of memory access (which range it is)

Implementation

- Process broken into named segments of variable sizes
- Manage memory at level of memory segments
- Segments itself are mapped to contiguous physical partitions
  – base address and limit (range of segment)
- Logical address <SegID/name, Offset>
  – SegID used to find <Base add, Limit> in segment table

Evaluation (Pros and Cons)

+ Independent contiguous memory space matches programmers view of memory
+ More efficient bookkeeping
+ Segments can grow/shrink and be protected/shared independently
- Cause external fragmentation due to variable sized contiguous memory regions

Segmentation with paging

- Each segment contains fixed sized pages with its own page table
- Segment grows by allocating new page and adding to its page table

11. Virtual Memory Management

Motivation

- Logical memory space may be >> than phy mem
- Not portable to different phy memory sizes

Extension of paging scheme

- Split logical address space into fixed size pages
  – May reside in phy mem or secondary storage
- 2 new page types to denote phy location of information
  Memory resident Pages in phy memory
  Non-memory resident Pages in secondary mem
  Resident bits - Used to denote whether resident in mem
- **Page fault** - CPU access non-memory resident page
  – CPU can only access mem resident pages
  – OS needs to bring pages from secondary storage to phy mem

Execution

1. Check page table if page is mem resident
   + Access phy mem loc directly
   - Throw page fault **exception**
2. Locate page in secondary memory
3. Load page into phy memory
4. Update page table
5. Re-execute step 1 with mem-resident page

Page Fault

- Page transfer is I/O operation done by DMA controller
  - Direct Access Media - abstract I/O from CPU
- Faulted process is in **blocked** state
- **Thrashing** - System slow down due to multiple page faults

Locality

Temporal Mem address likely used multiple times

Spatial Adjacent mem address likely accessed soon

Paging scheme

Objectives

- Reduce startup cost when allocating pages during initialization
- Reduce footprint of processes in phy mem

Demand Paging

- Only allocate mem resident pages when page fault
- Processes start with no mem resident pages

\+ Fast startup time and small mem footprint

\- Sluggish proc initially due to multiple page faults

\- Thrash other processes during page fault

Page table structure

Consideration

- Large logical and phy mem space $\rightarrow$ Large page size
- Every proc needs a page table
- Minimize page table size
  - High overhead
  - Page table may occupy several frames (Difficult to keep track locations)

2-level paging

- Split page table into regions with page table num
- Regions allocated when mem usage grows
- Page directory keep track of smaller page tables

Problems

- 2 serialized memory access to get frame number
  - MMU cache frequent page directory entries
  - Speed up page-table walk upon TLB miss
  - Usual: log$\rightarrow$page directory$\rightarrow$page table$\rightarrow$phy frame
  - MMU: log page$\rightarrow$page-table$\rightarrow$phy frame
  - TLB: log page$\rightarrow$phy frame

Inverted Page Table

- Map physical frames to <pid, page number>
- Upper bound on table size (limited to num phy frames)
- One table for all processes but slow translation
  - Need search whole table to find the phy frame that has the specific page

Page Replacement Algorithms

- Deciding the phy memory frame to *evict* during page fault
- $T_{mem\ access} = (1-p)T_{mem} + p * T_{page\ fault}$
  - p = probability page fault, T_mem = access time for mem resident page

Optimal Page Replacement

- Replace page that will not be needed again for longest period of time

\- Impossible to know future memory references

FIFO Page Replacement

- Evict oldest loaded memory page
- Maintain queue of resident page numbers and update queue during page faults
- **Belady's Anomaly** - More physical frames the higher likelihood of page faults
  - FIFO does not exploit temporal locality (commonly used frames evicted)

Least Recently Used (LRU)

- Replace page that has not been used in the longest time
- OS keeps track of last access time
- Logical Time counter incremented for every mem reference
  - Page table entry has a time-of-use field which increases when referenced
  - Replace pages that have the smallest TOU
  - O(n) operation and overflow possible (TOU strictly increasing)
- Maintain stack of page numbers
  - Page removed from stack and pushed to top when referenced
  - Replace page at bottom of stack during replacement
  - Hard to implement in hardware (entries removed randomly)
- Second-Change Page Replacement
  - Modified circular FIFO to give second chance to pages accessed
  - Every PTE maintains **Reference bit** - 1= accessed since last reset

    1. Oldest FIFO page is selected
    2. If ref bit == 0: page replaced, else..
    3. Page is skipped
       - Ref bit cleared to 0
       - **NOTE!!** Page does not refresh its position in queue
       - Next FIFO page selected/given chance

Page Replacement

Victim page Page that will be replaced

Global Victim page chosen among all physical frames

- **Self adjustment** - Processes that need more frames can get more
- Badly behaved processes affect others
- Non-deterministic number of frames allocated to processes during each run

Local Victim page chosen from pages of process that caused page fault

- More stable - number of frames allocated to each process remain constant
- Frame allocation matters - progress of process may be hindered

Frame Allocation

- How to distribute N physical memory frames among M processes

Approach

Equal Every process gets equal num frames N/M

Proportional Each process, P gets $\frac{size_p}{size_{total}} * N$

Problems

- Difficulty in finding right number of frames to prevent thrashing
- **Cascading thrashing** - Process steals page alloc from other proc
- I/O bandwidth costly and may degrade performance

Working Set Model

- **Working set** - Set of pages referenced by process during a period of time
- Working set may changes continuously but is relatively constant
- Model aims to find a good window to reduce possibility of page faults
- $W(t, \triangle)$ = pages in interval at time t, $\triangle$ = window size
- **Transient region** - Working set continuously changing in size
- **Stable region** - Working set stays the same for a long time

12. File System

Introduction

Motivation

- Volatile physical memory so external storage needed for longer term storage
- Storage media is not portable
  - Dependent on hardware specification and organisation

Services

- Provides abstraction on top of physical media
- High level resource management scheme
- Protection between processes and users
- Sharing between processes and users

Objectives

Self-contained Information stored on media is enough to describe organisation (plug and play)

- System knows how to read and write information on the storage system automatically

Persistent Retain and be retrieved beyond the lifetime of OS and processes

Efficient Good management of free and used space while having low overhead for bookkeeping information

Memory vs File System management

	Memory Management	File System Management
Underlying Storage	Ram	Disk
Access speed	Constant	Variable Disk I/O time
Unit of addressing	Phy mem address	Disk sector
Usage	Address space for process, Implict when process runs	Non-volatile data,Explicit access
Organization	Paging/Segmentation determined by OS and hardware	Different FS:ext(Linux), FAT(windows), HFS(mac)

File

Objective

- Abstraction for logical unit of information by processes
- Contains information structured in specific styles

Metadata

- Additional information associated with the file

Name Human readable reference to the file

- Consistent naming rule
- Case sensitivity, length of name, allowed symbols
- File extension (sometimes used to indicate file type)

Identifier Unique id for the file used internally by FS

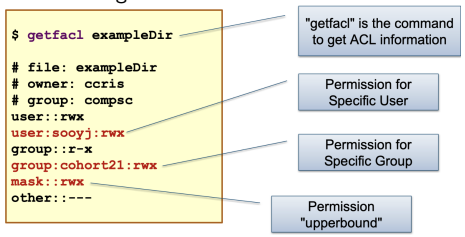
Type eg. directory, text, object, executable

- May have a predefined internal structure that must be processed by specific program (jar, pdf)
- Distinguishing Type is OS dependent (some use file extensions and some **magic numbers** - Embedded info in the file stored at the beginning)

Size

Protection Classified under reading writing and execution rights for owner, group, and everyone

- Types of access: Read, write, execute, append, delete, list (read metadata of file)
- **access control list** - List of user identity and allowed access types (very customisable but too much overhead)
  - Command: getfacl



- **permission bits** - Classify users into 3 classes (owner, group and all) and define permissions RWX for the classes

Time, date and owner info

Table of content Info for the FS on how to access the file

Types of file structures

- Array of bytes (every byte is addressed by a specific offset from the file start)
- Fixed length record
  - Array of records that grows and shrinks dynamically
  - Can jump to Nth offset of M record
  - Prone to internal fragmentation due to fixed size records
- Variable length records
  - Flexible size and saves space but harder to locate record
  - Incurs some overhead and external fragmentation

Access methods

Sequential Data read in order and cannot be skipped

Random access Read bytes in any order

- Can be read to specific (absolute) offset
- Seek to relative offset from current pointer location (used by unix and windows)

Direct access Random access to any record directly (Fixed length records

Operations

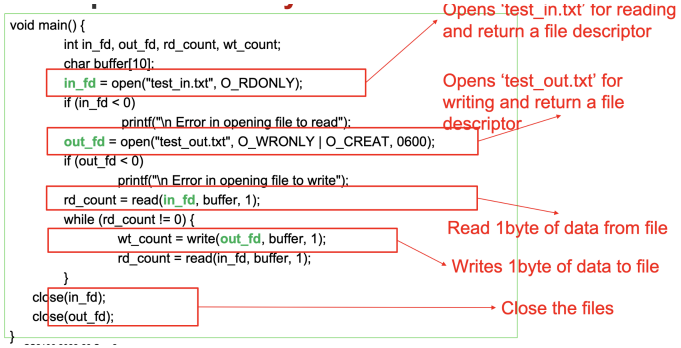
Create, read, write

Open Performed before any operation to prepare necessary info for file operations

Repositioning/Seek Move current position to new location

Truncate Removes data from specified position to end of file

- Done as system calls to OS for protection, concurrent efficient access
- Commands: 'open' 'read' 'write' 'lseek' 'close'



Implementation in OS

Information

File pointer Keeps track of current position within a file

File descriptor Unique identifier of file (int) Used internally in software rather than the name

Disk location Actual file location on disk

Open count/reference count How many process opened this file

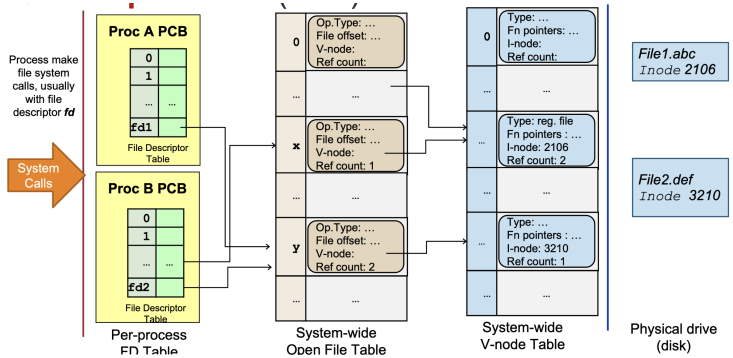
Criteria

- Multiple processes can open same file
- Multiple files can be opened concurrently

Approach

Using 3 tables to store information

1. Per-process open-file table
   - Keep track of open files for each process
   - Every entry points to system-wide open-file table entry
2. System-wide open-file table
   - Keep track of all open files in system
   - Each entry points to V-node entry
3. V-node table (virtual node)
   - Link with file on physical drive
   - Contains info about physical location of file on storage



Directory

Motivation

- Provides logical grouping of file
- Keep track of files (system usage of directory)

Structure

- Single level
  - All files in one directory (CD etc)
- Tree structure
  - Recursively embedded in other directory
  - Addressed by absolute or relative pathnames from curr working dir
- DAG
  - File can be shared using hard links (dir not allowed)
  - Shared file appearing in multiple directory referring to the same content using pointers
  - Low overhead (only pointers added) but deletion problems (synchronisation)
  - Hard link "ln" command (dir not allowed)
- General graph
  - Undesirable structure - hard to traverse (cycles)
  - Hard to determine when to remove file
  - Implementation via symbolic links (dir allowed)
  - Sym link is a special link file that contains the path name of file F - find out where F is and access it
  - Deletion is easy as only the special link file is deleted OR dangling link created (link without file)
  - Larger overhead as special link file is taking up actual disk space
  - Command: ln -s (cat and vim acts on the target file)

File system implementation

- Stored as 1-D logical blocks mapped into disk sector organised with unique ID
- Storage contains Master Boot Record (MBR) and ≥ 1 partitions

MBR

1. **Simple boot code** - Defines the partition to be initialised first
2. **Partition table** - Starting and ending address of each partition

Partitions

Partitions can contain independent file systems and OS

OS boot block All information needed to boot OS from the partition into memory

Partition details Metadata of partition, loc and num blocks used/free etc

Directory structure, files info and file data

13. File System Implementation

Objectives

- Keep track of logical blocks
- Allow efficient access and utilise disk space effectively

Allocation Policies

Contiguous

- Allocate consecutive disk blocks to a file
- Simple to keep track and fast (only need to keep track of the first block)
- External fragmentation because file size must be specified in advance

Linked list of disk blocks

- Stores pointer to the next disk block number and actual file data
- Need to keep track of the first and last disk block number
- Solves fragmentation but random access of file is very slow
- Overhead with storing next block number
- Less reliable (if one of the pointer breaks, all break)

File Allocation Table (FAT)

- All "next block" pointers stored in a single table rather than at each data block
- Table always in memory so simple and efficient (faster random access)
- Keeps track of all disk blocks in partition which may waste a lot of memory (valuable)

Indexed allocation

- Each block has index block
- Index block records pointers (and index) of blocks in file
- Lower memory overhead (only index block of opened file needs to be in memory)
- Faster direct access
- Have maximum file size (limited by number of indexes in index block)
- Index block overhead (waste one block for indexing)

Modified Index Allocation

Linked scheme Linked list of index nodes (normal)

Multilevel index Hierachial linked list (entries point to another linked list of nodes..)

Combined Direct and multi-level index schemes

- Fast access for small files and accomodates larger files

Partition Details

Free Space Management

- Maintain free space info (where and how much, remove/add when file created/deleted)
- **Bitmap** - Disk block represented by bits (1 if free)
  - Mem overhead - complete data structure has to be kept in memory
- **Linked List** - Each disk block contains some free disk blocks/pointer to next free space
  - Easy to locate free block and only one pointer needed in memory
  - BUT high overhead

Directory Info

Objectives

- Keep track of files in directory and metadata
- Map file name to file information
  - Locate the file information using pathname and file name to open for use
  - Parse the full path name by recursively searching directories along path

Linear List

- Each entry represents a file incl name + other metadata + file info/pointer to file info
- Locating file requires a linear search
  - Inefficient for large directories requiring deep tree traversals
  - Latest searches can be cached to improve latency

Hash tables

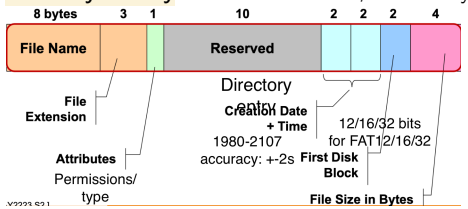
- Every directory contains hash table indexed by filename (with chained collision resolution)
- Fast lookup but may be limited in size and dependent on hash functions (to reduce collisions)

FAT

- Used by Microsoft
- File data allocated to blocks with allocation info kept as linked list
- Data block pointers in File Allocation Table with block info (free/next occupied block/EOF/unusable)
- OS cache table in Ram to facilitate linked list traversal
- Each partition contains the boot, FAT, root directory and multiple data blocks

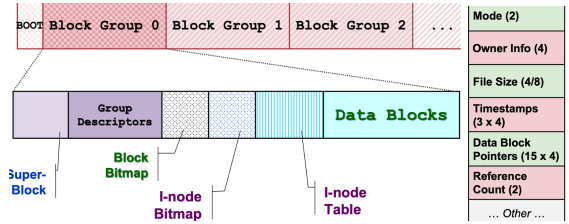
Directory Structure

- Special file with linear list of directory entries
- **Directory entry** - Fixed-size, 32 bytes for file/dir info



Extended-2 FS (Ext2)

- Split into blocks (corresponding to 1 or more disk sectors) and grouped into Block Groups
- **I-Node** - Special structure describing each file/directory
  - Contains file metadata (access right, creation time etc) and data block add
- **Superblock** - Describes whole FS including total num I-Node, I-Nodes per grp, total disk blocks + num in grps
- **Group descriptors** - Describes block grp: num free blocks, num free I-Nodes, bitmap locations
  - Superblock and descriptors duplicated in each block group for redundancy
- **Block/I-Node Bitmap** - Keep track usage status free(0)/occupied(1)
- **I-Node Table** - Array of I-nodes in particular block group accessible by unique index



I-Node Data Block Pointers (15)

Direct Block 1st 12 pointers to actual data

Single Indirect block 13th pointer to a disk block containing some direct pointers

Double Indirect Block 14th pointer to disk block with number of single indirect blocks

Triple Indirect Block 15th pointer to block containing double indirect blocks

Directory Structure

- Data block of directory store linked list of directory entry
- **Directory entry** - Variable sized to store file/subdirectory info
  - I-Node number for file
  - Size of this directory entry (to find next directory entry)
  - Length of file/subdirectory name
  - Type of file/subdirectory
  - File/subdirectory name (up to 255 chars)

Open

1. Process P opens file /.../.../F which is located
   - Split by "dir/" - If dir, locate directory entry in CurDir
   - Retrieve I-Node number, read actual I-Node and continue from NewDir
   - Else directly retrieve I-Node number and read actual I-Node
2. File info loaded into entry *F* in sys-wide table and *V* in I-Node table
3. Create entry in P table to point to *E* (file descriptor) and pointer from E to *V*
4. Return file descriptor to caller

Deletion

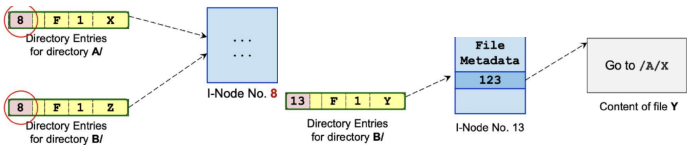
1. Remove its directory entry from parent directory
   - Point prev entry to next entry/end
   - Blank record may be needed
2. Mark specific I-Node in bitmap as free
3. Mark corresponding block in bitmap as free

Hard link

- New directory entry using same I-Node number as file
- Filename can be different

Multiple references of I-Node Hard to determine when to delete I-Node

- Maintain I-Node reference count
- Decrement for every deletion



Sym Link

- File created with I-Node pointing to memory location of symlink
- Content of symlink == pathname of file

Only pathname stored Link easily invalidated (during file name changes/deletion)