

Operating Systems Principles

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1 L3: Arpaci-Dusseau Chapter 5: Interlude: Process API

1.1 The fork() System Call

- Crux: How to create and control processes
- fork()
 - Creates new process; returns child's PID to parent; returns 0 to child;
 - Each has own PC, registers, address space
- Nondeterministic Behavior
 - Scheduler will decide which process to run
 - May lead to problems in multi-threaded programs

1.2 The wait() System Call

- wait()
 - Parent calls wait() to wait for child to finish execution

1.3 The exec() System Call

- exec()
 - Loads code, overwrites code segment, and reinitializes memory space
 - Takes executable name and arguments
 - Does not create a new process; transform current process

1.4 Why? Motivating The API

- Separation
 - Separating fork() and exec() allows code to alter the environment of the about-to-run program
- Example
 - Shell forks a process, execs the program, and waits until finished
 - The separation allows for things such as output to be redirected (closes stdout and opens file)

1.5 Other Parts Of The API

- kill()
 - System call sends signal to process to sleep, die, etc

2 L3: Arpaci-Dusseau Chapter 6: Mechanism: Limited Direct Execution

2.1 Basic Technique: Limited Direct Execution

- Crux: How to efficiently virtualize CPU with control
- Limited Direct Execution
 - OS will create entry for process list, allocate memory for program, load program into memory, setup stack with argc/v, clear registers, execute call to main()
 - Program will run main(), execute return
 - OS will free memory, remove from process list
- LDE good bc fast, but
 - Problem of keeping control
 - Problem of time sharing still

2.2 Problem 1: Restricted Operations

- User mode vs. Kernel mode
 - Restricted mode which needs to ask kernel to perform system calls
 - Calls like open() are actually procedure calls with trap to enter kernel and raise privilege
 - Return-from-trap is used to enter user mode from kernel and drop privilege
 - Push counters, flags, registers onto per-process kernel stack when trapping
- Trap table is used to control what code is executed when trapping
 - Trap handler used by hardware to cause interrupts
 - Telling hardware where trap table is is privileged
 - Trap handler actually uses system-call number, rather than specifying an address (another layer of protection)
- Two phases of LDE
 - At boot, kernel initializes trap table and remembers where it is

OS @ boot (kernel mode)	Hardware
initialize trap table	remember addresses of... syscall handler timer handler
start interrupt timer	start timer interrupt CPU in X ms

2.3 Problem 2: Switching Between Processes

- How can OS regain control?
 - Because process is running, so OS is not running
- Cooperative Approach
 - System calls include explicit yield system call, transferring control back to OS
- Noncooperative Approach
 - Reboot, Timer Interrupt
- Saving and Restoring Context
 - Scheduler will choose when to switch processes

OS @ run (kernel mode)	Hardware	Program (user mode)
		Process A
		...
	timer interrupt save regs(A) to k-stack(A) move to kernel mode jump to trap handler	
Handle the trap Call <code>switch()</code> routine save regs(A) to <code>proc-struct(A)</code> restore regs(B) from <code>proc-struct(B)</code> switch to k-stack(B) return-from-trap (into B)		
	restore regs(B) from k-stack(B) move to user mode jump to B's PC	
		Process B
		...

2.4 Worried About Concurrency?

- Interrupt during interrupt?
 - Many complex things to do
 - Could disable interrupts (but this might lose interrupts), or locking schemes, etc

2.5 Summary

- Reboot
 - Good technique because restores system to well-tested state
 - OS will 'baby-proof' by only allowing processes to run in restricted mode and with interrupt handlers

3 L3: Linking and Libraries: Object Modules, Linkage Editing, Libraries

3.1 Introduction

- Process as fundamental; as executing instance of program
 - Program as one or more files (these are not the executables though)
 - Source must be translated

3.2 The Software Generation Tool Chain

- Source module
 - Editable text in some language like C
- Relocatable object module
 - Sets of compiled instructions; incomplete programs
- Library
 - Collection of object modules
- Load module
 - Complete programs ready to be loaded into memory
- Compiler
 - Parse source modules; usually generates assembly, may generate pseudo-machine
- Assembler
 - Object module with mostly machine code
 - Memory addresses of functions, variables may not be filled in
- Linkage Editor
 - Find all required object modules and resolve all references
- Program Loader
 - Examines load module, creates virtual space, reads instructions, initializes data values
 - Find and map additional shared libraries

3.3 Object Modules

- Code in multiple files
 - Because more understandable if splitting functionality
 - Many functions are reused, so use external libraries
- Relocatable object modules are program fragments
 - Incomplete because make references to code in other modules
 - Even the references to other code are only relative
- ELF format
 - Header section with types, sizes, and location of other sections
 - Code and data section to be loaded contiguously
 - Symbol table of external symbols
 - Relocation entries describing location of field, width/type of field, symbol table entry

3.4 Libraries

- Reusable, standard functions in libraries
 - Libraries not always orthogonal and independent
- Build program by combining object modules and resolving external references

3.5 Linkage Editing

- Resolution
 - Search libraries to find object modules to resolve external references
- Loading
 - Lay text and data in single virtual address space
- Relocation
 - Ensure references correctly reflect chosen address

3.6 Load Modules

- Load module requires no relocation and is complete
- When loading new module
 - Determine required text and data sizes and locations, allocate segments, read contents, create a stack segment with pointer
- Load module has symbol table to help determine where exceptions occurred

3.7 Static vs. Shared Libraries

- Static Linking
 - Many copies, so inefficient; also, permanent copy, so don't receive updates
- Shared Libraries
 - Implementations vary, but one way
 - Reserve address for libraries, linkage edit, map with redirection table, etc, more mapping
 - Efficient, but doesn't work for static data because one copy
 - But can be slow to load many libraries, and must know library name at loadtime

3.8 Dynamically Loaded Libraries

- DLL loaded once needed
 - Choose and load library, binds, use library, unload
 - Resource efficient because can unload
- Implicitly Loaded Dynamically Loadable Libraries
 - Another implementation of DLL with different pros/cons

4 L3: Linkage Conventions: Stack Frames and Linkage Conventions

4.1 Introduction

- What is the state of computation and how can it be saved?
- What is the mechanism of requesting and receiving services?

4.2 The Stack Model of Programming Languages

- Procedure-local variables
 - Stored on a LIFO stack
 - New call frames pushed onto stack when procedure called; old frames popped when procedure returns
 - Long-lived resources on heap, not stack

4.3 Subroutine Linkage Conventions

- X86 Subroutine Linkage
 - Pass parameters to be called by routine
 - Save return address and transfer control to entry
 - Save content of non-volatile registers
 - Allocate space for local variables
- X86 Return Process
 - Return value to where routine expects it
 - Pop local storage
 - Restore registers
 - Subroutine transfer control to return address
- Responsibilities split between caller and callee
- Saving and restoring state of procedure is mostly a matter of stack frame and registers

4.4 Traps and Interrupts

- Procedure call vs Trap/Interrupt
 - Procedure requested by running software and expects result; linkage conventions under software control
 - After trap/interrupt, should restore state
- How
 - Number associated with every interrupt/exception, maps to PS/PC
 - Push new program counter and program status (from interrupt/trap vector table) onto CPU stack
 - Resume execution at new PC
 - First level handler
 - Save general registers on stack
 - Choose second level handler based on info from interrupt/trap
 - Second level handler (procedure call)
 - Deal with interrupt/exception
 - Return to first level handler
 - Restore saved registers and return-from-interrupt/trap
 - CPU reloads PC/PS and resumes execution
- Stacking/unstacking interrupt/trap is 100x+ slower than procedure call

5 L4: Arpaci-Dusseau Chapter 7: Scheduling: Introduction

5.1 Workload Assumptions

- Workload as the processes running in the system
- Fully-operational scheduling discipline
 - Assume each job runs for same amount of time, arrives at same time, once started will run to completion, only uses CPU, run-time length is known

5.2 Scheduling Metrics

- Scheduling metric is something we can measure is useful for scheduling
 - $Turnaround_{time} : Time_{completion} - Time_{arrival}$
- Performance and Fairness often at odds with each other
 - Fairness measured by Jain's Fairness Index

5.3 First In, First Out (FIFO)

- Properties of FIFO
 - Simple and easy to implement while working well based on assumptions
- Convoy Effect
 - FIFO fails if few high-resource consumers are ahead of low-resource consumers

5.4 Shortest Job First (SJF)

- SJF is optimal given the assumptions
 - But fails if relaxes arrival-time assumption
 - A long process may start, then a short process comes in

5.5 Shortest Time-to-Completion First (STCF)

- Preemptive schedulers will context switch to run another process
 - Non-preemptive schedulers run jobs to completion before considering another
 - SJF is nonpreemptive
- Shortest time-to-completion (STCF) also known as Preemptive shortest job first (PSJF)
 - Anytime a new job arrives, determine which job has shortest time remaining, and runs that one

5.6 A New Metric: Response Time

- $T_{response} : T_{firstrun} - T_{arrival}$
- STCF is especially bad for optimizing response time

5.7 Round Robin

- RR (time-slicing) runs job for a time slice (scheduling quantum) before switching to next
 - Length of time slice is essential; if long, then long $T_{response}$; if short, context switching dominates
 - Must choose a length of time which will amortize the cost well
 - Also must consider cost of flushing CPU caches, TLBs, branch predictors, chip hardware
- Performs extremely poorly wrt turnaround time
 - Most fair policies (evenly distribute) are like this

5.8 Incorporating I/O

- Overlap leads to higher utilization and better performance
 - Use for IO, messages, etc
- Overlap CPU when one process requires IO
 - While IO for process A, run process B on CPU (because A is blocked)

5.9 No More Oracle/Summary

- Assumption of known run-time length is highly invalid
- Shortest job remaining optimizes turnaround time
- Alternating between jobs optimizes response time
- Looking ahead
 - Multi-level feedback: Using past events to predict future

6 L4: Arpaci-Dusseau Chapter 8: Scheduling: The Multi-Level Feedback Queue

6.1 MLFQ: Basic Rules

- MFLQ has a number of distinct queues with different priority levels
- If $\text{priority}(A) < \text{priority}(B)$, A runs
- If $\text{priority}(A) == \text{priority}(B)$, A and B run in RR
- Vary priority based on observed behavior

6.2 Attempt 1: How To Change Priority

- When job enters, has highest priority
- If job uses entire time slice, priority is reduced
- If job gives up CPU early, priority remains the same
- Assume jobs are short so that it will either complete or move down in priority
- Starvation
 - If there are too many interactive (IO) jobs, then longer processes with low priority will never run
- Gaming the scheduler
 - Could write program to use less than entire timeslice, to always keep highest priority
- Changing Behavior
 - Program may become interactive after computations, so needs higher priority

6.3 Attempt 2: The Priority Boost

- Boost all processes to top priority after a certain time length
- Difficult to know correct value for these voo-doo constant parameters (refer to Ousterhouts Law)

6.4 Attempt 3: Better Accounting

- Account CPU time (Anti-gaming method)
 - Once job uses up time allotment on given level, priority is reduced

6.5 Tuning MLFQ And Other Issues

- Difficult to find correct parameters
 - High-priority queue contains interactive processes and run for short timeslices (20ms)
 - Low-priority queue contains long-running processes and so run for longer timeslices (up to a few hundred ms)
 - Many queues, like 60

- Priorities boosted every second or so
- Other schedulers use mathematical formulas to calculate priority (decay-usage)
- Even may offer advice to scheduler using Linux's nice program

6.6 MLFQ: Summary

- Multiple levels of queues with feedback to determine priority
- Rules
 - If $\text{priority}(A) > \text{priority}(B)$, A runs
 - If $\text{priority}(A) = \text{priority}(B)$, A and B run in RR
 - When a job enters the system, has highest priority
 - When a job uses entire time allotment at a given level, its priority is reduced
 - After some time period S, move all the jobs in the system to the topmost queue

7 L4: Real Time Scheduling

7.1 What are Real-Time Systems

- Priority scheduling is best effort
 - Sometimes need more than just best effort (space shuttle reentry, data, assembly line, media players)
- Traditional vs Real-time systems
 - Turn-around time, fairness, response time for traditional
 - Timeliness may be ms/day of accumulated tardiness
 - Predictability is deviation in delivered timeliness
 - Feasibility is whether possible to meet requirements
 - Hard real-time is a requirement to run specify tasks at specified intervals
 - Soft real-time requires good response time, at the cost of degraded performance or recoverable failure
- Real-time systems
 - May know length of jobs/priorities, and starvation of certain jobs may be acceptable

7.2 Real-Time Scheduling Algorithms

- Static scheduling
 - May be possible to define fixed schedule if know all tasks to run and expected completion time
- Dynamic Scheduling for changing workloads
 - Questions of how to choose next task and how to deal with overload
- If high enough frequency of work, may just work for sufficiently-light loaded systems

7.3 Real-Time and Linux

- Linux was not designed as embedded or real-time system
 - Supports a real-time scheduler `sched_setscheduler`, but still does not have same level of response-times
- Windows believes in general throughput not deadlines, and is bad for critical real-time operations

8 L5: Arpaci-Dusseau Chapter 12: A Dialogue on Memory Virtualization

8.1 Overview

- Every address generated by a user program is a virtual address
 - Large contiguous address space is easier to work with than small crowded space
 - Isolation and protection are also important in preventing processes each other's memory

9 L5: Arpaci-Dusseau Chapter 13: The Abstraction: Address Spaces

9.1 Early Systems

- OS as set of routines (a library)
- Program in physical memory used rest of space

9.2 Multiprogramming and Time Sharing

- Multiprogramming
 - Multiple processes ready to run at a given time with OS switching between them
 - Increases utilization of CPU; increased efficiency of CPU is very relevant bc so expensive
- Timesharing and interactivity
 - Long program-debug cycles bad for programmers
 - Giving all programs full access to memory is not safe

9.3 The Address Space

- Address space is easy to use abstraction of physical memory
 - Contains code, stack, heap
 - Every program thinks it had very large address space, even though it doesn't

9.4 Goals

- Transparency
 - Cannot tell that memory is virtual
- Efficiency
 - OS should make virtualization efficient wrt time and space, relying on hardware for this
- Protection
 - Isolate process memory from each other

10 L5: Arpaci-Dusseau Chapter 14: Interlude: Memory API

10.1 Types of Memory

- Stack
 - Automatic memory is managed implicitly by compiler
- Heap
 - Long lived memory where allocations and deallocations handled by programmer

10.2 The malloc()/free() Call

- `double *d = (double *) malloc(sizeof(double));`
- `free(d);` // prevents memory leaks

10.3 Common Errors

- Modern languages have automatic memory-management or a garbage collector because people don't free
- Seg fault if you forget to allocate
- Buffer overflow if not enough allocated space
- Dangling pointer if you free memory before finished using it
- Double freeing memory is undefined
- Incorrect use of free (passing it things other than pointer from malloc) is dangerous
- Use Valgrind and Purify to find memory leaks

10.4 Underlying OS Support

- Break is the location at the end of the heap
 - System call brk is used to increase/decrease size of heap

11 L5: Arpaci-Dusseau Chapter 17: Free-Space Management

11.1 Assumptions

- Free list manages the heap; contains references to all the free chunks in the region
- External fragmentation
 - Have enough space, but not contiguous, so can't malloc
- Internal fragmentation
 - Gives memory larger than requested, which remains unused

11.2 Low-level Mechanisms

- Splitting and Coalescing
 - Split free chunk in two, returning first to the caller
 - Coalesces adjacent free memory together, forming a single larger free chunk
- Header of allocated memory
 - Contains size of region and magic number to speed up deallocation
- Embedding free list
 - Build free list inside the free space itself
 - Nodes with size and next pointer
- Growing heap
 - Just give up and return NULL
 - Or call sbrk system call to OS to grow heap

11.3 Basic Strategies

- Best fit
 - Return smallest chunk that is equal or larger than the requested size
 - Requires linear search
- Worst fit
 - Find largest chunk, split it, return requested size
 - Requires linear search
- First fit
 - Returns first block big enough
 - Faster because no exhaustive search
- Next fit
 - Returns first block big enough starting from previous location
 - Spreads searches through free space more uniformly

11.4 Other Approaches

- Segregated Lists
 - Keep separated list to manage all objects of that size
 - Hard to determine much memory to dedicate to that list
- Slab allocator by Jeff Bonwick
 - Object caches for kernel objects
 - Each object cache are segregated free lists
 - Requests slabs of memory from general allocator, when running low
- Binary buddy Allocation
 - Big space of 2^N
 - Suffers from internal fragmentation but can recursively coalesce

12 Garbage Collection and Defragmentation

12.1 Garbage Collection

- Allocated resources are freed through explicit/implicit action by client
 - `close(2)`, `free(3)`, delete operator, returning from a C/C++ subroutin, `exit(2)`
- If shared by multiple concurrent clients
 - Free only if reference count is zero (don't free if others are still using it, just decrement the reference count)
- Garbage Collection
 - Analyzes allocated resources to determine which are still in use
 - Data structures assoc with resource references are designed to be easily enumerated to enable the scan for accessible resources
 - Comes at a performance cost

12.2 Defragmentation

- Shards of free memory are not useful
 - Coalescing is only useful if adjacent memory free at same time
- Defragmentation
 - Changes which resources are still allocated
- Flash management
 - NAND Flash is a pseudo-Write-Once-Read-Many medium
 - Identify large (64MB) block with many 4KB blocks not in use
 - Move all in use blocks and update resource allocation map
 - Erase large block and add 4KB blocks to free list
- Disk Space Allocation
 - Choose region to create contiguous free space
 - For each file in that region, move it elsewhere
 - Coalesce all that free memory
 - Move set of files into that region
 - Repeat until all files and free space is contiguous
- Internal fragmentation is like rust, it never sleeps
 - Defragmentation used to be run periodically, now is run continuously
- Conclusions
 - If using garbage collection, must make all resources discoverable, how to trigger scans, prevent race conditions with application
 - Must not disrupt running applications when using defragmentation

13 L5: Arpaci-Dusseau Chapter 14:

13.1 Overview