COM SCI 111 (Operating Systems Principles)

October 25, 2022

1 9.22 0th

```
$ ls -l big
-rw-r--r-- 1 eggert faculty 9223382036854775000 Sep 22 11:31 big
$ grep x big
$ time grep x big
real 0m0.009s
```

- grep scans at 10^{21} bytes/s (8 Zb/s) searching for an existent line in the file
- so it has to be doing smth other than sequentially searching thru the file
- "grep cheats"
  - "i know it cheats cuz i put the code in it" - eggert 2022
- "i hope you gain the intuition to know when is it ok to cheat and when is it not"
- paul eggert
- https://web.cs.ucla.edu/classes/fall22/cs111
- prereqs: cs32 <- c++, algs, data structurues / cs118 networking 33 <- computer org, machine code, etc. |-> cs111 - . . . 35l <- shell, python, scripting, . . . / . . .
- cs131 programming languages
- cs151b architecture
- textbooks
  - ad os 3ep (2018)
  - sk systems (2009)

1.1 whats a system

- *oxford english dictionary* (1928)
  - i. an organized or connected group of objects
  - ii. a set of principles, etc.; a scheme, method
  - from ancient greek $\sigma\iota\sigma\tau\eta\mu\alpha$(roots, "set up w")
- *principle of computer science design: an introduction* (2009)
  - smth that ops in an env and the boundary betw the 2 is called the interface
    - interface v important
    - system built from a lot of subsystems
    - standard design: decompose big system
    - often time its useful to have multiple views of the same system
      - sometimes we can look at the system from a diff viewpoint and come up w a completely different set of subsystems

1.2 operating system

- *american heritage dictionary* (2000)
  - software designed to control the hardware of a specific data processing system in order to allow users and application programs to make use of it
    - claims os is very system dependent, not true
- *encarta* (2007)
  - master control program in a computer
- *wikipdeia* (2016/8)
  - system software that manages computer, hardware, software resources, and provides common services for computer programs

1.3 goals of an operating system

- protection (of apps, data, . . .)
- performance (from users view)
- utilization (from check-writers view)
- robustness
  - does this operating system do well when given problems out of the ordinary
- flexibility
- simplicity / ease of use
- portability w diff hardware
- scalability
- safety

1.4 what are our main tools?

- abstraction + modularity
  - abstraction: look at the big pic of the system from a particular viewpoint and discard details to understand everything abt that aspect of the system
  - modularity: splitting up a big problem into little problems
    - since the diff in writing a program scales worse than linearly,
  - interface vs implementation
  - mechanisms vs policy
    - policy: high level concept in which u say what u want
      - "i want my interactive processes to have higher priority than background batches"
    - mechanism: how u actually get that stuff to work
- measurements + monitoring
  - measurements: measure how well ur system is working
    - performance + correctness

    - monitoring: monitor measurements, do smth w them

- *operating systems: three easy pieces*: main problems in os
    - virtualization: how to build efficient + effective virtual systems
    - concurrency: interacting, simultaneous tasks
    - persistence: data survive failures in hardware, software
    - more
        - security

1.5 a bad os interface

```
char* readline(int fd);
```

- read a line from `fd`, return pointer to the bytes read
- assumes infinite resources

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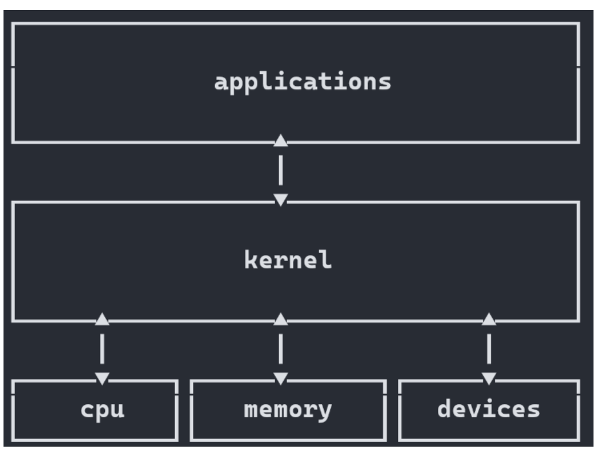
- kernel: lowest level of the os
    - decides what resources are available to apps (thus protecting the system)
    - provides layer of abstraction so that apps dont have to deal w hardware



2.1 kernel modules

- are pieces of code that can be loaded and unloaded into the kernel upon demand
- they extend the functionality of the kernel without the need to reboot the system
- why not just add all the new functionalities into the kernel image
    - would be bloated
    - security implications

- modules are stored in /usr/lib/modeuls/kernel_release
- to see what kernel modules are currently loaded use

```
lsmod
```

```
cat /proc/modules
```

- example

```c
#include <linux/module.h> /* needed by all modules */

#include <linux/kernel.h> /* needed for KERN_INFO */

int init_module(void) {
  printk(KERN_INFO "hello world 1.\n");
  return 0;
}

void cleanup_module(void) {
  printk(KERN_INFO "goodbye world 1.\n");
}
```

- printk
  - was not meant to communicate info to user
- to load a module: sudo insmod <module_name> [args]

```
sudo insmod proc_count.ko
```

- to unload a module: sudo rmmod <module_name>

```
sudo rmmod proc_count
```

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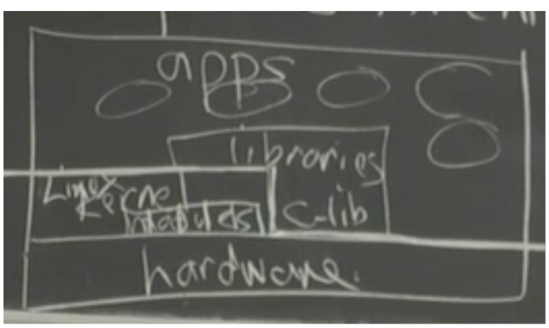
3.1 simple os architecture



- user mode code: apps, libraries / c-lib
- kernel mode: you can execute instructions here
  - e.g. `inb`
  - kernel-app interface: "imaginary instructions" that are not real
    - x84-64 instructions `ret`: "`rip = *(--rsp)`" in user mode
    - `syscall 35`: "`os[35]()`" in kernel mode
      - `syscalls` cannot be called in user mode, kernel will figure it out

```
char *readline(int fd)
```

- `fd`
  - `0` - `stdin`
  - `1` - `stdout`
  - `2` - `stderr`
  - `>2` - other files
- points to a newly allocated buffer, e.g. `"ab\0xyz\n"`
- problems
  - unbounded cost
  - allocates memory for the application
  - large potential for memory leaks & bad pointers
    - probles with giving the job to kernel
      - force same memory mgmt on all apps
      - syscall overhead

```
ssize_t read(int fd, void *buf, size_t bufsize);
```

- returns `-1` for fail, sets `errno`
- otherwise returns number of bytes read ≤ `bufsize`
- it is now the applications job to figure allocation out, kernel doesnt care
- there is now a limit on read size
- comes at a cost: a program that counts the number of lines in a file becomes more complicated although it has nice properties for the kernel
- waterbed effect: improved in one aspect, worse in another

3.2 problems with designing operating systems

- waterbed effect (tradeoffs): general problem in systems
- incommensurate scaling
  - economies of scale (pin factory)
    - if u just want a few pins then just go to local blacksmith
    - if u want 10mil pins u should create a pin factory
  - diseconomies of scale (star network)
- emergent properties (as u scale)
  - qualitative instead of quantitative changes

- ucla in school network used for music pirating

- propagation of effects
  - 2 features that independently work may not work when combined
  - e.g. msft invented shift-jis to encode japanese characters
    - 2-byte encoding w top bit on = 2^{15} characters
    - other feature: file names `C:\abc\def\ghi.txt`
    - combination doesnt work because 2nd byte of shift-jis character can be anything (could just happen to be `'\'`)
    - fixed by moving into kernel (complicating the os)
- complexity
  - moores law

3.3 app: count words in a file

- power button = count number of words and put it on screen
- historically called a standalone program
  - operates without benefits of an os
- modern desktop: cpu, cam, drive, monitor on bus

3.4 uefi: unified extensible firmware interface

- os-independent way to boot
- efi format for **bootloaders**
  - bootloader: find a program in 2ndary storage, copy it into ram and `jmp` to it
  - can be chained, not uncommon to see 3 or 4 chained bootloaders
    - for portability and stuff
    - each bootloader can be more complicated than the next one until one that knows how to boot linux
- guid: globally unique identifier
  - for partitions
  - 128-bit integer
- guid partion table
- uefi boot manager (in firmware)
  - read only but configurable via parameters in some sort of nvram (nonvolatile ram)
  - can read gpt tables
  - can access files in vfat format etc
  - can run code in efi format
  - 6 phases

3.5 coreboot

- more hardware-specific / lower level
- no large boot manager (but a small one)
- 4 phases
  - test rom (find out where it is) + flash / disk
  - test ram, early initialization of chipset
  - ram stage: init cpu, chipset, motherboard, devices, etc
  - load payload

3.6 intel core i3-9100

- supports an older, simpler way of booting
- 6 mib l3 cache, 3.6 ghz + 4 gib ddr3 sdram + 1 tb flash sata + intel uhd graphics
- sata: serial ata
  - 7-conductor connector
  - ata (pata): advance technology attachment (16-bit connector in parallel)
    - sequentization is the bane of parallel
  - before ata = ide: integrated drive electronics (western digital, 1986)
- x86 boot procedure
  - 1 mib of physical ram cpu can access
    - cpu starts off in real mode = no virtual memory
  - initial program counter `ip` points to rom @ `0xffff0` = $2^{20} - 16$
  - program in rom = bios: basic input output system
    - "horrible misdesign"
    - originally user apps ran in real mode, calling subroutines in bios
      - only protection is rom being read only
    - library + kernel + mini os basically
    - bios tries to do the 4 steps in coreboot
      - run in cache only mode
      - step 4: looks for a device containing a particular bit pattern in its first 512 bytes (sector) (mbr: master boot record, 446 bytes of x86 machine code, 64 bytes of partition table (list of 4 pieces of drive, takes role of gpt), 2 bytes of signature `0x55 0xaa` or `0xaa55`)
    - bios copies mbr into ram at `0x7c00` then `jmp`s there

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4.1 less modular os

- one happy program
- uses function calls

- count lines in a file only via function calls + machine instructions at lowest level
- last time we got 446 of bytes of machine code into `0x7c00`
- file is in flash drive
- bootloader reads word count program, say 20 sectors (of 512 bytes), into ram, say `0x1000`

```
static void read_ide_sector(long secno, char *addr) {
  while ((inb(0x1f7) & 0xc0) != 0x40) continue;
  outb(0x1f2, 1);              // sector count
  outb(0x1f3, secno);          // sector #...
  outb(0x1f4, secno >> 8);
  outb(0x1f5, secno >> 16);
  outb(0x1f6, secno >> 24);
  outb(0x1f7, 0x20);           // control
  while ((inb(0x1f7) & 0xc0) != 0x40) continue;
  insl(0x1f0, addr, 128);
}

void bootloader(void) {
  for (int i = 1; i <= 20; ++i) {
    read_ide_sector(i, nextprog_addr + (i - 1) * 512);
  }
  nextprog();
}
```

- inb reads from io registers
- `0x1f7`: status + control
- first `while` loop waits for drive to be ready
- `insl`: “insert long”, read 128 words (512 bytes) from `1f0` to `addr`

```
static unsigned char inb(unsigned short port) {
  unsigned char data;
  asm volatile("inb %0, %1" : "=a" (data) : "dN" (port));
  return data;
}
```

4.2 i/o

- programmed i/o (pio): special instructions for io
- memory-mapped i/o: more popular, use ordinary load / store instructions `mov_ _`
- intel: flash drive uses pio, monitor uses memory-mapped

```
void write_integer_to_console(long n) {
  unsigned short *p = (unsigned short*) 0xb8014;
  while (n) {
    *p-- = (7 << 8) | ('0' + n % 10);
    n /= 10;
  }
}
```

- at `0xb8000`, 2 bytes per char, 1st byte being format (7: gray on black), 2nd byte being ascii, 80×25 grid

```
static int isalpha(int x) { return 'a' <= x && x <= 'z' || 'A' <= x && x <= 'Z'; }

void main(void) {
  long words = 0;
  bool in_word = false;
  long secno = 100'000;
  for (;; ++secno) {
    char buf[512];
    read_ide_sector(secno, buf);
    for (int j = 0; j < 512; ++j) {
      if (!buf[j]) {
        write_integer_to_console(words + in_word);
        while (true);
      }
      bool this_alpha = isalpha((unsigned char) buf[j]);
      words += in_word & ~this_alpha;
      in_word = this_alpha;
    }
  }
}
```

- performance issues
  - read 1 sector at a time: change to 255 sectors
  - bus contention (controller ↔ cpu, cpu ↔ ram): dma (direct memory access), controller ↔ ram, cpu sends instruction to controller telling where to copy data to
  - cpu and controller doing work disjointly: double buffering—cpu issues command to read sector $n + 1$ *then* cpu counts words in sector n = overlapping work

5 10.4 2t

5.1 how not to have an os standalone program

- standalone program
  - pro: embedded systems

- con: double buffering api is more complex
- con: multitasking

```
read_ide_sector(...) {
  while (inb(...) & ...) {
    --> schedule(); <--
  }
}
```

- con: dma (direct memory access)
- want separation of concern, guy writing word count program only focuses on counting words
- need better modularity

5.2 what's wrong with fuction call modularity for apps

- too much pain to change implementation
- too much pain to reuse parts of os in other apps
- too much pain to run simultaneous apps
- too much pain to recover from faults
- not enough insulation between apps

5.3 advantages of modularity

- assume bugs $\propto$ (k)loc ((thousand) lines of code)
- assume cost to find & fix a bug $\propto$ kloc
- cost to fix all bugs: $O(\text{kloc}^2)$
  - not accurate: more bugs may appear, bugs appear superlinearly to kloc, bugs get harder to fix, etc
- modular: assume k modules, bugs are isolated $\rightarrow O\left(k \cdot \left(\frac{\text{kloc}}{k}\right)^2\right) = O\left(\frac{\text{kloc}}{k}\right)$

5.4 how can we tell whether our modularization is good or bad?

- performance
  - usually willing to sacrifice, say, 5% to 10%
- robustness: tolerance of faults / failures / errors
  - error: mistake in ur head
  - fault: potential problem in code
  - failure: observable behavior that is wrong
    - e.g. dereferencing a null pointer
- neutrality / flexbility / lack of assumptions
- simplicity (of use / to learn)

5.5 mechanism for modularity

0. no modularity
1. function call modularity (call and return instructions)
   - callee can modify caller's registers
   - callee can loop forever
   - callee can overslow the stack
   - callee can mess w wrong devices
   - callee can execute invalid instruction
   - soft modularity: if callee and caller are both well-behaved / bug-free
   - we want hard modularity: barrier

5.6 3 fundamental system abstractions

1. memory
   - `write(addr, value)`
   - `value = read(addr)`
   - ram, secondary storage
   - issues: thruput, latency, word size, volatility, coherence with caches
2. interpreter
   - `ip` instructor pointer + `ep` environment pointer + repertoire (instruction set)
   - in x86: `rip` and `rsp`
   - above for normal execution
   - interrupts: when normal execution is disturbed
3. link
   - think of 2 modules as different devices, send signals from one to another thru a link

5.7 2 major ways to get hard modularity

1. client / service
   - client and server w a link
   - if client wants work done, send signal thru link and wait
   - client

     ```
     send(factn, {"!", 5});
     receive(factn, response);
     if response.code == ok:
       print(response.val)
     else:
       print("error", response.err)
     ```

   - service

```
for (;;) {
  receive(factn, req);
  if (req.op.code == "!") {
    for (int i = 1; i <= req.n; ++i) {
      a *= i;
    }
    response = { "ok", a };
  } else {
    response = { "bad", 0 };
  }
  send(factn, response);
}
```

- pro: limits error propagation
  - client / server dying doesnt affect the other
- pro: no shared state
- pro: even if service loops forever, client can still make progress
  - timeout on `receive`
- con: more setup hassle (configuration overhead)
- con: more resources (in the simplest case, need 2 cpus)
- con: latency / thruput / reliability (thru network)

2. virtualization
   - using interpreters
   - simplest way: write an x86 emulator

```
int epi, eax;

for (;;) {
  char i = *epi++;
  switch (i) {
    case ...:
      add(eax, ...);
  }
}
```

   - “client” code: interpreted
   - “service” code: functions called by interpreter
   - pro: can put whatever checking code for safety
     - e.g. checking pointers before dereferencing
   - con: performance (2x - 10x)
   - for better speed
     - virtualizable hardware

    - user-mode instructions: `addq`, `call`, `ret`, `jlt`, ...
      - run at full speed in a virtuazlized (hw interpreter) program
    - kernel-mode instructions: `inb`, `outb`, `insl`, `reti`, ...
      - need them to be rare
  - we need **protected transfer of control** for hard modularity via virtualization
  - `int`, `0x80`: interrupt, traps in user mode
    - call kernel w
      - `eax` = syscall number
      - `args 1..n`: `ebx`, `ecx`, `edx`, `esi`, `edi`, `ebp`
    - hw pushes onto kernel stack
      - `ss`: stack segment
      - `esp`: (user) stack pointer
      - `eflags`
      - `cs`: code segment
      - `cip` (code) stack pointer
      - error code: type of trap
    - trap table: goes to code in kernel

6 10.6 2th

6.1 orthogonality

- processes, races
- how you handle files, stream / network io, processes, should not interfere with each other
- api / interfaces should be
  - simple
  - complete
  - composable

6.2 last time

- `INT 0x80` "meta instruction" → pushes onto kernel stack `ip` and `ep`, goes into kernel mode
  - kernel code does the syscall in question
  - `reti` instruction: inverse, pops `ip` and `ep` off the stack into register, gets out of kernel mode
  - `reti` can go to anywhere or run some other process
- seasnet: x86-64
  - user mode does not use `INT` instruction
  - uses `SYSCALL`: uses `INT` but the idea is that it's faster
    - `INT` is slower than a function call
      - pushing 6 words instead of 1
      - have to access ram (kernel stack)

      - make sure cache is right (context switch)
    - attempts to streamline, transfer to kernel mode and left kernel figure out what to use and what to restore
    - `rax` = syscall #
    - args: `rdi`, `rsi`, `rdx`, `r10`, `r8`, `r9`
    - sets `rip`, etc. to model specific registers
  - one way to implement "syscalls"

- `execlp(char const *file, char const *arg0, ...)`
  - thin wrapper around actual syscall

- 2 layers maybe too little protection, too trusting
  - hardware → microkernel (only know memory management, no scheduling etc) → process management → . . .
  - microsoft: ring structure approach
  - traditional intel: 4 levels (0, 1, 2, 3)

- `getpid()`: cheap syscall
  - suffer all the downside of the transition and stuff
  - linux does ↓

- `vdso`: virtual dynamically-linked shared obejct
  - `$ ldd /bin/sh`
  - `libc.so.6` ⇒ `/lib64/libc.so.6` shared object code
    - 1 copy of c lib read only shared
    - more complcated things such as `open()`
  - `linux-vdso.1` ⇒ some address in kernel memory, readonly for users
    - simple "syscalls" such as `getpid()` in here (just a `movl`)

6.3 processes

- built from virtualizable processor + os = program in execution in an isolated domain
  - safety
  - simplicity
- processes need to access
- registers: give cpu 1 process at a time
- process table
- `cr0` points at page table, maps virtual to physical addresses
- access registers (fast)
  - bare hardware
- access primary memory: each process has its own page table
  - (virtualizable hardware)
- access io devices (less common): syscall, devices do differ

- storage: flash, hard drive
  - request / response
  - random access
  - finite
- stream: keyboard, network
  - spontaneous data generation
  - infinite
- graphics: high performance
  - kind of a mix
- need a set of syscall primitives
  - `fd = open("/usr/lib/libc.so", O_WRONLY | O_NOFOLLOW | ..., 0644)`
    - puts a pointer (file descriptor = index) to file in file descriptor table in process table
    - "opaque handle"
  - `close(12)`
  - `read(12, buf, 512)`
    - will return -1, `errno = EBADF` bad file descriptor
    - has an implicit offset, needs to be stored somewhere
      - stored in file description pointed to by file descriptor
      - which then points to actual file
    - `(sed 1q; sed 's/a/b/;) < file`
      - second `sed` should start where first stopped
      - so offset shouldnt live in the `sed` process itself and hence the file description layer between file descriptor and actual file
  - `write(12, buf, 1024)`
  - `n = dup(12)` → `15`
    - same file descriptor
    - by convention, file descriptors 0, 1, 2 are `stdin`, `stdout`, `stderr`
    - `int fd0 = dup(0); close(0); int fd1 = open(...);`
- limitations
  - access is sequential
    - potential fix: have a different flavor of `read` for storage devices taking an extra argument
    - orthogonality → `lseek(12, 192308, 0)` position read / write pointer at 192308 from file start (`lseek(fd, offset, whence)`), whence: 0 = from file start `SEEK_SET`, 1 = from current location `SEEK_CUR`, 2 = from file end `SEEK_END`
    - `lseek read` / `lseek write` hurts performance → `pread` / `pwrite`: positioning read / write

6.4 next lecture

- process primitives
  - `fork()`

7 10.11 3t

7.1 file descriptor trouble

- use a fd thats closed (or never opened)

  ```
  #include <errno>

  write(47, "xy", 2)
  ```

  - returns -1, sets `errno == EBADF`

- closed and reopened

  ```
  int f = open(...);
  if (f < 0) { error; return; }
  read(f);
  somefun(f); // --> close(100); g = open(...);
  write(1, ...);
  ```

- `open`, but resource not available
  - pull flash drive out while running program
  - returns `-1` with some other `errno`

- io error
  - e.g. bad flash drive, hardware problem
  - `errno = EIO`

- end of file (`read` returns `0`)

- `errno`: lots of `if`s
  - exception handling (some other code handles it)
    - distant from code, may not have good diagnosis
    - linux does not do this (lower level)

7.2 process api in posix/linux

- `pid_t fork(void);`
  - `#include <sys/wait.h>`: `typedef int pid_t`
  - returns an integer containing a process id
  - returns `-1` on failure
  - otherwise returns new process id
    - positive integer
  - returns `0` if in child process

- `int execvp(char const *file, char * const *argv);`
- `pid_t waitpid(pid_t p, int *status, int options);`: wait for child process to die and store exit status into an integer in parent, returns `p` if successfully `p` to die, otherwise returns `-1` (e.g. wrong `p`, `p` already dead)

```
pid_t p = fork();
switch (p) {
  case -1: return error();
  case 0:
    alarm(10); // <-- kills process in 10 seconds w error
    execvp("/bin/date", (char*[]) {"date", "-u", NULL});
    return error(); // <-- executed in child process
  default:
    int status;
    if (waitpid(p, &status, 0) < 0) return error(...);
    if (!WIFEXITED(status) || WEXITSTATUS(status) != 0)
      return error(...);
}
```

- date.c:

```
int main(int argc, char **argv) {...}
```

  - replaces currently running code

- `pid_t waitpid(pid_t p, int *status, int options)`
  - can only wait for own children processes
- aside on `restrict`
  - caller not allowed to pass pointers pointing to the same place
- different api (not original)

```
int posix_spawnvp(
  pid_t *restrict pid,
  char const *restrict file,
  posix_spawn_file_actions_t const *restrict acts,
  posix_spawn_attr_t const *restrict attrp,
  char *const *restrict argv,
  char *const *restrict envp
);
```

  - more efficient than `fork exec` (vs orthogonality)
- `_Noreturn void _exit(int status);`
  - `exit()` is library code that does some other cleanup
    - e.g. writes out from `stdout` buffer

  - send message to parent process
  - does not destroy process, `waitpid` destroys process (needs to pick up exit status)

```
#!/bin/sh
exec date -u
```

  - run `date` but dont `fork`, process now runs `date`
  - kinda like bootloader

7.3 how does the os `fork`

- syscall for `fork` in kernel (e.g. process 27)
  - stuff
  - `sysexit(27's info)`
- copy entry in process table (e.g. fd table etc.)
  - except `rax` which stores result of system call
  - pid in `rax` of parent
  - `0` in `rax` of child
- `fork`: child = parent *except* for
  - return value of `fork`
  - pid
  - ppid (parent pid)
  - accumulated execution times
  - file descriptors (file descriptions are shared)
  - file locks (child does not have the lock)
  - pending signals (sent to parent)
- `exec` is opposite: it destroys / replaces program data (stack, heap), registers, signal handlers reset to default

7.4 processes do need to affect each other

- need controlled isolation
- files: simple, straightforward, slow, space, names, hassle
  - race conditions
    - occurs when behavior depends on timing
    - `(cat a & cat b) >outfile`: nondeterministic
    - `(cat >a & cat >b) <infile`
    - sorting a big file and using a temp file to store intermediate results: `int tmpfd = open("/tmp/sorttmp", O_WRONLY | O_CREAT | O_TRUNC, 0600);`
      - somone else might have it
      - wait for other `sort` instance to finish using it
        - still has space where race condition can happen

- toctou race

```
acquire_lock("/tmp");
// begin critical section
if (access(...))
  open(...);
// end critical section
release_lock("/tmp");
```

- `fcntl(fd, F_SETLK / F_SETLKW / F_GETLK / F_UNLOC)` system call
  - *voluntary* locks
  - performance problem:
- `O_EXCL` exclusive flag: fail if file already exists
- include pid in filename
  - everyone needs to cooperate
  - use random number + `O_EXCL` flag
    - work but somewhat unsatisfactory
- `O_TMPFILE` flag: create a file somewhere in directory but dont give it a name
  - `int fd = open("/tmp", O_TMPFILE | O_CREAT | ...);`
  - essentially do `open` and `unlink` atomically

- message-passing
- shared memory: 2 processes not isolated completely, fastest, most dangerous - race conditions
- exit status, signals `kill -HUP 1923`
- covert channels: e.g. cpu load

8 10.13 3th

8.1 breaking application down

- find data → $\boxed{\text{read input}}$ → $\boxed{\text{find words}}$ → $\boxed{\text{count words}}$ → output
- whos in charge
- lazy evaluation
  - minimize total amt of work done
  - `count_words` in charge
- eager evaluation
  - `read_input` in charge
- mixed evaluation
  - all 3 run simultaneously
  - allows for more parallelism
- pipes
  - control execution of multiple processes without any of the processes being in charge

8.2 what a pipe looks like inside the kernel

- buffer of certain size, depending on the kernel, say 4 KiB
- w/in the buffer there are values r / w: read / write pointer
- problems with pipes
  - write to a full pipe
    - consider as an error, return `-1`, set `errno = EAGAIN`
    - process blocks (default)
    - process gets `SIGPIPE` signal
      - if no reader
  - read from an empty pipe
    - rare (todo:??)
    - normal
    - if no writers: `read` returns `0 == EOF`
- pipes are nameless
  - unless named pipe

    ```
    $ mkfifo p
    $ ls -l p
    prw-rw-rw- ... p
    ```

    ```
    int pipe(int ds[2]);
    ```

  - to use the pipe, call `fork`
  - `$ A | B` want another shell prompt after this
  - need 3 processes
  - `sh` → `A`, `B`
    - `cat bigfile | less` → q
    - `less` is gone
    - shell only cares about `B` fishing
  - `sh` → `A`, `B`
  - `sh` → `B`, `A`
    - conventionally, this process tree is used
    - performance advantage: more parallelism, child process sets up pipeline
  - shell.c

    ```
    pid_t b = fork();
    if (b < 0) error();
    if (b == 0)
      setup_a_b(...);
    else if (waitpid(b, &status, 0) < 0)
      error();
    return status;
    ```

```c
...

void setup_a_b(void) {
  int fd[2];
  if (pipe(fd) != 0) error();
  pid_t a = fork();
  if (a < 0) error();
  if (a == 0) {
    dup2(fd[1], STDOUT_FILENO);
    close(fd[0]);
    close(fd[1]);
    execlp("A", "A", NULL);
    error();
  }
  dup2(fd[0], STDIN_FILENO);
  close(fd[0]);
  close(fd[1]);
  execlp("B", "B", NULL);
  error();
}
```

- no exit status for `A`

8.3 losing power

- small backup power (battery)
- copy cache / ram into secondary storage fast
- how to support this
  - simplify applications by saying kernel will handle everything
    - snapshots each process
    - as if nothing happened in the processes' pov
    - relatively expensive (efficiency problem)
    - assumes you can snapshot everything
      - often not the case when process is talking to the outside world (e.g. cloud)
      - cannot snapshot everything
      - clock will change (time dependent processes)
  - `/dev/power`
    - tells you the power status
    - make processes inspect `/dev/power` and do appropriate things
    - each program must be modified to read `/dev/power` (polling)
  - blocking read

```c
char c;
fd = open("/dev/power", ...);
read(fd, &c, 1);
```

    - cant do anything while blocked
    - unless assuming multithreading, but need to notify other threads
  - signals
    - rare events
    - localize handling
      - break out of an expensive / complicated loop
    - kill a process
    - timeouts

8.4 signals on linux

- `kill -HUP 19362`
  - send hangup signal to process 19362
  - `if (kill(SIGHUP, 19362) < 0)`
- ordinarily user code can only send signals to processes with the same user id
- user
  - `C-c`: send `SIGINT` to every process in the foreground
  - `SIGKILL`: i want you to die and i dont want you to be able to do anything abt it, cannot be ignored
    - `kill -KILL $$`
  - `SIGSTOP`
  - `SIGUSR1`...
  - `SIGHUP`
- internal errors
  - invalid instruction: `SIGILL`, illegal instruction signal
  - floating point exception: `SIGFPE`, not sent anymore, only sent when `INT_MIN / -1` or `0 / 0`
  - invalid address (bad ptr etc): `SIGSEGV`, `SIGBUS`
- io errors
  - `SIGIO`
  - `SIGPIPE`: writing to pipe w no readers
- death of a child process
  - `SIGCHLD`: rare, one of subsidiaries has died, prob want to clal `waitpid`
- alarm clock
  - `SIGALRM`
- `SIGXCPU`: sent to process when (just abt to) out of cpu time
- `SIGXFSZ`: file size
- `#include <signal.h>`
  - `typedef void (*sig_handler_t)(int);` function type, takes `int` and returns `void`
  - `sighandler_t signal(int signo, sighandler_t handler)` set signal handler and return previous

```c
void handle_control_C(int sig) {
  write(1, "?", 1);
}

int main(void) {
  signal(SIGINT, handle_control_C);
  ...
}
```

  - signal handling dispatch table in process table

- signal handlers can be called (by default) between any pair of machine instructions
  - instructions are atomic
  - syscalls are atomic
  - others are not: library calls
    - have to be prepared for the handler function to be called anywhere within a library call
    - e.g. `malloc(1000)`
      - `malloc` in handler = disaster
      - posix rule: dont do that, never call `malloc` from signal handler
    - e.g. `printf("?")`
      - may mess up internal data structure
  - reentrant functions: functions that you can call in the middle of their call
    - e.g. `sqrt`
    - !e.g. `malloc`, `printf`
    - how to know which functions are reentrant? read the manual

9 10.18 4t

9.1 signals

- `signal(int signaltype, handler)`
- can be called between any pair of instructions
- call only:
  - reentrant functions
  - async-safe functions
- blocking signals
  - `int pthread_sigmask(int how, sigset_t const *restrict set, sigset_t *restrict oset)`
  - how: `SIG_BLOCK`, `SIG_UNBLOCK`, `SIG_SETMASK`
  - `typedef long sigset_t;`
  - oset returns old signal set
  - block worrisome signals → delicate code (should be short and sweet) → restore the previous signal mask
    - delicate code should be short and sweet

- kernel will remember arrived signals and wait until unblock
- cant make `malloc` async-safe cuz too heavy (2 extra syscalls and not responsive to signals)
- *critical section*

9.2 gzip

- `gzip foo`
  - creates `foo.gz`
  - removes `foo`
  - as a user, want these to be atomic
- internally, `gzip` makes sure it either does both or neither (critical section)
  - reads `foo`, writes to `foo.tmp` (compressed output), takes a long time
  - in critical section:
    - (normal) rename `foo.tmp` to `foo.gz`, remove `foo`
    - (signal) unlink `foo.tmp`

```c
void cleanup() { unlink("foo.tmp"); }

int main() {
  signal(SIGINT, cleanup);
  in = open("foo", RD);
  out = open("foo.tmp", WR);
  compress();
  close(out);
  rename("foo.tmp", "foo.gz");
  remove("foo");
  close(in);
}
```

    - signal handler may clean up when we dont want it

```c
int tmpexists;

void cleanup() { if (tmpexists) unlink("foo.tmp"); }

int main() {
  signal(SIGINT, cleanup);
  in = open("foo", RD);
  // block SIGINT
  tmpexists = 1;
  out = open("foo.tmp", WR);
  // unblock
  compress();
  close(out);
  // block SIGINT
  tmpexists = 0;
```

```
    rename("foo.tmp", "foo.gz");
    remove("foo");
    // unblock
    close(in);
  }
```

- compiler might optimize and remove setting `tmpexists`
- decorate `tmpexists`: `volatile int tmpexists;`
  - tells compiler it can change at any time

9.3 signal handling

- pros
  - can manage processes better
  - fix some performance problems w polling
- cons
  - processes less isolated (harder to follow code)
  - can be signaled at any time (complicated code)
  - buggy apps (huge opportunities for race conditions)

9.4 why threads

- process isolation is too restrictive
- may want to communicate with other processes
  - large cost (2 syscalls `write` + `read` via pipe)
  - threading: `store` + `load`
- less latency in cooperation + better thruput (e.g. passing a ptr to a big piece of storage)
- process state
  - registers
  - — thread state —: as small as possible so threads are cheap
  - stack
  - signal mask
  - errno (syscall fail), (thread local storage (tls))
  - runnability (`RUNNABLE`, `BLOCKED`, `WAITING`)
  - id
  - — shared by all threads in same process —
  - pid
  - address space (code + heap + static vars)
  - file descriptor table
  - signal handler table
  - (working root) directory
    - `chroot` requires root privileges
  - usid / gid

    – umask

  – no protection in memory access
  – embarassing parallelism

    – no need to synchronize

9.5 threading

- `int pthread_create(pthread_t *id, pthread_attr_t const *attr, void * (*fn) (void*), void *arg);`
  - stores thread id
  - `fn`: code to be executed
  - `arg` gets passed to `fn`
- `int pthread_join(pthread_t tid, void **status);`
  - wait for `tid` thread to finish
- `void pthread_exit(void *status);`
- `int pthread_kill(pthread_t tid, int sig);`
  - sends signal to thread
  - thread will have all the problems in terms of signal handling
  - eggert does not recommend: too heavyweight, too powerful, too much control, deprecated
- `int pthread_cancel(pthread_t);`
  - no signal
  - arranges for the target thread to terminate but not yet
  - only terminates when it enters *cancellation point*

9.6 synchronization

```
long balance

/**
 * movq balance, %rax
 * addq %rsi, %rax
 * movq %rax, balance
 */
void deposit(long val) { // t1
  balance += val;
}

/**
 * movq balance, %rbx
 * ...
 */
bool withdraw(long val) { // t2
```

```
  if (val <= balance) {
    balance -= val;
    return true;
  }
  return false;
}
```

- could step on each others toes while data is cached in the registers
- `transfer(acct1, acct2, val)`
- `audit_all_accounts()`: get access to all accounts in an atomic way
- need avoid *race conditions*: buggy behavior exposed by a particular order of execution
    - hard to reproduce
- classic way to prevent race conditions: critical section
    - a sequence of instructions such that *indivisibility* is preserved
    - at most one thread's `ip` is in that sequence at any given time
    - enforcing a critical section
        1. mutual exclusion
        2. bounded wait

    ```
    volatile long balance

    void deposit(long val) { // t1
      // start critical
      balance += val;
      // end critical
    }

    bool withdraw(long val) { // t2
      // start crital
      if (val <= balance) {
        balance -= val;
        return true;
      }
      // end crital
      return false;
    }
    ```

```
#define N 512

struct pipe {
  char buf[N];
  size_t r, w;
};

void writec(struct pipe *p, char c) {
```

```
  // fix 2: lock();
  // fix: while (p->w - p->r == N);
  // still bad, race condition between two loads
  p->buf[p->w++ % N] = c;
  // fix 2: unlock();
  // still bad, while loop could go on forever
}

char readc(struct pipe *p) {
  // fix 2: lock();
  // fix: while (p->w == p->r);
  // still bad, race condition between two loads
  return p->buf[p->r++ % N];
  // fix 2: unlock();
  // still bad, while loop could go on forever
}
```

10 10.20 4th

10.1 uniprocessor case

- disable_interrupt();
- enable_interrupts();

10.2 multiprocessor case

- lock();
- unlock();

```
// need volatile here
static bool L;

// must not have lock to call
bool lock() {
  while (L);
  L = true; // race condition here
}

// must have lock to call
void unlock(void) {
  L = 0;
}
```

- indivisibility

- e.g.

  ```
  // t1:
  char buf[100];
  strcpy(buf, "Hello");
  strcpy(buf, "Goodbye");

  // t2:
  if (strcmp(buf, "Hello") != 0 && strcmp(buf, "Goodbye" != 0)) crash(); // can crash
  ```

- e.g.

  ```
  struct x {
    unsigned a : 1;
    unsigned b : 7;
  }

  v.a = 1;
  /**
   * movb v,   %al
   * orb  $1,  %al
   * movb %al, v
   */
  ```

- problem is with processor

- x86-64: aligned 32-bit loads and stores are atomic
  - causes slowdown
  - change `bool` to `int` in `lock()` `unlock()`

- `xchgl %eax, (%rbx)`

  ```
  t = %eax;
  %eax = *(%rbx);
  *(rbx) = t;
  ```

  - at hardware level, cpu sends signal saying it will store & load at location
  - performance cost

    ```
    int xchgl(int v, int *p) {
      int t = *p;
      *p = v;
      return t;
      // asm("xchgl ...");
    }
    ```

- fixed:

```
static int volatile L;

void lock(void) {
  while (!xchgl(1, &L));
}

void unlock(void) {
  L = 0;
}
```

10.3 critical section performance

- want to minimize size of critical section
- general technique / rule of thumb
  - find shared writes
  - find all dependent reads
  - critical section is minimal section that contains all of them
- barriers for code reordering: `volatile`, `asm`
- compare and swap
  - assume atomic

    ```
    bool compare_and_swap(int * addr, int old, int new) {
      if (*addr == old) {
        *addr = new;
        return true;
      } else {
        return false;
      }
    }
    ```

  - expensive code `static int x; x = ef(x)`
    - using `compare_and_swap`:

      ```
      int r, o;
      do r = ef(o = x);
      while (!compare_and_swap(&x, o, r));
      ```

    - doesnt scale to large objects
- global lock (coarse grained lock) = bad
  - want finer grained locks, 1 lock per pipe

    ```
    typedef int lock_t;

    void lock(lock_t *l) {
      while (xchgl(1, l));
    }
    ```

```c
void unlock(lock_t *l) {
  l = 0;
}

// update struct pipe
#define N 512
struct pipe {
  char buf[N];
  size_t r, w;
  lock_t l;
}

// usage
lock(&p -> l);
// critical section
unlock(&p -> l);
```

10.4 blocking mutex

- spin lock will infinitely loop
- BLOCKED bit in process table entry

```c
typedef struct {
  lock_t l;
  bool acquired;
  struct pte *waiter; // pte = process table entry
} bmutex_t;

void acquire(bmutex_t *b)l{
  for(;;) {
    lock(&b->l);
    if (!b->acquired) {
      b->acquired = true;
      unlock(&b->l);
      return;
    } else {
      unlock();
      b->waiter = this_thread;
      this_thread->next = b->waiter;
      schedule();
    }
  }
}
```

```c
void release(bmutex_t *b) {
  lock(&b->l);
  b->acquired = false;
  // using while may be beneficial with sophisticated scheduler
  if (b->waiter) {
    b->waiter->blocked = false;
    b->waiter = b->waiter->next;
  }
  unlock(&b->l);
}
```

10.5 deadlock

- `sed 's/a/b/' | cat file - | sed 's/c/d/'`

  ```c
  char buf[1024];
  fd = open("file", ...);
  while (read(fd, buf, ...) > 0) {
    write(1, buf, ...);
  }
  while (read(0, buf, ...) > 0) {
    write(1, buf, ...);
  }
  ```

- why not

  ```c
  while (rw(fd, 1, 1024) > 0);
  while (rw(0, 1, 1024) > 0);
  ```

  - p1:

    ```c
    acquire(input);
    acquire(output);
    ```

  - p2:

    ```c
    acquire(output);
    acquire(input);
    ```

- `copy_file_range()` avoids deadlock
- dead lock is a *race condition* w 4 conditions
  - circular wait
  - mutual exclusion
  - no preemption of locks
  - hold and wait
- two ways to prevent deadlock

  - add code to acquire to look for cycles in processes and objects
    - fail if it would create a cycle
    - slowdown
  - lock order
    - arbitrarily number locks
    - if need multiple objects, have to acquire them in order
    - if cannot acquirea lock, release all locks and restart

- p:

  ```
  pipe(a);
  pipe(b);
  fork();
  exec("sort");
  ```

  - p `writes` and `reads`, `sort` `reads` and deadlocks

10.6 alternate programming strategy (!multithreading)

- event programming

  ```
  for (;;) {
    wait for an event E;
    handle(E); // event handler cannot wait, must finish quickly
  }
  ```

- ~~`read(...);`~~: `aio_read(...);`