INF333 - Operating Systems

Lecture II

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Course website

burakarslan.com/inf333

Based On

cs111.stanford.edu

cs212.stanford.edu

OSC-10 Slides

File Systems

A Gentle Introduction

File Systems

Memory (RAM)

- Fast, less space, more expensive
- Byte-addressable: can quickly access any byte of data by address, but not individual bits by address
- Not persistent: cannot store data between power-offs

Storage

- Slower, more space, cheaper
- Sector-addressable: cannot read/write just one byte of data – can only read/write "sectors" of data at a time
- Persistent: stores data between power-offs

File Systems

File systems are designed to work on hardware like **hard disk drives** or **solid state drives**

- They only understand sectors.
- This is the only api we are ever going to get:

```
void readSector(size_t sectorNumber, void *data);
void writeSector(size_t sectorNumber, const void *data);
```

File Systems

But!

- We want files and folders and permissions and links ...
- We need a software layer that translates between file system primitives and sector operations

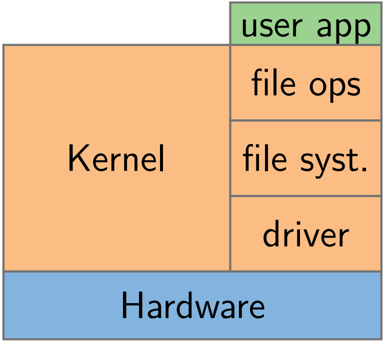
File Systems

But!

- We want files and folders and permissions and links ...
- We need a software layer that translates between file system primitives and sector operations
- This layer is called a **file system**.

File Systems

- File systems translate file operations to sector operations
- They sit on top of protocols like SATA, USB, NVME etc.



File Systems

File systems implement operations like:

- Creating a new file on disk
- Looking up the location of a file on disk
- Reading/editing all or part of an existing file from disk – e.g., sequential/random access creating folders on disk
- Getting the contents of folders on disk
- etc.

File Systems

File systems are still a very active field.

Certainly not "a solved problem"
though pretty mature implementations exist

File Systems

Problems that file systems have to deal with:

Space Management

- Fast access to files (maximize locality)
- Sharing space between users
- Efficient use of disk space

Naming How do users find files?

Reliability Information must survive OS crashes and hardware failures.

Protection Isolation between users, controlled sharing.

File Systems

File systems also deal with two classes of data:

- Payload (contents of files)
- Metadata (file names, permissions, directory contents, etc.)

Since both are held in persistent storage, some blocks must store data other than file contents.

File Systems

Many designs exist, some wildly different than others.

From here onwards, we will focus on native Linux filesystems

File Systems

Terminology

A filesystem generally defines its own unit of data, a "block", that it reads/writes at a time.

Sector Hardware storage unit

Block Filesystem storage unit (1 or more sectors) – software abstraction related to storage

Page Kernel's I/O unit, another software abstraction related to I/O in general — be it RAM, block storage, pipes, etc.

File Systems

Terminology

Sector sizes are medium-dependent and sometimes customizable:

```
# nvme id-ns /dev/nvme0n1 | grep lbads
lbaf  0 : ms:0   lbads:9  rp:0x2 (in use)
lbaf  1 : ms:0   lbads:12 rp:0x1
```

File Systems

Terminology

Similarly, block sizes are fs-dependent and can be tuned [1].

```
# xfs_info /dev/nvme0n1p2
meta-data=/dev/nvme0n1p2 isize=512 agcount=4, agsize=7864320 blks
      sectsz=512   attr=2, projid32bit=1 crc=1 finobt=1, sparse=1
      rmapbt=1 reflink=1 bigtime=1 inobtcount=1 nrext64=0
data     =                bsize=4096   blocks=31457280, imaxpct=25
         =                sunit=0      swidth=0 blks
naming   =version 2       bsize=4096   ascii-ci=0, ftype=1
log      =internal log    bsize=4096   blocks=16384, version=2
         =                sectsz=512   sunit=0 blks, lazy-count=1
realtime =none            extsz=4096   blocks=0, rtextents=0
```

[1] It's very tricky to do so though! eg. XFS: Mount overrides sunit and swidth options

File Systems

Terminology

A page is the I/O unit of the kernel – it's the same everywhere.

```
$ getconf PAGESIZE
4096
```

Changing it is a whole project:

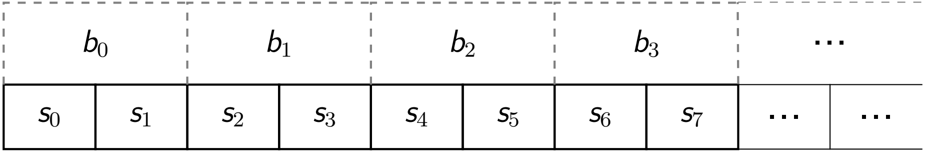
- HugePages support in Linux
- This got stabilized circa 2010: Huge pages: Introduction

File Systems

Terminology

A correctly-tuned block size is an essential factor in the performance of storage systems.

- Fewer transfer operations if larger
- But smaller files may read in more data than necessary



File Systems

Terminology

An **inode** ("index node") is a data structure that describes a file-system object such as a file or a directory.

```
# stat /etc/passwd
  File: /etc/passwd
  Size: 2325      Blocks: 33         IO Block: 2560   regular file
Device: 0,25      Inode: 10004479   Links: 1
Access: (0644/-rw-r--r--)           Uid: (0/root)   Gid: (0/root)
Access: 2024-02-06 08:39:38.557196113 +0300
Modify: 2024-02-03 00:56:48.431922259 +0300
Change: 2024-02-03 00:56:48.431922259 +0300
 Birth: 2024-02-03 00:56:48.431922259 +0300
```

File Systems

Terminology

A **directory** is a list of inodes with their assigned names.
The list includes an entry for itself (.), its parent (..), and each of its children.

```
# ls -if /etc
 67108993 .             67109039 inittab.d
      128 ..           134462512 nanorc
134348929 pam.d         68298267 gentoo-release      ...
201326721 gpm          203011796 protocols
 67512281 subgid        67109044 .pwd.lock

                       ...
```

File Systems

Terminology

Discussion

Can a file be retrieved by its inode?

Discussion

What happens when more than one directory contains an entry for the same inode?

File Systems

Terminology

It's called a **hard link**:

```
$ echo foo > a
$ stat a
  File: a      Size: 4
Device: 0,32  Inode: 2646944  Links: 1
$ ln a b
$ stat b
  File: b      Size: 4
Device: 0,32  Inode: 2646944  Links: 2
$ cat a
foo
$ echo bar > a
$ cat b
bar
$
```

Discussion

Creating hard links to directories is not allowed. Why do you think this is the case?

File Systems

An inode is "scheduled for deletion" when its refcount reaches zero

- When a file is opened, it will remain on the fs until closed
- Deleting a file immediately after opening it is a nice way to implement temporary files on Linux.

Remaining parts of the OS

A not-so-gentle continuation

You can handle it now 😅

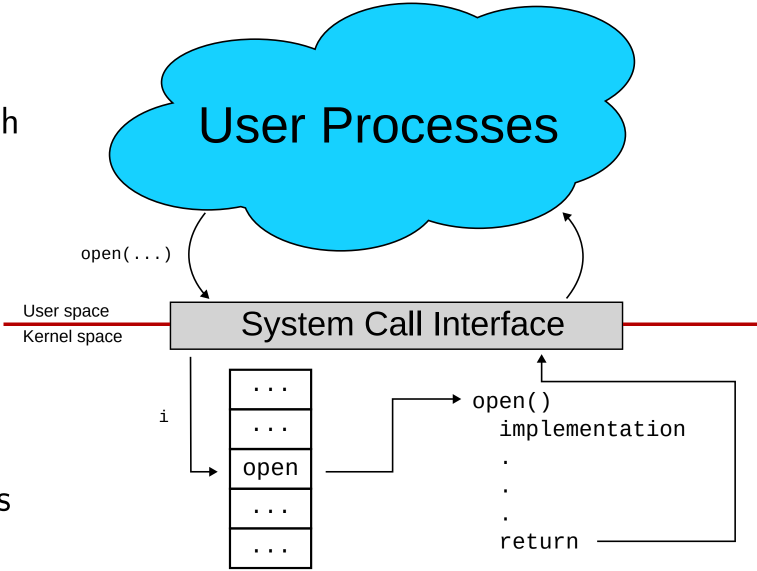
System Calls

- Applications still need to work with the hardware to make progress
- OS supplies a well-defined **system call** interface
- **For example:** Apps normally don't write to storage directly, but to designated regions in the storage device sanctioned by the OS
- Uses system calls to (try to) obtain access to said addresses.

System Calls

To open a file in a FS with the `open()` system call:

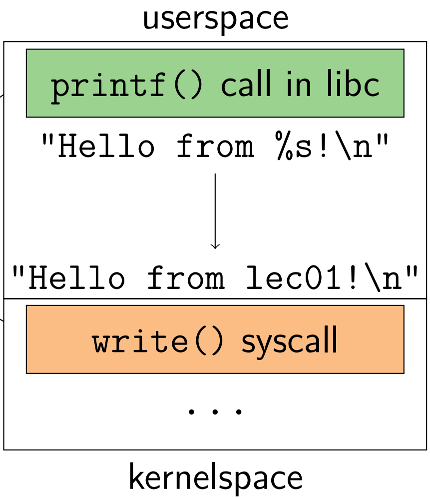
- App sets up the system call id and arguments and lets the kernel know
- The kernel executes the requested operation and returns the result



System Calls

Closer look: `printf()`

```
$ cat lec01.c
#include <stdio.h>
int main(int argc, char **argv) {
  printf("Hello from %s!\n", argv[0]);
  return 0;
}
$ gcc -o lec01 lec01.c && ./lec01
Hello from lec01!
```



System Calls

Closer look: `open()`

- Applications "open" files (or devices) by name
- `int open(char *path, int flags, /*int mode*/...);`
- Returns a **file descriptor** (fd) – used for all I/O to files and file-like objects

System Calls

Error handling

- What if `open` fails? Returns -1 (invalid fd)
- Most system calls return -1 on failure
  - Specific kind of error in global int `errno`
  - In retrospect, bad design decision for threads/modularity
- `#include <sys/errno.h>` for possible values
- `perror` function prints human-readable message
- Use the `strace` command [2] to log all the system calls that a process makes

[2] Linux-only but equivalents exist on all popular platforms

File Descriptors

A file descriptor is a simple integer that is:

- Inherited by processes when one process spawns another,
- By convention, descriptors 0, 1, and 2 have special meaning:
  - 0 – "standard input" (`stdin` in ANSI C)
  - 1 – "standard output" (`stdout`, `printf` in ANSI C)
  - 2 – "standard error" (`stderr`, `perror` in ANSI C)
  - Normally all three attached to terminal

File Descriptors

type.c

```c
void
typefile (char *filename)
{
  int fd, nread;
  char buf[1024];

  fd = open (filename, O_RDONLY);
  if (fd == -1) {
    perror (filename);
    return;
  }

  while ((nread = read (fd, buf, sizeof (buf))) > 0)
    write (1, buf, nread);

  close (fd);
}
```

Protection

Example: CPU preemption

This is a way to implement preemptive scheduling:

- Kernel programs timer to interrupt every 10 ms. This is called a **tick**. [3]
- Kernel sets interrupt vector back to kernel
  - Regains control whenever interval timer fires
  - User code is not allowed to do so
- Result: No process can monopolize the CPU

[3] It's popular yet suboptimal way: See "(Nearly) full tickless operation in [Linux] 3.10"

Protection

Example: CPU preemption

This is technique doesn't protect against:

- A malicious user constantly starting new processes
- A malicious user constantly allocating memory

Possible solutions:

- Yell at the guy who's doing it (no, seriously)
- Remove that app from the play store
- Enforce per-user resource limits

Protection

Address translation

Goal:

Protect memory of one program from actions of another

Protection

Address translation

Definitions:

- *Address space*: all memory locations a program can name
- *Virtual address*: addresses in process' address space
- *Physical address*: address of real memory
- *Translation*: map virtual to physical addresses

Protection

Address translation

- Translation done on every load, store, and instruction fetch
  - Modern CPUs do this in hardware for speed
- Idea: If you can't name it, you can't touch it
  - Ensure one process' translations don't include any other process' memory

Protection

More memory protection

- CPU allows kernel-only virtual addresses
  - Kernel typically part of all address spaces, e.g., to handle system call in same address space
  - But must ensure apps can't touch kernel memory
- CPU lets OS disable (invalidate) particular virtual addresses
  - Catch and halt buggy program that makes wild accesses
  - Make virtual memory seem bigger than physical (e.g., bring a page in from disk only when accessed)

Protection

More memory protection

- CPU enforced read-only virtual addresses useful
  - E.g., allows sharing of code pages between processes
  - Plus many other optimizations
- CPU enforced execute disable of VAs
  - Makes certain code injection attacks harder

Protection

Different system contexts I

At any point, a CPU (core) is in one of several contexts:

- *User-level* – CPU in user mode running application
- Kernel process context – i.e., running kernel code on behalf of a particular process
  - E.g., performing system call, handling exception (memory fault, numeric exception, etc.)
  - Or executing a kernel-only process (e.g., network file server)

Protection

Different system contexts II

- Kernel code not associated with a process
  - Timer interrupt (hardclock)
  - Device interrupt
  - "Softirqs", "Tasklets" (Linux-specific terms)
- Context switch code – change which process is running
  - Requires changing the current address space
- Idle – nothing to do (bzero pages, put CPU in low-power state)

Protection

Transitions between contexts

CPU context transitions:

- User → kernel process context: syscall, page fault, ...
- User/process context → interrupt handler: hardware
- Process context → user/context switch: return
- Process context → context switch: sleep
- Context switch → user/process context

Protection

Resource allocation & performance

Multitasking permits higher resource utilization.

Simple example:

- Process downloading large file mostly waits for network
- You play a game while downloading the file
- Higher CPU utilization than if just downloading

Protection

Transitions between contexts

Complexity arises with cost of switching:

Example: Say disk 1,000 times slower than memory:

- 1 GiB memory in machine
- 2 Processes want to run, each use 1 GiB
- Can switch processes by swapping them out to disk
- Faster to run one at a time than keep context switching