Penn Engineering

ESE

Lecture #11 – Storage/Filesystems

ESE 150 – Digital Audio Basics

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Lecture Topics

- Where are we on course map?
- Overview of Today's Lecture
- How/Where do we store our digital music?
  - Persistent Storage Technology
  - Filesystems
    - Abstraction 1 : files/directories
    - Abstraction 2: b-nodes/i-nodes
    - Abstraction 3: filesystems
- Next Lab

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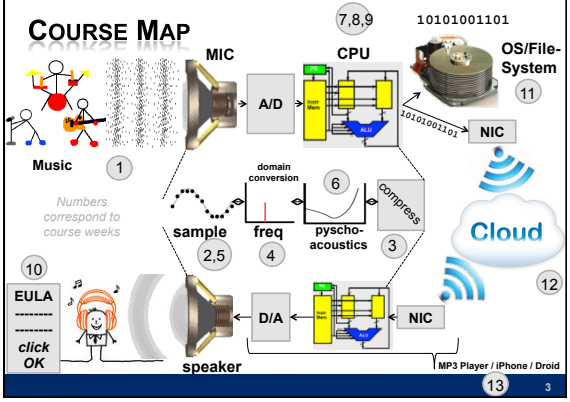
Course Map



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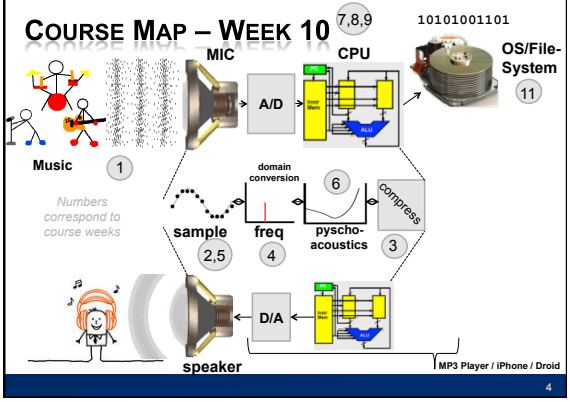
Course Map – Week 10



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What We'll Cover Today…

10101001101

The mighty File System!

- Last Lecture…
  - We discussed the idea of an OS
    - Virtualizes Hardware
  - Key part of any OS is its filesystem…we'll talk about that today
  - From floppy disk/hard disk/compact disc/flash drive… "virtually" the same!

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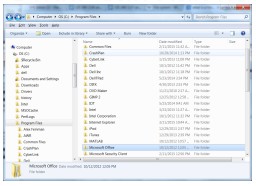
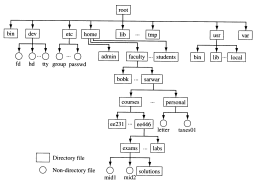
Store and Find Data





- MP3 encoded Songs on Smart Phone
- Assignments on your laptop
- Programs on eniac

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Persistent Storage Technology

Flash-drives / **Hard-drives**

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Persistent Storage

- **Persistent Storage vs. non-persistent storage**
  - We've discussed "memory" in a computer (regFile/cache/RAM)
    - This is considered non-persistent storage
    - Turn off computer, information is lost
  - Persistent Storage – long term storage
    - Information/data stored across on/off cycles of the machine
    - Power goes off, data doesn't disappear!
- **Persistent Storage Technology**
  - Many different kinds:
    - Flash drives/SSD drives/Floppy disk/Hard drive/compact discs/ etc.

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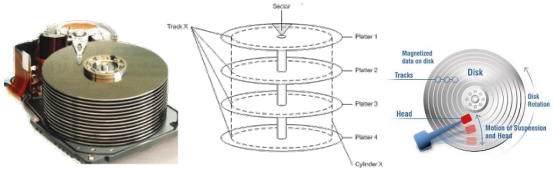
Hard Drives / Hard Disks (HD)

- **A collection of metallic "platters"**
- **Each platter covered with magnetic material**
- **Magnetic charge 'stores' 1 bit of information**
- **Can vary charge across platter!**



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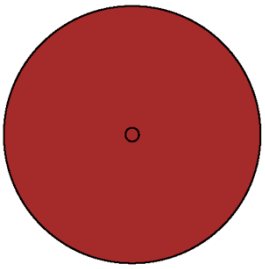
Hard Disk

- **Disk with magnetic material on its surface**



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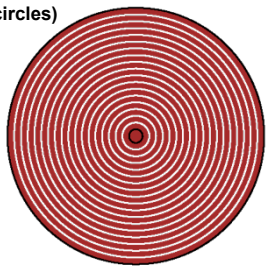
Hard Disk

- **Disk with magnetic material on its surface**
- **Divided into tracks (circles)**
- **Modern disks**
  - 300,000 TPI
  - TPI = Tracks Per Inch



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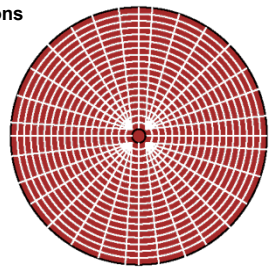
Hard Disk

- **Disk with magnetic material on its surface**
- **Divided into bit regions**
- **Modern disks**
  - 1.5M BPI
  - BPI= bits per inch



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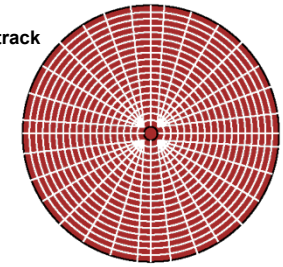
HARD DISK

- Each bit located at a position (R,Θ)
- R = select track
- Θ = select bit from track
- disk spins
  - Traces through Θ



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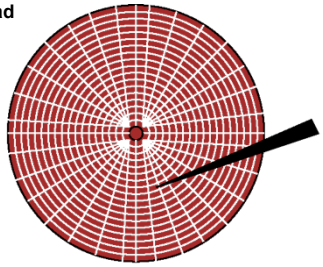
HARD DISK

- Each bit located at a position (R,Θ)
- Add arm to move head



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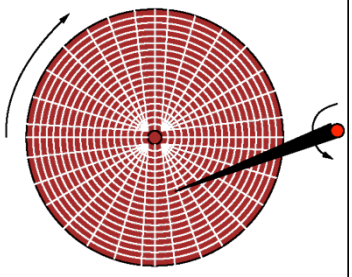
HARD DISK

- Each bit located at a position (R,Θ)
- Head arm moves
  - Varies R



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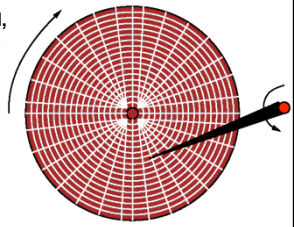
DISK BANDWIDTH (PRECLASS 1, 2)

- Typical Disk speed
  - 15,000 RPM
  - Time for revolution in seconds?
- At R=1 inch and 1.5M BPI,
  - How many bits in revolution?
  - How many bits/second?



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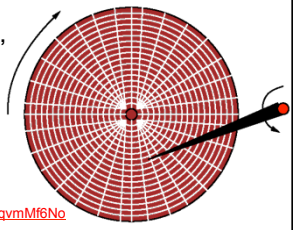
DISK BANDWIDTH

- Typical Disk speed?
  - 15,000 RPM
  - One rotation every
    - 60s/15,000=4ms
- At R=1 inch and 1.5M BPI,
- How many bits/second?
  - 2 π × 1 in × 1.5MB/in / 4ms
  - 9Mbits/4ms = 2.25Gb/s
    - ≈ 280 MB/s



https://www.youtube.com/watch?v=3owqvmMf6No

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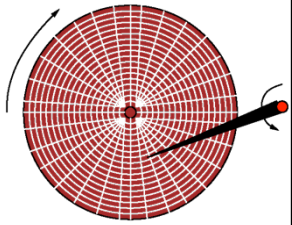
DISK ACCESS TIME

- **Move head in R?**
  - Also a few milliseconds: 6
- **How long to access a random bit?**



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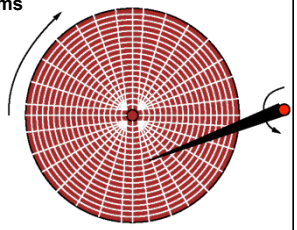
Disk Access Time

- **Move head in R?**
  - Also a few milliseconds: 6
- **Typical Data access: ~10ms**
  - *E.g.* 4ms rotate +6ms seek
- **Random bit throughput (b/s) ?**
- ***Note: CD-ROMs similar mechanism***



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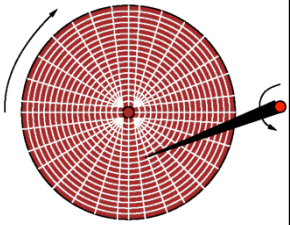
Disk Read/Write Performance

- **Typical Data access: ~10ms**
  - *E.g.* 4ms rotate +6ms seek
- **Throughput reading**
  - 4KB sequential chunk
  - 1MB sequential chunk



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Throughput and Implications

- **Disk throughput and access time**
  - 10ms latency
  - 280MB/s throughput (~1B/4ns)
- **Observations?**
  - Throughput faster than access time
  - 10ms seek → Random bit access 100b/s
  - Sequential access 280MB/s
- **Conclude:**
  - **Want to exploit sequential access!**
    - **Read blocks of data**

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Seagate 2.5" Disk Drive

Specifications	160GB[1]
Model Number	ST91608220AS
Interface Options	SATA 1.5Gb/s
Performance	
Transfer Rate	
Sustained Internal (MB/s)	44
Maximum External (MB/s)	150
Flash Memory (MB)	256
Cache, Multisegmented (MB)	8
Average Seek (ms)	12.5
Average Latency (ms)	5.6
Performance Level	5400

5400 RPM

http://www.seagate.com/docs/pdf/datasheet/disk/ds_momentus_5400_psd.pdf

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Persistent Storage Technology

Flash-drives / Hard-drives

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Flash Memory

- **A little like memory circuits we have learned about…**
  - Except it is non-volatile or simply…persistent storage
  - Data won't go away when power is turned off
  - Based on the "floating gate" transistor
- **Today's Examples**
  - Persistent storage in your MP3 player, cell phone
    - FYI: first iPod had a hard disk…
  - USB Flash drive
  - Solid-State Disk (SSD)

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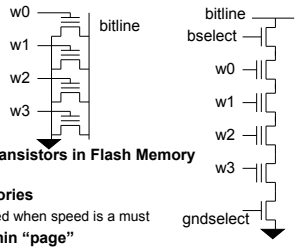
FLASH MEMORY



- **Two ways to configure FG transistors in Flash Memory**
  - NOR/NAND
- **NOR -- Read like other memories**
  - Fast, but not very dense…used when speed is a must
- **NAND – Sequential read within "page"**
  - Denser than NOR, but slower, use when area is a must
- **Can only "erase" in blocks**
  - 4KB, 64KB→256KB
- **Once erased can write byte (page) at a time**
  - Write time variable
  - Typically need feedback to sense when written

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SAMSUNG 256MX8 NAND FLASH

Parameter		Symbol	Min	Typ	Max	Unit
Program Time		tPROG(1)	-	200	500	µs
Dummy Busy Time for Multi Plane Program		tDBSY		1	10	µs
Number of Partial Program Cycles in the Same Page	Main Array	Nop	-	-	1	cycle
	Spare Array		-	-	2	cycle
Block Erase Time		tBERS	-	2	3	ms
$\overline{RE}$ Pulse Width		tRP	25		-	ns
$\overline{WE}$ High to Busy		tWB	-		100	ns
Read Cycle Time		tRC	50		-	ns
$\overline{CE}$ Access Time		tCEA	-		45	ns
$\overline{RE}$ Access Time		tREA	-		30	ns
$\overline{RE}$ High to Output Hi-Z		tRHZ	-		30	ns
$\overline{CE}$ High to Output Hi-Z		tCHZ	-		20	ns
$\overline{RE}$ or $\overline{CE}$ High to Output hold		tOH	15		-	ns
$\overline{RE}$ High Hold Time		tREH	15		-	ns
Output Hi-Z to $\overline{RE}$ Low		tIR	0		-	ns
$\overline{WE}$ High to $\overline{RE}$ Low		tWHR	60		-	ns
Device Resetting Time(Read/Program/Erase)		tRST	-		5/10/500(1)	µs
Last $\overline{RE}$ High to Busy(at sequential read)		tRB	-		100	ns
$\overline{CE}$ High to Ready(in case of interception by $\overline{CE}$ at read)		tCRY	-		50 + tr(R/$\overline{B}$)(2)	ns
$\overline{CE}$ High Hold Time(at the last serial read)(2)		tCEH	100			ns

http://www.datasheetcatalog.com/datasheets_pdf/K/9/F/2/K9F2G08U0M.shtr

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INTEL SOLID-STATE DRIVE (SSD)

Table 3. Maximum Sustained Read and Write Bandwidth

Access Type	MB/s
Sequential Read	up to 250
Sequential Write	up to 170

Table 4. Random Read and Write Input/Output Operations per Second (IOPS)

Access Type	IOPS
4K Read	35,000
4K Write	3,300

35,000/s x 4KB = 140MB/s

Table 5. Latency Specifications

Type	Average Latency
Read	75 µs (TYP)
Write	85 µs (TYP)
Power On to Ready	1 s

SSDhttp://download.intel.com/design/flash/nand/extreme/extreme-sata-ssd-datasheet.p

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FLASH MEMORY

- **Similar phenomenon**
  - T ~= A + B×N
  - Large fixed expense A
    - Move in R and Θ for disk ~ 10ms
    - Erase block for flash ~ 3ms
  - High bandwidth B for sequential data
    - Both … ~100s of MB/s
- **Conclude**
  - More efficient to operate on large chunks of data

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FILE

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HOW ORGANIZE DATA

- **Have technology to store bits**
  - GB, TB of data
- **How do we find our data?**
  - Remembering a (R,Θ) pair could be hard
  - Even remembering a 40b address
- **How do we distinguish used/unused storage?**
  - Make sure someone doesn't overwrite our data

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FILE

Example File: my_file.txt (14 characters)

```
I LOVE ESE150!
```

```
X49 x20 x4C x4F x56 x45
x20 x45 x53 x45 x31 x35
x30 x21
```

```
01001001 00100000
01001100 01001111
01010110 01000101 …
```

- **A file is simply a collection of bits**
  - Whether it's an ASCII file or a binary file (.docx, pdf, etc)
  - A program gives the bits meaning
  - Sequential access to bits efficient → useful to group together so can read all at once

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FILES → BLOCKS → PHYSICAL DISK

Mapping physical storage media to "bit/bytes/blocks"

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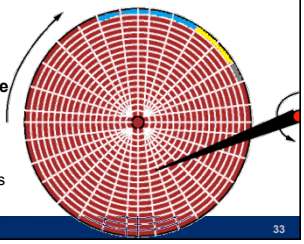
HOW IS A FILE STORED?

- **A file is an abstraction of the physical storage media**
  - Media "independent"
  - Don't care how technology is implemented, just read/write file!
- **Recall a file consists of:**
  - A bunch of bits
  - Logically related
  - Ex: my_report.docx, etc
- **A file system is responsible for providing this abstraction of the disk**
  - On storage media, at lowest level, file is in "blocks" of bits



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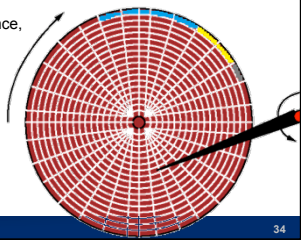
HOW WE STORE FILES ON PHYSICAL MEDIA

- **As we write data to a disk, we do it sequentially…**
  - Data in File 1 = blue, Data in File 2 = yellow, Data in file 3 = grey…
- **Sequentially written files have huge advantage in terms of seek time…**
  - Head/needle only moves once, then disk spins and we read many bits at a time



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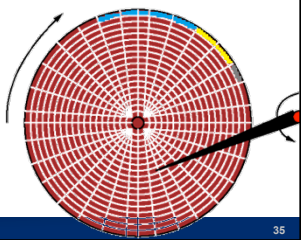
HOW WE STORE FILES ON PHYSICAL MEDIA

First Model

- File
  - start address
  - Length
- Allocate space sequentially
  - Keep track of first free address
- **But what happens when…**
  - we delete file?
  - Append to a file?



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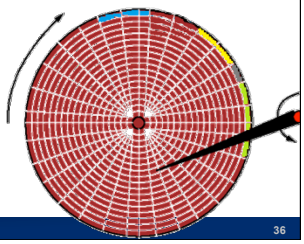
FRAGMENTATION

- **Let's say we shorten file1 (blue file)…**
  - We now have 2 open spaces (blocks) on disk
  - What happens when write a 4th file of 4 blocks?
  - The freespace is now "fragmented"
    - Still usable, just fragmented



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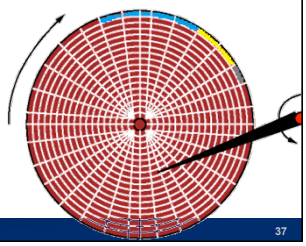
How we store files on physical media

- **We could also lengthen file1 (blue file)…**
  - Ex. Need 2 **more** open spaces (blocks) to store file
  - How accommodate?



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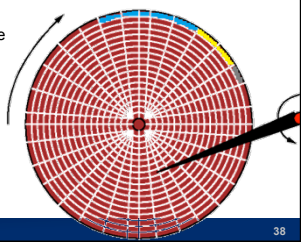
Fragmentation

- **We could also lengthen file1 (blue file)…**
  - Ex. Need 2 **more** open spaces (blocks) to store file
  - Should we actually move it on the disk?
    - Expensive
    - Now the address change
      - How programs and people find the file when it needs to move?



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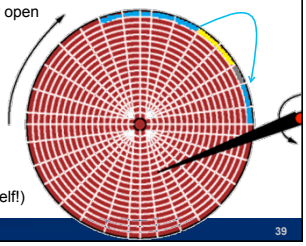
Fragmentation

- **We could also lengthen file1 (blue file)…**
  - What if we need 2 **more** open spaces (blocks) to store file
  - Should we actually move it on the disk? *expensive…*
    - Or instead…find 2 other open spaces and create a link
  - The file is no longer sequential
    - Take longer to access but functional; still one "logical" file (abstraction of media itself!)



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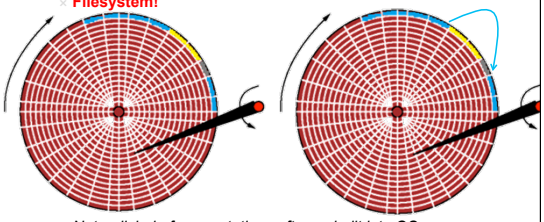
Fragmentation

- **Fragmentation is a fact of life**
  - But who is keeping track of all this fragmentation?
    - **Filesystem!**



- *Note: disk de-fragmentation software built into OSs now*

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What is a filesystem?

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Formation of a File / Filesystem

- **Represent File**
  - Not always just a sequence of bits on the media
- **When files become fragmented…**
  - How account for and manage fragmentation?
- **How do we know where freespace is?**
- **For that matter…**
  - How are all the files kept track of, or even found on the disk?
- **The file system**
  - Part of the operating system that organizes/keeps track of the disk
  - To understand what its keeping track of, we need to see what a file is…

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File Representation

- **File is not just a sequence of bits**
- **Contains some data about it**
  - Length
  - Type
  - Timestamp, ….
- **Set of pointers to the data (when large)**
  - Allowing the data to be non-sequential

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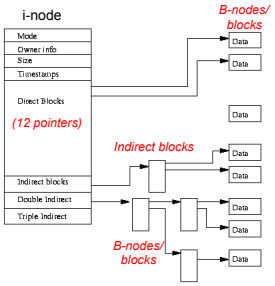
Files → i-nodes → b-nodes/blocks



- **In the Linux OS**
  - Popular filesystem named: ext3
  - Derived from original Unix File System (UFS)
  - Uses i-nodes
- **What is an i-node?**
  - A data-structure that represents a file on the storage media
  - Consists of file information:
    - Owner, size, timestamp, etc.
  - Also 15 pointers
    - 12 pointers that point directly to "blocks"
    - 3 additional pointer that point to other pointers! (indirect blocks)

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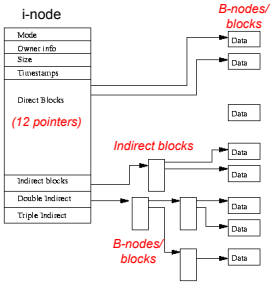
Files → i-nodes → b-nodes/blocks



- **How does it work?**
  - If a file only needs 12 blocks on disk…
    - 12 direct block pointers are used
    - Each of them point to a "bnode" or "block" of data on the disk
  - If a file requires 13 blocks…
    - 12 direct blocks are set/allocated
    - 1 indirect block is also needed

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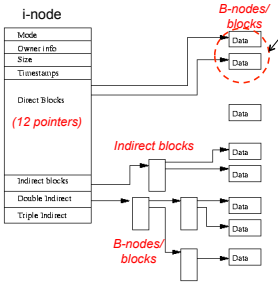
Files → i-nodes → b-nodes/blocks



- **What exactly is a b-node?**
  - Smallest unit of storage allocation
  - Fixed-size of data on the disk itself
  - Typical sizes:
    - 512 bytes for hard drives
    - 2048 bytes for CDs/DVDs
    - 4096 bytes (4kB) for todays drives
  - Smallest "addressable" unit on disk
    - Example: bnode address 76
    - *Would get 76 x 4096 = 311,296th byte on disk*
  - Address actually maps to physical address on disk
    - Example: bnode address 76
    - *R=1.012in, θ=32.07 degrees*
    - *Actual location on disk*
  - One level above media itself

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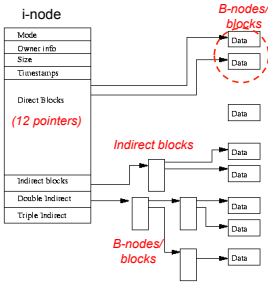
Files → i-nodes → b-nodes/blocks



- At 4KB / Bnode
- How large a file can represent using only Direct Blocks?
  - (assuming get full 4KB block for data)

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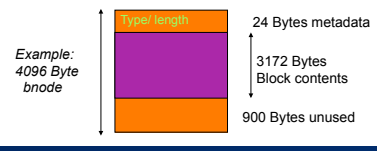
Files → i-nodes → b-nodes/blocks

- **Bnode's structure:**
  - Bnode contains metadata (like a header)
    - Description of data to follow
    - Block type, File type, length
  - Bnode contains data itself (contents)
    - This is actual data for the file in question
    - Example shows only a 3172 block file (could use all 4072 bytes)



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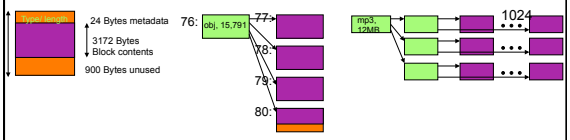
FILES → I-NODES → B-NODES/BLOCKS

- **Bnode's structure:**
  - bnode contains metadata (like a header)
    - Description of data to follow
    - Block type, File type, length
  - Alternatively…can be table of pointers (indirect block)
    - Can be a multi-level tree if necessary (doubly/triply indirect)



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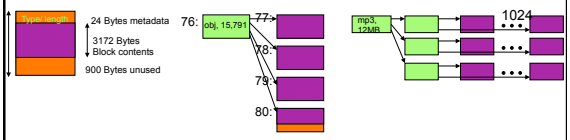
FILES → I-NODES → B-NODES/BLOCKS

- **How help with shortening or appending to file?**



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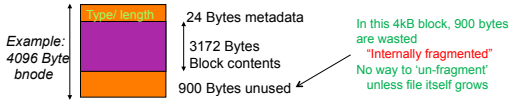
SIZE OF B-NODE/BLOCK REPRESENTATION

- **Why not make block sizes smaller?** ***(say 1-bit)***
  - How about 1 bit at a time? Addressing each bit wouldn't be easy…
    - 1 TB disk ~ 9 trillion bits…9 trillion addresses!
  - Most times files are larger than just a few bits
- **Why not make block sizes larger?** ***(512, 2048, 4096 bytes)***
  - Usually, we transfer "blocks" of data to/from media at a time
  - Why not go larger?
  - Remember, block size is, smallest unit of addressable space



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B-NODE/BLOCK SIZE

- **Performance: Balance**
  - Number of blocks need to read
  - Efficiency of reading large blocks
- **Space efficiency: Balance**
  - Internal fragmentation
  - Overhead for metadata and links

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EXT3 FILE SIZE LIMITATIONS

- **Limits?**
  - i-node is an array of (15) 32-bit pointers
  - If block = 4 KB, first 12 pointers represent 48 KB file
  - 13th pointer – single Indirect bnode, 1024 pointers
    - Why 1024 pointers?
    - file size?
  - 14th pointer – double indirect: file size?
  - 15th pointer – triple indirect: file size?
- **Will that become a limit?**
  - (Hint, welcome ext4 file system!)

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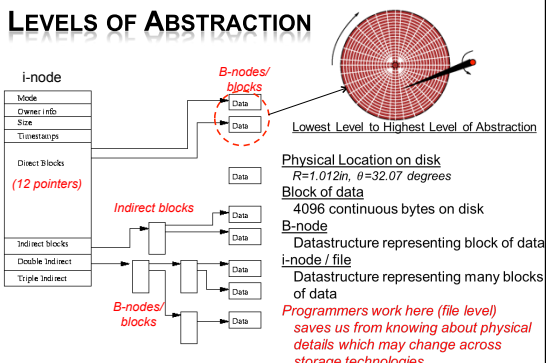
LEVELS OF ABSTRACTION



Physical Location on disk
R=1.012in, θ=32.07 degrees
Block of data
4096 continuous bytes on disk
B-node
Datastructure representing block of data
i-node / file
Datastructure representing many blocks of data
Programmers work here (file level) saves us from knowing about physical details which may change across storage technologies

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How keep track of files?

- **Add another file that tells us where the files are**
  - Directory
- **On ext3 filesystem…**
  - Directories are just files themselves!
  - Pairs of (Name, i-node)
  - Contain pointers to other nodes
- **…and since files can be directories**
  - Directories can contain directory files
    …which can contain directory files…
- **Leading to a directory hierarchy**

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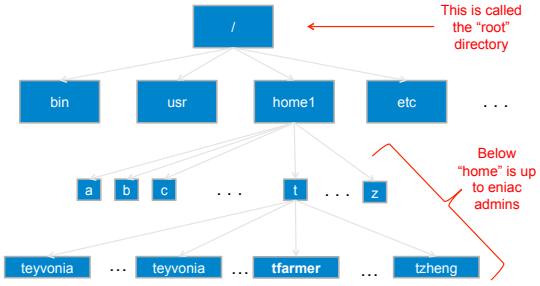
Unix System File Structure



ESE150 "Home directory" is **/home1/e/ese150** or simply: ~
Because the structure under "home" is typically different on all unix systems,
~ is a convention, and is always points to *your* home directory

Preclass 4

- **10^9 data items**
- **Assume at bottom of balanced tree**
- **Each tree-node has c leaves**
- **Directory i-node to hold c leaves needs**
  - 32×c Bytes
- **How many tree nodes must visit?**
- **How long to read a tree node?**
- **Time to lookup item (traverse tree)?**
  - c=2, c=10^3, c=10^9

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Looking at inodes

- **All directories start from "root" or / directory**

```
ese150@plus:/> cd /
ees150@plus:/> ls -al
total 164
drwxr-xr-x  25 root root  4096 Mar 31 05:44 .
drwxr-xr-x  25 root root  4096 Mar 31 05:44 ..
drwxr-xr-x   2 root root  4096 Mar 31 05:44 bin
drwxr-xr-x   4 root root  4096 Mar 31 05:40 boot
drwxr-xr-x  18 root root  4020 Feb 19 13:37 dev
```

```
ese150@plus:/> ls -ali
total 164
     2 drwxr-xr-x  25 root root  4096 Mar 31 05:44 .
     2 drwxr-xr-x  25 root root  4096 Mar 31 05:44 ..
393222 drwxr-xr-x   2 root root  4096 Mar 31 05:44 bin
     2 drwxr-xr-x   4 root root  4096 Mar 31 05:40 boot
  1025 drwxr-xr-x  18 root root  4020 Feb 19 13:37 dev
```

First block of disk is inode 1, called "masterblock" / "superblock"

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Superblock

- **For bootstrapping and file system management**
  - Each file system has a master block in a canonical location (first block on device)
  - Describes file-system type
  - Root bnode
  - Keeps track of free lists …at least the head pointers to (bnodes, blocks)
- **Corruption on superblock makes file system unreadable**
  - ➔Store backup copies on disk

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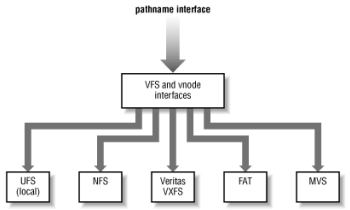
Higher Level ex: Virtual File System (VFS)

- **Provides common interface to many different underlying filesystems!**



cd /home/d/data may live on NFS (on a server) or on local disk/CD-rom!

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Format Disk

- **Identify all non-defective bnodes**
  - Defective blocks skipped
  - ➔ those addresses not assigned to bnodes
- **Create free bnode data structure**
- **Create superblock**

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Disk Data Security

- **How is security enforced?**
  - OS demands credentials for login
  - User doesn't get direct access to hardware
  - OS intermediates

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Security Caveats

- **On standard Unix/Windows setups**
  - Without the OS to provide protection, all the data is accessible
    - Sometimes good for recovery
  - On standard Unix/Windows setups
    - rm/del doesn't make the data go away
      - Also sometimes useful for recovery
  - Even format does not guarantee data overwritten
- **See:** Remembrance of Data Passed: A Study of Disk Sanitization Practices
- **What about iPhone?**

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Security Example: File Permissions in Unix

- **Best to show with an example:**
  - Assuming you been typing in examples thus far, type:

`cd ~/ese150`

    - Puts you into the "ese150" subdirectory of your "~" home directory

`ls -al`

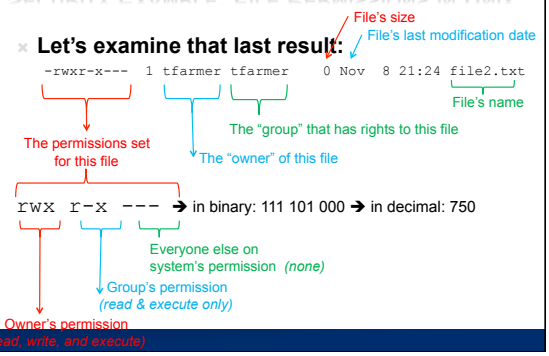
    - Passes two "arguments" to the ls command:
    - "a" (shows all files/even hidden)
    - "l" (stands for long formatted listing, you will see)

`ls -al` will return the following directory listing:

```
student@minus:~/ese250> ls -al
total 12
drwxr-x---  2 tfarmer tfarmer 4096 Nov  8 21:25 .
drwxr-x--x 36 tfarmer tfarmer 8192 Nov  8 21:24 ..
-rw-r-----  1 tfarmer tfarmer    0 Nov  8 21:25 file1.txt
-rw-r-----  1 tfarmer tfarmer    0 Nov  8 21:24 file2.txt
```

Security Example: File Permissions in Unix

- **Let's examine that last result:**



Security Example: File Permissions in Unix

- **To change permission on a file (or directory) you own:**

```
-rwxr-x---  1 tfarmer tfarmer    0 Nov  8 21:24 file2.txt
```

Type:
chmod 700 file2.txt

ls –al shows the change:

```
-rwx------  1 tfarmer tfarmer    0 Nov  8 21:24 file2.txt
```

Notice, the group lost its permission to see this file! (700, convert to binary)

- **To change ownership on a file you own:**

Type:
chown edin:ese-facu file2.txt *(changes owner & group)*

Careful, now your TA Edin, owns the file (and you don't!!):

```
-rwx------  1 edin ese-facu    0 Nov  8 21:24 file2.txt
```

OS's and their Filesystems

- **Typically an OS has a native filesystem it supports:**
  - Early PC OS: DOS (Disk Operating System)
    - File system: FAT (File Allocation Table)
  - Early Apple OS: Macintosh's "System"
    - File system: MFS (Machintosh File System)
  - Today's PC OS: Windows
    - File System: NTFS (New Technology File System)
  - Today's Apple OS: Mac OSx
    - File System: HFS+ (Hierarchical File System)
  - Today's Linux OS: Ubutnu, Debian, Fedora, Red Hat, SUSE, etc)
    - File System: EXT (Extended File System)
- **Now a days, many OS include support for more than one file system**
  - Example…CDs/DVDs have their own file system:
    - CDs: CDFS (Compact Disc File System): ISO 9660
    - DVDs: UDF (Universal Disk Format)

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Big Ideas…Filesystem

- **Filesystem**
  - Responsible for governing/organizing the persistent storage media (harddrive/flash/etc)
  - Provides a logical/common abstraction of the media to the OS and eventually the programmer/user
  - Provides structures to keep data on disk logically organized
    - Files may be all over the place physically, but programmer would never know!
  - Provides mechanism for securing files on physical disk
    - Security not always respected without presence of OS

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This Week In Lab

- **Lab 10: Design multi-view file system**
  - As might want for MP3 player
- **In Ketterer again**
- **Lab posted**

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Learn More at Penn!

- **Online reading/pointers**
  - Unix File System Tutorial
  - Flash, SSD, Hard drive data sheets
  - Data found on hard drive articles
- **Courses**
  - CIS121 – efficient data structures
  - CIS380 – operating systems

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