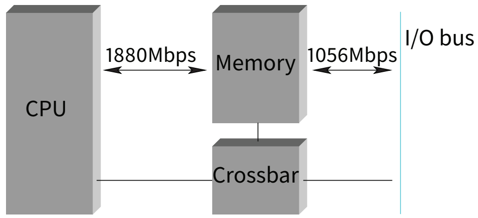
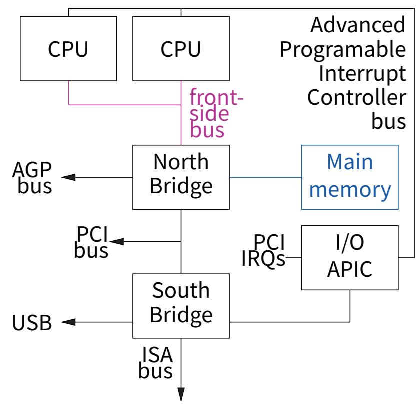
Memory and I/O buses

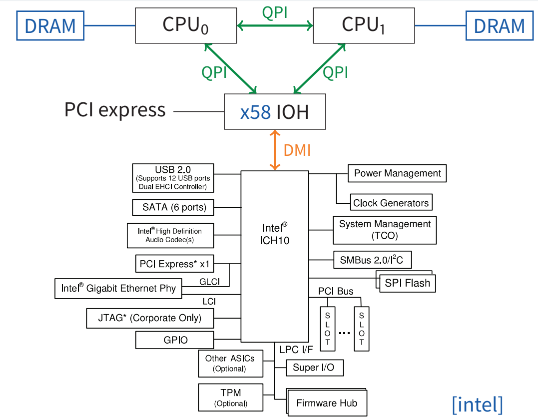


- CPU accesses physical memory over a bus
- Devices access memory over I/O bus with DMA
- Devices can appear to be a region of memory

Realistic ~2005 PC architecture



Modern PC architecture (intel)

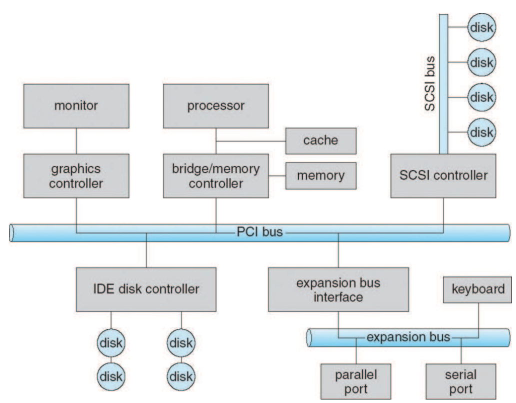


[intel]

What is memory?

- SRAM – Static RAM
  - Like two NOT gates circularly wired input-to-output
  - 4–6 transistors per bit, actively holds its value
  - Very fast, used to cache slower memory
- DRAM – Dynamic RAM
  - A capacitor + gate, holds charge to indicate bit value
  - 1 transistor per bit – extremely dense storage
  - Charge leaks – need slow comparator to decide if bit 1 or 0
  - Must re-write charge after reading, and periodically refresh
- VRAM – "Video RAM"
  - Dual ported DRAM, can write while someone else reads

What is I/O bus? E.g., PCI



Communicating with a device

- Memory-mapped device registers
  - Certain *physical* addresses correspond to device registers
  - Load/store gets status/sends instructions – not real memory
- Device memory – device may have memory OS can write to directly on other side of I/O bus
- Special I/O instructions
  - Some CPUs (e.g., x86) have special I/O instructions
  - Like load & store, but asserts special I/O pin on CPU
  - OS can allow user-mode access to I/O ports at byte granularity
- DMA – place instructions to card in main memory
  - Typically then need to "poke" card by writing to register
  - Overlaps unrelated computation with moving data over (typically slower than memory) I/O bus

x86 I/O instructions

```
static inline uint8_t
inb (uint16_t port)
{
  uint8_t data;
  asm volatile ("inb %w1, %b0" : "=a" (data) : "Nd" (port));
  return data;
}

static inline void
outb (uint16_t port, uint8_t data)
{
  asm volatile ("outb %b0, %w1" : : "a" (data), "Nd" (port));
}

static inline void
insw (uint16_t port, void *addr, size_t cnt)
{
  asm volatile ("rep insw" : "+D" (addr), "+c" (cnt)
                : "d" (port) : "memory");
}
:
```


Example: parallel port (LPT1)

- **Simple hardware has three control registers:**

D_7	D_6	D_5	D_4	D_3	D_2	D_1	D_0

read/write data register (port 0x378)

$\overline{\text{BSY}}$	$\overline{\text{ACK}}$	PAP	OFON	$\overline{\text{ERR}}$	–	–	–

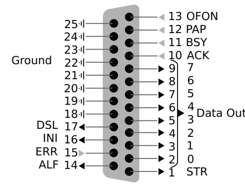
read-only status register (port 0x379)

–	–	–	IRQ	DSL	$\overline{\text{INI}}$	ALF	STR

read/write control register (port 0x37a)

[Messmer]

- **Every bit except IRQ corresponds to a pin on 25-pin connector:**



[image credits: Wikipedia]

Writing bit to parallel port [osdev]

```
void
sendbyte(uint8_t byte)
{
  /* Wait until BSY bit is 1. */
  while ((inb (0x379) & 0x80) == 0)
    delay ();

  /* Put the byte we wish to send on pins D7-0. */
  outb (0x378, byte);

  /* Pulse STR (strobe) line to inform the printer
   * that a byte is available */
  uint8_t ctrlval = inb (0x37a);
  outb (0x37a, ctrlval | 0x01);
  delay ();
  outb (0x37a, ctrlval);
}
```


IDE disk driver

```
void IDE_ReadSector(int disk, int off, void *buf)
{
  outb(0x1F6, disk == 0 ? 0xE0 : 0xF0); // Select Drive
  IDEWait();
  outb(0x1F2, 1);           // Read length (1 sector = 512 B)
  outb(0x1F3, off);         // LBA low
  outb(0x1F4, off >> 8);    // LBA mid
  outb(0x1F5, off >> 16);   // LBA high
  outb(0x1F7, 0x20);        // Read command
  insw(0x1F0, buf, 256);    // Read 256 words
}

void IDEWait()
{
  // Discard status 4 times
  inb(0x1F7); inb(0x1F7);
  inb(0x1F7); inb(0x1F7);
  // Wait for status BUSY flag to clear
  while ((inb(0x1F7) & 0x80) != 0)
    ;
}
```

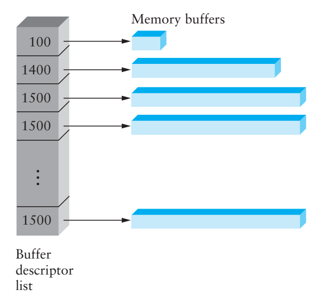

Memory-mapped IO

- `in`/`out` **instructions slow and clunky**
  - Instruction format restricts what registers you can use
  - Only allows 2^{16} different port numbers
  - Per-port access control turns out not to be useful
    (any port access allows you to disable all interrupts)
- **Devices can achieve same effect with physical addresses, e.g.:**

```
volatile int32_t *device_control
    = (int32_t *) (0xc0100 + PHYS_BASE);
*device_control = 0x80;
int32_t status = *device_control;
```

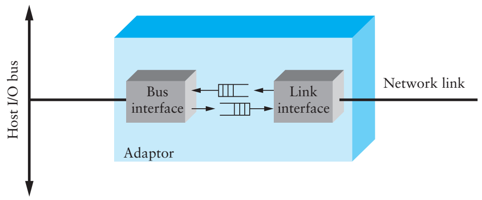
  - OS must map physical to virtual addresses, ensure non-cachable
- **Assign physical addresses at boot to avoid conflicts. PCI:**
  - Slow/clunky way to access configuration registers on device
  - Use that to assign ranges of physical addresses to device

DMA buffers



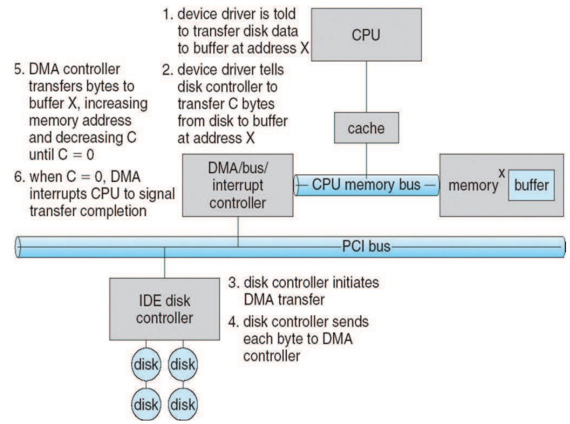
- **Idea: only use CPU to transfer control requests, not data**
- **Include list of buffer locations in main memory**
  - Device reads list and accesses buffers through DMA
  - Descriptions sometimes allow for scatter/gather I/O

Example: Network Interface Card



- **Link interface talks to wire/fiber/antenna**
  - Typically does framing, link-layer CRC
- **FIFOs on card provide small amount of buffering**
- **Bus interface logic uses DMA to move packets to and from buffers in main memory**

Example: IDE disk read w. DMA



Driver architecture

- **Device driver provides several entry points to kernel**
  - Reset, ioctl, output, interrupt, read, write, strategy ...
- **How should driver synchronize with card?**
  - E.g., Need to know when transmit buffers free or packets arrive
  - Need to know when disk request complete
- **One approach: *Polling***
  - Sent a packet? Loop asking card when buffer is free
  - Waiting to receive? Keep asking card if it has packet
  - Disk I/O? Keep looping until disk ready bit set
- **Disadvantages of polling?**

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- **Disadvantages of polling?**

  - Can't use CPU for anything else while polling
  - Schedule poll in future? High latency to receive packet or process disk block bad for response time

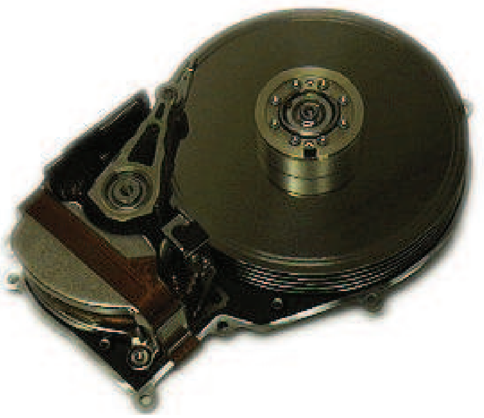
Interrupt driven devices

- **Instead, ask card to interrupt CPU on events**
  - Interrupt handler runs at high priority
  - Asks card what happened (xmit buffer free, new packet)
  - This is what most general-purpose OSes do
- **Bad under high network packet arrival rate**
  - Packets can arrive faster than OS can process them
  - Interrupts are very expensive (context switch)
  - Interrupt handlers have high priority
  - In worst case, can spend 100% of time in interrupt handler and never make any progress – *receive livelock*
  - Best: Adaptive switching between interrupts and polling
- **Very good for disk requests**
- **Rest of today: Disks (network devices in 3 lectures)**

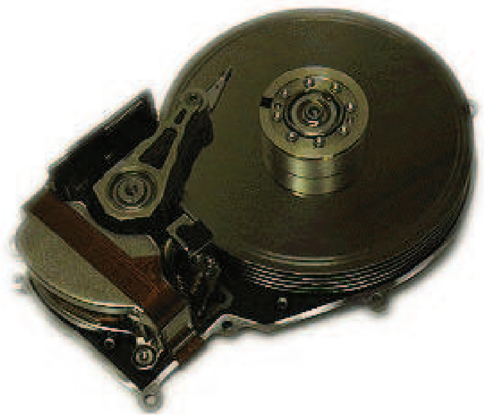
Anatomy of a disk [Ruemmler]

- **Stack of magnetic platters**
  - Rotate together on a central spindle @3,600-15,000 RPM
  - Drive speed drifts slowly over time
  - Can't predict rotational position after 100-200 revolutions
- **Disk arm assembly**
  - Arms rotate around pivot, all move together
  - Pivot offers some resistance to linear shocks
  - One disk head per recording surface (2×platters)
  - Sensitive to motion and vibration [Gregg] (demo on youtube)

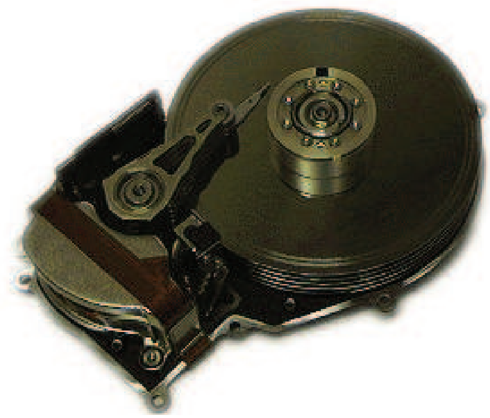
Disk



Disk



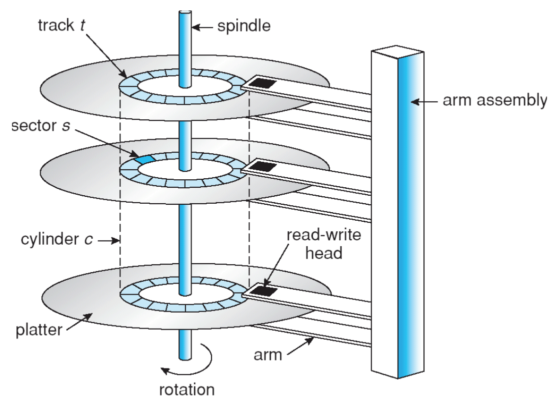
Disk



Storage on a magnetic platter

- **Platters divided into concentric *tracks***
- **A stack of tracks of fixed radius is a *cylinder***
- **Heads record and sense data along cylinders**
  - Significant fractions of encoded stream for error correction
- **Generally only one head active at a time**
  - Disks usually have one set of read-write circuitry
  - Must worry about cross-talk between channels
  - Hard to keep multiple heads exactly aligned

Cylinders, tracks, & sectors



Disk positioning system

- **Move head to specific track and keep it there**
  - Resist physical shocks, imperfect tracks, etc.
- **A *seek* consists of up to four phases:**
  - *speedup*–accelerate arm to max speed or half way point
  - *coast*–at max speed (for long seeks)
  - *slowdown*–stops arm near destination
  - *settle*–adjusts head to actual desired track
- **Very short seeks dominated by settle time (∼1 ms)**
- **Short (200-400 cyl.) seeks dominated by speedup**
  - Accelerations of 40g

Seek details

- **Head switches comparable to short seeks**
  - May also require head adjustment
  - Settles take longer for writes than for reads – Why?
- **Disk keeps table of pivot motor power**
  - Maps seek distance to power and time
  - Disk interpolates over entries in table
  - Table set by periodic "thermal recalibration"
  - But, e.g., ∼500 ms recalibration every ∼25 min bad for AV
- **"Average seek time" quoted can be many things**
  - Time to seek 1/3 disk, 1/3 time to seek whole disk

Seek details

- **Head switches comparable to short seeks**
  - May also require head adjustment
  - Settles take longer for writes than for reads
    If read strays from track, catch error with checksum, retry
    If write strays, you've just clobbered some other track
- **Disk keeps table of pivot motor power**
  - Maps seek distance to power and time
  - Disk interpolates over entries in table
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Sectors

- **Disk interface presents linear array of *sectors***
  - Historically 512 B, but 4 KiB in "advanced format" disks
  - Written atomically (even if there is a power failure)
- **Disk maps logical sector #s to physical sectors**
  - *Zoning*–puts more sectors on longer tracks
  - *Track skewing*–sector 0 pos. varies by track (why?)
  - *Sparing*–flawed sectors remapped elsewhere
- **OS doesn't know logical to physical sector mapping**
  - Larger logical sector # difference means longer seek time
  - Highly non-linear relationship (*and* depends on zone)
  - OS has no info on rotational positions
  - Can empirically build table to estimate times

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Disk interface

- **Controls hardware, mediates access**
- **Computer, disk often connected by bus (e.g., ATA, SCSI, SATA)**
  - Multiple devices may contentd for bus
- **Possible disk/interface features:**
- **Disconnect from bus during requests**
- **Command queuing: Give disk multiple requests**
  - Disk can schedule them using rotational information
- **Disk cache used for read-ahead**
  - Otherwise, sequential reads would incur whole revolution
  - Cross track boundaries? Can't stop a head-switch
- **Some disks support write caching**
  - But data not stable—not suitable for all requests

SCSI overview [Schmidt]

- **SCSI *domain* consists of devices and an SDS**
  - Devices: host adapters & SCSI controllers
  - *Service Delivery Subsystem* connects devices—e.g., SCSI bus
- **SCSI-2 bus (SDS) connects up to 8 devices**
  - Controllers can have >1 "logical units" (LUNs)
  - Typically, controller built into disk and 1 LUN/target, but "bridge controllers" can manage multiple physical devices
- **Each device can assume role of *initiator* or *target***
  - Traditionally, host adapter was initiator, controller target
  - Now controllers act as initiators (e.g., COPY command)
  - Typical domain has 1 initiator, ≥ 1 targets

SCSI requests

- A *request* is a command from initiator to target
  - Once transmitted, target has control of bus
  - Target may disconnect from bus and later reconnect (very important for multiple targets or even multitasking)
- Commands contain the following:
  - *Task identifier*—initiator ID, target ID, LUN, tag
  - *Command descriptor block*—e.g., read 10 blocks at pos. *N*
  - Optional *task attribute*—SIMPLE, ORDERD, HEAD OF QUEUE
  - Optional: output/input buffer, sense data
  - *Status byte*—GOOD, CHECK CONDITION, INTERMEDIATE, . . .

Executing SCSI commands

- Each LUN maintains a queue of *tasks*
  - Each task is DORMANT, BLOCKED, ENABLED, or ENDED
  - SIMPLE tasks are dormant until no ordered/head of queue
  - ORDERED tasks dormant until no HoQ/more recent ordered
  - HoQ tasks begin in enabled state
- Task management commands available to initiator
  - Abort/terminate task, Reset target, etc.
- Linked commands
  - Initiator can link commands, so no intervening tasks
  - E.g., could use to implement atomic read-modify-write
  - Intermediate commands return status byte INTERMEDIATE

SCSI exceptions and errors

- After error stop executing most SCSI commands
  - Target returns with CHECK CONDITION status
  - Initiator will eventually notice error
  - Must read specifics w. REQUEST SENSE
- Prevents unwanted commands from executing
  - E.g., initiator may not want to execute 2nd write if 1st fails
- Simplifies device implementation
  - Don't need to remember more than one error condition
- Same mechanism used to notify of media changes
  - I.e., ejected tape, changed CD-ROM

Disk performance

- Placement & ordering of requests a huge issue
  - Sequential I/O much, much faster than random
  - Long seeks much slower than short ones
  - Power might fail any time, leaving inconsistent state
- Must be careful about order for crashes
  - More on this in next two lectures
- Try to achieve contiguous accesses where possible
  - E.g., make big chunks of individual files contiguous
- Try to order requests to minimize seek times
  - OS can only do this if it has a multiple requests to order
  - Requires disk I/O concurrency
  - High-performance apps try to maximize I/O concurrency
- Next: How to schedule concurrent requests

Scheduling: FCFS

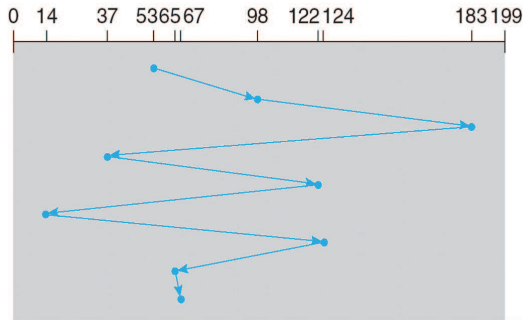
- "First Come First Served"
  - Process disk requests in the order they are received
- Advantages
- Disadvantages

Scheduling: FCFS

- "First Come First Served"
  - Process disk requests in the order they are received
- Advantages
  - Easy to implement
  - Good fairness
- Disadvantages
  - Cannot exploit request locality
  - Increases average latency, decreasing throughput

FCFS example

queue = 98, 183, 37, 122, 14, 124, 65, 67
head starts at 53



Shortest positioning time first (SPTF)

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  - Always pick request with shortest seek time
- Also called Shortest Seek Time First (SSTF)
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  - Exploits locality of disk requests
  - Higher throughput
- Disadvantages
  - Starvation
  - Don't always know what request will be fastest
- Improvement?

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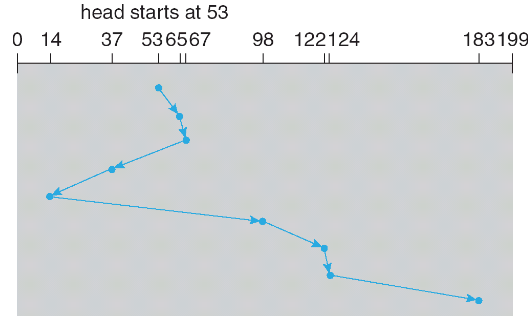
- Advantages
  - Exploits locality of disk requests
  - Higher throughput
- Disadvantages
  - Starvation
  - Don't always know what request will be fastest
- Improvement: Aged SPTF
  - Give older requests higher priority
  - Adjust "effective" seek time with weighting factor: $T_{\mathrm{eff}} = T_{\mathrm{pos}} - W \cdot T_{\mathrm{wait}}$

SPTF example

queue = 98, 183, 37, 122, 14, 124, 65, 67
head starts at 53



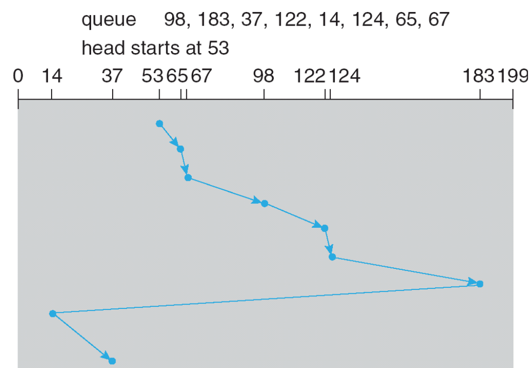
"Elevator" scheduling (SCAN)

- Sweep across disk, servicing all requests passed
  - Like SPTF, but next seek must be in same direction
  - Switch directions only if no further requests
- Advantages
- Disadvantages

“Elevator” scheduling (SCAN)

- **Sweep across disk, servicing all requests passed**
  - Like SPTF, but next seek must be in same direction
  - Switch directions only if no further requests
- **Advantages**
  - Takes advantage of locality
  - Bounded waiting
- **Disadvantages**
  - Cylinders in the middle get better service
  - Might miss locality SPTF could exploit
- **CSCAN: Only sweep in one direction**
  Very commonly used algorithm in Unix
- **Also called LOOK/CLOOK in textbook**
  - (Textbook uses [C]SCAN to mean scan entire disk uselessly)

CSCAN example



VSCAN(r)

- **Continuum between SPTF and SCAN**
  - Like SPTF, but slightly changes “effective” positioning time
    If request in same direction as previous seek: $T_{\mathrm{eff}} = T_{\mathrm{pos}}$
    Otherwise: $T_{\mathrm{eff}} = T_{\mathrm{pos}} + r \cdot T_{\mathrm{max}}$
  - when r = 0, get SPTF, when r = 1, get SCAN
  - E.g., r = 0.2 works well
- **Advantages and disadvantages**
  - Those of SPTF and SCAN, depending on how r is set
- **See [Worthington] for good description and evaluation of various disk scheduling algorithms**

Flash memory

- **Today, people increasingly using flash memory**
- **Completely solid state (no moving parts)**
  - Remembers data by storing charge
  - Lower power consumption and heat
  - No mechanical seek times to worry about
- **Limited # overwrites possible**
  - Blocks wear out after 10,000 (MLC) – 100,000 (SLC) erases
  - Requires *flash translation layer* (FTL) to provide *wear leveling*, so repeated writes to logical block don’t wear out physical block
  - FTL can seriously impact performance
  - In particular, random writes *very* expensive [Birrell]
- **Limited durability**
  - Charge wears out over time
  - Turn off device for a year, you can potentially lose data

Types of flash memory

- **NAND flash (most prevalent for storage)**
  - Higher density (most used for storage)
  - Faster erase and write
  - More errors internally, so need error correction
- **NOR flash**
  - Faster reads in smaller data units
  - Can execute code straight out of NOR flash
  - Significantly slower erases
- **Single-level cell (SLC) vs. Multi-level cell (MLC)**
  - MLC encodes multiple bits in voltage level
  - MLC slower to write than SLC
  - MLC has lower durability (bits decay faster)

NAND Flash Overview

- **Flash device has 2112-byte *pages***
  - 2048 bytes of data + 64 bytes metadata & ECC
- ***Blocks* contain 64 (SLC) or 128 (MLC) pages**
- **Blocks divided into 2–4 *planes***
  - All planes contend for same package pins
  - But can access their blocks in parallel to overlap latencies
- **Can *read* one page at a time**
  - Takes 25 μsec + time to get data off chip
- **Must *erase* whole block before *programing***
  - Erase sets all bits to 1—very expensive (2 msec)
  - Programming pre-erased block requires moving data to internal buffer, then 200 (SLC)–800 (MLC) μsec

Flash Characteristics [Caulfield'09]

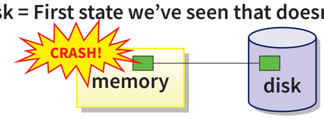
	Parameter	SLC	MLC
	Density Per Die (GB)	4	8
	Page Size (Bytes)	2048+32	2048+64
	Block Size (Pages)	64	128
	Read Latency (μs)	25	25
	Write Latency (μs)	200	800
	Erase Latency (μs)	2000	2000
40MHz, 16-bit bus	Read b/w (MB/s)	75.8	75.8
	Program b/w (MB/s)	20.1	5.0
133MHz	Read b/w (MB/s)	126.4	126.4
	Program b/w (MB/s)	20.1	5.0

File system fun

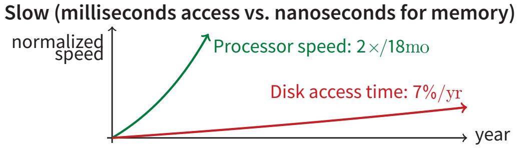
- **File systems: traditionally hardest part of OS**
  - More papers on FSes than any other single topic
- **Main tasks of file system:**
  - Don't go away (ever)
  - Associate bytes with name (files)
  - Associate names with each other (directories)
  - Can implement file systems on disk, over network, in memory, in non-volatile ram (NVRAM), on tape, w/ paper.
  - We'll focus on disk and generalize later
- **Today: files, directories, and a bit of performance**

Why disks are different

- **Disk = First state we've seen that doesn't go away**



  - So: Where all important state ultimately resides
- **Slow (milliseconds access vs. nanoseconds for memory)**



- **Huge (100–1,000x bigger than memory)**
  - How to organize large collection of ad hoc information?
  - File System: Hierarchical directories, Metadata, Search

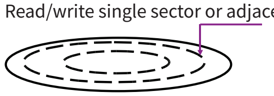
Disk vs. Memory

	Disk	MLC NAND Flash	DRAM
Smallest write	sector	sector	byte
Atomic write	sector	sector	byte/word
Random read	8 ms	3-10 μs	50 ns
Random write	8 ms	9-11 μs*	50 ns
Sequential read	100 MB/s	550–2500 MB/s	> 1 GB/s
Sequential write	100 MB/s	520–1500 MB/s*	> 1 GB/s
Cost	\$0.03/GB	\$0.35/GB	\$6/GiB
Persistence	Non-volatile	Non-volatile	Volatile

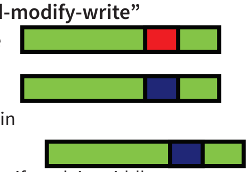
*Flash write performance degrades over time

Disk review

- **Disk reads/writes in terms of sectors, not bytes**
  - Read/write single sector or adjacent groups



- **How to write a single byte? "Read-modify-write"**
  - Read in sector containing the byte
  - Modify that byte
  - Write entire sector back to disk
  - Key: if cached, don't need to read in



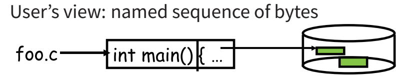
- **Sector = unit of atomicity.**
  - Sector write done completely, even if crash in middle (disk saves up enough momentum to complete)
- **Larger atomic units have to be synthesized by OS**

Some useful trends

- **Disk bandwidth and cost/bit improving exponentially**
  - Similar to CPU speed, memory size, etc.
- **Seek time and rotational delay improving *very* slowly**
  - Why? require moving physical object (disk arm)
- **Disk accesses a huge system bottleneck & getting worse**
  - Bandwidth increase lets system (pre-)fetch large chunks for about the same cost as small chunk.
  - Trade bandwidth for latency if you can get lots of related stuff.
- **Desktop memory size increasing faster than typical workloads**
  - More and more of workload fits in file cache
  - Disk traffic changes: mostly writes and new data
- **Memory and CPU resources increasing**
  - Use memory and CPU to make better decisions
  - Complex prefetching to support more IO patterns
  - Delay data placement decisions reduce random IO

Files: named bytes on disk

- **File abstraction:**
  - User's view: named sequence of bytes



  - FS's view: collection of disk blocks
  - File system's job: translate name & offset to disk blocks:

{file, offset} ⟶ FS ⟶ disk address

- **File operations:**
  - Create a file, delete a file
  - Read from file, write to file
- **Want: operations to have as few disk accesses as possible & have minimal space overhead (group related things)**

What's hard about grouping blocks?

- **Like page tables, file system metadata are simply data structures used to construct mappings**
  - Page table: map virtual page # to physical page #
    23 → Page table → 33
  - File metadata: map byte offset to disk block address
    512 → Unix inode → 8003121
  - Directory: map name to disk address or file #
    foo.c → directory → 44

FS vs. VM

- **In both settings, want location transparency**
  - Application shouldn't care about particular disk blocks or physical memory locations
- **In some ways, FS has easier job than than VM:**
  - CPU time to do FS mappings not a big deal (= no TLB)
  - Page tables deal with sparse address spaces and random access, files often denser $(0 \ldots \text{filesize} - 1)$, ~sequentially accessed
- **In some ways FS's problem is harder:**
  - Each layer of translation = potential disk access
  - Space a huge premium! (But disk is huge?!?!) Reason? Cache space never enough; amount of data you can get in one fetch never enough
  - Range very extreme: Many files <10 KB, some files many GB

Some working intuitions

- **FS performance dominated by # of disk accesses**
  - Say each access costs ~10 milliseconds
  - Touch the disk 100 extra times = 1 *second*
  - Can do a *billion* ALU ops in same time!
- **Access cost dominated by movement, not transfer:**
  $\boxed{\textbf{seek time} + \textbf{rotational delay} + \text{\# bytes/disk-bw}}$
  - 1 sector: 5ms + 4ms + 5μs ($\approx 512\,\text{B}/(100\,\text{MB/s})$) $\approx$ 9ms
  - 50 sectors: 5ms + 4ms + .25ms = 9.25ms
  - Can get 50x the data for only ~3% more overhead!
- **Observations that might be helpful:**
  - All blocks in file tend to be used together, sequentially
  - All files in a directory tend to be used together
  - All names in a directory tend to be used together

Common addressing patterns

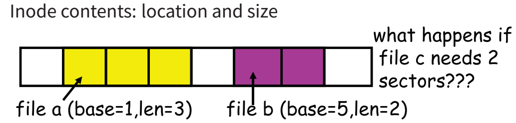
- **Sequential:**
  - File data processed in sequential order
  - By far the most common mode
  - Example: editor writes out new file, compiler reads in file, etc
- **Random access:**
  - Address any block in file directly without passing through predecessors
  - Examples: data set for demand paging, databases
- **Keyed access**
  - Search for block with particular values
  - Examples: associative data base, index
  - Usually not provided by OS

Problem: how to track file's data

- **Disk management:**
  - Need to keep track of where file contents are on disk
  - Must be able to use this to map byte offset to disk block
  - Structure tracking a file's sectors is called an index node or *inode*
  - Inodes must be stored on disk, too
- **Things to keep in mind while designing file structure:**
  - Most files are small
  - Much of the disk is allocated to large files
  - Many of the I/O operations are made to large files
  - Want good sequential and good random access (what do these require?)

Straw man: contiguous allocation

- **"Extent-based": allocate files like segmented memory**
  - When creating a file, make the user pre-specify its length and allocate all space at once
  - Inode contents: location and size



- **Example: IBM OS/360**
- **Pros?**
- **Cons? (Think of corresponding VM scheme)**

Straw man: contiguous allocation

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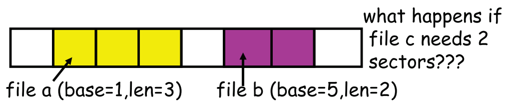
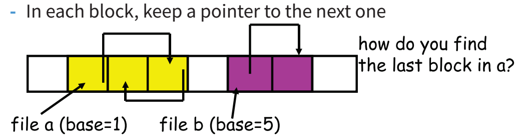


- **Example: IBM OS/360**
- **Pros?**
  - Simple, fast access, both sequential and random
- **Cons? (Think of corresponding VM scheme)**
  - External fragmentation

Straw man #2: Linked files

- **Basically a linked list on disk.**
  - Keep a linked list of all free blocks
  - Inode contents: a pointer to file's first block
  - In each block, keep a pointer to the next one



- **Examples (sort-of): Alto, TOPS-10, DOS FAT**
- **Pros?**
- **Cons?**

Straw man #2: Linked files

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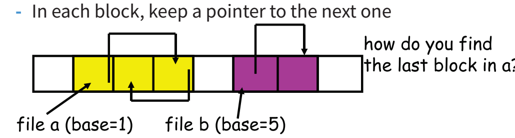


- **Examples (sort-of): Alto, TOPS-10, DOS FAT**
- **Pros?**
  - Easy dynamic growth & sequential access, no fragmentation
- **Cons?**
  - Linked lists on disk a bad idea because of access times
  - Random very slow (e.g., traverse whole file to find last block)
  - Pointers take up room in block, skewing alignment

Example: DOS FS (simplified)

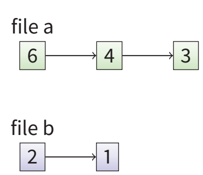
- **Linked files with key optimization: puts links in fixed-size "file allocation table" (FAT) rather than in the blocks.**

Directory (5)

a: 6
b: 2

FAT (16-bit entries)

0	free
1	eof
2	1
3	eof
4	3
5	eof
6	4
	...



- **Still do pointer chasing, but can cache entire FAT so can be cheap compared to disk access**

FAT discussion

- **Entry size = 16 bits**
  - What's the maximum size of the FAT?
  - Given a 512 byte block, what's the maximum size of FS?
  - One solution: go to bigger blocks. Pros? Cons?
- **Space overhead of FAT is trivial:**
  - 2 bytes / 512 byte block = $\sim$ 0.4% (Compare to Unix)
- **Reliability: how to protect against errors?**
  - Create duplicate copies of FAT on disk
  - State duplication a very common theme in reliability
- **Bootstrapping: where is root directory?**
  - Fixed location on disk:

FAT	(opt) FAT	root dir	...

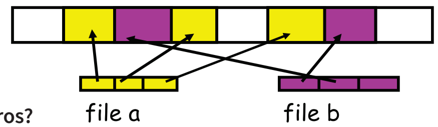
FAT discussion

- **Entry size = 16 bits**
  - What's the maximum size of the FAT? 65,536 entries
  - Given a 512 byte block, what's the maximum size of FS? 32 MiB
  - One solution: go to bigger blocks. Pros? Cons?
- **Space overhead of FAT is trivial:**
  - 2 bytes / 512 byte block = $\sim$ 0.4% (Compare to Unix)
- **Reliability: how to protect against errors?**
  - Create duplicate copies of FAT on disk
  - State duplication a very common theme in reliability
- **Bootstrapping: where is root directory?**
  - Fixed location on disk:

FAT	(opt) FAT	root dir	...

Another approach: Indexed files

- **Each file has an array holding all of its block pointers**
  - Just like a page table, so will have similar issues
  - Max file size fixed by array's size (static or dynamic?)
  - Allocate array to hold file's block pointers on file creation
  - Allocate actual blocks on demand using free list



- **Pros?**
- **Cons?**

Another approach: Indexed files

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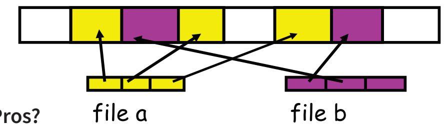
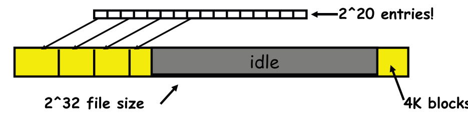


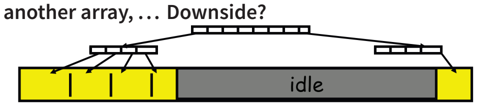
- **Pros?**
  - Both sequential and random access easy
- **Cons?**
  - Mapping table requires large chunk of contiguous space
    ... Same problem we were trying to solve initially

Indexed files

- **Issues same as in page tables**

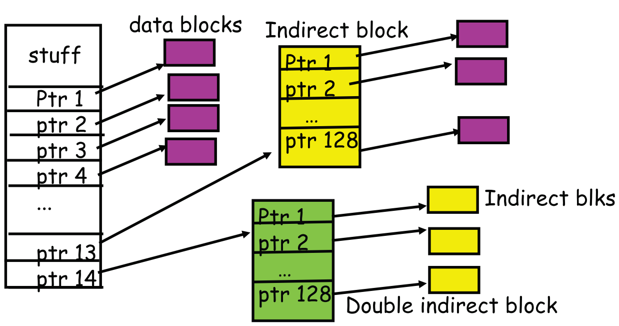


  - Large possible file size = lots of unused entries
  - Large actual size? table needs large contiguous disk chunk
- **Solve identically: small regions with index array, this array with another array, ... Downside?**



Multi-level indexed files (old BSD FS)

- **Solve problem of first block access slow**
- **inode = 14 block pointers + "stuff"**

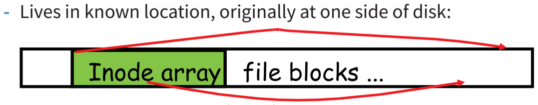


Old BSD FS discussion

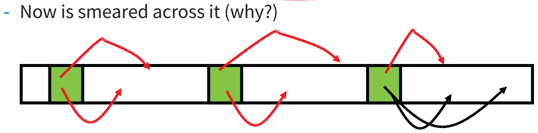
- **Pros:**
  - Simple, easy to build, fast access to small files
  - Maximum file length fixed, but large.
- **Cons:**
  - What is the worst case # of accesses?
  - What is the worst-case space overhead? (e.g., 13 block file)
- **An empirical problem:**
  - Because you allocate blocks by taking them off unordered freelist, metadata and data get strewn across disk

More about inodes

- **Inodes are stored in a fixed-size array**
  - Size of array fixed when disk is initialized; can't be changed
  - Lives in known location, originally at one side of disk:



  - Now is smeared across it (why?)



  - The index of an inode in the inode array called an i-number
  - Internally, the OS refers to files by inumber
  - When file is opened, inode brought in memory
  - Written back when modified and file closed or time elapses

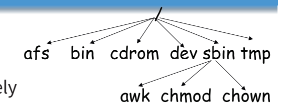
Directories

- **Problem:**
  - "Spend all day generating data, come back the next morning, want to use it." – F. Corbato, on why files/dirs invented
- **Approach 0: Users remember where on disk their files are**
  - E.g., like remembering your social security or bank account #
- **Yuck. People want human digestible names**
  - We use directories to map names to file blocks
- **Next: What is in a directory and why?**

A short history of directories

- **Approach 1: Single directory for entire system**
  - Put directory at known location on disk
  - Directory contains ⟨name, inumber⟩ pairs
  - If one user uses a name, no one else can
  - Many ancient personal computers work this way
- **Approach 2: Single directory for each user**
  - Still clumsy, and `ls` on 10,000 files is a real pain
- **Approach 3: Hierarchical name spaces**
  - Allow directory to map names to files *or other dirs*
  - File system forms a tree (or graph, if links allowed)
  - Large name spaces tend to be hierarchical (ip addresses, domain names, scoping in programming languages, etc.)

Hierarchical Unix



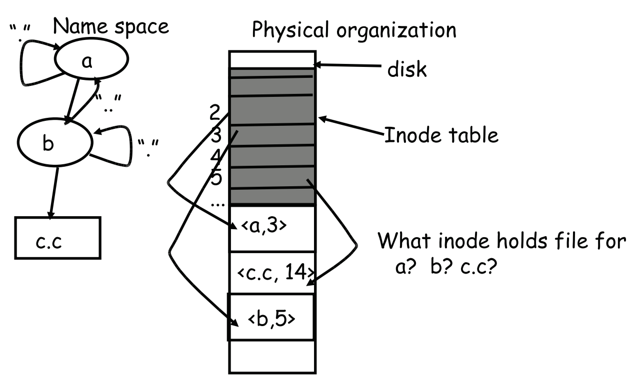
- **Used since CTSS (1960s)**
  - Unix picked up and used really nicely
- **Directories stored on disk just like regular files**
  - Special inode type byte set to directory
  - User's can read just like any other file
  - Only special syscalls can write (why?)
  - Inodes at fixed disk location
  - File pointed to by the index may be another directory
  - Makes FS into hierarchical tree (what needed to make a DAG?)
- **Simple, plus speeding up file ops speeds up dir ops!**

<*name*,*inode#*>
`<afs,1021>`
`<tmp,1020>`
`<bin,1022>`
`<cdrom,4123>`
`<dev,1001>`
`<sbin,1011>`
⋮

Naming magic

- **Bootstrapping: Where do you start looking?**
  - Root directory always inode #2 (0 and 1 historically reserved)
- **Special names:**
  - Root directory: "/"
  - Current directory: "`.`"
  - Parent directory: "`..`"
- **Some special names are provided by shell, not FS:**
  - User's home directory: "∼"
  - Globbing: "`foo.*`" expands to all files starting "`foo.`"
- **Using the given names, only need two operations to navigate the entire name space:**
  - `cd` *name*: move into (change context to) directory *name*
  - `ls`: enumerate all names in current directory (context)

Unix example: `/a/b/c.c`



Default context: working directory

- **Cumbersome to constantly specify full path names**
  - In Unix, each process has a "current working directory" (cwd)
  - File names not beginning with "/" are assumed to be relative to cwd; otherwise translation happens as before
  - Editorial: root, cwd should be regular fds (like stdin, stdout, ...) with *openat* syscall instead of *open*
- **Shells track a default list of active contexts**
  - A "search path" for programs you run
  - Given a search path $A : B : C$, a shell will check in A, then check in B, then check in C
  - Can escape using explicit paths: "./foo"
- **Example of locality**

Hard and soft links (synonyms)

- **More than one dir entry can refer to a given file**
  - Unix stores count of pointers ("hard links") to inode
  - To make: "`ln foo bar`" creates a synonym (`bar`) for *file* `foo`

foo bar

inode #31279
refcount = 2

- **Soft/symbolic links = synonyms for *names***
  - Point to a file (or dir) *name*, but object can be deleted from underneath it (or never even exist).
  - Unix implements like directories: inode has special "symlink" bit set and contains name of link target

```
ln -s /bar baz
```

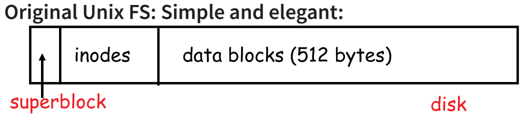
baz

"/bar"
refcount = 1

  - When the file system encounters a symbolic link it automatically translates it (if possible).

Case study: speeding up FS

- **Original Unix FS: Simple and elegant:**



- **Components:**
  - Data blocks
  - Inodes (directories represented as files)
  - Hard links
  - Superblock. (specifies number of blks in FS, counts of max # of files, pointer to head of free list)
- **Problem: slow**
  - Only gets 20Kb/sec (2% of disk maximum) even for sequential disk transfers!

A plethora of performance costs

- **Blocks too small (512 bytes)**
  - File index too large
  - Too many layers of mapping indirection
  - Transfer rate low (get one block at time)
- **Poor clustering of related objects:**
  - Consecutive file blocks not close together
  - Inodes far from data blocks
  - Inodes for directory not close together
  - Poor enumeration performance: e.g., "`ls`", "`grep foo *.c`"
- **Usability problems**
  - 14-character file names a pain
  - Can't atomically update file in crash-proof way
- **Next: how FFS fixes these (to a degree) [McKusic]**

Problem: Internal fragmentation

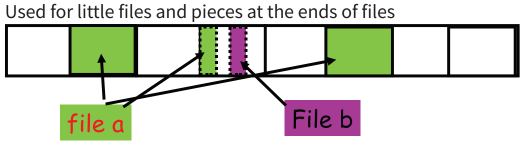
- **Block size was too small in Unix FS**
- **Why not just make block size bigger?**

Block size	space wasted	file bandwidth
512	6.9%	2.6%
1024	11.8%	3.3%
2048	22.4%	6.4%
4096	45.6%	12.0%
1MB	99.0%	97.2%

- **Bigger block increases bandwidth, but how to deal with wastage ("internal fragmentation")?**
  - Use idea from malloc: split unused portion.

Solution: fragments

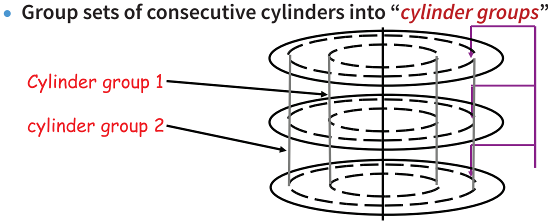
- **BSD FFS:**
  - Has large block size (4096 or 8192)
  - Allow large blocks to be chopped into small ones ("fragments")
  - Used for little files and pieces at the ends of files



- **Best way to eliminate internal fragmentation?**
  - Variable sized splits of course
  - Why does FFS use fixed-sized fragments (1024, 2048)?

Clustering related objects in FFS

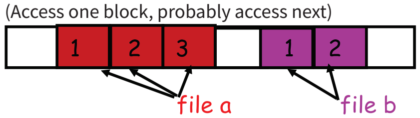
- **Group sets of consecutive cylinders into "*cylinder groups*"**



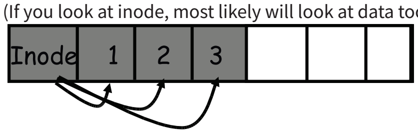
  - Key: can access any block in a cylinder without performing a seek. Next fastest place is adjacent cylinder.
  - Tries to put everything related in same cylinder group
  - Tries to put everything not related in different group

Clustering in FFS

- **Tries to put sequential blocks in adjacent sectors**
  - (Access one block, probably access next)



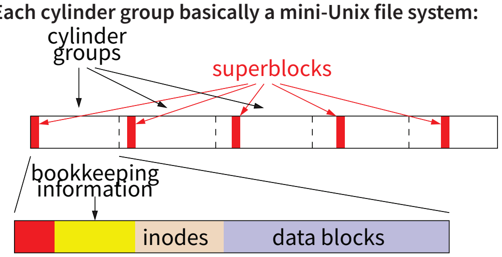
- **Tries to keep inode in same cylinder as file data:**
  - (If you look at inode, most likely will look at data too)



- **Tries to keep all inodes in a dir in same cylinder group**
  - Access one name, frequently access many, e.g., “`ls -l`”

What does disk layout look like?

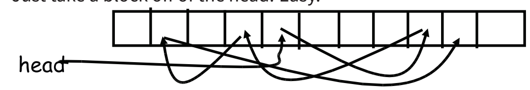
- **Each cylinder group basically a mini-Unix file system:**



- **How how to ensure there’s space for related stuff?**
  - Place different directories in different cylinder groups
  - Keep a “free space reserve” so can allocate near existing things
  - When file grows too big (1MB) send its remainder to different cylinder group.

Finding space for related objs

- **Old Unix (& DOS): Linked list of free blocks**
  - Just take a block off of the head. Easy.



  - Bad: free list gets jumbled over time. Finding adjacent blocks hard and slow
- **FFS: switch to bit-map of free blocks**
  - 1010101111111000001111111000101100
  - Easier to find contiguous blocks.
  - Small, so usually keep entire thing in memory
  - Time to find free block increases if fewer free blocks

Using a bitmap

- **Usually keep entire bitmap in memory:**
  - 4G disk / 4K byte blocks. How big is map?
- **Allocate block close to block x?**
  - Check for blocks near `bmap[x/32]`
  - If disk almost empty, will likely find one near
  - As disk becomes full, search becomes more expensive and less effective
- **Trade space for time (search time, file access time)**
- **Keep a reserve (e.g, 10%) of disk always free, ideally scattered across disk**
  - Don’t tell users (`df` can get to 110% full)
  - Only root can allocate blocks once FS 100% full
  - With 10% free, can almost always find one of them free

So what did we gain?

- **Performance improvements:**
  - Able to get 20-40% of disk bandwidth for large files
  - 10-20x original Unix file system!
  - Better small file performance (why?)
- **Is this the best we can do? No.**
- **Block based rather than extent based**
  - Could have named contiguous blocks with single pointer and length (Linux ext2fs, XFS)
- **Writes of metadata done synchronously**
  - Really hurts small file performance
  - Make asynchronous with write-ordering (“soft updates”) or logging/journaling… more next lecture
  - Play with semantics (/tmp file systems)

Other hacks

- **Obvious:**
  - Big file cache
- **Fact: no rotation delay if get whole track.**
  - How to use?
- **Fact: transfer cost negligible.**
  - Recall: Can get 50x the data for only $\sim$3% more overhead
  - 1 sector: 5ms + 4ms + 5μs ($\approx 512\,\mathrm{B}/(100\,\mathrm{MB/s})$) $\approx$ 9ms
  - 50 sectors: 5ms + 4ms + .25ms = 9.25ms
  - How to use?
- **Fact: if transfer huge, seek + rotation negligible**
  - LFS: Hoard data, write out MB at a time
- **Next lecture:**
  - FFS in more detail
  - More advanced, modern file systems