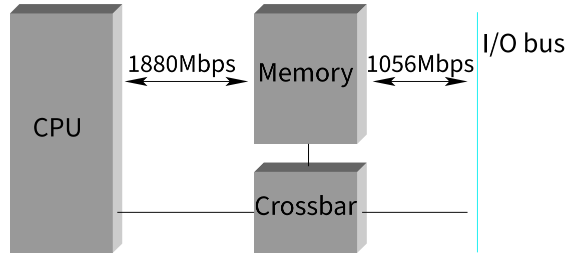
Outline

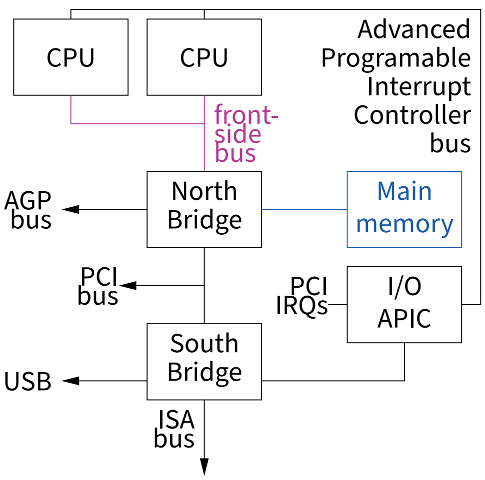
1. PC system architecture
2. Driver architecture
3. Disks
4. Disk scheduling
5. Flash

Old-school memory and I/O buses

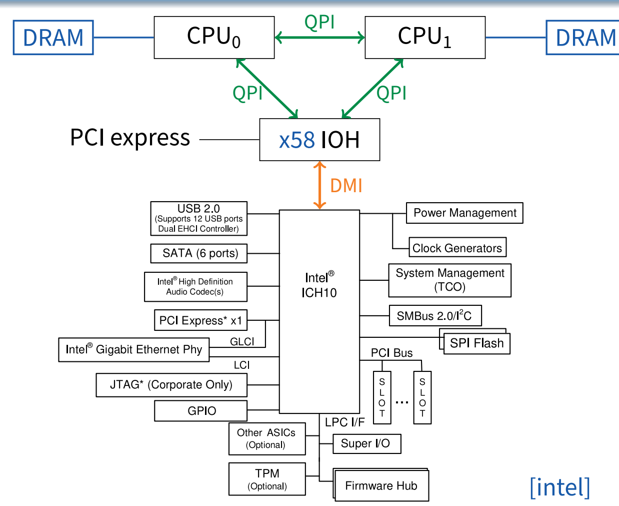


- CPU accesses physical memory over a bus
- Devices access memory over I/O bus with DMA
- Devices can appear to be a region of memory

Realistic ~2005 PC architecture

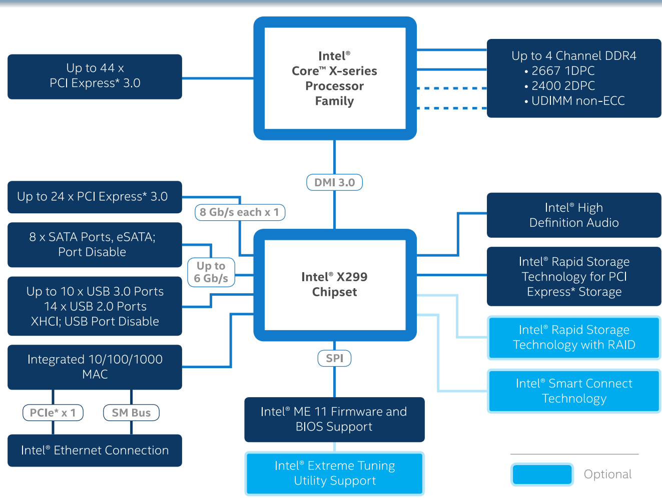


Modern PC architecture (intel)

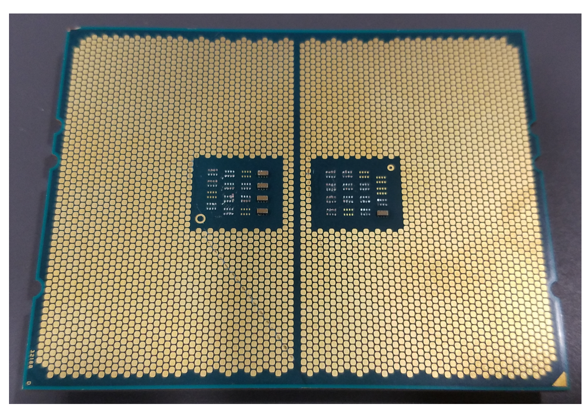


[intel]

CPU now entirely subsumes IOH [intel]



AMD EPYC is essentially an SoC

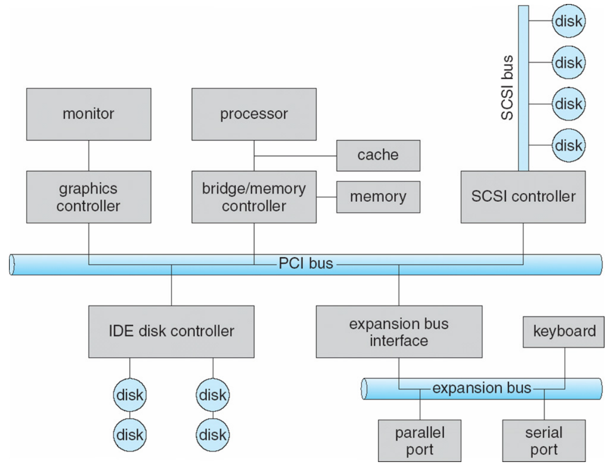


- 4094 pins: both memory controller and 128 lanes PCIe directly on chip!

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



Outline

1. PC system architecture
2. Driver architecture
3. Disks
4. Disk scheduling
5. Flash

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)

BSY	ACK	PAP	OFON	ERR	–	–	–

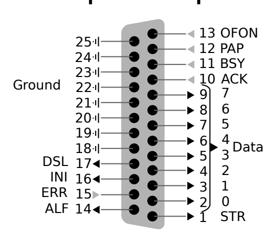
read-only status register (port 0x379)

–	–	–	IRQ	DSL	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)
    ;
}
```

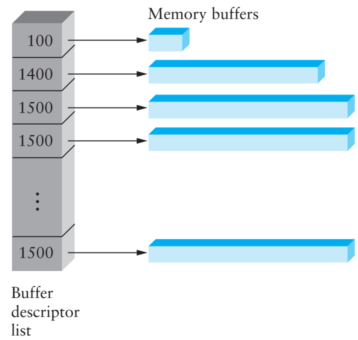

Memory-mapped IO

- `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;
```

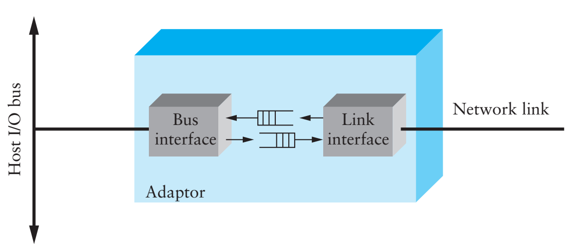
  - OS must map physical to virtual addresses, ensure non-cachable
- **Assign physical addresses at boot to avoid conflicts. PCI:**
  - Slow/clunky way to access configuration registers on device
  - Use that to assign ranges of physical addresses to device

DMA buffers



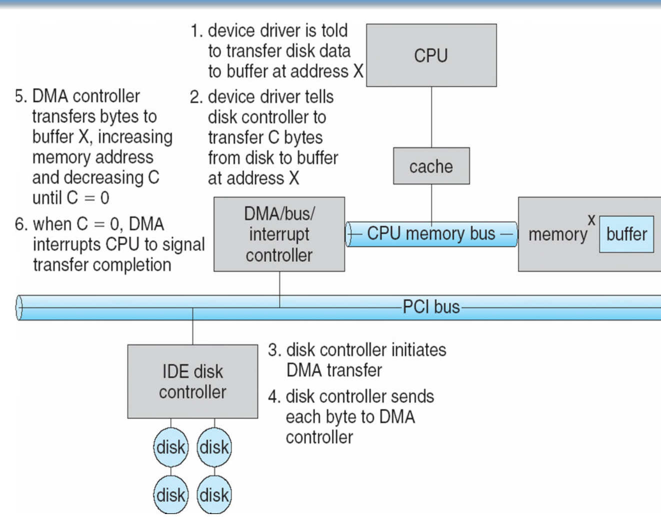
- **Idea: only use CPU to transfer control requests, not data**
- **Include list of buffer locations in main memory**
  - Device reads list and accesses buffers through DMA
  - Descriptions sometimes allow for scatter/gather I/O

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?**

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?**
  - 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 expensive
  - 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)**

Outline

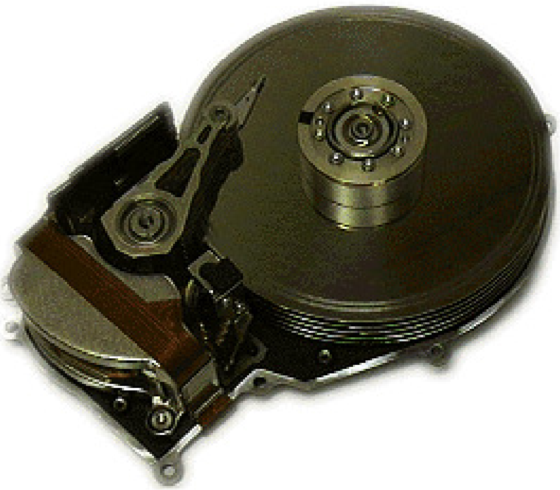
1. PC system architecture
2. Driver architecture
3. Disks
4. Disk scheduling
5. Flash

Anatomy of a disk [Ruemmler]

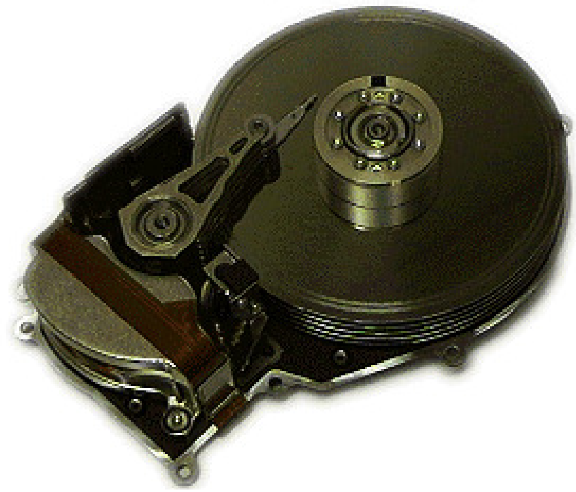
- **Stack of magnetic platters**
  - Rotate together on a central spindle @3,600-15,000 RPM
  - Drive speed drifts slowly over time
  - Can't predict rotational position after 100-200 revolutions
- **Disk arm assembly**
  - Arms rotate around pivot, all move together
  - Pivot offers some resistance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

Disk

Disk



Disk

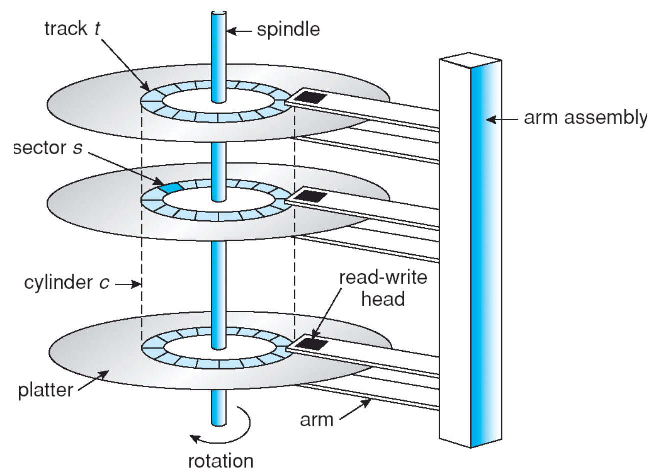


23 / 45

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
  - Table set by periodic "thermal recalibration"
  - But, e.g., $\sim$500 ms recalibration every $\sim$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

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

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 (sequential access speed
  - *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

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

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 multiple requests to order
  - Requires disk I/O concurrency
  - High-performance apps try to maximize I/O concurrency
- **Next: How to schedule concurrent requests**

Outline

1. PC system architecture
2. Driver architecture
3. Disks
4. Disk scheduling
5. Flash

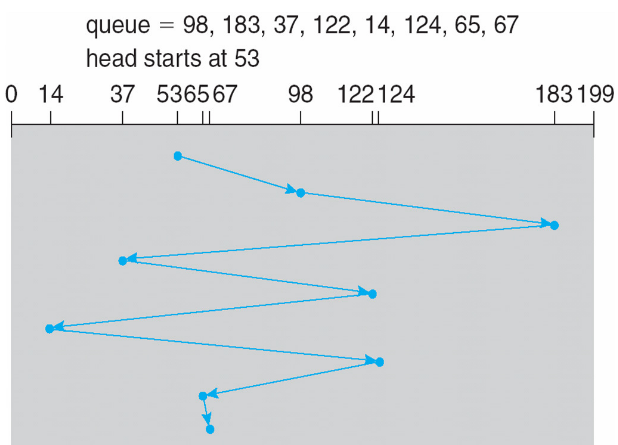
Scheduling: FCFS

- **“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



Shortest positioning time first (SPTF)

- **Shortest positioning time first (SPTF)**
  - Always pick request with shortest seek time
- **Also called Shortest Seek Time First (SSTF)**
- **Advantages**
- **Disadvantages**

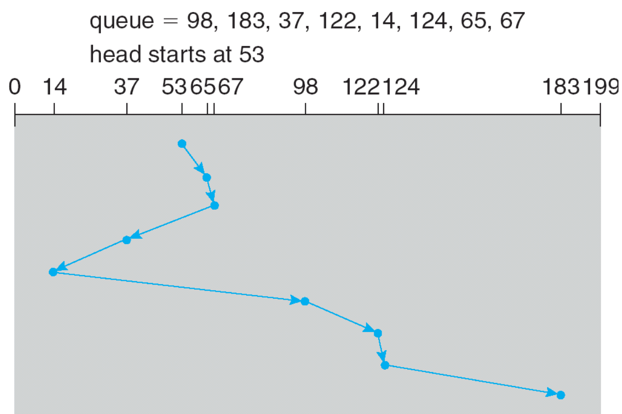
Shortest positioning time first (SPTF)

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

Shortest positioning time first (SPTF)

- **Shortest positioning time first (SPTF)**
  - Always pick request with shortest seek time
- **Also called Shortest Seek Time First (SSTF)**
- **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: $T_{\text{eff}} = T_{\text{pos}} - W \cdot T_{\text{wait}}$

SPTF example



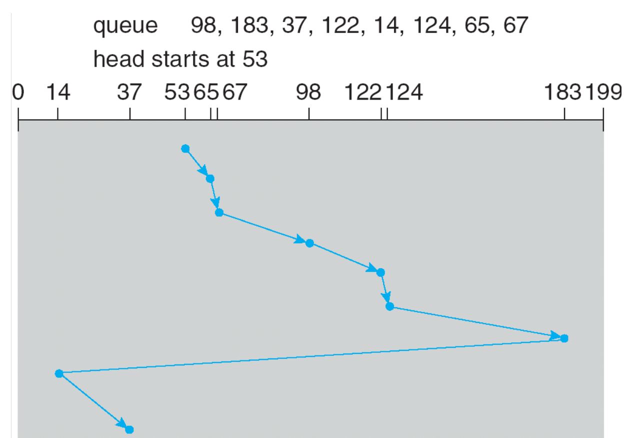
"Elevator" scheduling (SCAN)

- **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**

Outline

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 (two) bits in voltage level
  - MLC slower to write than SLC
  - MLC has lower durability (bits decay faster)
- **Nowadays, most flash drives are TLC (or even QLC)**

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 segregated 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

FTL straw man: in-memory map

- **Keep in-memory map of logical $\rightarrow$ physical page #**
  - On write, pick unused page, mark previous physical page free
  - Repeated writes of a logical page will hit different physical pages
- **Store map in device memory, but must rebuild on power-up**
- **Idea: Put header on each page, scan all headers on power-up: $\langle$logical page #, *Allocated* bit, *Written* bit, *Obsolete* bit$\rangle$**
  - A-W-O = 1-1-1: free page
  - A-W-O = 0-1-1: about to write page
  - A-W-O = 0-0-1: successfully written page
  - A-W-O = 0-0-0: obsolete page (can erase block without copying)
- **Why the 0-1-1 state?**
- **What's wrong still?**

FTL straw man: in-memory map

- **Keep in-memory map of logical $\rightarrow$ physical page #**
  - On write, pick unused page, mark previous physical page free
  - Repeated writes of a logical page will hit different physical pages
- **Store map in device memory, but must rebuild on power-up**
- **Idea: Put header on each page, scan all headers on power-up: $\langle$logical page #, *Allocated* bit, *Written* bit, *Obsolete* bit$\rangle$**
  - A-W-O = 1-1-1: free page
  - A-W-O = 0-1-1: about to write page
  - A-W-O = 0-0-1: successfully written page
  - A-W-O = 0-0-0: obsolete page (can erase block without copying)
- **Why the 0-1-1 state?** After power failure partly written $\neq$ free
- **What's wrong still?**

FTL straw man: in-memory map

- **Keep in-memory map of logical $\rightarrow$ physical page #**
  - On write, pick unused page, mark previous physical page free
  - Repeated writes of a logical page will hit different physical pages
- **Store map in device memory, but must rebuild on power-up**
- **Idea: Put header on each page, scan all headers on power-up:** $\langle$**logical page #**, $\overline{Allocated}$ **bit**, $\overline{Written}$ **bit**, $\overline{Obsolete}$ **bit**$\rangle$
  - A-W-O = 1-1-1: free page
  - A-W-O = 0-1-1: about to write page
  - A-W-O = 0-0-1: successfully written page
  - A-W-O = 0-0-0: obsolete page (can erase block without copying)
- **Why the 0-1-1 state?** After power failure partly written $\neq$ free
- **What's wrong still?**
  - FTL requires a lot of RAM on device, plus time to scan all headers
  - Some blocks still get erased more than others (w. long-lived data)
  - Blocks with obsolete pages may also contain live pages

More realistic FTL

- **Store the FTL map in the flash device itself**
  - Add one header bit to distinguish map page from data page
  - Logical read may miss map cache, require 2 flash reads
  - Keep smaller "map-map" in memory, cache some map pages
- **Must garbage-collect blocks with obsolete pages**
  - Copy live pages to a new block, erase old block
  - Always need free blocks, can't use 100% physical storage
- **Problem: write amplification**
  - Small random writes punch holes in many blocks
  - If small writes require garbage-collecting a 90%-full blocks
    ...means you are writing 10$\times$ more physical than logical data!
- **Must also periodically re-write even blocks w/o holes**
  - *Wear leveling* ensures active blocks don't wear out first