- 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

- CPU
- CPU
- North Bridge
- South Bridge
- Main memory
- I/O APIC
- AGP bus
- PCI bus
- PCI IRQs
- USB
- ISA bus
- Advanced Programmable Interrupt Controller bus

Diagram depicts various components and connections in a realistic PC architecture from around 2005, including CPUs, bridges, memory, and I/O devices.
Modern PC architecture (intel)

CPU0 ➔ QPI ➔ CPU1

PCI express ➔ x58 IOH ➔ DMI

- DRAM
- CPU0
- CPU1
- QPI
- QPI
- QPI
- DRAM
- USB 2.0 (Supports 12 USB ports Dual EHCI Controller)
- SATA (6 ports)
- Intel® High Definition Audio Codec(s)
- PCI Express x1
- Intel® Gigabit Ethernet Phy
- GLCI
- LCI
- JTAG* (Corporate Only)
- GPIO
- Intel® ICH10
- Other ASICs (Optional)
- TPM (Optional)
- Power Management
- Clock Generators
- System Management (TCO)
- SMBus 2.0/I²C
- SPI Flash
- PCI Bus
- LPC I/F
- Super I/O
- Firmware Hub
- [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
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:

<table>
<thead>
<tr>
<th>(D_7)</th>
<th>(D_6)</th>
<th>(D_5)</th>
<th>(D_4)</th>
<th>(D_3)</th>
<th>(D_2)</th>
<th>(D_1)</th>
<th>(D_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>read/write data register (port 0x378)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BSY</th>
<th>ACK</th>
<th>PAP</th>
<th>OFON</th>
<th>ERR</th>
<th>–</th>
<th>–</th>
<th>–</th>
</tr>
</thead>
<tbody>
<tr>
<td>read-only status register (port 0x379)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>–</th>
<th>–</th>
<th>–</th>
<th>IRQ</th>
<th>DSL</th>
<th>INI</th>
<th>ALF</th>
<th>STR</th>
</tr>
</thead>
<tbody>
<tr>
<td>read/write control register (port 0x37a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

[Image credits: Wikipedia]
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);
}
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.:**
  
  ```c
  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
- 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

1. Device driver is told to transfer disk data to buffer at address X

2. Device driver tells disk controller to transfer C bytes from disk to buffer at address X

3. Disk controller initiates DMA transfer

4. Disk controller sends each byte to DMA controller

5. DMA controller transfers bytes to buffer X, increasing memory address and decreasing C until C = 0

6. When C = 0, DMA interrupts CPU to signal transfer completion
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
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

track $t$

sector $s$

cylinder $c$

platter

spindle

arm assembly

read-write head

rotation

arm
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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- “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

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- **Disk maps logical sector #s to physical sectors**
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  - **Track skewing**—sector 0 pos. varies by track (sequential access speed)
  - **Sparing**—flawed sectors remapped elsewhere

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  - 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 contend 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, \( \geq 1 \) 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
• “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
queue = 98, 183, 37, 122, 14, 124, 65, 67
head starts at 53
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)

- 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?

\[ T_{\text{eff}} = T_{\text{pos}} - W \cdot T_{\text{wait}} \]
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:
  \[ T_{\text{eff}} = T_{\text{pos}} - W \cdot T_{\text{wait}} \]
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)
queue: 98, 183, 37, 122, 14, 124, 65, 67
head starts at 53
VSCAN(r)

- Continuum between SPTF and SCAN
  - Like SPTF, but slightly changes “effective” positioning time
    If request in same direction as previous seek: \( T_{\text{eff}} = T_{\text{pos}} \)
    Otherwise: \( T_{\text{eff}} = T_{\text{pos}} + r \cdot T_{\text{max}} \)
  - 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 $\mu$sec + time to get data off chip
- Must erase whole block before programming
  - 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) $\mu$sec
### Flash Characteristics [Caulfield’09]

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

**Note:** The table presents characteristics for SLC (Single Level Cell) and MLC (Multi Level Cell) flash memory. The values for SLC and MLC are compared across various parameters such as density, page size, block size, read and write latencies, and bus read/write speeds at different clock rates.