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

Modern PC architecture (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

Realistic ~2005 PC architecture

CPU now entirely subsumes IOH [intel]
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 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

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Example: parallel port (LPT1)

- Simple hardware has three control registers:
  - D7 D6 D5 D4 D3 D2 D1
    - 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)

- Every bit except IRQ corresponds to a pin on 25-pin connector:
  - [Image credits: Wikipedia](#)

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IDE disk driver

```c
void IDE_ReadSector(int disk, int off, void *buf)
{
    outb(0x1F6, disk == 0 ? 0xEO : 0xF0); // Select Drive
    IDEWait();
    outb(0x1F2, 1); // Read length (1 sector = 512 B)
    outb(0x1F3, off); // LBA low
    outb(0x1F4, off >> 8); // 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)
        delay();
}
```

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x86 I/O instructions

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

---

Writing bit to parallel port [osdev]

```c
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);
    outb (0x37a, ctrlval);
}
```

---

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;
  
  /* Wait for status BUSY flag to clear */
  while (((status & 0x80) != 0)
      delay();
  /* Discard status 4 times */
  outb(0x378, byte);
  /* Put the byte we wish to send on pins D7-0. */
  outb (0x37a, ctrlval);
  /* Pulse STR (strobe) line to inform the printer */
  /* that a byte is available */
  uint8_t ctrlval = inb (0x37a);
  outb (0x37a, ctrlval | 0x01);
  outb (0x37a, ctrlval);
  
  /* Clear status */
  status = inb (0x37a);
  
  volatile int32_t *resume_control
  = (int32_t *) (0xc0100 + PHYS_BASE);
  *resume_control = 0x80;
  int32_t resume_status = *resume_control;
  
  /seven.pnum / /four.pnum/one.pnum
  `` `

- **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
  ```c
  /* Assign physical addresses at boot to avoid conflicts. PCI: */
  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);
      outb (0x37a, ctrlval);
      
      /* Clear status */
      status = inb (0x37a);
      
      volatile int32_t *resume_control
      = (int32_t *) (0xc0100 + PHYS_BASE);
      *resume_control = 0x80;
      int32_t resume_status = *resume_control;
  
  /seven.pnum / /four.pnum/one.pnum
  `` `

```c
/one.pnum/two.pnum / /four.pnum/one.pnum
```

---

IDE disk driver

```c
void IDE_ReadSector(int disk, int off, void *buf)
{
    outb(0x1F6, disk == 0 ? 0xEO : 0xF0); // Select Drive
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    // Wait for status BUSY flag to clear
    while (((inb(0x1F7) & 0x80) != 0)
        delay();
}
```
**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**

- 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

**Driver architecture**

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**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)

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

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 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, ≥ 1 targets

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**

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, ORDERED, 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

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
  - 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:
    \[ T_{eff} = T_{pos} - W \cdot T_{wait} \]
“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)

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 µsec + 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) µsec

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>
</tbody>
</table>

- **40MHz, 16-bit bus**
  - Read b/w (MB/s) 75.8
  - Program b/w (MB/s) 75.8

- **133MHz**
  - Read b/w (MB/s) 20.1
  - Program b/w (MB/s) 20.1