Devices and I/O

key concepts: device registers, device drivers, program-controlled I/O, DMA, polling, disk drives, disk head scheduling

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Devices

- **devices** are how a computer receives input and produces output
  - a **keyboard** is an input device
  - a **printer** is an output device
  - a **touch screen** is both input and output
- sys/161 example devices:
  - timer/clock - current time, timer, beep
  - disk drive - persistent storage
  - serial console - character input/output
  - text screen - character-oriented graphics
  - network interface - packet input/output

keyboards, mice, printers, graphics cards, USB fans, joysticks, key-loggers, CD drives, card readers, sound cards, ... are all devices

Terminology

- **bus:** a communication pathway between various devices in a computer
  - **internal bus:** memory bus or front side bus is for communication between the CPU and RAM. It is fast and close to the CPU(s).
  - **peripheral:** or expansion bus, allows devices in the computer to communicate
- **bridge:** connects two different buses

Device Register Example: Sys/161 timer/clock

- communication with devices carried out through **device registers**
- three primary types of device registers
  - **status**: tells you something about the device's current state. Typically, a status register is **read**.
  - **command**: issue a command to the device by writing a particular value to this register.
  - **data**: used to transfer larger blocks of data to/from the device.
- some device registers are combinations of primary types
  - a **status and command** register is read to discover the device's state and written to issue the device a command.

Device Register Example: Sys/161 timer/clock

Offset	Size	Type	Description
0	4	status	current time (seconds)
4	4	status	current time (nanoseconds)
8	4	command	restart-on-expiry
12	4	status and command	interrupt (reading clears)
16	4	status and command	countdown time (microseconds)
20	4	command	speaker (causes beeps)

The clock is used in preemptive scheduling.

Device Register Example: Serial Console

Offset	Size	Type	Description
0	4	command and data	character buffer
4	4	status	writeIRQ
8	4	status	readIRQ

If a write is in progress, the device exhibits **undefined** behaviour if another write is attempted.

Device Drivers

- a **device driver** is a part of the kernel that interacts with a device
- example: write character to serial output device

```
// only one writer at a time
P(output device write semaphore)
// trigger the write operation
write character to device data register
repeat {
    read writeIRQ register
} until status is ``completed''
// make the device ready again
write writeIRQ register to ack completion
V(output device write semaphore)
```

- this example illustrates **polling**: the kernel driver repeatedly checks device status

> Although the majority of device drivers are a (dynamically loadable) part of the kernel, some drivers exist in user-space.

Using Interrupts to Avoid Polling

Device Driver Write Handler:

```
// only one writer at a time
P(output device write semaphore)
// trigger write operation
write character to device data register
```

Interrupt Handler for Serial Device:

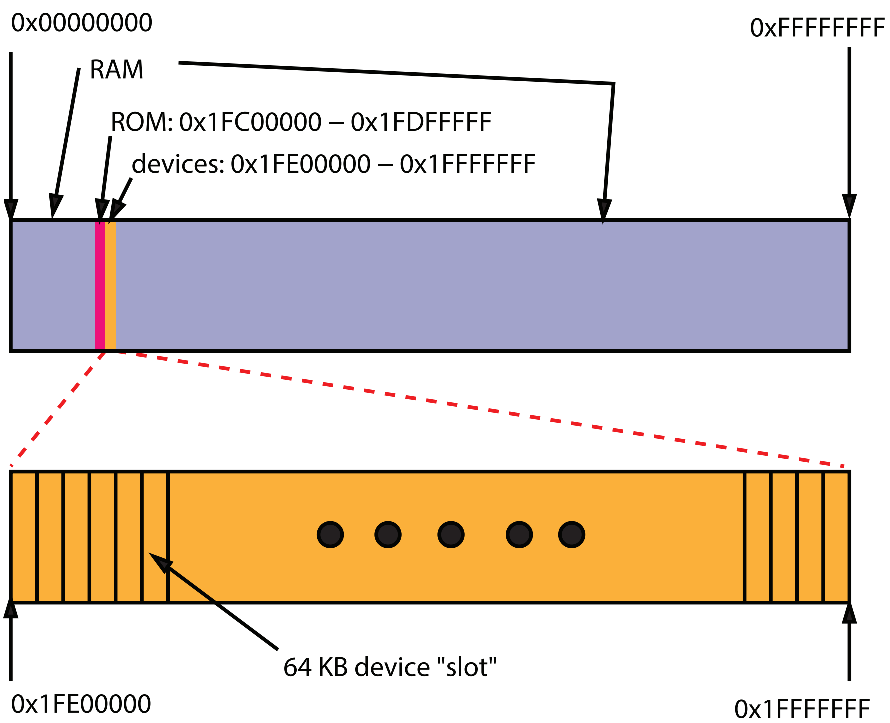
```
// make the device ready again
write writeIRQ register to ack completion
V(output device write semaphore)
```

Accessing Devices

- how can a device driver access device registers?
- Option 1: **Port-Mapped I/O** with special I/O instructions
  - device registers are assigned "port" numbers, which correspond to regions of memory in a separate, smaller address space
  - special I/O instructions, such as `in` and `out` instructions on x86 are used to transfer data between a specified port and a CPU register
- Option 2: **memory-mapped I/O**
  - each device register has a physical memory address
  - device drivers can read from or write to device registers using normal load and store instructions, as though accessing memory

A system may use both port-mapped and memory-mapped I/O.

MIPS/OS161 Physical Address Space



Each device is assigned to one of 32 64KB device "slots". A device's registers and data buffers are memory-mapped into its assigned slot.

Large Data Transfer To/From Devices

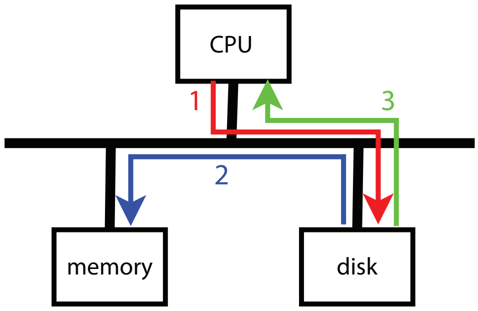
In addition to port and memory mapped I/O, large data blocks can be transferred using other strategies.

- **program-controlled I/O**

  The device driver moves the data between memory and a buffer on the device. The CPU is **busy** while the data is being transferred.

- **direct memory access (DMA)**

  The device itself is responsible for moving data to/from memory. CPU is **not busy** during this data transfer, and is free to do something else.



> Sys/161 disks do program-controlled I/O.

Persistant Storage Devices

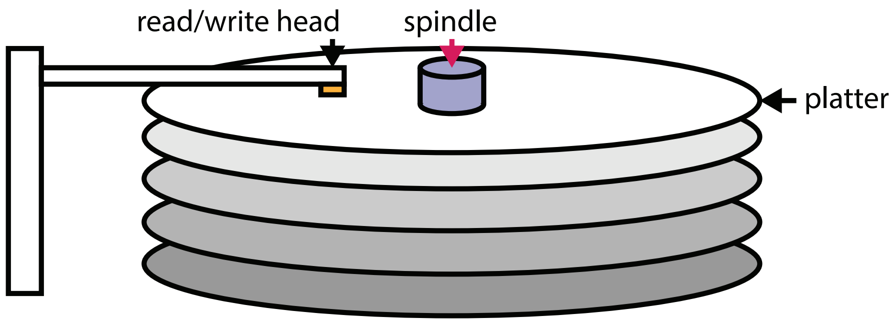
- **persistant** storage is any device where data persists even when the device is without power
  - physical memory is not persistant
  - a hard disk is persistant
  - also referred to as **non-volatile**
- persistant storage comes in many forms
  - punched cards of metal or paper (1700s-1970s)
  - magnetic drums (1930s-1960s), tapes (1920s)
  - floppy (1970s-2000s) and hard disks (1950s)
  - CDs (1980s), DVDs (1990s), Blu-ray (2000s)
  - solid state memory (1970s, 1990s)
  - ReRam (resistive RAM) (2000s)

> The earliest form of persistant storage was punched metal cards which held the "programs" for Jacquard weaving looms in the 1700s.

> Magnetic tapes are still in active use today!

Hard Disks

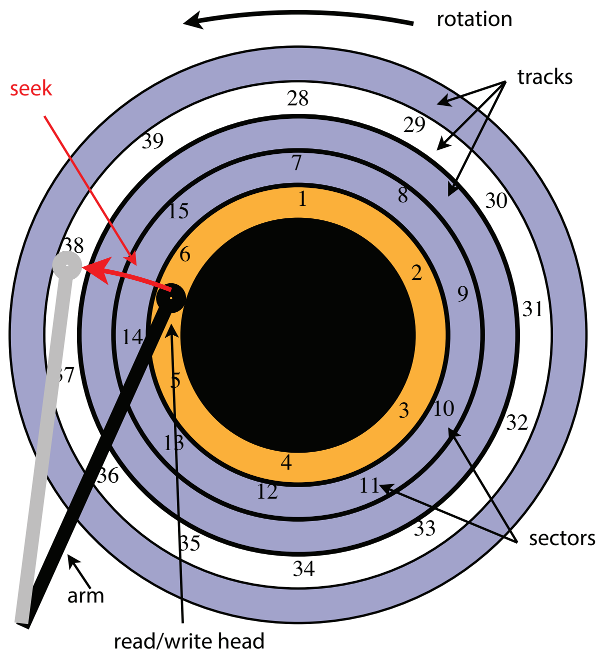
- commonly used persistant storage device
- a number of spinning, ferromagnetic-coated platters read/written by a moving R/W head



Platters are typially made from glass or porcelain. Hence, they are exceptionally fragile.

Often called mechanical disks, both patter and read/write head must move to perform a read or write operation. This motion is costly.

Logical View of a Disk Drive



- disk is an array of numbered blocks (or sectors)
- each block is the same size (e.g., 512 bytes)
- blocks are the unit of transfer between the disk and memory
  - typically, one or more contiguous blocks can be transferred in a single operation
- assume, for simplicity, that each track contains the same number of sectors

Cost Model for Disk I/O

- moving data to/from a disk involves:
  1. **seek time:** move the read/write heads to the appropriate track
     - depends on **seek distance**, the distance (in tracks) between previous and current request
     - value: 0 milliseconds to cost of max seek distance
  2. **rotational latency:** wait until the desired sectors spin to the read/write heads
     - depends on rotational speed of disk
     - disk is always spinning
     - value: 0 milliseconds to cost of single rotation
  3. **transfer time:** wait while the desired sectors spin past the read/write heads
     - depends on the rotational speed of the disk and the amount of data accessed
- Request Service Time = Seek Time + Rotational Latency + Transfer Time

Request Service Time Example

A disk has a total capacity of 2^{32} bytes. The disk has a single platter with 2^{20} tracks. Each track has 2^{8} sectors. The disk operates at 10000RPM and has a maximum seek time of 20 milliseconds.

1. How many bytes are in a track?
   $BytesPerTrack = DiskCapacity/NumTracks$
2. How many bytes are in a sector?
   $BytesPerSector = BytesPerTrack/NumSectorsPerTrack$
3. What is the maximum rotational latency?
   $MaxLatency = 60/RPM$
4. What is the average seek time and rotational latency?
   $AverageSeek = MaxSeek/2$
   $AverageLatency = MaxLatency/2$
5. What is the cost to transfer 1 sector?
   $SectorLatency = MaxLatency/NumSectorsPerTrack$
6. What is the expected cost to read 10 consecutive sectors from this disk?
   $RequestServiceTime = Seek + RotationalLatency + TransferTime$

Request Service Time Example

A disk has a total capacity of 2^{32} bytes. The disk has a single platter with 2^{20} tracks. Each track has 2^8 sectors. The disk operates at 10000RPM and has a maximum seek time of 20 milliseconds.

1. How many bytes are in a track?
   $= 2^{32}/2^{20} = 2^{12}$ bytes per track
2. How many bytes are in a sector?
   $= 2^{12}/2^8 = 2^4$ bytes per sector
3. What is the maximum rotational latency?
   $= 60/10000 = 0.006$ or 6 milliseconds
4. What is the average seek time and rotational latency?
   $= 20/2 = 10$ milliseconds average seek time
   $= 6/2 = 3$ milliseconds average rotational latency
5. What is the cost to transfer 1 sector?
   $= 6/2^8 = 6/256 = 0.0195$ milliseconds per sector
6. What is the expected cost to read 10 consecutive sectors from this disk?
   $= 10 + 3 + 10(0.0195) = 13.195$ milliseconds
   Note that since we do not know the position of the head, or the platter, we use the average seek and average rotational latency.

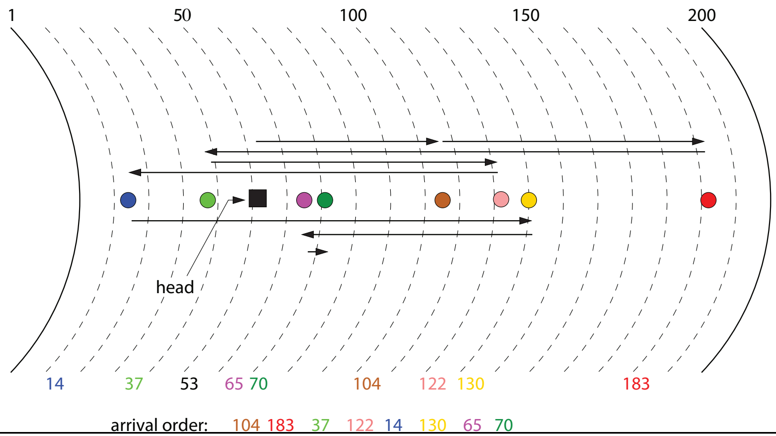
Performance Implications of Disk Characteristics

- larger transfers to/from a disk device are **more efficient** than smaller ones. That is, the cost (time) per byte is smaller for larger transfers. (Why?)
- sequential I/O is faster than non-sequential I/O
  - sequential I/O operations eliminate the need for (most) seeks
- while sequential I/O is not always possible, we can group requests to try and reduce average request time

> Historically, seek time is the dominating cost. High-end drives can have maximum seek times around 4 milliseconds. Consumer grade drives more commonly have seek times between 9 and 12 milliseconds.

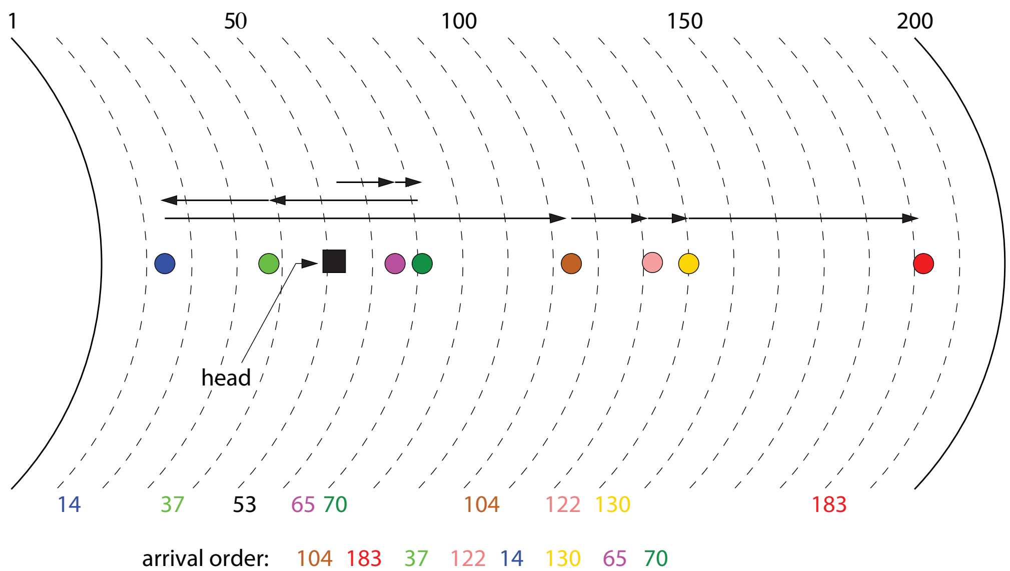
Disk Head Scheduling

- goal: reduce seek times by controlling the order in which requests are serviced
- disk head scheduling may be performed by the device, by the operating system, or both
- for disk head scheduling to be effective, there must be a queue of outstanding disk requests (otherwise there is nothing to reorder)
- **first-come, first served** is fair and simple, but offers no optimization for seek times



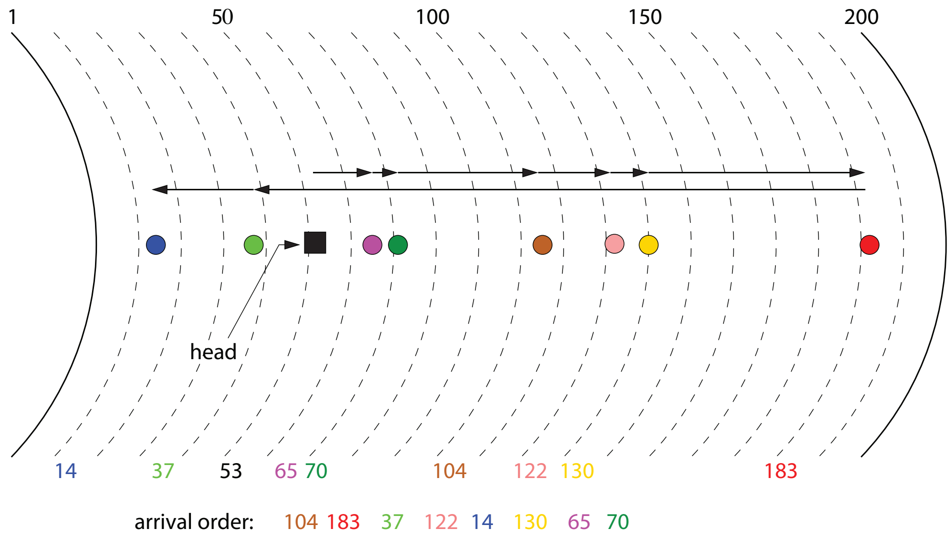
Shortest Seek Time First (SSTF)

- choose closest request (a greedy approach)
- seek times are reduced, but requests may starve



Elevator Algorithms (SCAN)

- Under SCAN, aka the elevator algorithm, the disk head moves in one direction until there are no more requests in front of it, then reverses direction.
- there are many variations on this idea
- SCAN reduces seek times (relative to FCFS), while avoiding starvation



Device Register Example: Sys/161 disk controller

Offset	Size	Type	Description
0	4	status	number of sectors
4	4	status and command	status
8	4	command	sector number
12	4	status	rotational speed (RPM)
32768	512	data	transfer buffer

Writing to a Sys/161 Disk

Device Driver Write Handler:

```
// only one disk request at a time
P(disk semaphore)
copy data from memory to device transfer buffer
write target sector number to disk sector number register
write ‘‘write’’ command to disk status register
// wait for request to complete
P(disk completion semaphore)
V(disk semaphore)
```

Interrupt Handler for Disk Device

```
// make the device ready again
write disk status register to ack completion
V(disk completion semaphore)
```

The thread that initiates the write should wait until that write is completed before continuing.

Reading From a Sys/161 Disk

Device Driver Read Handler:

```
// only one disk request at a time
P(disk semaphore)
write target sector number to disk sector number register
write ‘‘read’’ command to disk status register
// wait for request to complete
P(disk completion semaphore)
copy data from device transfer buffer to memory
V(disk semaphore)
```

Interrupt Handler for Disk Device

```
// make the device ready again
write disk status register to ack completion
V(disk completion semaphore)
```

The thread that initiates the read **must** wait until that read is completed before continuing.

Solid State Drives(SSD)

- no mechanical parts; use integrated circuits for persistant storage instead of magnetic surfaces
- variety of implementations
  - DRAM: requires constant power to keep values
  - Flash Memory: traps electrons in quantum cage
- logically divided into blocks and pages
  - 2, 4 or 8KB pages
  - 32KB-4MB blocks
- reads/writes at page level
  - pages are initialized to 1s; can transition $1 \rightarrow 0$ at page level (i.e., write new page)
  - a high voltage is required to switch $0 \rightarrow 1$ (i.e., overwrite/delete page)
  - cannot apply high voltage at page level, only to blocks
    - overwriting/deleting data must be done at the block level

Writing and Deleting from Flash Memory

- **Naive Solution (slow):**
  - read whole block into memory
  - re-initialize block (all page bits back to 1s)
  - update block in memory; write back to SSD
- **SSD controller handles requests (faster):**
  - mark page to be deleted/overwritten as invalid
  - write to an unused page
  - update translation table
  - requires garbage collection

> Each block of an SSD has a limited number of write cycles before it becomes read-only. SSD controllers perform **wear leveling**, distributing writes evenly across blocks, so that the blocks wear down at an even rate.
> Hence, defragmentation, which takes files spread across multiple, non-sequential pages and makes them sequential, can be harmful to the lifespan of an SSD. Additionally, since there are no moving parts, defragmentation serves no performance advantage.

Persistent RAM

- values are persistant in the absence of power
  - ReRAM: resistive RAM
  - 3D XPoint, Intel Optane
- can be used to improve the performance of secondary storage
  - traditional CPU caches are small; not effective for caching many disk blocks
  - RAM can cache i-nodes and data blocks; but should be used for address spaces
  - use persistant RAM instead
    - i-nodes and data blocks silently cached to this special memory
    - Intel Optane, for example, modules are 16-32GB, so many blocks can be cached giving big performance improvements when mechanical disks are used