Devices and I/O

key concepts

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

reading

Three Easy Pieces: Chapters 36-37

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Sys/161 Device Examples

- 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

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Device Register Example: Sys/161 timer/clock

Offset	Size	Туре	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)

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Device Register Example: Serial Console

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

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

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Using Interrupts to Avoid Polling

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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)
```

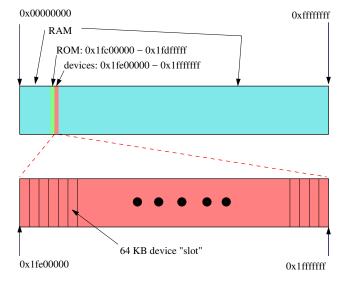
Accessing Devices

- how can a device driver access device registers?
- Option 1: special I/O instructions
 - such as in and out instructions on x86
 - device registers are assigned "port" numbers
 - instructions 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

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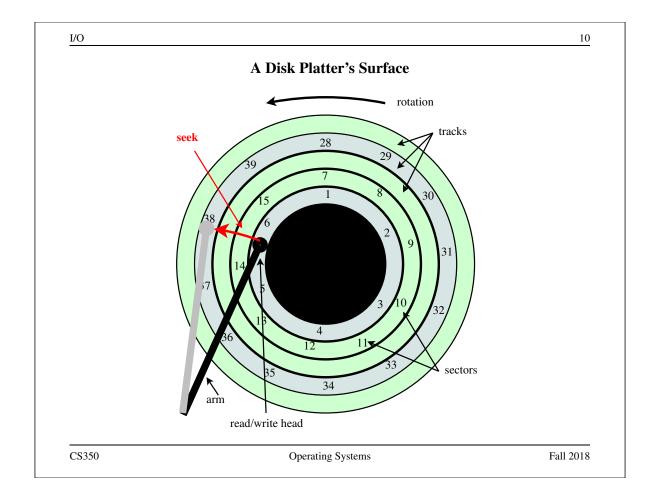
MIPS/OS161 Physical Address Space



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.

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
- storage is non-volatile, i.e., data persists even when the device is without power



Cost Model for Disk I/O

• moving data to/from a disk involves:

seek time: move the read/write heads to the appropriate cylinder

 depends on distance (in tracks) between previous request and current request - called the *seek distance*

rotational latency: wait until the desired sectors spin to the read/write heads

- depends on the rotational speed of the disk

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 being read/written
- request service time is the *sum* of seek time, rotational latency, and transfer time

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Seek, Rotation, and Transfer

- Seek time:
 - If the next request is for data on the same track as the previous request, seek distance and seek time will be zero.
 - In the worst case, e.g., seek from outermost track to innermost track, seek time may be 10 milliseconds or more.
- Rotational Latency:
 - Consider a disk that spins at 12,000 RPM
 - One complete rotation takes 5 millseconds.
 - Rotational latency ranges from 0ms to 5ms.
- Transfer Time:
 - Once positioned, the 12,000 RPM disk can read/write all data on a track in one rotation (5ms)
 - If only X% of the track's sectors are being read/written, transfer time will be X% of the complete rotation time (5ms).

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

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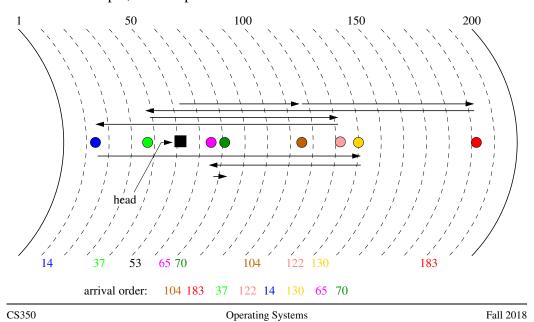
Disk Head Scheduling

- 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)
- an on-line approach is required: new I/O requests may arrive at any time



FCFS Disk Head Scheduling

- handle requests in the order in which they arrive
- fair and simple, but no optimization of seek times



Shortest Seek Time First (SSTF)

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

1 50 100 150 200

head

head

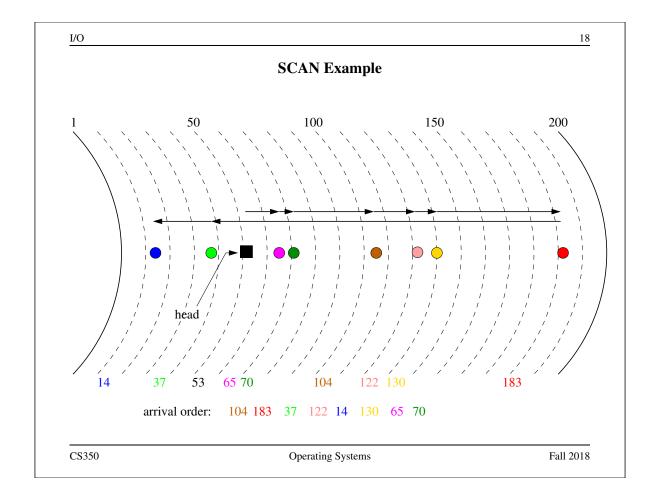
14 37 53 65 70 104 122 130 183

arrival order: 104 183 37 122 14 130 65 70

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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



Data Transfer To/From Devices

• Option 1: program-controlled I/O

The device driver moves the data between memory and a buffer on the device.

- Simple, but the CPU is *busy* while the data is being transferred.
- Option 2: 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.

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Device Register Example: Sys/161 disk controller

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Offset	Size	Туре	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)
```

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Reading From a Sys/161 Disk

Device Driver Read Handler:

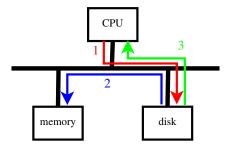
```
// only one disk request at a time
P(disk semaphore)
write target sector number to disk sector number register
write ''read'' command to disk status register
// wait for request to complete
P(disk completion semaphore)
copy data from device transfer buffer to memory
V(disk semaphore)
```

Interrupt Handler for Disk Device

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

Direct Memory Access (DMA)

- DMA is used for block data transfers between devices (e.g., a disk) and memory
- Under DMA, the CPU initiates the data transfer and is notified when the transfer is finished. However, the device (not the CPU) controls the transfer itself.



- 1. CPU issues DMA request to device
- 2. device directs data transfer
- 3. device interrupts CPU on completion

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Solid State Drives(SSD)

- no mechanical parts; use integrated circuits for persistant storage instead of magnetic surfaces
- DRAM: requires constant power to keep values
 - transistors with capacitors
 - capacitor holds microsecond charge; periodically refreshed by primary power
- Flash Memory: traps electrons in quantum cage
 - floating gate transistors
 - usually NAND (not-and gates)

SSD Data Arrangement

- 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

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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

Wear Leveling

- SSDs are not impervious
- blocks have limited number of write cycles
 - if block is no longer writeable; it becomes ready-only
 - when a certain % of blocks are read-only; disk becomes read-only
- SSD controller wear-levels; ensuring that write cycles are evenly spread across all blocks

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Defragmentation

- defragmentation takes files spread across multiple, non-sequential pages and makes them sequential
 - it re-writes many pages of memory, possibly several times
 - SSD random and sequential access have approximately the same cost
 - * no clear advantage to defragmenting
 - * extra, unnecessary writes performed by defragmenting—causes pre-mature disk aging