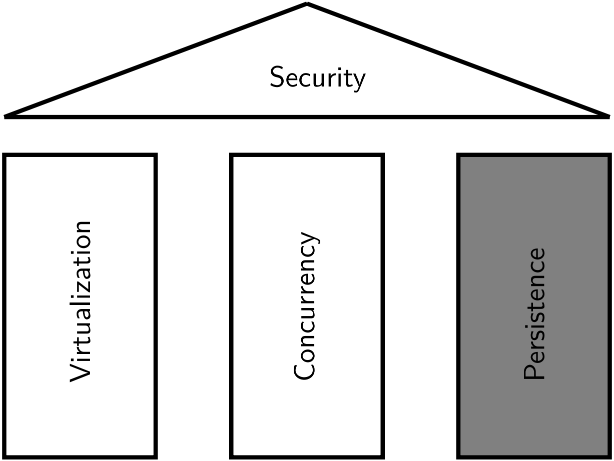
Drivers and IO

CSC 343, Operating Systems

Persistence



Topics covered in this lecture

- How does the OS interact with devices
- Design of device drivers
- Types of IO devices
- Components of hard drives
- Calculating hard drive throughput
- Scheduling algorithms for IO

This slide deck covers chapters 36, 37 in OSTEP.

Motivation

- So far we have talked about the CPU and about RAM
- How do we get data into RAM?
  - Load programs and data from storage
  - Read and write packets from the network (maybe even streams?)
  - Write data to a terminal or the screen
  - Read data from input devices such as keyboard/mouse/camera
- Devices provide input/output (IO) to a system
- IO allows information to *persist* (RAM is volatile)!
- Enables interesting computation!

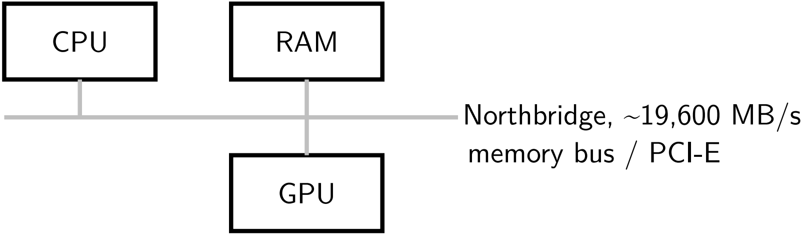
Ancient device history

- Each device (not type!) had a unique hardware interface
- Applications contained code to communicate with devices
- Application polled device to set/get information

Modern device interface

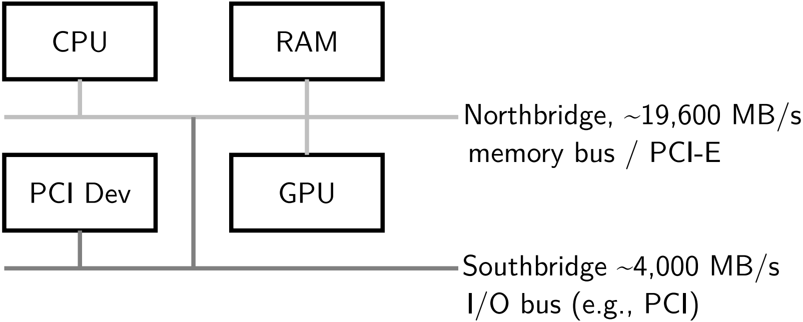
- The OS handles device management (and access)
- OS exposes a uniform interface to applications
- IO is interrupt driven

Hardware support for devices: Northbridge



What about other devices?

Hardware support for devices: Southbridge



CPU

RAM

PCI Dev

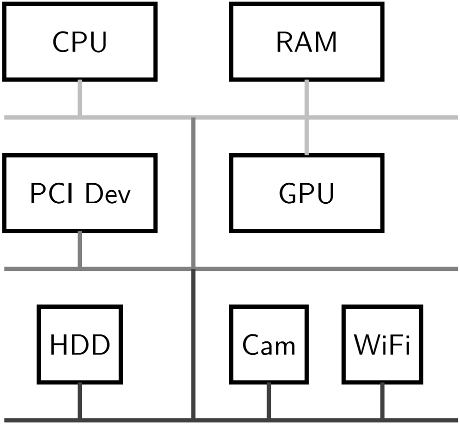
GPU

Northbridge, ~19,600 MB/s
memory bus / PCI-E

Southbridge ~4,000 MB/s
I/O bus (e.g., PCI)

What about "slow" IO?

Hardware support for devices: Other IO



Northbridge, ∼19,600 MB/s
memory bus / PCI-E

Southbridge ∼4,000 MB/s
I/O bus (e.g., PCI)

Peripheral I/O bus, ∼2,000 MB/s
(e.g., SATA, USB)

Terminology

- Northbridge is also called memory controller hub
- Southbridge is also called I/O Controller Hub (ICH / Intel) or Fusion Controller Hub (FCH / AMD)
- The southbridge is connected to the CPU through the northbridge which has a direct connection

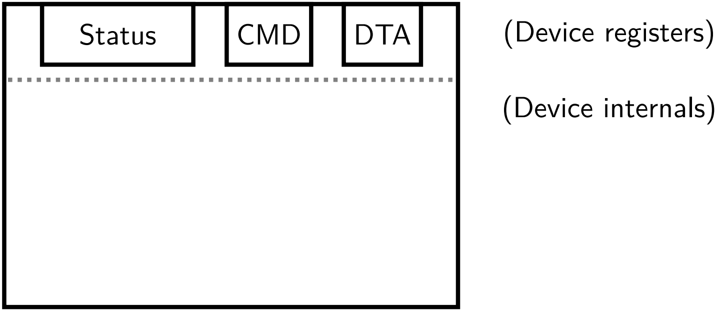
But how do devices work?

Terminology

- Northbridge is also called memory controller hub
- Southbridge is also called I/O Controller Hub (ICH / Intel) or Fusion Controller Hub (FCH / AMD)
- The southbridge is connected to the CPU through the northbridge which has a direct connection

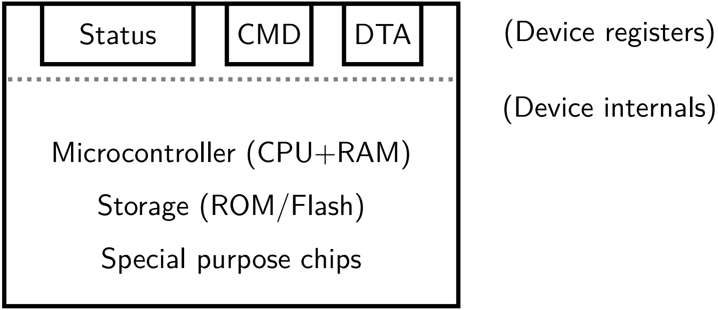
But how do devices work?

Canonical device (1/2)



- OS writes device registers (by executing CPU instructions)
- Device internals are hidden (abstraction)

Canonical device (2/2)



- OS communicates based on agreed protocol (through “driver”)
- Device signals OS through memory or interrupt

Device protocol (1/3)

```
while (STATUS == BUSY) ; // 1. spin
// 2. Write data to DTA register
*dtaRegister = DATA;
// 3. Write command to CMD register
*cmdRegister = COMMAND;
while (STATUS == BUSY) ; // 4. spin
```

- Wait until device is ready
- Set data and command (why send data first?)
- Wait until command has completed

Where do you see problems?

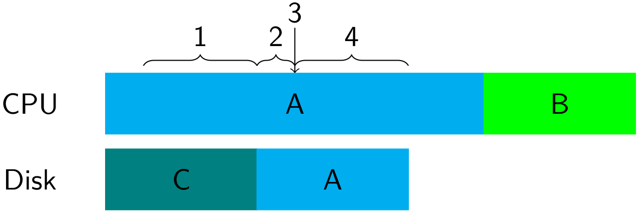
Device protocol (1/3)

```
while (STATUS == BUSY) ; // 1. spin
// 2. Write data to DTA register
*dtaRegister = DATA;
// 3. Write command to CMD register
*cmdRegister = COMMAND;
while (STATUS == BUSY) ; // 4. spin
```

- Wait until device is ready
- Set data and command (why send data first?)
- Wait until command has completed

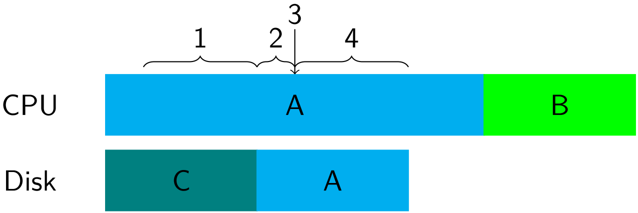
Where do you see problems?

Device protocol (2/3)



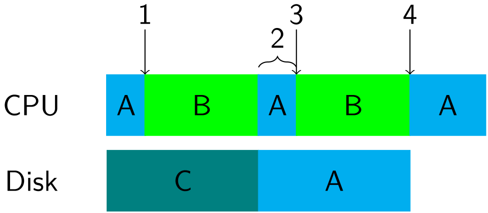
- Busy waiting (1. and 4.) wastes cycles twice
- CPU should not need to wait for completion of command
- Solution: embrace asynchronous communication
  - Inform device of request (to get rid of 1.)
  - Wait for signal of completion (to get rid of 4.)

Device protocol (2/3)



- Busy waiting (1. and 4.) wastes cycles twice
- CPU should not need to wait for completion of command
- Solution: embrace asynchronous communication
    - Inform device of request (to get rid of 1.)
    - Wait for signal of completion (to get rid of 4.)

Device protocol (3/3): interrupts



- Instead of spinning, the OS (driver) waits for an interrupt
  - Interrupts are handled centrally through a dispatcher
  - On interrupt arrival, wake up kernel thread that waits on that interrupt

Interrupt performance

- Can interrupts lead to worse performance than polling?

- Yes: livelock (e.g., a flood of arriving network packets)
  - A livelock is *similar to a deadlock* (no process makes progress, resulting in starvation) with the difference that the states of the processes constantly change
  - For example: network packets arrive; interrupt handling and context switch is costly, prohibiting the application from reacting to the packets and them simply queuing up.

- Real systems therefore use a mix between polling and interrupts
  - Interrupts allow overlap between computation and IO, most useful for slow devices;
  - Use polling for short bursts or small amounts of data
- Another optimization is *coalescing*, i.e., the device waits for a bit until more requests complete, then batch sends everything.

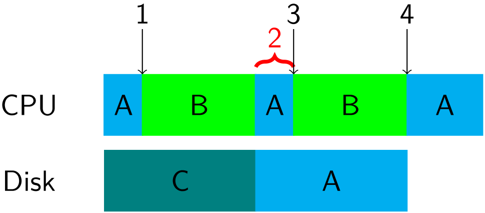
Interrupt performance

- Can interrupts lead to worse performance than polling?
- Yes: livelock (e.g., a flood of arriving network packets)
  - A livelock is *similar to a deadlock* (no process makes progress, resulting in starvation) with the difference that the states of the processes constantly change
  - For example: network packets arrive; interrupt handling and context switch is costly, prohibiting the application from reacting to the packets and them simply queuing up.
- Real systems therefore use a mix between polling and interrupts
  - Interrupts allow overlap between computation and IO, most useful for slow devices;
  - Use polling for short bursts or small amounts of data
- Another optimization is *coalescing*, i.e., the device waits for a bit until more requests complete, then batch sends everything.

Interrupt performance

- Can interrupts lead to worse performance than polling?
- Yes: livelock (e.g., a flood of arriving network packets)
  - A livelock is *similar to a deadlock* (no process makes progress, resulting in starvation) with the difference that the states of the processes constantly change
  - For example: network packets arrive; interrupt handling and context switch is costly, prohibiting the application from reacting to the packets and them simply queuing up.
- Real systems therefore use a mix between polling and interrupts
  - Interrupts allow overlap between computation and IO, most useful for slow devices;
  - Use polling for short bursts or small amounts of data
- Another optimization is *coalescing*, i.e., the device waits for a bit until more requests complete, then batch sends everything.

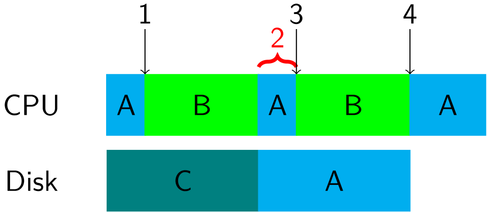
Optimize data transfer



- **PIO (Programmed IO)**: CPU tells the device *what* data
  - One instruction for each byte/word
  - Efficient for a few bytes, scales terribly

- **DMA (Direct Memory Access)**: tell device *where* data *is*
  - One instruction to send a pointer
  - Efficient for large data transfers

Optimize data transfer



- **PIO (Programmed IO)**: CPU tells the device *what* data
  - One instruction for each byte/word
  - Efficient for a few bytes, scales terribly
- **DMA (Direct Memory Access)**: tell device *where* data *is*
  - One instruction to send a pointer
  - Efficient for large data transfers

How to transfer data?

- IO ports
  - Each device has an assigned IO port
  - Special instructions (`in`/`out` on x86) communicate with device
- Memory mapped IO
  - Device maps its registers to memory
  - Loads/stores interact with device
- Both are used in practice. Architectures now support both. Differences are a matter of choice and preference.

How to transfer data?

- IO ports
  - Each device has an assigned IO port
  - Special instructions (`in`/`out` on x86) communicate with device
- Memory mapped IO
  - Device maps its registers to memory
  - Loads/stores interact with device
- Both are used in practice. Architectures now support both. Differences are a matter of choice and preference.

Support for different devices

- Challenge: different devices have *different protocols*
- Drivers are specialized pieces of code for a particular device
  - Low end communicates with the device
  - High end exposes generic interface to OS
- Drivers are an example of *encapsulation*
  - Different drivers adhere to the same API
  - OS only implements support for APIs based on device class
- Requirement: well-designed interface/API
  - Trade-off between versatility and over-specialization
  - Due to device class complexity, OS ends with layers of APIs

Support for different devices

- Challenge: different devices have *different protocols*
- Drivers are specialized pieces of code for a particular device
  - Low end communicates with the device
  - High end exposes generic interface to OS
- Drivers are an example of *encapsulation*
  - Different drivers adhere to the same API
  - OS only implements support for APIs based on device class
- Requirement: well-designed interface/API
  - Trade-off between versatility and over-specialization
  - Due to device class complexity, OS ends with layers of APIs

Complexity of API layers

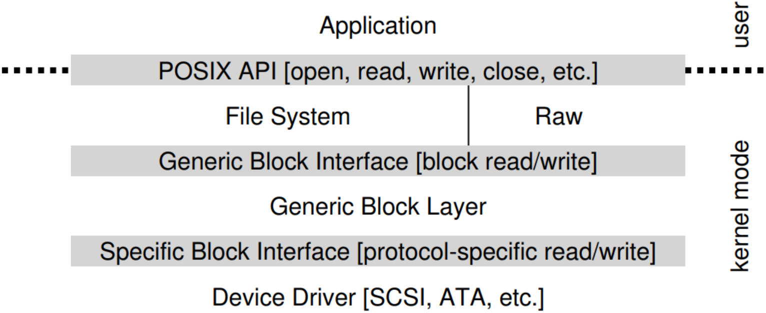
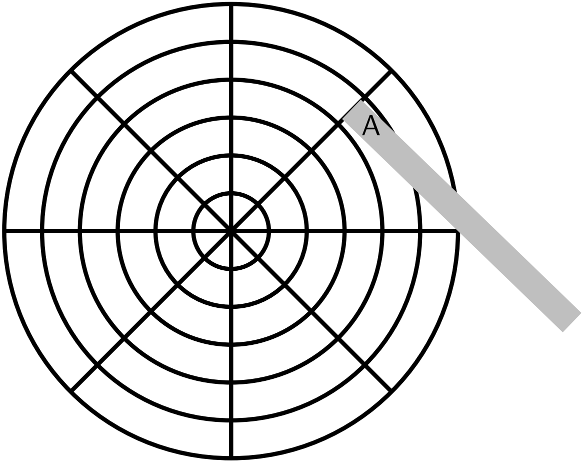

user
Application
POSIX API [open, read, write, close, etc.]
File System
Raw
Generic Block Interface [block read/write]
Generic Block Layer
Specific Block Interface [protocol-specific read/write]
Device Driver [SCSI, ATA, etc.]
kernel mode

Figure 1: File system stack

IO subsystem: hard disks

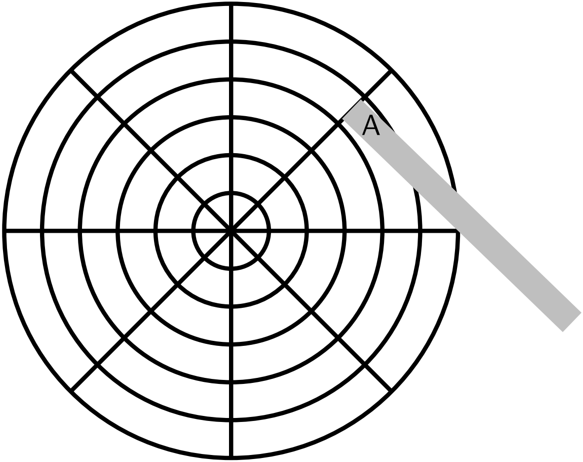
- Disk has a sector-addressable address space
- Sectors are 512 or 4096 bytes
- Main operations: read/write

Hard disk



- IO cost is sum of:
    - seek time (adjust angle of reader)
    - rotation time (rotate the start of the sector to the reader)
    - transfer time (rotate sector under reader)

Disc drives



- Open hard drive spinning up
- How floppy drives work
- Alternate use for floppy drives

HDD: seek, rotate, transfer

- Seek is costly (several ms, “an eternity”)
  - function of cylinder distance
  - operations: accelerate, coast, decelerate, settle
- Rotate: 7200 RPM, 8.3 ms/rotation
- Transfer: (100MB/s): 5 us for 512 B
- Seeks and rotation is slow, transfer is fast
  - Sequential access is much faster (blocks are ordered)
  - Random access is slow

HDD: seek, rotate, transfer

- Seek is costly (several ms, “an eternity”)
  - function of cylinder distance
  - operations: accelerate, coast, decelerate, settle
- Rotate: 7200 RPM, 8.3 ms/rotation
- Transfer: (100MB/s): 5 us for 512 B

- Seeks and rotation is slow, transfer is fast
  - Sequential access is much faster (blocks are ordered)
  - Random access is slow

IO scheduling

- Given concurrent IO requests, how should they be scheduled?
    - Different constraints than CPU scheduling
    - . . . but the same algorithms!
- Position of disk head relative to requested position matters more than length of the transfer

IO scheduling

- Given concurrent IO requests, how should they be scheduled?
  - Different constraints than CPU scheduling
  - . . . but the same algorithms!
- Position of disk head relative to requested position matters more than length of the transfer

Optimization: buffering

- A buffer cache between the disk and the higher level of the OS keeps most recently used disk blocks around
- Proactively fetches blocks that are likely accessed
- Keep track of dirty blocks that need to be written back

First come first serve

- Assume 10ms average seek and rotation time
- Requests: 30001, 70001, 30002, 70002, 30003, 70003: 60ms
  - How can we improve?
- Requests: 30001, 30002, 30003, 70001, 70002, 70003: 20ms
  - Shortest seek time: seek to closest block (minding starvation)
  - Elevator/SCAN: go outwards/inwards, serve requests along
  - Clever optimizations of shortest seek time/elevator

First come first serve

- Assume 10ms average seek and rotation time
- Requests: 30001, 70001, 30002, 70002, 30003, 70003: 60ms
    - How can we improve?
- Requests: 30001, 30002, 30003, 70001, 70002, 70003: 20ms
    - Shortest seek time: seek to closest block (minding starvation)
    - Elevator/SCAN: go outwards/inwards, serve requests along
    - Clever optimizations of shortest seek time/elevator

Completely fair queuing (Linux)

- Queue for each process
- Weighted round-robin between queues with slice-time proportional to priority
- Yield slice only if idle for given time

Scheduling algorithms for CPU time are also useful for I/O

Completely fair queuing (Linux)

- Queue for each process
- Weighted round-robin between queues with slice-time proportional to priority
- Yield slice only if idle for given time

Scheduling algorithms for CPU time are also useful for I/O

Going beyond one disk

- A single disk has many limitations
  - Single point of failure
  - Limited performance
  - Limited size
- File systems work on a single disk (or partition)
- How can we increase flexibility?
- One more layer of indirection: a virtual disk!

Going beyond one disk

- A single disk has many limitations
  - Single point of failure
  - Limited performance
  - Limited size
- File systems work on a single disk (or partition)
- How can we increase flexibility?
- One more layer of indirection: a virtual disk!

RAID: Redundant Array of Inexpensive Disks

- Idea: build logical disk from (many) physical disks
- RAID0: Striping (no mirroring or parity)
  - n performance, n capacity, 0/n can fail
- RAID1: Data mirroring (no parity or striping)
  - n performance, (n-1)/n can fail
- RAID2: bit level striping (historic, sync'd, one parity drive)
- RAID3: byte level striping (historic, sync'd, one parity drive)
- RAID4: block level striping (historic, one drive holds parity)
- RAID5: block level striping, distributed parity
  - n performance, n-1 capacity, 1/n can fail
- RAID6: block level striping, distributed parity
  - n performance, n-2 capacity, 2/n can fail

RAID: Redundant Array of Inexpensive Disks

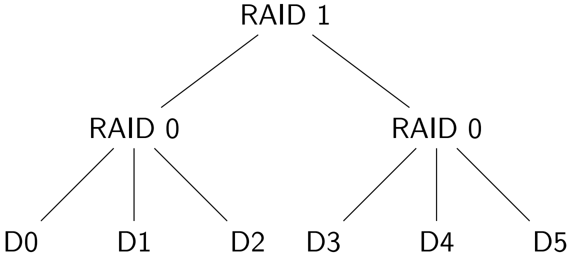
- Idea: build logical disk from (many) physical disks

- RAID0: Striping (no mirroring or parity)
  - n performance, n capacity, 0/n can fail
- RAID1: Data mirroring (no parity or striping)
  - n performance, (n-1)/n can fail
- RAID2: bit level striping (historic, sync'd, one parity drive)
- RAID3: byte level striping (historic, sync'd, one parity drive)
- RAID4: block level striping (historic, one drive holds parity)
- RAID5: block level striping, distributed parity
  - n performance, n-1 capacity, 1/n can fail
- RAID6: block level striping, distributed parity
  - n performance, n-2 capacity, 2/n can fail

RAID: combinations

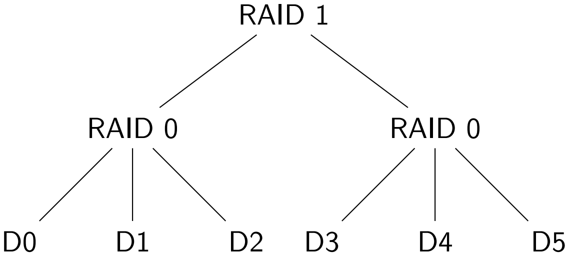
- RAID 01: two stripes (RAID0) that are mirrored (RAID1)
- RAID 10: stripe (RAID0) a set of mirrored devices (RAID1)
- Which one is more reliable?

RAID 01



- During rebuild (a disk has failed), no other drive from the *alternate* group may fail
- Given D0 fails, if any of D3, D4, or D5 fails the system halts (3/5)
- Given D0 fails, if D3 fails the system is dead (1/5)

RAID 01



RAID 1

RAID 0

RAID 0

D0

D1

D2

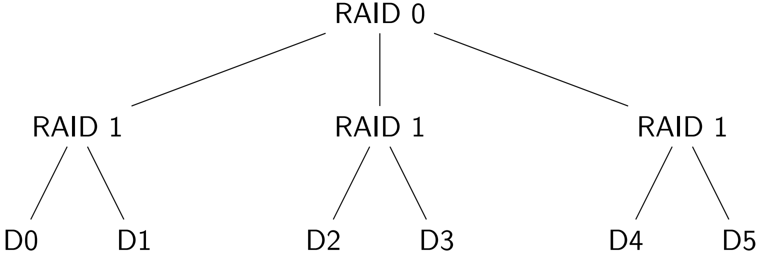
D3

D4

D5

- During rebuild (a disk has failed), no other drive from the *alternate* group may fail
- Given D0 fails, if any of D3, D4, or D5 fails the system halts (3/5)
- Given D0 fails, if D3 fails the system is dead (1/5)

RAID 10



- Of each mirror, at least one disk must remain healthy
- Given D0 fails, if D1 fails the system is dead (1/5)
- Given D0 fails, any other disk (except D1) may fail without impact (1/5)

Summary

- Overlap IO and computation as much as possible!
    - Use interrupts
    - Use DMA
- Driver classes provide common interface
- Storage: read/write/seek of blocks
- Minimize random IO (i.e., quick sort is really bad on HDDs)
- Carefully schedule IO on slow devices
- RAID virtualizes disks