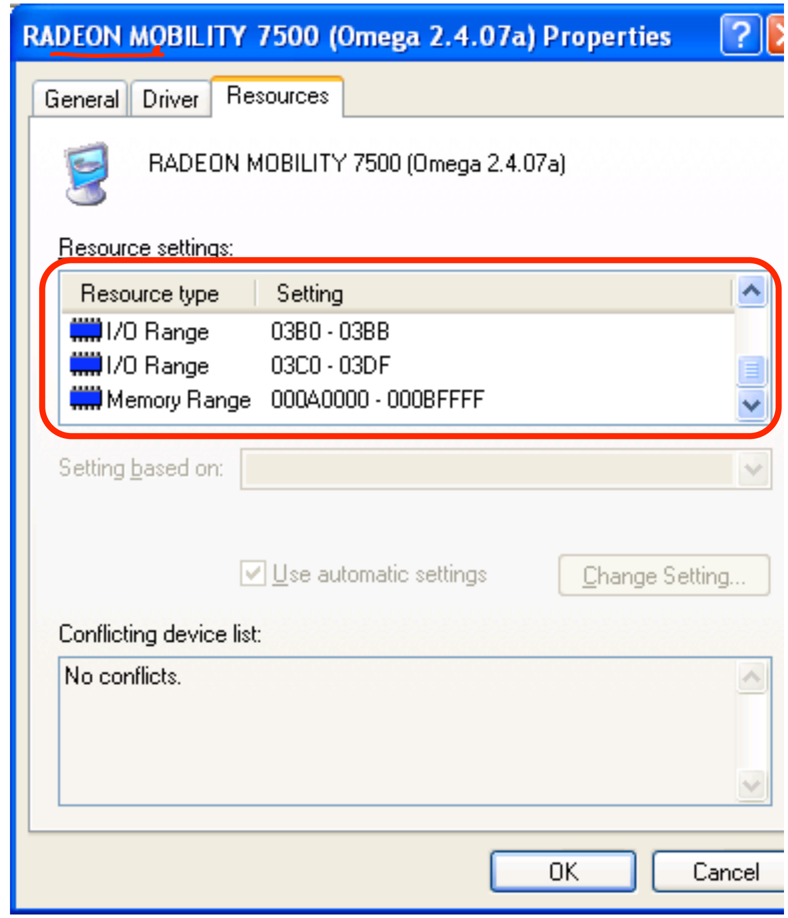
Introduction to I/O

- Where does the data for our CPU and memory come from or go to?
- Computers communicate with the outside world via I/O devices.
  – Input devices supply computers with data to operate on.
  – Results of computations can be sent to output devices.
- Today we'll talk a bit about I/O system issues.
  – I/O performance affects the overall system speed.
  – We'll look at some common devices and estimate their performance.
  – We'll look at how I/O devices are connected (by buses).

Communicating with devices

- Most devices can be considered as memories, with an "address" for reading or writing.
- Many instruction sets often make this analogy explicit. To transfer data to or from a particular device, the CPU can access special addresses.
- Here you can see a video card can be accessed via addresses 3B0-3BB, 3C0-3DF and A0000-BFFFF.
- There are two ways these addresses can be accessed.



Mem-mapped I/O

ISOLATED I/O

I/O is important!

- Many tasks involve reading and processing enormous quantities of data.
  - Institutions like banks and airlines have huge databases that must be constantly accessed and updated.
  - Celera Genomics is a company that sequences genomes, with the help of computers and 100 trillion bytes of storage!
- I/O is important for us small people too!
  - People use home computers to edit movies and music.
  - Large software packages may come on multiple compact discs.
  - Everybody surf the web!

I/O is slow!

- How fast can a typical I/O device supply data to a computer?
  - A fast typist can enter 9-10 characters a second on a keyboard.
  - Common local-area network (LAN) speeds go up to 100 Mbit/s, which is about 12.5MB/s.
  - Today's hard disks provide a lot of storage and transfer speeds around 40-60MB per second.
- Unfortunately, this is excruciatingly slow compared to modern processors and memory systems:
  - Modern CPUs can execute more than a billion instructions per second.
  - Modern memory systems can provide 2-4 GB/s bandwidth.

- I/O performance has not increased as quickly as CPU performance, partially due to neglect and partially to physical limitations.
  - This is changing, with faster networks, better I/O buses, RAID drive arrays, and other new technologies.

I/O speeds often limit system performance

- Many computing tasks are I/O-bound, and the speed of the input and output devices limits the overall system performance.
- This is another instance of Amdahl's Law. Improved CPU performance alone has a limited effect on overall system speed.

$$\text{Execution time after improvement} = \frac{\text{Time affected by improvement}}{\text{Amount of improvement}} + \text{Time unaffected by improvement}$$

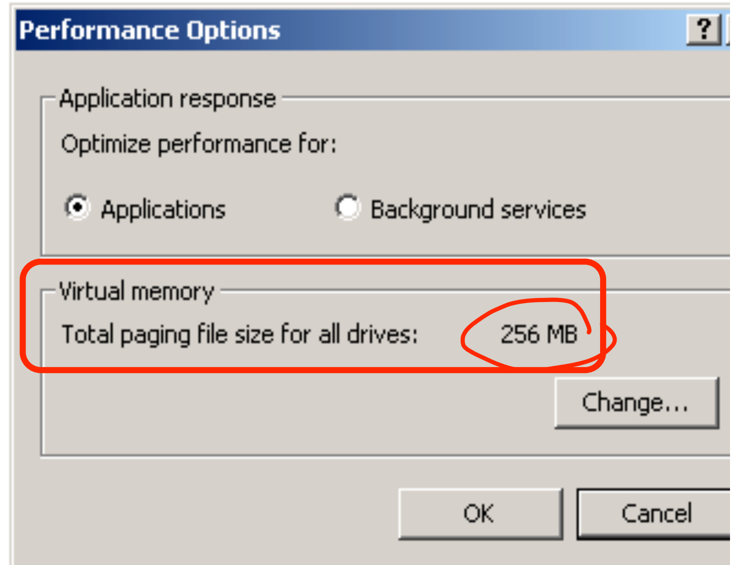
$$\frac{\cancel{0.2}}{100} + 0.8$$

$$0$$

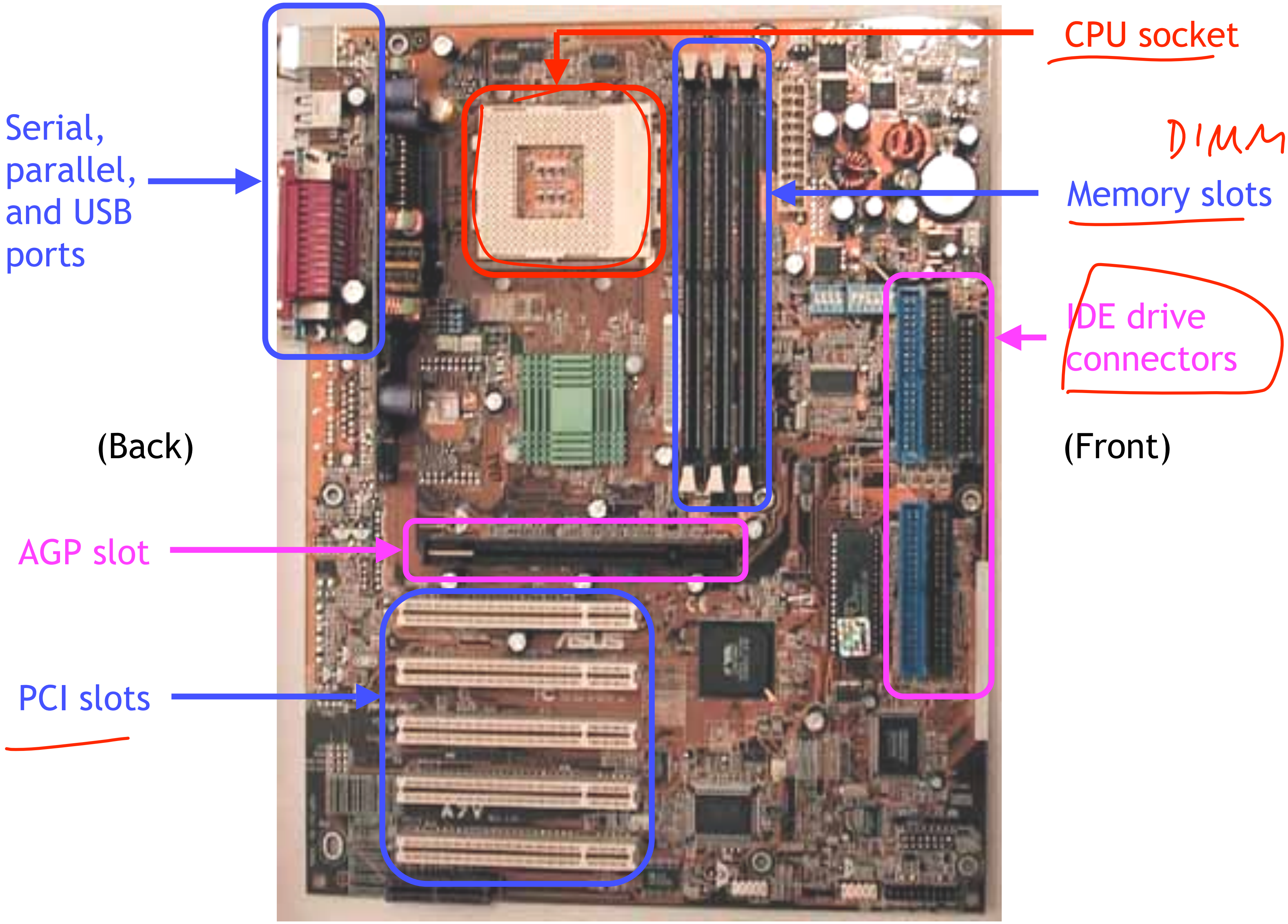
$$= 0.8$$

Common I/O devices

- Hard drives are almost a necessity these days, so their speed has a big impact on system performance.
  - They store all the programs, movies and assignments you crave.
  - Virtual memory systems let a hard disk act as a large (but slow) part of main memory.
- Networks are also ubiquitous nowadays.
  - They give you access to data from around the world.
  - Hard disks can act as a cache for network data. For example, web browsers often store local copies of recently viewed web pages.



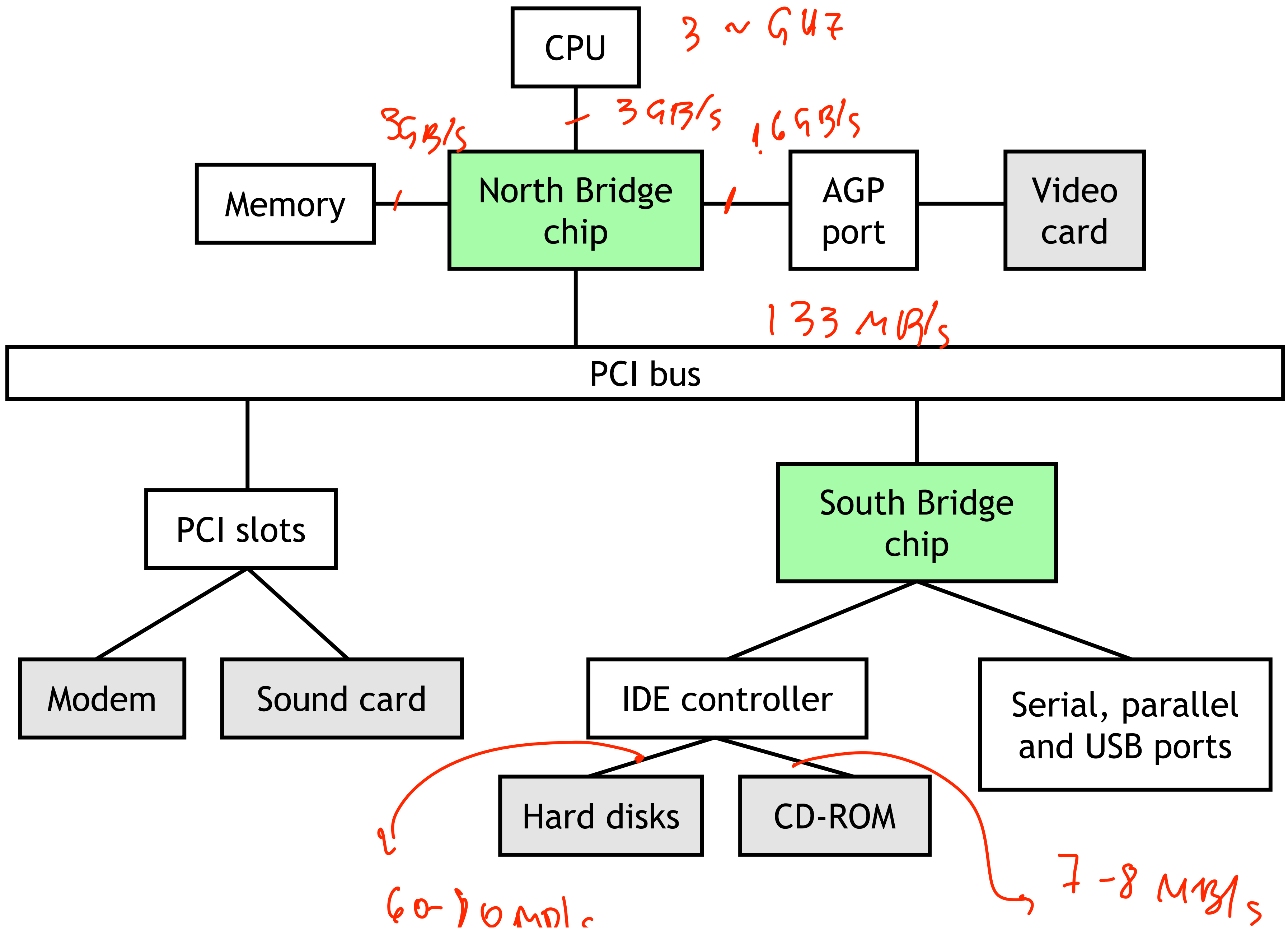
The Hardware (the motherboard)



What is all that stuff?

- Different motherboards support different CPUs, types of memories, and expansion options.
- The picture is an Asus A7V.
  - The CPU socket supports AMD Duron and Athlon processors.
  - There are three DIMM slots for standard PC100 memory. Using 512MB DIMMs, you can get up to 1.5GB of main memory.
  - The AGP slot is for video cards, which generate and send images from the PC to a monitor.
  - IDE ports connect internal storage devices like hard drives, CD-ROMs, and Zip drives.
  - PCI slots hold other internal devices such as network and sound cards and modems.
  - Serial, parallel and USB ports are used to attach external devices such as scanners and printers.

How is it all connected?

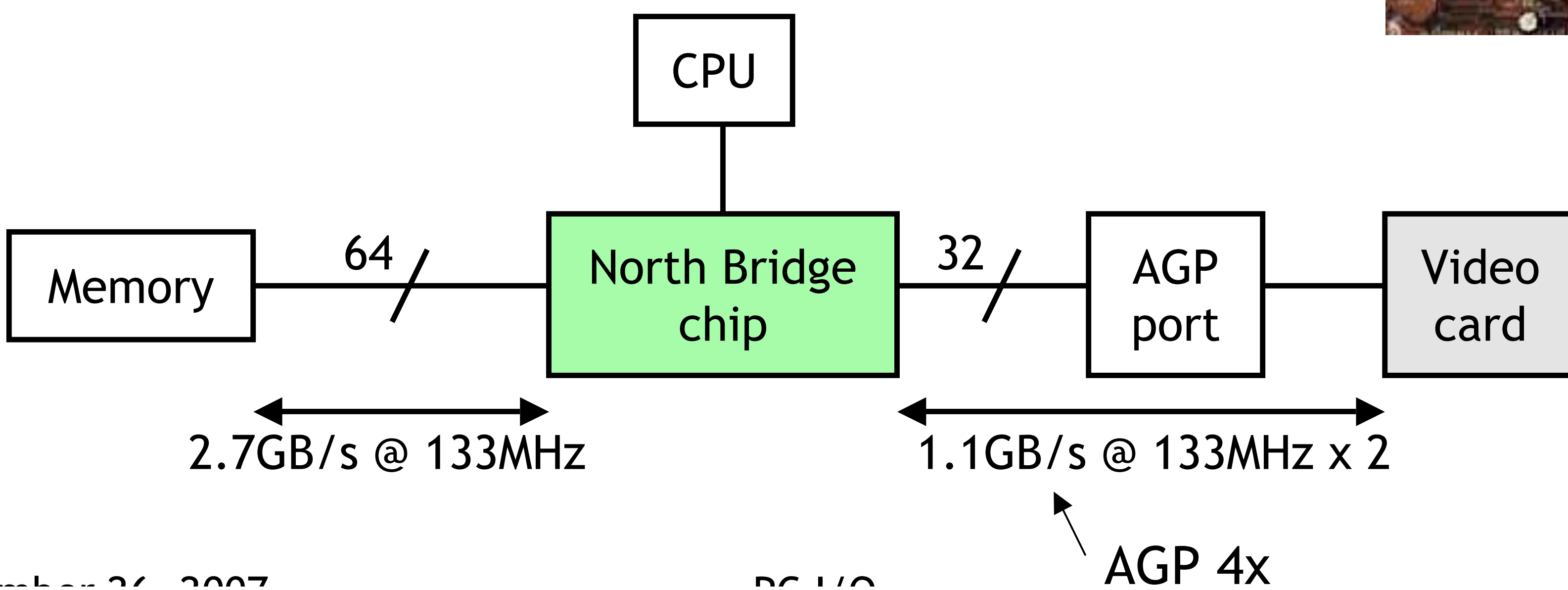


Frequencies

- CPUs actually operate at two frequencies.
  - The internal frequency is the clock rate inside the CPU, which is what we've been talking about so far.
  - The external frequency is the speed of the processor bus, which limit how fast the CPU can transfer data.
- The internal frequency is usually a multiple of the external bus speed.
  - A 2.167 GHz Athlon XP sits on a 166 MHz bus (166 x 13).
  - A 2.66 GHz Pentium 4 might use a 133 MHz bus (133 x 20).
    - *You may have seen the Pentium 4's bus speed quoted at 533MHz. This is because the Pentium 4's bus is "quad-pumped", so that it transfers 4 dat items every clock cycle.*
- Processor and Memory data rates far exceed PCI's capabilities:
  - With an 8-byte wide "533 MHz" bus, the Pentium 4 achieves 4.3GB/s
  - A bank of 166MHz Double Data Rate (DDR-333) Memory achieves 2.7GB/s

The North Bridge

- To achieve the necessary bandwidths, a "frontside bus" is often dedicated to the CPU and main memory.
  - "bus" is actually a bit of a misnomer as, in most systems, the interconnect consists of point-to-point links.
  - The video card, which also need significant bandwidth, is also given a direct link to memory via the Accelerated Graphics Port (AGP).
- All this CPU-memory traffic goes through the "north bridge" controller, which can get very hot (hence the little green heatsink).

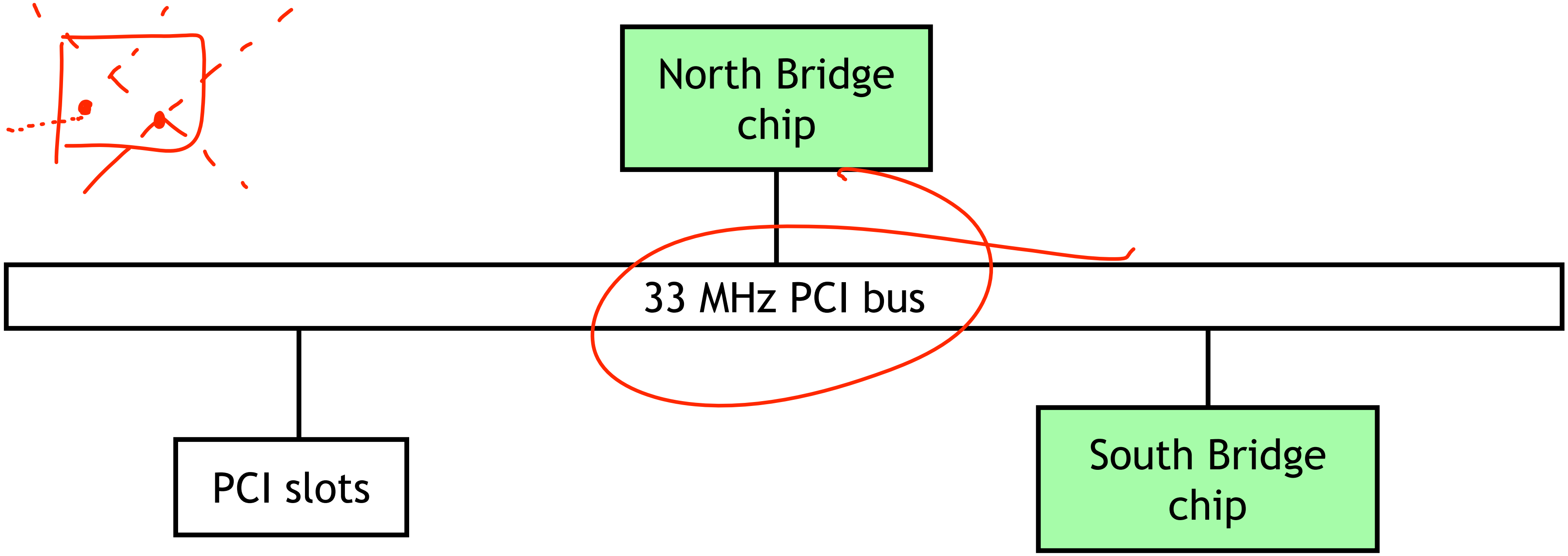


PCI

- Peripheral Component Interconnect is a synchronous 32-bit bus running a 33MHz, although it can be extended to 64 bits and 66MHz.
- The maximum bandwidth is about 132 MB/s.

33 million transfers/second x 4 bytes/transfer = 132MB/s

- Cards in the motherboard PCI slots plug directly into the PCI bus.
- Devices made for the older and slower ISA bus standard are connected vi a "south bridge" controller chip, in a hierarchical manner.



External buses

- External buses are provided to support the frequent plugging and un-plugging of devices
  - As a result their designs significantly differ from internal buses

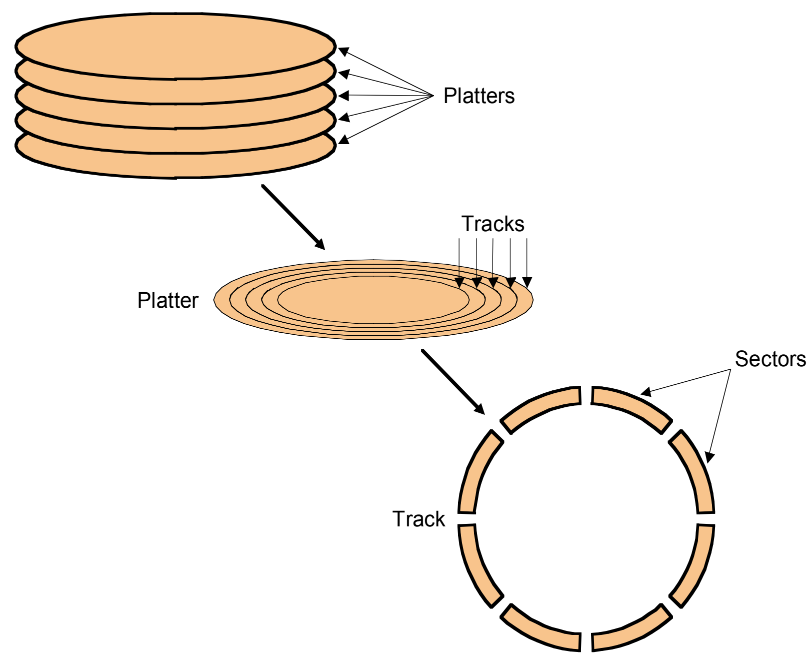
- Two modern external buses, Universal Serial Bus (USB) and FireWire, hav the following (desirable) characteristics:
  - Plug-and-play standards allow devices to be configured with software, instead of flipping switches or setting jumpers.
  - Hot plugging means that you don't have to turn off a machine to add or remove a peripheral.
  - The cable transmits power! No more power cables or extension cords.
  - Serial links are used, so the cable and connectors are small.

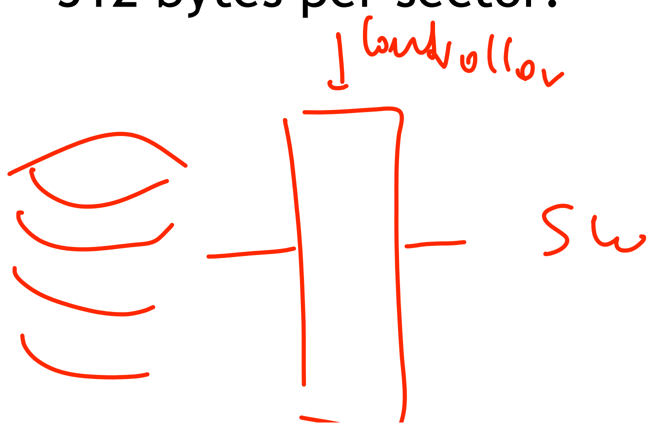
The Serial/Parallel conundrum

- Why are modern external buses serial rather than parallel?
- Generally, one would think that having more wires would increase bandwidth and reduce latency, right?
  - Yes, but only if they can be clocked at comparable frequencies.
- Two physical issues allow serial links to be clocked significantly faster:
  - On parallel interconnects, interference between the signal wires becomes a serious issue.
  - Skew is also a problem; all of the bits in a parallel transfer could arrive at slightly different times.
- Serial links are being increasingly considered for internal buses:
  - Serial ATA is a new standard for hard drive interconnects
  - PCI-Express (aka 3GI/O) is a PCI bus replacement that uses serial link

Hard drives

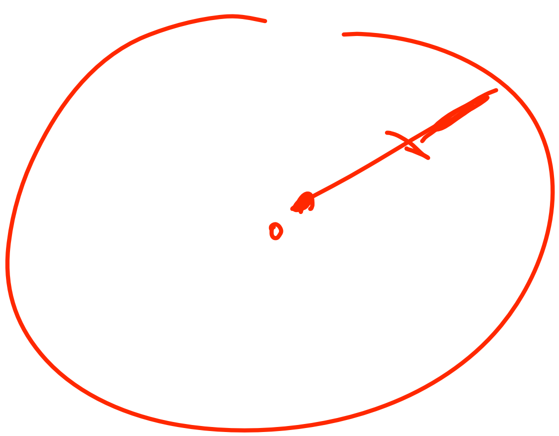
- Figure 8.4 in the textbook shows the ugly guts of a hard disk.
  - Data is stored on double-sided magnetic disks called platters.
  - Each platter is arranged like a record, with many concentric tracks.
  - Tracks are further divided into individual sectors, which are the basic unit of data transfer.
  - Each surface has a read/write head like the arm on a record player, but all the heads are connected and move together.
- A 75GB IBM Deskstar has roughly:
  - 5 platters (10 surfaces),
  - 27,000 tracks per surface,
  - 512 sectors per track, and
  - 512 bytes per sector.

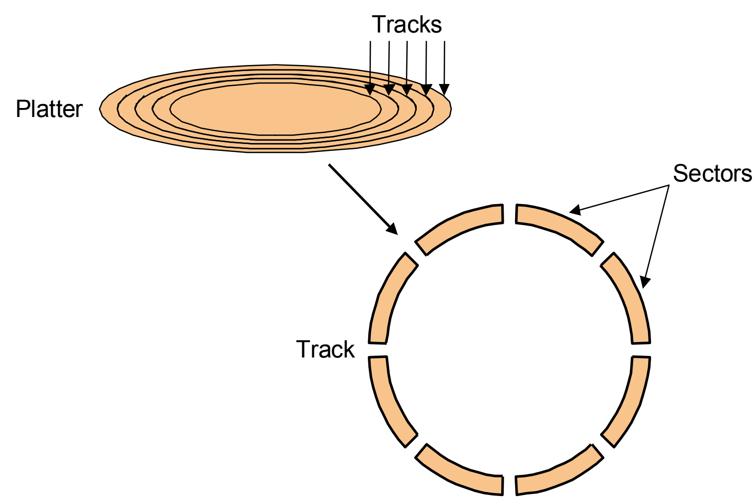




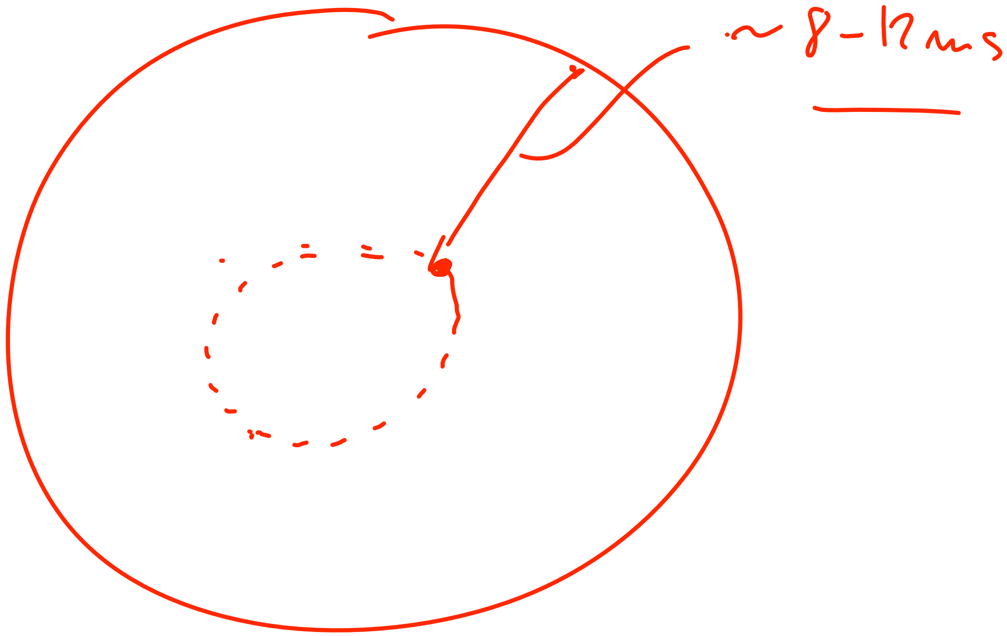
Accessing data on a hard disk

- Accessing a sector on a track on a hard disk takes a lot of time!
  - Seek time measures the delay for the disk head to reach the track.
  - A rotational delay accounts for the time to get to the right sector.
  - The transfer time is how long the actual data read or write takes.
  - There may be additional overhead for the operating system or the controller hardware on the hard disk drive.
- Rotational speed, measured in revolutions per minute or RPM, partially determines the rotational delay and transfer time.



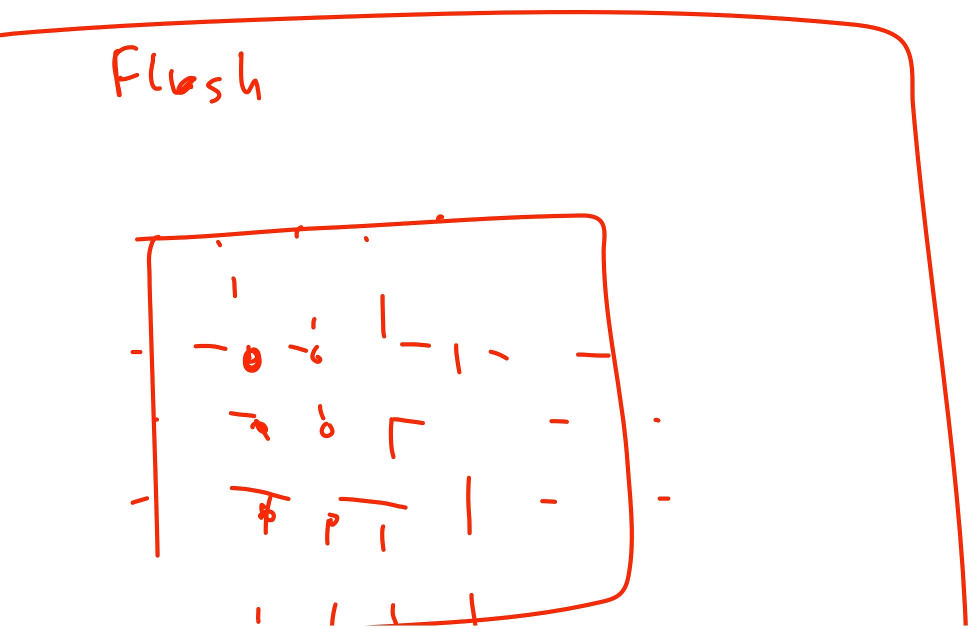


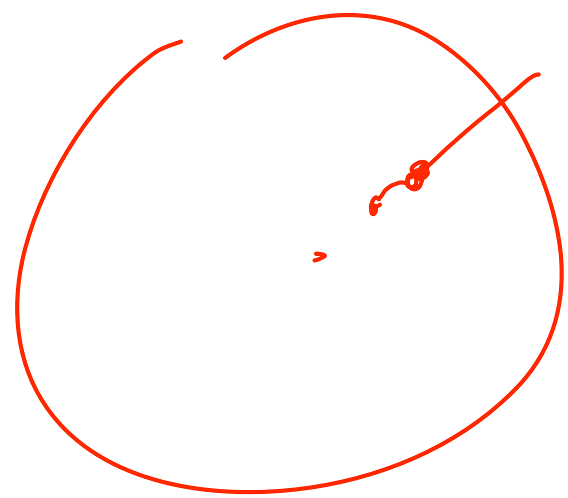
So, why so slow?



Estimating disk latencies (seek time)

- Manufacturers often report *average* seek times of 8-10ms.
  - These times average the time to seek from any track to any other track.
- In practice, seek times are often much better.
  - For example, if the head is already on or near the desired track, then seek time is much smaller. In other words, locality is important!
  - Actual average seek times are often just 2-3ms.





Estimating Disk Latencies (rotational latency)

- Once the head is in place, we need to wait until the right sector is underneath the head.
  - This may require as little as no time (reading consecutive sectors) or as much as a full rotation (just missed it).
  - On average, for random reads/writes, we can assume that the disk spins halfway on average.

- Rotational delay depends partly on how fast the disk platters spin.

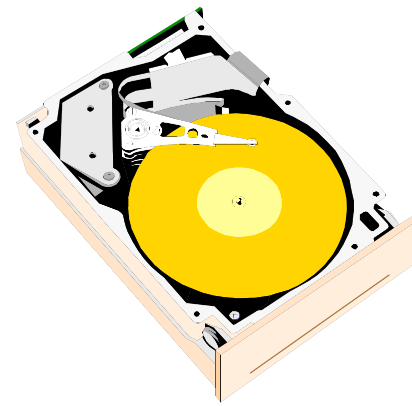
  Average rotational delay = 0.5 x rotations x rotational speed

  - For example, a 5400 RPM disk has an average rotational delay of:

  0.5 rotations / (5400 rotations/minute) = 5.55ms

Estimating disk times

- The overall response time is the sum of the seek time, rotational delay, transfer time, and overhead.
- Assume a disk has the following specifications.
  - An average seek time of 9ms
  - A 5400 RPM rotational speed
  - A 10MB/s average transfer rate
  - 2ms of overheads



- How long does it take to read a random 1,024 byte sector?
  - The average rotational delay is 5.55ms.
  - The transfer time will be about (1024 bytes / 10 MB/s) = 0.1ms.
  - The response time is then 9ms + 5.55ms + 0.1ms + 2ms = 16.7ms. That's 16,700,000 cycles for a 1GHz processor!

$\dfrac{\cancel{10}^{3}}{10 \cdot \cancel{10}}$

- One possible measure of throughput would be the number of random sectors that can be read in one second.

(1 sector / 16.7ms) x (1000ms / 1s) = 60 sectors/second.

Parallel I/O

- Many hardware systems use parallelism for increased speed.
  - Pipelined processors include extra hardware so they can execute multiple instructions simultaneously.
  - Dividing memory into banks lets us access several words at once.
- A redundant array of inexpensive disks or RAID system allows access to several hard drives at once, for increased bandwidth.
  - The picture below shows a single data file with fifteen sectors denoted A-O, which are "striped" across four disks.
  - This is reminiscent of interleaved main memories from last week.