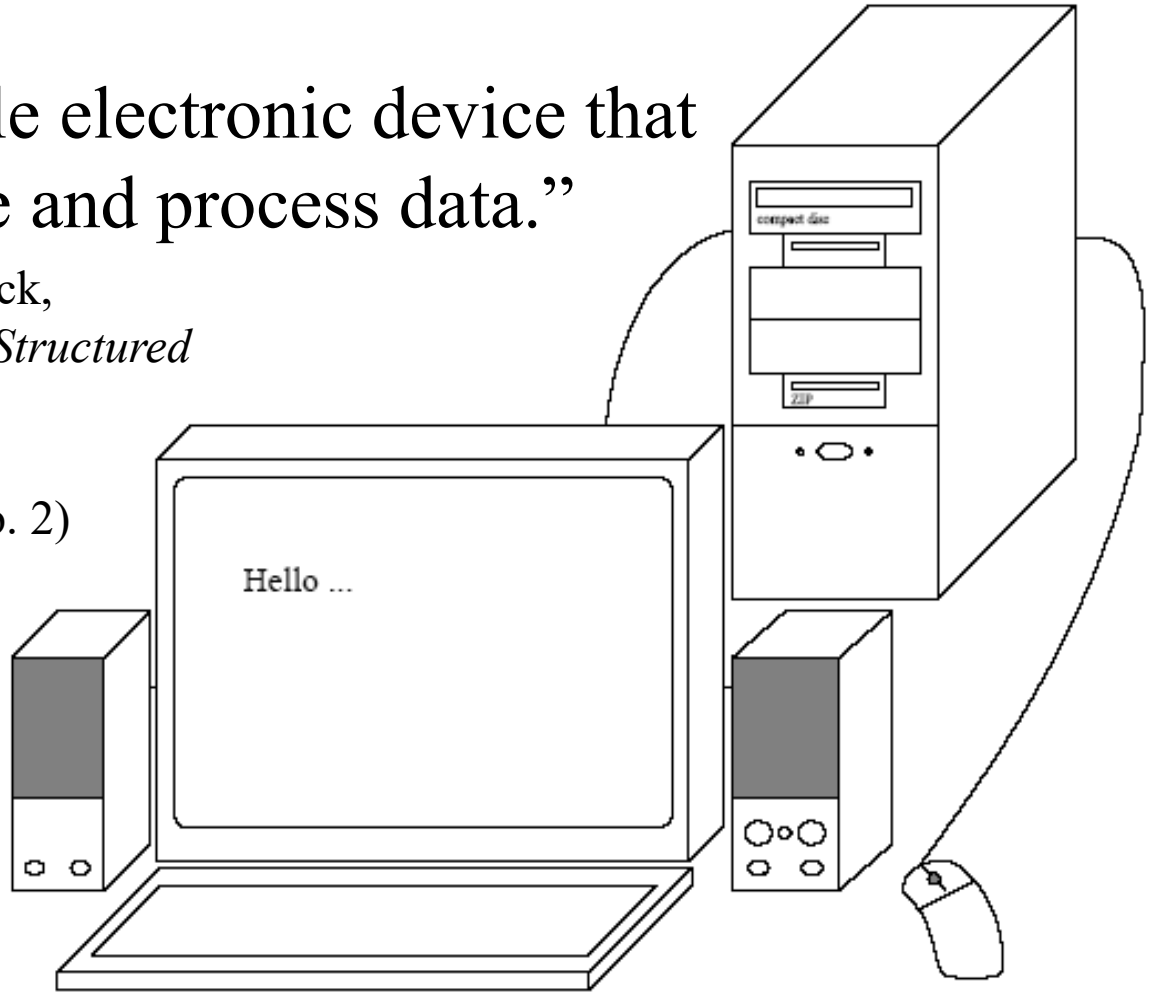
Hardware Outline

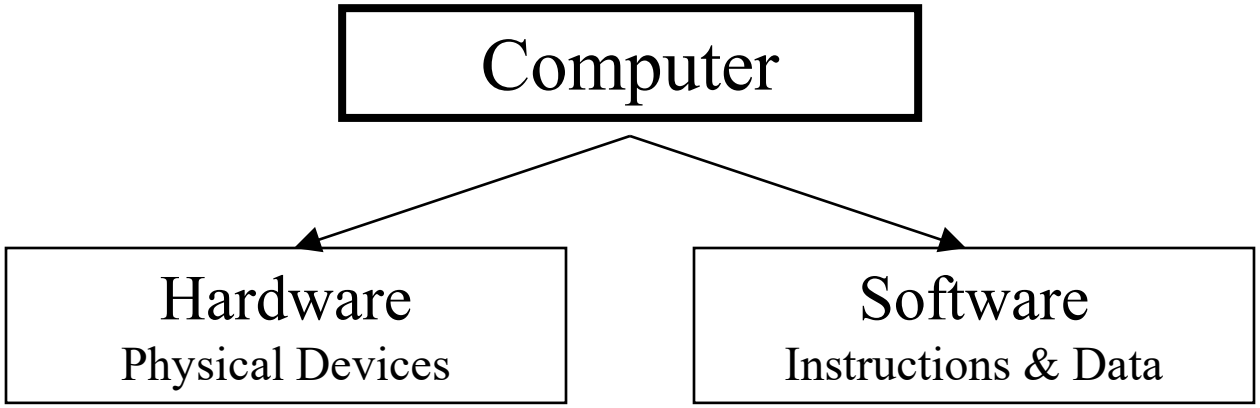
What is a Computer?

"… [A] programmable electronic device that can store, retrieve and process data."

(N. Dale & D. Orshalick,
Introduction to PASCAL and Structured Design,
D.C. Heath & Co.,
Lexington MA, 1983, p. 2)



Components of a Computer



DON'T PANIC!

This discussion may be confusing at the moment;
it'll make more sense after you've written a few programs.

Categories of Computer Hardware

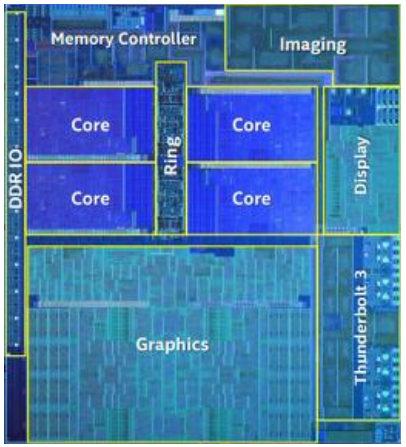
- ***Central Processing Unit*** (CPU)
- ***Storage***
  - ***Primary***: Cache, RAM
  - ***Secondary***: Hard disk, removable (e.g., USB thumb drive)
- ***I/O***
  - ***Input*** Devices
  - ***Output*** Devices

Central Processing Unit (CPU)

The ***Central Processing Unit*** (CPU), also called the ***processor***, is the "**brain**" of the computer.

Intel Ice Lake exterior

https://2.bp.blogspot.com/-KZiDqFY8mWM/XOKeSN34jqI/AAAAAAAACA0/PuVjQ0_gGYURDodUvaECRfj5_-EWXGI4ACEwYBhgL/s640/ezgif.com-webp-maker%2B%252810%2529.webp



Intel Ice Lake quad core innards

https://d2skuhm0vrry40.cloudfront.net/2019/articles/2019-05-26-23-55/2019_05_26_23_55_22_PowerPoint_Presentation.png

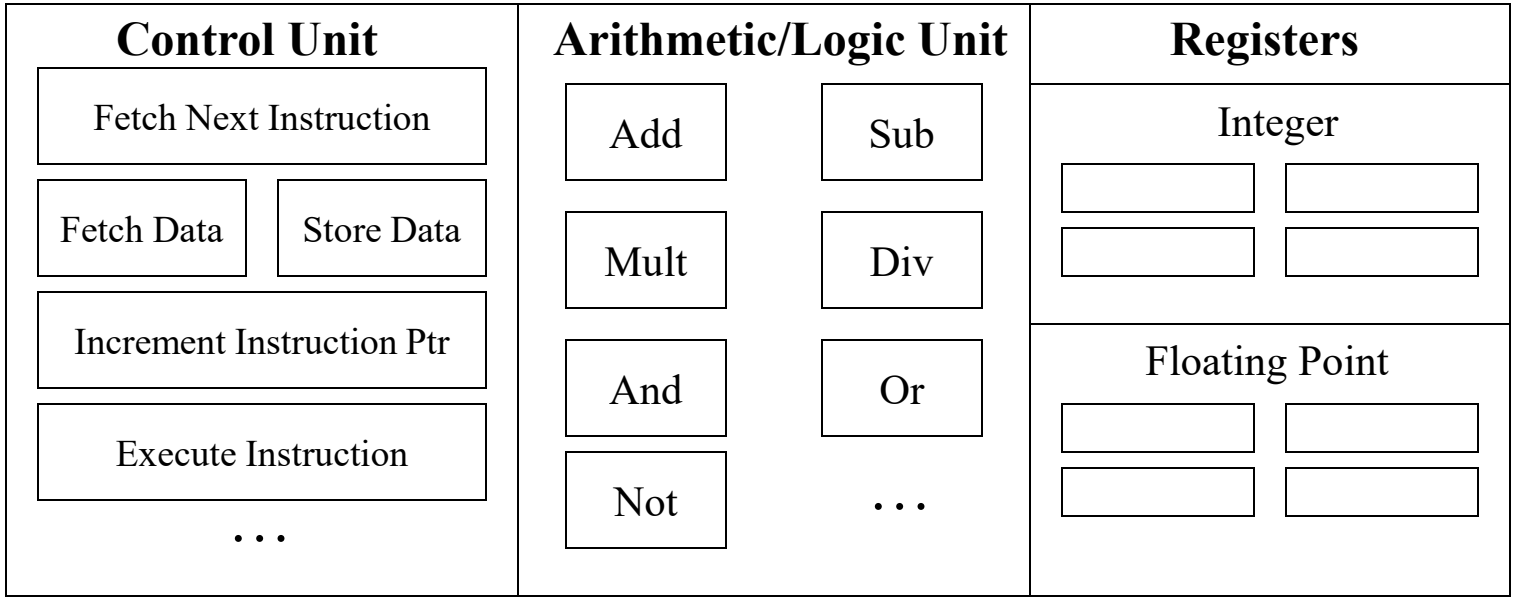
CPU Examples

- ***x86***: Intel Celeron/Pentium/Core/i3/i5/i7/i9/Xeon and AMD Athlon/Sempron/Turion/Ryzen/Threadripper/EPYC (and related models from smaller manufacturers) (Windows, MacOS and Linux PCs; some Android tablets)
  http://en.wikipedia.org/wiki/X86
  - Market Share: Intel 60.3%, AMD 39.6%
    https://www.statista.com/statistics/735904/worldwide-x86-intel-amd-market-share/
- ***ARM*** (in 90% of mobile "applications processors")
  http://en.wikipedia.org/wiki/ARM_processor
  https://seekingalpha.com/article/4414315-why-nvidia-arm-acquisition-should-be-approved
  https://www.arm.com/-/media/global/company/investors/PDFs/Arm_SBG_Q1_2019_Roadshow_Slides_FINAL.pdf
- ***IBM POWER9*** (servers)
  https://en.wikipedia.org/wiki/Power_Architecture

CPU Parts

The CPU consists of three main parts:

- Control Unit
- Arithmetic/Logic Unit
- Registers



CPU: Control Unit

The ***Control Unit*** decides what to do next.

For example:

- ***memory operations***: for example,
  - ***load*** data from ***main memory*** (RAM) into the ***registers***;
  - ***store*** data from the registers into main memory;
- ***arithmetic/logical operations***: e.g., add, multiply;
- ***branch***: choose among several possible courses of action.

CPU: Arithmetic/Logic Unit

The ***Arithmetic/Logic Unit*** (ALU) performs arithmetic and logical operations.

- ***Arithmetic* operations**: e.g., add, subtract, multiply, divide, square root, cosine, etc.
- ***Logical* operations**: e.g.,
  compare two numbers to see which is greater,
  check whether both of a pair of true/false statements are true,
  etc.

CPU: Registers

Registers are memory-like locations inside the CPU where data and instructions reside that are **being used right now**.

That is, registers hold the operands being used by the current arithmetic or logical operation, and/or the result of the arithmetic or logical operation that was just performed.

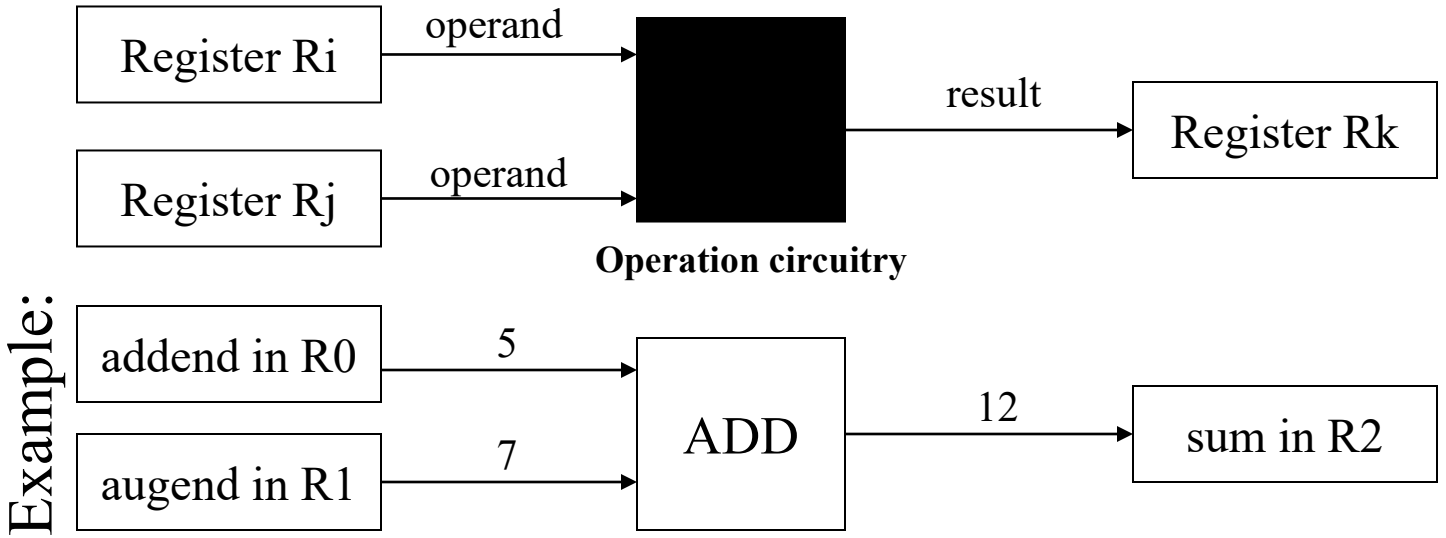
For example, if the CPU is adding two numbers, then

- the addend is in some register;
- the augend is in another register;
- after the addition is performed, the sum shows up in yet another register.

A typical CPU has only **a few hundred to a few thousand bytes** of registers.

How Registers Are Used

- Every arithmetic or logical operation has one or more operands and one result.
- Operands are contained in registers ("source").
- A "black box" of circuits performs the operation.
- The result goes into a register ("destination").

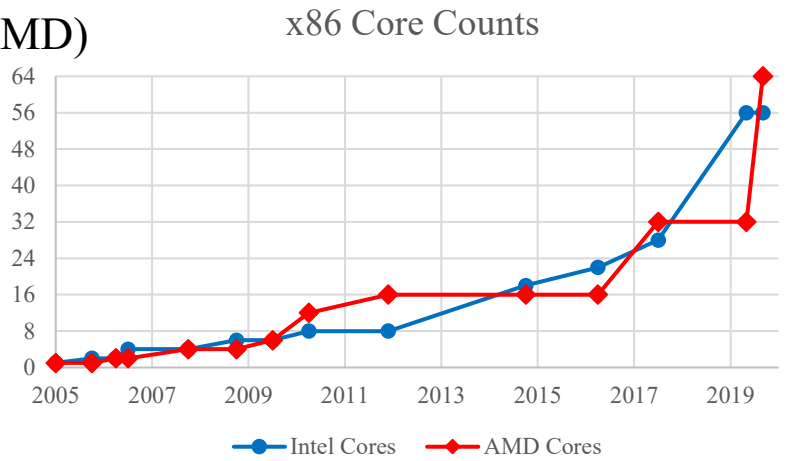


Multicore

- A ***multicore*** CPU is a chip with multiple, independent "brains," known as ***cores***.
- These multiple cores can run completely separate programs, or they can cooperate together to work simultaneously in parallel on different parts of the same program.
- All of the cores share the same connection to memory – and the same ***bandwidth*** (memory speed).

Multicore History (x86)

- Single core: November 1971 (Intel 4004)
- Dual core: October 2005 (Intel), March 2006 (AMD)
- Quad core: June 2006 (Intel), Sep 2007 (AMD)
- Hex core: Sep 2008 (Intel), June 2009 (AMD)
- 8-core (Intel & AMD): March 2010
- 12-core (AMD only): March 2010
- 16-core: Nov 2011 (AMD only)
- 18-core: Sep 2014 (Intel only)
- 22-core: March 2016 (Intel only)
- 28-core: July 2017 (Intel only)
- 32-core: June 2017 (AMD only)
- 56-core: Apr 2019 (Intel only)
- 64-core: Aug 2019 (AMD only)



Note that this is only for x86 – other processor families (for example, POWER) introduced multicore earlier.

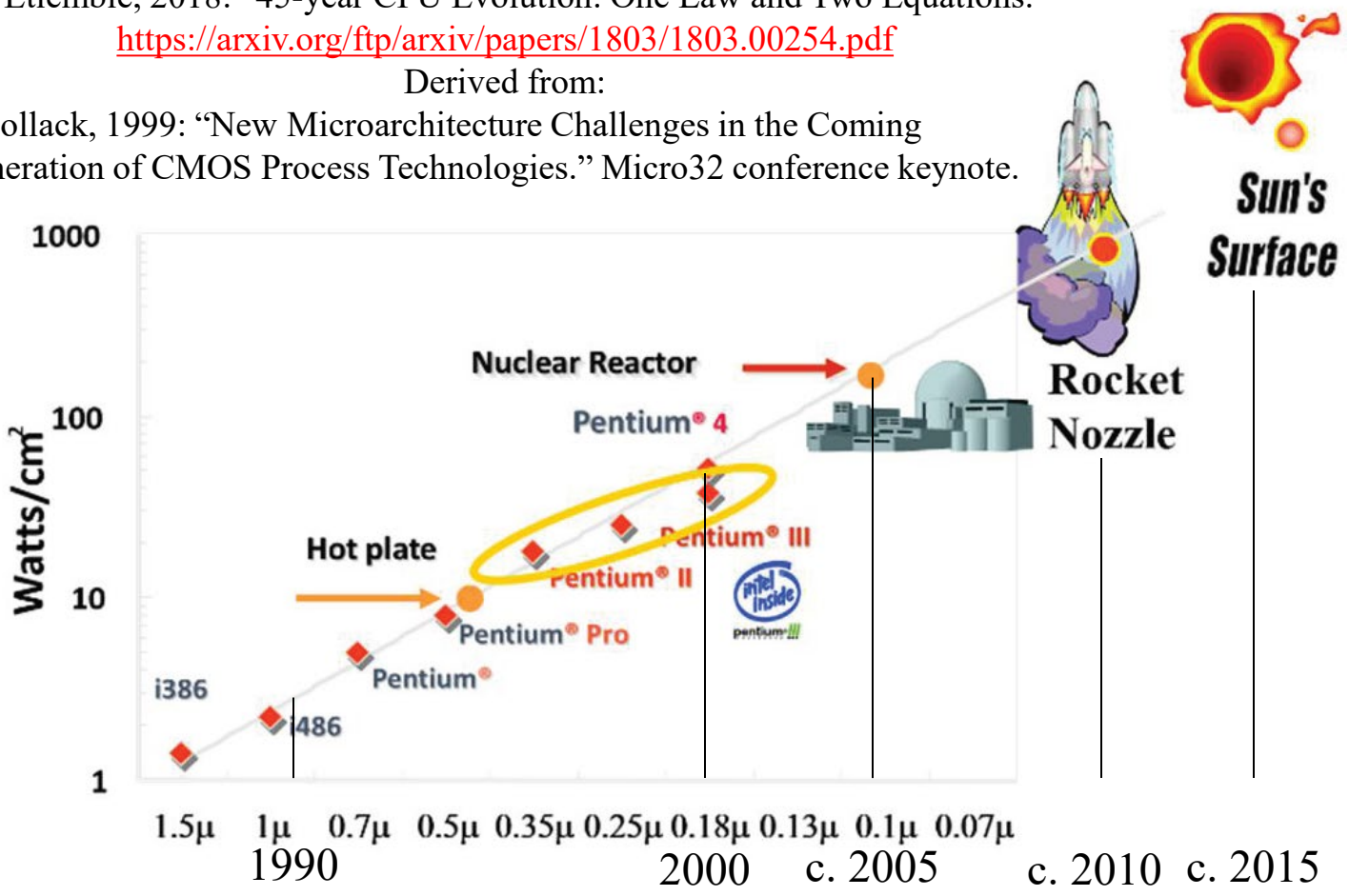
http://www.intel.com/pressroom/kits/quickreffam.htm (dual core, quad core)
http://ark.intel.com/products/family/34348/Intel-Xeon-Processor-7000-Sequence#@Server (hex core)
http://ark.intel.com/ProductCollection.aspx?familyID=594&MarketSegment=SRV (oct core)
http://en.wikipedia.org/wiki/Intel_Nehalem_(microarchitecture) (oct core)
http://en.wikipedia.org/wiki/AMD_Opteron (12-core)
https://en.wikipedia.org/wiki/Broadwell_(microarchitecture) (22-core)
https://en.wikipedia.org/wiki/Skylake_(microarchitecture) (28-core)
https://en.wikipedia.org/wiki/Cascade_Lake_(microarchitecture) (56-core)
https://en.wikipedia.org/wiki/Epyc (64-core, 32-core)

Why Multicore? #1

- In the golden olden days (through about 2005), the way to speed up a CPU was to increase its "clock speed."
  - Every CPU has a little crystal inside it that vibrates at a fixed frequency (for example, 1 GHz = 1 billion vibrations per second).
  - Each operation (add, subtract, multiply, divide, etc) requires a specific number of clock ticks to complete.
- But, the power density (watts per square cm) of a CPU chip is proportional to the **square** of the clock speed.
- So, continuing to increase the clock speed would have been, quite literally, a dead end, because by now such CPU chips would have already reached the power density of the sun.

Why Multicore? #2

D. Etiemble, 2018: "45-year CPU Evolution: One Law and Two Equations."
https://arxiv.org/ftp/arxiv/papers/1803/1803.00254.pdf
Derived from:
F. Pollack, 1999: "New Microarchitecture Challenges in the Coming Generation of CMOS Process Technologies." Micro32 conference keynote.



Storage

There are two major categories of storage:

- ***Primary***
  - Cache
  - Main memory (RAM)
- ***Secondary***
  - Hard disk
  - Removable (e.g., thumb drive, CD, floppy)

Primary Storage

Primary storage is where data and instructions reside when they're **being used by a program that is currently running**.

- Typically is ***volatile***: The data disappear when the power is turned off.
- Typically comes in two subcategories:
  - Cache
  - Main memory (RAM)

Cache

Cache memory is where data and instructions reside when they are **going to be used very very soon**, or have just been used.

- Cache is **very fast** (typically 5% - 100% of the speed of the registers) compared to RAM (~1% of the speed of the registers).
- Therefore, it's **very expensive** (e.g., $17 per MB)

  https://ark.intel.com/products/77493/Intel-Core-i3-4360-Processor-4M-Cache-3_70-GHz ($149)
  https://ark.intel.com/products/77490/Intel-Core-i3-4170-Processor-3M-Cache-3_70-GHz ($132)
  http://www.pricewatch.com/

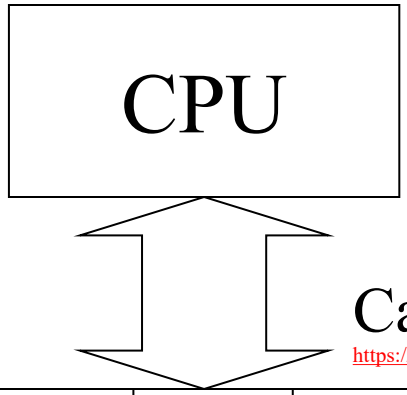
  Therefore, it's **very small** (e.g., under 1 MB to 256 MB)

https://en.wikipedia.org/wiki/Epyc

… but still **much bigger than registers**.

From Cache to the CPU

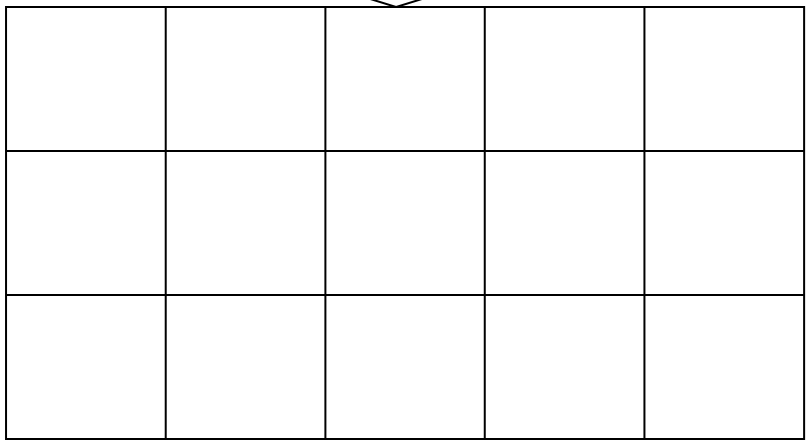
https://i.dell.com/is/image/DellContent//content/dam/global-site-design/product_images/dell_client_products/notebooks/latitude_notebooks/13_3590/global_spi/notebooks-latitude-15-3590-campaign-hero-504x350-ng.psd?fmt=png-alpha&wid=570&hei=400



CPU: Up to 1229 GB/sec on a 1.6 GHz Intel i-8250U Kaby Lake

Cache: 40 GB/sec (3.3%)

https://www.softpedia.com/get/System/Benchmarks/BenchMem.shtml



Cache

Typically, data move between cache and the CPU at speeds closer to that of the CPU performing calculations.

Main Memory (RAM)

Main memory (RAM) is where data and instructions reside when a **program that is currently running** is going to use them at some point during the run (whether soon or not).

- **Much slower** than cache
  (e.g., less than 1% of CPU speed for RAM, vs
  5-100% of CPU speed for cache)
- Therefore, **much cheaper** than cache
  (e.g., ~$0.005/MB for RAM vs $17/MB for cache)
  http://www.pricewatch.com/, http://www.ebay.com/,
  http://www.crucial.com/usa/en/compatible-upgrade-for/Dell/latitude-e5540
- Therefore, **much larger** than cache –
  for example, 1 GB (1024 MB) to 8 TB (~8M MB) for RAM vs under 1 MB to 256 MB for cache)
  https://en.wikipedia.org/wiki/Epyc

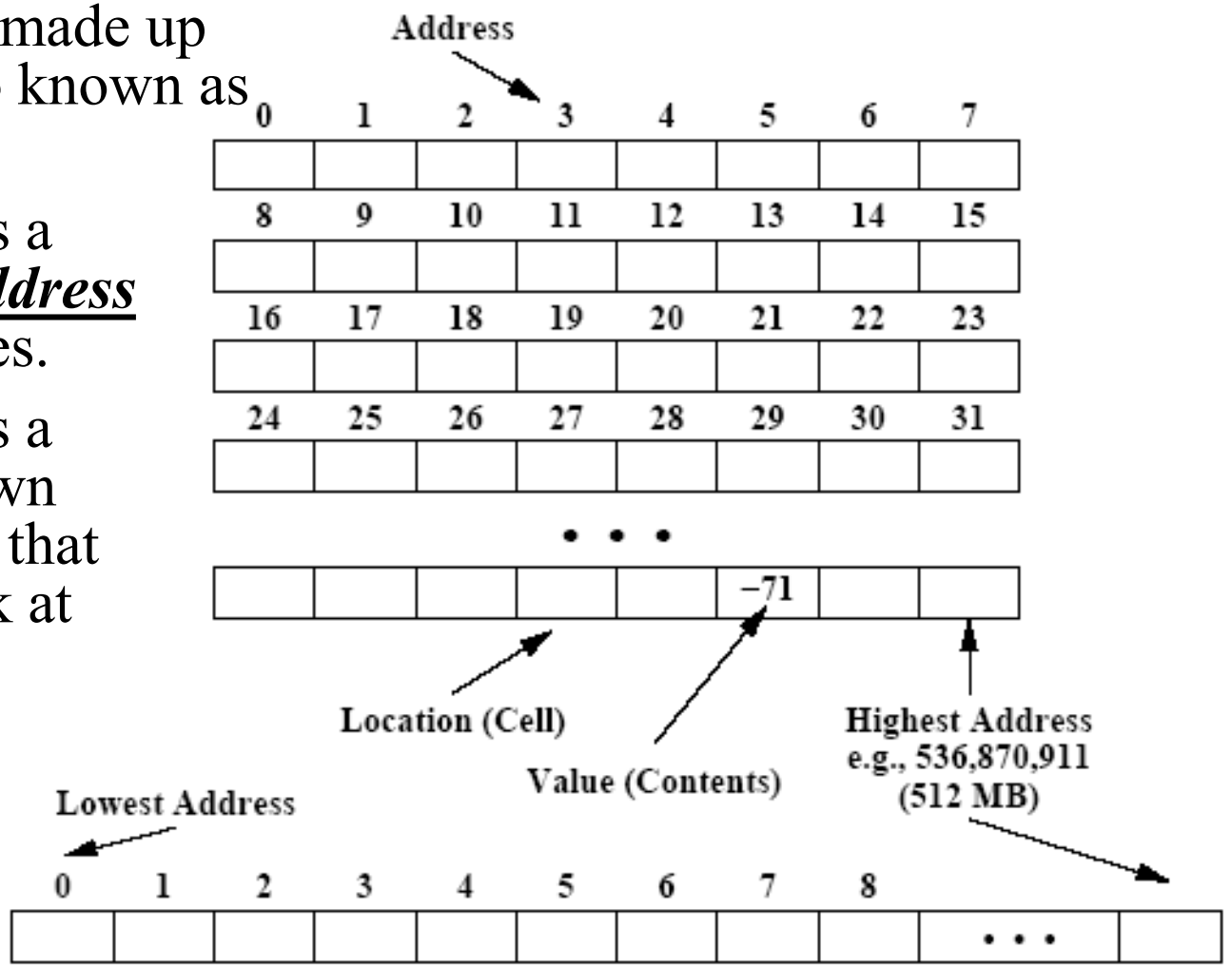
Main Memory Layout

Main memory is made up of ***locations***, also known as ***cells***.

Each location has a unique integer ***address*** that never changes.

Each location has a ***value*** – also known as the ***contents*** – that the CPU can look at and change.

We can think of memory as one ***contiguous*** line of cells. →



RAM vs ROM

***RAM*: Random Access Memory**

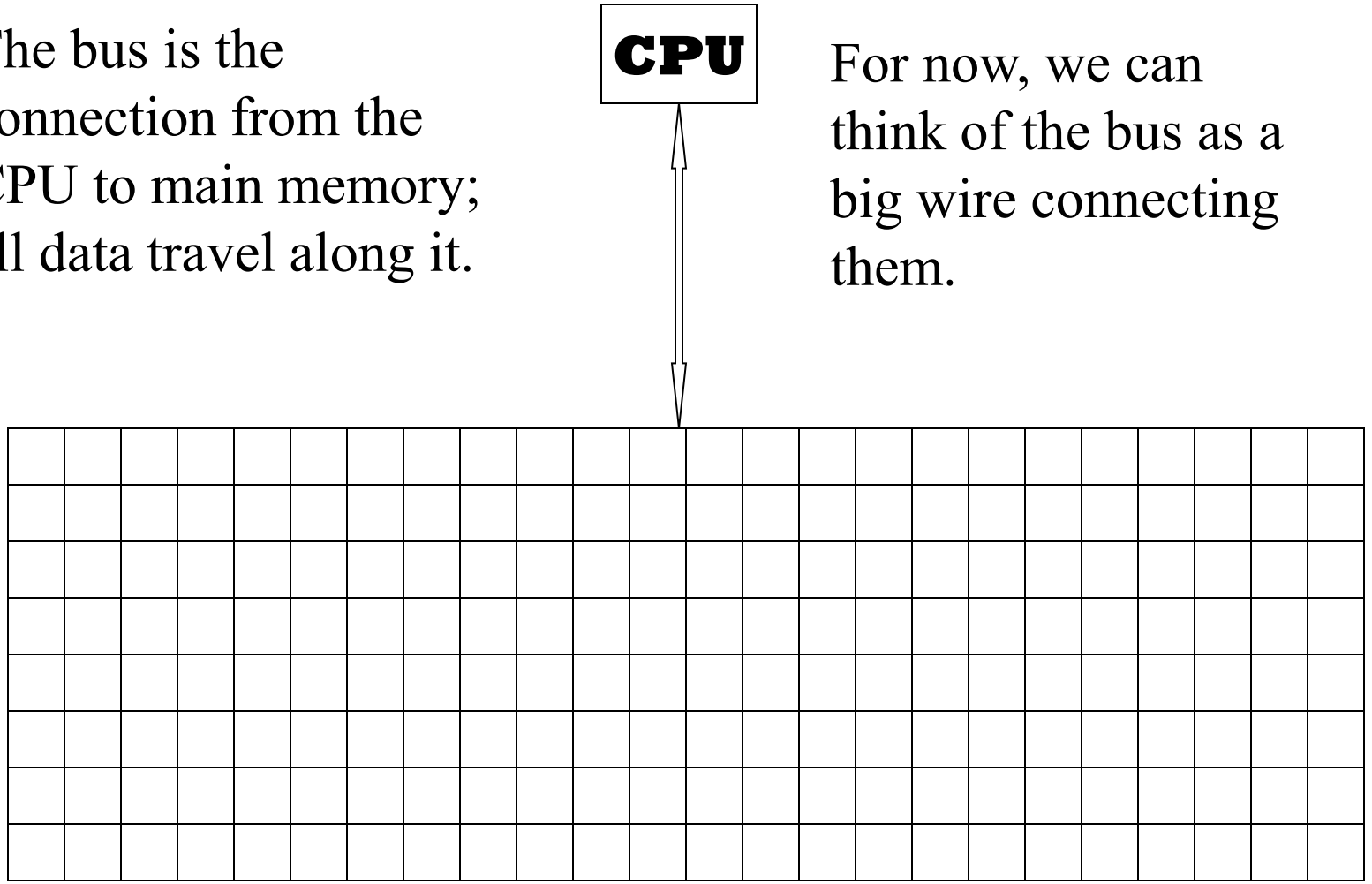
- Memory that the CPU can look at and change arbitrarily (i.e., can load from or store into any location at any time, not just in a sequence).
- We often use the terms **Main Memory**, **Memory** and **RAM** interchangeably.
- Sometimes known as ***core*** memory, named for an older memory technology. (Note that this use of the word "core" is unrelated to "multi-core.")

Speed => Price => Size

- Registers are **VERY fast**, because they are etched directly into the CPU.
- Cache is also **very fast**, because it's also etched into the CPU, but it isn't directly connected to the Control Unit or Arithmetic/Logic Unit in the same way as registers. Cache operates at speeds similar to registers, but cache is **MUCH bigger** than the collection of registers (typically on the order of 1,000 to 100,000 times as big).
- Main memory (RAM) is **much slower** than cache, because it isn't part of the CPU; therefore, it's **much cheaper** than cache, and therefore it's **much bigger** than cache (for example, 1000 times as big).

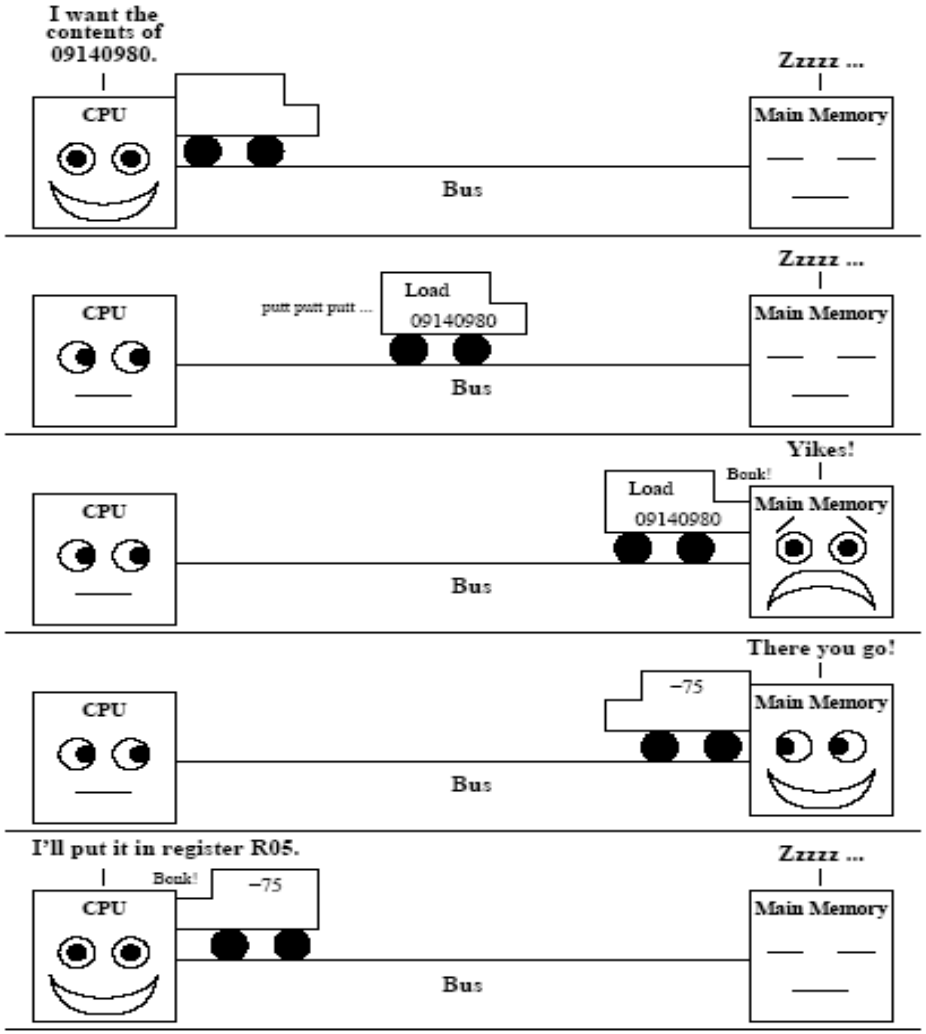
How Data Travel Between RAM and CPU

The bus is the connection from the CPU to main memory; all data travel along it.



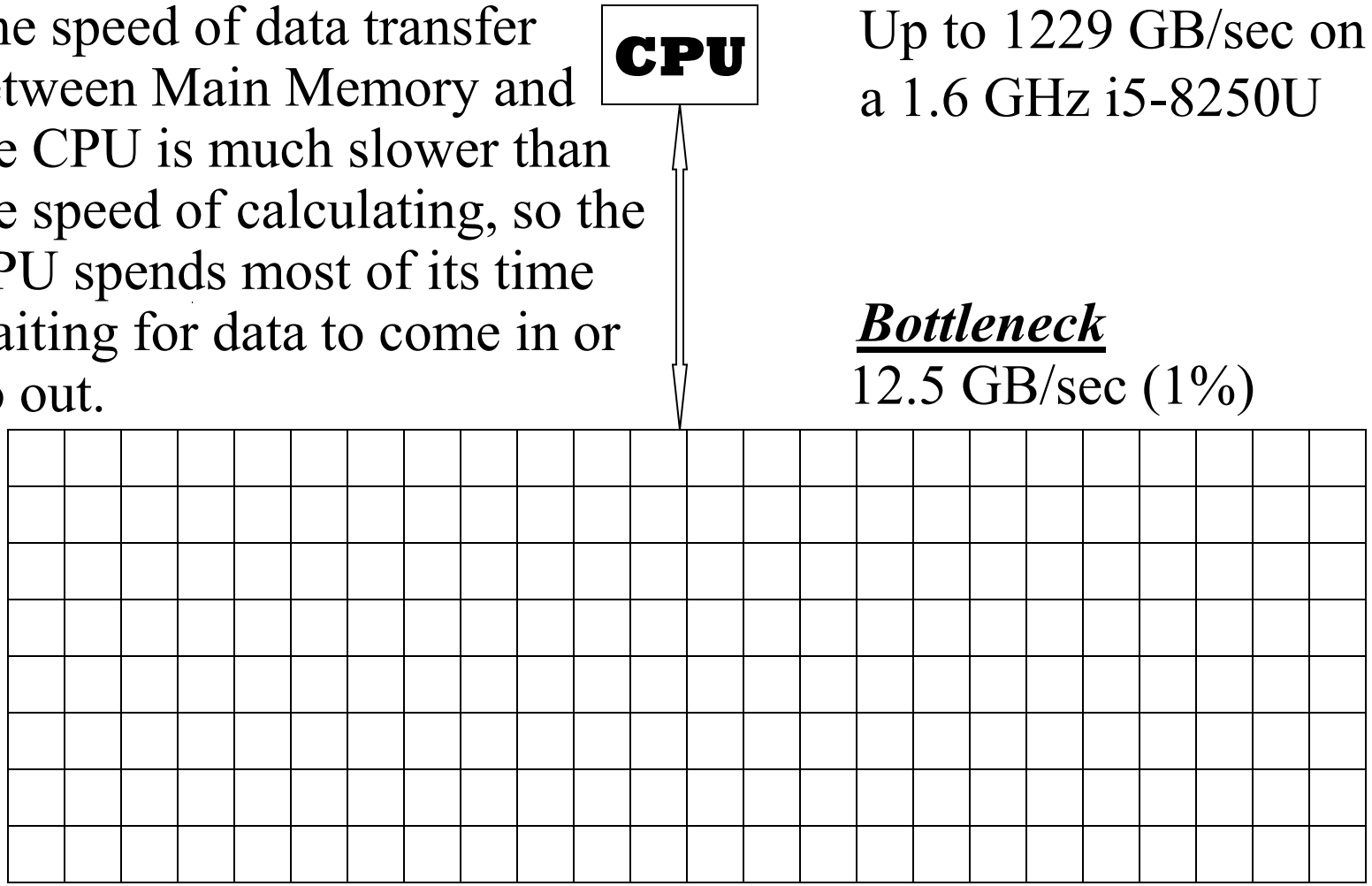
For now, we can think of the bus as a big wire connecting them.

Loading Data from RAM into the CPU



RAM is Slow

The speed of data transfer between Main Memory and the CPU is much slower than the speed of calculating, so the CPU spends most of its time waiting for data to come in or go out.



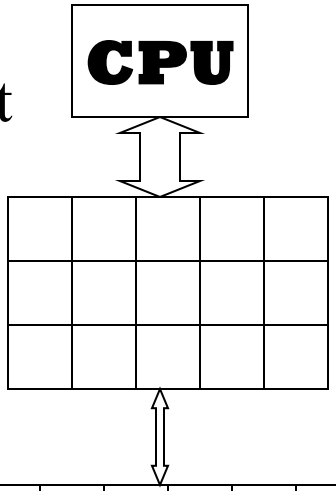
Up to 1229 GB/sec on a 1.6 GHz i5-8250U

Bottleneck

12.5 GB/sec (1%)

Why Have Cache?

Cache is much faster than RAM, so the CPU doesn't have to wait nearly as long for stuff that's already in cache: it can do more operations per second!

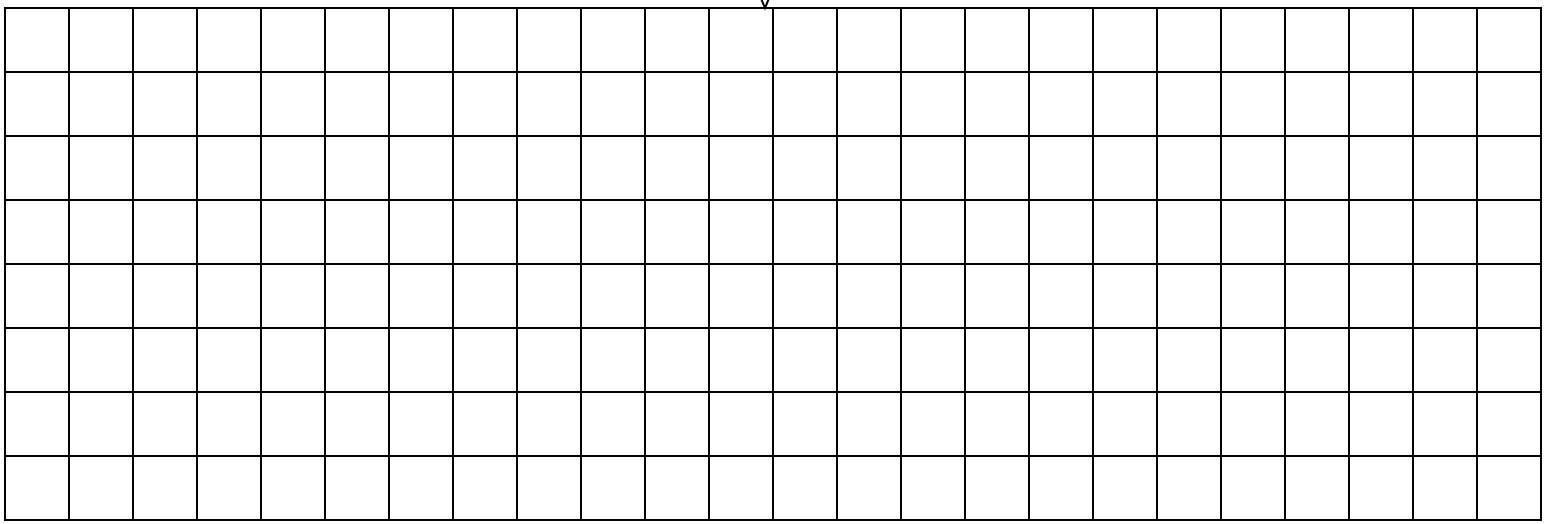


Up to 1229 GB/sec on a 1.6 GHz i5-8250U

40 GB/sec (3.3%)

https://www.softpedia.com/get/System/Benchmarks/BenchMem.shtml

12.5 GB/sec (1%)



Multiple Levels of Cache

- Nowadays, most CPUs have multiple levels of cache.
- For example, Henry's laptop has:
  - L1 cache: 32 KB per core, 266.0 GB/sec (22% of register speed)
  - L2 cache: 256 KB per core, 123.0 GB/sec (10% of register speed)
  - L3 cache: 6144 KB shared by all cores, 40.0 GB/sec (3% of register speed)
  - RAM (for comparison): 12.5 GB/sec (1% of register speed)
- So, the goal is to get the data you need into the fastest (but therefore smallest) cache by the time you need it.

Secondary Storage

- Where data and instructions reside that are going to be used **in the future**
- ***Nonvolatile***: data don't disappear when power is turned off.
- **Much slower** than RAM, therefore **much cheaper**, therefore **much larger.**
- Other than hard disk, most are ***portable***: they can be easily removed from your computer and taken to someone else's.

Media Types

- ***Solid State*** (for example, flash drive)
  - Always can be read
  - Always can be written and rewritten multiple times
  - Contents don't degrade much over time
  - Can't be erased by magnets
- ***Magnetic*** (for example, spinning disk drive)
  - Always can be read
  - Always can be written and rewritten multiple times
  - Contents degrade relatively rapidly over time
  - Can be erased by magnets
- ***Optical*** (for example, DVD)
  - Always can be read
  - Some can be written only once, some can be rewritten multiple times
  - Contents degrade more slowly than magnetic media
  - Can't be erased by magnets
- **Paper**: forget about it!

Speed, Price, Size

Medium	Speed (MB/sec)	Size (MB)	Media Type	Can write to it?	Port-able?	Pop-ular?	Drive cost ($)	Media cost ($/MB)
Cache	40,000	32	L1/L2/L3	Y	N	Req'd		$17.0000000
RAM	12,500	16,777,216	DDR4	Y	N	Req'd		$0.0045700
USB 3 Flash	625	2,000,000	Solid	Y	Y	Y		$0.0000275
Hard Disk	100	20,000,000	Mag	Y	N	Y		$0.0000191
Blu-ray	72	25,000	Opt	Y	Y	N	$64	$0.0000560
DVD±RW	32	4,700	Opt	Y	Y	N	$7	$0.0000511
CD-RW	7.8	700	Opt	Y	Y	N	$4	$0.0002282
Mag tape	360	9,000,000	Mag	Y	Y	N	$4049	$0.0000047
Floppy	0.03	1.44	Mag	Y	Y	N	$20	$1.7900000
Cassette	<< 1	<< 1	Mag	Y	Y	Historical		
Paper tape	<< 1	<< 1	Paper	Y	Y	Historical		
Punch card	<< 1	<< 1	Paper	Y	Y	Historical		

* Maximum among models commonly available for PCs

Note: All numbers are approximate as of Aug 2021 (amazon.com, bestbuy.com, cendyne.com, creativelabs.com, dell.com, ebay.com, floppydisk.com, nextag.com, pcworld.com, pricewatch.com, rakuten.com, sony.com, storagetek.com, toshiba.com, walmart.com, wikipedia.org). Tape drive is LTO-8, tape cartridge is LTO-7 Type M.

CD-ROM/DVD-ROM/BD-ROM

When a CD or DVD or Blu-ray holds data instead of music or a movie, it acts very much like Read Only Memory (ROM):

- it can only be read from, but not written to;
- it's nonvolatile;
- it can be addressed essentially arbitrarily (it's not actually arbitrary, but it's fast enough that it might as well be).

CD-ROM/DVD-ROM/BD-ROM: Disadvantage

Disadvantage of CD-ROM/DVD-ROM/BD-ROM compared to ROM:

- **Speed**: CD-ROM/DVD-ROM/BD-ROM are **much slower** than ROM:
  - CD-ROM is 7.8 MB/sec (peak); DVD-ROM is 32 MB/sec; BD-ROM is 72 MB/sec.
  - Most ROM these days is 10-300 GB/sec (hundreds or thousands of times as fast as secondary storage).

CD-ROM & DVD-ROM: Advantages

Advantages of CD-ROM/DVD-ROM compared to ROM:

- **Price**: CD-ROM and DVD-ROM are **much cheaper** than ROM.
  - Blank BD-REs are roughly $0.00006 per MB;
    blank DVD-RWs are roughly $0.00005 per MB;
    blank CD-RWs are roughly $0.00023 per MB.
  - ROM is even more expensive than RAM (which is ~$0.005/MB), because it has to be programmed special (with "firmware").
- **Size**: CD-ROM and DVD-ROM are **much larger** – they can have **arbitrary amount of storage** (on many CDs or DVDs); ROM is limited to a few GB.

Why Are Floppies So Expensive Per MB?

BD-REs cost roughly $0.00006 per MB, but floppy disks cost about $1.79 per MB, about 30,000 times as expensive per MB. **Why?**

Well, an individual BD-RE has **much greater capacity** than an individual floppy (25-100 GB vs. 1.44 MB), and the costs of manufacturing the actual physical objects are similar.

And, because floppies are much less popular than CDs, they aren't manufactured in high quantities – so it's tricky to amortize the high fixed costs of running the factory.

So, the cost of a floppy **per MB** is much higher.

I/O

We often say ***I/O*** as a shorthand for **"Input/Output."**

I/O: Input Devices

We often say ***I/O*** as a shorthand for **"Input/Output."**

Input Devices transfer data into computer (e.g., from a user into memory).

For example:

- Keyboard
- Mouse
- Scanner
- Microphone
- Touchpad
- Joystick

I/O: Output Devices

We often say ***I/O*** as a shorthand for **"Input/Output."**

Output Devices transfer data out of computer (for example, from memory to a user).

For example:

- Monitor
- Printer
- Speakers

NOTE: A device can be **both** input and output – for example, a touchscreen.

Bits

Bit (**B**inary dig**IT**)

- Tiniest possible piece of memory.
- Made of teeny tiny transistors wired together (the most recent are smaller than 10 nanometers)
- Has 2 possible values that we can think of in several ways:
  - **Low or High**: Voltage into transistor
  - **Off or On**: Conceptual description of transistor state
  - **False or True**: ***Boolean*** value for symbolic logic
  - **0 or 1**: Integer value
- Bits aren't individually ***addressable***: the CPU can't load from or store into an individual bit of memory.

Bytes

Byte: a sequence of 8 contiguous bits (typically)

- On most ***platforms*** (kinds of computers), a bit is the smallest ***addressable*** piece of memory: typically, the CPU can load from, or store into, an individual byte.
- Possible integer values: 0 to 255 or -128 to127 (to be explained later)
- Can also represent a character (for example, letter, digit, punctuation; to be explained later)

Words

Word: a sequence of 4 or 8 contiguous bytes (typically); that is, 32 or 64 contiguous bits

- Standard size for storing a **number** (integer or real)
- Standard size for storing an **address** (special kind of integer)

Putting Bits Together

1 bit: $2^1 = 2$ possible values: | 0 | or | 1 |

2 bits: $2^2 = 4$ possible values

| 0 | 0 | | 0 | 1 | | 1 | 0 | | 1 | 1 |

3 bits: $2^3 = 8$ possible values

| 0 | 0 | 0 | | 0 | 0 | 1 | | 0 | 1 | 0 | | 0 | 1 | 1 |

| 1 | 0 | 0 | | 1 | 0 | 1 | | 1 | 1 | 0 | | 1 | 1 | 1 |

Putting Bits Together (cont'd)

4 bits: $2^4 = 16$ possible values

…

8 bits: $2^8 = 256$ possible values

…

10 bits: $2^{10} = 1024$ possible values

…

16 bits: $2^{16} = 65{,}536$ possible values

…

32 bits: $2^{32} = 4{,}294{,}967{,}296$ possible values

(typical size of an integer in most computers today)

Powers of 2

2^0	=	1	2^{11}	=	2,048
2^1	=	2	2^{12}	=	4,096
2^2	=	4	2^{13}	=	8,192
2^3	=	8	2^{14}	=	16,384
2^4	=	16	2^{15}	=	32,768
2^5	=	32	2^{16}	=	65,536
2^6	=	64	2^{17}	=	131,072
2^7	=	128	2^{18}	=	262,144
2^8	=	256	2^{19}	=	524,288
2^9	=	512	2^{20}	=	1,048,576 (about a million)
2^{10}	=	1,024 (about a thousand)			

Powers of 2 vs Powers of 10

A rule of thumb for comparing powers of 2 to powers of 10:

$2^{10} \approx 10^3$ (that is, $1024 \approx 1000$)

So:

- $2^{10} \approx 1{,}000$ (thousand)
- $2^{20} \approx 1{,}000{,}000$ (million)
- $2^{30} \approx 1{,}000{,}000{,}000$ (billion)
- $2^{40} \approx 1{,}000{,}000{,}000{,}000$ (trillion)
- $2^{50} \approx 1{,}000{,}000{,}000{,}000{,}000$ (quadrillion)
- $2^{60} \approx 1{,}000{,}000{,}000{,}000{,}000{,}000$ (quintillion)

KB, MB, GB, TB, PB

Kilobyte (KB): 2^{10} bytes, which is approximately 1,000 bytes (thousand)

Megabyte (MB): 2^{20} bytes, which is approximately 1,000,000 bytes (million)

Gigabyte (GB): 2^{30} bytes, which is approximately 1,000,000,000 bytes (billion)

Terabyte (TB): 2^{40} bytes, which is approximately 1,000,000,000,000 bytes (trillion)

Petabyte (PB): 2^{50} bytes, which is approximately 1,000,000,000,000,000 bytes (quadrillion)

Kilo, Mega, Giga, Tera, Peta

Kilobyte (KB): 2^{10} bytes = 1,024 bytes ≃ 1,000 bytes

Approximate size: one e-mail (plain text)

Desktop Example: TRS-80 w/4 KB RAM (1977)

Megabyte (MB): 2^{20} bytes = 1,048,576 bytes ≃ 1,000,000 bytes

Approximate size: 30 phonebook pages

Desktop Example: IBM PS/2 PC w/1 MB RAM (1987)

Gigabyte (GB): 2^{30} bytes = 1,073,741,824 bytes ≃ 1,000,000,000 bytes

Approximate size: 15 copies of the OKC white pages

Desktop: c. 1997

Terabyte (TB): 2^{40} bytes = 1,099,511,627,776 bytes ≃ 1,000,000,000,000 bytes

Approximate size: 5,500 copies of a phonebook listing everyone in the world

Desktop: Example: Dell T630 workstation (2014)

Petabyte (PB): 2^{50} bytes ≃ 1,000,000,000,000,000 bytes

Desktop: ???

EB, ZB, YB

- ***Exabyte*** (EB): 2^{60} bytes, which is approximately 1,000,000,000,000,000,000 bytes (quintillion)

  (global monthly Internet traffic reached 1 EB in 2004; global daily Internet traffic was ~1.7 EB in 2013; ~20,000 copies of every book ever written)
- ***Zettabyte*** (ZB): 2^{70} bytes, which is approximately 1,000,000,000,000,000,000,000 bytes (sextillion)

  (By late 2016, annual Internet traffic was ~1 ZB.)
- ***Yottabyte*** (YB): 2^{80} bytes, which is approximately 1,000,000,000,000,000,000,000,000 bytes (septillion)

  (At current growth rates, by 2043, all data in the world will be ~1 YB; 1 YB ≈ 1400 metric tons of DNA.)

http://en.wikipedia.org/wiki/Exabyte

https://www.import.io/wp-content/uploads/2017/04/Seagate-WP-DataAge2025-March-2017.pdf

http://www.extremetech.com/extreme/134672-harvard-cracks-dna-storage-crams-700-terabytes-of-data-into-a-single-gram

Moore's Law

Moore's Law: Computing speed and capacity double every 24 months.

In 1965 Gordon Moore (Chairman Emeritus, Intel Corp) observed the "doubling of transistor density on a manufactured die every year."

People have noticed that computing speed and capacity are roughly proportional to transistor density.

Moore's Law is usually hedged by saying that computing speed doubles every 24 months.

See:

http://www.intel.com/content/www/us/en/silicon-innovations/moores-law-technology.html
http://www.intel.com/pressroom/kits/quickreffam.htm
http://en.wikipedia.org/wiki/Transistor_count
http://en.wikipedia.org/wiki/Beckton_%28microprocessor%29#6500.2F7500-series_.22Beckton.22
https://en.wikipedia.org/wiki/List_of_Intel_Nehalem-based_Xeon_microprocessors#"Beckton"_(45_nm)

Implication of Moore's Law

If computing speed and capacity double every 24 months, what are the implications in our lives?

Well, the average undergrad student is – to one significant figure – about 20 years old.

And the average lifespan in the US – to one significant figure – is about 80 years.

So, the average undergrad student has 60 years to go.

So how much will computing speed and capacity increase during the time you have left?

Double, double, …

60 years / 2 years = 30 doublings

What is 2^{30}?

Consider the computer on your desktop today, compared to the computer on your desktop the day you die.

How much faster will it be?

Can we possibly predict what the future of computing will enable us to do?