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Great Ideas in Computer Architecture

(a.k.a. Machine Structures)

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Caches I

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Binary Prefix

Kilo, Mega, Giga, Tera, Peta, Exa, Zetta, Yotta

- Common use prefixes (all SI, except K [= k in SI])
- Confusing! Common usage of "kilobyte" means 1024 bytes, but the "correct" SI value is 1000 bytes
- Hard Disk manufacturers & Telecommunications are the only computing groups that use SI factors
  - What is advertised as a 1 TB drive actually holds about 90% of what you expect
  - A 1 Mbit/s connection transfers 10^6 bps.

Name	Abbr	Factor	SI size
Kilo	K	2^{10} = 1,024	10^3 = 1,000
Mega	M	2^{20} = 1,048,576	10^6 = 1,000,000
Giga	G	2^{30} = 1,073,741,824	10^9 = 1,000,000,000
Tera	T	2^{40} = 1,099,511,627,776	10^{12} = 1,000,000,000,000
Peta	P	2^{50} = 1,125,899,906,842,624	10^{15} = 1,000,000,000,000,000
Exa	E	2^{60} = 1,152,921,504,606,846,976	10^{18} = 1,000,000,000,000,000,000
Zetta	Z	2^{70} = 1,180,591,620,717,411,303,424	10^{21} = 1,000,000,000,000,000,000,000
Yotta	Y	2^{80} = 1,208,925,819,614,629,174,706,176	10^{24} = 1,000,000,000,000,000,000,000,000

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kibi, mebi, gibi, tebi, pebi, exbi, zebi, yobi

- IEC Standard Prefixes [only to exbi officially]

Name	Abbr	Factor
kibi	Ki	2^{10} = 1,024
mebi	Mi	2^{20} = 1,048,576
gibi	Gi	2^{30} = 1,073,741,824
tebi	Ti	2^{40} = 1,099,511,627,776
pebi	Pi	2^{50} = 1,125,899,906,842,624
exbi	Ei	2^{60} = 1,152,921,504,606,846,976
zebi	Zi	2^{70} = 1,180,591,620,717,411,303,424
yobi	Yi	2^{80} = 1,208,925,819,614,629,174,706,176

- International Electrotechnical Commission (IEC) in 1999 introduced these to specify binary quantities.
- Names come from shortened versions of the original SI prefixes (same pronunciation) and *bi* is short for "binary", but pronounced "bee" :-(
- Now SI prefixes only have their base-10 meaning and never have a base-2 meaning.

Kilo, Mega, Giga, Tera, Peta, Exa, Zetta, Yotta

1. Kid meets giant Texas people exercising zen-like yoga. – Rolf O
2. Kind men give ten percent extra, zestfully, youthfully. – Hava E
3. Kissing Mentors Gives Testy Persistent Extremists Zealous Youthfulness. – Gary M
4. Kindness means giving, teaching, permeating excess zeal yourself. – Hava E
5. Killing messengers gives terrible people exactly zero, yo
6. Kindergarten means giving teachers perfect examples (of) zeal (&) youth
7. Kissing mediocre giraffes teaches people (to) expect zero (from) you
8. Kinky Mean Girls Teach People Exciting Zen Yoga
9. Kissing Mel Gibson, Teddy Pendergrass exclaimed: "Zesty, yo!" – Dan G
10. Kissing me gives ten percent extra zeal & youth! – Dan G (borrowing parts)

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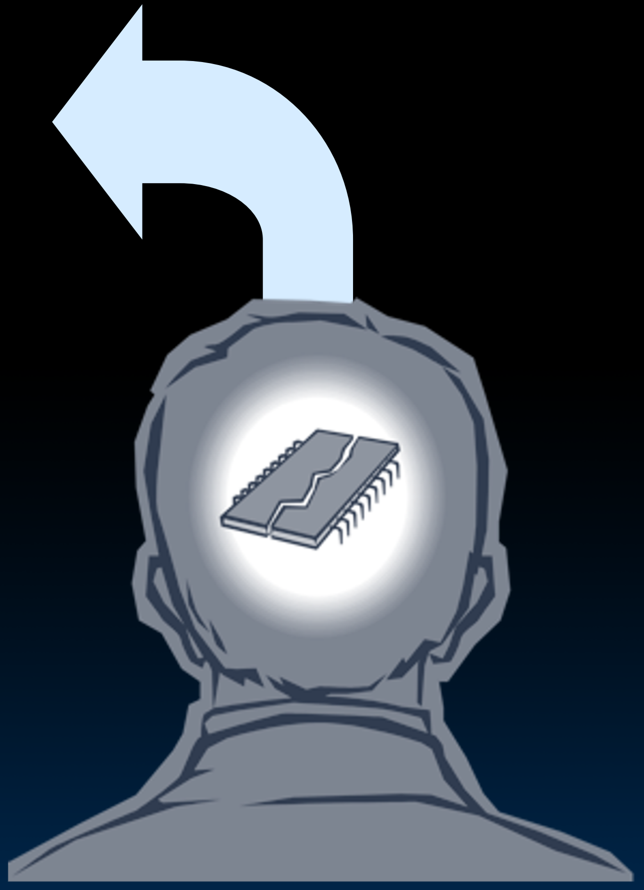
The way to remember #s

- **What is 2^{34}? How many bits to address (I.e., what's `ceil` $\texttt{log}_2$ = `lg` of) 2.5 TiB?**
- **Answer! 2^{XY} means…**

X=0 ⇒ ---	Y=0 ⇒ 1
X=1 ⇒ kibi ~10^3	Y=1 ⇒ 2
X=2 ⇒ mebi ~10^6	Y=2 ⇒ 4
X=3 ⇒ gibi ~10^9	Y=3 ⇒ 8
X=4 ⇒ tebi ~10^{12}	Y=4 ⇒ 16
X=5 ⇒ pebi ~10^{15}	Y=5 ⇒ 32
X=6 ⇒ exbi ~10^{18}	Y=6 ⇒ 64
X=7 ⇒ zebi ~10^{21}	Y=7 ⇒ 128
X=8 ⇒ yobi ~10^{24}	Y=8 ⇒ 256
	Y=9 ⇒ 512



MEMORIZE!

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Library Analogy

New-School Machine Structures

Software

Parallel Requests
Assigned to computer
e.g., Search "Cats"

Parallel Threads
Assigned to core e.g., Lookup, Ads

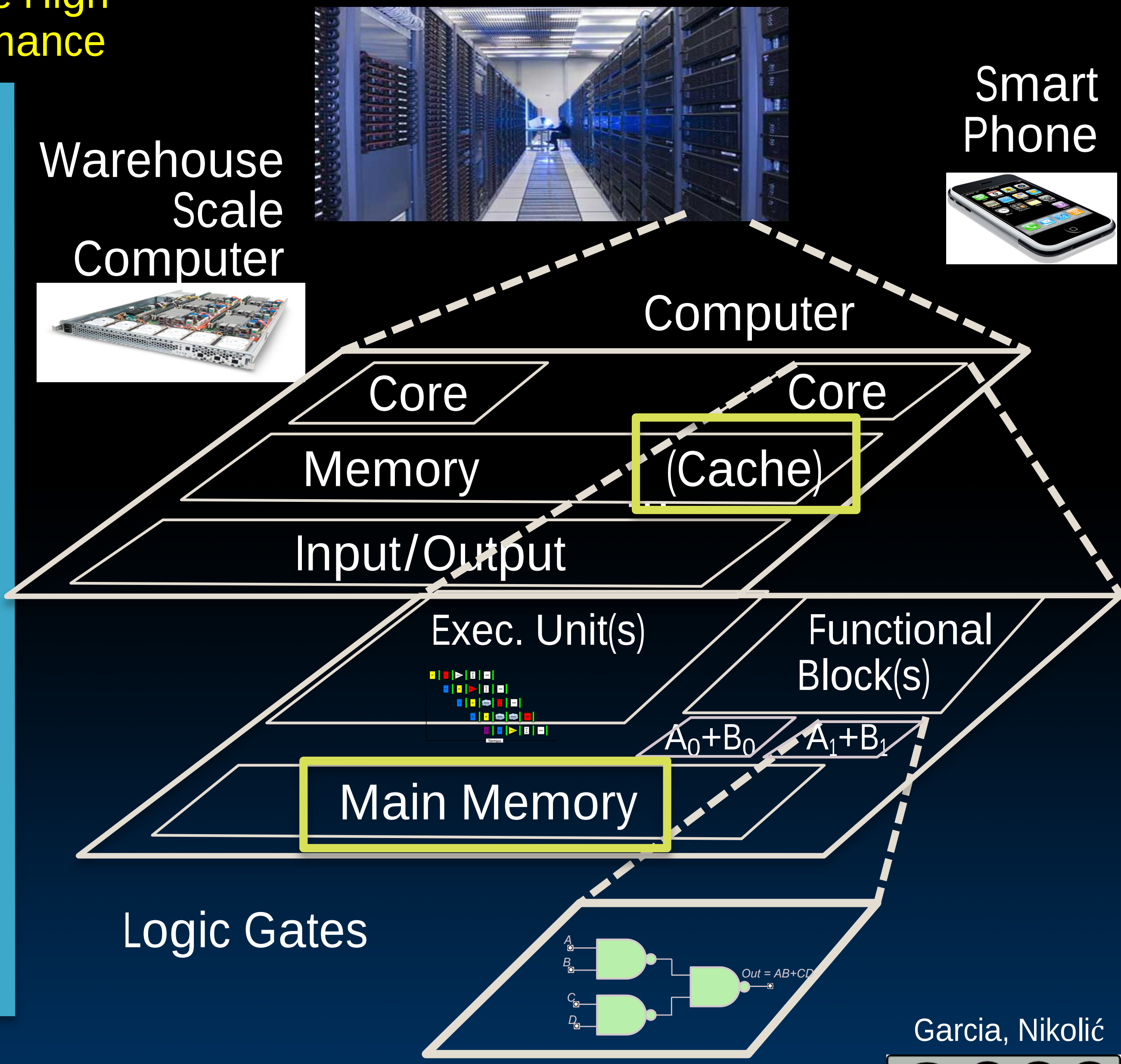
Parallel Instructions
>1 instruction @ one time
e.g., 5 pipelined instructions

Parallel Data
>1 data item @ one time
e.g., Add of 4 pairs of words

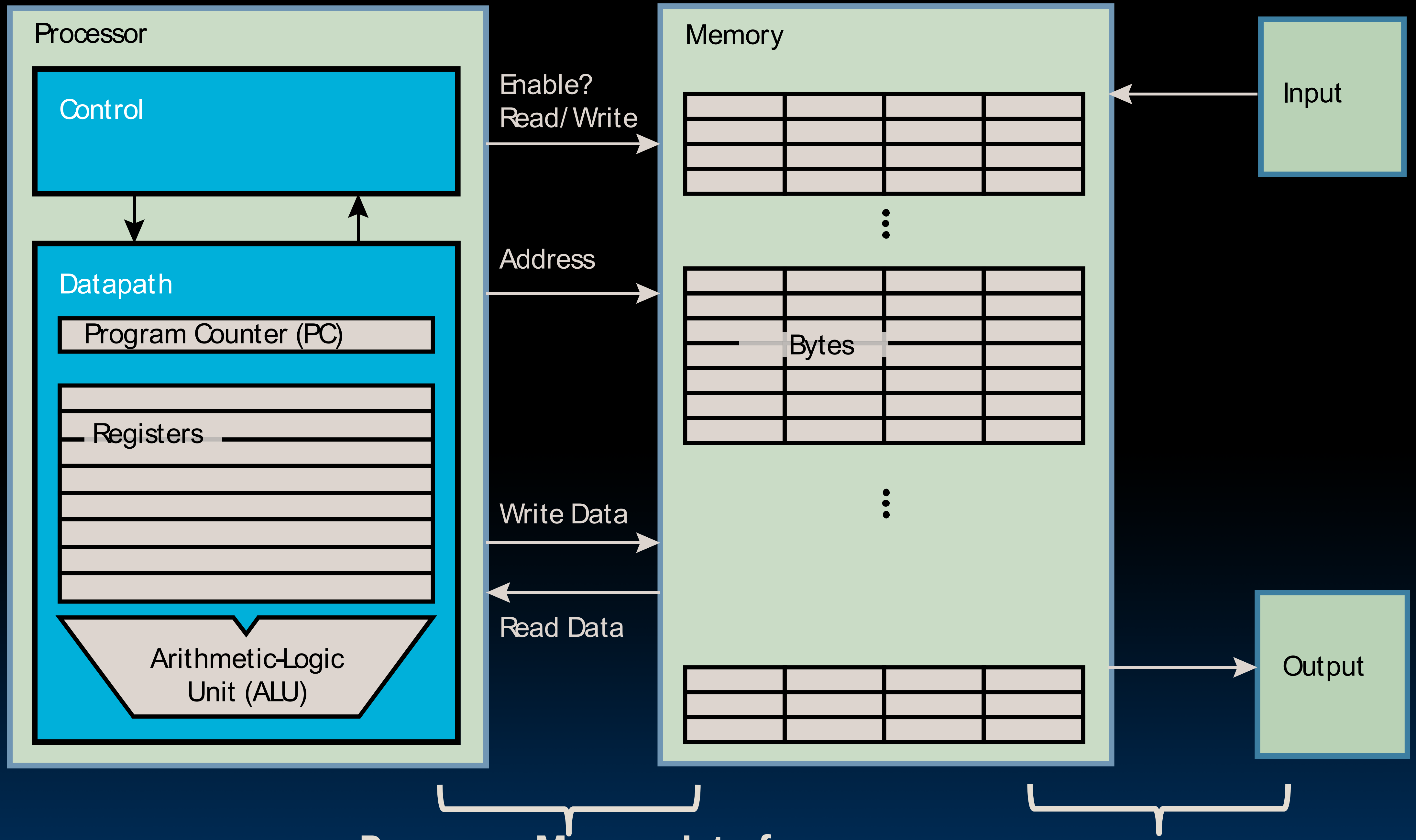
Hardware descriptions
All gates work in parallel at same time

Harness Parallelism & Achieve High Performance

Hardware



Components of a Computer



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Why are Large Memories Slow? Library Analogy

- **Time to find a book in a large library**
  - Search a large card catalog – (mapping title/author to index number)
  - Round-trip time to walk to the stacks and retrieve the desired book
- **Larger libraries worsen both delays**
- **Electronic memories have same issue, *plus* the technologies used to store a bit slow down as density increases (e.g., SRAM vs. DRAM vs. Disk)**

What we want is a large, yet fast memory!

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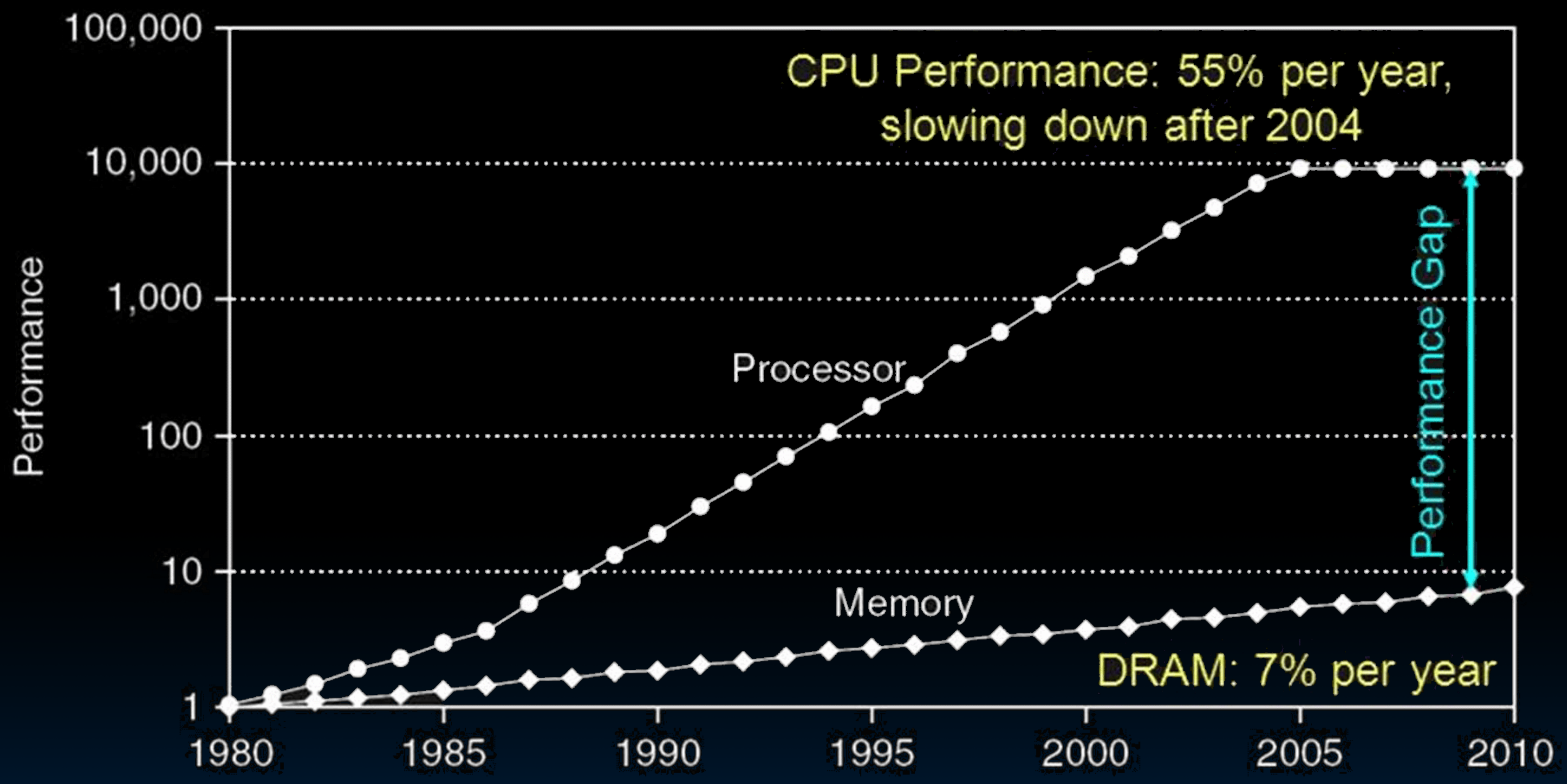
Processor-DRAM Gap (Latency)



1980 microprocessor executes ~one instruction in same time as DRAM access

2020 microprocessor executes ~1000 instructions in same time as DRAM access ☑

Slow DRAM access has disastrous impact on CPU performance!

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Memory Hierarchy

What To Do: Library Analogy

- **Write a report using library books**
  - E.g., works of J.D. Salinger
- **Go to library, look up books, fetch from stacks, and place on desk in library**
- **If need more, check out, keep on desk**
  - But don't return earlier books since might need them
- **You hope this collection of ~10 books on desk enough to write report, despite 10 being only 0.00001% of books in UC Berkeley libraries**

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Memory Caching

- **Mismatch between processor and memory speeds leads us to add a new level…**
  - Introducing a "memory cache"
- **Implemented with same IC processing technology as the CPU (usually integrated on same chip)**
  - faster but more expensive than DRAM memory.
- **Cache is a copy of a subset of main memory**
- **Most processors have separate caches for instructions and data.**

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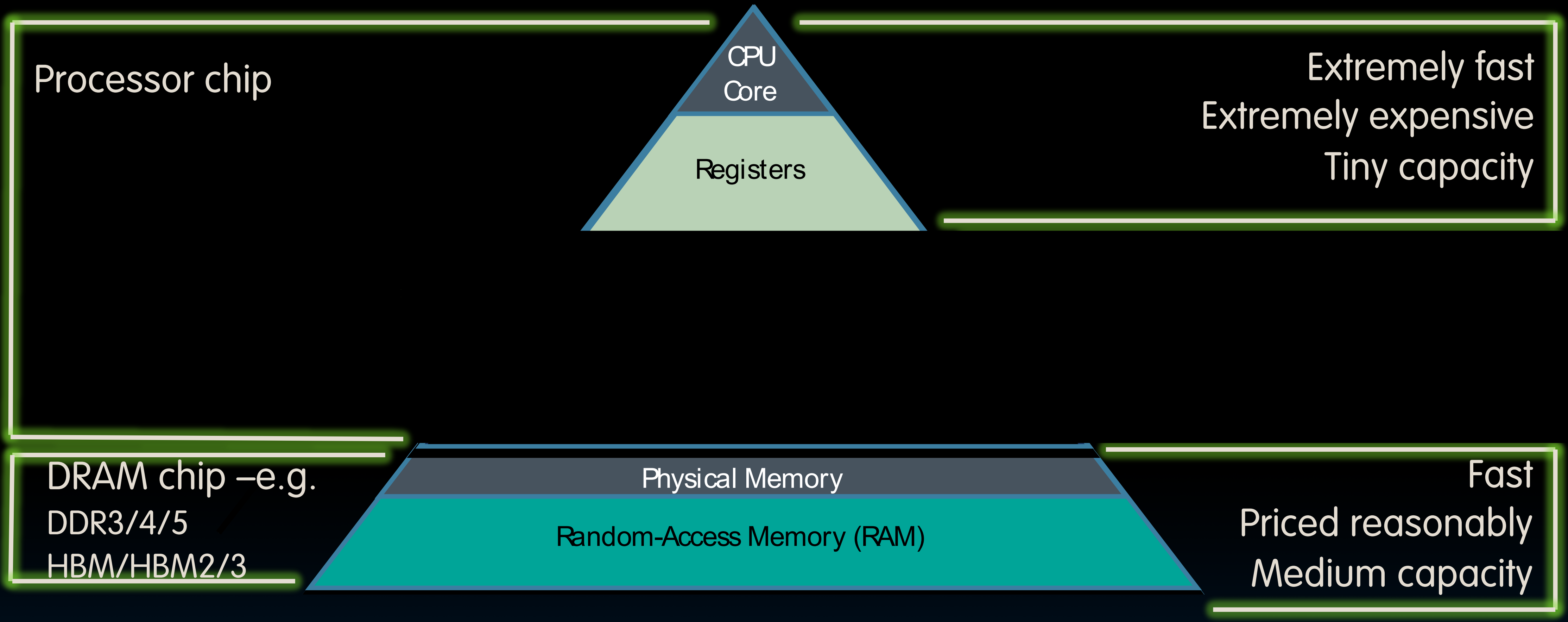
Great Idea #3: Principle of Locality / Memory Hierarchy



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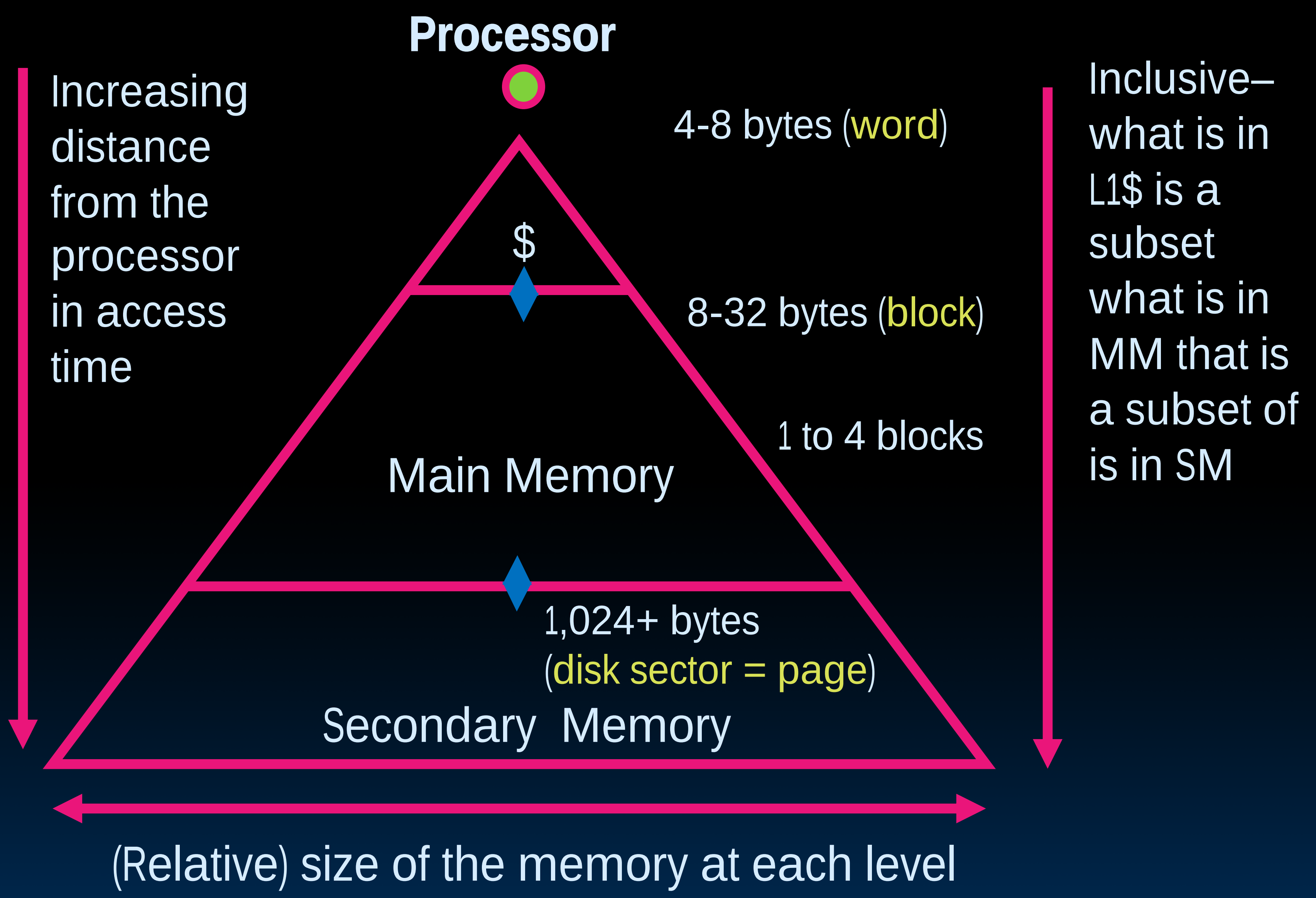
Jim Gray's Storage Latency Analogy: How Far Away is the Data?

Jim Gray
Turing Award
B.S. Cal 1966
Ph.D. Cal 1969

[ns]			
100	Memory	Sacramento	1.5 hr
2	On-chip cache	This Room	2 min
1	Registers	My Head	1 min

Characteristics of the Memory Hierarchy



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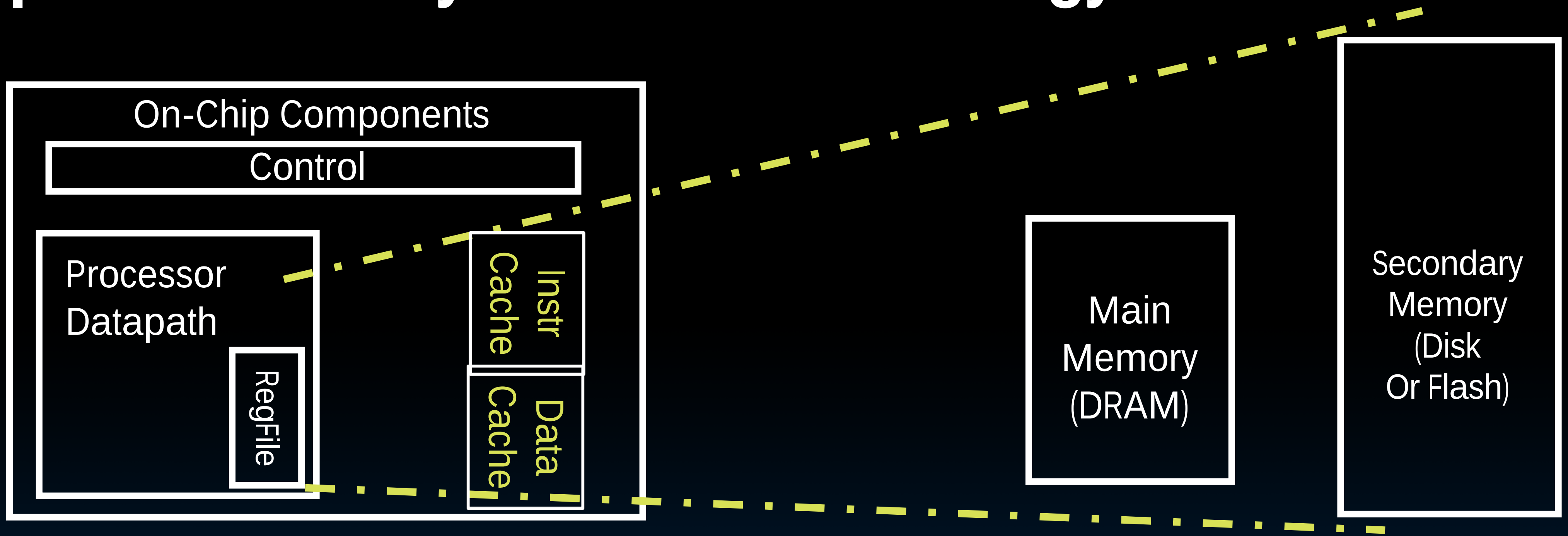
Typical Memory Hierarchy

- **The Trick: present processor with as much memory as is available in the *cheapest* technology at the speed offered by the *fastest* technology**



Speed (#cycles):	½'s	1's	10's	100's	10,000's
Size (bytes):	100's	10K's	M's	G's	T's
Cost:	highest				lowest

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Memory Hierarchy

- **If level closer to Processor, it is:**
  - Smaller
  - Faster
  - More expensive
  - subset of lower levels (contains most recently used data)
- **Lowest Level (usually disk=HDD/SSD) contains all available data (does it go beyond the disk?)**
- **Memory Hierarchy presents the processor with the illusion of a very large & fast memory**

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Locality, Design, Management

Memory Hierarchy Basis

- **Cache contains copies of data in memory that are being used.**
- **Memory contains copies of data on disk that are being used.**
- **Caches work on the principles of temporal and spatial locality.**
  - Temporal locality (locality in time): If we use it now, chances are we'll want to use it again soon.
  - Spatial locality (locality in space): If we use a piece of memory, chances are we'll use the neighboring pieces soon.

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What to Do About Locality

- ***Temporal Locality***
  - If a memory location is referenced then it will tend to be referenced again soon

  $\Rightarrow$ Keep most recently accessed data items closer to the processor

- ***Spatial Locality***
  - If a memory location is referenced, the locations with nearby addresses will tend to be referenced soon

  $\Rightarrow$ Move blocks consisting of contiguous words closer to the processor

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Cache Design

- **How do we organize cache?**
- **Where does each memory address map to?**
  - (Remember that cache is subset of memory, so multiple memory addresses map to the same cache location.)
- **How do we know which elements are in cache?**
- **How do we quickly locate them?**

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How is the Hierarchy Managed?

- **registers ↔ memory**
  - By compiler (or assembly level programmer)
- **cache ↔ main memory**
  - By the cache controller hardware
- **main memory ↔ disks (secondary storage)**
  - By the operating system (virtual memory)
  - Virtual to physical address mapping assisted by the hardware ('translation lookaside buffer' or TLB)
  - By the programmer (files)

Also a type of cache

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"And in Conclusion…"

- **Caches provide an illusion to the processor that the memory is infinitely large and infinitely fast**

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