



中国科学院大学

University of Chinese Academy of Sciences

CS101

# Systems Thinking

Seamless Transition-2:  
Amdahl's Law, Computer Landscape

zxu@ict.ac.cn  
zhangjialin@ict.ac.cn

# Outline

- What is systems thinking?
- Three objectives of systems thinking
- Abstraction
- Modularization
- Seamless transition
  - The symphony of four principles
  - Yang's cycle principle
  - Postel's robustness principle
  - von Neumann's exhaustiveness principle
  - **Amdahl's law**
    - Pipeline
    - Cache
    - Parallelism
  - **Landscape of computing systems**

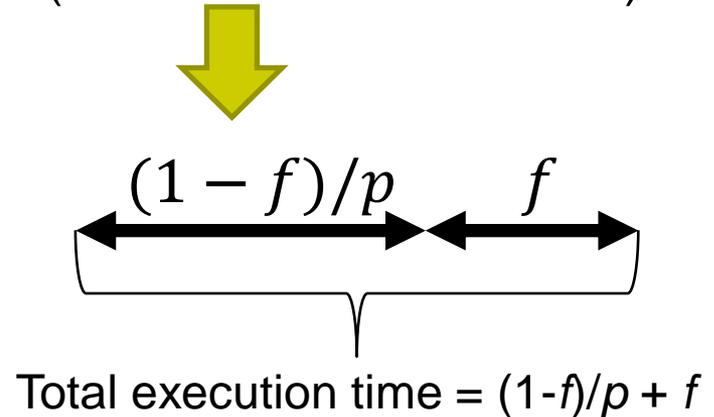
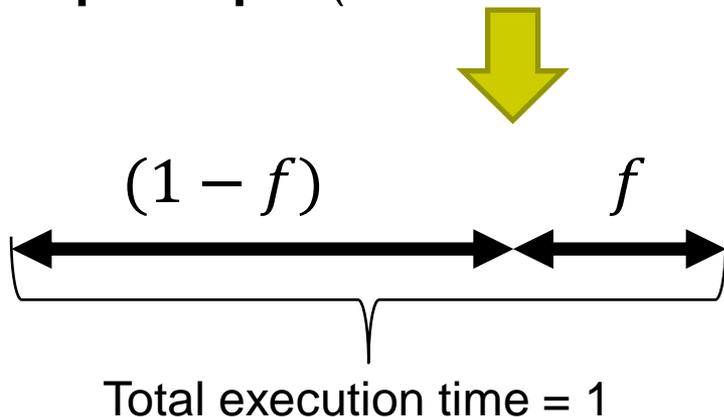
*These slides acknowledge sources for additional data not cited in the textbook*

## 5.5 Amdahl's law

- Previous 3 principles regard correctness (seamless transition)
- Amdahl's law focuses on performance (smooth transition)
- 1-minute quiz
  - A student writes a program `sort.go` to read a 8-GB file of 64-bit integers, sort the integers, and write the sorted result into another file on his laptop computer. Suppose the total execution time is  $T$ , where  $0.8 \cdot T$  is spent on I/O operations.
    - Q1: What is the problem size  $N$ , i.e., the number of integers?
    - A1: (a) 8 (b) 64 (c) 1024 (d)  $64 \cdot 1024 \cdot 1024$  (e)  $1024 \cdot 1024 \cdot 1024$
    - Q2: The student upgrades his laptop with a new wonder processor that is 100 times as fast as the old processor. How much time (approximately) is needed to execute `sort.go` on the same 8-GB file?
    - A1: (a)  $T/100$  (b)  $T/5$  (c)  $0.1 \cdot T$  (d)  $0.8 \cdot T$

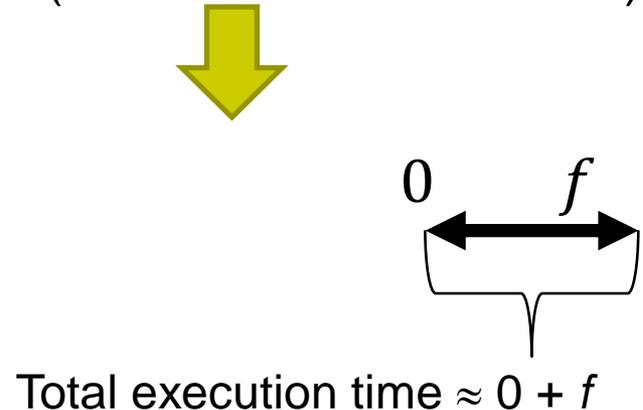
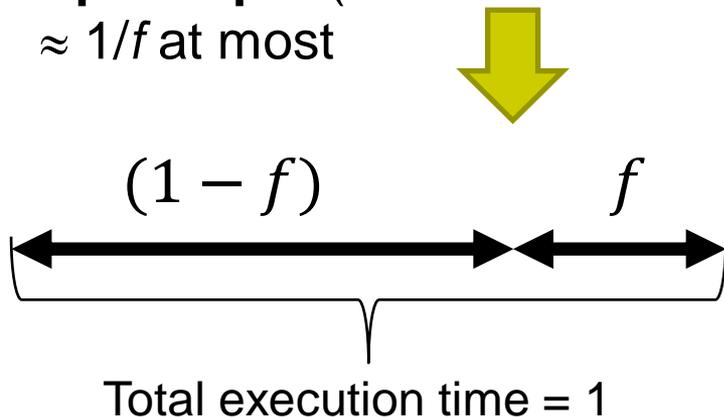
# Amdahl's law

- After enhancing a portion of a system, the speedup obtained is upper bounded by the reciprocal of the other portion's time.
- Suppose a system's execution time is broken into two portions  $(1 - f)$  and  $f$ , such that  $(1 - f) > f$
- Amdahl's law: Enhancement on the  $(1 - f)$  portion can lead to a speedup no more than  $1/f$ 
  - Speedup approaches but never exceeds  $1/f$
  - **Speedup** = (time before enhancement) / (time after enhancement)



# Amdahl's law

- After enhancing a portion of a system, the speedup obtained is upper bounded by the reciprocal of the other portion's time.
- Suppose a system's execution time is broken into two portions  $(1 - f)$  and  $f$ , such that  $(1 - f) > f$
- Amdahl's law: Enhancement on the  $(1 - f)$  portion can lead to a speedup no more than  $1/f$ 
  - Speedup approaches but never exceeds  $1/f$
  - **Speedup** = (time before enhancement) / (time after enhancement)  
 $\approx 1/f$  at most

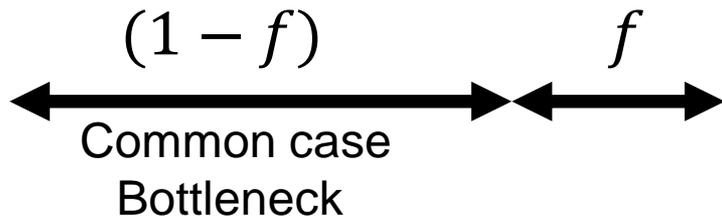


## 5.5 Amdahl's law

- 1-minute quiz
  - A student writes a program `sort.go` to read a 8-GB file of 64-bit integers, sort the integers, and write the sorted result into another file on his laptop computer. Suppose the total execution time is  $T$ , where  $0.8 \cdot T$  is spent on file I/O operations.
  - Q1: What is the problem size  $N$ , i.e., the number of integers?
  - A1: (a) 8 (b) 64 (c) 1024 (d)  $64 \cdot 1024 \cdot 1024$  (e)  $1024 \cdot 1024 \cdot 1024$
  - Q2: The student upgrades his laptop with a new wonder processor that is 100 times as fast as the old processor. How much time (approximately) is needed to execute `sort.go` on the same 8-GB file?
  - A1: (a)  $T/100$  (b)  $T/5$  (c)  $0.1 \cdot T$  (d)  $0.8 \cdot T$ 
    - The processing time is about  $0.2 \cdot T / 100$ , but the I/O time stays the same. Thus, the total time is about  $0.2 \cdot T / 100 + 0.8 \cdot T = 0.802 \cdot T$
    - The speedup is  $T / 0.802T \approx 1.247$ , only 24.7% faster

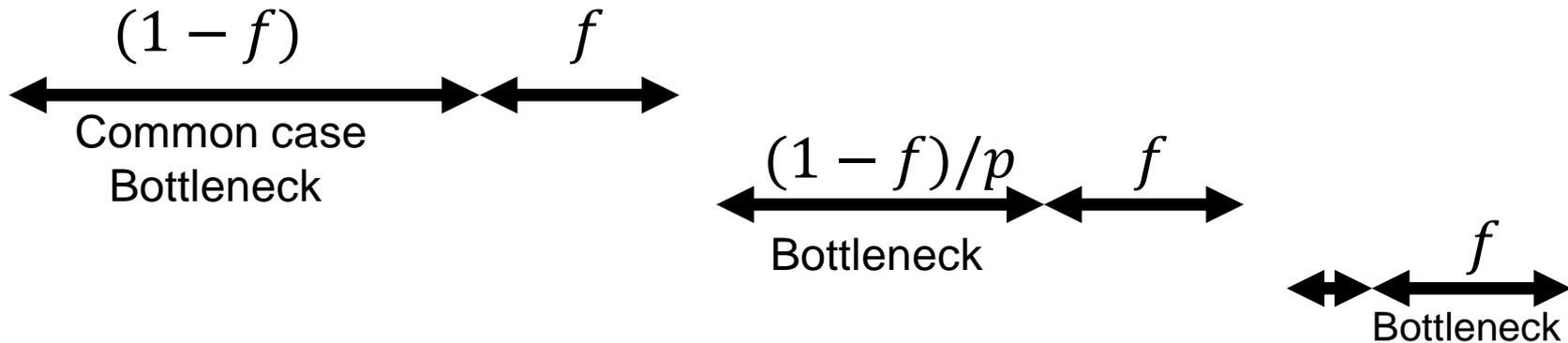
# Implications of Amdahl's law

- Amdahl's law offers two advices for system design
  - *Optimize the common case.* System enhancement, or system optimization, should focus on the common case, also known as the bottleneck, i.e., the most time consuming portion



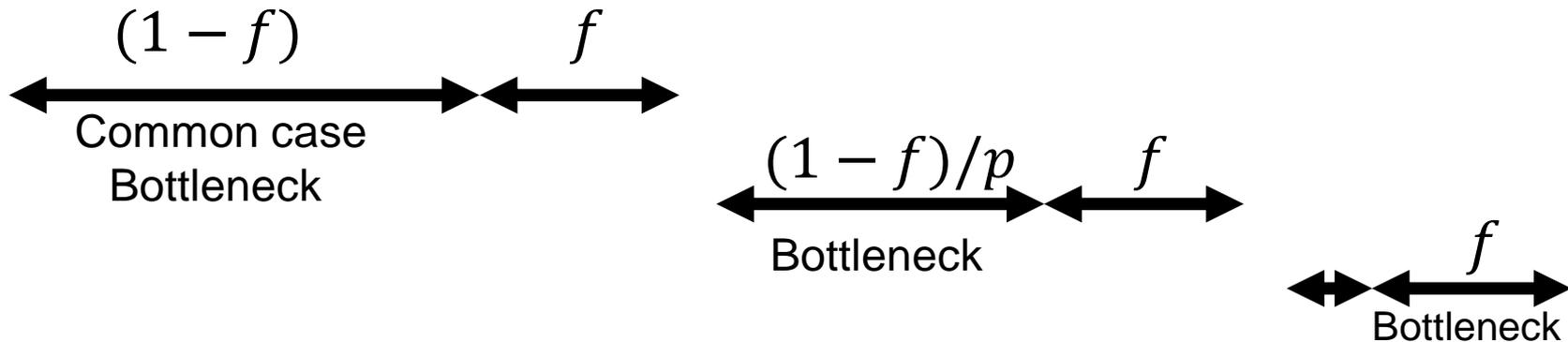
# Implications of Amdahl's law

- Amdahl's law offers two advices for system design
  - *Optimize the common case.* System enhancement, or system optimization, should focus on the common case, also known as the bottleneck, i.e., the most time consuming portion
  - *Chase the bottleneck.* When the system bottleneck changes, so does our optimization target



# Implications of Amdahl's law

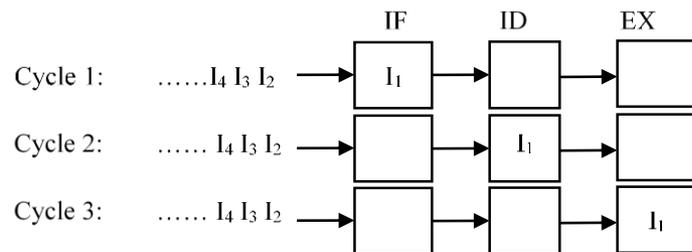
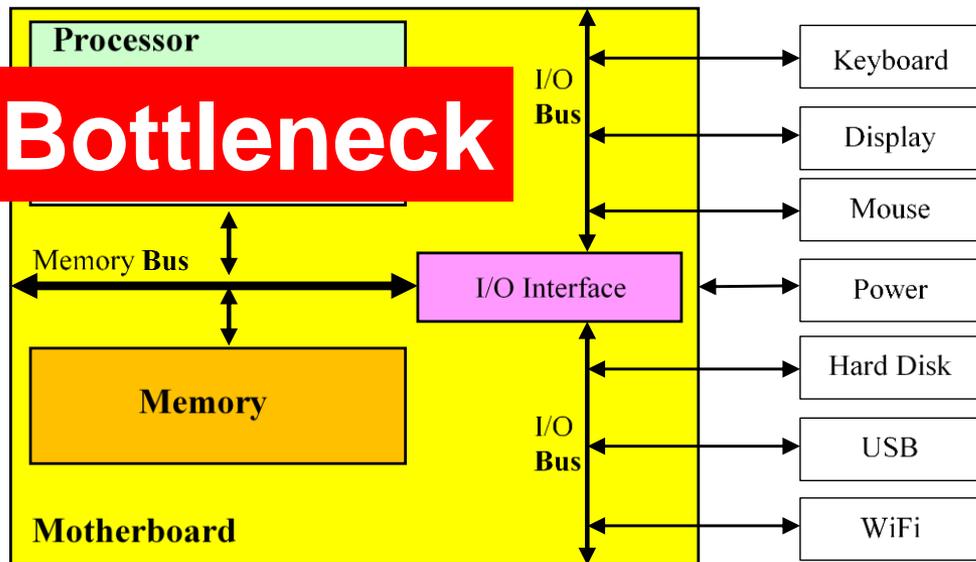
- Amdahl's law offers two advices for system design
  - *Optimize the common case.* System enhancement, or system optimization, should focus on the common case, also known as the bottleneck, i.e., the most time consuming portion
  - *Chase the bottleneck.* When the system bottleneck changes, so does our optimization target



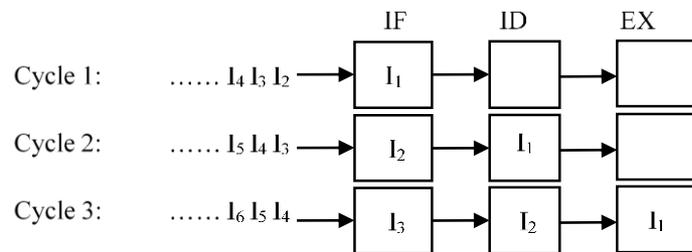
- Three techniques to utilize Amdahl's law
  - Pipelining, caching, parallel computing

## 5.5.1 Pipelining: multiple instructions overlap

- Optimize the bottleneck of the CPU's instruction pipeline
  - Key technique: overlapping pipeline stages with multiple instructions
    - Using about the same amount of resource, plus some overhead
- Assuming 1-GHz clock cycle, the average performance is
  - Without overlapping: executing an instruction needs 3 cycles and 3 ns
  - With overlapping: executing an instruction needs 1 cycle and 1 ns



(a) No overlapping of pipeline stages



(b) Overlapping of pipeline stages

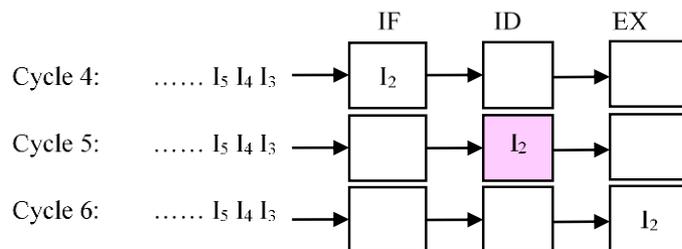
# 1-minute quiz

- Q: Continue to draw the instruction pipeline configurations for clock cycles 4, 5, 6. Which of the following configurations is correct? (Assume the ideal case)

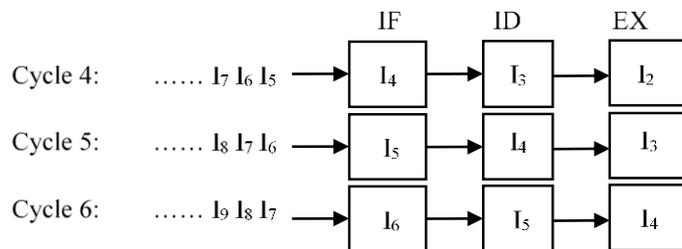
- The colored box indicates that instruction  $I_2$  is executing the Instruction Decode (ID) stage at clock cycle 5

- A:

## Configuration 1

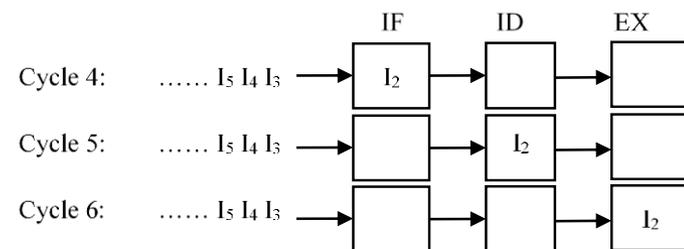


(a) No overlapping of pipeline stages

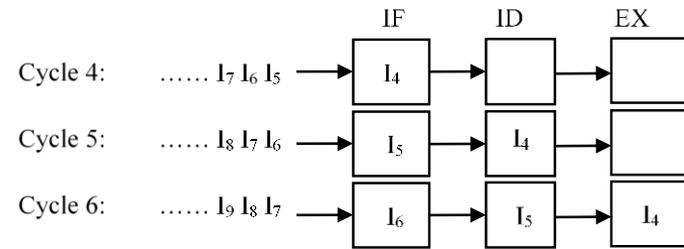


(b) Overlapping of pipeline stages

## Configuration 2



(a) No overlapping of pipeline stages



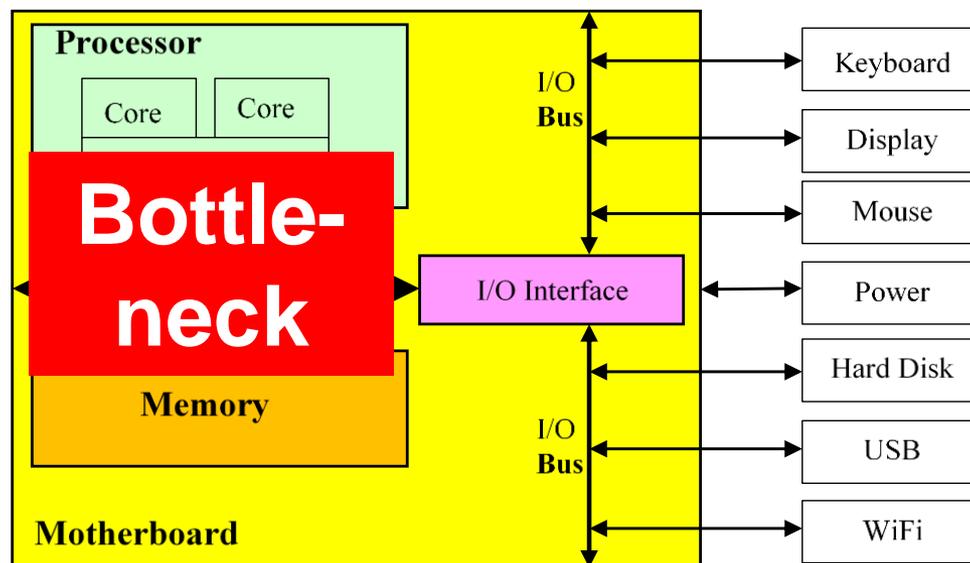
(b) Overlapping of pipeline stages

# 1-minute quiz

- Two computers X and Y have the same pipelined CPU with the same clock frequency of 3.07 GHz.
  - Q1: Do the two computers show the same speed when executing the same code (of Fibonacci loop)?
  - Q2: If computer X is 30 times faster than computer Y, what may be a reason?

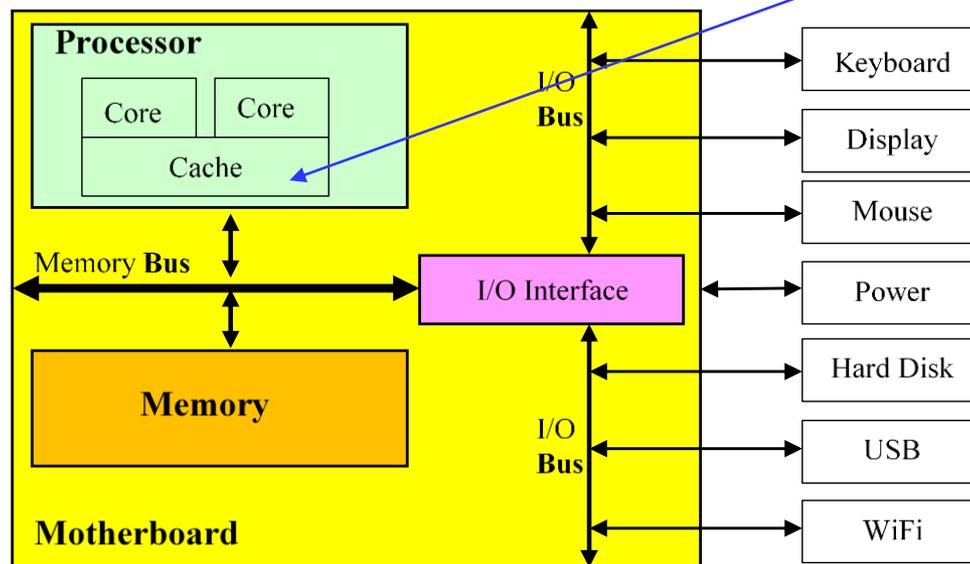
## 5.5.2 Caching: use a small but faster buffer

- Optimize the von Neumann bottleneck
  - Memory is too slow to feed data to CPU
  - On the other hand, programs have spatial and temporal **localities**
  - Key technique: caching, i.e., using a small but faster buffer



## 5.5.2 Caching: use a small but faster buffer

- Optimize the von Neumann bottleneck
  - Memory is too slow to feed data to CPU
  - On the other hand, programs have spatial and temporal localities
  - Key technique: caching, i.e., using a small but faster **buffer**
    - Without having to change the instruction set



- Design and back-of-envelop performance analysis

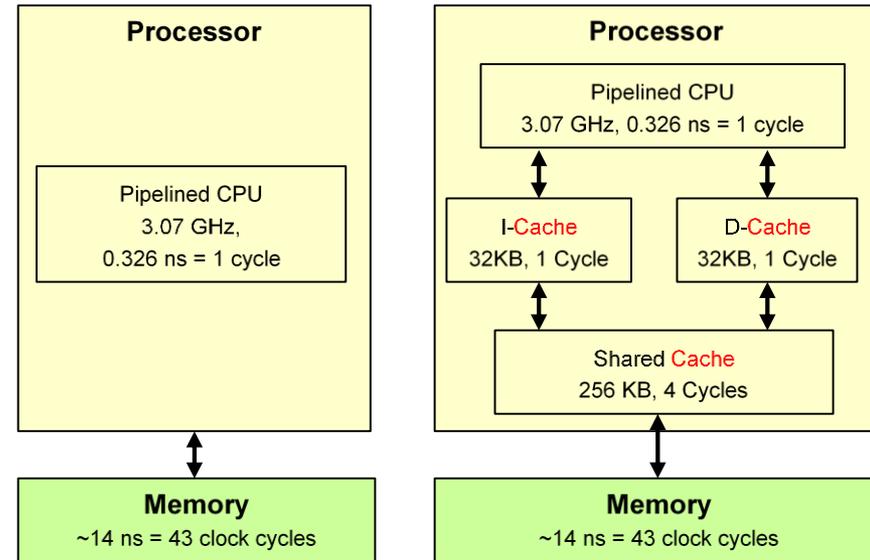
# \*\*\*Caching using the Fibonacci Computer

- Two-layer caching
  - Layer 1: separate instruction and data caches
  - Layer 2: shared cache for instruction and data
- Assume 92 iterations of the loop code in red are executed

Clock cycles of instructions without caching

Instruction type	Times of memory accesses	Clock cycles needed
MOV 0, R1	1	1*43 +1 → 43
MOV R1, M[...]	2	2*43 +1 → 86
ADD M[...], R1	2	2*43 +1 → 86
INC R2	1	1*43 +1 → 43
CMP 51, R2	1	1*43 +1 → 43
JL Loop	1	1*43 +1 → 43

Numbers in blue are canceled out due to pipeline overlapping. A simpler analysis does not consider such optimizations, and calculate the cycles for “MOV 0, R1” to be 1\*43+1=44. This simplification leads to similar performance analysis results.

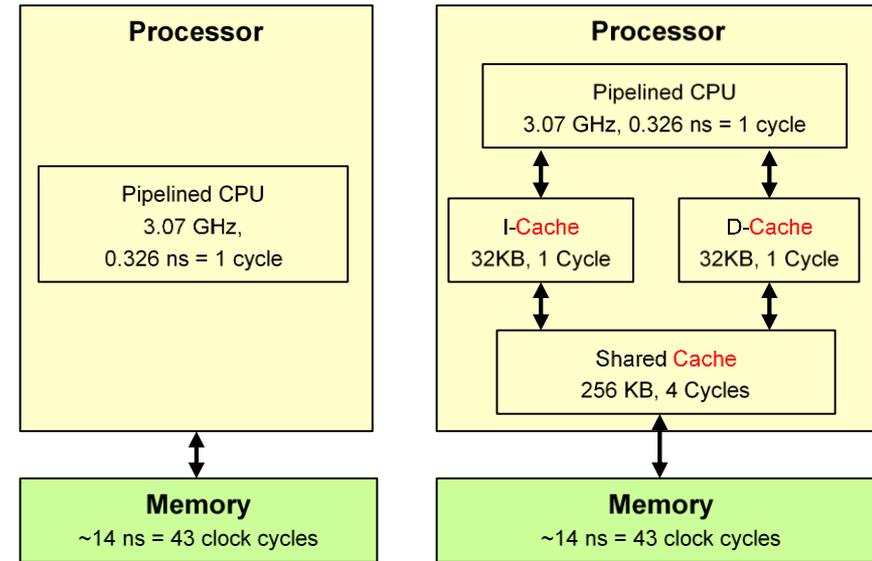


	No Caching	Caching
MOV 0, R1	43	
MOV R1, M[R0]	86	
MOV 1, R1	43	
MOV R1, M[R0+8]	86	
MOV 2, R2	43	
Loop: MOV 0, R1	43	1
ADD M[R0+R2*8-16], R1	86	1
ADD M[R0+R2*8-8], R1	86	2
MOV R1, M[R0+R2*8-0]	86	2
INC R2	43	1
CMP 51, R2	43	2
JL Loop	43	3

Assume all internal operations together take 1 cycle. Every instruction execution needs to access memory at least once to fetch instruction. Some instructions need two accesses to also fetch data.

# \*\*\*When code and data are stored in level-1 caches

- Instruction Fetch needs only 1 cycle
  - This is why 1<sup>st</sup> MOV needs 1 cycle
- Instruction Fetch and Operand Fetch can be done simultaneously, thanks to Harvard architecture
  - This is why 1<sup>st</sup> ADD needs 1 cycle
- Data and control **dependencies** may cause pipeline to stall (wait)
  - This is why 2<sup>nd</sup> ADD needs 2 cycles and JL needs 3 cycles



## Clock cycles of instructions **with caching**

Instruction type	Times of memory accesses	Clock cycles needed
MOV 0, R1	1	1*1 +1 → 1
MOV R1, M[...]	2	1*1 +1 → 1
ADD M[...], R1	2	1*1 +1 → 1
INC R2	1	1*1 +1 → 1
CMP 51, R2	1	1*1 +1 +1 → 2
JL Loop	1	1*1 +1 +2 → 3

	No Caching	Caching
MOV 0, R1	43	
MOV R1, M[R0]	86	
MOV 1, R1	43	
MOV R1, M[R0+8]	86	
MOV 2, R2	43	
Loop: MOV 0, R1	43	1
ADD M[R0+R2*8-16], R1	86	1
ADD M[R0+R2*8-8], R1	86	2
MOV R1, M[R0+R2*8-0]	86	2
INC R2	43	1
CMP 51, R2	43	2
JL Loop	43	3

Assume all internal operations together take 1 cycle.  
Every instruction execution needs to access memory at least once to fetch instruction. Some instructions need two accesses to also fetch data.

# Simplified performance analysis

- Simplify by consider a single iteration of loop

- Without caching

- Total time =  $4 \cdot 43 + 3 \cdot 86$   
= 430 clock cycles  
=  $430 \cdot 0.326 = 140$  ns

	No Caching	Caching
Loop: MOV 0, R1	43	1
ADD M[R0+R2*8-16], R1	86	1
ADD M[R0+R2*8-8], R1	86	2
MOV R1, M[R0+R2*8-0]	86	2
INC R2	43	1
CMP 51, R2	43	2
JL Loop	43	3

- With caching

- Total time =  $1 \cdot 3 + 2 \cdot 3 + 3 \cdot 1$   
= 12 clock cycles  
=  $12 \cdot 0.326 = 3.91$  ns

- Caching brings about significant speedup

- Speedup =  $140 \text{ ns} / 3.91 \text{ ns} = 35.8$ , or 34.8 times faster

# Performance metrics of the 3.07-GHz FC

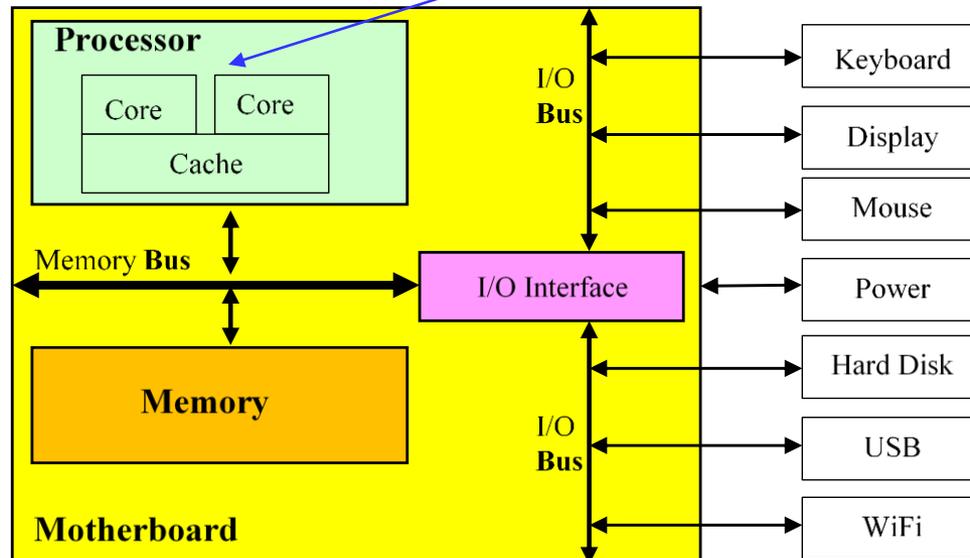
- The **peak speed** of the Fibonacci Computer is the maximal speed possible
  - Peak speed = 1 instruction per cycle = 3.07 GIPS
- The **sustained speed** of the Fibonacci Computer is the real speed achieved when executing the loop application code
  - Sustained speed =  $7/140 = 0.05$  GIPS
    - Each iteration takes 140 ns to execute 7 instructions
  - **Efficiency** = sustained speed / peak speed =  $0.05 / 3.07 = 1.63\%$

# Performance metrics of the 3.07-GHz FC

- The **peak speed** of the Fibonacci Computer is the maximal speed possible
  - Peak speed = 1 instruction per cycle = 3.07 GIPS
- The **sustained speed** of the Fibonacci Computer is the achieved speed when executing the loop application code
  - Sustained speed =  $7/140 = 0.05$  GIPS
  - **Efficiency** = sustained speed / peak speed =  $0.05 / 3.07 = 1.63\%$
- For the Fibonacci Computer with caching
  - Sustained speed =  $7/12 = 1.79$  GIPS
  - **Speedup** =  $1.79 \text{ GIPS} / 0.05 \text{ GIPS} = 35.8$
  - Efficiency = sustained speed / peak speed =  $1.79 / 3.07 = 58.3\%$
- Both have the same peak speed, but caching significantly improves real speed (sustained speed)

## 5.5.3 Parallel computing

- Also known as parallel processing
- What if one CPU is not enough?
  - What if we need 10 GIPS, 1 million GIPS, 1 trillion GIPS?
- Use multiple CPUs/processors/computers in one system
  - A processor having multiple CPUs is called a **multicore** processor
    - Each CPU is called a **core**



# Supercomputer examples

- Top500.org is a list ranking the world's fastest supercomputers
  - Maintained since 1993 by scientists in Europe and USA
- Rank the 500 fastest supercomputers by their speeds in executing the Linpack benchmark
  - Speed = executed 64-bit floating-point operations per second (FLOPS)
- The main contributing factor of progress is parallel computing

**The Linpack benchmark** program for solving a system of linear equations using Gaussian elimination. It finds  $\mathbf{x}$  in  $\mathbf{Ax} = \mathbf{b}$ , where  $\mathbf{A}$  is an  $N \times N$  matrix, and  $\mathbf{x}$ ,  $\mathbf{b}$  are two  $N$ -dimensional vectors. For  $N=3$ , we have

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \times \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$$

Time of Test	1993	2020	1993-2020 Growth Factor
Top-1 Name	Thinking Machine CM-5	Fujitsu Fugaku	N/A
Problem Size	N = 52,224	N = 20,459,520	392
Speed	59.7 GFlop/s	415,530 TFlop/s	6,960,302
Clock Frequency	32 MHz	2.2 GHz	69
Parallelism	1,024 cores	7,299,072 cores	7,128
Memory	32 GB	4,866,048 GB	152,064
Power	96.5 KW	28,334.5 KW	294
Cost	US \$30 million	US \$1 billion	33

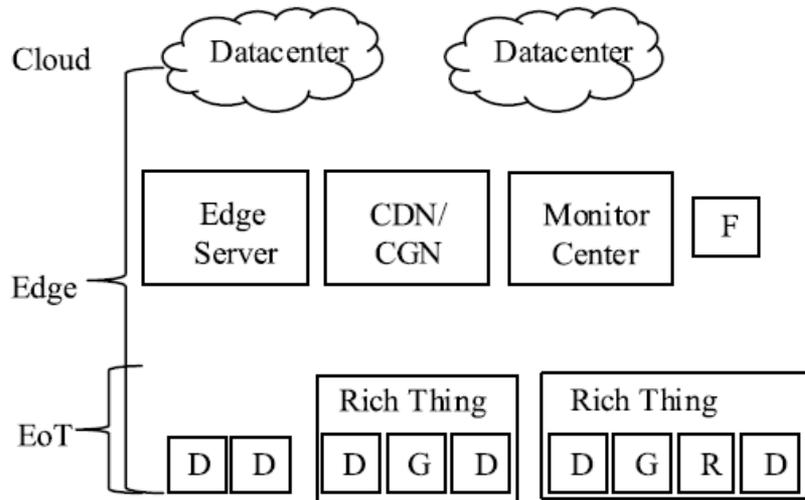
## 5.5.4\*\*\* The landscape of computing systems

- Focus on growing systems and future trends
  - Students may see when they graduate
- Computers
  - **Datacenters** for cloud computing
    - Computer **cluster**, i.e., a system of multiple computers
  - Computers for cyber-human-physical systems
  - Domain-specific computers
  - Open-source computers
- Application systems
  - AI + traditional applications
  - The network is the computer
    - The Internet is a computer

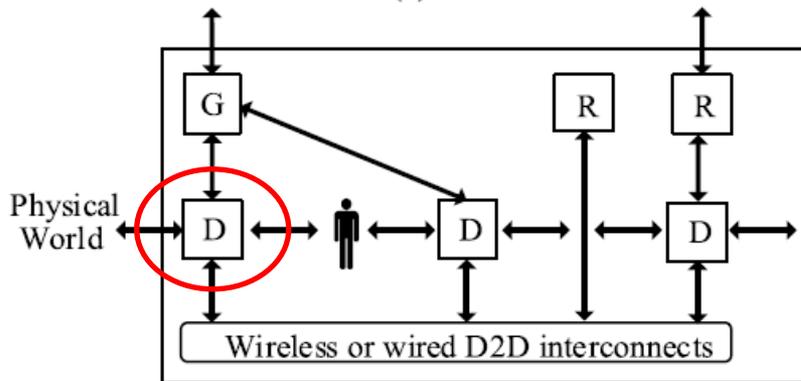
<https://www.gartner.com/en/newsroom/press-releases/2020-01-25-gartner-forecasts-worldwide-it-spending-to-grow-6-point-2-percent-in-2021>

<b>Gartner Worldwide IT Prediction</b>	2020 Spending (US\$B)	2020 Growth (%)	2021 Spending (US\$B)	2021 Growth (%)
Data Center Systems	215	0.0	228	6.2
Enterprise Software	465	-2.4	506	8.8
Devices	653	-8.2	705	8.0
IT Services	1012	-2.7	1073	6.0
Communications Services	1350	-1.7	1411	4.5
Overall IT	3695	-3.2	3923	6.2

# Computing devices of cloud, edge, and things



(a)



(b)

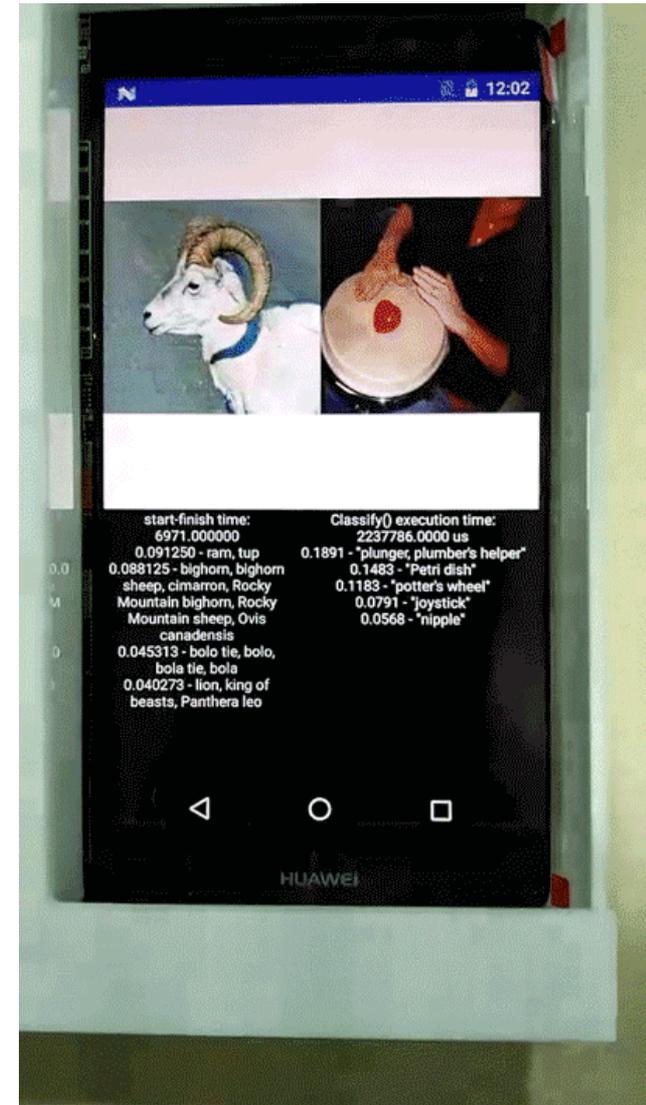
Term (Label)	Description
Cloud devices	Datacenters (cloud servers).
Edge devices	Any device out of the cloud, including fog device and things device.
Fog device (F)	Edge device that is not a things device, such as an edge server or a CDN.
Simple device (D)	Device for a simple thing, <i>e.g.</i> , a smart lamp, a microwave oven.
Rich thing, Rich device	An integrated set of multiple simple devices with a natural physical enclosure, such as a smart vehicle or a smart home. A rich thing can be viewed as a rich device.
Gateway (G)	Device used to connect the rich thing to other edge devices or the cloud, such as a WiFi router.
Remote (R)	Device used by users to interact with other devices in a rich thing, such as a smartphone.

## A device of thing has four interfaces

- West: bridging the physical world
- East: bridging the human society
- South: bridging other devices of things
- North: bridging edge and cloud devices

# Domain-specific computers

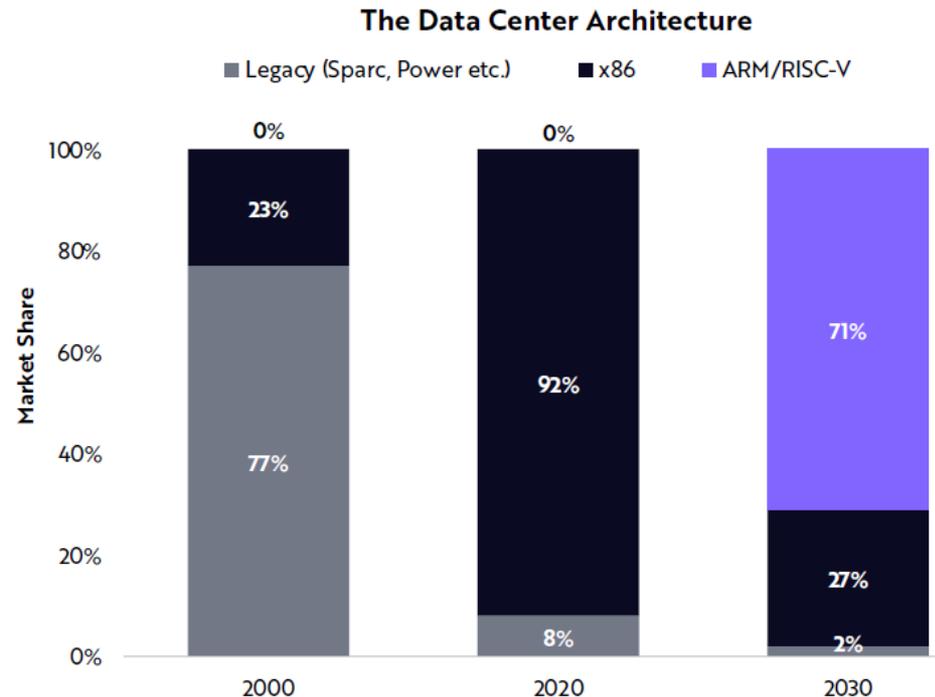
- A computer or a part of a computing system
  - Specifically designed for a application domain,
  - such that its functionality, performance, interface, efficiency, etc., are particularly effective for the target domain
- Processor examples
  - DSP: digital signal processing
  - GPU: graphic processing unit
    - A domain-specific processor may also be good for other domains
    - GPUs have been used for scientific computing and AI
  - DPU: for deep learning
- An inspirational perspective
  - Hennessy, J. L., & Patterson, D. A. (2019). A new golden age for computer architecture. *Communications of the ACM*, 62(2), 48-60.



# Open-source computer example: RISC-V

- Form the official site: <https://riscv.org/about/>
  - RISC-V is a free and open ISA enabling a new era of processor innovation through open standard collaboration.
  - The RISC-V ISA delivers a new level of free, extensible software and hardware freedom on architecture, paving the way for the next 50 years of computing design and innovation.
    - ISA = instruction set architecture
- Originated at UC-Berkeley
  - RISC-V = Berkeley RISC Five
- RISC-V has become an international effort
  - RISC-V International
  - > 1000 members in 50 countries

Asanović K, Patterson D A. Instruction sets should be free: The case for risc-v. EECS Department, University of California, Berkeley, Tech. Rep. UCB/EECS-2014-146, 2014.

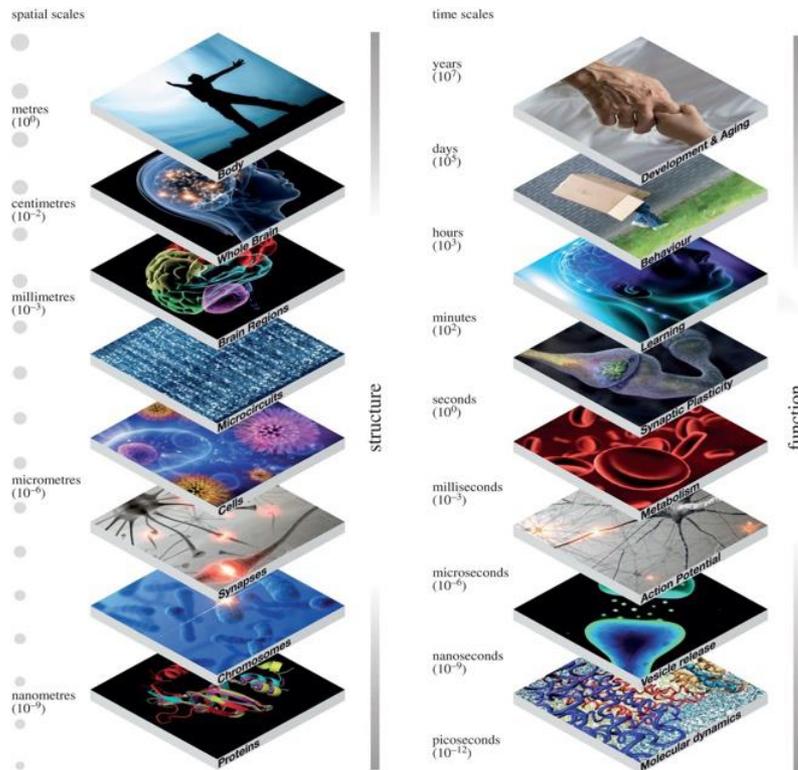


ARK Invest, Big Ideas 2021 Report, <https://ark-invest.com/big-ideas-2021/>

# The trend of intelligent application systems

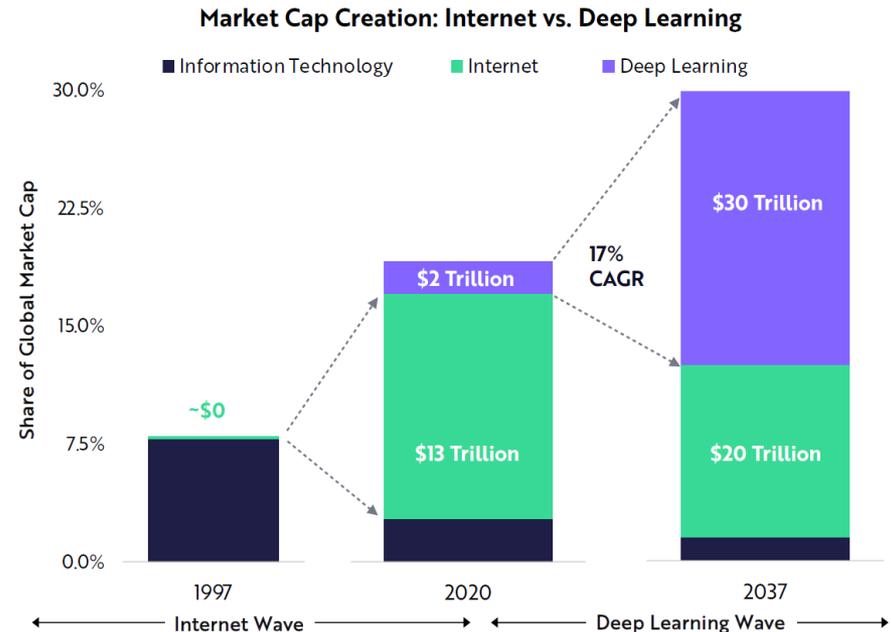
## For sciences

Enable inquiry of all structures & functions



## For economy

Value of AI companies > IT + Internet



Stevens, R., Taylor, V., Nichols, J., Maccabe, A. B., Yelick, K., & Brown, D. (2020). AI for Science (No. ANL-20/17). Argonne National Lab.(ANL), Argonne, IL (United States).

ARK Invest, Big Ideas 2021 Report, <https://ark-invest.com/big-ideas-2021/>