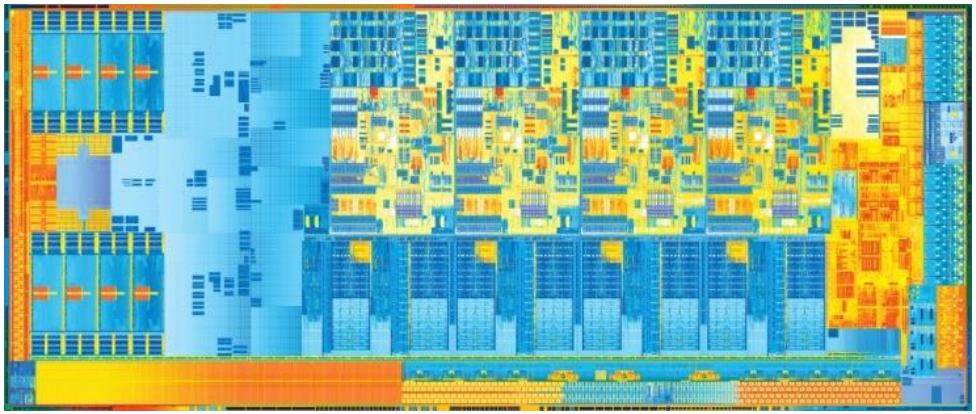
6.823 Computer System Architecture

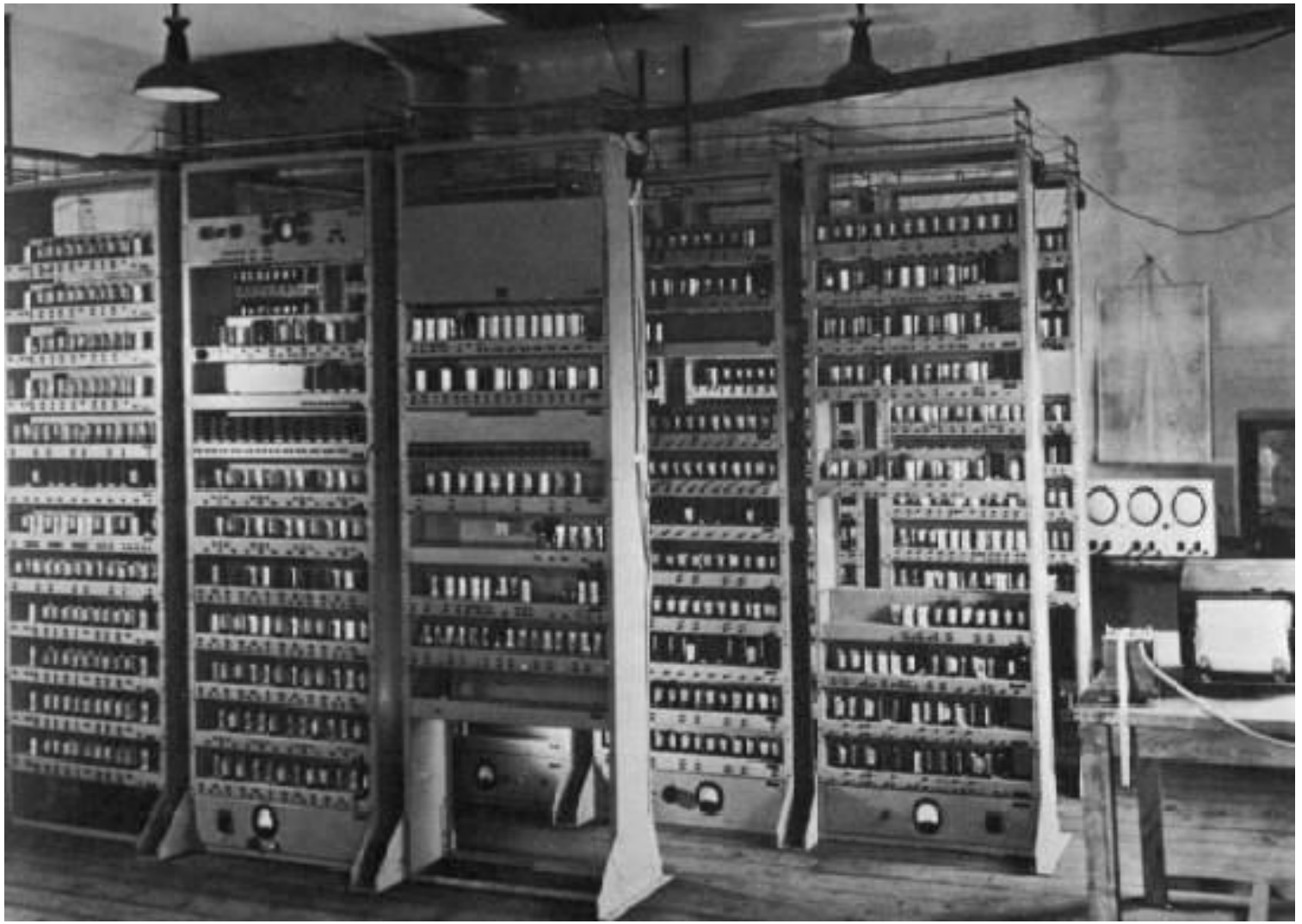
Instructor: *Daniel Sanchez*
TA: *Hyun Ryong (Ryan) Lee*

The processor you built in 6.004*

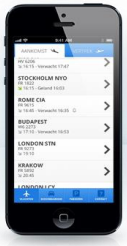


What you'll understand after taking 6.823

Computing devices then…



Computing devices now



A journey through this space

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- Illustrate via historical examples
  - Early days: ENIAC, EDVAC, and EDSAC
  - Arrival of IBM 650 and then IBM 360
  - Seymour Cray – CDC 6600, Cray 1
  - Microprocessors and PCs
  - Multicores
  - Cell phones

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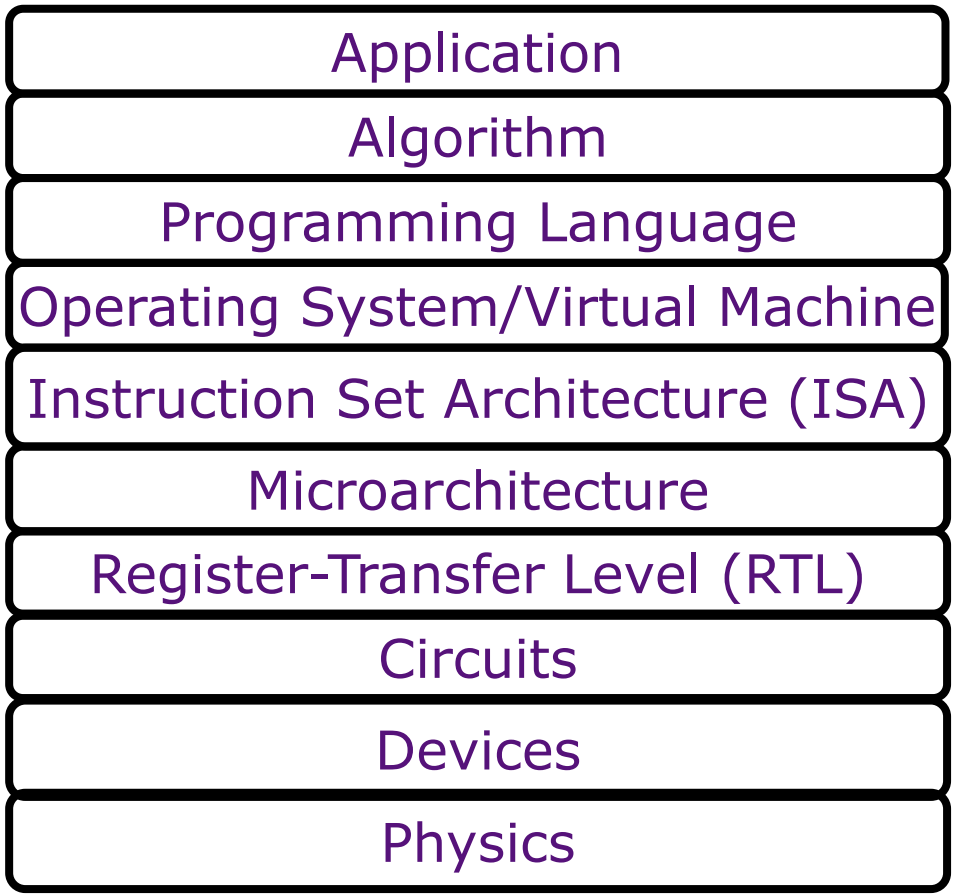
  - Microprocessors and PCs
  - Multicores
  - Cell phones
- Focus on ideas, mechanisms, and principles, especially those that have withstood the test of time

Abstraction layers



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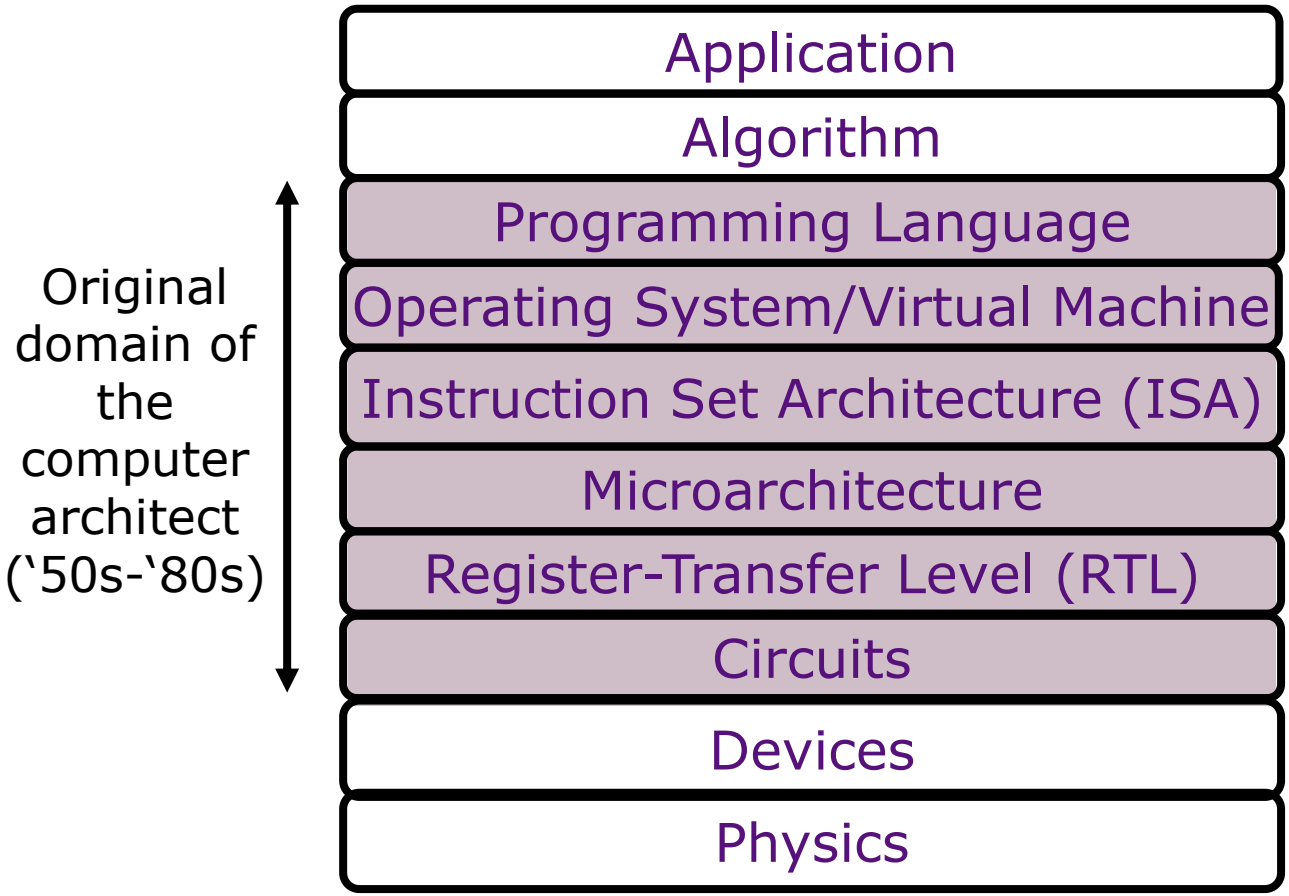

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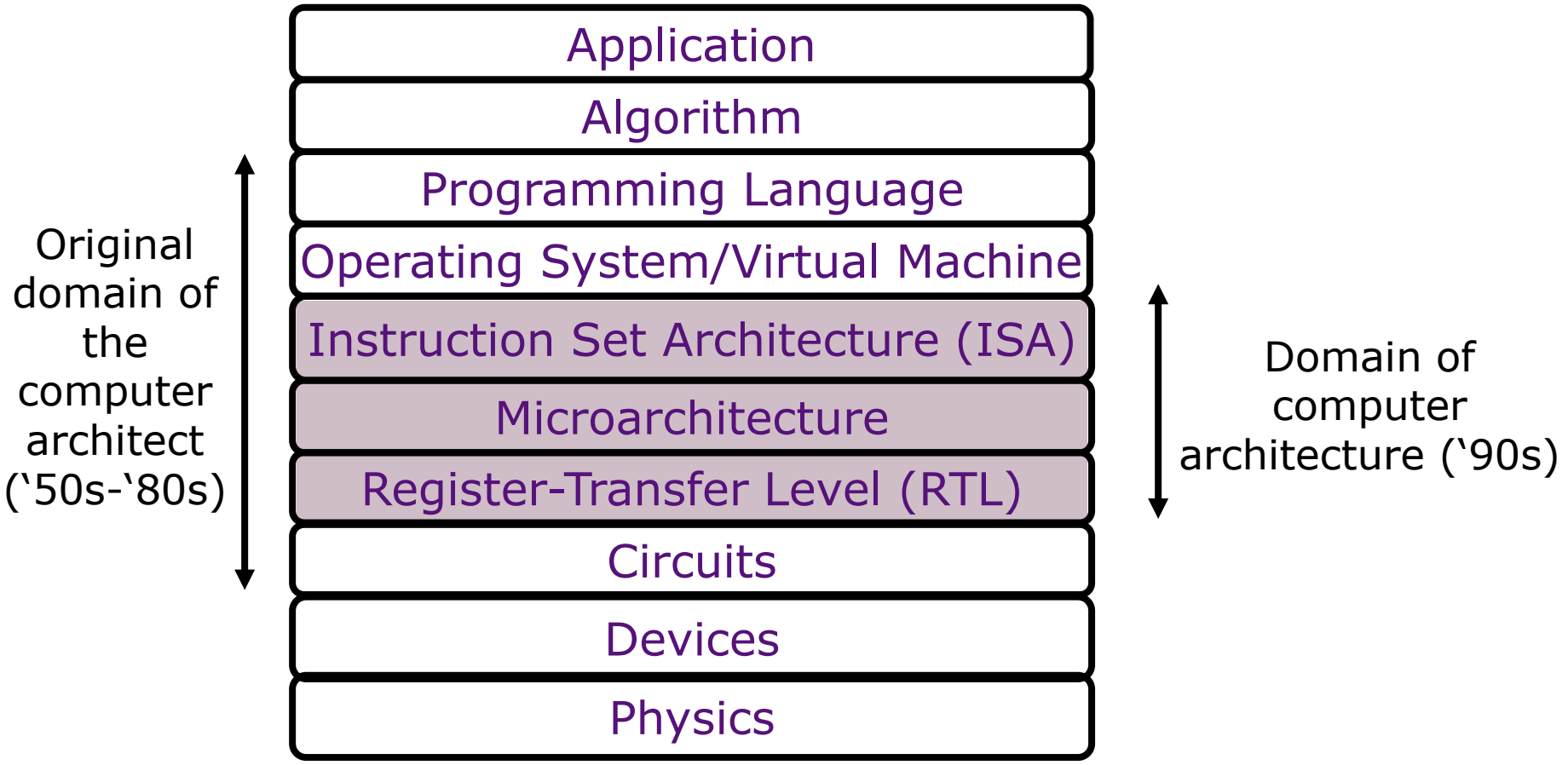

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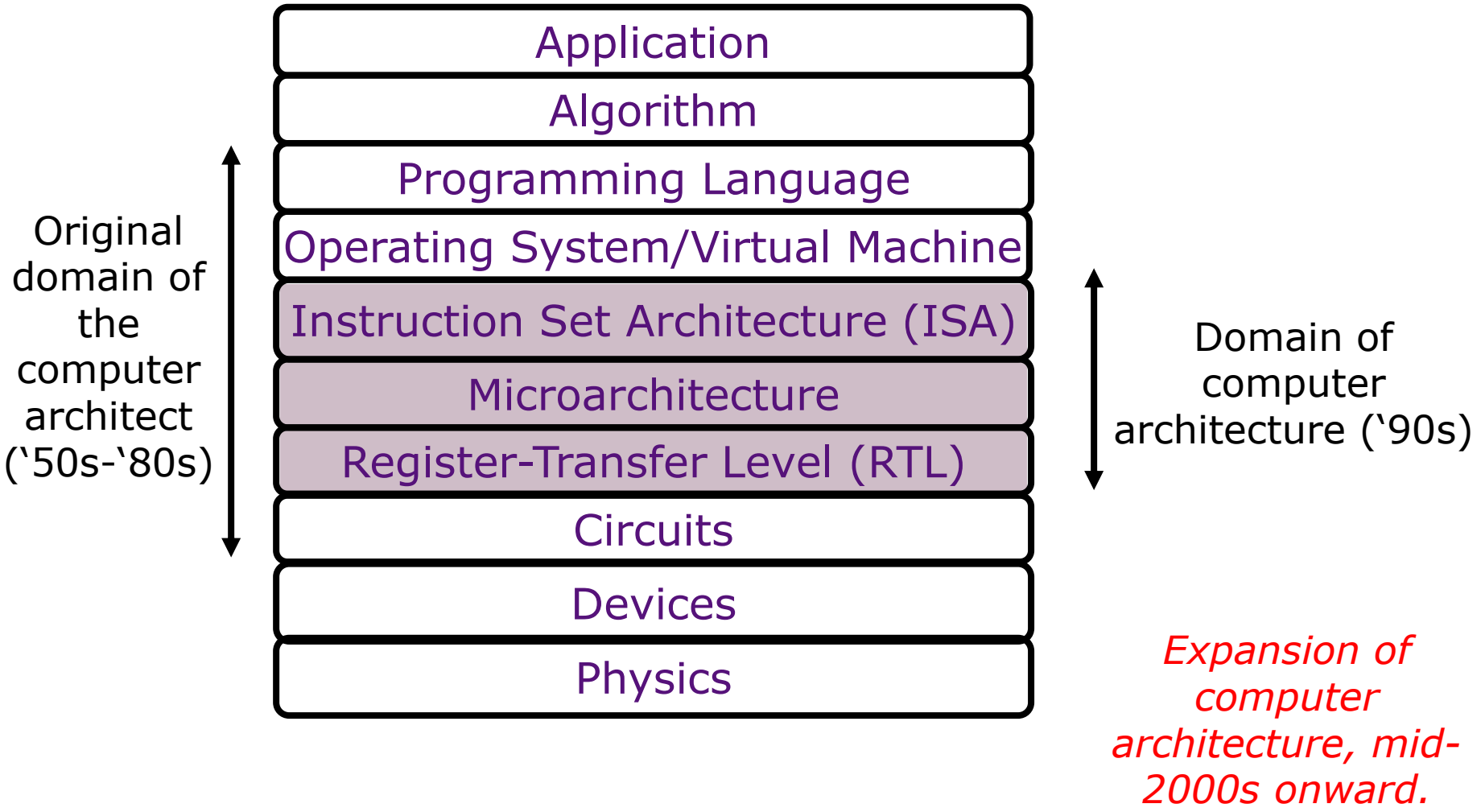

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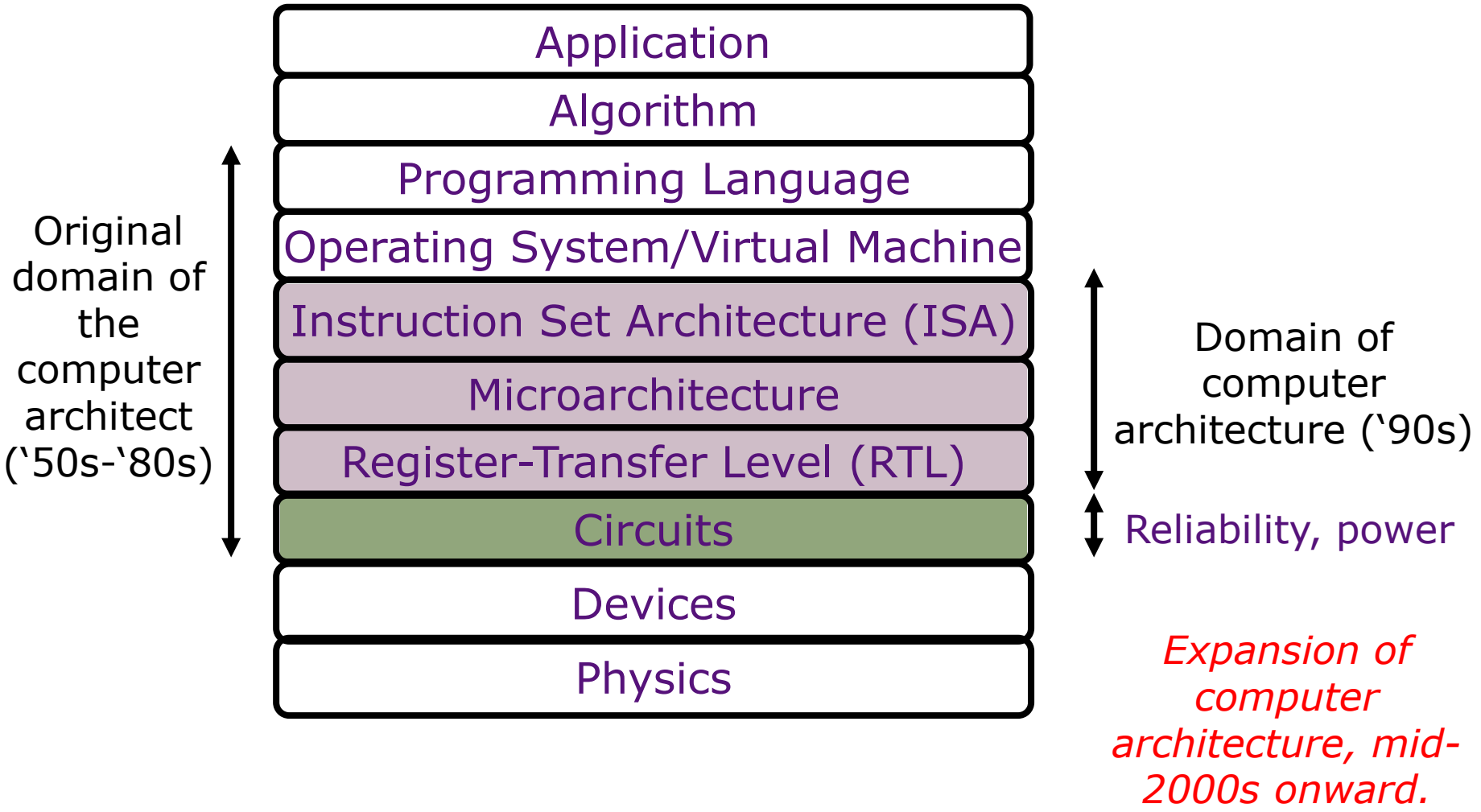

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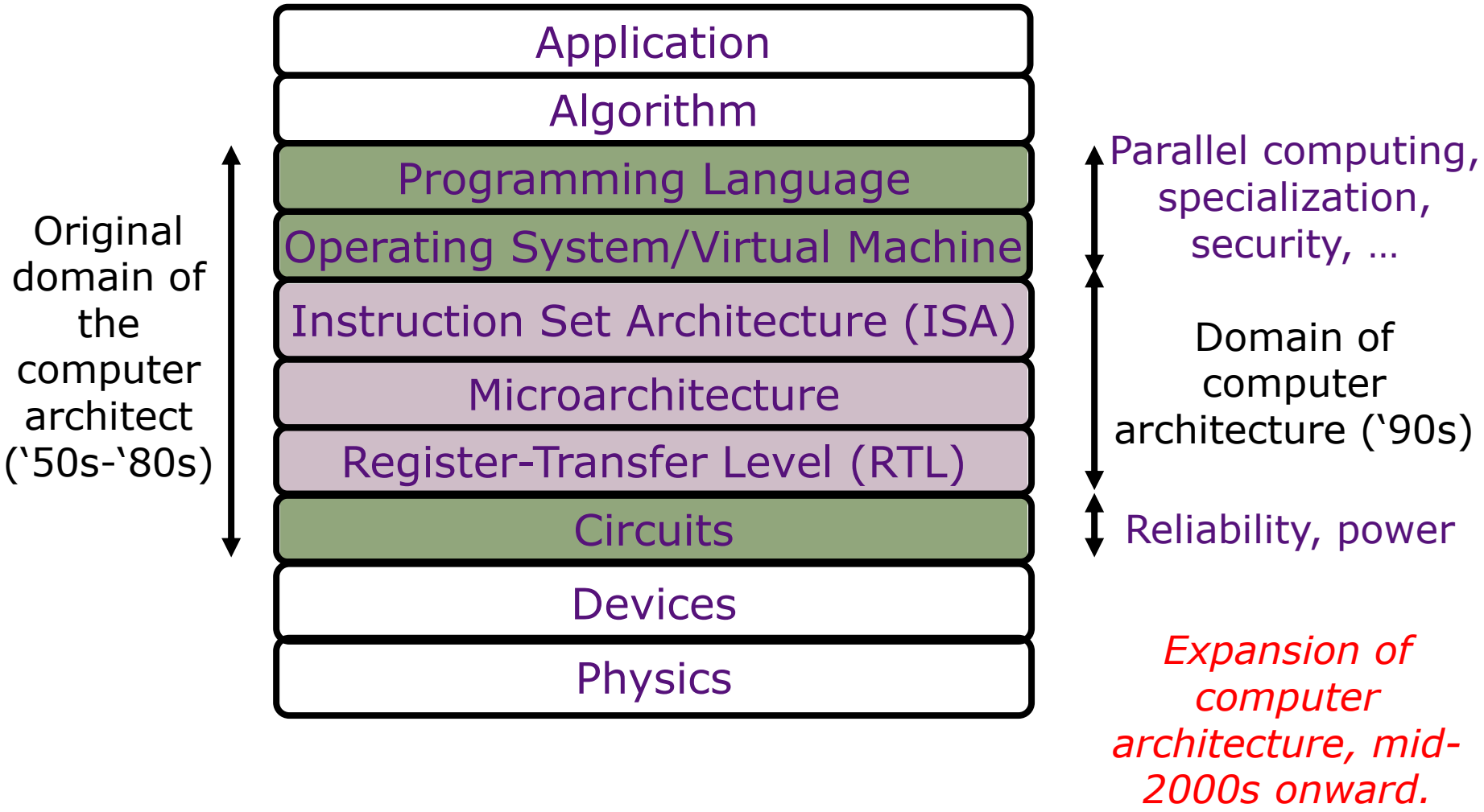

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- What do abstraction layers provide?
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- What do abstraction layers provide?
  - Environmental stability within generation
  - Environmental stability across generations
  - Consistency across a large number of units
- What are the consequences?
  - *Encouragement to create reusable foundations:*
    - *Toolchains, operating systems, libraries*
  - Enticement for application innovation

Technology is the dominant factor in computer design

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Technology

- *Transistors*
- *Integrated circuits*
- *VLSI (initially)*
- *Flash memories, …*

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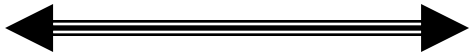
Technology
- *ROMs, RAMs*
- *VLSI*
- *Packaging*
- *Low Power*



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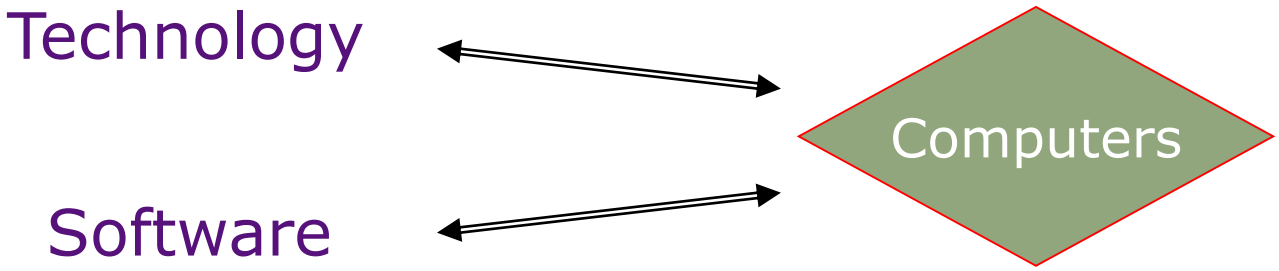

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At different times, and for different applications at the same point in time, the relative balance of these factors can result in widely varying architectural choices

Course Information

All info kept up to date on the website:

`http://www.csg.csail.mit.edu/6.823`

Contact times

- Lectures Tuesdays and Thursdays
  - 1:00pm to 2:30pm
- Tutorial on Fridays
  - 1:00pm to 2:00pm
  - Attendance is optional
  - Additional tutorials will be held in weeks before quizzes
- Quizzes on Friday *(except last quiz)*
  - 1:00pm to 2:30pm
  - Attendance is NOT optional
- Instructor office hours
  - After class or by email appointment
- TA office hours
  - Wednesday 4-5:30pm

Lectures and tutorials

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- If you can, please enable video ☺
  - Helps you stay engaged, helps us get to know you and get nonverbal feedback like in an in-person lecture
  - Your video won't appear on recordings, and recordings won't be publicly available

Online resources & help

- We use Piazza extensively
  - Fastest way to get your questions answered
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- This is not a normal term; if you need help, let us know!
  - We can be accommodating

The course has four modules

Module 1
- Instruction Set Architecture (ISA)
- Caches and Virtual Memory
- Simple Pipelining and Hazards

Module 2
- Complex Pipelining and Out of Order Execution
- Branch Prediction and Speculative Execution

Module 3
- Multithreading and Multiprocessors
- Coherence and consistency
- On-chip networks

Module 4
- VLIW, EPIC
- Vector machines and GPUs

Textbook and readings

- "Computer Architecture: A Quantitative Approach", Hennessy & Patterson, 5th / 6th ed.
  - 5th edition available online through MIT Libraries
  - Recommended, but not necessary

- Course website lists H&P reading material for each lecture, and optional readings that provide more in-depth coverage

Grading

- Grades are not assigned based on a predetermined curve
  - Most of you are capable of getting an A
- 75% of the grade is based on four closed book 1.5 hour quizzes
  - The first three quizzes will be held during the tutorials; the last one during the last lecture (dates on web syllabus)
  - We'll have distant-timezone quizzes and makeups if needed
- 25% of the grade is based on four laboratory exercises
- No final exam
- No final project

Problem sets & labs

- Problem sets
  - One problem set per module, not graded
  - Intended for private study and for tutorials to help prepare for quizzes
  - Quizzes assume you are very familiar with the content of problem sets
- Labs
  - Four graded labs (Lab 0 is introductory)
  - Based on widely-used PIN tool
  - Labs 2 and 4 are open-ended challenges

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- You must complete labs and quizzes individually
  - Please review the collaboration & academic honesty policy

Self evaluation take-home quiz

- Goal is to help you judge for yourself whether you have prerequisites for this class, and to help refresh your memory
- We assume that you understand digital logic, a simple 5-stage pipeline, and simple caches
- Please work by yourself on this quiz – not in groups
- Remember to complete self-evaluation section at end of the quiz
- Due by Friday (on recitation or send answers to TA mailing list)

Please email us if you have concerns about your ability to take the class

Early Developments: From ENIAC to the mid 50's

Prehistory

- 1800s: Charles Babbage
  - Difference Engine (conceived in 1823, first implemented in 1855 by Scheutz)
  - Analytic Engine, the first conception of a general purpose computer (1833, never implemented)
- 1890: Tabulating machines
- Early 1900s: Analog computers
- 1930s: Early electronic (fixed-function) digital computers

Electronic Numerical Integrator and Computer (ENIAC)

- Designed and built by Eckert and Mauchly at the University of Pennsylvania during 1943-45
- The first, completely electronic, operational, general-purpose analytical calculator!
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- Performance
  - Read in 120 cards per minute
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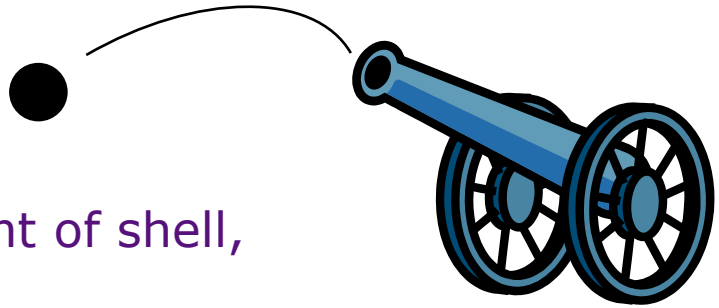
WW-2 Effort

Application: Ballistic calculations

angle = f (location, tail wind, cross wind,
air density, temperature, weight of shell,
propellant charge, ...)



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- *First Draft of a report on EDVAC* was published in 1945, but just had von Neumann's signature!
  - Without a doubt the most influential paper in computer architecture

Stored Program Computer

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plug board	ENIAC 1946
read-only memory	ENIAC 1948
read-write memory	EDVAC 1947 *(concept)*

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EDSAC	1950	Maurice Wilkes

The Spread of Ideas

ENIAC & EDVAC had immediate impact

brilliant engineering: Eckert & Mauchly
lucid paper: Burks, Goldstein & von Neumann

IAS	Princeton	46-52	Bigelow
EDSAC	Cambridge	46-50	Wilkes
MANIAC	Los Alamos	49-52	Metropolis
JOHNIAC	Rand	50-53	
ILLIAC	Illinois	49-52	
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SWAC	UCLA-NBS		

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Alan Turing's direct influence on these developments is often debated by historians.

Dominant Technology Issue: *Reliability*

ENIAC ⇒ EDVAC

18,000 tubes
20 10-digit numbers

4,000 tubes
2000 word storage
mercury delay lines

Mean time between failures (MTBF)

MIT's Whirlwind with an MTBF of 20 min. was perhaps the most reliable machine!

Reasons for unreliability:

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CORE J. Forrester 1954

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- Programmer's view of the machine was inseparable from the actual hardware implementation

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LOAD	x	AC ← M[x]
STORE	x	M[x] ← (AC)
ADD	x	AC ← (AC) + M[x]
SUB	x	
MUL	x	Involved a quotient register
DIV	x	
SHIFT LEFT		AC ← 2 × (AC)
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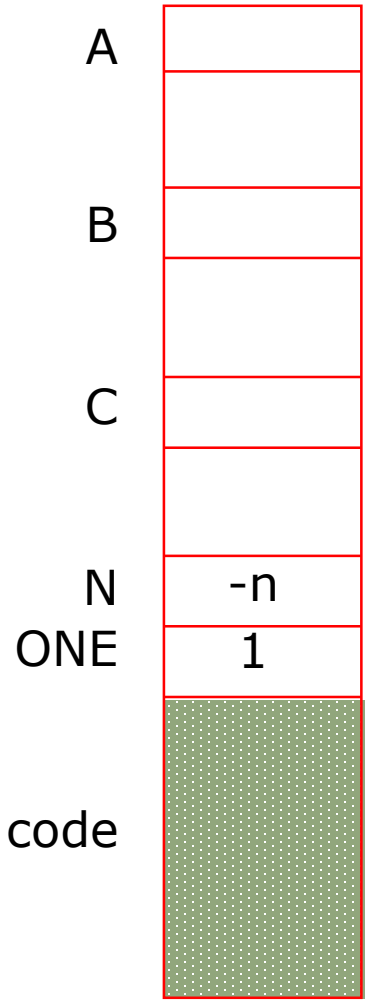
Typically less than 2 dozen instructions!

Programming: Single Accumulator Machine

$C_i \leftarrow A_i + B_i, \quad 1 \leq i \leq n$



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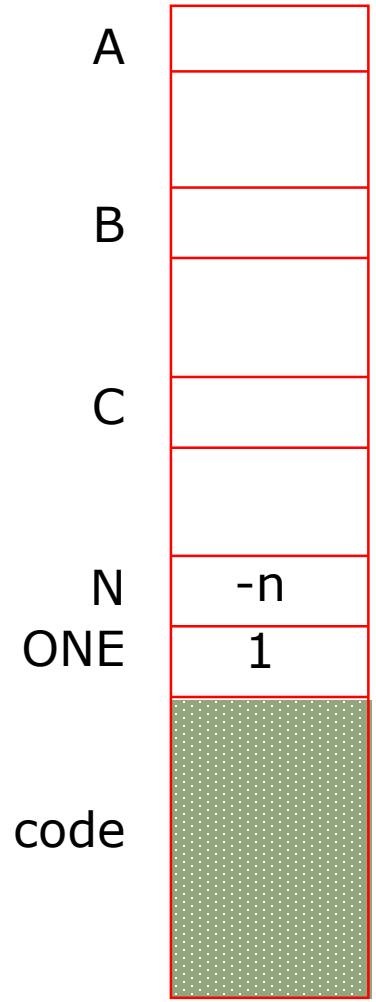
        JGE      DONE
        ADD      ONE
        STORE    N
F1      LOAD     A
F2      ADD      B
F3      STORE    C
        JUMP     LOOP
DONE    HLT
```



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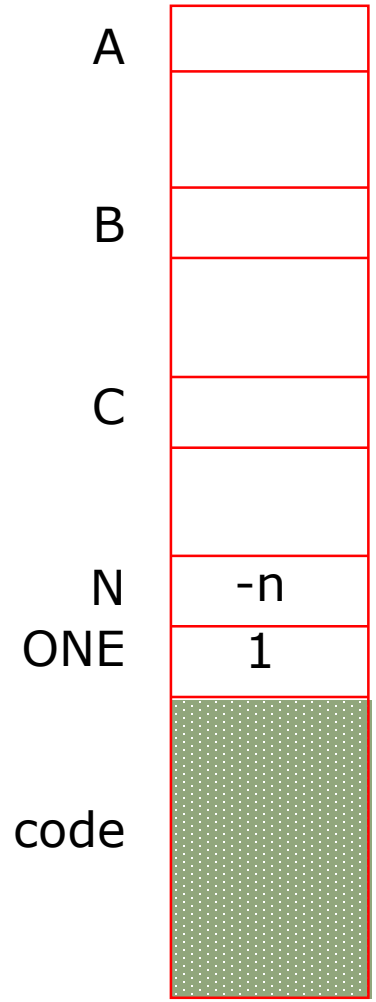
Problem?



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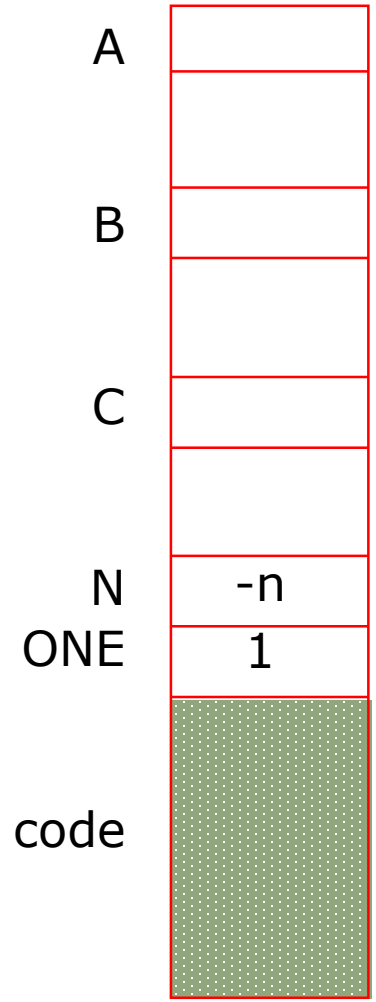

Problem?

How to modify the addresses A, B and C ?

Self-Modifying Code

$C_i \leftarrow A_i + B_i, \quad 1 \leq i \leq n$

```
LOOP    LOAD     N
        JGE      DONE
        ADD      ONE
        STORE    N
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modify the program for the next iteration

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        ADD         ONE
        STORE ADR   F1
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Each iteration involves

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operand fetches		
stores		

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modify the program for the next iteration

Each iteration involves

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modify the program for the next iteration

Each iteration involves

	total	*book-keeping*
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operand fetches	*10*	
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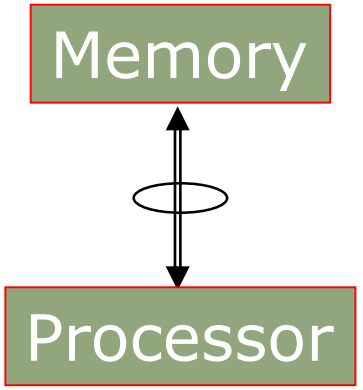
Most of the executed instructions are for bookkeeping!

Processor-Memory Bottleneck: Early Solutions

- Indexing capability
- Fast local storage in the processor
  - 8-16 registers as opposed to one accumulator
- Complex instructions
- Compact instructions
  - implicit address bits for operands



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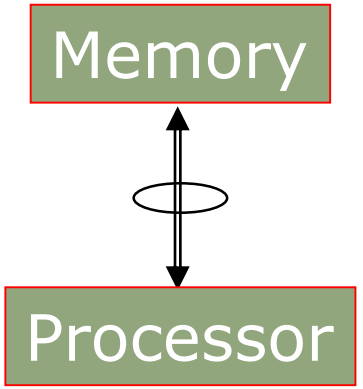

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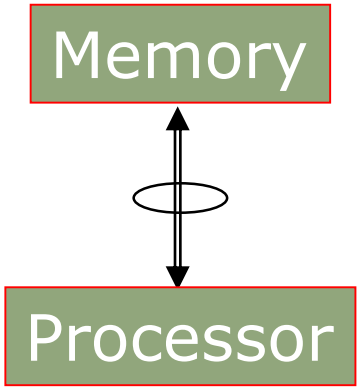

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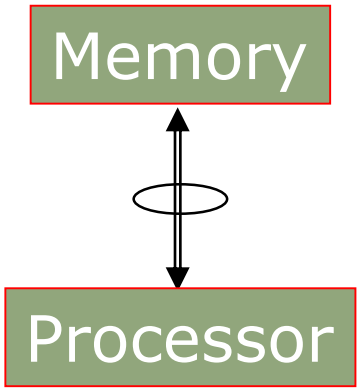

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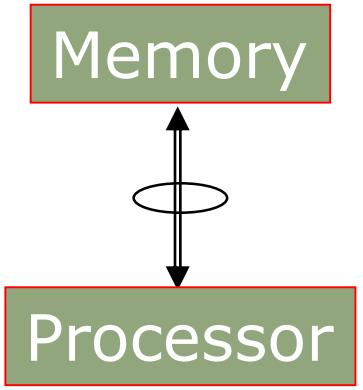
  - to reduce instruction fetch cost



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Tom Kilburn, Manchester University, mid 50's

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Index registers have accumulator-like characteristics

Using Index Registers

$$C_i \leftarrow A_i + B_i, \quad 1 \le i \le n$$

```
        LOADi   N, IX
LOOP    JZi     DONE, IX
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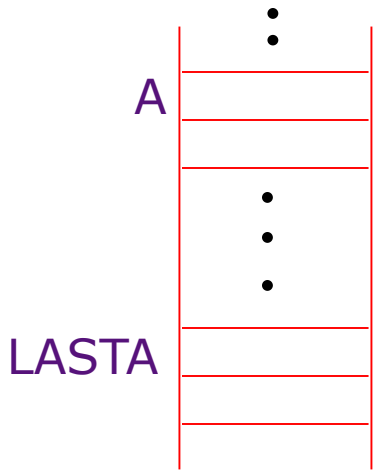
        STORE   LASTC, IX
        JUMP    LOOP
DONE    HALT
```

N starts with -n



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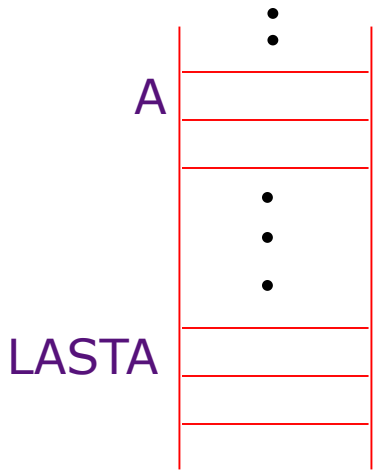

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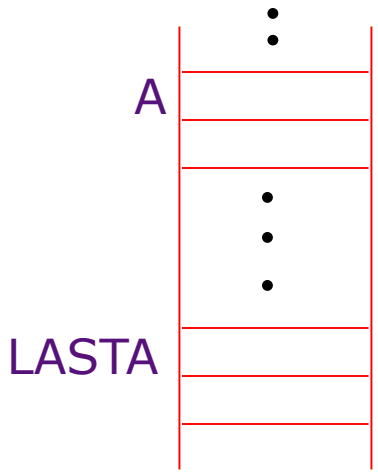

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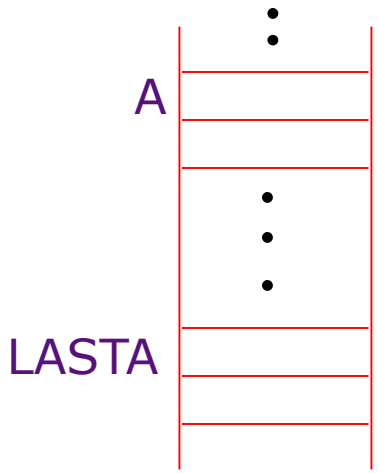

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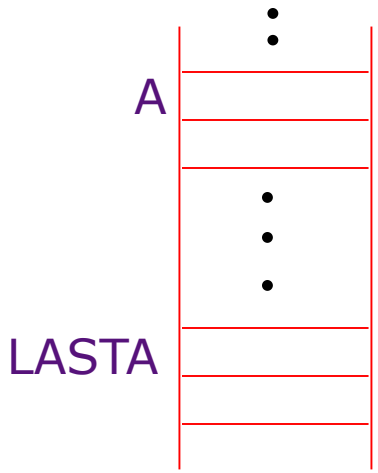

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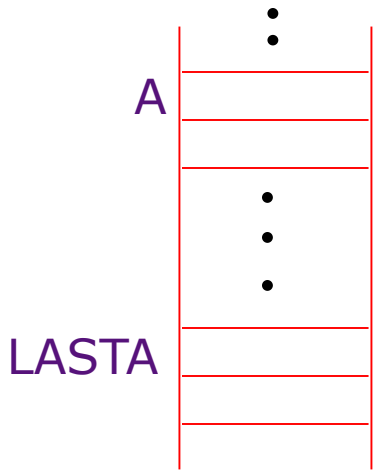

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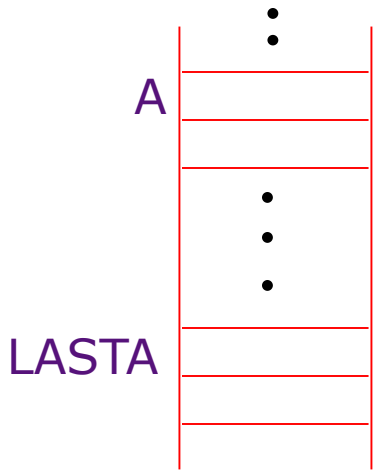

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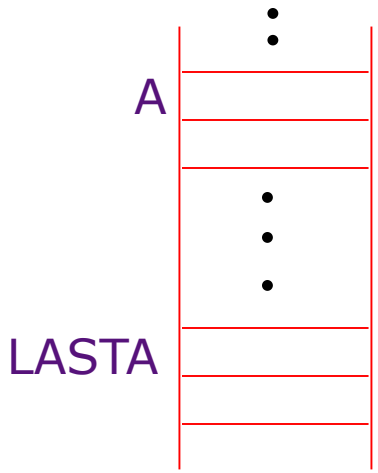

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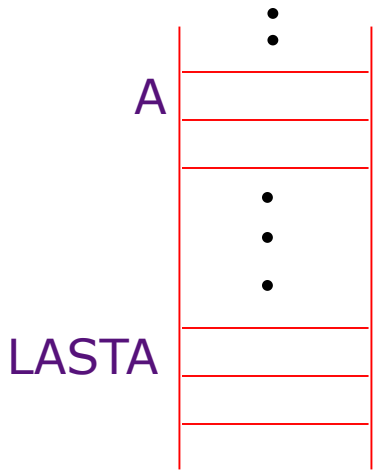

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- *Costs?*
  - *Complex control*
  - Index register computations (ALU-like circuitry)
  - Instructions 1 to 2 bits longer

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To increment index register by k

AC $\leftarrow$ (IX)	*new instruction*
AC $\leftarrow$ (AC) + k	
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IX begins to look like an accumulator

⇒ several index registers
several accumulators
⇒ *General Purpose Registers*

Evolution of Addressing Modes

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1. Single accumulator, absolute address

```
LOAD    x
```

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4. Multiple accumulators, index registers, indirection

   LOAD R, IX, x

   or LOAD R, IX, (x)

   the meaning?

   $R \leftarrow M[M[x] + (IX)]$

   or $R \leftarrow M[M[x + (IX)]]$

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   LOAD R_I, (R_J)

6. The works

   LOAD R_I, R_J, (R_K) R_J = index, R_K = base addr

Variety of Instruction Formats

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- *Three address formats:* One destination and up to two operand sources per instruction

(Reg op Reg) to Reg	$R_I \leftarrow (R_J)$ op (R_K)
(Reg op Mem) to Reg	$R_I \leftarrow (R_J)$ op M[x]

  - x can be specified directly or via a register
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- *Two address formats:* the destination is same as one of the operand sources

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- *Zero address formats:* operands on a stack

```
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load    M[sp] ← M[M[sp]]
```

  - Stack can be in registers or in memory
    - usually top of stack cached in registers

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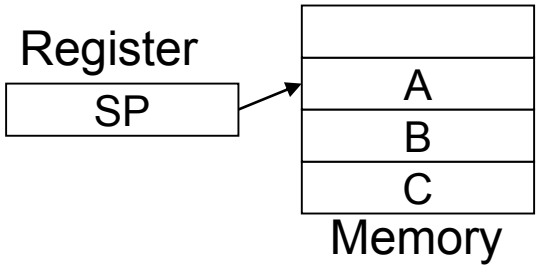
load    M[sp] ← M[M[sp]]
```



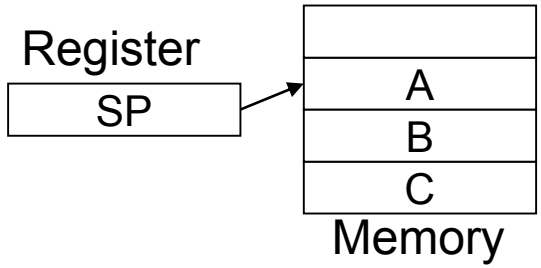
  - Stack can be in registers or in memory
    - usually top of stack cached in registers

More Instruction Formats

- *One address formats:* Accumulator machines
  - Accumulator is always other implicit operand

- *Zero address formats:* operands on a stack

```
add     M[sp-1] ← M[sp] + M[sp-1]
load    M[sp] ← M[M[sp]]
```



  - Stack can be in registers or in memory
    - usually top of stack cached in registers

Many different formats are possible!

Instruction sets in the mid 50's

- Great variety of instruction sets, but all intimately tied to implementation details

- Programmer's view of the machine was inseparable from the actual hardware implementation!

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Next Lecture:

Instruction Set Architectures: Decoupling Interface and Implementation