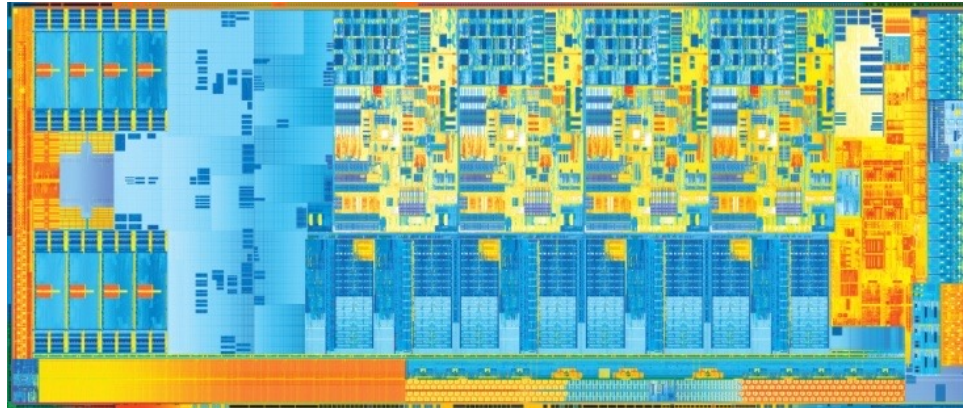


6.5900 Computer System Architecture

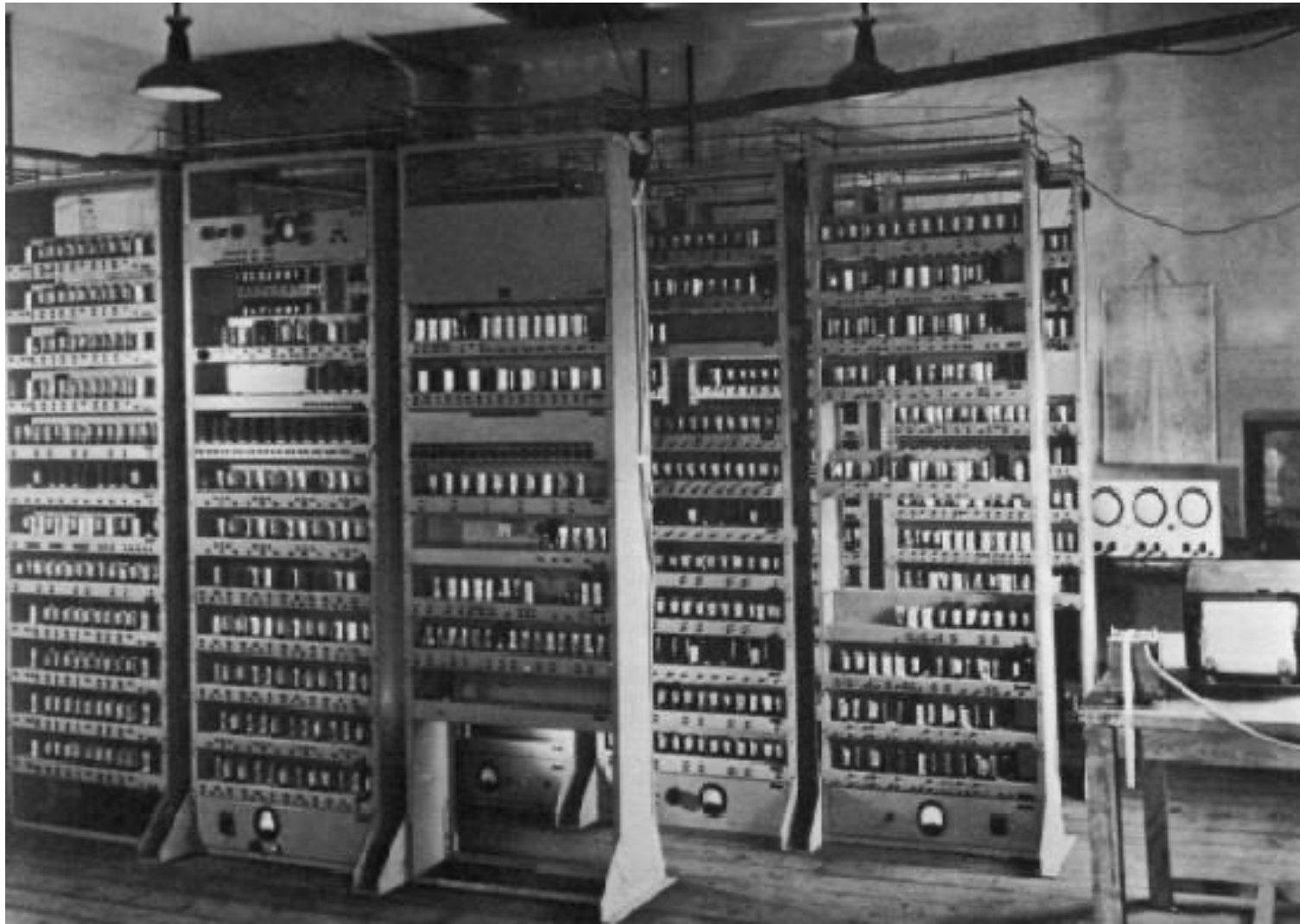
Instructors: *Daniel Sanchez*
Joel Emer
TA: *Axel Feldmann*



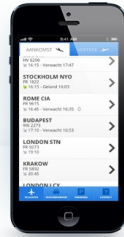
↖
The processor you
built in 6.1910

↖ What you'll
understand after
taking 6.5900

Computing devices then...



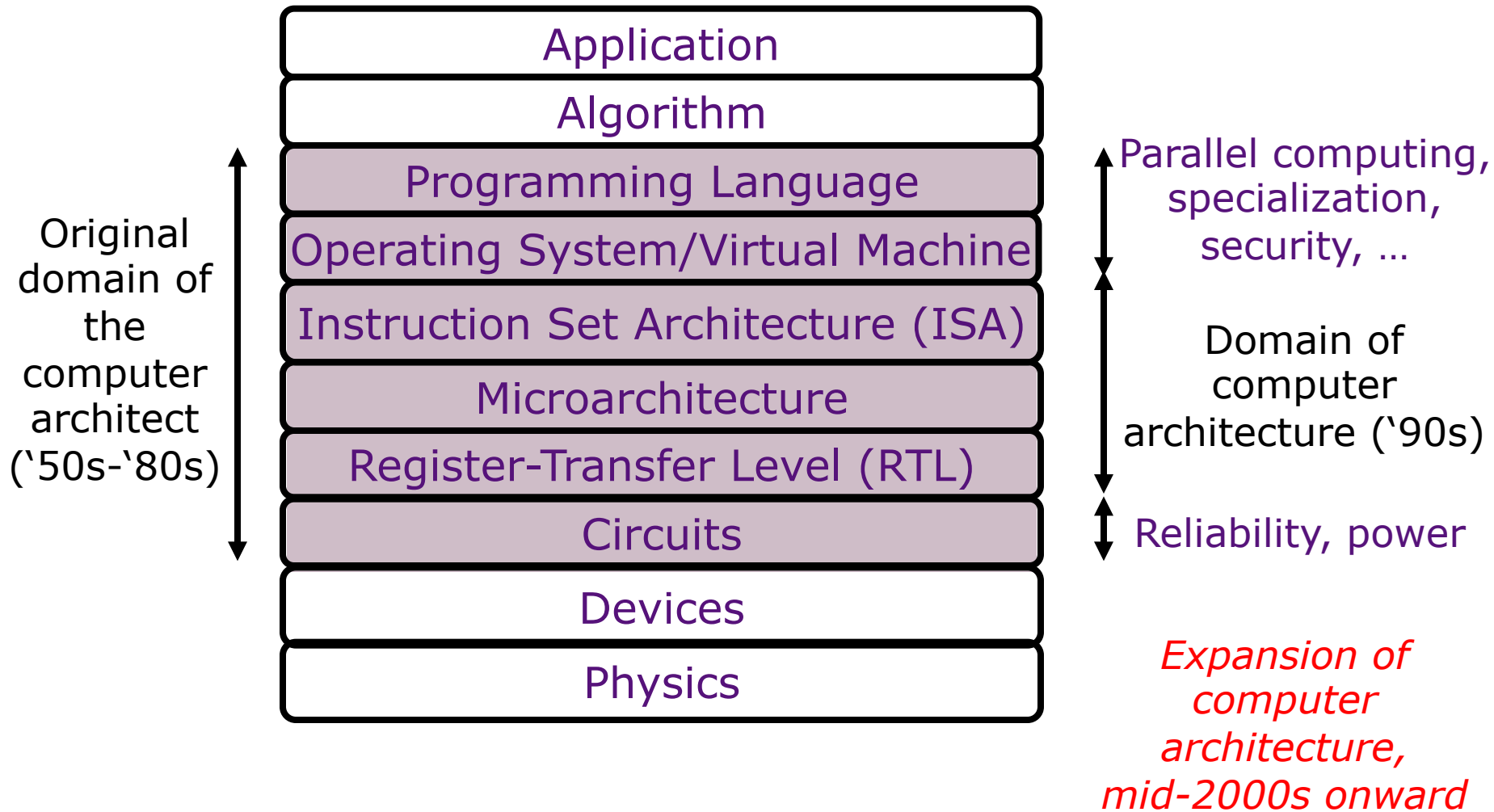
Computing devices now



A journey through this space

- What do computer architects actually do?
- 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
- Focus on ideas, mechanisms, and principles, especially those that have withstood the test of time

Abstraction layers



Computer Architecture is the design of abstraction layers

- 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

Technology

Transistors
Integrated circuits
VLSI (initially)
Flash memories, ...



Computers

Technology

Core memories
Magnetic tapes
Disks



Computers

Technology

ROMs, RAMs
VLSI
Packaging
Low Power



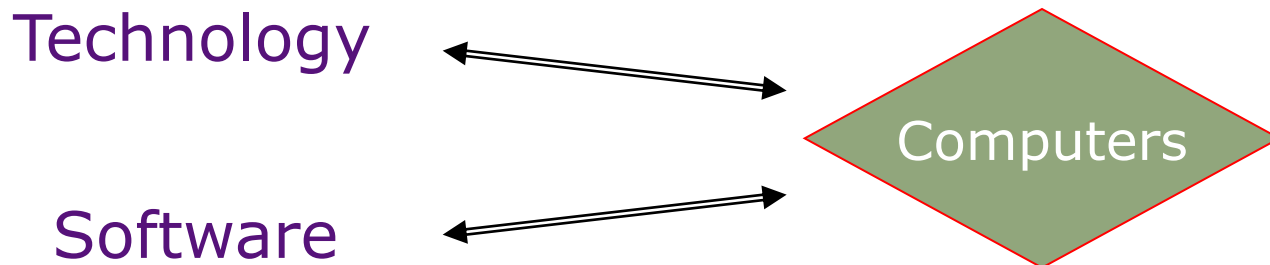
Computers

But Software...

As people write programs and use computers, our understanding of *programming* and *program behavior* improves.

This has profound though slower impact on computer architecture

Modern architects must pay attention to software and compilation issues.



Architecture is engineering design under constraints

Factors to consider:

- Performance of whole system on target applications
 - Average case & worst case
- Cost of manufacturing chips and supporting system
- Power to run system
 - Peak power & energy per operation
- Reliability of system
 - Soft errors & hard errors
- Cost to design chips (engineers, computers, CAD tools)
 - Becoming a limiting factor in many situations, fewer unique chips can be justified
- Cost to develop applications and system software
 - Often the dominant constraint for any programmable device

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://csg.csail.mit.edu/6.5900>

Contact times

- Lectures on Monday and Wednesday
 - 1:00pm to 2:30pm in room 32-141
- Tutorial on Friday
 - 1:00pm to 2:00pm in room 32-141
 - Attendance is optional
 - Additional tutorials will be held in evenings before quizzes
- Quizzes on Friday (*except last quiz*)
 - 1:00pm to 2:30pm in room 32-141
 - Attendance is NOT optional
- Instructor office hours
 - After class or by email appointment
- TA office hours
 - Wednesday 4:00-5:30 pm @ Stata 7th floor lounge

Online resources

- We use Piazza extensively
 - Fastest way to get your questions answered
 - All course announcements are made on Piazza

The course has three modules

Module 1

- ISA and Simple In-Order Pipelines
- Caches and Virtual Memory
- Complex Pipelining and Out-of-Order Execution
- Branch Prediction and Speculative Execution

Module 2

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

Module 3

- Microcoding and VLIW
- Vector machines and GPUs
- Hardware accelerators
- Hardware security

Textbook and readings

- “Computer Architecture: A Quantitative Approach”, Hennessy & Patterson, 6th ed.
 - 5th edition available online through MIT Libraries
 - Recommended, but not necessary
 - NOTE: 6th edition (and 6.5900) uses RISC-V as the main ISA; prior editions (and 6.5900/6.823 before Fall 2023) use MIPS
- 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 three closed book 1.5 hour quizzes
 - The first two quizzes will be held during the tutorials; the last one during the last lecture (dates on web syllabus)
 - We'll have 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
 - Based on widely-used PIN tool
 - Labs 2 and 4 are open-ended challenges
- You must complete labs & 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 by email to TA)

Please contact 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

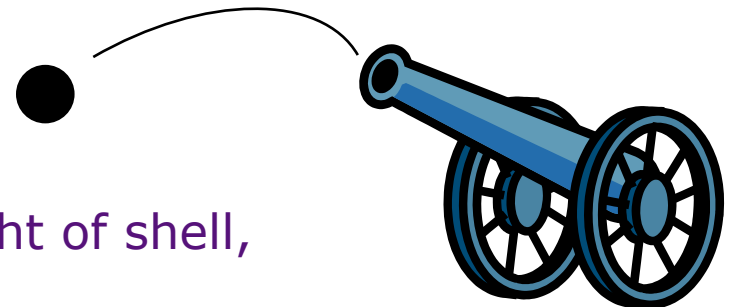
Electronic Numerical Integrator and Computer (ENIAC)

- Designed and built by Eckert and Mauchly at the University of Pennsylvania during 1943-45
- The first completely **digital, electronic, operational, general-purpose analytical calculator!**
 - 30 tons, 72 square meters, 200KW
- Performance
 - Read in 120 cards per minute
 - Addition took 200 μ s, Division 6 ms
- Not very reliable!

WW-2 Effort

Application: Ballistic calculations

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



Electronic Discrete Variable Automatic Computer (EDVAC)

- ENIAC's programming system was external
 - Sequences of instructions were executed independently of the results of the calculation
 - Human intervention required to take instructions “out of order”
- EDVAC was designed by Eckert, Mauchly, and von Neumann in 1944 to solve this problem
 - Solution was the *stored program computer*
 - ⇒ “*program can be manipulated as data*”
- *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

Program = A sequence of instructions

How to control instruction sequencing?

manual control

calculators

automatic control

external (paper tape)

Harvard Mark I, 1944
Zuse's Z1, WW2

internal

plug board

ENIAC 1946

read-only memory

ENIAC 1948

read-write memory

EDVAC 1947 (*concept*)

– The same storage can be used to store program and data

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	
	Argonne	49-53	
SWAC	UCLA-NBS		

UNIVAC - the first commercial computer, 1951

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

Dominant Technology Issue: *Reliability*

ENIAC

18,000 tubes

20 10-digit numbers

⇒

EDVAC

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:

1. Vacuum tubes

2. Storage medium

Acoustic delay lines

Mercury delay lines

Williams tubes

Selections

CORE

J. Forrester

1954

Computers in the mid 50's

- Hardware was expensive
- Memories were small (1000 words)
 - ⇒ No resident system-software!
- Memory access time was 10 to 50 times slower than the processor cycle
 - ⇒ Instruction execution time was totally dominated by the *memory reference time*
- The *ability to design complex control circuits* to execute an instruction was the central design concern as opposed to *the speed* of decoding or an ALU operation
- Programmer's view of the machine was inseparable from the actual hardware implementation

Accumulator-based computing



Photo: Joel Emer

- *Single Accumulator*
 - Calculator design carried over to computers

Why?

Registers expensive

The Earliest Instruction Sets

Burks, Goldstein & von Neumann ~1946

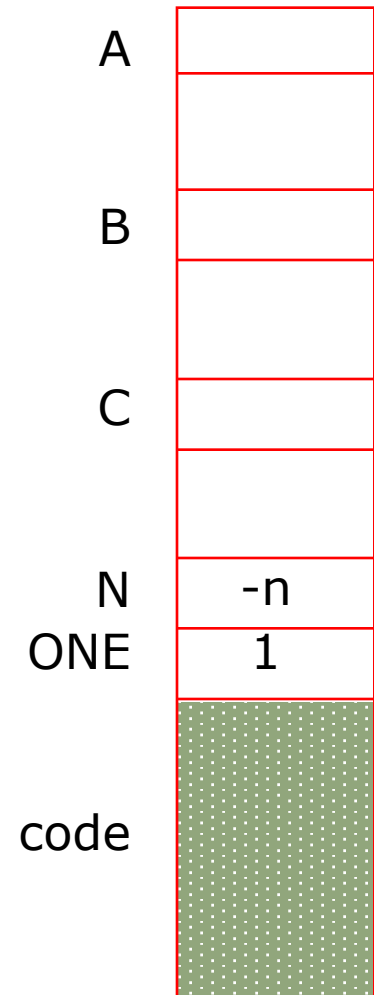
LOAD	x	$AC \leftarrow M[x]$
STORE	x	$M[x] \leftarrow (AC)$
ADD	x	$AC \leftarrow (AC) + M[x]$
SUB	x	
MUL	x	Involved a quotient register
DIV	x	
SHIFT LEFT		$AC \leftarrow 2 \times (AC)$
SHIFT RIGHT		
JUMP	x	$PC \leftarrow x$
JGE	x	if $(AC) \geq 0$ then $PC \leftarrow x$
LOAD ADR	x	$AC \leftarrow \text{Extract address field}(M[x])$
STORE ADR	x	

Typically less than 2 dozen instructions!

Programming: Single Accumulator Machine

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

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



Problem?

How to modify the addresses A, B and C ?

Self-Modifying Code

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

modify the program for the next iteration

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

Each iteration involves

	<i>total</i>	<i>book-keeping</i>
<i>instruction fetches</i>	17	14
<i>operand fetches</i>	10	8
<i>stores</i>	5	4

Most of the executed instructions are for bookkeeping!

Index Registers

Tom Kilburn, Manchester University, mid 50's

One or more specialized registers to simplify address calculation

Modify existing instructions

LOAD	x, IX	$AC \leftarrow M[x + (IX)]$
ADD	x, IX	$AC \leftarrow (AC) + M[x + (IX)]$
...		

Add new instructions to manipulate *index registers*

JZi	x, IX	if (IX)=0 then $PC \leftarrow x$ else $IX \leftarrow (IX) + 1$
LOADi	x, IX	$IX \leftarrow M[x]$ (truncated to fit IX)
...		

Index registers have accumulator-like characteristics

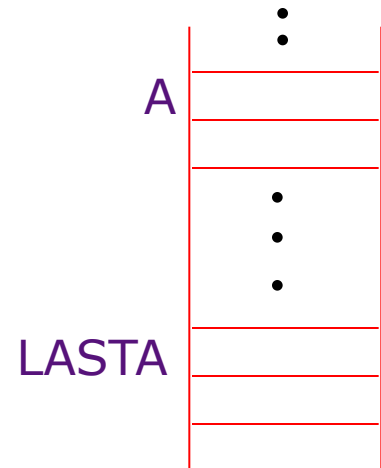
Using Index Registers

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

```

LOADi  N, IX
LOOP   JZi   DONE, IX
      LOAD  LASTA, IX
      ADD   LASTB, IX
      STORE LASTC, IX
      JUMP  LOOP
DONE   HALT
    
```

N starts with -n



- *Program does not modify itself*
- *Efficiency has improved dramatically (ops / iter)*

	with index regs	without index regs
instruction fetch	5(2)	17 (14)
operand fetch	2	10 (8)
store	1	5 (4)

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

Operations on Index Registers

To increment index register by k

$AC \leftarrow (IX)$ *new instruction*

$AC \leftarrow (AC) + k$

$IX \leftarrow (AC)$ *new instruction*

also the AC must be saved and restored

It may be better to increment IX directly

$INCi \quad k, IX \quad IX \leftarrow (IX) + k$

More instructions to manipulate index register

$STOREi \quad x, IX \quad M[x] \leftarrow (IX)$ (extended to fit a word)

...

IX begins to look like an accumulator

\Rightarrow several index registers

several accumulators

\Rightarrow *General Purpose Registers*

Evolution of Addressing Modes

1. Single accumulator, absolute address

LOAD x

2. Single accumulator, index registers

LOAD x, IX

3. Indirection

LOAD (x)

4. Multiple accumulators, index registers, indirection

LOAD R, IX, x

or

LOAD R, IX, (x)

the meaning?

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

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

5. Indirect through registers

LOAD $R_I, (R_J)$

6. The works

LOAD $R_I, R_J, (R_K)$

$R_J = \text{index}, R_K = \text{base addr}$

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!

**Next Lecture:
Instruction Set Architectures
and Caches**