CSC 631: High-Performance Computer Architecture

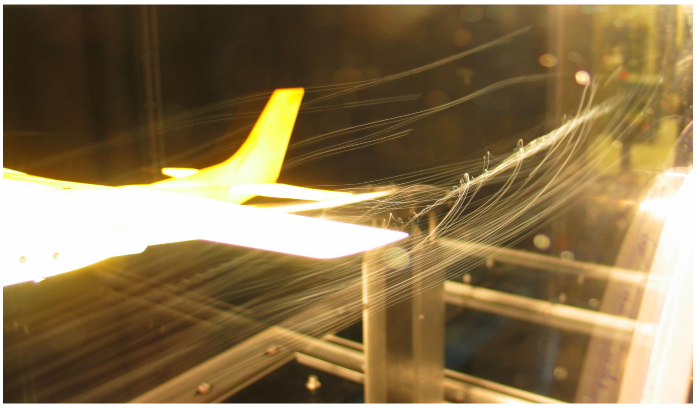
Spring 2017
Lecture 2: Instruction Set Architectures

Analog Computers

- Analog computer represents problem variables as some physical quantity (e.g., mechanical displacement, voltage on a capacitor) and uses scaled physical behavior to calculate results


[Marsyas, Creative Commons BY-SA 3.0]

Antikythera mechanism c.100BC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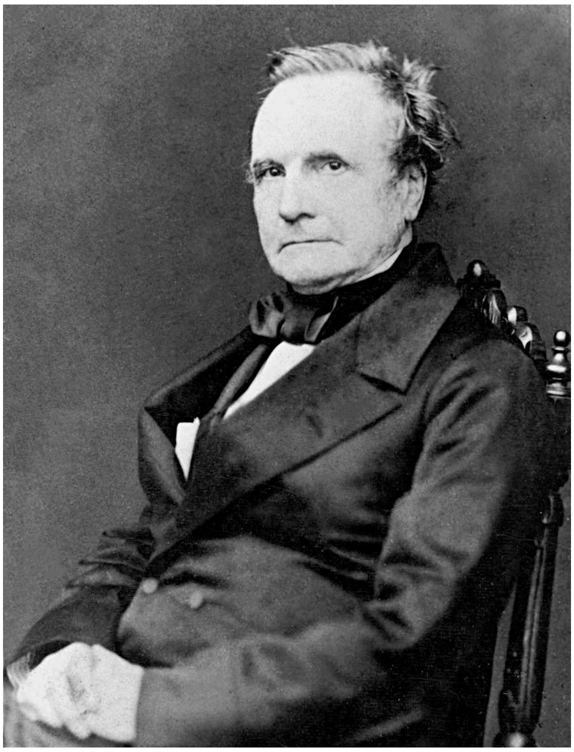
Wingtip vortices off Cesna tail in wind tunnel

Digital Computers

- Represent problem variables as numbers encoded using discrete steps
  - Discrete steps provide noise immunity
- Enables accurate and deterministic calculations
  - Same inputs give same outputs exactly
- Not constrained by physically realizable functions
- Programmable digital computers are the focus of computer architectures

Charles Babbage (1791-1871)



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- Lucasian Professor of Mathematics, Cambridge University, 1828-1839
- A true "polymath" with interests in many areas
- Frustrated by errors in printed tables, wanted to build machines to evaluate and print accurate tables
- Inspired by earlier work organizing human "computers" to methodically calculate tables by hand

Difference Engine 1822

- Continuous functions can be approximated by polynomials, which can be computed from difference tables:

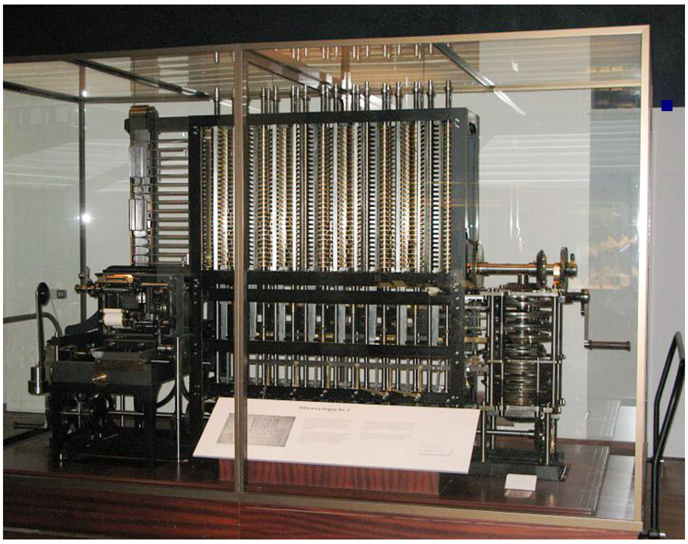
$$f(n) = n^2 + n + 41$$
$$d1(n) = f(n) – f(n\text{-}1) = 2n$$
$$d2(n) = d1(n) – d1(n\text{-}1) = 2$$

- Can calculate using only a single adder:

n	0	1	2	3	4
d2(n)			2	2	2
d1(n)		2	4	6	8
f(n)	41	43	47	53	61

Realizing the Difference Engine

- Mechanical calculator, hand-cranked, using decimal digits
- Babbage did not complete the DE, moving on to the Analytical Engine (but used ideas from AE in improved DE 2 plan)
- Scheutz completed working version in 1855, sold copy to British Government



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- Modern day recreation of DE2, including printer, showed entire design possible using original technology
  - first at British Science Museum
  - copy at Computer History Museum in San Jose

Analytical Engine 1837

- Recognized as first general-purpose digital computer
  - Many iterations of the design (multiple Analytical Engines)
- Contains the major components of modern computers:
  - "Store": Main memory where numbers and intermediate results were held (1,000 decimal words, 40-digits each)
  - "Mill": Arithmetic unit where processing was performed including addition, multiplication, and division
  - Also supported conditional branching and looping, and exceptions on overflow (machine jams and bell rings)
  - Had a form of microcode (the "Barrel")
- Program, input and output data on punched cards
- Instruction cards hold opcode and address of operands in store
  - 3-address format with two sources and one destination, all in store
- Branches implemented by mechanically changing order cards were inserted into machine
- Only small pieces were ever built

Analytical Engine Design Choices

- Decimal, because storage on mechanical gears
  - Babbage considered binary and other bases, but no clear advantage over human-friendly decimal
- 40-digit precision (equivalent to >133 bits)
  - To reduce impact of scaling given lack of floating-point hardware
- Used "locking" or mechanical amplification to overcome noise in transferring mechanical motion around machine
  - Similar to non-linear gain in digital electronic circuits
- Had a fast "anticipating" carry
  - Mechanical version of pass-transistor carry propagate used in CMOS adders (and earlier in relay adders)

Ada Lovelace (1815-1852)

[By Margaret Sarah Carpenter,
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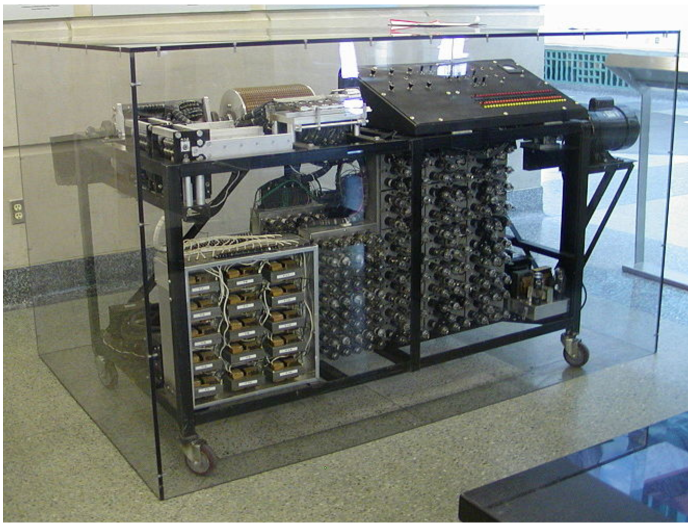
- Translated lectures of Luigi Menabrea who published notes of Babbage's lectures in Italy
- Lovelace considerably embellished notes and described Analytical Engine program to calculate Bernoulli numbers that would have worked if AE was built
  - The first program!
- Imagined many uses of computers beyond calculations of tables
- Was interested in modeling the brain

Early Programmable Calculators

- Analog computing was popular in first half of 20th century as digital computing was too expensive
- But during late 30s and 40s, several programmable digital calculators were built (date when operational)
  - Atanasoff Linear Equation Solver (1939)
  - Zuse Z3 (1941)
  - Harvard Mark I (1944)
  - ENIAC (1946)

Atanasoff-Berry Linear Equation Solver (1939)

- Fixed-function calculator for solving up to 29 simultaneous linear equations
- Digital binary arithmetic (50-bit fixed-point words)
- Dynamic memory (rotating drum of capacitors)
- Vacuum tube logic for processing



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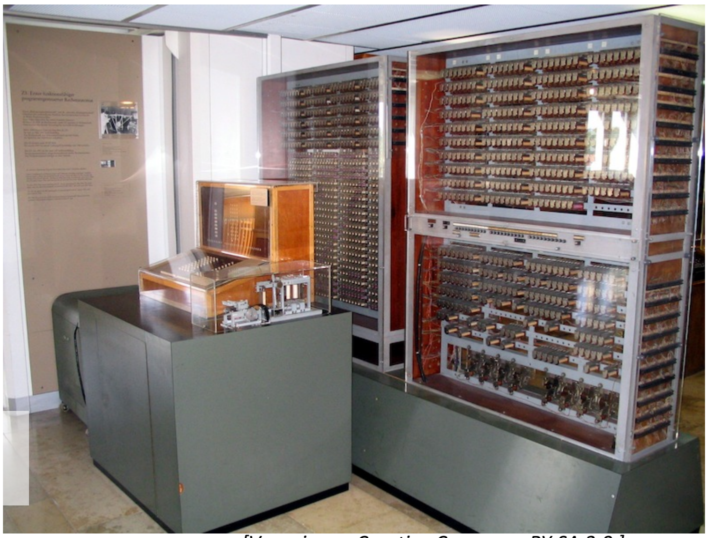
In 1973, Atanasoff was credited as inventor of "automatic electronic digital computer" after patent dispute with Eckert and Mauchly (ENIAC)

Zuse Z3 (1941)

- Built by Konrad Zuse in wartime Germany using 2000 relays
- Had normalized floating-point arithmetic with hardware handling of exceptional values (+/- infinity, undefined)
  - 1-bit sign, 7-bit exponent, 14-bit significand
- 64 words of memory
- Two-stage pipeline 1) fetch&execute 2) writeback
- No conditional branch
- Programmed via paper tape



Replica of the Zuse Z3 in the Deutsches Museum, Munich

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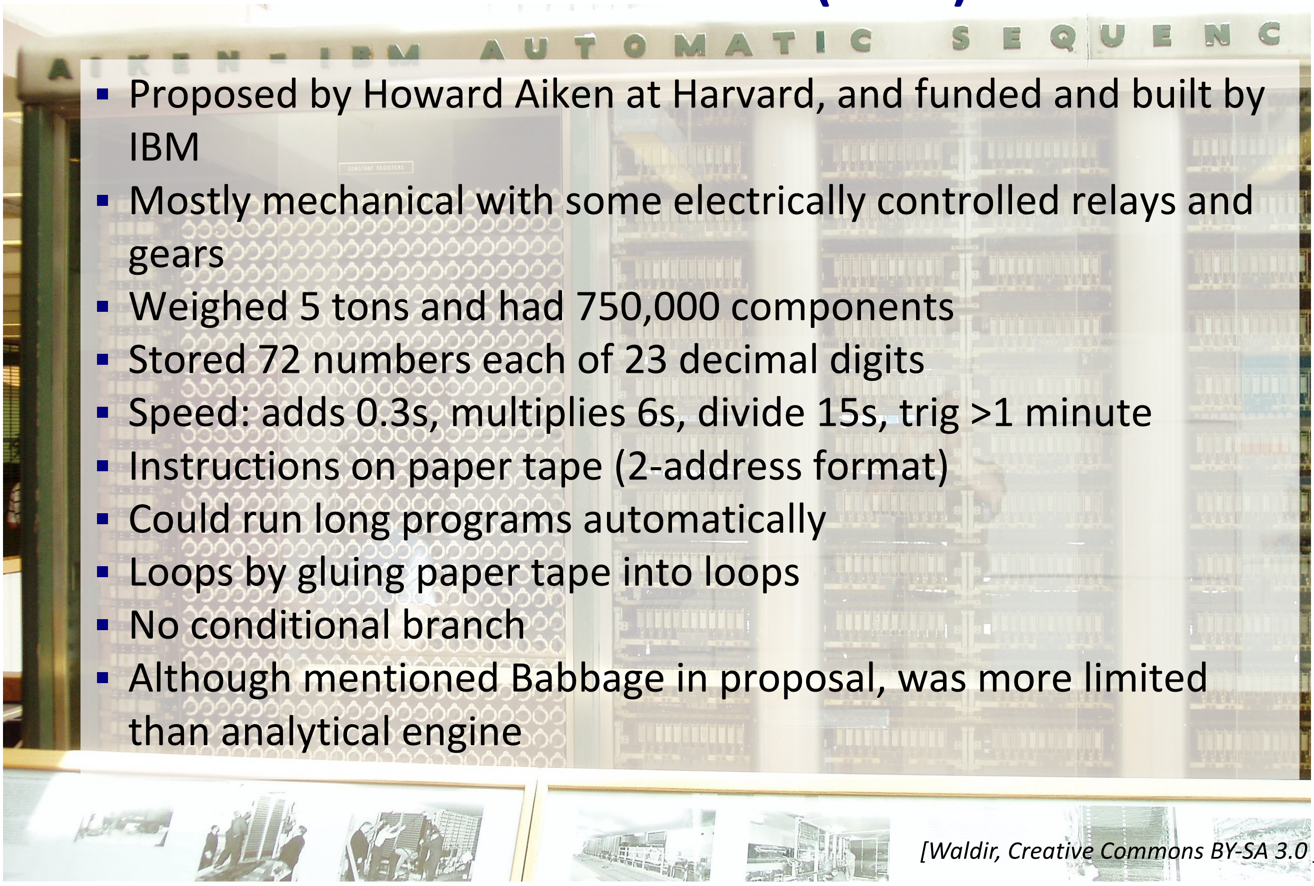
Harvard Mark I (1944)



- Proposed by Howard Aiken at Harvard, and funded and built by IBM
- Mostly mechanical with some electrically controlled relays and gears
- Weighed 5 tons and had 750,000 components
- Stored 72 numbers each of 23 decimal digits
- Speed: adds 0.3s, multiplies 6s, divide 15s, trig >1 minute
- Instructions on paper tape (2-address format)
- Could run long programs automatically
- Loops by gluing paper tape into loops
- No conditional branch
- Although mentioned Babbage in proposal, was more limited than analytical engine

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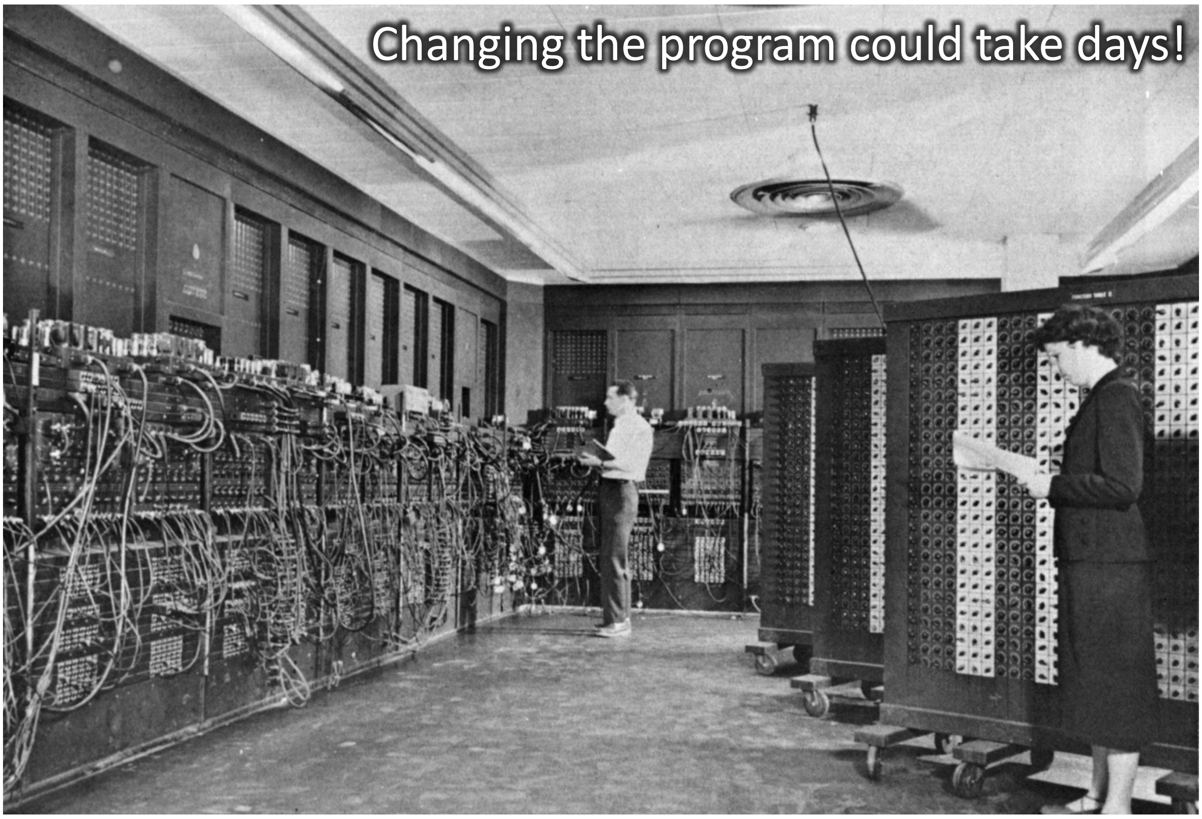
ENIAC (1946)

- First electronic general-purpose computer
- Construction started in secret at UPenn Moore School of Electrical Engineering during WWII to calculate firing tables for US Army, designed by Eckert and Mauchly
- 17,468 vacuum tubes
- Weighed 30 tons, occupied 1800 sq ft, power 150kW
- Twelve 10-decimal-digit accumulators
- Had a conditional branch!
- Programmed by plugboard and switches, time consuming!
- Purely electronic instruction fetch and execution, so fast
  - 10-digit x 10-digit multiply in 2.8ms (2000x faster than Mark-1)
- As a result of speed, it was almost entirely I/O bound
- As a result of large number of tubes, it was often broken (5 days was longest time between failures)

ENIAC



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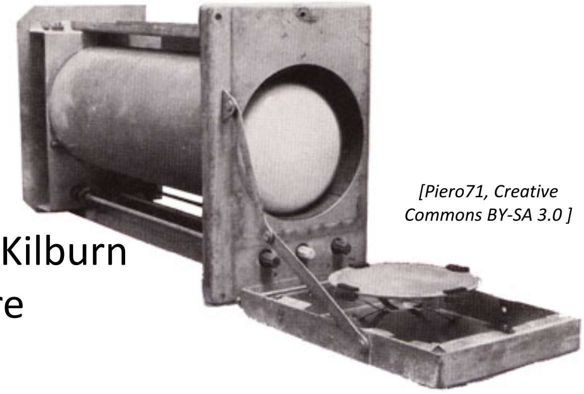
EDVAC

- ENIAC team started discussing stored-program concept to speed up programming and simplify machine design
- John von Nuemann was consulting at UPenn and typed up ideas in "First Draft of a report on EDVAC"
- Herman Goldstine circulated the draft June 1945 to many institutions, igniting interest in the stored-program idea
  - But also, ruined chances of patenting it
  - Report falsely gave sole credit to von Neumann for the ideas
  - Maurice Wilkes was excited by report and decided to come to US workshop on building computers
- Later, in 1948, modifications to ENIAC allowed it to run in stored-program mode, but 6x slower than hardwired
  - Due to I/O limitations, this speed drop was not practically significant and improvement in productivity made it worthwhile
- EDVAC eventually built and (mostly) working in 1951
  - Delayed by patent disputes with university

Manchester SSEM "Baby" (1948)

- Manchester University group build small-scale experimental machine to demonstrate idea of using cathode-ray tubes (CRTs) for computer memory instead of mercury delay lines
- *Williams-Kilburn Tubes were first random access electronic storage devices*
- 32 words of 32-bits, accumulator, and program counter
- Machine ran world's first stored-program in June 1948
- Led to later Manchester Mark-1 full-scale machine
  - Mark-1 introduced *index* registers
  - Mark-1 commercialized by Ferranti



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Williams-Kilburn
Tube Store

Cambridge EDSAC (1949)

- Maurice Wilkes came back from workshop in US and set about building a stored-program computer in Cambridge
- EDSAC used mercury-delay line storage to hold up to 1024 words (512 initially) of 17 bits (+1 bit of padding in delay line)
- Two's-complement binary arithmetic
- Accumulator ISA with self-modifying code for indexing
- David Wheeler, who earned the world's first computer science PhD, invented the subroutine ("Wheeler jump") for this machine
  - Users built a large library of useful subroutines
- UK's first commercial computer, LEO-I (Lyons Electronic Office), was based on EDSAC, ran business software in 1951
  - Software for LEO was still running in the 1980s in emulation on ICL mainframes!
- EDSAC-II (1958) was first machine with microprogrammed control unit

Commercial computers: BINAC (1949) and UNIVAC (1951)

- Eckert and Mauchly left U.Penn after patent rights disputes and formed the Eckert-Mauchly Computer Corporation
- World's first commercial computer was BINAC with two CPUs that checked each other
  - BINAC apparently never worked after shipment to first (only) customer
- Second commercial computer was UNIVAC
  - Used mercury delay-line memory, 1000 words of 12 alpha characters
  - Famously used to predict presidential election in 1952
  - Eventually 46 units sold at >$1M each
  - Often, mistakingly called the IBM UNIVAC

IBM 701 (1952)

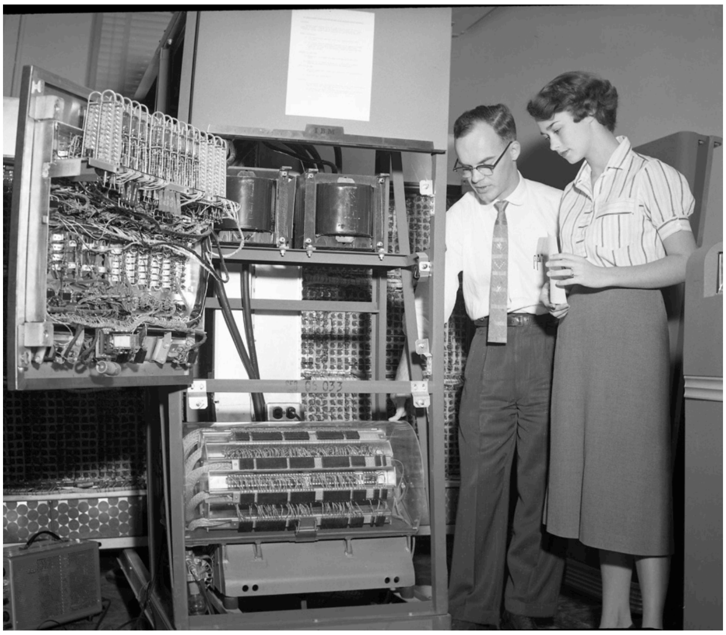
- IBM's first commercial scientific computer
- Main memory was 72 William's Tubes, each 1Kib, for total of 2048 words of 36 bits each
  - Memory cycle time of 12µs
- Accumulator ISA with multipler/quotient register
- 18-bit/36-bit numbers in sign-magnitude fixed-point
- Misquote from Thomas Watson Sr/Jr:

  "I think there is a world market for maybe five computers"
- Actually TWJr said at shareholder meeting:

  "as a result of our trip [selling the 701]***, on which we expected to get orders for five machines, we came home with orders for 18."***

IBM 650 (1953)

- The first mass-produced computer
- Low-end system with drum-based storage and digit serial ALU
- Almost 2,000 produced



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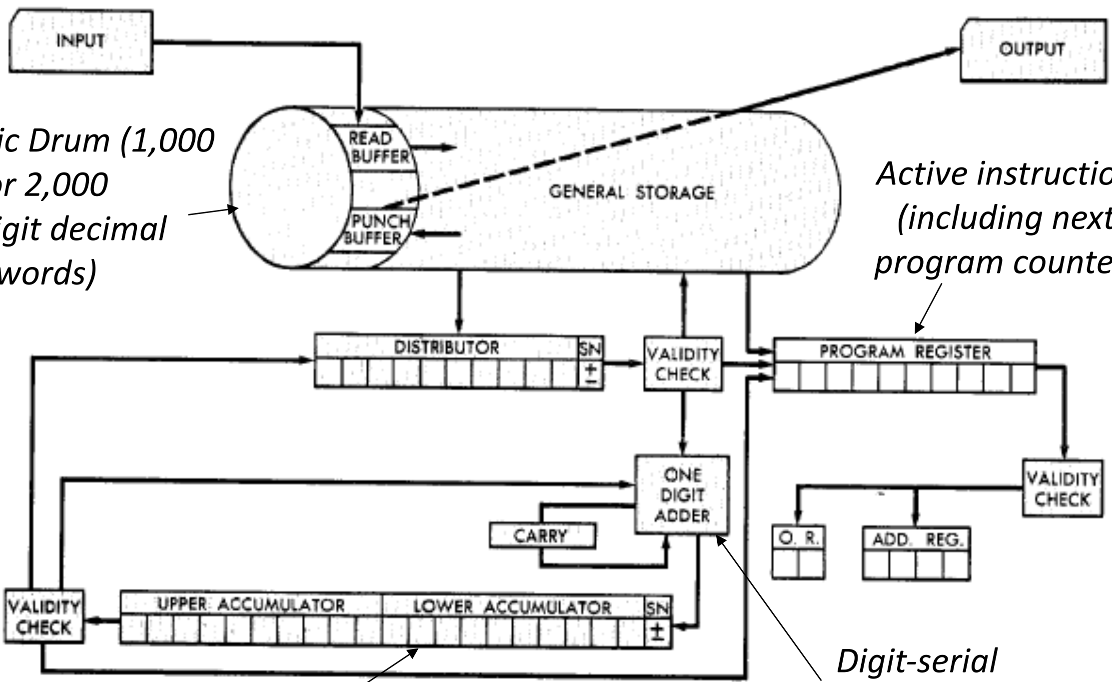
IBM 650 Architecture



Magnetic Drum (1,000 or 2,000 10-digit decimal words)

Active instruction (including next program counter)

Digit-serial ALU

20-digit accumulator

[From 650 Manual, © IBM]

IBM 650 Instruction Set

- Address and data in 10-digit decimal words
- Instructions encode:
  - Two-digit opcode encoded 44 instructions in base instruction set, expandable to 97 instructions with options
  - Four-digit data address
  - Four-digit next instruction address
    - Programmer's arrange code to minimize drum latency!
- Special instructions added to compare value to all words on track

Early Instruction Sets

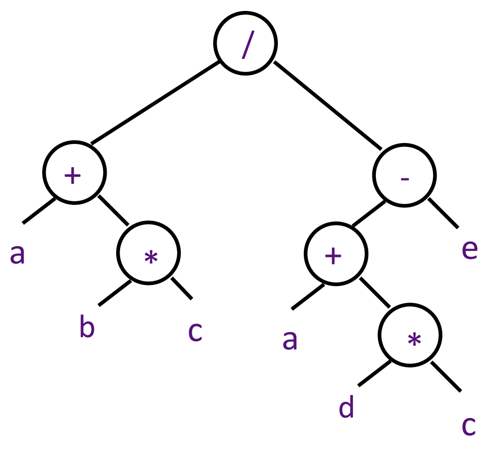
- Very simple ISAs, mostly single-address accumulator-style machines, as high-speed circuitry was expensive
  - Based on earlier "calculator" model
- Over time, appreciation of software needs shaped ISA
- Index registers (Kilburn, Mark-1) added to avoid need for self-modifying code to step through array
- Over time, more index registers were added
- And more operations on the index registers
- Eventually, just provide general-purpose registers (GPRs) and orthogonal instruction sets
- But some other options explored…

Burrough's B5000 Stack Architecture: Robert Barton, 1960

- Hide instruction set completely from programmer using high-level language (ALGOL)
- Use stack architecture to simplify compilation, expression evaluation, recursive subroutine calls, interrupt handling,…

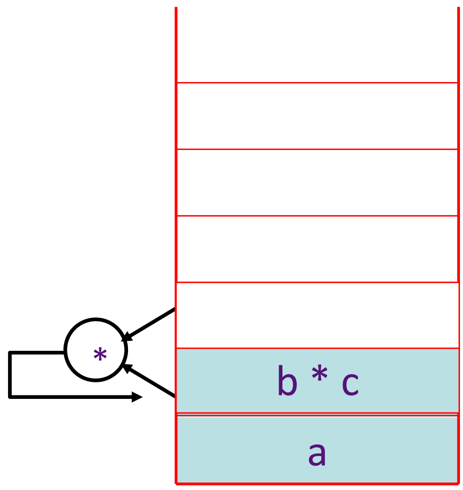
Evaluation of Expressions

(a + b * c) / (a + d * c - e)



Reverse Polish

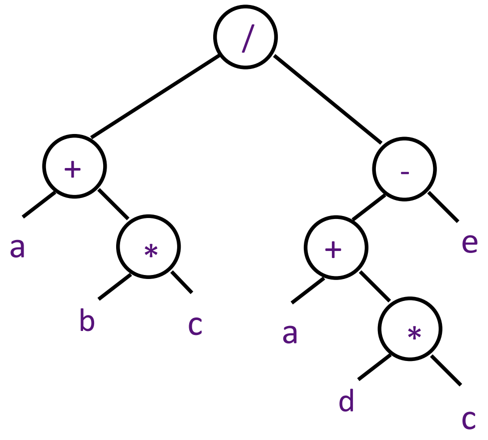
a b c * + a d c * + e - /



Evaluation Stack

Evaluation of Expressions

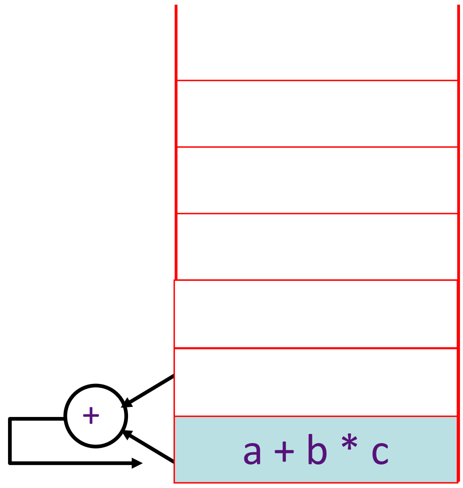
(a + b * c) / (a + d * c - e)



Reverse Polish

a b c * + a d c * + e - /

add



Evaluation Stack

IBM's Big Bet: 360 Architecture

- By early 1960s, IBM had several incompatible families of computer:

  701 → 7094
  650 → 7074
  702 → 7080
  1401 → 7010

- Each system had its own
  - Instruction set
  - I/O system and secondary storage (magnetic tapes, drums and disks)
  - assemblers, compilers, libraries,...
  - market niche (business, scientific, real time, ...)

IBM 360 : Design Premises
Amdahl, Blaauw and Brooks, 1964

- The design must lend itself to growth and successor machines
- General method for connecting I/O devices
- Total performance - answers per month rather than bits per microsecond $\Rightarrow$ programming aids
- Machine must be capable of supervising itself without manual intervention
- Built-in hardware fault checking and locating aids to reduce down time
- Simple to assemble systems with redundant I/O devices, memories etc. for fault tolerance
- Some problems required floating-point larger than 36 bits

Stack versus GPR Organization

Amdahl, Blaauw and Brooks, 1964

1. The performance advantage of push-down stack organization is derived from the presence of fast registers and not the way they are used.
2. "Surfacing" of data in stack which are "profitable" is approximately 50% because of constants and common subexpressions.
3. Advantage of instruction density because of implicit addresses is equaled if short addresses to specify registers are allowed.
4. Management of finite-depth stack causes complexity.
5. Recursive subroutine advantage can be realized only with the help of an independent stack for addressing.
6. Fitting variable-length fields into fixed-width word is awkward.

IBM 360: A General-Purpose Register (GPR) Machine

- Processor State
  - 16 General-Purpose 32-bit Registers
    - may be used as index and base register
    - Register 0 has some special properties
  - 4 Floating Point 64-bit Registers
  - A Program Status Word (PSW)
    - PC, Condition codes, Control flags
- A 32-bit machine with 24-bit addresses
  - But no instruction contains a 24-bit address!
- Data Formats
  - 8-bit bytes, 16-bit half-words, 32-bit words, 64-bit double-words

The IBM 360 is why bytes are 8-bits long today!

IBM 360: Initial Implementations

	Model 30	. . .	*Model 70*
Storage	8K - 64 KB		256K - 512 KB
Datapath	8-bit		64-bit
Circuit Delay	30 nsec/level		5 nsec/level
Local Store	Main Store		Transistor Registers
Control Store	Read only 1 μ sec		Conventional circuits

IBM 360 instruction set architecture (ISA) completely hid the underlying technological differences between various models.

Milestone: The first true ISA designed as portable hardware-software interface!

With minor modifications it still survives today!

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