18-447 Lecture 4: Development of ISAs

James C. Hoe
Department of ECE
Carnegie Mellon University
Housekeeping

• Your goal today
  – understand how ISAs got to be the way they are

• Notices
  – Lab 1, Part A, due this week
  – Lab 1, Part B, due next week
  – HW1, due 2/7

• Readings
  – P&H Ch 2 (optional P&H App D: RISC Survey)
  – optional (in supplemental handout on Canvas)
    • 1946 von Neumann paper
    • 1964 IBM 360 paper
  – P&H Ch 1.6~1.9 for next time
Stored Program Architecture
a.k.a. von Neumann

- Memory holds both program and data
  - instructions and data in a linear memory array
  - instructions can be modified as data
- Sequential instruction processing
  1. program counter (PC) identifies current instruction
  2. fetch instruction from memory
  3. update some state (e.g. PC and memory) as a function of current state (according to instruction)
  4. repeat

Dominant paradigm since its invention
An Early ISA: EDSAC

- Single accumulator architecture, i.e.
  \[ \text{ACC} \leftarrow \text{ACC} \oplus M[n] \]
- Instruction examples
  - **A n**: add \( M[n] \) into ACC (also S, R, L)
  - **T n**: transfer the contents of ACC to \( M[n] \) and clear
  - **E n**: If \( \text{ACC} \geq 0 \), branch to \( M[n] \) or proceed serially
  - **I n**: Read the next character from paper tape, and store it as the least significant 5 bits of \( M[n] \)
  - **Z**: Stop the machine and ring the warning bell

Notice: address hardcoded in instruction
Let’s try some basic things

• Function call

• Array access in a loop

What was the “pioneering” way?
What is the proper fix?
Technology Context Calibration

[images from Wikipedia]
Evolution of Register Architecture

• Accumulator
  – a legacy from the “adding” machine days
    Ever wonder about that “AC” button on your calc?

• Accumulator + address registers
  – need register indirection
  – initially address registers were special-purpose,
    i.e., only used to hold address for indirection
  – eventually arithmetic on address registers

• General purpose registers (GPR)
  – all registers good for all purposes
  – grew from a few registers to 32 (common for RISC)
    to 128 in Intel Itanium

What drove the changes?
Operand Sources?

- Number of Specified Operands
  - **Niladic**  Op  \(\text{(e.g. Burroughs)}\)
  - **Monadic**  OP in2  \(\text{(e.g. EDSAC)}\)
  - **Dyadic**  OP inout, in2  \(\text{(e.g. IBM 360)}\)
  - **Triadic**  OP out, in1, in2  \(\text{(e.g. MIPS)}\)

- Can ALU operands be in memory?
  - No!  \(\text{e.g. MIPS/“RISC”/load-store arch.}\)
  - Yes!  \(\text{e.g. x86/VAX/“CISC”}\)

- How many different formats and addressing modes?
  - a very few  \(\text{e.g. MIPS / “RISC”}\)
  - a lot  \(\text{e.g. x86}\)
  - everything goes  \(\text{e.g. VAX}\)
Memory Addressing Modes

• Absolute        LW rt, 10000
   use immediate value as address
• Register Indirect: LW rt, (r_{base})
   use GPR[r_{base}] as address
• Displaced or based: LW rt, offset(r_{base})
   use offset+GPR[r_{base}] as address
• Indexed:        LW rt, (r_{base}, r_{index})
   use GPR[r_{base}]+GPR[r_{index}] as address
• Memory Indirect LW rt ((r_{base}))
   use value at M[ GPR[ r_{base} ] ] as address
• Auto inc/decrement LW Rt, (r_{base})
   use GPR[r_{base}] as address, and inc. or dec. GPR[r_{base}]
• Anything else you like to see ......
VAX-11: ISA in mid-life crisis

- First commercial 32-bit machine
- Ultimate in “orthogonality” and “completeness”
  
  All of the above addressing modes \( \times \) \{7 integer and 2 floating point formats\} \( \times \) \{more than 300 opcodes\}

- Opcode in excess
  - 2-operand and 3-operand versions of ALU ops
  - INS(/REM)QUE (for circular doubly-linked list)
  - “polyf”: 4\(^{\text{th}}\)-degree polynomial solve

- Variable length encoding
  
  \text{addl3} \ r1,737(r2),(r3)[r4]
  
  7-byte instruction, sequenced decoding
“RISC”

- Simple operations
  - 2-input, 1-output arithmetic and logical operations
  - few alternatives for accomplishing the same thing

- Simple data movements
  - ALU ops are register-to-register *(need large GPR file)*
  - “load-store” architecture, 1 addressing mode

- Simple branches
  - limited varieties of branch conditions and targets

- Simple instruction encoding
  - all instructions encoded in the same number of bits
  - few, simple encoding formats
  - motivated by/intended for compiled code over assembly
Evolution of ISAs

• Why were the earlier ISAs so simple? e.g., EDSAC
  – technology
  – precedence
• Why did it get so complicated later? e.g., VAX11
  – assembly programming
  – lack of memory size and performance
  – microprogrammed implementation
• Why did it become simple again? e.g., RISC
  – memory size and speed (cache!)
  – compilers
• Why is x86 still so popular?
  – technical merit vs. {SW base, psychology, deep pocket}
• Why has ARM thrived while other RISC ISAs vanished
  Why RISC-V now?
Intel IA-64/Itanium Architecture

- Late 90’s attempt to counter RISC in servers market
- IA-64 Instruction “Bundle”
  - three IA-64 instructions (aka syllables)
  - template bits specify dependencies within a bundle and between bundles
  - group=collection of dependence-free bundles
    encode instruction parallelism explicitly

  
  \[
  \begin{array}{| c | c | c |}
  \hline
  \text{inst}_1 & \text{inst}_2 & \text{inst}_3 \\
  \hline
  \end{array}
  \begin{array}{ c }
  \text{template} \\
  \hline
  \end{array}
  \]

- “Thin” abstraction for simple/fast hardware
  - shift from dynamic HW to compiler static analysis and/or profile-driven
  - expose inst-by-inst performance mechanisms to SW
  - very hard to produce high performing code by hand
Example: Rotating Registers

- 128 general purpose physical integer registers
- Register names R0 to R31 are static; refer to the first 32 physical GPRs
- Register names R32 to R127 are “rotating registers”; renamed onto the remaining 96 physical registers by an offset
- Simplifies register use on function call/return and on loop optimizations (when register names are reused in code)
Example: Predicated Execution

- 64 one-bit predicate register file
  - each instruction carries a 6-bit predicate operand field
  - instruction has no effect if predicate operand is false
- A way to realize conditionals without control flow

A good idea when branch very expensive and excess resources ready to absorb “extra” work
Example: Exposed Memory Hierarchies

• ISA included the concept of cache hierarchy
  – multiple levels
  – separate “temporal” vs “non-temporal”

• Memory instructions give hints where best to cache

As hints, microarchitecture does not have to

(temporal) L1 → L2 → L3
(none-temporal-L1) NT L1
(none-temporal-L2) NT L2
(none-temporal-All) NT L3

Main Memory
Intel iAPX 432, circa 1980

- Was to be a follow-on to 8080 contemporary development with RISC and x86
- Way off the beaten path
  - bit-aligned variable length instruction objects
  - stack instead of GPRs
- High-level abstraction in HW
  - object-oriented (down to instructions)
  - capability-based memory protection
  - HW garbage collection
- Architectural vision too aggressive for technology and commercial demand of the time
How much should ISA still matter?
Birth of “Binary Compatibility”

• “The term *architecture* is used here to describe the attributes of a system as seen by the programmer, i.e., the conceptual structure and functional behavior, as distinct from the organization of the data flow and controls, the logical design, and the physical implementation.”


• A single architecture with multiple price&perf variants replaced 4 incompatible product lines
Key Idea 1: Open-Ended Design

“a dependable base for a decade of customer planning and customer programming . . .”

- Asynchronous operation of components—abstract out exact time, performance etc. to allow changing technology and relative speed of components
- Parameterization of storage capacity, multi CPU, multi I/O, etc.
- Standard interfaces for expansion sub-systems
- Permit future extensions by “reserving” spare bits in instruction encoding

[Amdahl, Blaauw and Brooks, 1964]
Key Idea 2: General Purpose

- Effective support for “large and small, separate and mixed applications” in many domains
- Code-independent operation
  - no special interpretation of bit pattern in data
    e.g. ASCII character has no special significance
  - except where essential
    e.g., integer, floating point, etc.
- Support full generality of logic manipulation on bit and data entities
- Fine-grain memory addressability (down to small units of bits)

[Amdahl, Blaauw and Brooks, 1964]
Key Idea 3: Inter-Model Compatibility

“a valid program whose logic will not depend implicitly upon time of execution and which runs upon configuration A, will also run on configuration B if the latter includes at least the required storage, at least the required I/O devices ....”

• Invalid programs not constrained to yield same result
  – “invalid”==violating architecture manual
  – “exceptions” are architecturally defined

• The King of Binary Compatibility: Intel x86, IBM 360
  – stable software base and ecosystem
  – performance scalability

[Amdahl, Blaauw and Brooks, 1964]
Binary Translation

- Generate a new executable in **target ISA** with same functional behavior as the original in **source ISA**
  - not the same as interpretation or VM
  - not easy but doable *(for the right source and target)*
  - static vs dynamic

- Holy grail
  - all software run on the ISA/processor I sell
  - all processors can run the software I sell

- “Architecture” need not be the HW/SW contract
  - binary compatibility by translation virtualization
  - ISA and processor can become commodity
  - old software and ISA can live on for ever

What is CUDA?
Transmeta Crusoe & Code Morphing

<table>
<thead>
<tr>
<th>Complete x86 Abstraction</th>
<th>x86 applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x86 OS</td>
</tr>
<tr>
<td></td>
<td>x86 BIOS</td>
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<tr>
<td>Native SW</td>
<td>Code Morphing Dynamic Binary Translation</td>
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<tr>
<td>HW</td>
<td>Crusoe VLIW Processor (**with superset of x86 ISA state)</td>
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- Crusoe boots “Code Morpher” from ROM at power-up
- Crusoe+Code Morphing == x86 processor

x86 software (including BIOS) cannot tell the difference

BTW, this really worked in the early 2000s
Code Morphing Software (CMS)

• Begins execution at power-up
  – fetches first-time x86 basic block from memory
  – translates BB into Crusoe VLIW and caches the translation for reuse
  – jumps to the generated Crusoe code for execution
  – continue directly from BB to BB if translation already cached; CMS regains control on new BBs

  BB with “unsafe” x86 instructions not translated

• Re-optimize a translated block after runtime profiling

• The only native SW for Crusoe ISA

  Crusoe processors do not need to be binary compatible between generations
Not really so different from Intel’s own

Transmeta

- Translation Cache
- Code Morphing SW (translate & interpret)

Intel Supercalar OOO

- Translate
- P4 uOP Trace Cache
- Out-of-Order Dispatch
- Parallel FUs
- In-Order Retire
von Neumann abstraction not free

• Significant transistor and energy overhead in presenting the simplifying abstraction
  – per-instruction access to program memory
  – dataflow through reading/writing of registers and memory state
  – “appearance” of sequentiality and atomicity

• In fact, von Neumann processors mostly overhead

• ISA future?
  – move away from von Neumann as doctrine?
  – do away with ISAs (lower-level, more explicit HW)?

Depend on what languages and compilers can do