CS61C: Great Ideas in Computer Architecture (aka Machine Structures)

Lecture 7: RISC-V Part 1

Instructors: Dan Garcia, Justin Yokota

Computing in the News

Memory safe programming languages are on the rise. Here's how developers should respond

In 2019, Microsoft revealed that 70% of security bugs it had fixed during the past 12 years were memory safety issues. The figure was high because Windows was written mostly in C and C++. Since then, the National Security Agency (NSA) has recommended developers make a strategic shift away from C++ in favor C#, Java, Ruby, Rust, and Swift.

During the past two years, more and more projects have started gradually adopting Rust for codebases written in C and C++ to make code more memory safe. Among them are initiatives from Meta, Google's Android Open Source Project, the C++-dominated Chromium project (sort of), and the Linux kernel.

The report highlights that computer science professors have a "golden opportunity here to explain the dangers" and could, for example, increase the weight of memory safety mistakes in assessing grades. But it adds that teaching parts of some courses in Rust could add "inessential complexity" and that there's a perception Rust is harder to learn, while C seems a safe bet for employability in future for many students.

Memory safe programming languages are on the rise. Here's how developers should respond | ZDNET

Agenda

- Warm-Up: Floating Point
- Intro to Assembly Languages
- RISC-V Programming Paradigm
  - `add` and `sub`
  - Immediates: The `addi` instruction
- Demo: Venus

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For what integers n does (1.0/n)+(1.0/n)+... (n times) == 1.0?

- All n
- Most n
- A few n
- No n

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Building a computer from the ground up

- Ultimately, any program we write needs to run on a circuit in order to be useful.
- However, circuit-level programming is highly restrictive.
  - With C, someone designed the programming language, so that person had full control over the operators allowed, and thus could choose how those operators were defined to be useful: the primitive components were defined to reflect the demands of the language.
  - Once you get to the circuit level, every primitive component we use is a piece of silicon that happens to behave in predictable and useful ways: the language needs to be defined to reflect the available components.
- Early computers essentially had to be rebuilt for every program you wanted to run, since different computations required different circuits.
- One major advancement in computer science was the creation of software-based languages. Instead of making a new circuit for every problem you want to solve, make a circuit (called a CPU) that solves the problem “Carry out a sequence of instructions stored as binary data”. Then solve your problem by writing instructions in binary data.

Assembly Language

- We don’t want to change the CPU after we build it, so when designing our CPU, we need to decide on a specific set of instructions that will be supported by the CPU, along with a way to translate each instruction to a binary form.
- Different CPUs implement different sets of instructions. The set of instructions a particular CPU implements is an Instruction Set Architecture (ISA), and the programming language defined by the ISA is commonly known as an assembly language.
  - Examples: ARM (cell phones), Intel x86 (i9, i7, i5, i3), IBM/Motorola PowerPC (old Macs), MIPS, RISC-V, ...

Assembly Language

- C is generally considered a “lower-level” language than Java or Python, because it’s “closer” to the underlying CPU
  - Less is automated by the language, so you get faster runtimes, but have to keep track of more things
- Ultimately, though, C is still considered a high-level language, because there’s still a lot done for you.
  - C lets you write a bunch of operations in a single line of code, and splits it up for you
  - C sets up the stack for you and keeps track of where it stored local variables
  - C lets you just call a function, and you can expect that calling functions won’t affect any local variables you have.
  - C lets you name variables, and will keep track of that name, and even the type of variable that name refers to.
- Once you start working with assembly languages, almost everything is the result of an explicit instruction by the programmer.

Instruction Set Architectures

- Early trend in ISA design was to add more and more instructions to new CPUs to do elaborate operations
  - VAX architecture had an instruction to multiply polynomials!
- RISC philosophy (Cocke IBM, Patterson, Hennessy, 1980s) – Reduced Instruction Set Computing
  - Keep the instruction set small and simple.
  - Let software do complicated operations by composing simpler ones.
  - A simpler CPU is easier to iterate on (allowing for faster development), and can generally be made faster than a complex CPU (we're often limited by the slowest instruction we decide to implement)

RISC-V

- For the purposes of this class, we'll be learning RISC-V as our assembly language
- Why?
  - RISC-V is relatively simple, in that there's only a few instructions in the base instruction set, and that instructions themselves follow a consistent format.
    - x86 is a more popular language (base CPU for most laptops/desktops), but is a CISC language that Huffman encodes its instructions
    - Project 3: Build a complete RISC-V CPU
  - RISC-V is relatively popular, open-source, and growing in popularity
  - RISC-V was invented in Berkeley in 2010.

RISC-V Resources

- CS 61C Reference Card
  - https://cs61c.org/sp23/pdfs/resources/reference-card.pdf
  - Lists out the entire base architecture
- Venus
  - https://venus.cs61c.org/
  - Online RISC-V simulator

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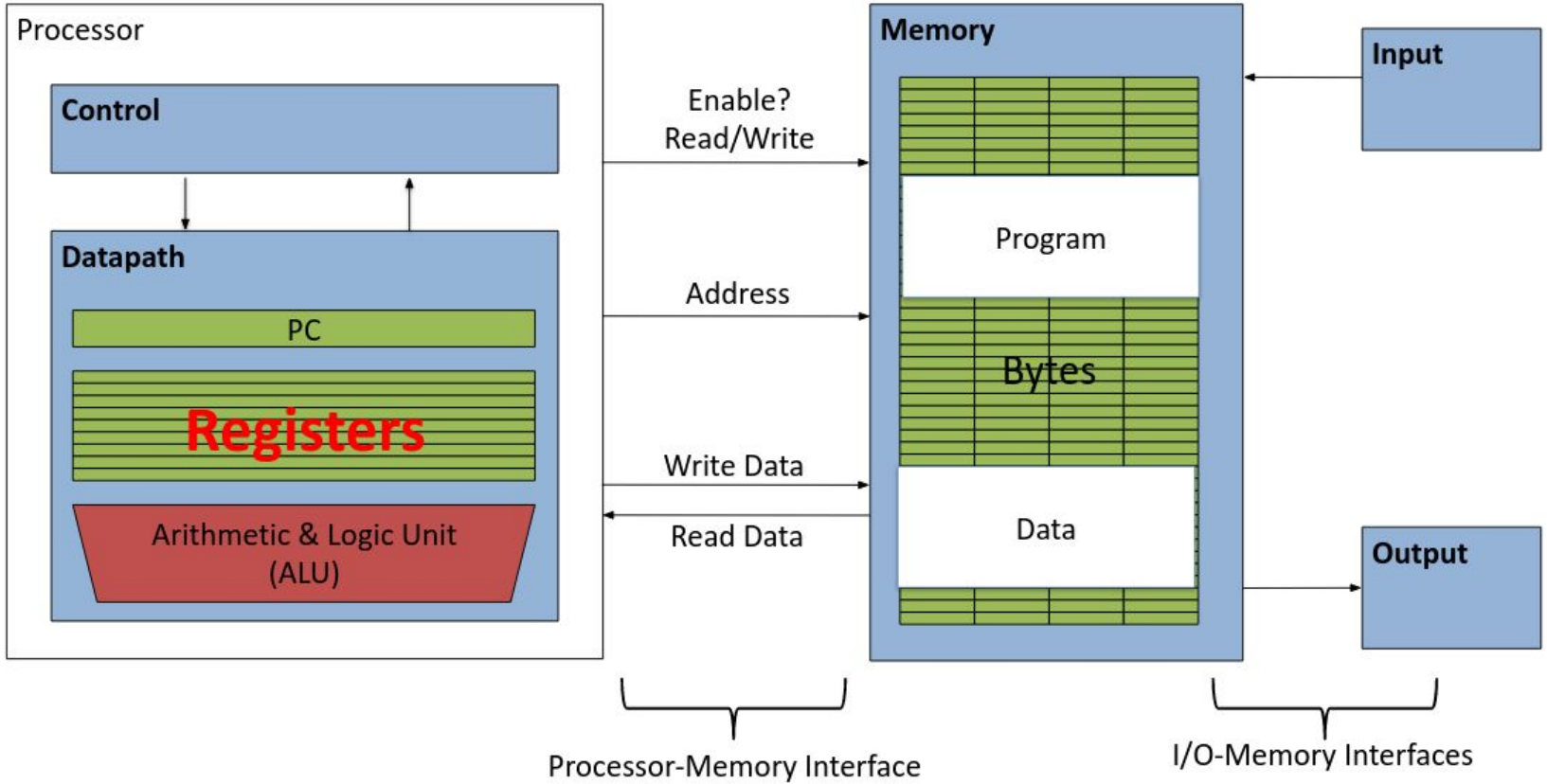
Overarching view of RISC-V

- A RISC-V system is composed of two main parts:
  - The CPU, which is responsible for computing
  - Main memory, which is responsible for long-term data storage (Wednesday)
- The CPU is designed to be extremely fast, often completing one instruction every nanosecond or faster
  - Note: Light travels 30 cm in 1 nanosecond. In other words, it takes longer for light to travel from one end of my laptop to the other, than it does for a CPU to finish one instruction.
- Going to main memory often takes hundreds or even thousands of times longer.
- The CPU can store a small amount of memory, through components called registers.

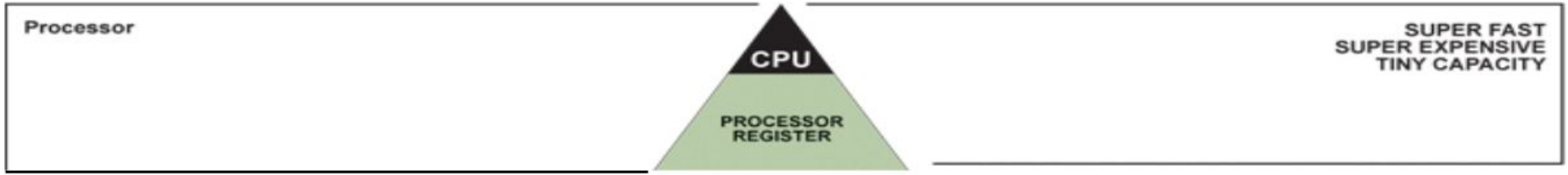
Registers

- A register is a CPU component specifically designed to store a small amount of data. Each register stores 32 bits of data (for a 32-bit system) or 64 bits of data (for a 64-bit system). For the purposes of this class, we consider RV32 only (which uses 32-bit registers)
- This data is purely binary; types do not exist at the assembly level, so if we use a register to store something, it's the programmer's responsibility to keep track of that register and its intended use.
- Registers are a hardware component, so once you make the CPU, you can't change the number of registers available.
- RISC-V gives access to 32 integer registers

Aside: Registers are Inside the Processor



Great Idea #3: Principle of Locality / Memory Hierarchy



Registers

- Registers are a hardware component, so once you make the CPU, you can't change the number of registers available.
- RISC-V gives access to 32 integer registers
- Registers are numbered from 0 to 31
  - Referred to by number: x0 – x31
- The register x0 is special and always stores 0 (More on this later). So only 31 registers are available to hold variables
- The other 31 registers are all identical in behavior; the only difference between different registers is the conventions we follow when using them.
- Later, we'll give them names to hint at what conventions get used on which registers.

Instructions

- Each line of RISC-V code is a single instruction, which executes a simple operation on registers.
- Instructions are generally written in the format
  - <instruction name> <destination register> <operands>
  - Ex. “`add x5 x6 x7`” means “Add the values stored in x6 and x7, and store the result in x5”
  - Commas can be added between registers (“`add x5, x6, x7`”), but this is optional.
- Comments are written using the # symbol.
  - Anything written after a # on a line gets ignored
  - Similar to Python comment syntax
- Important: Comments are far more important in RISC-V than in other languages. In a higher level language, you can sometimes get away with choosing variable names so that the code is self-documenting. **In RISC-V, we don’t have variable names!**
- Uncommented RISC-V code is practically impossible to debug properly. If you don’t comment your code, we may not be able to help debug in office hours.

Addition and Subtraction of Integers (1/3)

- Addition in Assembly
- Example: `add x1,x2,x3` (in RISC-V)
- Equivalent to: `a = b + c` (in C)
- where C variables ⇔ RISC-V registers are:

  `a ⇔ x1, b ⇔ x2, c ⇔ x3`
- Subtraction in Assembly
- Example: `sub x3,x4,x5` (in RISC-V)
- Equivalent to: `d = e - f` (in C)
- where C variables ⇔ RISC-V registers are:

  `d ⇔ x3, e ⇔ x4, f ⇔ x5`

Addition and Subtraction of Integers (2/3)

- How to do the following C statement?

```
a = b + c + d - e;
```

- Break into multiple instructions

```
add x10, x1, x2  # a_temp = b + c
add x10, x10, x3 # a_temp = a_temp + d
sub x10, x10, x4 # a = a_temp - e
```

- Notice: A single line of C may break up into several lines of RISC-V.
- Notice: Everything after the hash mark on each line is ignored (comments).

Addition and Subtraction of Integers (3/3)

- How do we do this?

```
f = (g + h) - (i + j);
```

- Use intermediate temporary register

```
add x5, x20, x21 # a_temp = g + h
add x6, x22, x23 # b_temp = i + j
sub x19, x5, x6  # f = (g + h) - (i + j)
```

- Notice: By using x5 and x6 in this way, we overwrite any data that used to be in those registers. As such, we generally keep a few "temporary" registers free (i.e. not containing any important data) to help with intermediate calculations.
- Note: We could also have written this as `f = g + h - i - j;` which allows us to compute this without any temporary registers. A smart compiler may write code this way instead

Immediates

- Immediates are numerical constants.
- They appear often in code, so there are special instructions for them.
- Add Immediate:
  - `addi x3,x4,10` (in RISC-V)
  - `f = g + 10` (in C)
  - where RISC-V registers `x3,x4` are associated with C variables `f,g`
- Syntax similar to add instruction, except that last argument is a number instead of a register.
- Common mistake: `addi x3,x4,x5` / `add x3,x4,10` are both invalid RISC-V instructions; be careful with using the register version vs the immediate version of an instruction!

Immediates

- There is no Subtract Immediate in RISC-V: Why?
  - There are add and sub, but no addi counterpart
- Limit types of operations that can be done to absolute minimum
  - if an operation can be decomposed into a simpler operation, don't include it
  - **`addi …, -X = subi …, X`** => so no subi

    `addi x3,x4,-10` (in RISC-V)

    `f = g - 10` (in C)
- where RISC-V registers **`x3,x4`** are associated with C variables **`f,g`**

Register Zero

- One particular immediate, the number zero (0), appears very often in code.
- So the register zero (**`x0`**) is ‘hard-wired’ to value 0; e.g.

  `add x3,x4,x0` (in RISC-V)

  `f=g` (in C)
- where RISC-V registers **`x3,x4`** are associated with C variables f, g
- Defined in hardware, so an instruction

  `add x0,x3,x4` will not do anything!

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Venus Demo

- Done in lecture
- Add 1+2+3+4+5

```
addi x5 x0 0
addi x6 x0 10
add x5 x5 x6
addi x6 x6 -1
add x5 x5 x6
addi x6 x6 -1
add x5 x5 x6
addi x6 x6 -1
add x5 x5 x6
addi x6 x6 -1
add x5 x5 x6
addi x6 x6 -1
```