RISC-V Calling Conventions

6.1810 Fall 2024

C code is compiled to machine instructions

How does the machine work at a lower level?

How does this translation work?

How to interact between C and asm?

```
Thread 1 hit Breakpoint 1, syscall () at kernel/syscall.
c:165
165         num = * (int *) 0;
```

```
    0x80001c24 <syscall+14> jal     ra,0x80000cf8 <myp
    0x80001c28 <syscall+18> mv      s1,a0
B+> 0x80001c2a <syscall+20> lw      s2,0(zero) # 0x0
    0x80001c2e <syscall+24> addiw   a4,s2,-1
    0x80001c32 <syscall+28> li      a5,21
    0x80001c34 <syscall+30> bltu    a5,a4,0x80001c82 <
```

RISC-V abstract machine

No C-like control flow, no concept of variables, types ...

Base ISA: Program counter, 32 general-purpose registers (x0 – x31)

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reg	name	saver	description
x0	zero		hardwired zero
x1	ra	caller	return address
x2	sp	callee	stack pointer
x3	gp		global pointer
x4	tp		thread pointer
x5-7	t0-2	caller	temporary registers
x8	s0/fp	callee	saved register / frame pointer
x9	s1	callee	saved register
x10-11	a0-1	caller	function arguments / return values
x12-17	a2-7	caller	function arguments
x18-27	s2-11	callee	saved registers
x28-31	t3-6	caller	temporary registers
pc			program counter

Translating C to Assembly

Example: sum_to(n)

```
int sum_to(int n) {
  int acc = 0;
  for (int i = 0; i <= n; i++) {
    acc += i;
  }
  return acc;
}
```

What does this look like in assembly code?

```c
int sum_to(int n) {
    int acc = 0;

    for (int i = 0; i <= n; i++) {
        acc += i;
    }
    return acc;
}
```

```
# sum_to(n)
# expects argument in a0
# returns result in a0
sum_to:
  mv t0, a0            # t0 <- a0
  li a0, 0             # a0 <- 0
loop:
  add a0, a0, t0       # a0 <- a0 + t0
  addi t0, t0, -1      # t0 <- t0 - 1
  bnez t0, loop        # if t0 != 0: pc <-
loop
  ret
```

Limited abstractions in assembly

No local variables and scopes

Only a fixed set of hardware registers

- RISC-V has 32 registers
- Modern CPUs and GPUs have much more

No typed, positional arguments

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Assembly instructions directly translated to machine code

- Each instruction translated to 16 or 32 bit sequence

Calling and Returning Functions in Assembly

How would another function call `sum_to`?

Example main function

```
main:
  li a0, 10
  call sum_to
```

How does the call to `sum_to` work?

How would another function call `sum_to`?

Example main function

```
main:
 li a0, 10
 call sum_to
```

How does the call to sum_to work?

```
call {label} :=
   ra <- pc + 4          ; ra <- address of next instruction
   pc <- {label}         ; jump to {label}
```

Machine doesn't understand labels – translated to either `pc`-relative or absolute jumps

What are the semantics of return?

```
ret :=
  pc <- ra
```

What are the semantics of return?

```
ret :=
  pc <- ra
```

```
(  call {label} :=
       ra <- pc + 4
       pc <- {label}  )
```

Calling Convention & the Stack

Limited Registers Can Create Problems

Only 32 registers in RISC V

Function calls another function

- Called function can use and overwrite some register values
- When we return to the original function, it’s register values have been corrupted

Need a convention on who saves what registers?

Where do we save register values?

Example: what's the bug? (hint: it's on the right)

```
sum_to:
 mv t0, a0           # t0 <- a0
 li a0, 0            # a0 <- 0
loop:
 add a0, a0, t0      # a0 <- a0 + t0
 addi t0, t0, -1     # t0 <- t0 - 1
 bnez t0, loop       # if t0 != 0: pc <- loop
 ret
```

```
 # sum_then_double(n): expects argument in a0,
returns result in a0
 # expects argument in a0
 # returns result in a0
 sum_then_double:
   call sum_to
   li t0, 2             # t0 <- 2
   mul a0, a0, t0       # a0 <- a0 * t0
   ret

 main:
   li a0, 10
   call sum_then_double
```

What’s the issue with the program?

We get an infinite loop

Why?

```
sum_then_double:
  call sum_to
  li t0, 2              # t0 <- 2
  mul a0, a0, t0        # a0 <- a0 * t0
  ret

main:
  li a0, 10
  call sum_then_double
```

What's the issue with the program?

We get an infinite loop

Why?

- `sum_then_double` calls the function `sum_to`
- Sets the `ra` register to instruction immediately after `(li t0, 2)`
- Return in `sum_then_double` sets `pc` to `ra`, but that does not return it to main

```
sum_then_double:
  call sum_to
  li t0, 2            # t0 <- 2
  mul a0, a0, t0      # a0 <- a0 * t0
  ret

main:
  li a0, 10
  call sum_then_double
```

Fixing the bug

Save `ra` onto the stack in `sum_them_double`

- Allocate space on the stack
- Save `ra` onto the stack (before calling `sum_to`)
- At the end, load `ra` from the stack
- Deallocate stack space

Required coordination between caller and callee on who saves what

Need convention if including programs from different sources

```
sum_then_double:
    addi sp, sp, 16     # function prologue:
    sd ra, 0(sp)        # make space on stack,
                        # save registers
    call sum_to
    li t0, 2
    mul a0, a0, t0
    ld ra, 0(sp)        # function epilogue:
    addi sp, sp, -16    # restore registers,
                        # restore stack pointer
    ret
```

Calling Convention

Conventions surrounding this: "calling convention"

- How are arguments passed? `a0, a1, ..., a7,` rest on the stack
- How are values returned? `a0, a1`

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Who saves registers?

- Designated as *caller* or *callee* saved
- Q. Could `ra` be a *callee*-saved register?

Calling Convention

- Conventions surrounding this: "calling convention"
  - How are arguments passed? `a0, a1, ..., a7,` rest on the stack
  - How are values returned? `a0, a1`
- Who saves registers?
  - Designated as *caller* or *callee* saved
- Our assembly code should follow this convention
  - C code generated by GCC follows this convention
    - → This means that everyone's code can interop

Summary of Calling Convention

reg	name	saver	description
x0	zero		hardwired zero
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x3	gp		global pointer
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pc			program counter

Stack Pointer & Frame Pointer

The Stack, Visually

```
Stack
                    .
                    .
     +->            .
     |    +-----------------+    |
     |    | return address  |    |
     |    |   previous fp -------+
     |    | saved registers |
     |    | local variables |
     |    |       ...       | <-+
     |    +-----------------+    |
     |    | return address  |    |
     +------- previous fp   |    |
          | saved registers |    |
          | local variables |    |
     +->  |       ...       |    |
     |    +-----------------+    |
     |    | return address  |    |
     |    |   previous fp -------+
     |    | saved registers |
     |    | local variables |
     |    |       ...       | <-+
     |    +-----------------+    |
     |    | return address  |    |
     +------- previous fp   |    |
          | saved registers |    |
          | local variables |    |
 $fp -->  |       ...       |    |
          +-----------------+    |
          | return address  |    |
          |   previous fp -------+
          | saved registers |
 $sp -->  | local variables |
          +-----------------+
```

The Stack, Visually

Composed of many stack frames, growing downward (hi → lo)

```
Stack
                    .
                    .
      +->           .
      |   +------------------+   |
      |   | return address   |   |
      |   |   previous fp -------+
      |   | saved registers  |
      |   | local variables  |
      |   |       ...        | <-+
      |   +------------------+   |
      |   | return address   |   |
      +------ previous fp    |   |
          | saved registers  |   |
          | local variables  |   |
      +-> |       ...        |   |
      |   +------------------+   |
      |   | return address   |   |
      |   |   previous fp -------+
      |   | saved registers  |
      |   | local variables  |
      |   |       ...        | <-+
      |   +------------------+   |
      |   | return address   |   |
      +------ previous fp    |   |
          | saved registers  |   |
          | local variables  |   |
  $fp --> |       ...        |   |
          +------------------+   |
          | return address   |   |
          |   previous fp -------+
          | saved registers  |
  $sp --> | local variables  |
          +------------------+
```

The Stack, Visually

Composed of many stack frames, growing downward (hi → lo)

- `sp` points to base of current stack
- `fp` points to end of previous stack frame

```
Stack
                    .
                    .
       +->          .
       |   +-----------------+   |
       |   | return address  |   |
       |   |   previous fp ------+
       |   | saved registers |
       |   | local variables |
       |   |       ...       | <-+
       |   +-----------------+   |
       |   | return address  |   |
       +------ previous fp   |   |
           | saved registers |   |
           | local variables |   |
       +-> |       ...       |   |
       |   +-----------------+   |
       |   | return address  |   |
       |   |   previous fp ------+
       |   | saved registers |
       |   | local variables |
       |   |       ...       | <-+
       |   +-----------------+   |
       |   | return address  |   |
       +------ previous fp   |   |
           | saved registers |   |
           | local variables |   |
   $fp --> |       ...       |   |
           +-----------------+   |
           | return address  |   |
           |   previous fp ------+
           | saved registers |
   $sp --> | local variables |
           +-----------------+
```

The Stack, Visually

Composed of many stack frames, growing downward (hi → lo)

- `sp` points to base of current stack
- `fp` points to end of previous stack frame

Why the frame pointer is useful

- The previous frame's `fp` is a fixed offset (-16) from the current frame's `fp`
- The return address (`ra`) lives at a fixed offset (-8) from the current frame's `fp`

```
Stack
                    .
                    .
      +->           .
      |     +-----------------+   |
      |     | return address  |   |
      |     |   previous fp ------+
      |     | saved registers |
      |     | local variables |
      |     |       ...       | <-+
      |     +-----------------+   |
      |     | return address  |   |
      +------ previous fp     |   |
            | saved registers |   |
            | local variables |   |
      +->   |       ...       |   |
      |     +-----------------+   |
      |     | return address  |   |
      |     |   previous fp ------+
      |     | saved registers |
      |     | local variables |
      |     |       ...       | <-+
      |     +-----------------+   |
      |     | return address  |   |
      +------ previous fp     |   |
            | saved registers |   |
            | local variables |   |
  $fp -->   |       ...       |   |
            +-----------------+   |
            | return address  |   |
            |   previous fp ------+
            | saved registers |
  $sp -->   | local variables |
            +-----------------+
```

The Stack, Visually

Composed of many stack frames, growing downward (hi → lo)

- `sp` points to base of current stack
- `fp` points to end of previous stack frame

Why the frame pointer is useful

- The previous frame's `fp` is a fixed offset (-16) from the current frame's `fp`
- The return address (`ra`) lives at a fixed offset (-8) from the current frame's `fp`

Can traverse previous stack frames by repeatedly finding the previous `fp`, and get useful information out of it (e.g. `ra`)

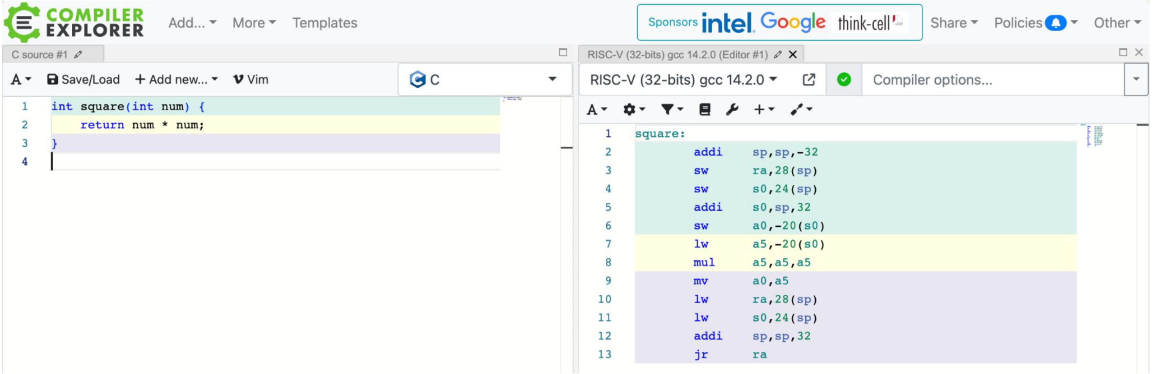
You'll do this in lab traps!

```
Stack
                   .
                   .
      +->          .
      |   +-----------------+   |
      |   | return address  |   |
      |   |   previous fp ------+
      |   | saved registers |
      |   | local variables |
      |   |       ...       | <-+
      |   +-----------------+   |
      |   | return address  |   |
      +------ previous fp   |   |
          | saved registers |   |
          | local variables |   |
      +-> |       ...       |   |
      |   +-----------------+   |
      |   | return address  |   |
      |   |   previous fp ------+
      |   | saved registers |
      |   | local variables |
      |   |       ...       | <-+
      |   +-----------------+   |
      |   | return address  |   |
      +------ previous fp   |   |
          | saved registers |   |
          | local variables |   |
  $fp --> |       ...       |   |
          +-----------------+   |
          | return address  |   |
          |   previous fp ------+
          | saved registers |
  $sp --> | local variables |
          +-----------------+
```

Resources

Resources

[Godbolt]



GDB

```
0x0000000000001000 in ?? ()
(gdb) b syscall
Breakpoint 1 at 0x80001c16: file kernel/syscall.c, line
160.
(gdb) c
Continuing.
[Switching to Thread 1.2]

Thread 2 hit Breakpoint 1, syscall () at kernel/syscall.
c:160
warning: Source file is more recent than executable.
160     {
```

[6.191 RISC-V ISA Reference Card]