Compiling Code, and Implementing Procedures

Silvina's office hours:

- Held weekly in lab
- Send email to sign up

Unconditional Control Instructions: Jumps

- jal: Unconditional jump and link
  - Example: `jal x3, label`
  - Jump target specified as label
  - label is encoded as an offset from current instruction
  - Link: is stored in x3

type of instruction

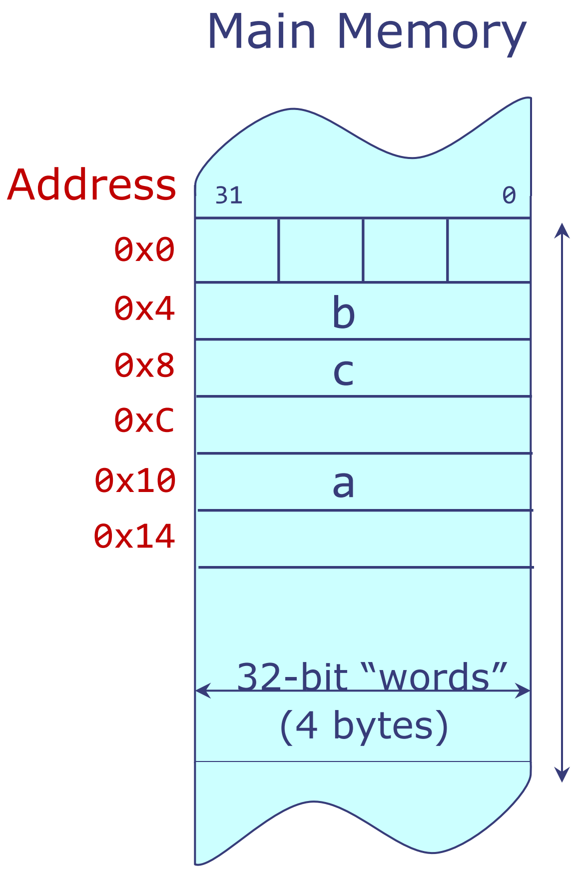
31 … 12	11 … 7	6 … 0
20 bit immediate	dest	1101111

- jalr: Unconditional jump via register and link
  - Example: `jalr x3, 4(x1)`
  - Jump target specified as register value plus constant offset
  - Example: Jump target = x1 + 4
  - Can jump to any 32 bit address – supports long jumps

Performing Computations on Values in Memory

a = b + c

```
b: x1 ← load(Mem[0x4])
c: x2 ← load(Mem[0x8])
x3 ← x1 + x2
a: store(Mem[0x10]) ← x3
```



RISC-V Load and Store Instructions

- Address is specified as a <base address, offset> pair;
  - base address is always stored in a register
  - the offset is encoded as a 12 bit constant in the instruction
  - Format: lw dest, offset(base)   sw src, offset(base)

- Assembly:

```
lw x1, 0x4(x0)
lw x2, 0x8(x0)
add x3, x1, x2
sw x3, 0x10(x0)
```

- Behavior:

```
x1 ← load(Mem[x0 + 0x4])
x2 ← load(Mem[x0 + 0x8])
x3 ← x1 + x2
store(Mem[x0 + 0x10]) ← x3
```

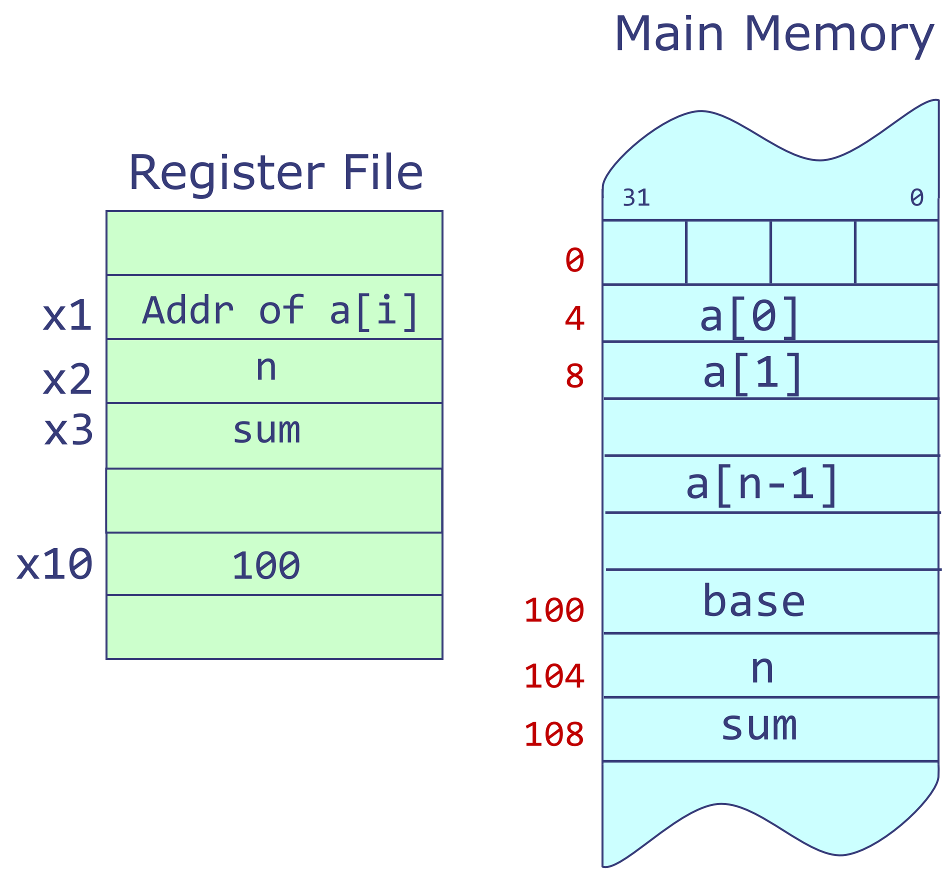
Program to sum array elements

sum = a[0] + a[1] + a[2] + ... + a[n-1]

(Assume 100 (address of base) already loaded into x10)

```
   lw x1, 0x0(x10)
   lw x2, 0x4(x10)
   add x3, x0, x0
loop:
   lw x4, 0x0(x1)
   add x3, x3, x4
   addi x1, x1, 4
   addi x2, x2, -1
   bnez x2, loop

   sw x3, 0x8(x10)
```



Pseudoinstructions

- Aliases to other actual instructions to simplify assembly programming.

Pseudoinstruction:	Equivalent Assembly Instruction:
`mv x2, x1`	`addi x2, x1, 0`
`ble x1, x2, label`	`bge x2, x1, label`
① `li x2, 3` (小于12bit的数)	`addi x2, x0, 3`
② `li x3, 0x4321` (大于12bit)	1° `lui x3, 0x4` ⇔ x3 = 0x4000
	2° `addi x3, x3, 0x321`

0x4321

lui ← 0100 | 0011 0010 0001 | → 12bit load in imm

Registers vs Memory

```
add x1, x2, x3
```
x1 = 0x1C

```
mv x4, x3
```
x4 = 0x14

```
lw x5, 0(x3)
```
x5 = 0x23 0x14在内存中是0x23

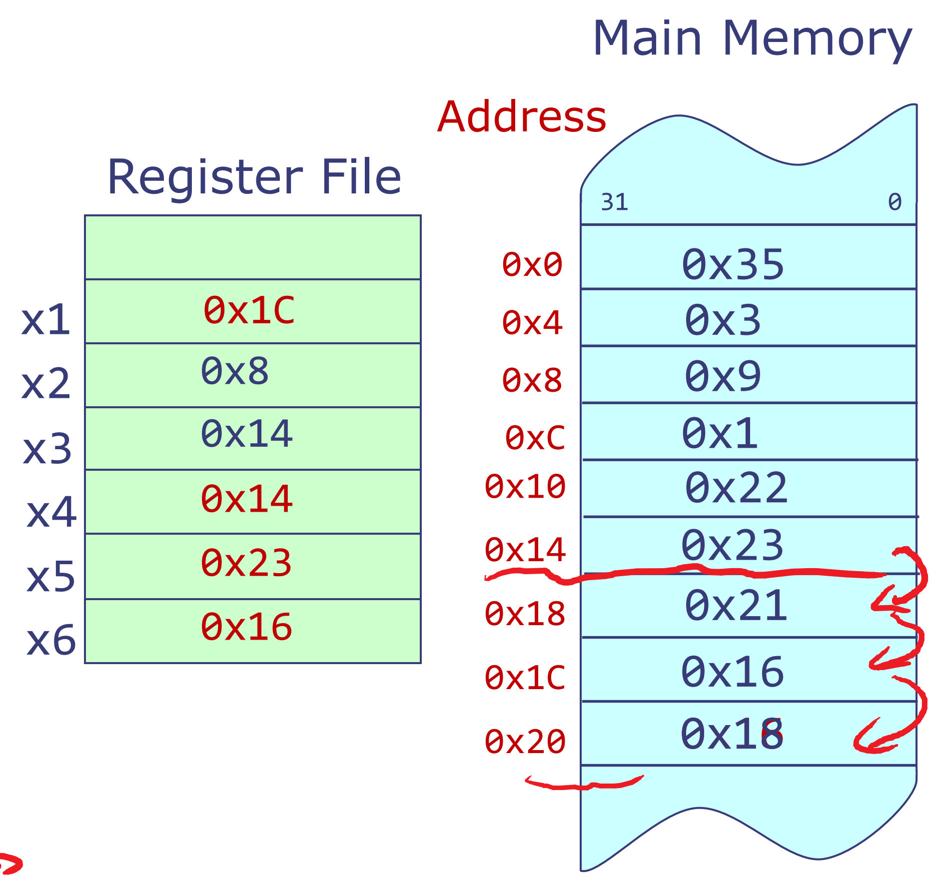
```
lw x6, 8(x3)
```
x6 = 0x16

```
sw x6, 0xC(x3)
```

value of x6 (0x16)
is written to M[0x14+0xC]

0x20

0xC → 0x4 x3 →



Compiling Simple Expressions

- Assign variables to registers
- Translate operators into computational instructions
- Use register-immediate instructions to handle operations with small constants
- Use the `li` pseudoinstruction for large constants

Example C code

```c
int x, y, z;
…
y = (x + 3) | (y + 123456);
z = (x * 4) ^ y;
```

xor

RISC-V Assembly

```
// x: x10, y: x11, z: x12
// x13, x14 used for temporaries
addi x13, x10, 3
li x14, 123456
add x14, x11, x14
or x11, x13, x14
slli x13, x10, 2
xor x12, x13, x11
```

非常大，如果想要Lui则需分两步

or y

Compiling Conditionals

- *if* statements can be compiled using branches:

C code

```
if (expr) {
  if-body
}
```

RISC-V Assembly

```
  (compile expr into xN)
  beqz xN, endif
  (compile if-body)
endif:
```

- *Example: Compile the following C code*

```
int x, y;
…
if (x < y) {
  y = y - x;
}
```

set less than

```
  // x: x10, y: x11
  slt x12, x10, x11
  beqz x12, endif
  sub x11, x11, x10
endif:
```

We can sometimes combine *expr* and the branch

```
  bge x10, x11, endif
  sub x11, x11, x10
endif:
```

Compiling Conditionals

- *if-else* statements are similar:

C code

```
if (expr) {
    if-body
} else {
    else-body
}
```

RISC-V Assembly

```
  (compile expr into xN)
  beqz xN, else
  (compile if-body)
  j endif
else:
  (compile else-body)
endif:
```

Compiling Loops

- Loops can be compiled using *backward* branches:

C code

```
while (expr) {
  while-body
}
```

RISC-V Assembly

```
while:
  (compile expr into xN)
  beqz xN, endwhile
  (compile while-body)
  j while
endwhile:
```

```
  // Version with one branch
  // or jump per iteration
  j compare
loop:
  (compile while-body)
compare:
  (compile expr into xN)
  bnez xN, loop
```

- *Can you write a version that executes fewer instructions?*

Do while

Putting it all together

C code

```
while (x != y) {
    if (x > y) {
        x = x - y;
    } else {
        y = y - x;
    }
}
```

RISC-V Assembly

```
// x: x10, y: x11
j compare
loop:
  (compile while-body)
compare:
      bne x10, x11, loop
```

Putting it all together

C code

```
while (x != y) {
   if (x > y) {
      x = x - y;
    } else {
      y = y - x;
    }
}
```

RISC-V Assembly

```
// x: x10, y: x11
j compare
loop:
  ble x10, x11, else
  sub x10, x10, x11
  j endif
else:
  sub x11, x11, x10
endif:
compare:
     bne x10, x11, loop
```

Procedures

C code

```c
int gcd(int a, int b)
{
  int x = a;
  int y = b;
  while (x != y) {
   if (x > y) {
      x = x - y;
    } else {
      y = y - x;
    }
  }
  return x;
}
```

RISC-V Assembly

```
// x: x10, y: x11
j compare
loop:
  ble x10, x11 else
  sub x10, x10, x11
  j endif
else:
  sub x11, x11, x10
endif:
compare:
      bne x10, x11, loop
```

Procedures

Just a lable

子程序

- Procedure (a.k.a. function or subroutine): Reusable code fragment that performs a specific task
  - Single named entry point
  - Zero or more formal arguments
  - Local storage
  - Returns to the caller when finished

```
int gcd(int a, int b) {
  int x = a;
  int y = b;
  while (x != y) {
   if (x > y) {
      x = x - y;
    } else {
      y = y - x;
    }
  }
  return x;
}
```

- Using procedures enables abstraction and reuse
  - Compose large programs from collections of simple procedures

```
bool coprimes(int a, int b) {
  return gcd(a, b) == 1;
}

coprimes(5, 10); // false
coprimes(9, 10); // true
```

Arguments and return values

调用者　　　　　　　传参　　　　　　　　　　　　　被调用

- A caller needs to pass arguments to the called procedure, as well as get results back from the called procedure
  - Both are done through registers

- A calling convention specifies rules for register usage across procedures
- RISC-V calling convention gives symbolic names to registers x0-x31 to denote their role:

argument register

Symbolic name	Registers	Description
a0 to a7	x10 to x17	Function arguments
a0 and a1	x10 and x11	Function return values

Calling procedures

- A procedure can be called from many different places
  - The caller can get to the called procedure code simply by executing an unconditional jump instruction
  - However, to return to the correct place in the calling procedure, the called procedure has to know which of the possible return addresses it should use

```
        …
[0x100] j sum
        …
[0x678] j sum
        …

sum:
        …
        j ?

0x104?
0x67C?
```

procedures

返回地址

Return address must be saved and passed to the called procedure!

Procedure Linking

- How to transfer control to callee and back to caller?

  `proc_call: jal ra, label`

  1. Stores address of proc_call + 4 in register ra (return address register)
  2. Jumps to instruction at address label where label is the name of the procedure
  3. After executing procedure, `jr ra` to return to caller and continue execution

```
        …
[0x100] jal ra, sum
        …
[0x678] jal ra, sum
        …
```

ra = 0x104

ra = 0x67C

```
sum:
    …
    jr ra
```

1st time: jump to 0x104

2nd time: jump to 0x67C

Managing a procedure's register space

同一套 register

- A caller uses the same $\boxed{\text{register set}}$ as the called procedure
  - A caller should not rely on how the called procedure manages its register space
  - Ideally, procedure implementation should be able to use all registers → to be shared
- Either the caller or the callee saves the caller's registers in memory and restores them when the procedure call has completed execution

term of procedure

Calling Convention

调用规则

- RISC-V calling convention gives symbolic names to registers x0-x31 to denote their role:

temporily

非易失性寄存器

确保数据不被破坏

Symbolic name	Registers	Description	Saver
a0 to a7	x10 to x17	Function arguments	Caller
a0 and a1	x10 and x11	Function return values	Caller
ra	x1	Return address	Caller
t0 to t6	x5-7, x28-31	Temporaries	Caller
s0 to s11	x8-9, x18-27	Saved registers	Callee
sp	x2	Stack pointer	Callee
gp	x3	Global pointer	---
tp	x4	Thread pointer	---
zero	x0	Hardwired zero	---

Procedure Storage Needs

- Basic requirements for procedure calls:
  - Input arguments
  - Return address
  - Results

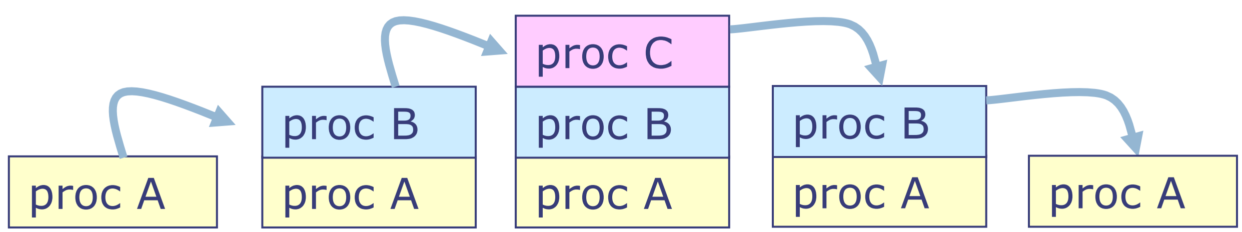
  Use registers for procedures arguments, return address, and results.

- Local storage:
  - Variables that compiler can't fit in registers
  - Space to save register values according to the calling convention (e.g., s registers that procedure will overwrite)

  Each procedure call has its own instance of local storage known as the procedure's *activation record.*

Activation record and procedure calls

- An *Activation record* holds all storage needs of procedure that do not fit in registers
  - A new activation record is allocated in memory when a procedure is called
  - An activation record is deallocated at the time of the procedure exit
- Activation records are allocated in a stack manner (Last-In-First-Out)



- The current procedure's activation record (a.k.a. stack frame) is always at the top of the stack

Caller-Saved vs Callee-Saved Registers

- A caller-saved register is not preserved across function calls (callee can overwrite it)
  - If caller wants to preserve its value, it must save it on the stack before transferring control to the callee
  - argument registers (aN), return address (ra), and temporary registers (tN)

- A callee-saved register is preserved across function calls
  - If callee wants to use it, it must save its value on stack and restore it before returning control to the caller
  - Saved registers (sN), stack pointer (sp)

Thank you!

Next lecture:
Procedures, Stacks, and MMIO