Compiling Code, Procedures and Stacks

RISC-V Recap

- Computational Instructions executed by ALU
  - Register-Register: op dest, src1, src2
  - Register-Immediate: op dest, src1, const

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  - Unconditional: jal label and jalr register
  - Conditional: br_comp src1, src2, label

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- Loads and Stores
  - lw dest, offset(base)
  - sw src, offset(base)
  - Base is a register, offset is a small constant

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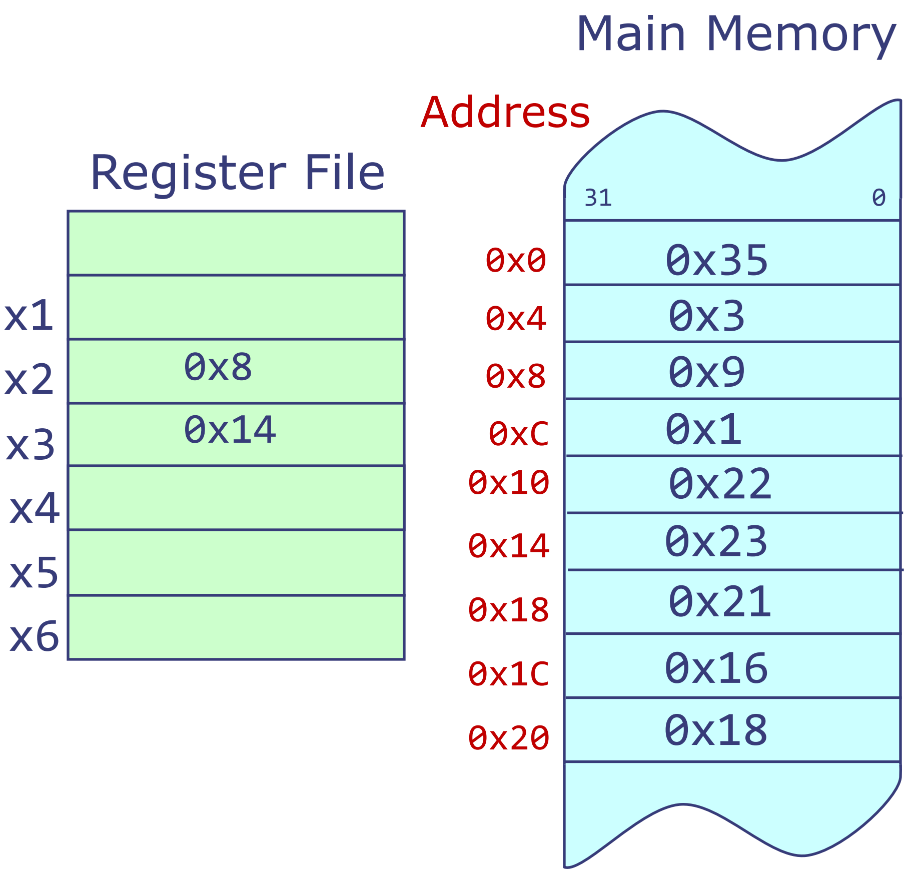
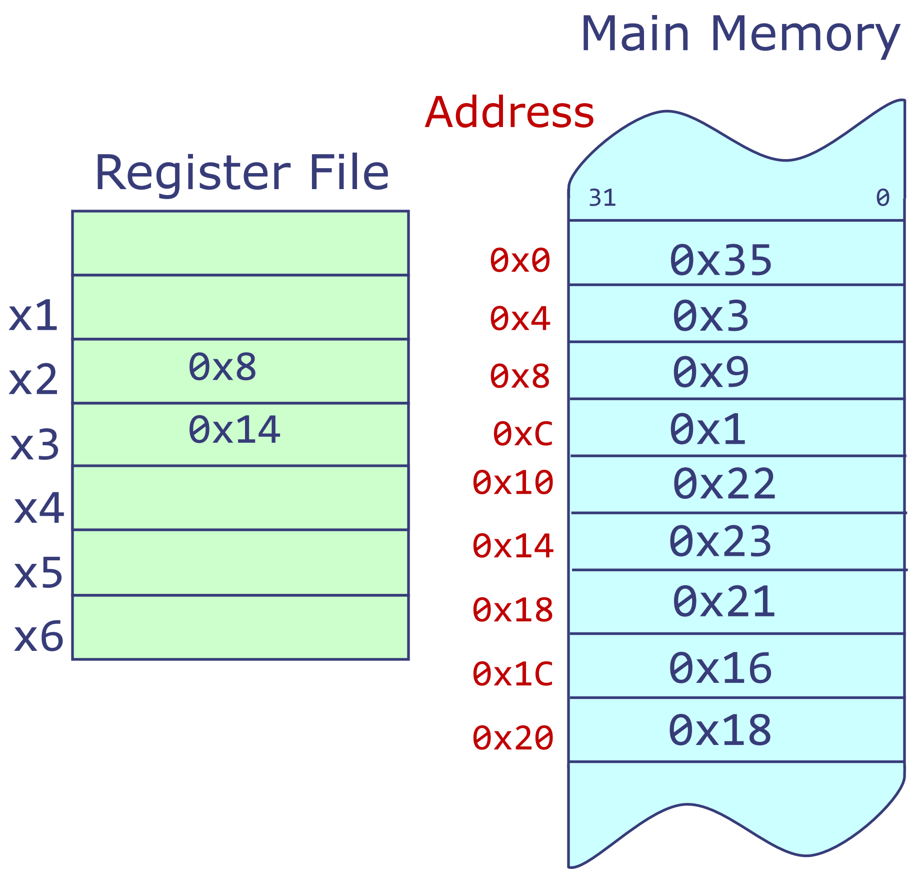
- Loads and Stores
  - lw dest, offset(base)
  - sw src, offset(base)
  - Base is a register, offset is a small constant
- Pseudoinstructions
  - Shorthand for other instructions

Registers vs Memory



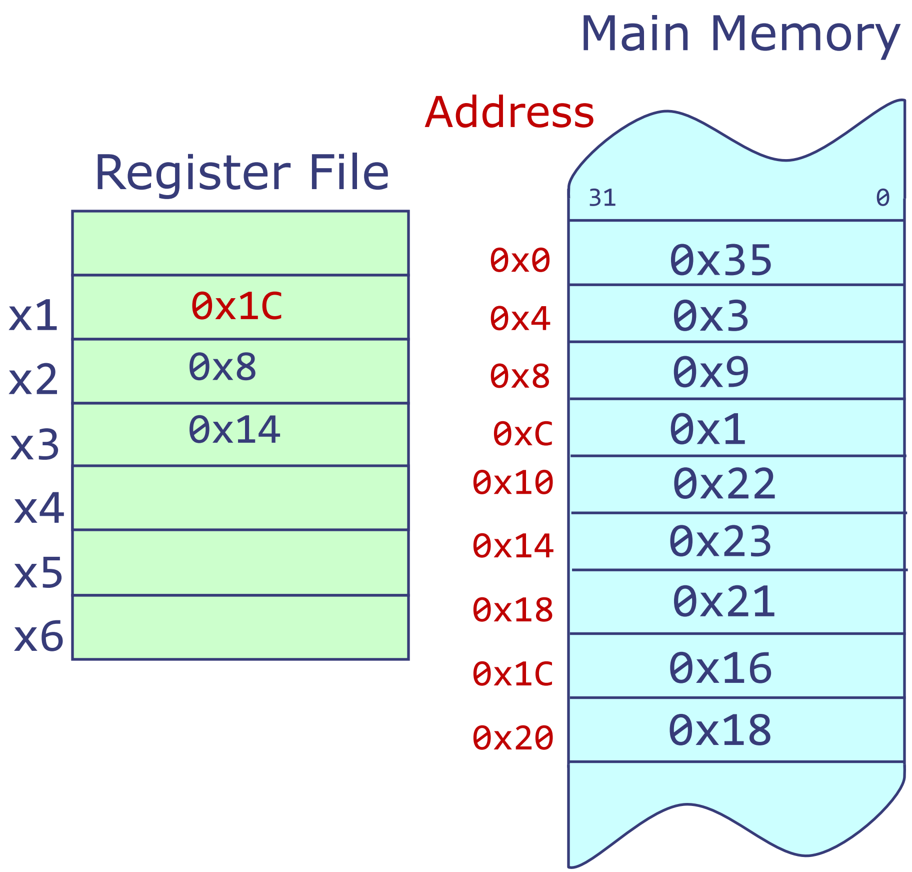
Registers vs Memory

```
add x1, x2, x3
    x1 =
```



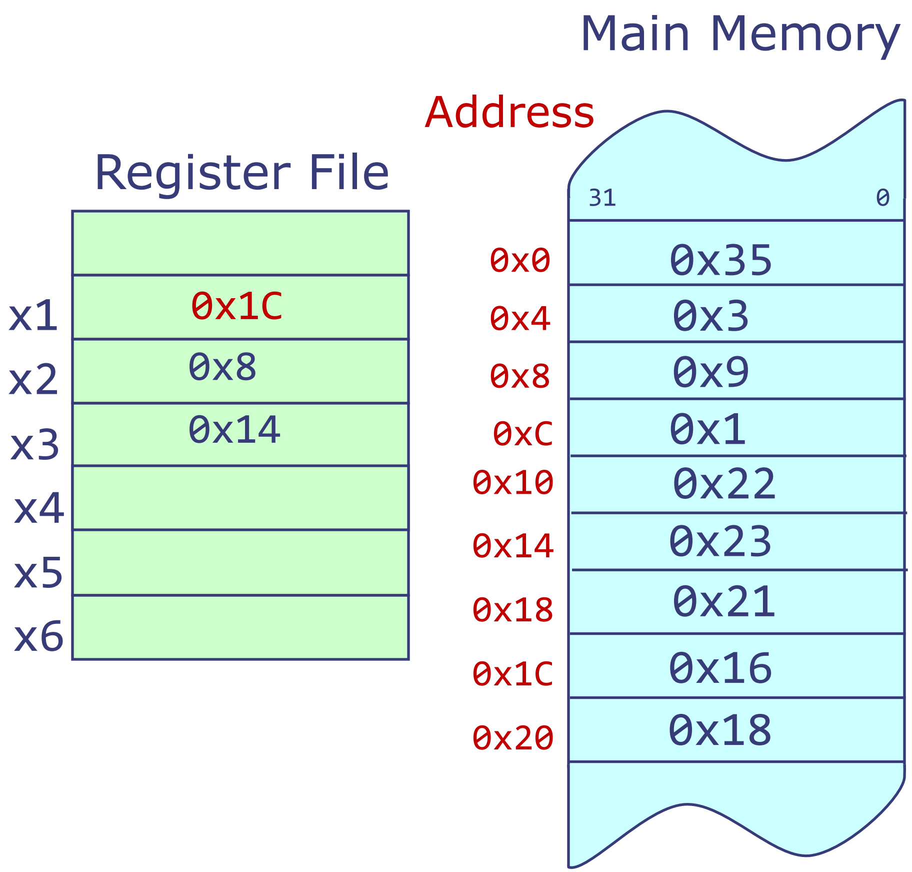
Registers vs Memory

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



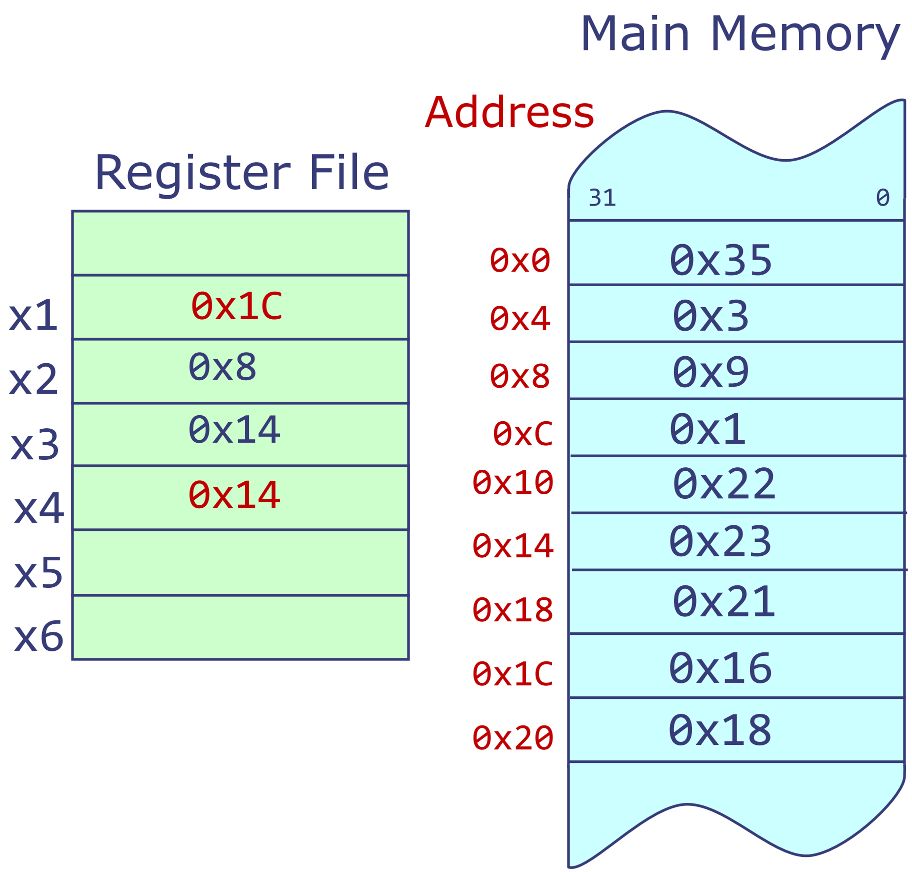
Registers vs Memory

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

mv x4, x3
    x4 =
```



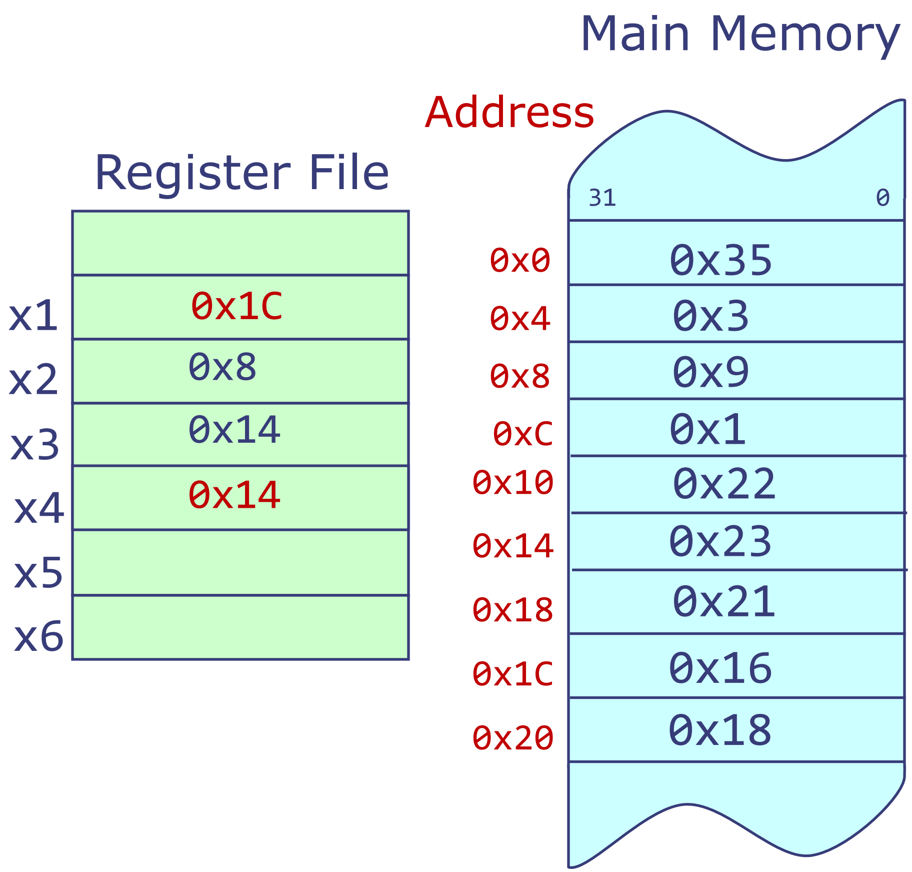
Registers vs Memory

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

mv x4, x3
    x4 = 0x14
```



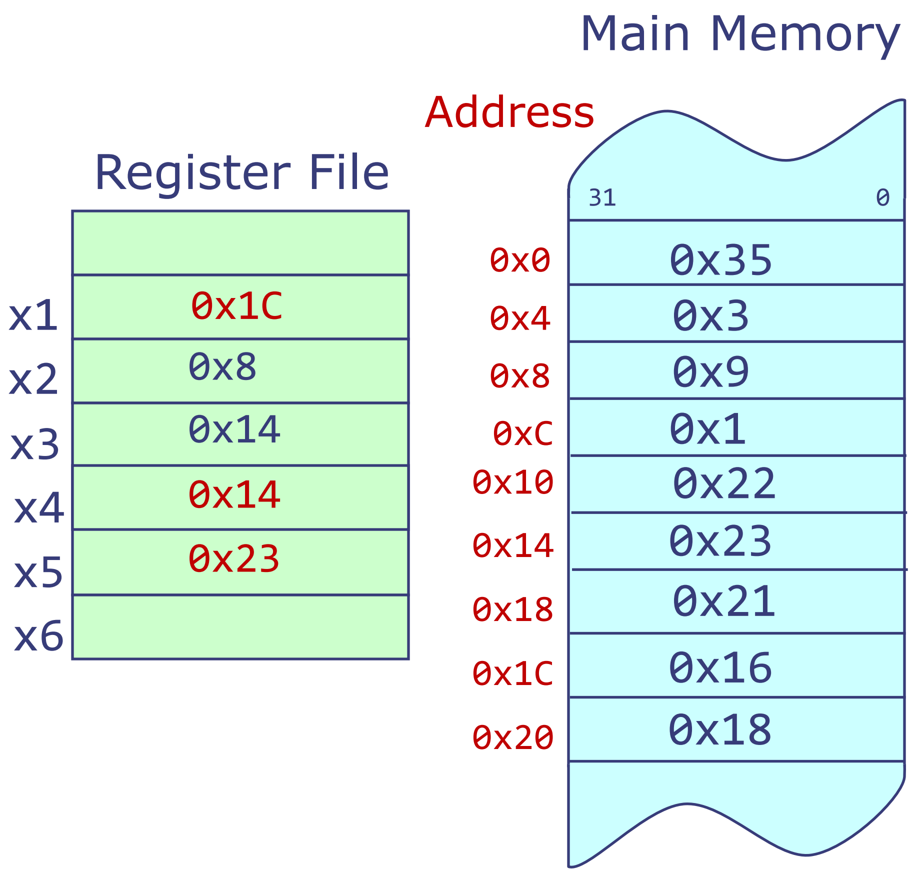
Registers vs Memory

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

mv x4, x3
    x4 = 0x14

lw x5, 0(x3)
    x5 =
```



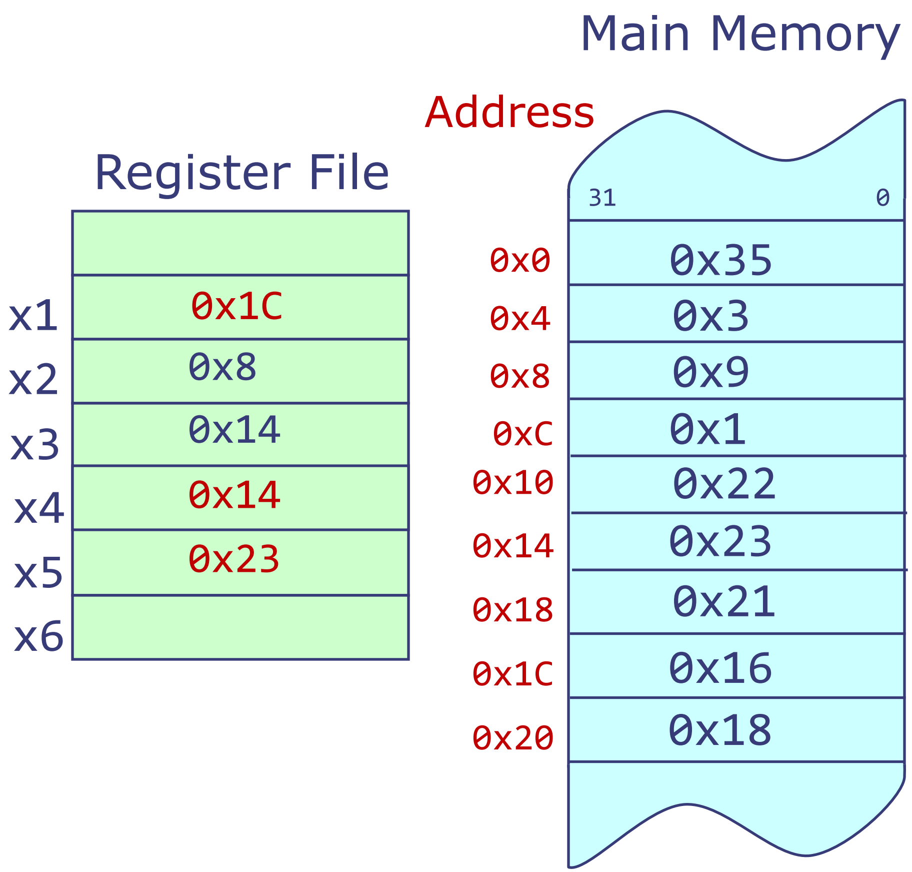
Registers vs Memory

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

mv x4, x3
    x4 = 0x14

lw x5, 0(x3)
    x5 = 0x23
```



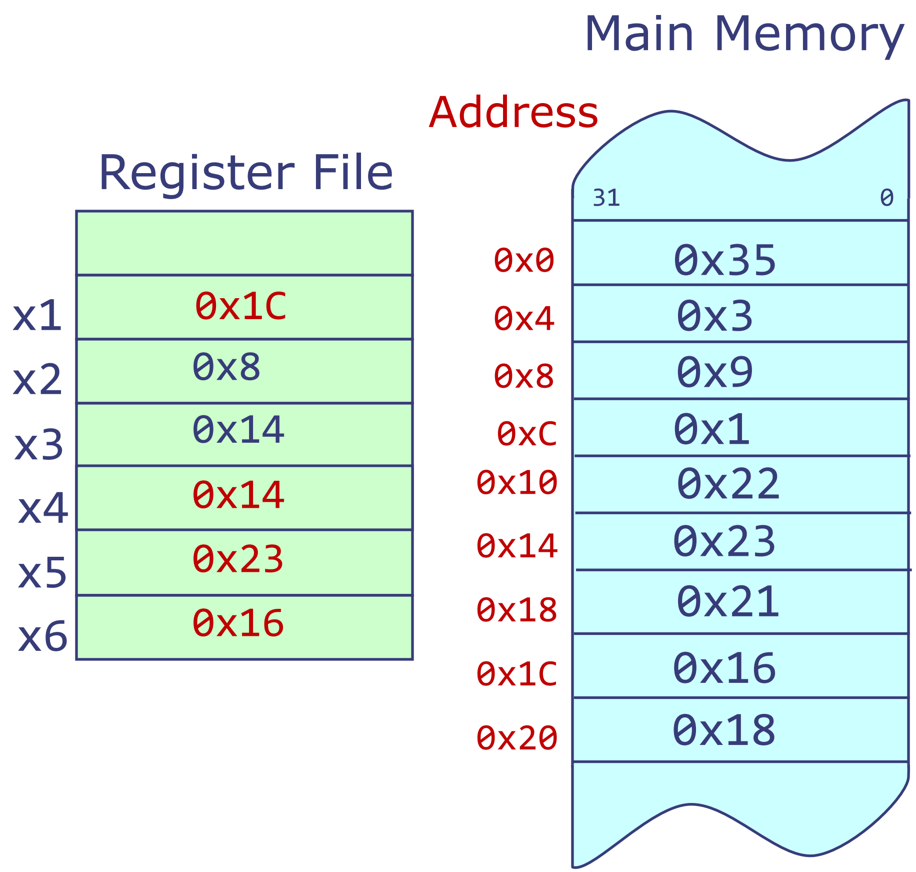
Registers vs Memory

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

mv x4, x3
    x4 = 0x14

lw x5, 0(x3)
    x5 = 0x23

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



Registers vs Memory

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

mv x4, x3
    x4 = 0x14

lw x5, 0(x3)
    x5 = 0x23

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



Registers vs Memory

```
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    x1 = 0x1C

mv x4, x3
    x4 = 0x14

lw x5, 0(x3)
    x5 = 0x23

lw x6, 8(x3)
    x6 = 0x16

sw x6, 0xC(x3)
```
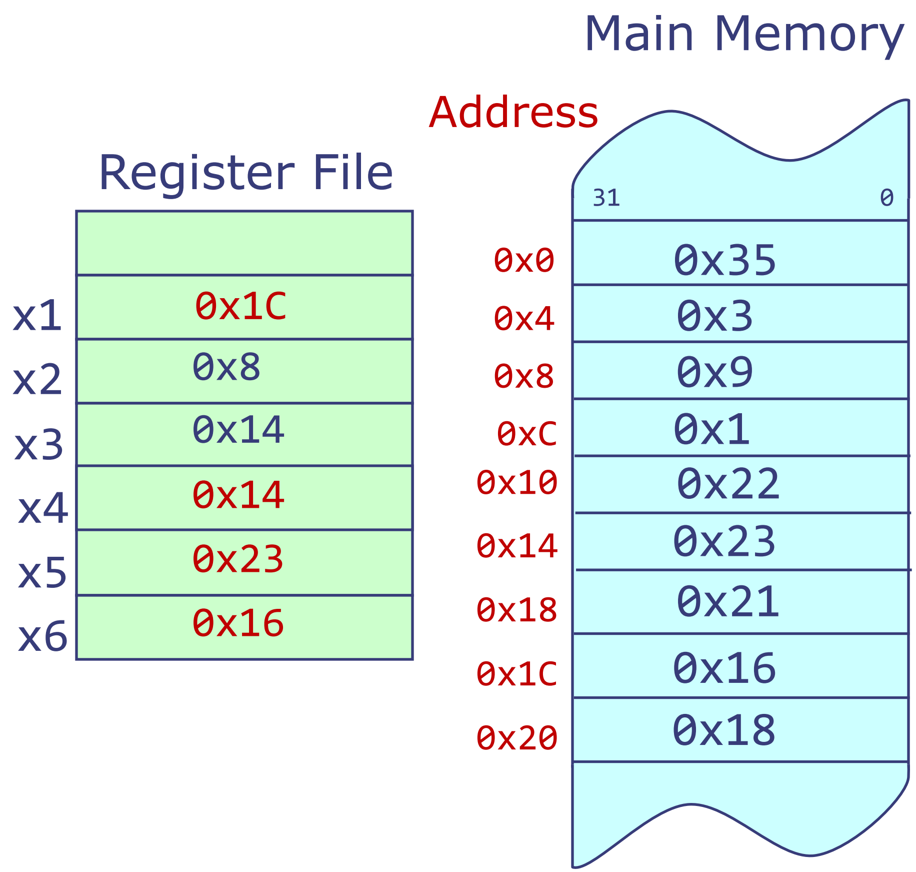
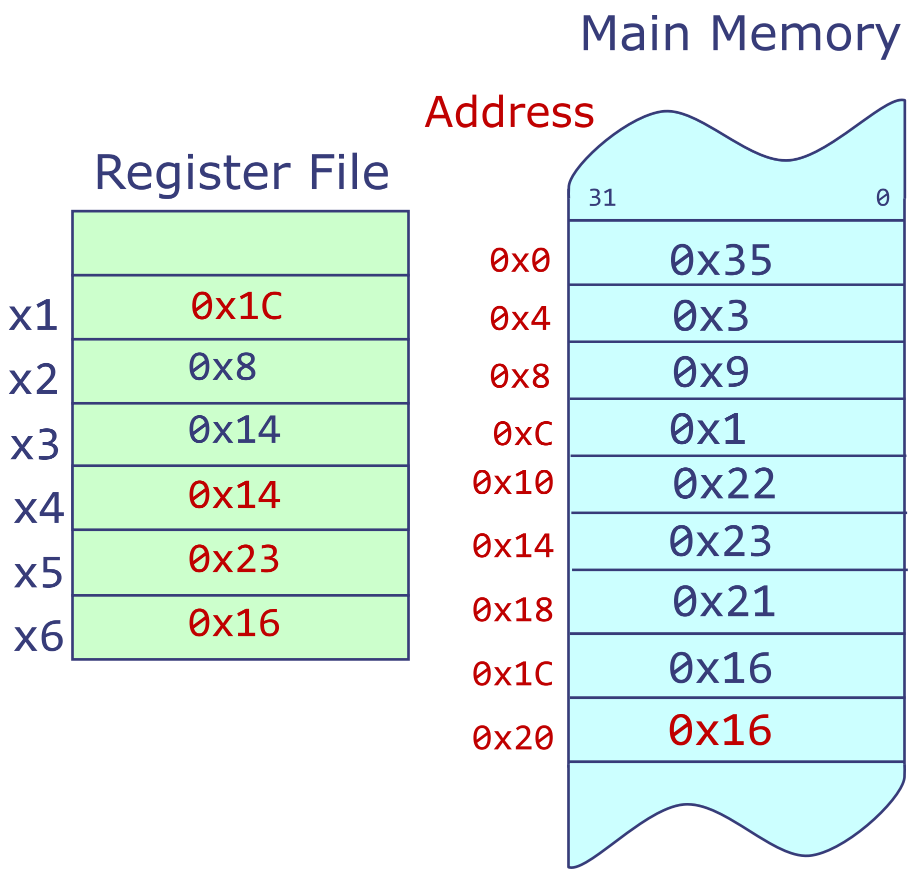



Registers vs Memory

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

mv x4, x3
    x4 = 0x14

lw x5, 0(x3)
    x5 = 0x23

lw x6, 8(x3)
    x6 = 0x16

sw x6, 0xC(x3)
value of x6 (0x16)
is written to M[0x14+0xC]
```



Dealing with Constants

- Execute `a = b+3`

Assume a is in register x1 and b is in x2.

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```
addi x1, x2, 3
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- Execute `a = b+0x123456`

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- Execute `a = b+0x123456`
  - Largest 12 bit 2's complement constant is 2^{11}-1 = 2047 (0x7FF)
  - Use `li` pseudoinstruction to set register to large constant

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```
li x4, 0x123456
```

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```
li x4, 0x123456
```

```
lui x4, 0x123
addi x4, x4, 0x456
```

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`x4 = 0x123000`

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```
li x4, 0x123456
```

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lui x4, 0x123
addi x4, x4, 0x456
```

x4 = 0x123000

  - Can also use `li` pseudoinstruction for small constants

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- Execute `a = b+0x123456`
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```
li x4, 0x123456
```

```
lui x4, 0x123
addi x4, x4, 0x456
```

`x4 = 0x123000`

  - Can also use `li` pseudoinstruction for small constants

```
li x4, 0x12
```

```
addi x4, x0, 0x12
```

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

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

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RISC-V Assembly

```
// x: x10, y: x11, z: x12
// x13, x14 used for temporaries
```

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// x13, x14 used for temporaries
addi x13, x10, 3
```

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```
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// x13, x14 used for temporaries
addi x13, x10, 3
li x14, 123456
add x14, x11, x14
```

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RISC-V Assembly

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// x13, x14 used for temporaries
addi x13, x10, 3
li x14, 123456
add x14, x11, x14
```

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```

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
```

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add x14, x11, x14
or x11, x13, x14
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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
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add x14, x11, x14
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slli x13, x10, 2
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```
// 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
```

Compiling Conditionals

- *if* statements can be compiled using branches:

C code	RISC-V Assembly

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

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;
}
```

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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;          // x: x10, y: x11
…
if (x < y) {
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}
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Compiling Conditionals

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C code

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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;
}
```

```
// x: x10, y: x11
slt x12, x10, x11
```

Compiling Conditionals

- *if* statements can be compiled using branches:

C code

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

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

endif:
```

Compiling Conditionals

- *if* statements can be compiled using branches:

C code

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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;
}
```

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

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;
}
```

```
  // 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:
```

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:
```

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:
```

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

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:
```

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

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

Putting it all together

C code

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

RISC-V Assembly

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
```

Putting it all together

C code	RISC-V Assembly

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

```c
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

- Procedure (a.k.a. function or subroutine): Reusable code fragment that performs a specific task

```
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;
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```

Procedures

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

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

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

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

Managing a procedure's register space

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  - A caller should not rely on how the called procedure manages its register space
  - Ideally, procedure implementation should be able to use all registers
- Either the caller or the callee saves the caller's registers in memory and restores them when the procedure call has completed execution

Implementing procedures

- 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

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        …
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        …
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        …
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0x67C?

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```
0x104?
0x67C?
```

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)

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        …
[0x100] jal ra, sum
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      …
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ra = 0x104

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ra = 0x67C

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1st time: jump to 0x104

2nd time: jump to 0x67C

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ra = 0x67C

```
sum:
      …
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```

1st time: jump to 0x104

2nd time: jump to 0x67C

Procedure calls: Complications

- Suppose proc A calls proc B calls proc C
  - a single return address register won't work; the return address for proc B would wipe out the return address for proc A!
  - a similar complication arises in the memory space where the registers of proc A are saved – this space has to be different from the place where the registers of proc B are saved

Procedure Storage Needs

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

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  - Input arguments
  - Return address
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  - Space to save caller’s register values for registers that we overwrite

Each procedure call has its own instance of all this data known as the procedure’s *activation record.*

Insight (ca. 1960): We Need a Stack!

- Need data structure to hold activation records

- Activation records are allocated and deallocated in last-in-first-out (LIFO) order

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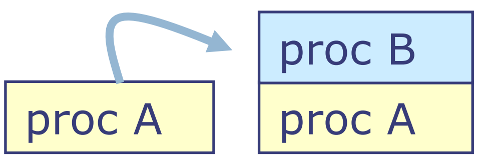

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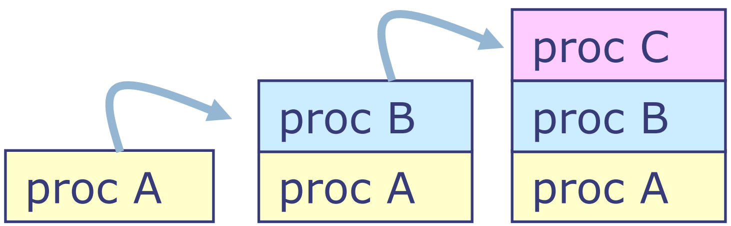

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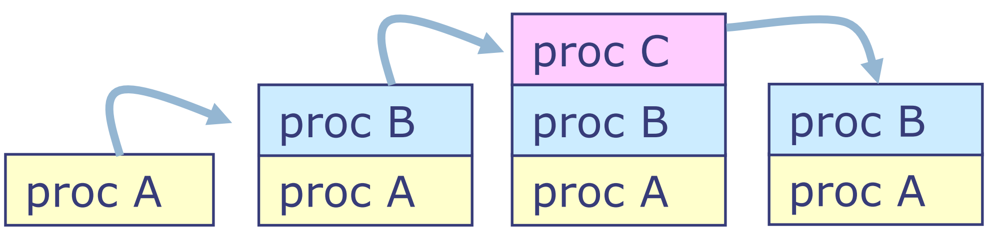

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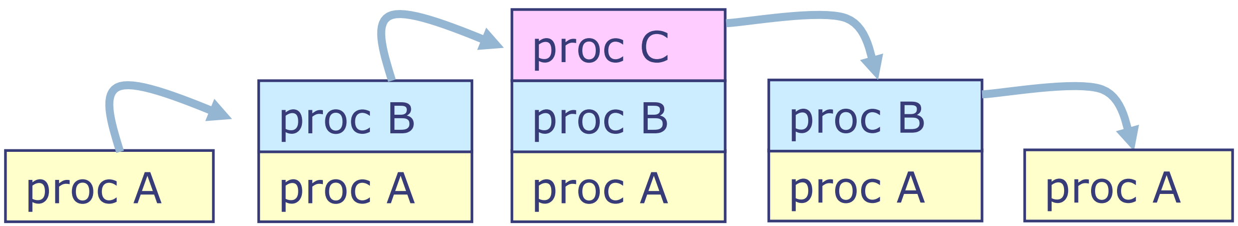

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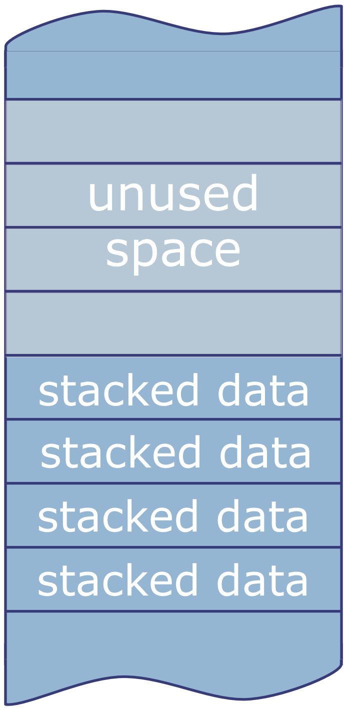
RISC-V Stack

- Stack is in memory → need a register to point to it
  - In RISC-V, stack pointer `sp` is `x2`

Lower Addresses



Higher Addresses

RISC-V Stack

- Stack is in memory → need a register to point to it
  - In RISC-V, stack pointer `sp` is `x2`
- Stack grows down from higher to lower addresses
  - Push decreases `sp`
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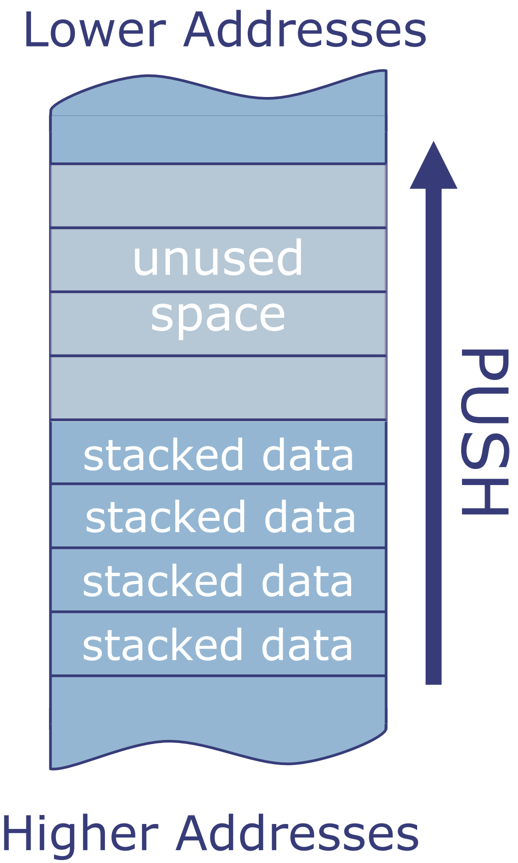

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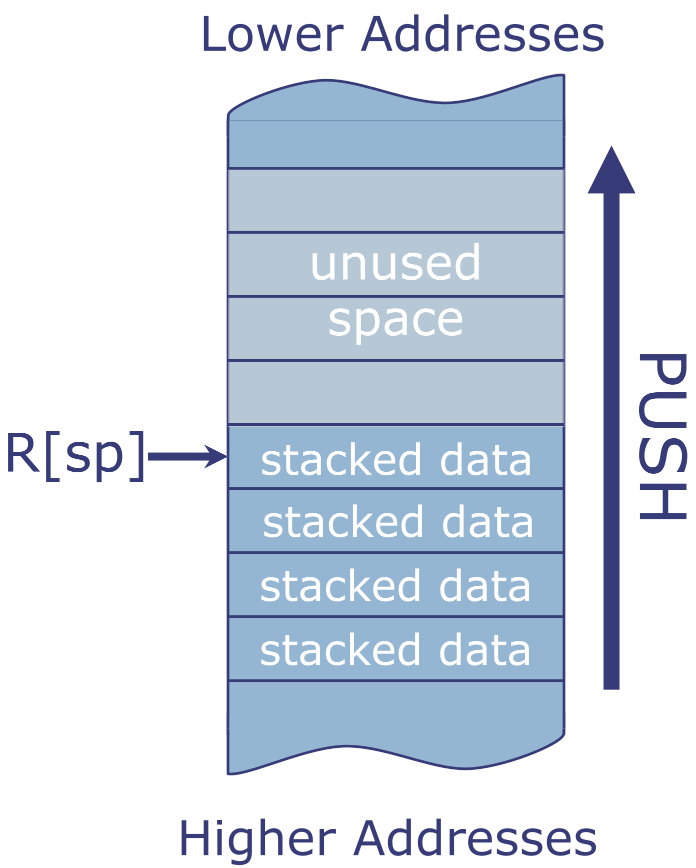

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- Stack grows down from higher to lower addresses
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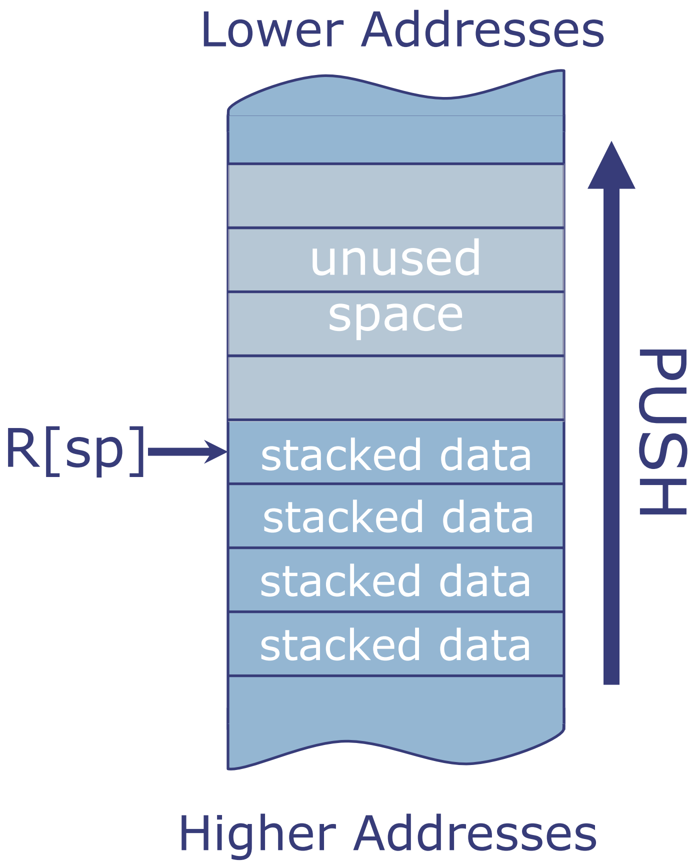
- `sp` points to top of stack (last pushed element)
- Discipline: Can use stack *at any time*, but leave it as you found it!



Using the stack

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Sample entry sequence

```
addi sp, sp, -8
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Corresponding Exit sequence

```
lw ra, 0(sp)
lw a0, 4(sp)
addi sp, sp, 8
```

Calling Convention

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tp	x4	Thread pointer	---
zero	x0	Hardwired zero	---

Caller-Saved vs Callee-Saved Registers

- A caller-saved register is not preserved across function calls (callee can overwrite it)
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  - Saved registers (sN), stack pointer (sp)

Example: Using callee-saved registers

- Implement `f` using `s0` and `s1` to store temporary values

```
int f(int x, int y) {
    return (x + 3) | (y + 123456);
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    addi s0, a0, 3
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    add s1, a1, s1
    or a0, s0, s1



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int f(int x, int y) {
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```
f:
  addi sp, sp, -8   // allocate 2 words (8 bytes) on stack
  sw s0, 4(sp)      // save s0
  sw s1, 0(sp)      // save s1
  addi s0, a0, 3
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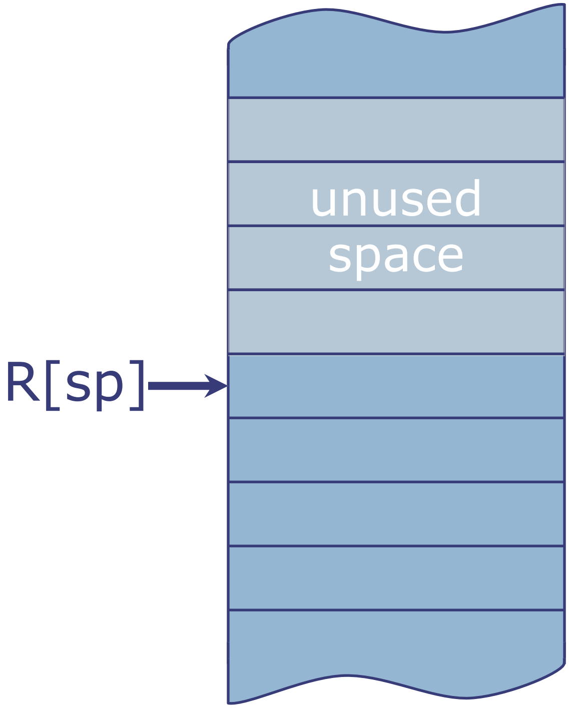
  or a0, s0, s1
  lw s1, 0(sp)      // restore s1
  lw s0, 4(sp)      // restore s0
  addi sp, sp, 8    // deallocate 2 words from stack
                    // (restore sp)
  ret
```

Example: Using callee-saved registers

- Stack contents:

Before call to `f`



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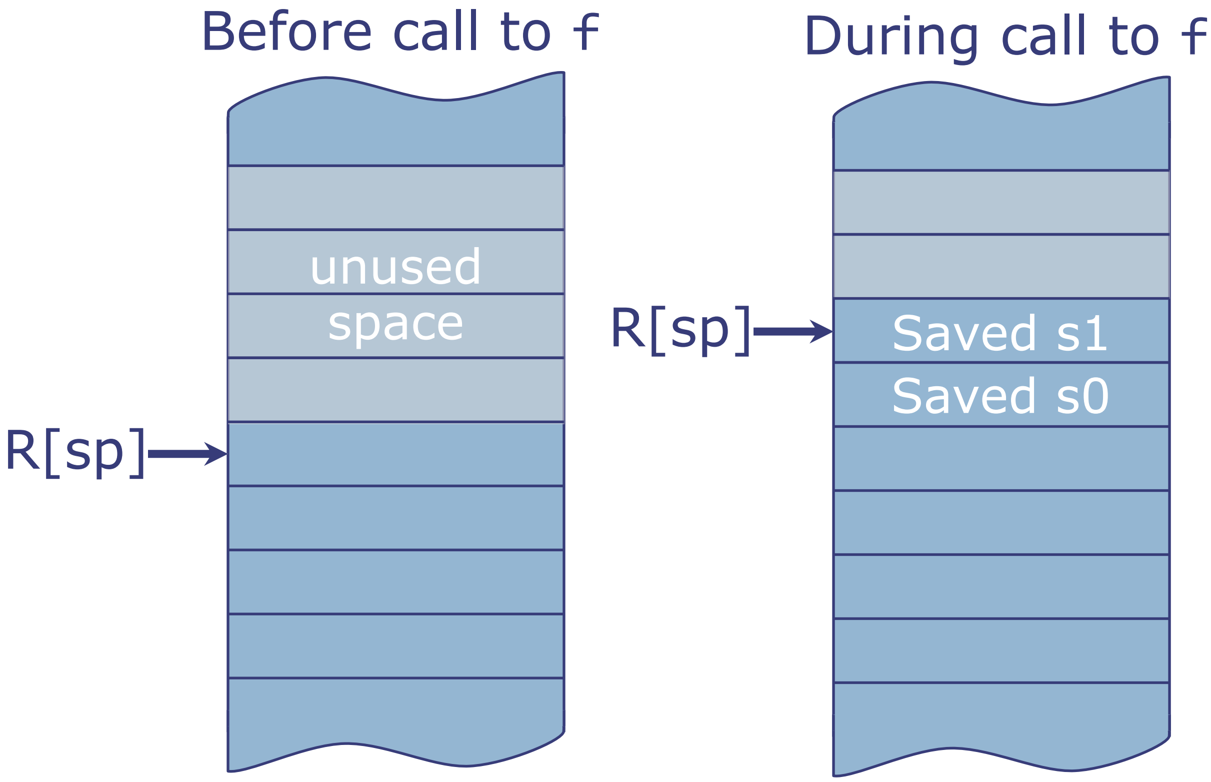

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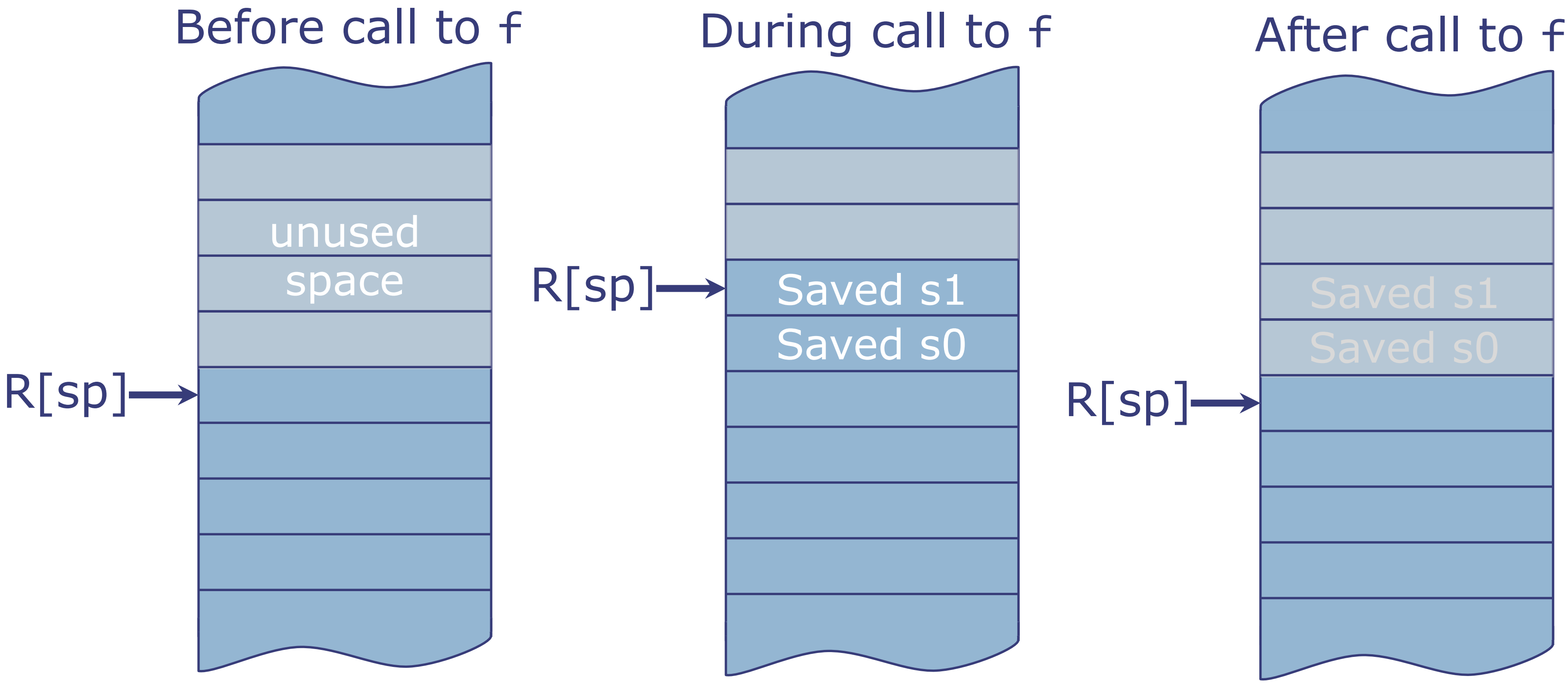

Example: Using caller-saved registers

Caller

```
int x = 1;
int y = 2;
int z = sum(x, y);
int w = sum(z, y);
```

Callee

```
int sum(int a, int b) {
    return a + b;
}
```

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int x = 1;
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li a0, 1
li a1, 2




jal ra, sum
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int sum(int a, int b) {
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```
sum:
  add a0, a0, a1
  ret
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Example: Using caller-saved registers

Caller

```
int x = 1;
int y = 2;
int z = sum(x, y);
int w = sum(z, y);

li a0, 1
li a1, 2
addi sp, sp, -8
sw ra, 0(sp)
sw a1, 4(sp) // save y
jal ra, sum
// a0 = sum(x, y)
```

Callee

```
int sum(int a, int b) {
    return a + b;
}

sum:
  add a0, a0, a1
  ret
```

Example: Using caller-saved registers

Caller

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int x = 1;
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int z = sum(x, y);
int w = sum(z, y);
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Callee

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Why did we save a1?

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Why did we save a1?

Callee may have modified a1 (caller doesn't see implementation of sum!)

Example: Using caller-saved registers

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int x = 1;
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// a0 = sum(x, y)
lw a1, 4(sp) // restore y
```

Callee

```
int sum(int a, int b) {
    return a + b;
}
```

```
sum:
  add a0, a0, a1
  ret
```

Why did we save a1?

Callee may have modified a1 (caller doesn't see implementation of sum!)

Example: Using caller-saved registers

Caller

```c
int x = 1;
int y = 2;
int z = sum(x, y);
int w = sum(z, y);
```

```
li a0, 1
li a1, 2
addi sp, sp, -8
sw ra, 0(sp)
sw a1, 4(sp) // save y
jal ra, sum
// a0 = sum(x, y)
lw a1, 4(sp) // restore y
jal ra, sum
// a0 = sum(z, y)
```

Callee

```c
int sum(int a, int b) {
    return a + b;
}
```

```
sum:
  add a0, a0, a1
  ret
```

Why did we save a1?

Callee may have modified a1 (caller doesn't see implementation of sum!)

Example: Using caller-saved registers

Caller

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int x = 1;
int y = 2;
int z = sum(x, y);
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addi sp, sp, -8
sw ra, 0(sp)
sw a1, 4(sp) // save y
jal ra, sum
// a0 = sum(x, y)
lw a1, 4(sp) // restore y
jal ra, sum
// a0 = sum(z, y)
lw ra, 0(sp)
addi sp, sp, 8
```

Callee

```
int sum(int a, int b) {
    return a + b;
}
```

```
sum:
  add a0, a0, a1
  ret
```

Why did we save a1?

Callee may have modified a1 (caller doesn't see implementation of sum!)

Thank you!

Next lecture:
More Procedures and MMIO