# Machine-level Representation of Programs

Jin-Soo Kim
(jinsoo.kim@snu.ac.kr)

Systems Software & Architecture Lab.

Seoul National University

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# RISC-V:
# Representing Instructions

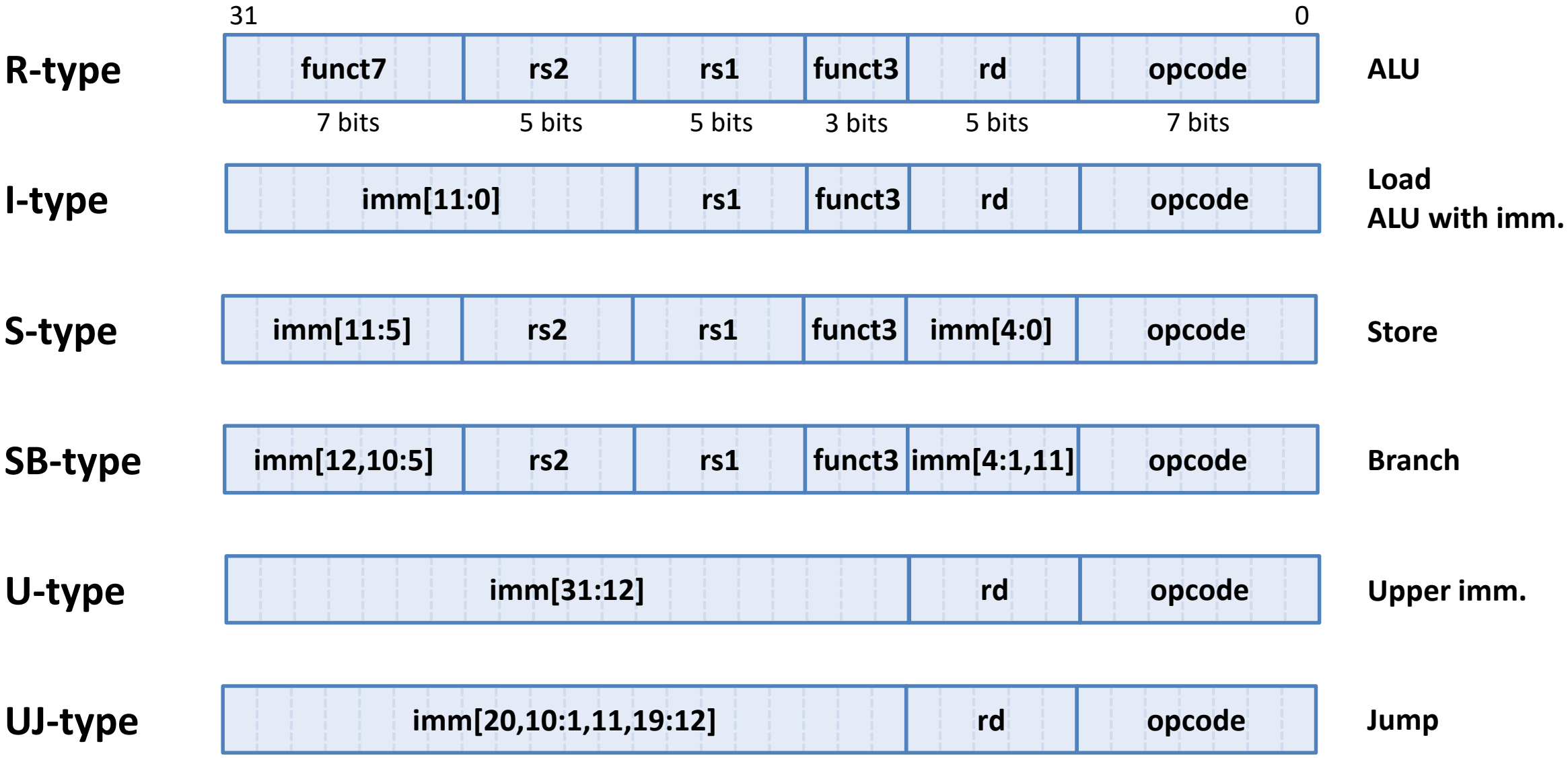
Chap. 2.5

# Representing Instructions

- Instructions are encoded in binary
  - Called machine code

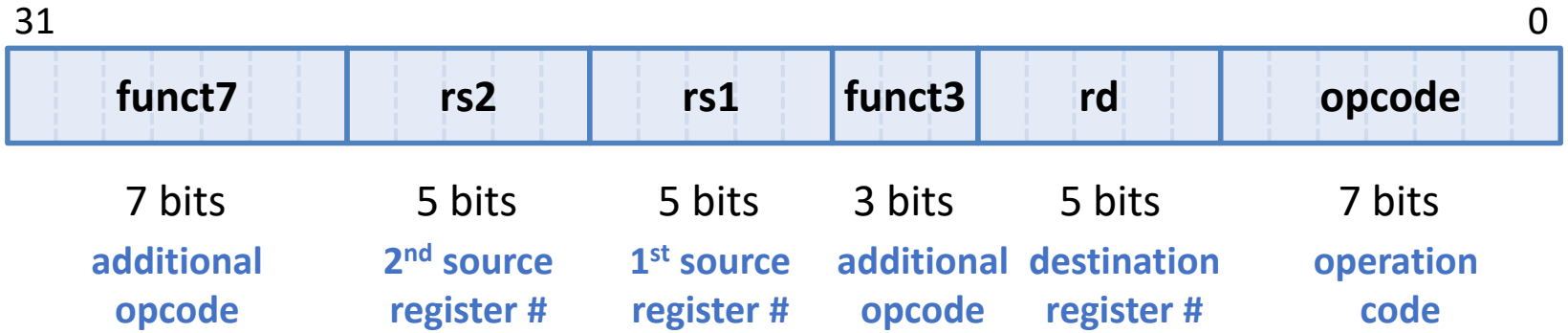
- RISC-V instructions
  - Encoded as 32-bit instruction words
  - Small number of formats encoding operation code (opcode), register numbers, …
  - Regularity!

# RISC-V Instruction Formats



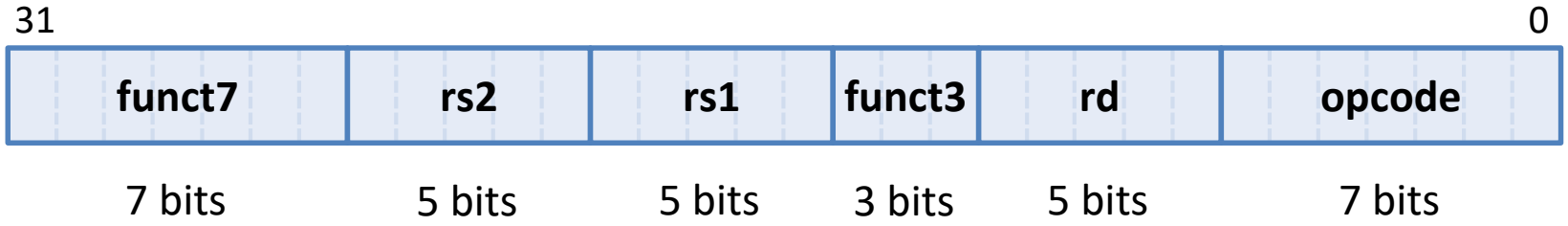
# RISC-V R-type Instructions

**R-type**

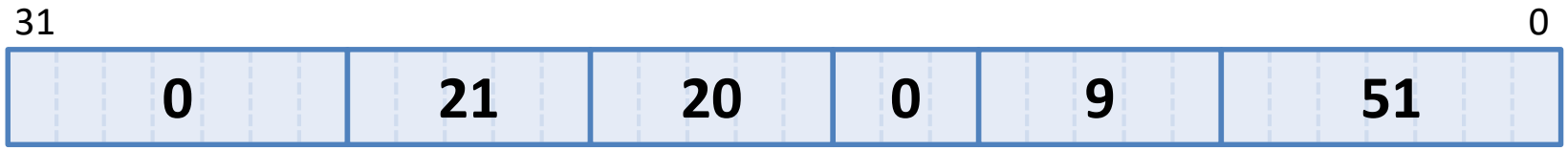


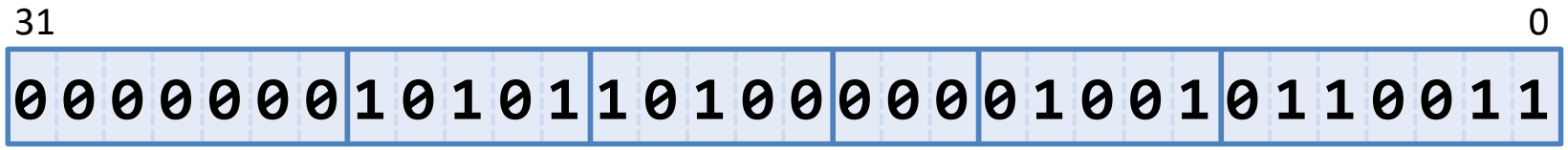

| Instruction | Type | Example | funct7 | funct3 | opcode |
|---|---|---|---|---|---|
| **add** | **R** | `add rd, rs1, rs2` | 0000000 | 000 | 0110011 |
| **sub** | **R** | `sub rd, rs1, rs2` | 0100000 | 000 | 0110011 |
| **sll** | **R** | `sll rd, rs1, rs2` | 0000000 | 001 | 0110011 |
| **slt** | **R** | `slt rd, rs1, rs2` | 0000000 | 010 | 0110011 |
| **sltu** | **R** | `sltu rd, rs1, rs2` | 0000000 | 011 | 0110011 |
| **xor** | **R** | `xor rd, rs1, rs2` | 0000000 | 100 | 0110011 |
| **srl** | **R** | `srl rd, rs1, rs2` | 0000000 | 101 | 0110011 |
| **sra** | **R** | `sra rd, rs1, rs2` | 0100000 | 101 | 0110011 |
| **or** | **R** | `or rd, rs1, rs2` | 0000000 | 110 | 0110011 |
| **and** | **R** | `and rd, rs1, rs2` | 0000000 | 111 | 0110011 |

# R-type Example

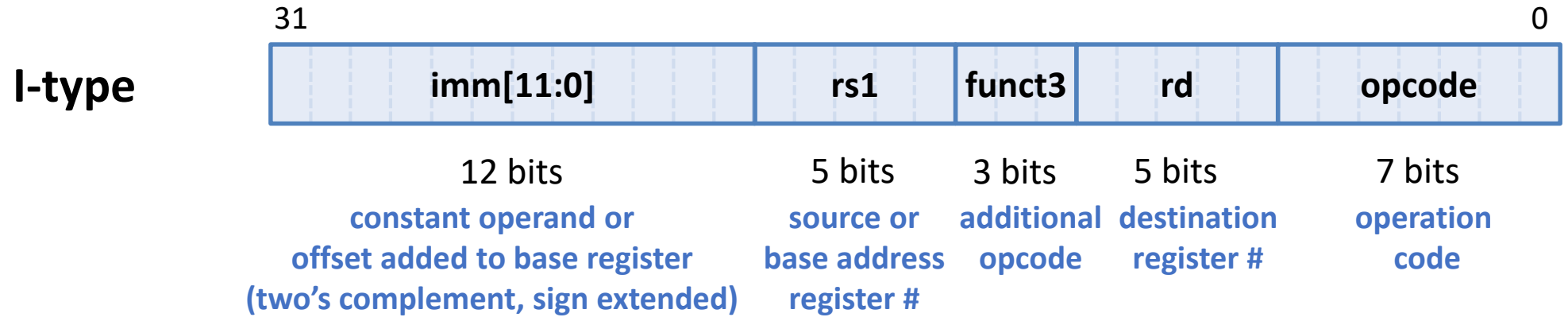



`add x9, x20, x21` == $015A04B3_{16}$



# RISC-V I-type Instructions



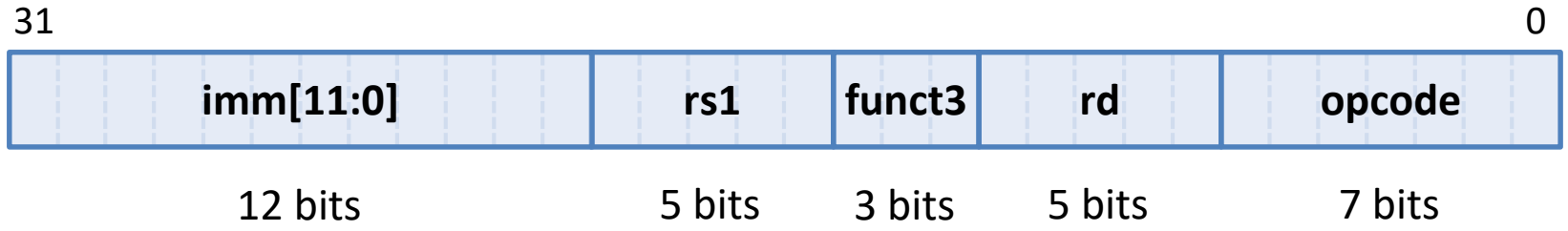

- Immediate arithmetic or load instructions

- Design Principle 3: Good design demands good compromises
  - Different formats complicate decoding, but allow 32-bit instructions uniformly
  - Keep formats as similar as possible

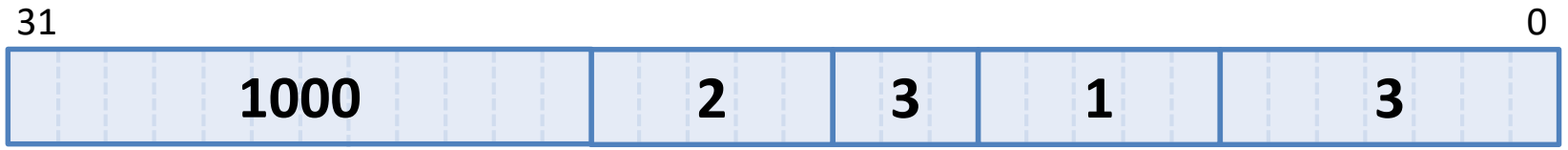
# RISC-V I-type Instructions (cont'd)

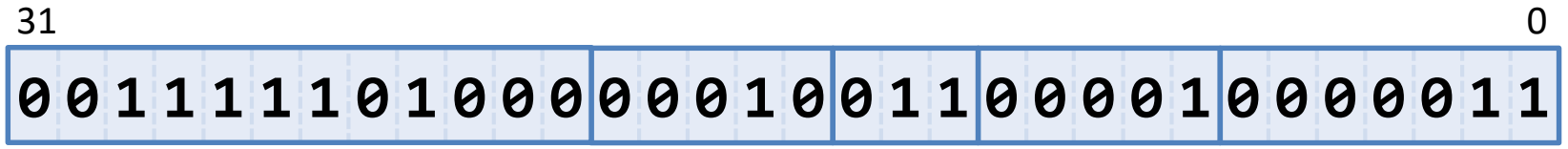
| Instruction | Type | Example | funct7 | funct3 | opcode |
|---|---|---|---|---|---|
| addi | I | addi rd, rs1, imm12 | - | 000 | 0010011 |
| slti | I | slti rd, rs1, imm12 | - | 010 | 0010011 |
| sltiu | I | sltiu rd, rs1, imm12 | - | 011 | 0010011 |
| xori | I | xori rd, rs1, imm12 | - | 100 | 0010011 |
| ori | I | ori rd, rs1, imm12 | - | 110 | 0010011 |
| andi | I | andi rd, rs1, imm12 | - | 111 | 0010011 |
| slli | I | slli rd, rs1, shamt | 000000 \| shamt | 001 | 0010011 |
| srli | I | srli rd, rs1, shamt | 000000 \| shamt | 101 | 0010011 |
| srai | I | srai rd, rs1, shamt | 010000 \| shamt | 101 | 0010011 |
| lb | I | lb rd, imm12(rs1) | - | 000 | 0000011 |
| lh | I | lh rd, imm12(rs1) | - | 001 | 0000011 |
| lw | I | lw rd, imm12(rs1) | - | 010 | 0000011 |
| ld | I | ld rd, imm12(rs1) | - | 011 | 0000011 |
| lbu | I | lbu rd, imm12(rs1) | - | 100 | 0000011 |
| lhu | I | lhu rd, imm12(rs1) | - | 101 | 0000011 |
| lwu | I | lwu rd, imm12(rs1) | - | 110 | 0000011 |
| jalr | I | jalr rd, imm12(rs1) | - | 000 | 1100111 |

# I-type Example

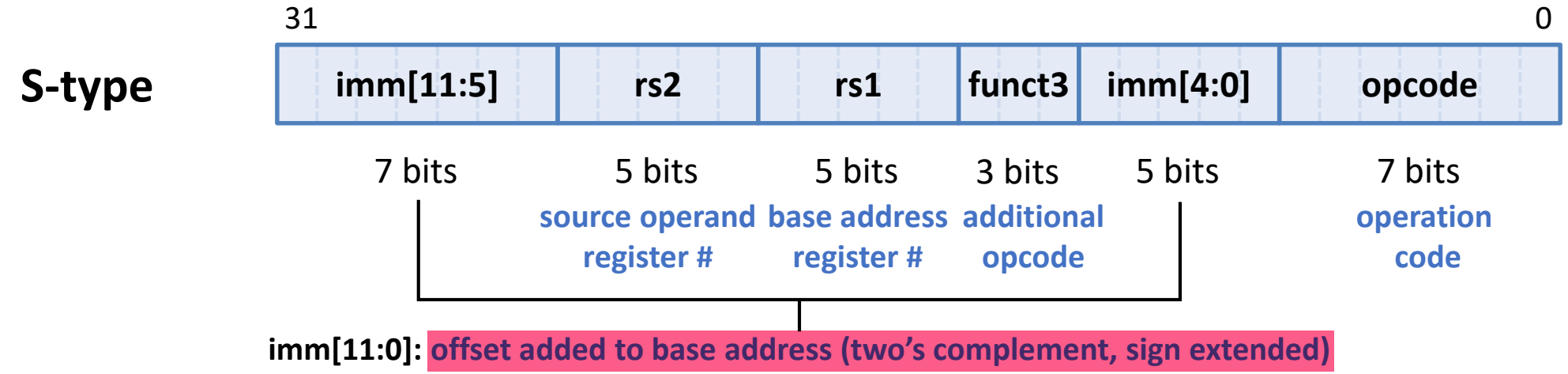



`ld x1, 1000(x2)` == $3E813083_{16}$



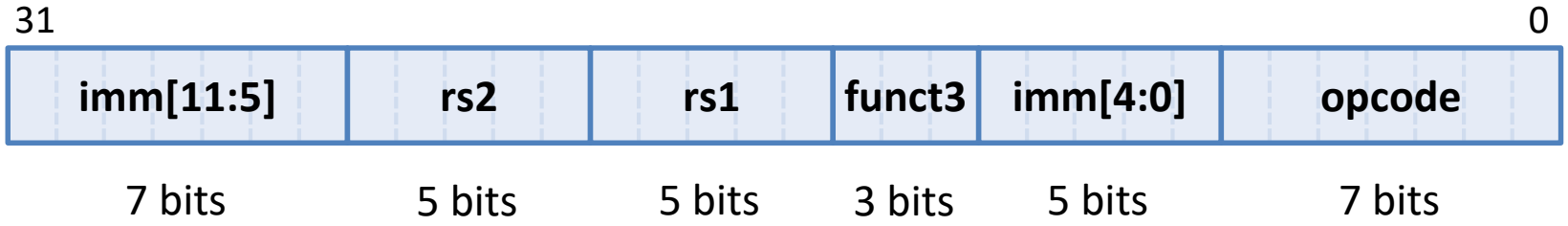
# RISC-V S-type Instructions



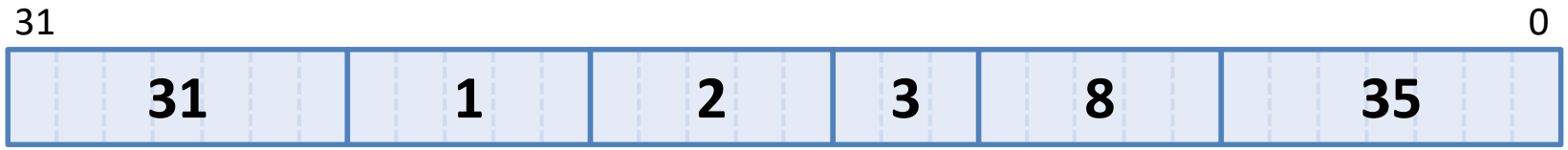

- Different immediate format for store instructions
  - Split so that rs1 and rs2 fields always in the same place

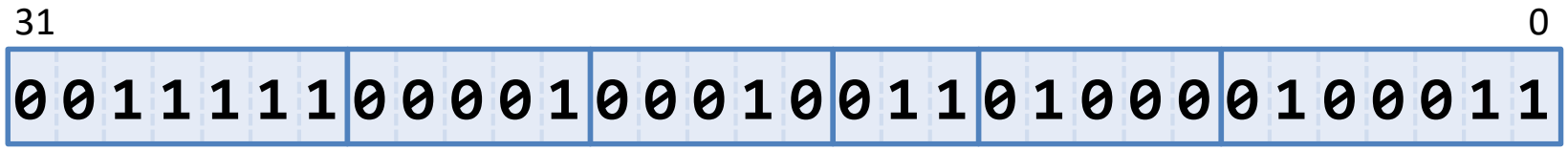
| Instruction | Type | Example | funct7 | funct3 | opcode |
|---|---|---|---|---|---|
| **sb** | **S** | `sb rs2, imm12(rs1)` | - | 000 | 0100011 |
| **sh** | **S** | `sh rs2, imm12(rs1)` | - | 001 | 0100011 |
| **sw** | **S** | `sw rs2, imm12(rs1)` | - | 010 | 0100011 |
| **sd** | **S** | `sd rs2, imm12(rs1)` | - | 011 | 0100011 |

# S-type Example

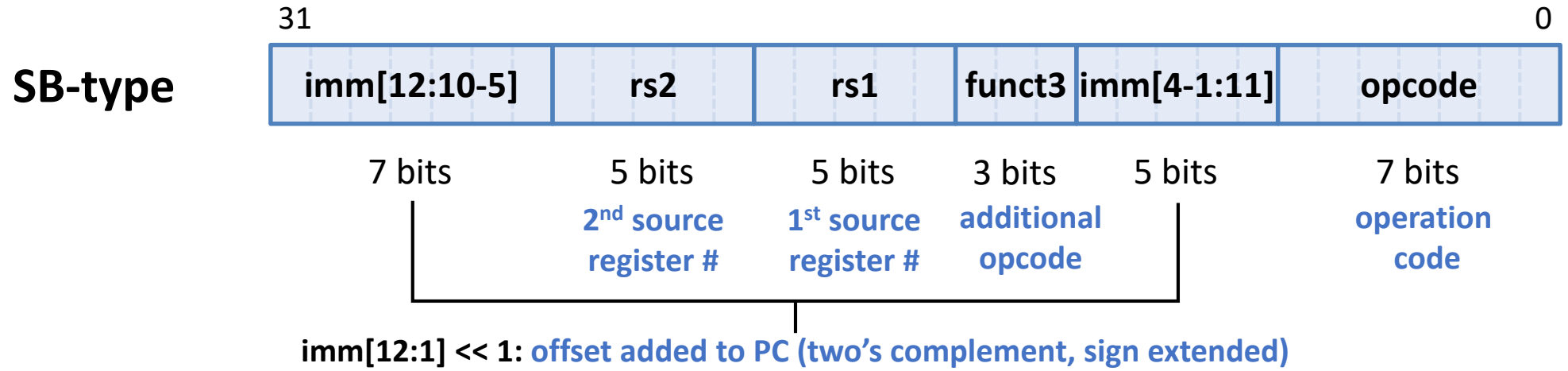



`sd x1, 1000(x2)` == $3E113423_{16}$



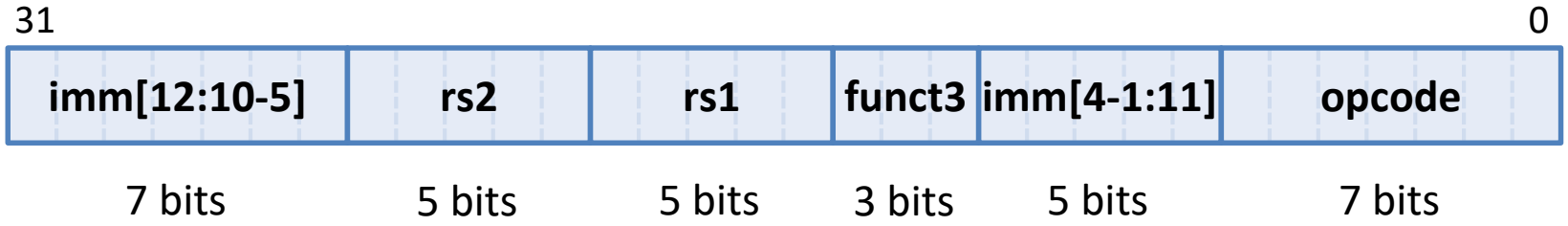



# RISC-V SB-type Instructions



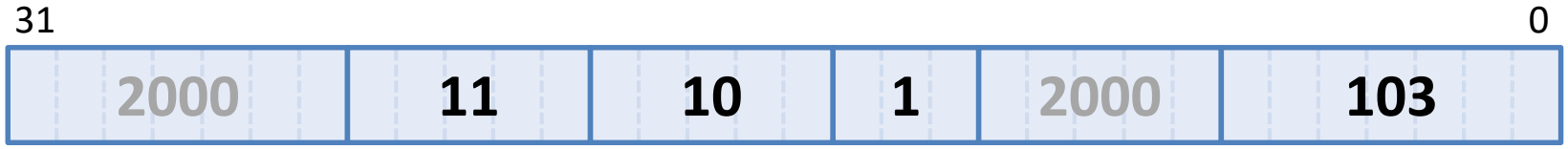

| Instruction | Type | Example | funct7 | funct3 | opcode |
|---|---|---|---|---|---|
| **beq** | **SB** | `beq rs1, rs2, imm12` | - | 000 | 1100011 |
| **bne** | **SB** | `bne rs1, rs2, imm12` | - | 001 | 1100011 |
| **blt** | **SB** | `blt rs1, rs2, imm12` | - | 100 | 1100011 |
| **bge** | **SB** | `bge rs1, rs2, imm12` | - | 101 | 1100011 |
| **bltu** | **SB** | `bltu rs1, rs2, imm12` | - | 110 | 1100011 |
| **bgeu** | **SB** | `bgeu rs1, rs2, imm12` | - | 111 | 1100011 |

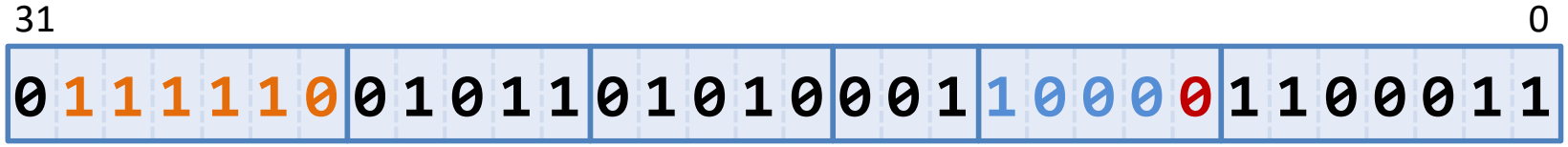
# SB-type Example



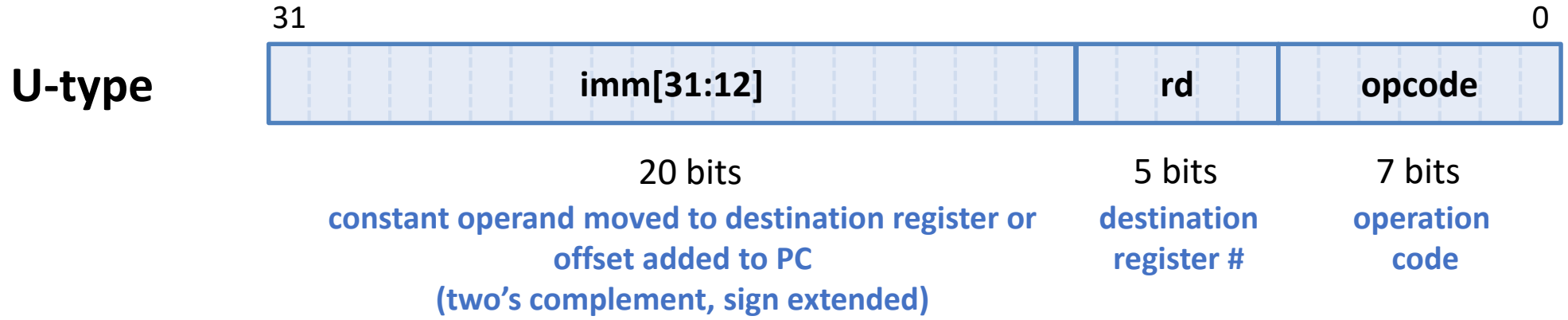

bne x10, x11, 2000 == $7CB51863_{16}$

($0111\ 1101\ 0000_2$)



# RISC-V U-type Instructions



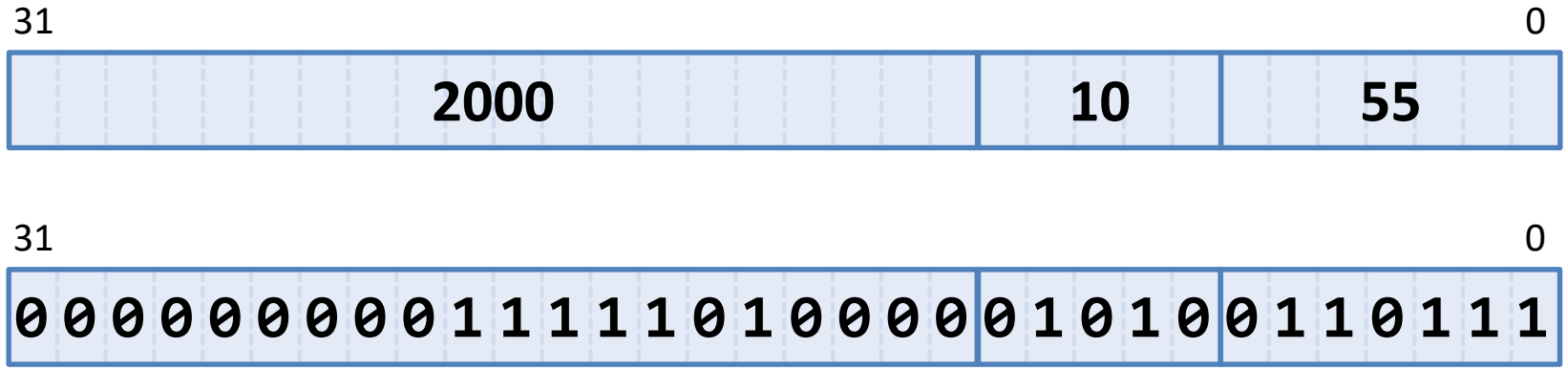

- 20-bit immediate is shifted left by 12 bits

| Instruction | Type | Example | funct7 | funct3 | opcode |
|---|---|---|---|---|---|
| **lui** | U | `lui rd, imm20` | - | - | 0110111 |
| **auipc** | U | `auipc rd, imm20` | - | - | 0010111 |

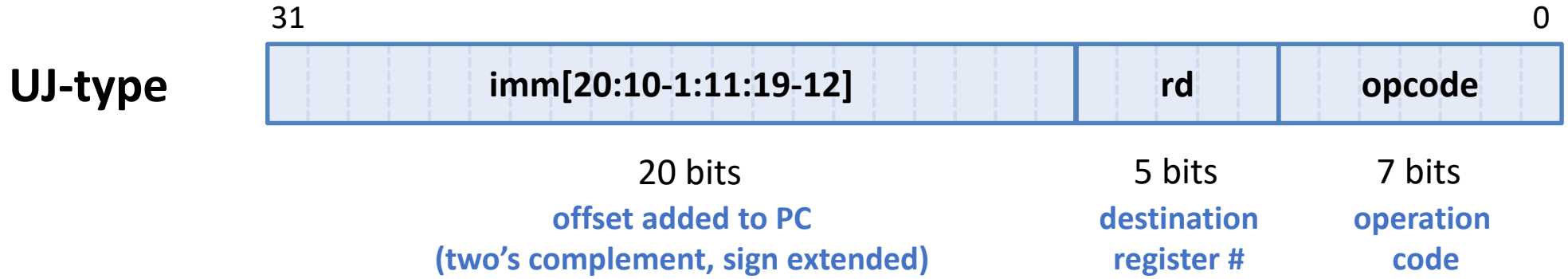
# U-type Example


`lui x10, 2000` == $007D0537_{16}$

**($0000\ 0000\ 0111\ 1101\ 0000_2$)**



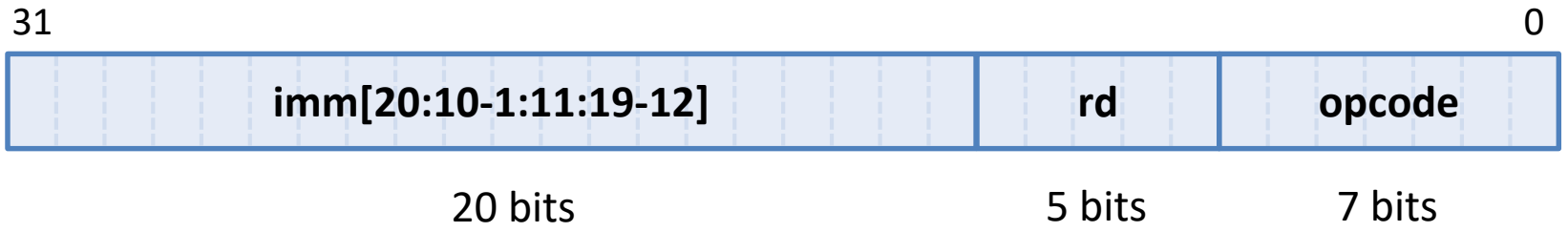
# RISC-V UJ-type Instructions




- 20-bit immediate is shifted left by 1 bit and added to PC

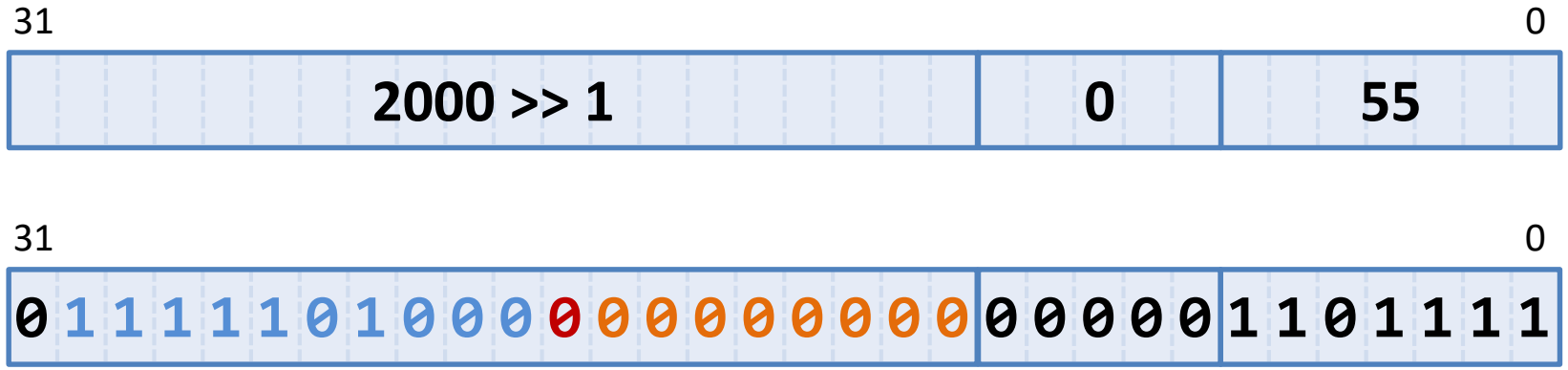
| Instruction | Type | Example | funct7 | funct3 | opcode |
|---|---|---|---|---|---|
| **jal** | **UJ** | `jal  rd, imm20` | - | - | 1101111 |

# UJ-type Example

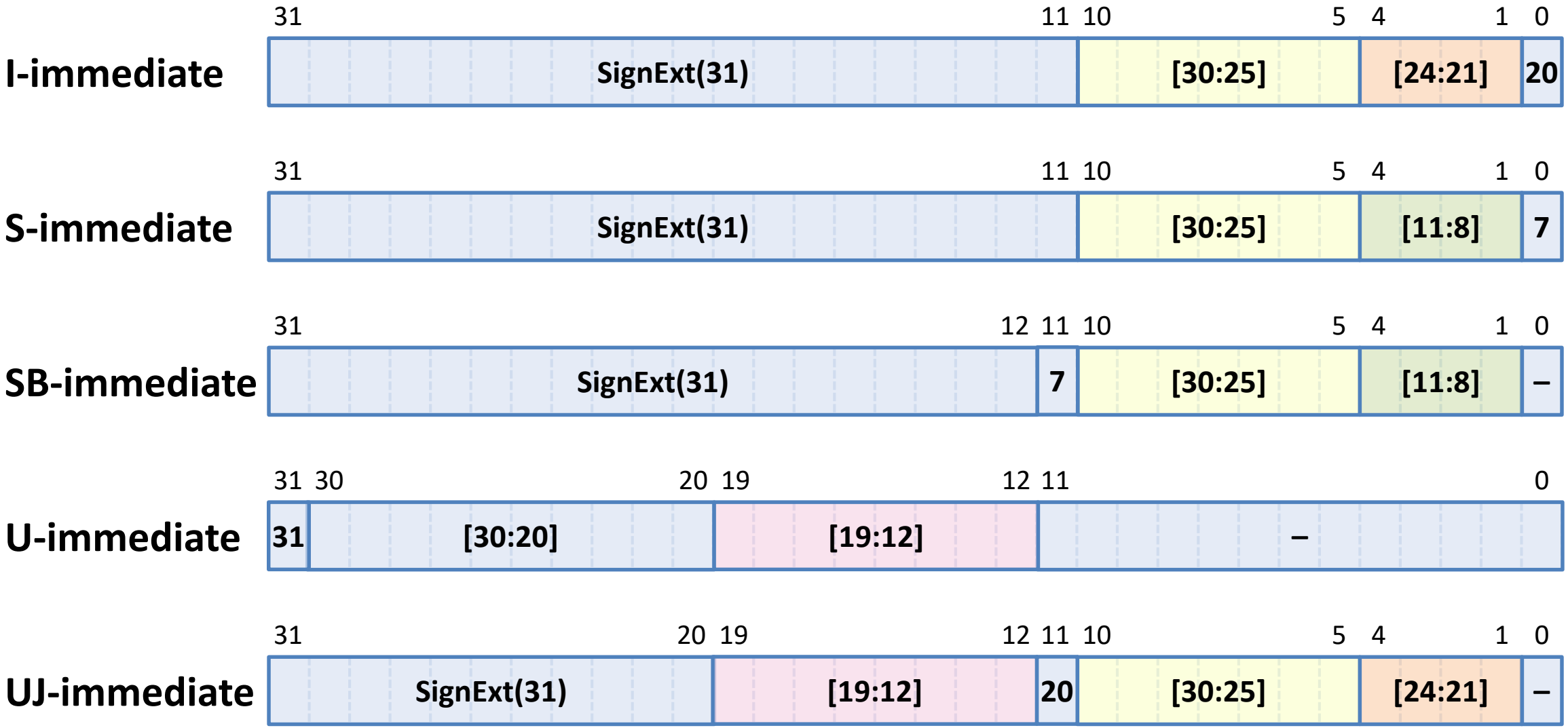



jal x0, 2000 == $7D00006F_{16}$

(0000 0000 0111 1101 0000$_2$)



# RISC-V Immediate Values

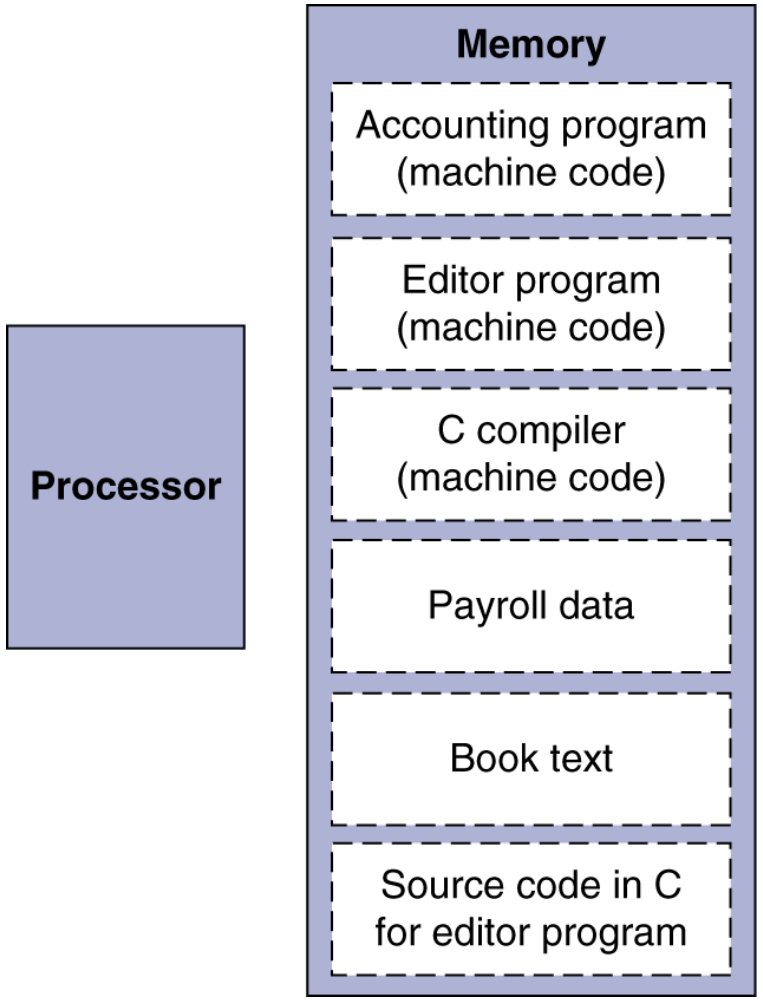


# Translating and Starting a Program

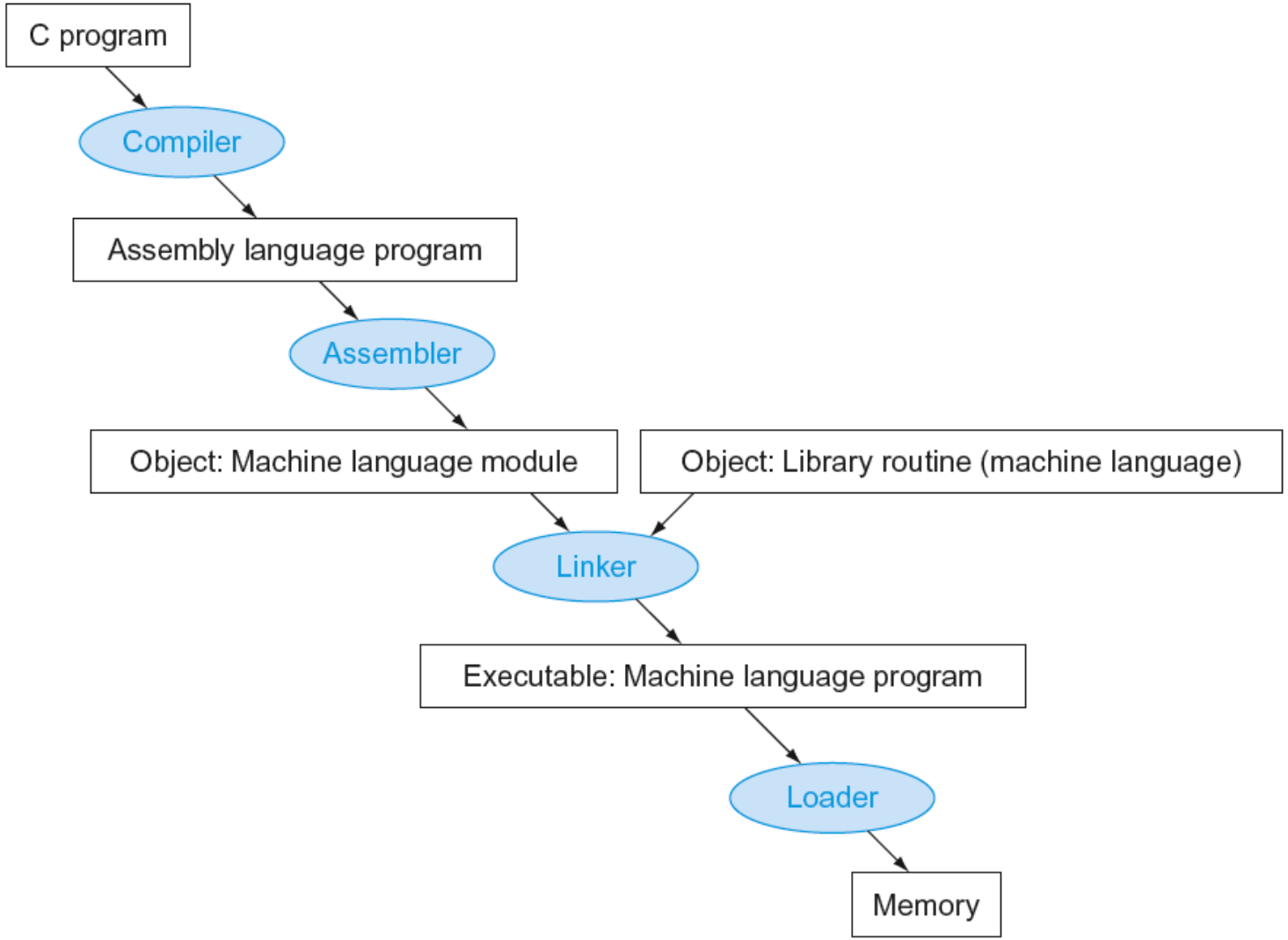
Chap. 2.12

# Stored Program Computers

- Instructions represented in binary, just like data
- Instructions and data stored in memory
- Programs can operate on programs
  - e.g., compilers, linkers, …
- Binary compatibility allows compiled programs to work on different computers
  - Standardized ISAs



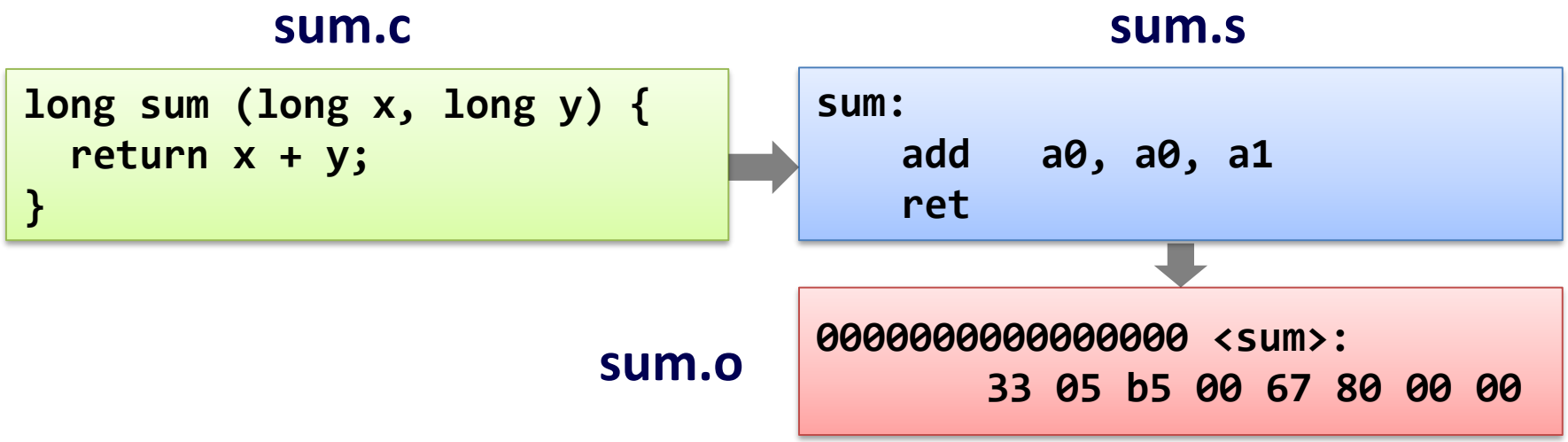
# Translation and Startup




**Static linking**

# Compiling into Machine Code

- Machine code (or binary code)
  - The byte-level programs that a processor executes
- Assembly code
  - A text representation of machine code
- **`riscv64-unknown-elf-gcc -Og -S sum.c`**



# Producing an Object Module

- Assembler (or compiler) translates program into machine instructions
- Nearly-complete image of executable code
- Missing linkages between code in different files
- Provides information for building a complete program from the pieces
  - Header: described contents of object module
  - Text segment: translated instructions
  - Static data segment: data allocated for the life of the program
  - Relocation info: for contents that depend on absolute location of loaded program
  - Symbol table: global definitions and external references
  - Debug info: for associating with source code

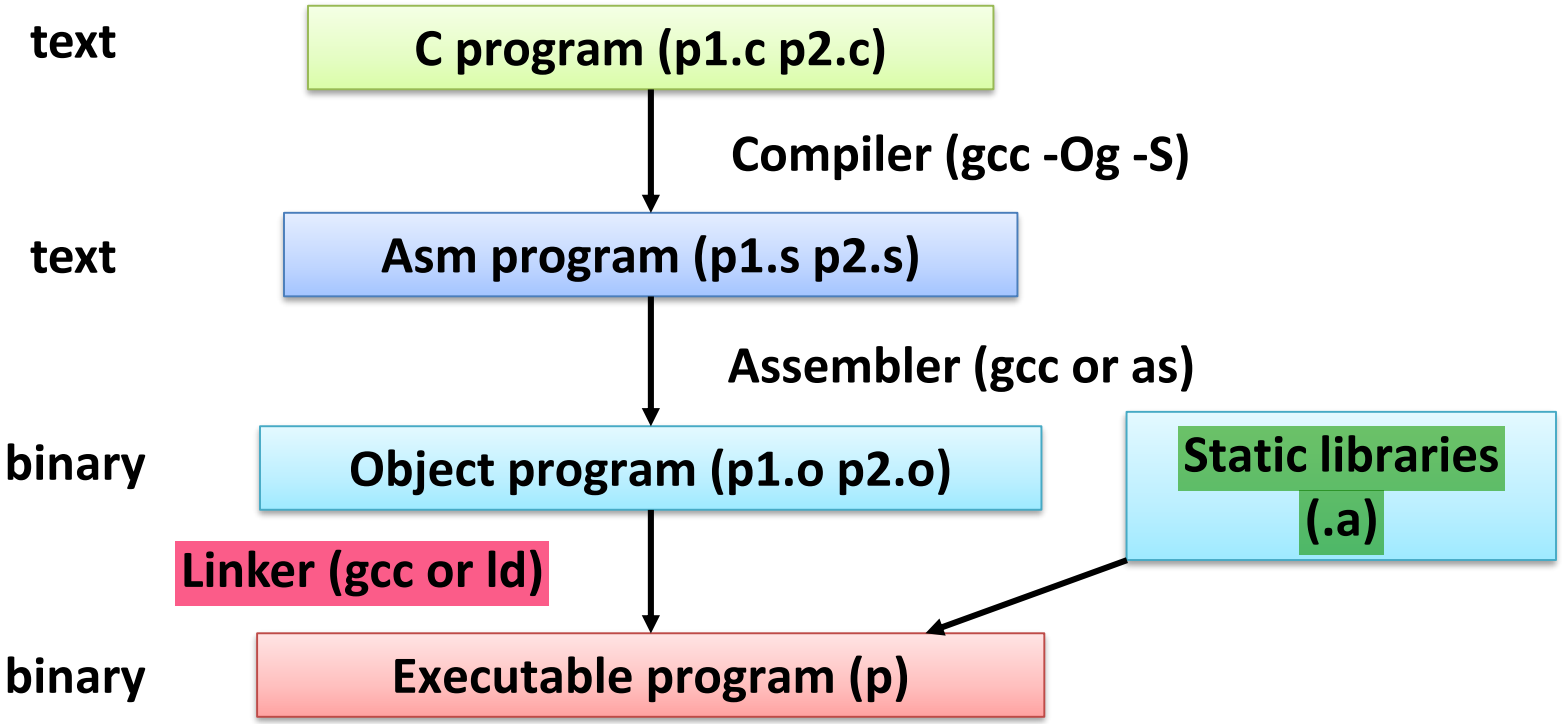
# Linking Object Modules

- Produces an executable image
  - Merges segments
  - Resolve labels (determine their addresses)
  - Patch location-dependent and external references
  - Combines with static run-time libraries
  - Some libraries are dynamically linked: linking occurs when program begins execution

- Could leave location dependencies for fixing by a relocating loader
  - But with virtual memory, no need to do this
  - Program can be loaded into absolute location in virtual memory space

# Turning C into Executable Program

- `riscv64-unknown-elf-gcc -Og p1.c p2.c -o p`
  - Use basic optimizations (-0g)
  - Put resulting binary in file p



# Loading a Program

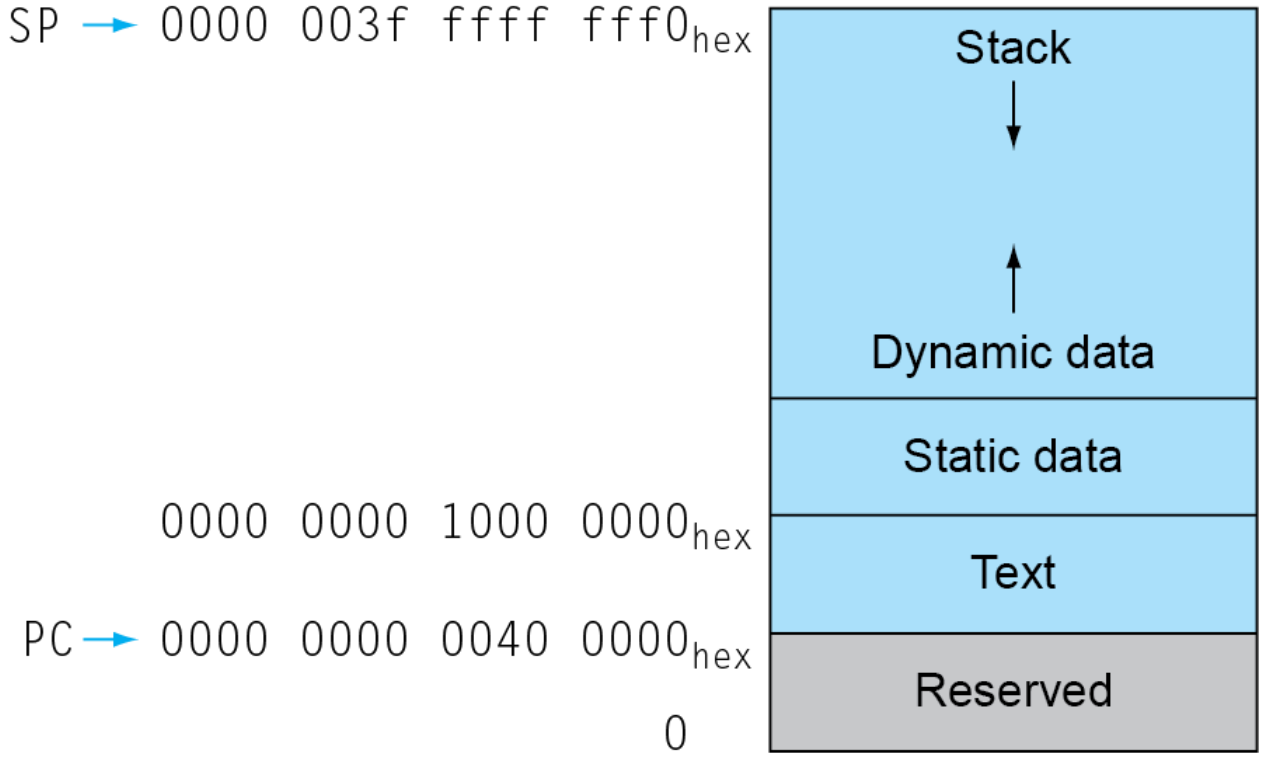
- Create a process

- Load from image file on disk into memory
  - Read header to determine segment sizes
  - Copy text and initialized data into memory
  - Set up stack
  - Initialize registers (including sp, fp, gp)

- Jump to startup routine
  - Copies arguments to x10, … and calls main
  - When main returns, do exit syscall

# Memory Layout

- Text: program code
- (Static) Data: global variables
  - e.g., static variables in C, constant arrays and strings
  - x3 (global pointer or gp) initialized to address allowing ± offsets into this segment
- Heap: dynamic data
  - e.g., `malloc` in C, `new` in Java
- Stack: automatic storage



# Disassembling

- Disassembler: **`riscv64-unknown-elf-objdump -d sum.o`**
  - Useful tool for examining object code
  - Analyzes bit pattern of series of instructions
  - Produces approximate rendition of assembly code
  - Can be run on either `a.out` (complete executable) or `.o` (object code) file

```
./sum.o:     file format elf64-littleriscv

Disassembly of section .text:

0000000000000000 <sum>:
   0:   00b50533                add     a0,a0,a1
   4:   00008067                ret
```

# Disassembling with gdb

- Disassemble procedure `sum`

```
$ riscv64-unknown-elf-gcc -Og -g sum.c main.c
$ riscv64-unknown-elf-gdb a.out
(gdb) disassemble sum
Dump of assembler code for function sum:
   0x0000000000010164 <+0>:     add     a0,a0,a1
   0x0000000000010168 <+4>:     ret
End of assembler dump.
```

- Examine 8 bytes starting at `sum`

```
(gdb) x/8xb sum
0x10164 <sum>:  0x33    0x05    0xb5    0x00    0x67    0x80    0x00    0x00
```