ZHEJIANG UNIVERSITY

系统结构与网络安全研究所

计算机组成与设计
Computer Organization & Design

The Hardware/Software Interface

Chapter 2

Instructions: Language of the Machine

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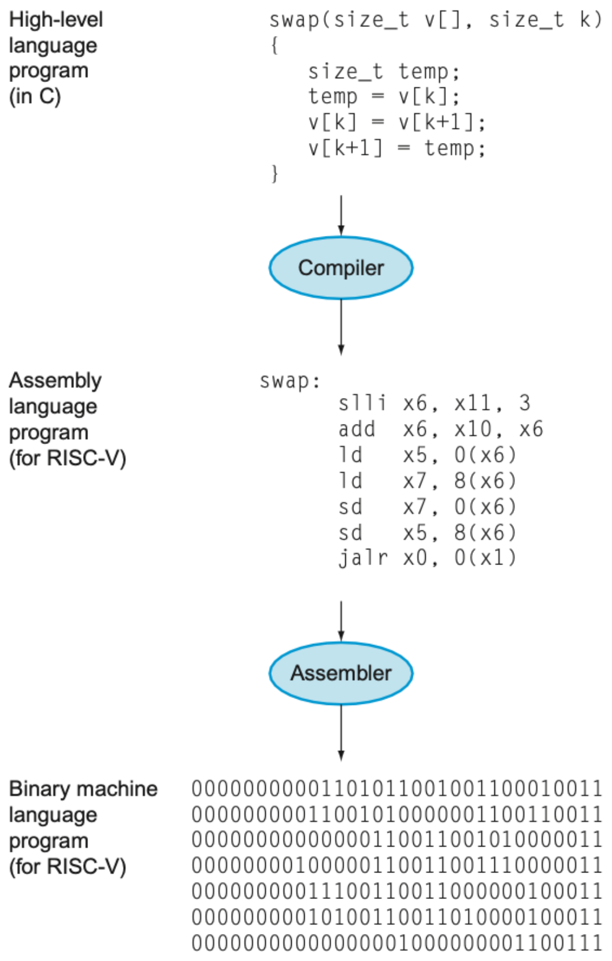
The process of compiling

- **High-level programming language**
  - Notations more closer to the natural language ex. Y = A + B
  - The compiler translates into assembly language
  - Advantages over assembly language
    - Think in a more natural language
    - Programs can be independent of hardware
- **Assembly language**
  - Symbolic notations ex. add Y, A, B
  - The assembler translates them into machine instruction
- **Machine language**
  - Computers only understands electrical signals on/off
  - Binary numbers express machine instructions

    ex. 1000110010100000 means to add two numbers


High-level language program (in C)
Compiler
Assembly language program (for RISC-V)
Assembler
Binary machine language program (for RISC-V)

```
swap(size_t v[], size_t k)
{
   size_t temp;
   temp = v[k];
   v[k] = v[k+1];
   v[k+1] = temp;
}
```

```
swap:
      slli x6, x11, 3
      add  x6, x10, x6
      ld   x5, 0(x6)
      ld   x7, 8(x6)
      sd   x7, 0(x6)
      sd   x5, 8(x6)
      jalr x0, 0(x1)
```

```
00000000001101011001001100010011
00000000011001010000001100110011
00000000000000110011001010000011
00000000100000110011001110000011
00000000011100110011000000100011
00000000010100110011010000100011
00000000000000001000000001100111
```

Outline

- Introduction
- Operations of the computer hardware
- Operands of the computer hardware
- Signed and a numbers
- Representing instructions in the computer
- Logical operations
- Instructions for making decision
- Supporting procedures in computer hardware
- Instruction addressing

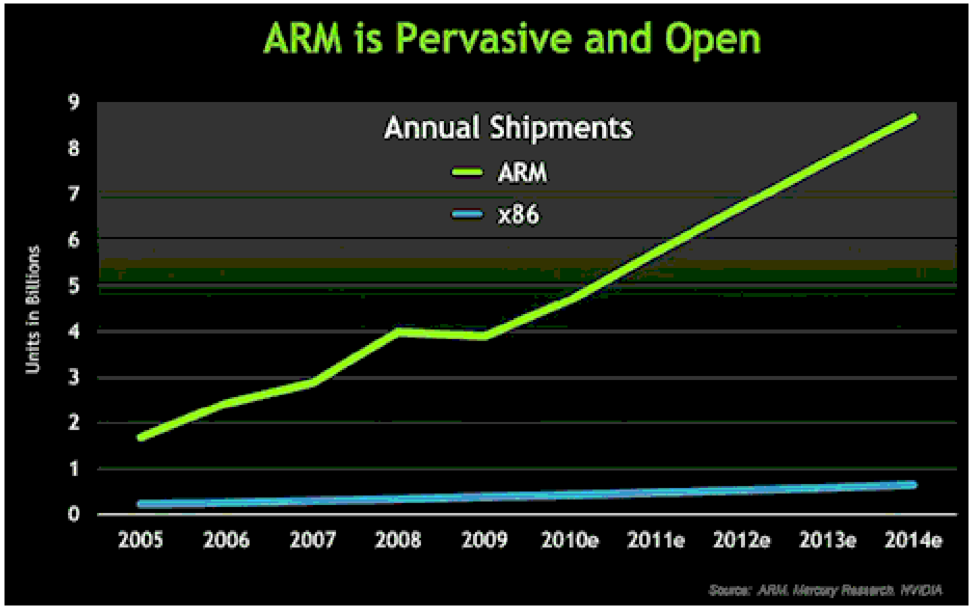
2.1 Introduction

- **Language of the machine**
  - Instructions → Word
  - Instruction set → Vocabulary
- **Design goals**
  - Maximize performance
  - Minimize cost
  - Reduce design time
- **Our chosen instruction set: RISC-V**

Instruction Set

- Different computers have different instruction sets
- But with many aspects in common
- Early computers had very simple instruction sets
- Simplified implementation
- Many modern computers also have simple instruction sets

RISC vs CISC

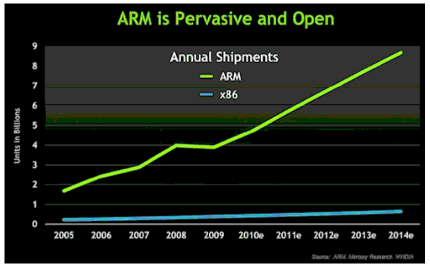


CISC vs RISC

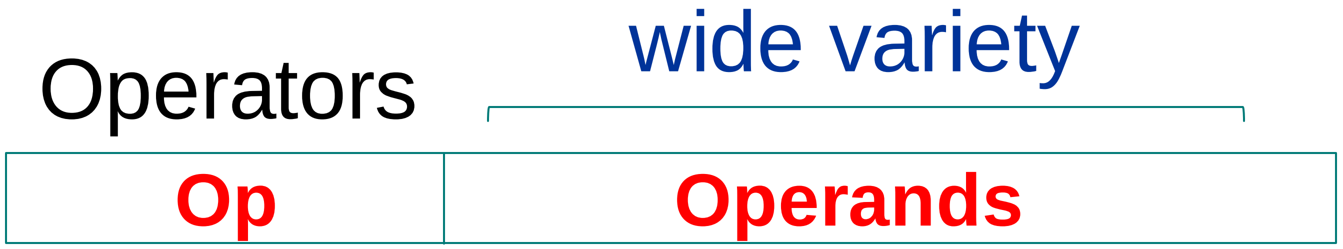
CISC complex instruction set computer	**RISC** reduce instruction set computer
Emphasis on hardware (>200 instructions)	Emphasis on software (<100 instructions)
Multiple instruction sizes and formats	Instructions of same size with few formats
Less registers	Uses more registers
More addressing modes	Fewer addressing modes (Load/Store)
Extensive use of microprogramming	Complexity in compiler
Instructions take a varying amount of cycle time	Instructions take one cycle time
Pipelining is difficult	Pipelining is easy

The RISC-V Instruction Set

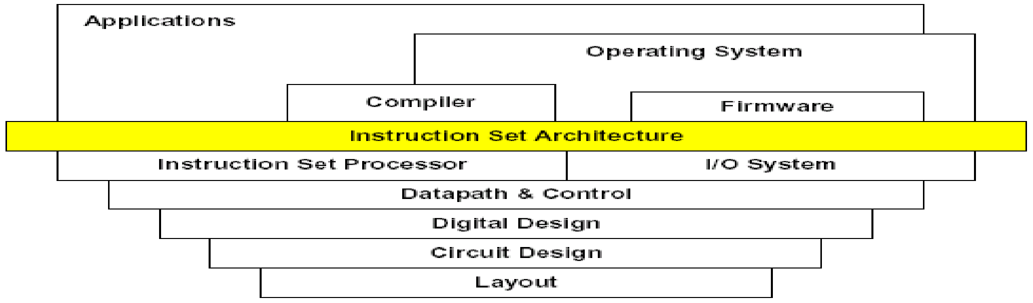
- Developed at UC Berkeley as open ISA (since 2010)
- Now managed by the RISC-V Foundation (riscv.org)
- Typical modern ISAs
  - See RISC-V Reference Data tear-out card
- Similar ISAs have a large share of embedded core market
  - Applications in consumer electronics, network/storage equipment, cameras, printers, …



Instruction formats



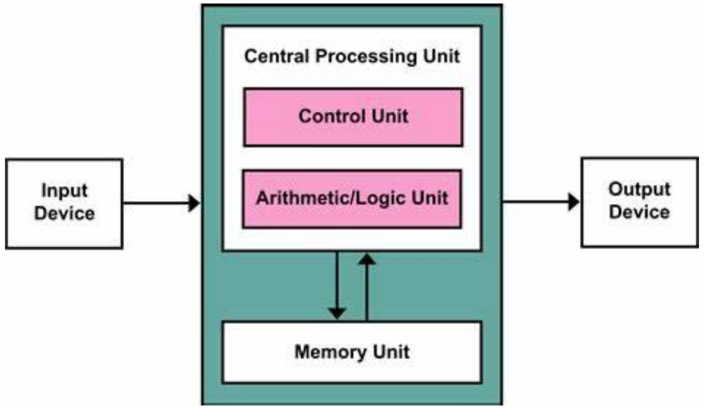
- Type of internal storage in processer
- The number of the memory operand in the instruction
- Operations in the instruction Set
- Type and Size of Operands
- Representing Instructions in the Computer
  - Encoding



Stored-program concept

- **Today's computers are built on 2 key principles: (Stored-program concept)**
  - ①Instruction are represented as numbers.
  - ②Programs can be stored in memory to be read or written just like numbers.

Von Neumann' Computer



2.2 Arithmetic Operations

- **Every computer should perform arithmetic**
  - Only one operation per instruction
  - Add and subtract, three operands
    (Two sources and one destination)
    add a, b, c // a gets b + c
- **All arithmetic operations have this form**
- **Design Principle 1:** *Simplicity favors regularity*
  - Regularity makes implementation simpler
  - Simplicity enables higher performance at lower cost

Arithmetic Example

Example 2.2 Compiling a complex C statement

- C code:

```
f = ( g + h ) – ( i + j );
```

- Compiled RISC-V code:

```
add  t0, g, h          # temporary variable t0 contains g + h
add  t1, i, j          # temporary variable t1 contains i + j
sub  f, t0, t1         # f gets t0 – t1
```

RISC-V assembly language

Category	Instruction	Example	Meaning	Comments
Arithmetic	add	add a,b,c	a←b+c	Always three operand
	subtract	sub a,b,c	a←b-c	Always three operand

2.3 Operands

- **Arithmetic instructions use register operands**
- **RISC-V has a 32 × 64-bit register file**
  - Use for frequently accessed data
  - 64-bit data is called a “doubleword”
    - 32 x 64-bit general purpose registers x0 to x31
  - 32-bit data is called a “word”
- ***Design Principle 2:* Smaller is faster**
  - c.f. main memory: millions of locations

RISC-V Registers

- Lumped Model
  - C only
  - RC model

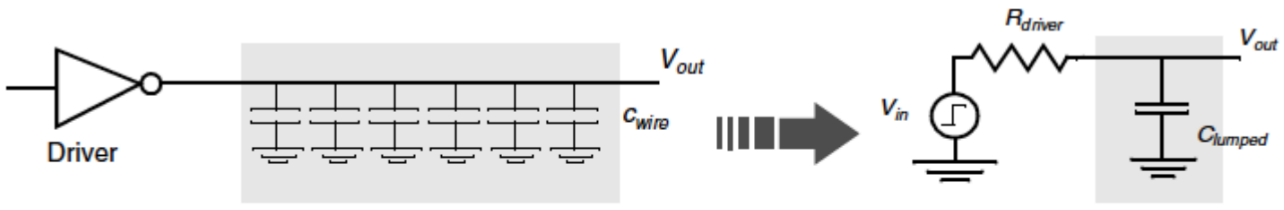


Figure 4.11 Distributed versus lumped capacitance model of wire. $C_{lumped} = L \times c_{wire}$, with L the length of the wire and c_{wire} the capacitance per unit length. The driver is modeled as a voltage source and a source resistance R_{driver}.

$$C_{lumped}\frac{dV_{out}}{dt} + \frac{V_{out} - V_{in}}{R_{driver}} = 0$$

$$\tau = R_{driver} \times C_{lumped},$$

$$V_{out}(t) = (1 - e^{-t/\tau})\, V$$

$$t_{50\%} = 0.69 \times 10\ \text{K}\Omega \times 11\ \text{pF} = 76\ \text{nsec}$$

$$t_{90\%} = 2.2 \times 10\ \text{K}\Omega \times 11\ \text{pF} = 242\ \text{nsec}$$

RISC-V Registers

Name	Register Name	Usage	Preserved On Call?
x0	0	The constant value 0	n.a.
x1(ra)	1	Return address(link register)	yes
x2(sp)	2	Stack pointer	yes
x3(gp)	3	Global pointer	yes
x4(tp)	4	Thread pointer	yes
x5-x7	5-7	Temporaries	no
x8-x9	8-9	Saved	yes
x10-x17	10-17	Arguments/results	no
x18-x27	18-27	Saved	yes
x28-x31	28-31	Temporaries	no

Register Operand Example

- C code:

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

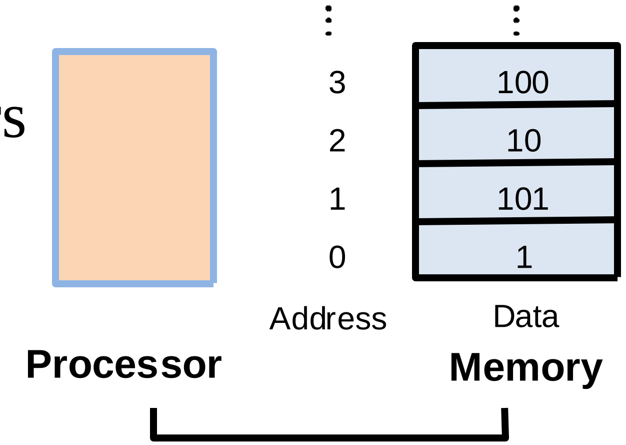
  - f, …, j in x19, x20, …, x23

- Compiled RISC-V code:

```
add x5, x20, x21
add x6, x22, x23
sub x19, x5, x6
```

Memory Operands

- **Main memory used for composite data**
  - Arrays, structures, dynamic data
- **To apply arithmetic operations**
  - Load values from memory into registers
  - Store result from register to memory
- **Memory is byte addressed**
  - Each address identifies an 8-bit byte
- **RISC-V is Little Endian**
  - Least-significant byte at least address of a word
  - *c.f.* Big Endian: most-significant byte at least address
- **RISC-V does not require words to be aligned in memory**
  - Unlike some other ISAs



Memory Alignment

```
struct {
        int a;
        char b;
        char c[2];
        char d[3]
        float e;
}
```

Correct

e			
d[1]	d[2]	No use	No use
b	c[0]	c[1]	d[0]
a			

Wrong

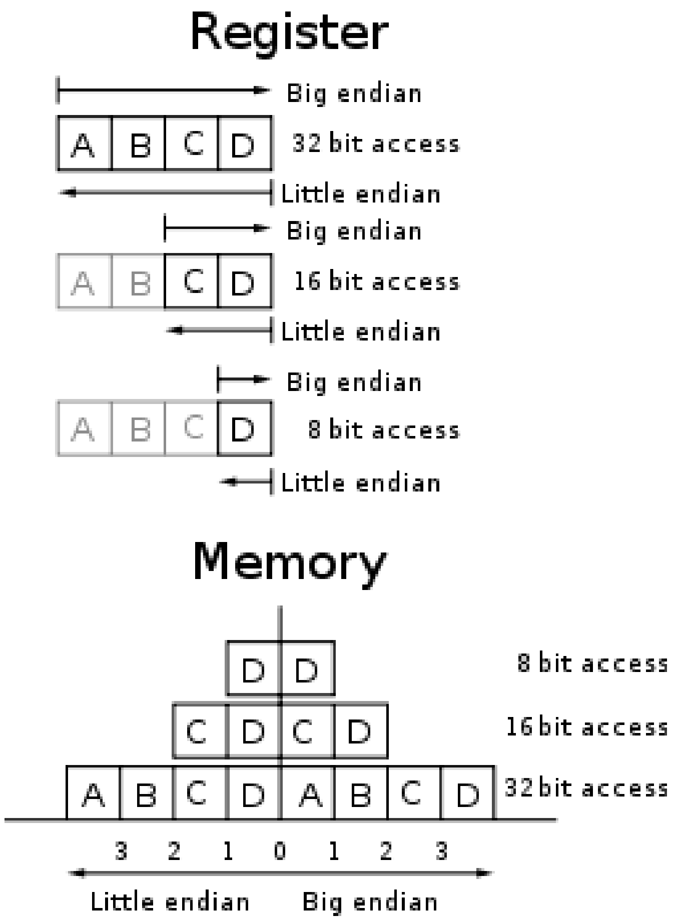
e		No use	No use
d[1]	d[2]	e	
b	c[0]	c[1]	d[0]
a			

因为一次只能读出4字节内存中的一行

这样布局，e变量不能一次读出

Endianness/byte order

- **Big end： Leftmost**
  - PowerPC
  - 01 02 = 513
- **Little end： Rightmost**
  - RISC-V
  - 01 02 = 258
- **Bi-endian**
  - MIPS, ARM , Alpha, SPARC



Memory Operand Example

- **C code:**

```
A[12] = h + A[8];
```

  - h in x21, base address of A in x22

- **Compiled RISC-V code:**
  - Index 8 requires offset of 64
    - 8 bytes per doubleword
  - Offset: the constant in a data transfer instruction
  - Base register: the register added to form the address

```
ld          x9, 64(x22)
add         x9, x21, x9
sd          x9, 96(x22)
```

Register vs. Memory

- **Registers are faster to access than memory**
- **Operating on memory data requires loads and stores**
  - More instructions to be executed
- **Compiler must use registers for variables as much as possible**
  - Only spill to memory for less frequently used variables
  - Register optimization is important!

Discussion： How to represent?

Constant

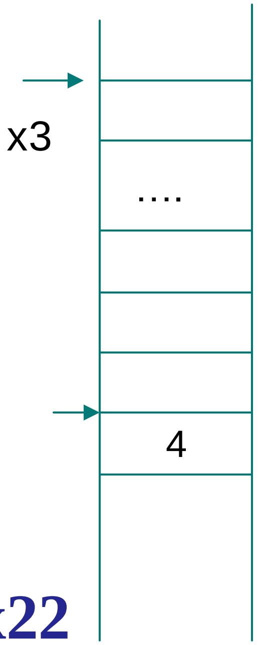
g = h + 55

Many time a program
will use a constant in an operation

Constant or immediate Operands

- **Many time a program will use a constant in an operation**
  - Incrementing index to point to next element of array
  - Add the constant 4 to register x9
  - Assuming AddrConstants 4 is address pointer of constant 4

```
ld      x9, AddrConstant4(x3)    // x9=constant 4
add     x22, x22, x9
```



- **Immediate: Other method for adding constant 4 to x22**
  - Avoids the load instruction
  - Offer versions of the instruction

    addi   x22, x22, 4   // x22= x22+ 4
  - Constant zero: a register x0

- **Design Principle 3: Make common case fast**

Brief summary

RISC-V operands

Name	Example	Comments
32 register	x0~x31	Fast locations for data. In RISC-V, data must be in registers to perform arithmetic. Register x0 always equals 0.
2^{61} memory (double) words	Memory[0], Memory[8] , …… , Memory[18446744073709551608]	Accessed only by data transfer instructions. RISC-V uses byte addresses, so sequential doubleword accesses differ by 8. Memory holds data structures, arrays, and spilled registers.

RISC-V assembly language

Category	Instruction	Example	Meaning	Comments
Arithmetic	add	add x5,x6,x7	x5=x6 + x7	Add two source register operands
	subtract	sub x5,x6,x7	x5=x6 - x7	First source register subtracts second one
	add immediate	addi x5,x6,20	x5=x6+20	Used to add constants
Data transfer	load doubleword	ld x5, 40(x6)	x5=Memory[x6+40]	doubleword from memory to register
	store doubleword	sd x5, 40(x6)	Memory[x6+40]=x5	doubleword from register to memory

2.4 Signed and unsigned numbers

- Bits are just bits (no inherent meaning): conventions define relationship between bits and numbers
- Binary numbers (base 2)
  0000 0001 0010 0011 0100 0101 0110 0111 1000 1001...
  decimal: 0...2^n-1
- Of course it gets more complicated:
  - numbers are finite (overflow)
  - fractions and real numbers
  - negative numbers
- How do we represent negative numbers?
  - which bit patterns will represent which numbers?

Unsigned Binary Integers

- Given an n-bit number

$$x = x_{n-1}2^{n-1} + x_{n-2}2^{n-2} + \cdots + x_1 2^1 + x_0 2^0$$

- Range: 0 to $+2^n - 1$
- Example
  - $0000\ 0000\ \ldots\ 0000\ 1011_2$
    $= 0 + \ldots + 1\times2^3 + 0\times2^2 + 1\times2^1 + 1\times2^0$
    $= 0 + \ldots + 8 + 0 + 2 + 1 = 11_{10}$
- Using 64 bits: 0 to +18,446,774,073,709,551,615

2s-Complement Signed Integers

- Given an n-bit number

$$x = -x_{n-1}2^{n-1} + x_{n-2}2^{n-2} + \cdots + x_1 2^1 + x_0 2^0$$

- Range: -2^{n-1} to $+2^{n-1} - 1$
- Example
  - $1111\ 1111 \ldots 1111\ 1100_2$
    $= -1\times2^{31} + 1\times2^{30} + \ldots + 1\times2^2 + 0\times2^1 + 0\times2^0$
    $= -2{,}147{,}483{,}648 + 2{,}147{,}483{,}644 = -4_{10}$
- Using 64 bits: −9,223,372,036,854,775,808
  to 9,223,372,036,854,775,807

2s-Complement Signed Integers

- **Bit 63 is sign bit**
  - 1 for negative numbers
  - 0 for non-negative numbers
- **$-(-2^{n-1})$ can't be represented**
- **Non-negative numbers have the same unsigned and 2s-complement representation**
- **Some specific numbers**
  - 0: 0000 0000 … 0000
  - –1: 1111 1111 … 1111
  - Most-negative: 1000 0000 … 0000
  - Most-positive: 0111 1111 … 1111

Signed Negation

- **Complement and add 1**
  - Complement means 1 → 0, 0 → 1

$$x + \bar{x} = 1111\ldots111_2 = -1$$

$$\bar{x} + 1 = -x$$

- **Example: negate +2**
  - $+2 = 0000\ 0000\ \ldots\ 0010_{two}$
  - $-2 = 1111\ 1111\ \ldots\ 1101_{two} + 1$
    $= 1111\ 1111\ \ldots\ 1110_{two}$

Sign Extension

- Representing a number using more bits
  - Preserve the numeric value
- Replicate the sign bit to the left
  - c.f. unsigned values: extend with 0s
- Examples: 8-bit to 16-bit
  - +2: 0000 0010 => 0000 0000 0000 0010
  - –2: 1111 1110 => 1111 1111 1111 1110

- In RISC-V instruction set
  - lb: sign-extend loaded byte
  - lbu: zero-extend loaded byte

2.5 Representing Instructions

- **All information in computer consists of binary bits**
- **Instructions are encoded in binary**
  - Called machine code
- **Mapping registers into numbers**
  - map registers x0 to x31 onto registers 0 to 31
- **RISC-V instructions**
  - Encoded as 32-bit instruction words
  - Small number of formats encoding operation code (opcode), register numbers, …
  - Regularity

Example: Translating Assembly Code

- **(p81) Translating assembly into machine instruction**

  RISC-V code

  add x9, x20, x21

  Decimal version of machine code

0	21	20	0	9	51

  Binary version of machine code

0000000	10101	10100	000	01001	0110011
7 bits	5 bits	5 bits	3 bits	5 bits	7 bits

Hexadecimal

- **Base 16**
  - Compact representation of bit strings
  - 4 bits per hex digit

0	0000	4	0100	8	1000	c	1100
1	0001	5	0101	9	1001	d	1101
2	0010	6	0110	a	1010	e	1110
3	0011	7	0111	b	1011	f	1111

- **Example: eca8 6420**
  - 1110 1100 1010 1000 0110 0100 0010 0000

RISC-V R-Format Instructions

funct7	rs2	rs1	funct3	rd	opcode
7 bits	5 bits	5 bits	3 bits	5 bits	7 bits

- **Instruction fields**
  - opcode: operation code
  - rd: destination register number
  - funct3: 3-bit function code (additional opcode)
  - rs1: the first source register number
  - rs2: the second source register number
  - funct7: 7-bit function code (additional opcode)
- **Design Principle 3**
  - ***Good design demands good compromises***
- **All instructions in RISC-V have the same length**
  - Conflict: same length ←--→ single instruction

R-format Example

funct7	rs2	rs1	funct3	rd	opcode
7 bits	5 bits	5 bits	3 bits	5 bits	7 bits

```
add x9,x20,x21
```

0	21	20	0	9	51

0000000	10101	10100	000	01001	0110011

$0000\ 0001\ 0101\ 1010\ 0000\ 0100\ 1011\ 0011_{two} =$

$015A04B3_{16}$

RISC-V I-Format Instructions

immediate	rs1	funct3	rd	opcode
12 bits	5 bits	3 bits	5 bits	7 bits

- **Immediate arithmetic and load instructions**
  - rs1: source or base address register number
  - immediate: constant operand, or offset added to base address
    - 2s-complement, sign extended
- ***Design Principle 3:* Good design demands good compromises**
  - Different formats complicate decoding, but allow 32-bit instructions uniformly
  - Keep formats as similar as possible
- **Example：ld x9, 64(x22)**
  - 22 (x22) is placed in rs1;
  - 64 is placed in immediate
  - 9 (x9) is placed in rd

RISC-V S-Format Instructions

imm[11:5]	rs2	rs1	funct3	imm[4:0]	opcode
7 bits	5 bits	5 bits	3 bits	5 bits	7 bits

- **Different immediate format for store instructions**
  - rs1: base address register number
  - rs2: source operand register number
  - immediate: offset added to base address
    - Split so that rs1 and rs2 fields always in the same place

- **Example:** sd x9, 64(x22)
  - 22 (x22) is placed rs1;
  - 64 is placed immediate
  - 9 (x9) is placed rs2

RISC-V instruction encoding

Name	Format	Example						Comment
add	R	0	3	2	0	1	51	add x1, x2, x3
sub	R	32	3	2	0	1	51	sub x1, x2, x3
addi	I	1000		2	0	1	19	addi x1,x2,1000
ld	I	1000		2	3	1	3	ld x1, 1000(x2)
sd	S	31	1	2	3	8	35	sd x1, 1000(x2)

Example

- **Example(p85)** **Translating assembly into machine instruction**

  C code:

  A[30] = h + A[30] + 1 ;

  (Assume: h ---- x21 base address of A ---- x10)

- RISC-V assembly code:

```
ld     x9, 240(x10)          // temporary reg x9 gets A[30]
add    x9, x21, x9           // temporary reg x9 gets  h  +  A[30]
addi   x9, x9, 1             // temporary reg x9 gets  h  +  A[30]  +  1
sd     x9, 240(x10)          // stores h + A[30] + 1  back into A[30]
```

- RISC-V machine language code:
  - Decimal version

	immediate	rs1	funct3	rd	opcode
ld	240	10	3	9	3

add	funct7	rs2	rs1	funct3	rd	opcode
	0	9	21	0	9	51

addi	immediate	rs1	funct3	rd	opcode
	1	9	0	9	19

sd	im[11:5]	rs2	rs1	funct3	im[4:0]	opcode
	7	9	10	3	16	35

- **Two key principles of today's computers**
  - Instructions are represented as numbers
  - Programs can be stored in memory like numbers

Stored-program

RISC-V fields (format)

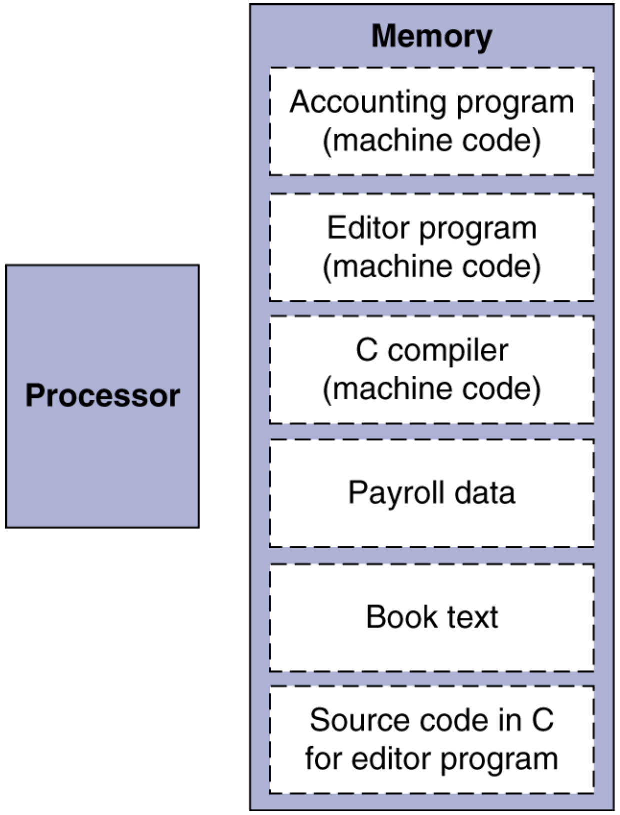
Imm Region: $\pm 2^{11}$

Name	Fields						Comments
Field size	31 *7bits* 25	24 *5bits* 20	19 *5bits* 15	14 *3bits* 12	11 *5bits* 7	6 *7bits* 0	All RISC-V instruction 32 bits
R-type	**funct7**	**rs2**	**rs1**	**funct3**	**rd**	**opcode**	Arithmetic instruction format
I-type	immediate[11:0]		**rs1**	**funct3**	**rd**	**opcode**	Loads & immediate arithmetic
S-type	immed[11:5]	rs2	**rs1**	**funct3**	immed[4:0]	**opcode**	Stores
SB-type	*imm[12,10:5]*	rs2	**rs1**	**funct3**	*imm[4:1,11]*	**opcode**	Conditional branch format
UJ-type	*immediate[20,10:1,11,19:12]*				**rd**	**opcode**	Unconditional jump format
U-type	immediate[31:12]				**rd**	**opcode**	Upper immediate format

Must bear in mind !

Stored Program Computer

The BIG Picture


Memory
Accounting program (machine code)
Editor program (machine code)
C compiler (machine code)
Payroll data
Book text
Source code in C for editor program
Processor

- **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

2.6 Logical Operations

- Instructions for bitwise manipulation

Operation	C	Java	RISC-V
Shift left	<<	<<	`slli`
Shift right	>>	>>>	`srli`
Bit-by-bit AND	&	&	`and, andi`
Bit-by-bit OR	|	|	`or, ori`
Bit-by-bit XOR	^	^	`xor, xori`
Bit-by-bit NOT	~	~	

- Useful for extracting and inserting groups of bits in a word

Shift Operations

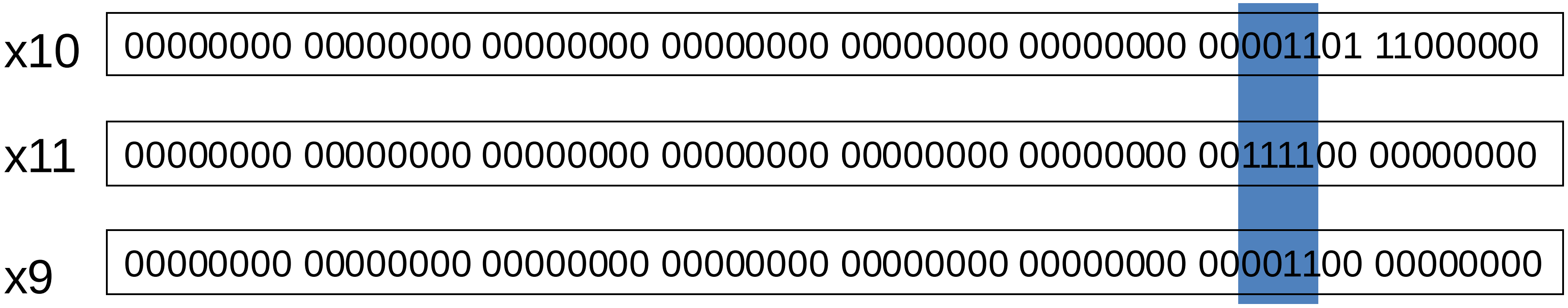
funct6	immed	rs1	funct3	rd	opcode
6 bits	6 bits	5 bits	3 bits	5 bits	7 bits

- **immed: how many positions to shift**
- **Shift left logical**
  - Shift left and fill with 0 bits
  - `slli` by *i* bits multiplies by 2^i
- **Shift right logical**
  - Shift right and fill with 0 bits
  - `srli` by *i* bits divides by 2^i (unsigned only)

AND Operations

- **Useful to mask bits in a word**
  - Select some bits, clear others to 0

```
and x9,x10,x11
```



```
x10  00000000 00000000 00000000 00000000 00000000 00000000 00001101 11000000
x11  00000000 00000000 00000000 00000000 00000000 00000000 00111100 00000000
x9   00000000 00000000 00000000 00000000 00000000 00000000 00001100 00000000
```

OR Operations

- **Useful to include bits in a word**
  - Set some bits to 1, leave others unchanged

```
or x9,x10,x11
```

x10	00000000 00000000 00000000 00000000 00000000 00000000 00001101 11000000
x11	00000000 00000000 00000000 00000000 00000000 00000000 00111100 00000000
x9	00000000 00000000 00000000 00000000 00000000 00000000 00111101 11000000

XOR Operations

- **Differencing operation**
  - Mark different bits between two words

```
xor x9,x10,x12  // NOT operation
```

```
x10   00000000 00000000 00000000 00000000 00000000 00000000 00001101  11000000
x12   11111111   11111111  11111111   11111111   11111111   11111111   11111111   11111111
x9    11111111   11111111  11111111   11111111   11111111   11111111   11110010  00111111
```

RISC-V operands

Name	Example	Comments
32 registers	*x*0-*x*31	Fast locations for data. In RISC-V, data must be in registers to perform arithmetic. Register x0 always equals 0.
2^{61} memory (double) words	Memory[0], Memory[8], …, Memory[18,446,744,073,709,551,608]]	Accessed only by data transfer instructions. RISC-V uses byte addresses, so sequential double word accesses differ by 8. Memory holds data structures, arrays, and spilled registers.

Category	Instruction	Example	Meaning	Comments
Logical	and	and x5, x6, 3	x5=x6 & 3	Arithmetic shift right by register
	inclusive or	or x5,x6,x7	x5=x6 | x7	Bit-by-bit OR
	exclusive or	xor x5,x6,x7	x5=x6 ^ x7	Bit-by-bit XOR
	and immediate	andi x5,x6,20	x5=x6 & 20	Bit-by-bit AND reg. with constant
	inclusive or immediate	ori x5,x6,20	x5=x6 | 20	Bit-by-bit OR reg. with constant
	exclusive or immediate	xori x5,x6,20	X5=x6 ^ 20	Bit-by-bit XOR reg. with constant
Shift	shift left logical	sll x5, x6, x7	x5=x6 << x7	Shift left by register
	shift right logical	srl x5, x6, x7	x5=x6 >> x7	Shift right by register
	shift right arithmetic	sra x5, x6, x7	x5=x6 >> x7	Arithmetic shift right by register
	shift left logical immediate	slli x5, x6, 3	x5=x6 << 3	Shift left by immediate

2.7 Instructions for making decisions

- **Branch instructions**
  - Branch to a labeled instruction if a condition is true
  - Otherwise, continue sequentially

- **beq rs1, rs2, L1**

  // (if (rs1 == rs2) branch to instruction labeled L1

- **bne rs1, rs2, L1**

  // if (rs1 != rs2) branch to instruction labeled L1

Example Compiling an if statement

- **Example 2.9**

  (Assume: f ~ j ---- x19 ~ x23)

  - C code:

```
        if ( i  = =  j )   goto  L1 ;
        f  =  g  +  h ;
L1:     f  =  f  -  i ;
```

  - RISC-V assembly code:

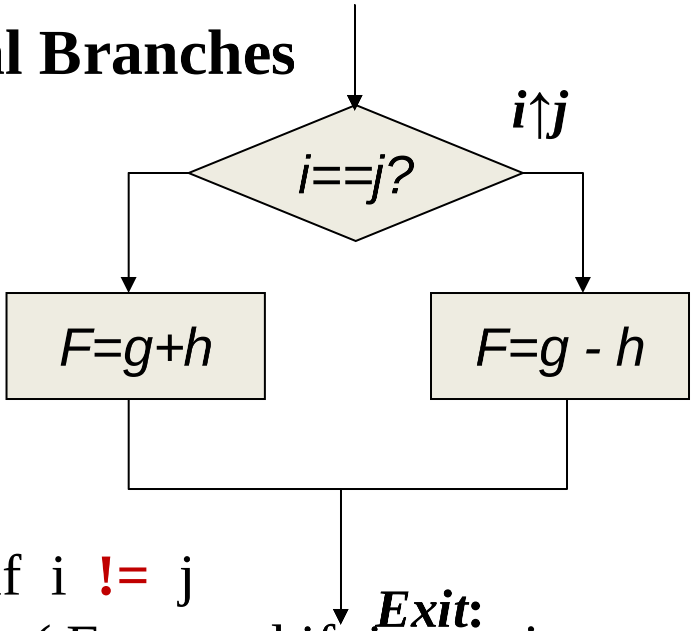
```
        beq     x21,  x22,  L1          # go to L1 if  i  equals  j
        add     x19,  x20,  x21         # f  =  g + h  ( skipped if  i  equals
j )
L1:     sub     x19,  x19,  x22         # f  =  f  -  i  ( always executed )
```

Compiling if-then-else

- **Example 2.10**

Compiling *if-then-else* into Conditional Branches

(Assume: f ~ j ---- x19 ~ x23)



- C code:

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

- RISCV assembly code:

```
        bne     x22, x23, Else    # go to Else if  i  !=  j
        add     x19, x20, x21     # f  =  g  +  h  ( Executed if  i  = =  j
if)
        beq   x0, x0,  EXIT       # go to Exit
Else:   sub    x19, x20, x21      # f  =  g  -  h  ( Executed if i ≠ j
else)
Exit:                             # the first instruction of the next C
        …… statement
```

Compiling LOOPs

- **Example 2.11 Compiling a loop with variable array index**

  (Assume: g ~ j ----x19 ~ x23 base of A[i] ---- x25)

  - C code:

```
Loop:    g = g + A[i] ;       // A is an array of 100 words
         i = i + j ;
         if ( i != h )  goto Loop ;
```

  - RISC-V assembly code:

```
Loop:  slli  x10, x22, 3         # temp reg x10 = 8 * i
       add   x10, x10, x25       # x10 = address of A[i]
       ld    x19, 0(x10)         # temp reg x19 = A[i]
       add   x20, x20, x19       # g = g + A[i]

       add   x22, x22, x23       # i = i + j
       bne   x22, x21, Loop      # go to Loop if i != h
```

Compiling while

- **Example 2.12** **Compiling a *while* loop**

  (Assume: i ~ k---- x22 and x24   base of save ---- x25)

  - C code:

    ```
    while ( save[i]  = =  k )
              i  = + i  ;
    ```

  - RISCV assembly code:

    ```
    Loop:   slli    x10, x22, 3          # temp reg $t1  =  8  *  i
            add     x10, x10, x25        # x10  =  address of save[i]
            ld      x9, 0(x10)           # x9 gets save[i]
            bne     x9, x24, Exit        # go to Exit  if  save[i]  !=  k
            addi    x22, x22, 1          # i  +=   1
            beq     x0, x0, Loop         # go to Loop
    Exit:
    ```

More Conditional Operations

- **blt rs1, rs2, L1**
  - if (rs1 < rs2) branch to instruction labeled L1
- **bge rs1, rs2, L1**
  - if (rs1 >= rs2) branch to instruction labeled L1
- **Example**
  - if (a > b) a += 1;
  - a in x22, b in x23

```
      bge  x23, x22, Exit       # branch if b >= a
      addi x22, x22, 1
Exit:
```

Signed vs. Unsigned

- **Signed comparison: blt, bge**
- **Unsigned comparison: bltu, bgeu**
- **Example**
  - x22 = 1111 1111 1111 1111 1111 1111 1111 1111
  - x23 = 0000 0000 0000 0000 0000 0000 0000 0001
  - `x22 < x23  # signed`
    - –1 < +1
  - `x22 > x23  # unsigned`
    - +4,294,967,295 > +1

Hold out Case/Switch

- **Used to select one of many alternatives**
- **Example 2.14**

Compiling a switch using *jump address* table

(Assume: f ~ k --x20 ~ x25   x5 contains 4/8)

C code:

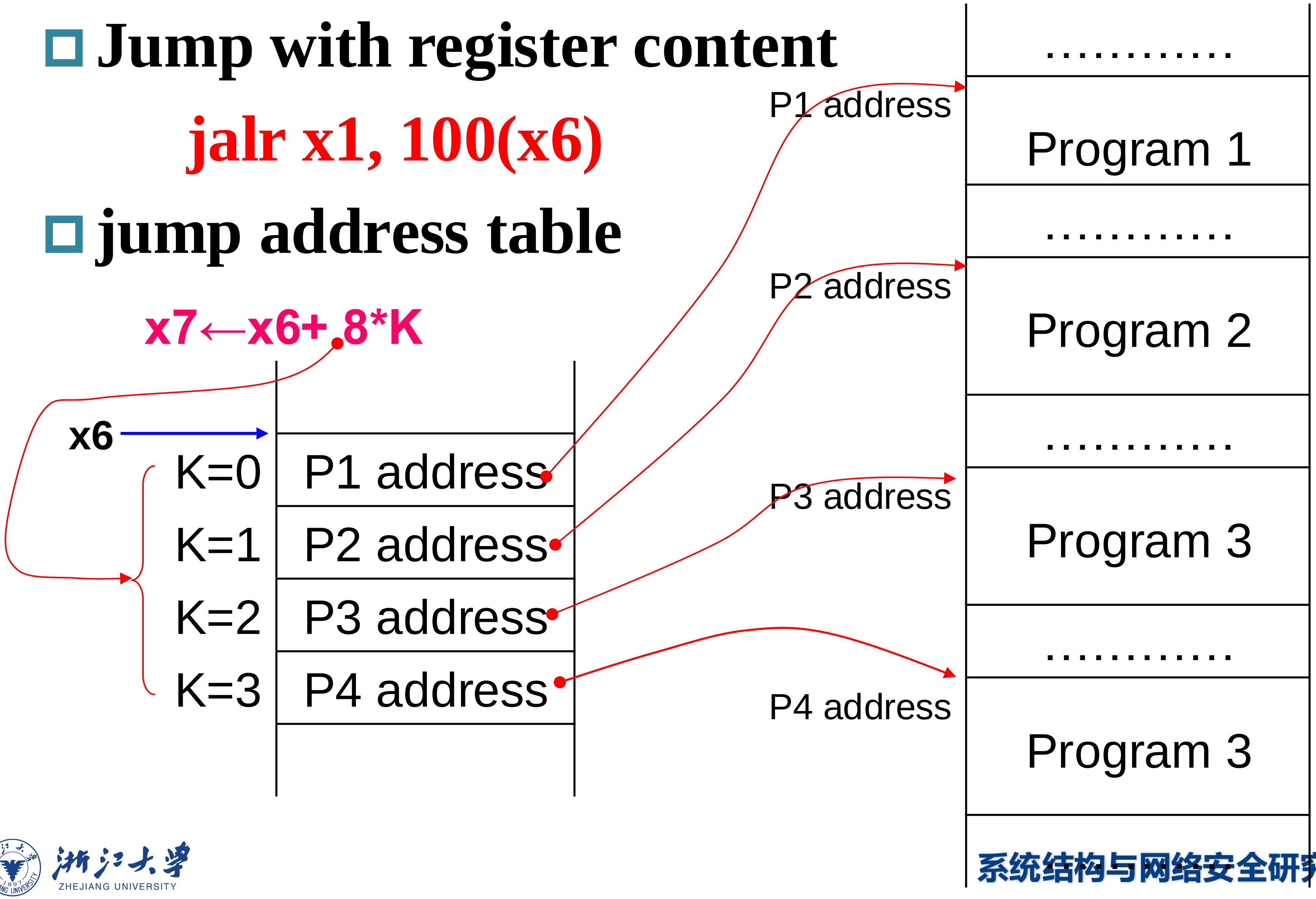
```
switch ( k )  {
        case  0 :   f  =  i  +  j ;  break ;    /*  k  =  0  */
        case  1 :   f  =  g +  h ;  break ;   /*  k  =  1  */
        case  2 :   f  =  g  -  h ;  break ;   /*  k  =  2  */
        case  3 :   f  =  i  -  j ;  break ;    /*  k  =  3  */
}
```

Jump register & jump address table

- Jump with register content

  jalr x1, 100(x6)

- jump address table



RISC-V assembly code:

Boundary

```
blt    x25, x0, Exit        # test if  k  <  0
bge    x25, x5, Exit        # if  k  >=  4,  go to Exit
slli   x7, x25, 3           # temp reg x7  =  8  *  k  (0<=k<=3)
add    x7, x7, x6           # x7  =  address of JumpTable[k]
ld     x7, 0(x7)            # temp reg x7 gets JumpTable[k]
jalr   x1, 0(x7)            # jump based on register x7(entrance)
```

Exit:

jump address table

x7= x6 +8 * k:

Memory1

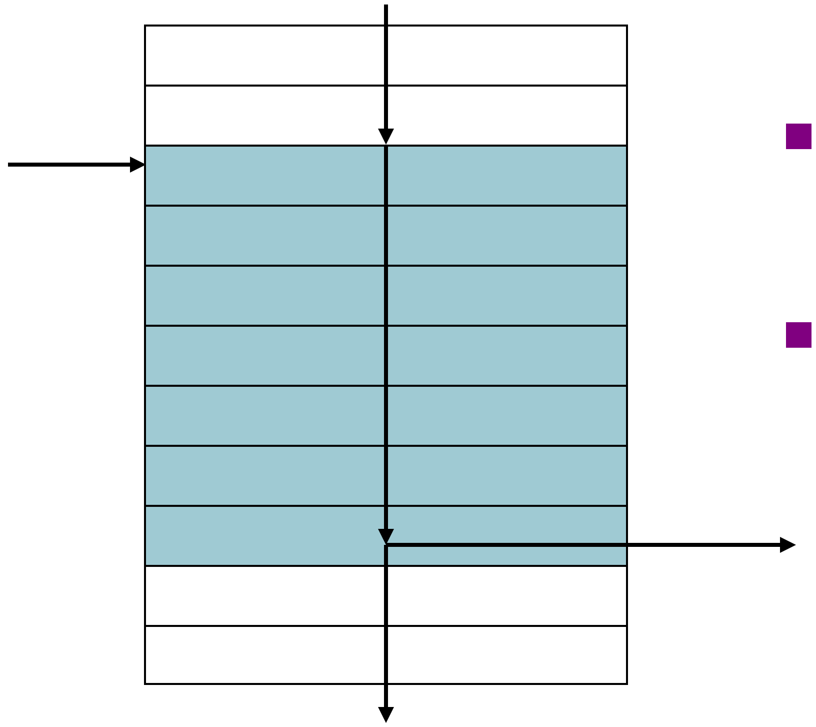
L0:address
L1:address
L2: address
L3:address

```
L0:   add   $s0, $s3, $s4      # k  =  0  so  f  gets  i  +  j
      jalr  x0, 0(x1)          # end of this case so go to Exit
L1:   add   $s0, $s1, $s2      # k  =  1  so  f  gets  g  +  h
      jalr  x0, 0(x1)          # end of this case so go to Exit
L2:   sub   $s0, $s1, $s2      # k  =  2  so  f  gets  g  -  h
      jalr  x0, 0(x1)          # end of this case so go to Exit
L3:   sub   $s0, $s3, $s4      # k  =  3  so  f  gets  i  -  j
      jalr  x0, 0(x1)          # end of  switch statement
```

Memory2

Important conception--Basic Blocks

- **A basic block is a sequence of instructions with**
  - No embedded branches (except at end)
  - No branch **targets** (except at beginning)



- A compiler identifies basic blocks for optimization
- An advanced processor can accelerate execution of basic blocks

2.8 Supporting Procedures

- **Procedure/function be used to structure programs**
  - A stored subroutine that performs a specific task based on the parameters with which it is provided
    - easier to understand, allow code to be reused
  - **Six step**

1. Place Parameters in a place where the procedure can access them
2. Transfer control to the procedure： jump to
3. Acquire the storage resources needed for the procedure
4. Perform the desired task
5. Place the result value in a place where the calling program can access it
6. Return control to the point of origin

Procedure Call Instructions

- Instruction for procedures: jal (jump-and-link)

  Caller **jal x1, ProcedureAddress**

  - Address of following instruction put in x1
  - Jumps to target address

PC+4 → ra

- Procedure return: jump and link register

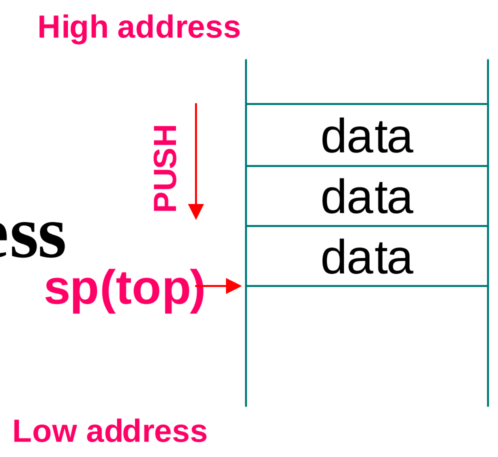
  Callee **jalr x0, 0(x1)**

  - Like jal, but jumps to 0 + address in x1
  - Use x0 as rd (x0 cannot be changed)
  - Can also be used for computed jumps
    - e.g., for case/switch statements

Special registers

Using More Registers

- **More Registers for procedure calling**
  - a0 ~ a7(x10-x17): eight argument registers to pass parameters & return values
  - ra/x1： one return address register to return to origin point
- **Stack**
  - ideal data structure for spilling registers
    - Push, pop
    - Stack pointer **(sp)**
- **Stack grow from higher address to lower address**



- Push: sp= sp - 8

```
addi sp,sp,-8
sd …,0(sp)
```

- Pop: sp = sp + 8

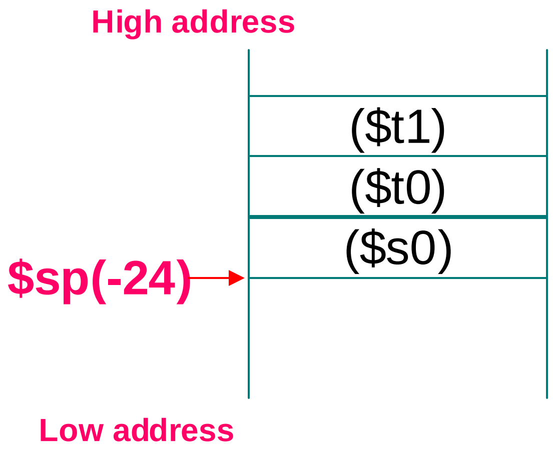
```
ld     …,0(sp)
addi sp,sp,8
```

Example 2.15 Compiling a leaf procedure

(Assume: g, …, j in x10, …, x13 and f in x20)

- C code:

```
long long int   leaf_example (
    long long int g, long long int h,
    long long int i, long long int j){
        long long int f;
        f = (g + h) - (i + j);
        return f;
    }
```



- RISC-V assembly code:

Save value

Return value

```
PUSH  addi   sp, sp, -24        # adjust stack to make room for 3 items
      sd     x5, 16(sp)         #These three instructions save three
      sd     x6,   8(sp)        # register x5,x6,x20
      sd     x20, 0(sp)         #  Let's consider why it need to be done.
```

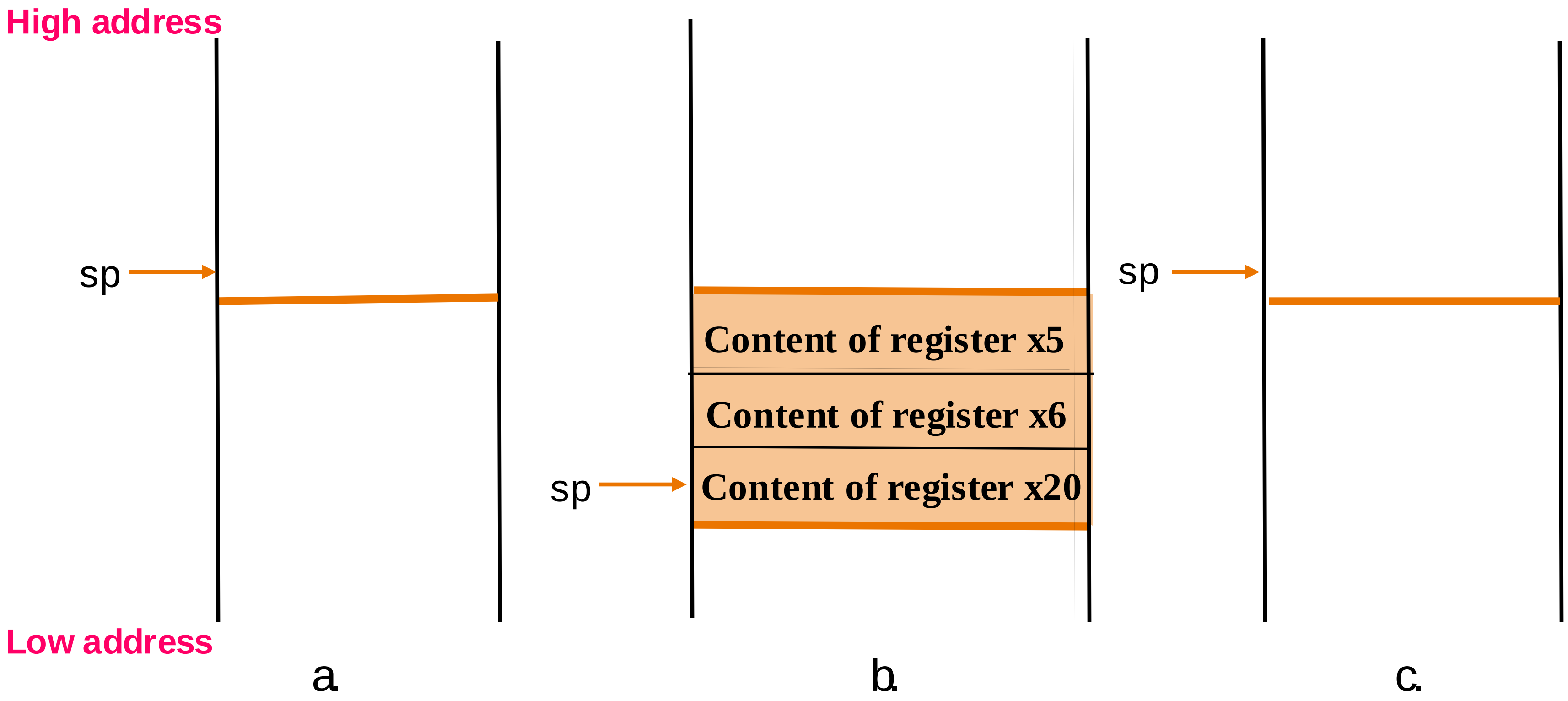
```
add  x5,x10,x11        # register x5contains  g + h
add  x6,x12,x1         # register x6 contains  i + j
sub  x20,x5,x6         # f = x5- x6, which is ( g + h ) – ( i + j )

addi x10,x20,0         # copy f to return register ( x10 = x20 + 0)

     ld    x20, 0(sp)       # restore register x20 for caller
     ld    x6,  8(sp)       # restore register x6 for caller
POP  ld    x5, 16(sp)       # restore register x5 for caller
     addi sp, sp, +24       # adjust stack to delete 3 items
jalr  x0,0(x1)              # jump back to calling routine
```

- **But maybe some of the three are not used by *the caller***
  - So, this way might be inefficient to save x5, x6, x20 on stack
  - Two classes of registers
    - t0 ~ t6: 7 temporary registers, by the callee not preserved
    - s0 ~ s11: 12 saved registers, must be preserved If used

The values of the stack pointer and stack before, during and after procedure call in Example 2.15



- Conflict over the use of register both
  - Push all the registers to stack
    - Caller: pushes a0~a7 or t0~t6
    - Callee: pushes ra (return address) and s0~s11

Nested Procedures

- **Example 2.16 Compiling a recursive procedure (Assume: n -- a0)**
  - C code for n!

```
int   fact ( int   n )
{
        if ( n  <  1 )   return  ( 1 ) ;
             else  return   ( n  *  fact ( n  -  1 ) ) ;
}
```

Argument n in a0
Result in a0

  - RISC-V assembly code

```
fact:  addi    sp, sp, -16              # adjust stack for 2 items
       sd      ra, 8(sp)                # save the return address：  x1
       sd      a0, 0(sp)                # save the argument  n: x10
       addi    t0, a0, -1               # x5 = n  -  1
       bge     t0, zero, L1             # if  n  >=  1, go to L1(else)
       addi    a0, zero, 1              # return 1 if n <1
       addi    sp, sp, 16       # Recover sp (Why not recover x1and x10 ?)
       jalr    zero, 0(ra)              # return to caller
```

Nested Procedures

Argument n in a0
Result in a0

- RISC-V assembly code

```
fact:  addi   sp, sp, -16          # adjust stack for 2 items
       sd     ra, 8(sp)            # save the return address：  x1
       sd     a0, 0(sp)            # save the argument  n: x10
       addi   t0, a0, -1           # x5 = n  -  1
       bge    t0, zero, L1         # if  n  >=  1, go to L1(else)
       addi   a0, zero, 1          # return 1 if n <1
       addi   sp, sp, 16       # Recover sp (Why not recover x1and x10 ?)
       jalr   zero, 0(ra)          # return to caller
L1:    addi   a0,  a0, -1        # n  >=  1: argument gets ( n  -  1 )
       jal    ra, fact           # call fact with ( n  -  1)
----------------------------------------------------------------------
       add    t1, a0, zero       #move result of fact(n - 1) to x6(t1)
       ld     a0, 0(sp)         # return from jal: restore argument n
       ld     ra, 8(sp)         # restore the return address
       add    sp, sp, 16         # adjust stack pointer to pop 2 items
       mul    a0, a0, t1        # return  n*fact ( n  -  1 )
       jalr   zero, 0(ra)       # return to the  caller
```

Nested Procedures-Continue

```
L1:  addi   a0,  a0, -1             # n  >=  1: argument gets ( n  -  1 )
     jal    ra, fact                # call fact with ( n  -  1)
     add    t1, a0, zero            #move result of fact(n - 1) to x6(t1)
     ld     a0, 0(sp)               # return from jal: restore argument n
     ld     ra, 8(sp)               # restore the return address
     add    sp, sp, 16              # adjust stack pointer to pop 2 items
     mul    a0, a0, t1              # return  n*fact ( n  -  1 )
     jalr   zero, 0(ra)             # return to the  caller
```

- **Why a0 is saved?   Why ra is saved?**
- **Preserved things across a procedure call**

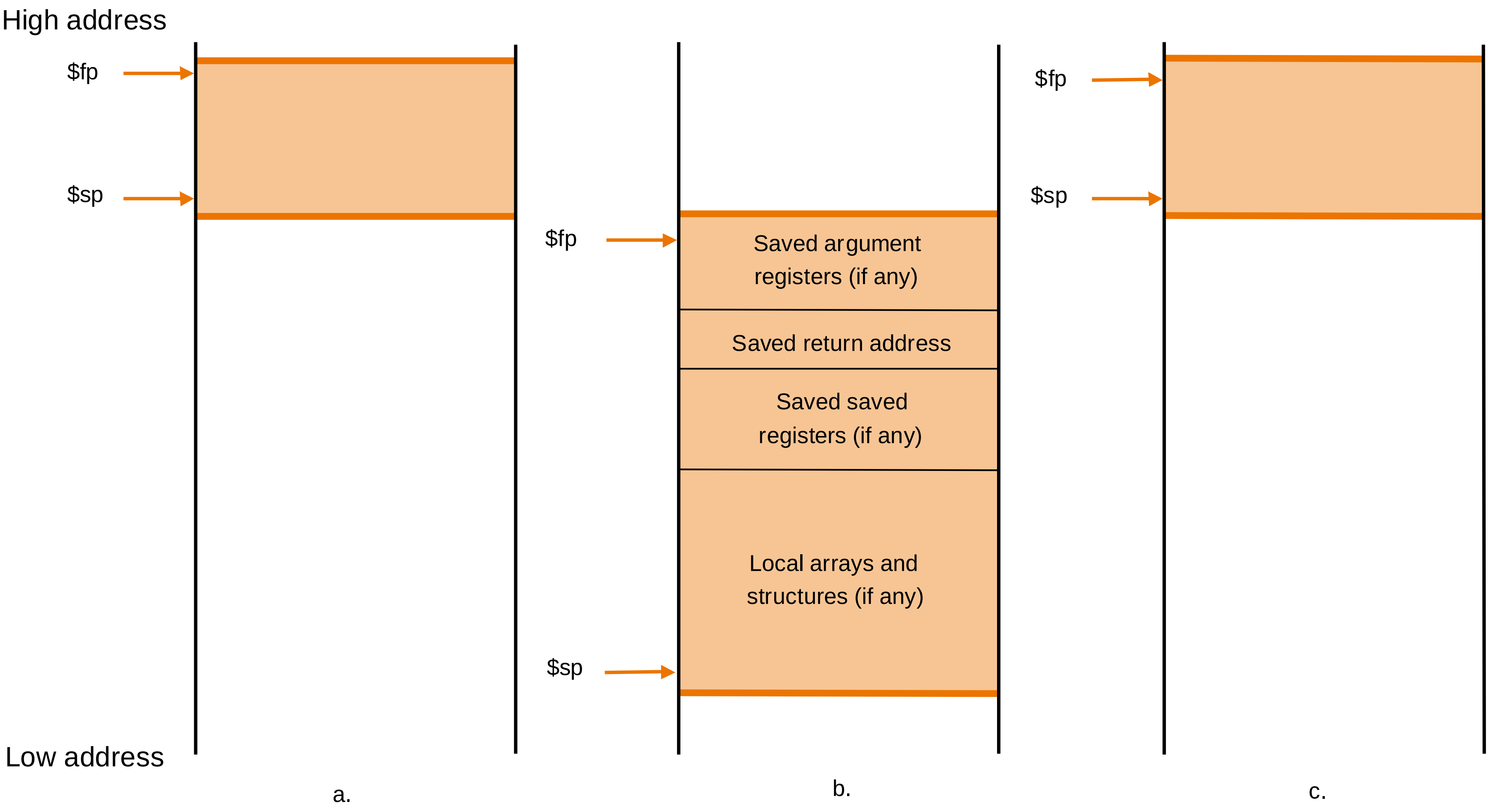
  Saved registers(s0 ~ s11), stack pointer register($sp), return address register(ra/x1), stack above the stack pointer
- **Not preserved things across a procedure call**

  Temporary registers(t0 ~ t7), argument registers(a0 ~ a7), return value registers(a0 ~ a7), stack below the stack pointer

What is and what is not preserved across a procedure call

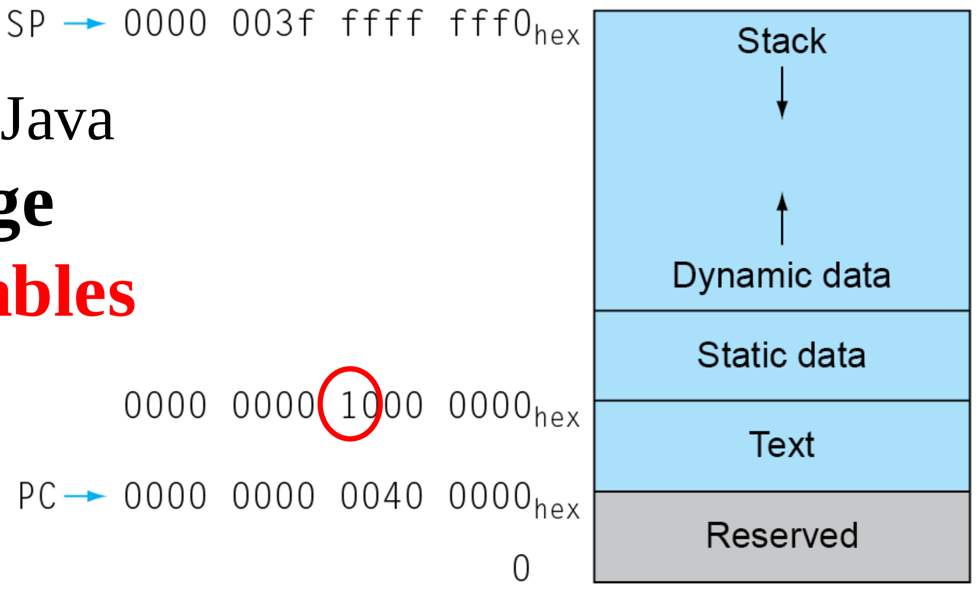
Preserved	Not preserved
Saved registers: x8-x9, x18-x27	Temporary registers: x5-x7, x28-x31
Stack pointer register: x2(sp)	Argument/result registers: x10-x17
Frame pointer: x8(fp)	
Return address: x1(ra)	
Stack above the stack pointer	Stack below the stack pointer

Stack allocation before, during and after procedure call


High address
$fp
$sp
$fp
Saved argument registers (if any)
Saved return address
Saved saved registers (if any)
Local arrays and structures (if any)
$sp
$fp
$sp
Low address
a.
b.
c.

Memory Layout

- **Text: program code**
- **Static data: global variables**
  - e.g., static variables in C, constant arrays and strings
  - x3 (global pointer) initialized to address allowing ±offsets into this segment
- **Dynamic data: heap**
  - E.g., malloc in C, new in Java
- **Stack: automatic storage**
- **Storage class of C variables**
  - *automatic*
  - *static*

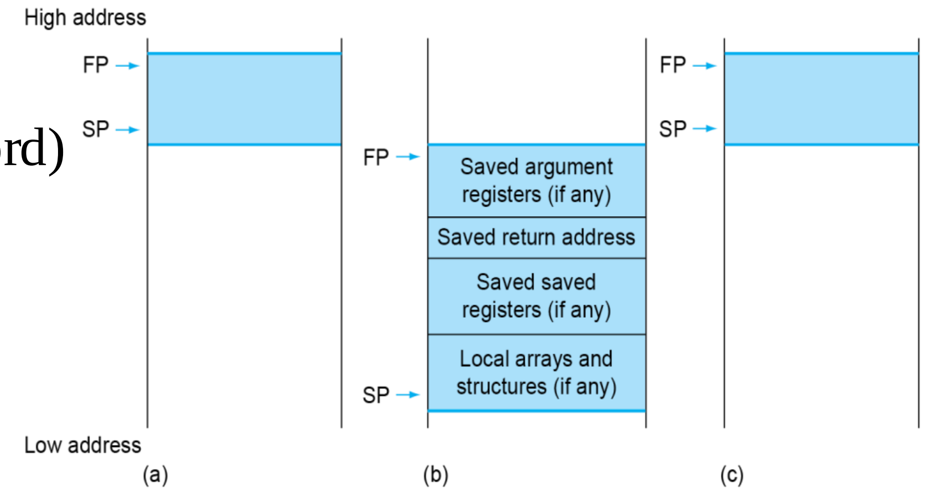


Local Data on the Stack

- **Allocating Space for New Data on the Stack**
  - Procedure frame/activation record
    - The segment of stack containing a procedure's saved registers and local variables
  - Frame pointer
    - A value denoting the location of saved register and local variables for a given procedure
    - Local data allocated by callee

      e.g., C automatic variables
    - Procedure frame (activation record)

      Used by some compilers to manage stack storage


High address
FP
SP
FP
Saved argument registers (if any)
Saved return address
Saved saved registers (if any)
Local arrays and structures (if any)
SP
FP
SP
Low address
(a)
(b)
(c)

RISC-V operands

Name	Example	Comments
32 registers	*x*0-*x*31	Fast locations for data. In RISC-V, data must be in registers to perform arithmetic. Register x0 always equals 0.
2^{61} memory double words	Memory[0], Memory[8], …, Memory[18,446,744,073,709,551,608]]	Accessed only by data transfer instructions. RISC-V uses byte addresses, so sequential double word accesses differ by 8. Memory holds data structures, arrays, and spilled registers.

Name	Register no.	Usage	Preserved on call
x0(zero)	**0**	**The constant value 0**	n.a.
*x*1(**ra**)	1	Return address(link register)	yes
*x*2(**sp**)	2	Stack pointer	yes
*x*3(gp)	3	Global pointer	yes
*x*4(tp)	4	Thread pointer	yes
*x*5-*x*7(t0-t2)	5-7	Temporaries	no
*x*8(s0/fp)	8	Saved/frame point	Yes
*x*9(s1)	9	Saved	Yes
*x*10-*x*17(a0-a7)	10-17	Arguments/results	no
*x*18-*x*27(s2-s11)	18-27	Saved	yes
*x*28-*x*31(t3-t6)	28-31	Temporaries	No
PC	-	Auipc(Add Upper Immediate to PC)	Yes

RISC-V assembly language

Category	Instruction	Example	Meaning	Comments
Arithmetic	add	add x5,x6,x7	x5=x6 + x7	Add two source register operands
	subtract	sub x5,x6,x7	x5=x6 - x7	First source register subtracts second one
	add immediate	addi x5,x6,20	x5=x6+20	Used to add constants
Data transfer	load doubleword	ld x5, 40(x6)	x5=Memory[x6+40]	doubleword from memory to register
	store doubleword	sd x5, 40(x6)	Memory[x6+40]=x5	doubleword from register to memory
	load word	lw x5, 40(x6)	x5=Memory[x6+40]	word from memory to register
	load word, unsigned	lwu x5, 40(x6)	x5=Memory[x6+40]	Unsigned word from memory to register
	store word	sw x5, 40(x6)	Memory[x6+40]=x5	word from register to memory
	load halfword	lh x5, 40(x6)	x5=Memory[x6+40]	Halfword from memory to register
Data transfer	load halfword, unsigned	lhu x5, 40(x6)	x5=Memory[x6+40]	Unsigned halfword from memory to register
	store halfword	sh x5, 40(x6)	Memory[x6+40]=x5	halfword from register to memory
	load byte	lb x5, 40(x6)	x5=Memory[x6+40]	byte from memory to register
	load word, unsigned	lbu x5, 40(x6)	x5=Memory[x6+40]	Unsigned byte from memory to register
	store byte	sb x5, 40(x6)	Memory[x6+40]=x5	byte from register to memory
	load reserved	lr.d x5,(x6)	x5=Memory[x6]	Load;1st half of atomic swap
	store conditional	sc.d x7,x5,(x6)	Memory[x6]=x5; x7 = 0/1	Store;2nd half of atomic swap
	Load upper immediate	lui x5,0x12345	x5=0x12345000	Loads 20-bits constant shifted left 12 bits

RISC-V assembly language

Category	Instruction	Example	Meaning	Comments
Logical	and	and x5, x6, 3	x5=x6 & 3	Arithmetic shift right by register
	inclusive or	or x5,x6,x7	x5=x6 | x7	Bit-by-bit OR
	exclusive or	xor x5,x6,x7	x5=x6 ^ x7	Bit-by-bit XOR
	and immediate	andi x5,x6,20	x5=x6 & 20	Bit-by-bit AND reg. with constant
	inclusive or immediate	ori x5,x6,20	x5=x6 | 20	Bit-by-bit OR reg. with constant
	exclusive or immediate	xori x5,x6,20	X5=x6 ^ 20	Bit-by-bit XOR reg. with constant
Shift	shift left logical	sll x5, x6, x7	x5=x6 << x7	Shift left by register
	shift right logical	srl x5, x6, x7	x5=x6 >> x7	Shift right by register
	shift right arithmetic	sra x5, x6, x7	x5=x6 >> x7	Arithmetic shift right by register
	shift left logical immediate	slli x5, x6, 3	x5=x6 << 3	Shift left by immediate
Shift	shift right logical immediate	srli x5,x6,3	x5=x6 >> 3	Shift right by immediate
	shift right arithmetic immediate	srai x5,x6,3	x5=x6 >> 3	Arithmetic shift right by immediate
Conditional branch	branch if equal	beq x5, x6, 100	if(x5 == x6) go to PC+100	PC-relative branch if registers equal
	branch if not equal	bne x5, x6, 100	if(x5 != x6) go to PC+100	PC-relative branch if registers not equal
	branch if less than	blt x5, x6, 100	if(x5 < x6) go to PC+100	PC-relative branch if registers less
	branch if greater or equal	bge x5, x6, 100	if(x5 >= x6) go to PC+100	PC-relative branch if registers greater or equal
	branch if less, unsigned	bltu x5, x6, 100	if(x5 >= x6) go to PC+100	PC-relative branch if registers less, unsigned
	branch if greater or equal, unsigned	bgeu x5, x6, 100	if(x5 >= x6) go to PC+100	PC-relative branch if registers greater or equal, unsigned
Unconditional branch	jump and link	jal x1, 100	x1 = PC + 4; go to PC+100	PC-relative procedure call
	jump and link register	jalr x1, 100(x5)	x1 = PC + 4; go to x5+100	procedure return; indirect call

2.9 Communicating with People
Character Data

- **Byte-encoded character sets**
  - ASCII (American Standard Code for Information Interchange)
    - 128 characters： 95 graphic, 33 control
  - Latin-1: 256 characters
    - ASCII, +96 more graphic characters
- **Unicode: 32-bit character set**
  - Used in Java, C++ wide characters, …
  - Most of the world’s alphabets, plus symbols
  - UTF-8, UTF-16: variable-length encodings

Byte/Halfword/Word Operations

- RISC-V byte/halfword/word load/store
  - Load byte/halfword/word: Sign extend to 64 bits in rd
    - `lb rd, offset(rs1)`
    - `lh rd, offset(rs1)`
    - `lw rd, offset(rs1)`
  - Load byte/halfword/word unsigned: 0 extend to 64 bits in rd
    - `lbu rd, offset(rs1)`
    - `lhu rd, offset(rs1)`
    - `lwu rd, offset(rs1)`
  - Store byte/halfword/word: Store rightmost 8/16/32 bits
    - `sb rs2, offset(rs1)`
    - `sh rs2, offset(rs1)`
    - `sw rs2, offset(rs1)`

String Copy Example

- **Example 2.17 Compiling a string copy procedure**

  (Assume: base addresses for i -- x19, x's base --x10, y's base --x11)

  - C code： Y→X

```
void   strcpy ( char   x[  ] ,   char   y[  ] )
{      size_t   i ;
       i  =  0 ;
       while ( ( x[ i ]  =  y[ i ] )  != '\ 0' )       /* copy and test byte  */
                 i  +=  1 ;
}
```

  - RISC-V assembly code:

```
strcpy:    addi   sp, sp, -8            # adjust stack for 1 doubleword
           sd     x19, 0(sp)            # save x19
           add    x19, x0, x0           # i  =  0
L1:        add    x5, x19, x11          # x5 = address of y[ i]
           lbu    x6, 0(x5)             # x6  =  y [ i ]
           add    x7, x19, x10          # x7 = address of x[ i ]
           sb     x6, 0(x7)             # x[ i ]  =  y[ i ]
```

```
        beq     x6, x0,  L2         # if y[i] == 0 then exit
        addi    x19, x19, 1                  # i  =  i  +  1
        jal     x0, L1                # next iteration of loop
L2:     ld      x19, 0(sp)            # restore saved old s3
        addi    sp, sp, 8            # pop 1 double word from stack
        jalr    zero  0(x1)           # return
```

Optimization for example 2.17

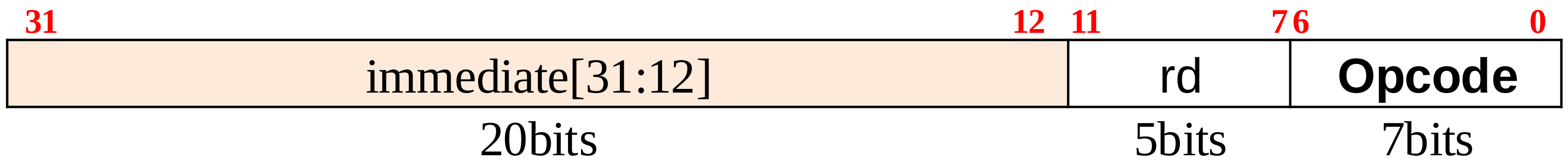
- strcpy is a leaf procedure
- Allocate i to a temporary register s3/x18

For a leaf procedure

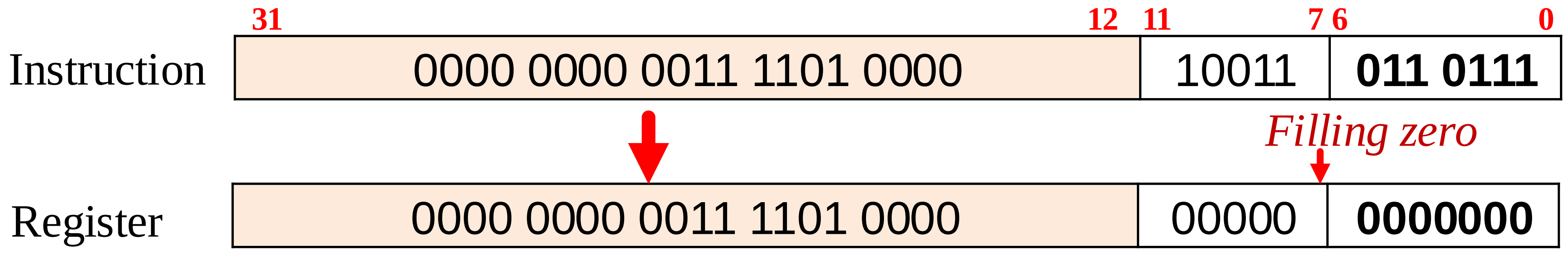
- The compiler exhausts all temporary registers
- Then use the registers it must save

2.10 Addressing for 32-Bit Immediate and Addresses

- **Wide Bit Immediate addressing**
  - most constants is short and fit into 12-bit field
  - Set upper 20 bits of a constants in a register with *load upper immediate* (lui rd, constant)
- instruction format (U-type)



- lui x19, 976 # 0x003D0



32-bit Constants

Example 2.19 Loading a 32-bit constant

- The 32-bit constant:

0000 0000 0011 1101 0000 *1001 0000 0000* $(976*16^3 + 2304=4000000)_{10}$

- RISC V code:

lui s3, 976 # 976 decimal = 0000 0000 0011 1101 0000 binary

0000 0000 0000 0000	0000 0000 0000 0000	0000 0000 0011 1101 0000	0000 0000 0000

(The value of s3 afterward is: 0000 0000 0011 1101 0000 0000 0000 0000)

addi s3, s3, 2304 # 2304 decimal = 1001 0000 0000 binary

1111 1111 1111 1111	1111 1111 1111 1111	1111 1111 1111 1111 1111	1001 0000 0000

The value of s3 afterward is: 实际补码值2304 become -1792 / sign extended

0000 0000 0000 0000	0000 0000 0000 0000	0000 0000 0011 1100 1111	1001 0000 0000	✗

S3 + 2304 become S3 - 1792 ↑

0000 0000 0000 0000	0000 0000 0000 0000	0000 0000 0011 1101 0000	1001 0000 0000	√

结果 + 4096（2^12）可以修正这个问题，所以就是bit 12 + 1

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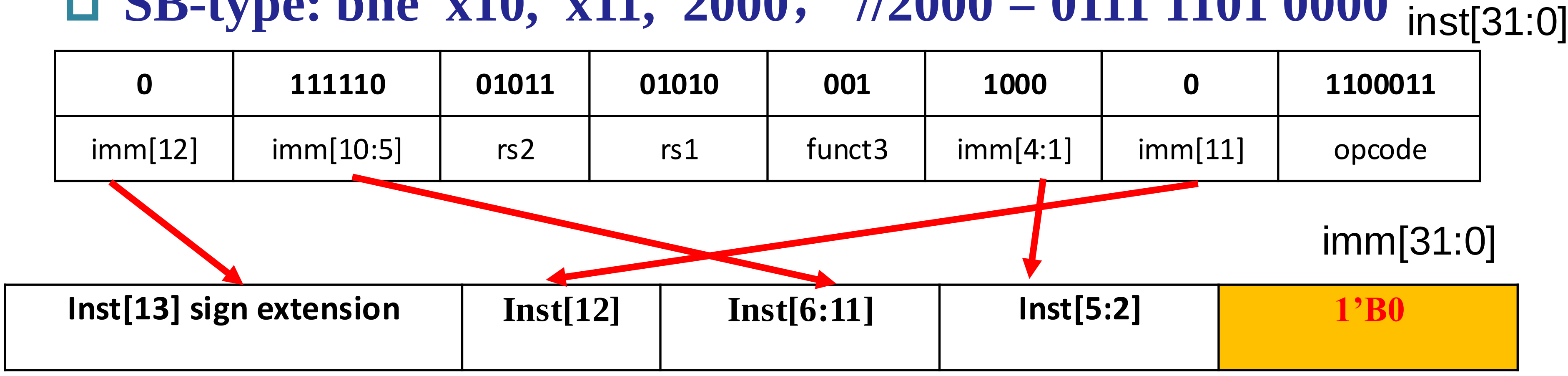
这样结果就是两个立即数的拼接！

Branch Addressing

- **Addressing in branches**
  - Branch instructions specify
    - Opcode, two registers, target address
  - Most branch targets are near branch
    - Forward or backward
- **SB-type: bne x10, x11, 2000， //2000 = 0111 1101 0000**



0	111110	01011	01010	001	1000	0	1100011
imm[12]	imm[10:5]	rs2	rs1	funct3	imm[4:1]	imm[11]	opcode

Inst[13] sign extension	Inst[12]	Inst[6:11]	Inst[5:2]	1’B0

  - PC-relative addressing

    Target address = PC + Branch offset

    = PC + immediate × 2

Jump Addressing

- **Jump and link (jal)**
  - target uses 20-bit immediate for larger range
- **UJ format:**

UJ = {{11{inst[31]}}, inst [31], inst[19:12], inst[20], inst[30:21],1'b0};

31	1bit	10bits	1bit	8bits	12	11	7	6	0
	inn[20]	*imm[10:1]*	*imm[11]*	*imm[19:12]*		**rd**		**Opcode**	
		20bit				5bit		7bit	

- **jal x0, 2000** **# 2000_{10} =(0 *00000000* 0 *111 1101 000*0)$_2$**

31	1bit	10bits	1bit	8bits	12	11	7	6	0
	0	***1111101000***	**0**	***00000000***		**00000**		**1101111**	
		20bit				5bit		7bit	

- **For more long jumps:** eg, to 32-bit absolute address
  - lui: load address[31:12] to temp register
  - jalr: add address[11:0] and jump to target

Show branch offset in machine language

- **Example 2.20** **P116/p94**
  - C language:

```
while (save[i]==k)  i=i+1;
```

RISC-V assembler code in Example 2.12:

```
Loop:  slli   x10,  x22, 3          # temp reg x10  =  8  *  i
       add    x10, x10, x25         # x10  =  address of save[i]
       ld     x9, 0(x10)            # temp reg x9  =  save[i]
       bne    x9, x24, Exit         # go to Exit  if  save[i]  !=  k
-----------------------------
       addi   x22, x22, 1           #  i  =  i  +  1
       beq    x0, x0, Loop        # go to Loop
Exit:
```

Instructions Addressing and their Offset

instructions Code with Binary

	Address	fun7	rs2	rs1	fun3	rd/offset	OP	Hex
Loop: slli	80000	0000000	00011	10110	001	01010	0010011	003B1513
add	80004	0000000	11001	01010	000	01010	0110011	01950533
ld	80008	0000000	00000	01010	011	01001	0000011	00053483
bne	*80012*	0000000	11000	01001	001	0110*0*	1100011	01849663
addi	80016	0000000	00001	10110	000	10110	0010011	001B0B13
beq	80020	1111111	00000	00000	000	0110*1*	1100011	FE0006E3
Exit:	80024	……						

-10

6 =0110

-20 = 80000 - 80020

PC + offset : 12 = 80024 - 80012

- Modification:
  - All RISC-V instructions are 4 bytes long
  - PC-relative addressing refers to the number of halfwords
    - The address field at 80012 above should be 6 instead of 12

While branch target is far away

- **Inserts an unconditional jump to target**
  - **Invert** the **condition** so that the branch decides whether to skip the jump
- **Example 2.21 p117: Branching far away**
  - Given a branch:

```
        beq   x10, x0, L1
```

  - Rewrite it to offer a much greater branching distance:

```
        bne   x10, x0, L2
        jal   x0,      L1
  L2:
```

Summary of RISC-V architecture in Ch. 2

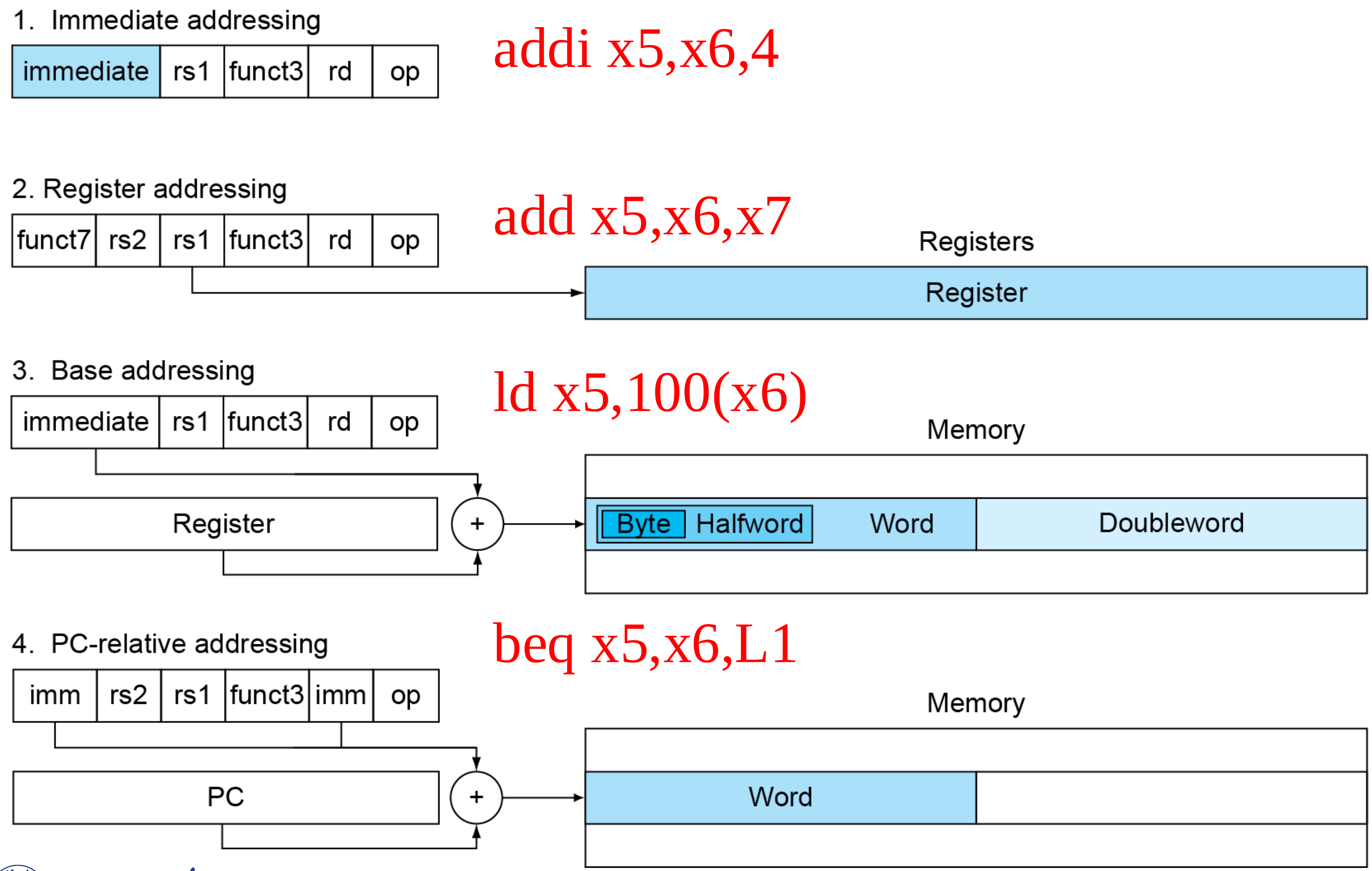
- **RISC-V Instruction Format and Their Operands**

Name	Fields						Comments
Field size	31 *7bits* 25	24 *5bits* 20	19 *5bits* 15	14 *3bits* 12	11 *5bits* 7	6 *7bits* 0	All RISC-V instruction 32 b
R-type	**funct7**	**rs2**	**rs1**	**funct3**	**rd**	**opcode**	Arithmetic instruction format
I-type	immediate[11:0]		**rs1**	**funct3**	**rd**	**opcode**	Loads & immediate arithmetic
S-type	immed[11:5]	rs2	**rs1**	**funct3**	immed[4:0]	**opcode**	Stores
SB-type	*imm[12,10:5]*	rs2	**rs1**	**funct3**	*imm[4:1,11]*	**opcode**	Conditional branch format
UJ-type	*immediate[20,10:1,11,19:12]*				**rd**	**opcode**	Unconditional jump format
U-type	immediate[31:12]				**rd**	**opcode**	Upper immediate format

Name	Operands
32 registers	$zero, ra, sp, gp, tp, t0-t6, s0~s11, a0~a7
Mem words	Memory[0], Memory[8], Memory[10], . . . , Memory[18,446,744,073,709,551,608]

*x*0(zero)	0	The constant value 0	n.a.
*x*1(**ra**)	1	Return address(link register)	yes
*x*2(**sp**)	2	Stack pointer	yes
*x*3(gp)	3	Global pointer	yes
*x*4(tp)	4	Thread pointer	yes
*x*5-*x*7(t0-t2)	5-7	Temporaries	no
*x*8(s0/fp)	8	Saved/frame point	Yes
*x*9(s1)	9	Saved	Yes
*x*10-*x*17(a0-a7)	10-17	Arguments/results	no
*x*18-*x*27(s2-s11)	18-27	Saved	yes
*x*28-*x*31(t3-t6)	28-31	Temporaries	No
PC	-	Auipc(Add Upper Immediate to PC)	

RISC-V Addressing Summary



addi x5,x6,4

add x5,x6,x7

ld x5,100(x6)

beq x5,x6,L1

RISC-V Disassembly

- **Example 2.22 P120: Decoding machine code**
  - **Machine instruction(0x00578833)**

(Bits: 31 25 24 20 7 2 0)

0000000 00101 01111 000 10000 0110011

Decoding

- Determine the operation from opcode

  opcode: 0110011→ **R-type arithmetic instruction**

funct7	rs2	rs1	funct3	rd	opcode
000 0000	00101	01111	000	10000	**0110011**

funct7 and funct3 are all 0 → **add instruction**

p107-P119

- Determine other fields

  rs2: x5/t0; rs1: x15/a5; rd: x16/a7

- Show the assembly instruction:

  add a7, a5, t0 (Note: add rd,rs,rt)

Summary of RISC-V instruction encoding

Format	Instruction	Opcode	Funct3	Funct6/7
R-type	add	0110011	000	0000000
	sub	0110011	000	0100000
	sll	0110011	001	0000000
	xor	0110011	100	0000000
	srl	0110011	101	0000000
	sra	0110011	101	0100000
	or	0110011	110	0000000
	and	0110011	111	0000000
	lr.d	0110011	011	0001000
	sc.d	0110011	011	0001100

Summary of RISC-V instruction encoding

Format	Instruction	Opcode	Funct3	Funct6/7
I-type	lb	0000011	000	n.a.
	lh	0000011	001	n.a.
	lw	0000011	010	n.a.
	ld	0000011	011	n.a.
	lbu	0000011	100	n.a.
	lhu	0000011	101	n.a.
	lwu	0000011	110	n.a.
	addi	0010011	000	n.a.
	slli	0010011	001	000000
	xori	0010011	100	n.a.
	srli	0010011	101	000000
	srai	0010011	101	010000
	ori	0010011	110	n.a.
	andi	0010011	111	n.a.
	jalr	1100111	000	n.a.

Summary of RISC-V instruction encoding

Format	Instruction	Opcode	Funct3	Funct6/7
S-type	sb	0100011	000	n.a.
	sh	0100011	001	n.a.
	sw	0100011	010	n.a.
	sd	0100011	111	n.a.
SB-type	beq	1100111	000	n.a.
	bne	1100111	001	n.a.
	blt	1100111	100	n.a.
	bge	1100111	101	n.a.
	bltu	1100111	110	n.a.
	bgeu	1100111	111	n.a.
U-type	lui	0110111	n.a.	n.a.
UJ-type	jal	1101111	n.a.	n.a.

2.11 Synchronization in RISC-V

- **Two processors sharing an area of memory**
  - P1 writes, then P2 reads
  - Data race if P1 and P2 don’t synchronize
    - Result depends of order of accesses
- **Hardware support required**
  - Atomic read/write memory operation
  - No other access to the location allowed between the read and write
- **Could be a single instruction**
  - E.g., atomic swap of register ↔ memory
  - Or an atomic pair of instructions

Synchronization in RISC-V

- **Load reserved: `lr.d rd,(rs1)`**
  - Load from address in rs1 to rd
  - Place reservation on memory address
- **Store conditional: `sc.d rd,(rs1),rs2`**
  - Store from rs2 to address in rs1
  - Succeeds if location not changed since the `lr.d`
    - Returns 0 in rd
  - Fails if location is changed
    - Returns non-zero value in rd

Synchronization in RISC-V

- **Example 1: atomic swap (to test/set lock variable)**

```
again: lr.d x10,(x20)
       sc.d x11,(x20),x23 // X11 = status
       bne  x11,x0,again  // branch if store failed
       addi x23,x10,0     // X23 = loaded value
```

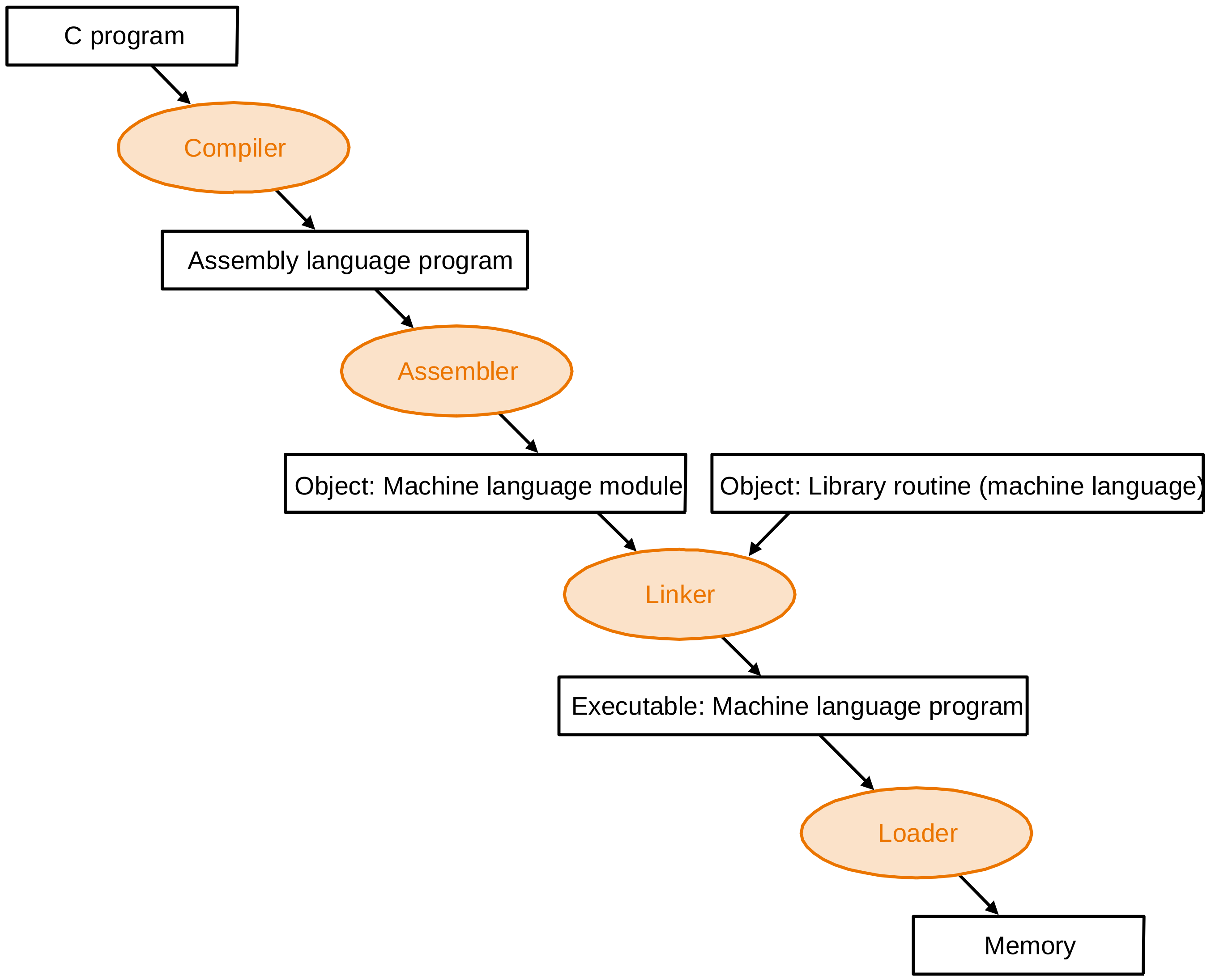
- **Example 2: lock**

```
       addi x12,x0,1          // copy locked value
again: lr.d x10,(x20)         // read lock
       bne  x10,x0,again      // check if it is 0 yet
       sc.d x11,(x20),x12     // attempt to store
       bne  x11,x0,again      // branch if fails
```

- **Unlock:**

```
       sd   x0,0(x20)         // free lock
```

2.12 Translating and starting a program


C program
Compiler
Assembly language program
Assembler
Object: Machine language module
Object: Library routine (machine language)
Linker
Executable: Machine language program
Loader
Memory

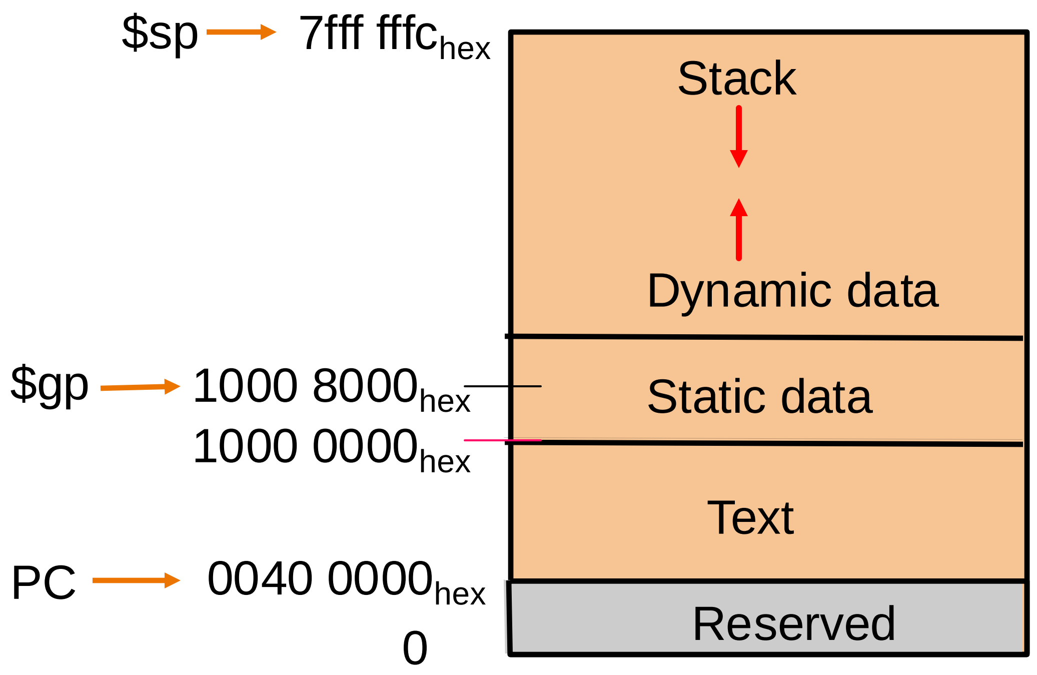
Producing an Object Module

- Assembler (or compiler) translates program into machine instructions
- 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 refs
  - Debug info: for associating with source code

Object file header			
	Name	**Procedure A**	
	Text size	**100_{hex}**	
	Data size	**20_{hex}**	
Text segment	**Address**	**instruction**	
	0	**ld x10, 0(gp)**	
	4	**jal x1, 0**	
	……	**--**	
Data segment	**0**	**(X)**	
	……	**……**	
Relocation information	**Address**	**Instruction type**	**Dependency**
	0	**ld**	**X**
	4	**jal**	**B**
Symbol table	**label**	**Address**	
	X	**--**	
	B	**--**	

Link

- Object modules(including library routine) → **executable program**
- 3 steps of Link
  - Place code and data modules symbolically in memory
  - Determine the addresses of data and instruction labels
  - Patch both the internal and external references (**Address of invoke**)



Loading a Program

- **Load from image file on disk into memory**
  1. Read header to determine segment sizes
  2. Create virtual address space
  3. Copy text and initialized data into memory
     - Or set page table entries so they can be faulted in
  4. Set up arguments on stack
  5. Initialize registers (including sp, fp, gp)
  6. Jump to startup routine
     - Copies arguments to x10, … and calls main
     - When main returns, do exit syscall

Dynamic Linking

- **Only link/load library procedure when it is called**
  - Requires procedure code to be relocatable
  - Avoids image bloat caused by static linking of all (transitively) referenced libraries
  - Automatically picks up new library versions

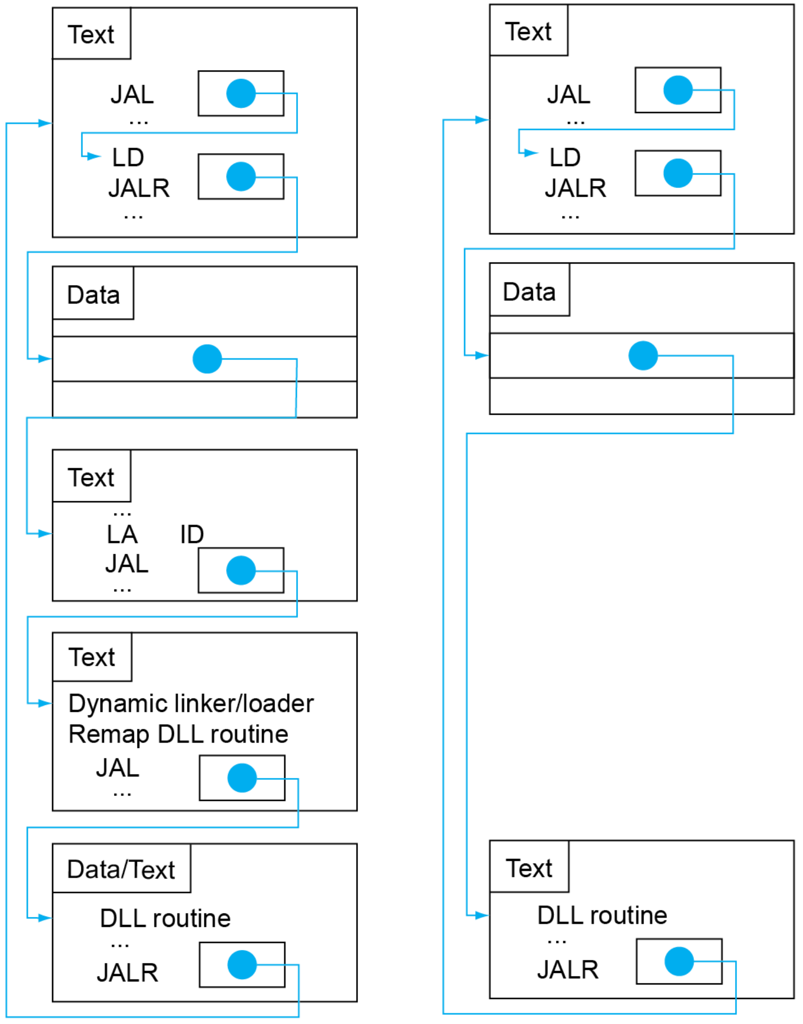
Lazy Linkage

Indirection table

Stub: Loads routine ID,
Jump to linker/loader

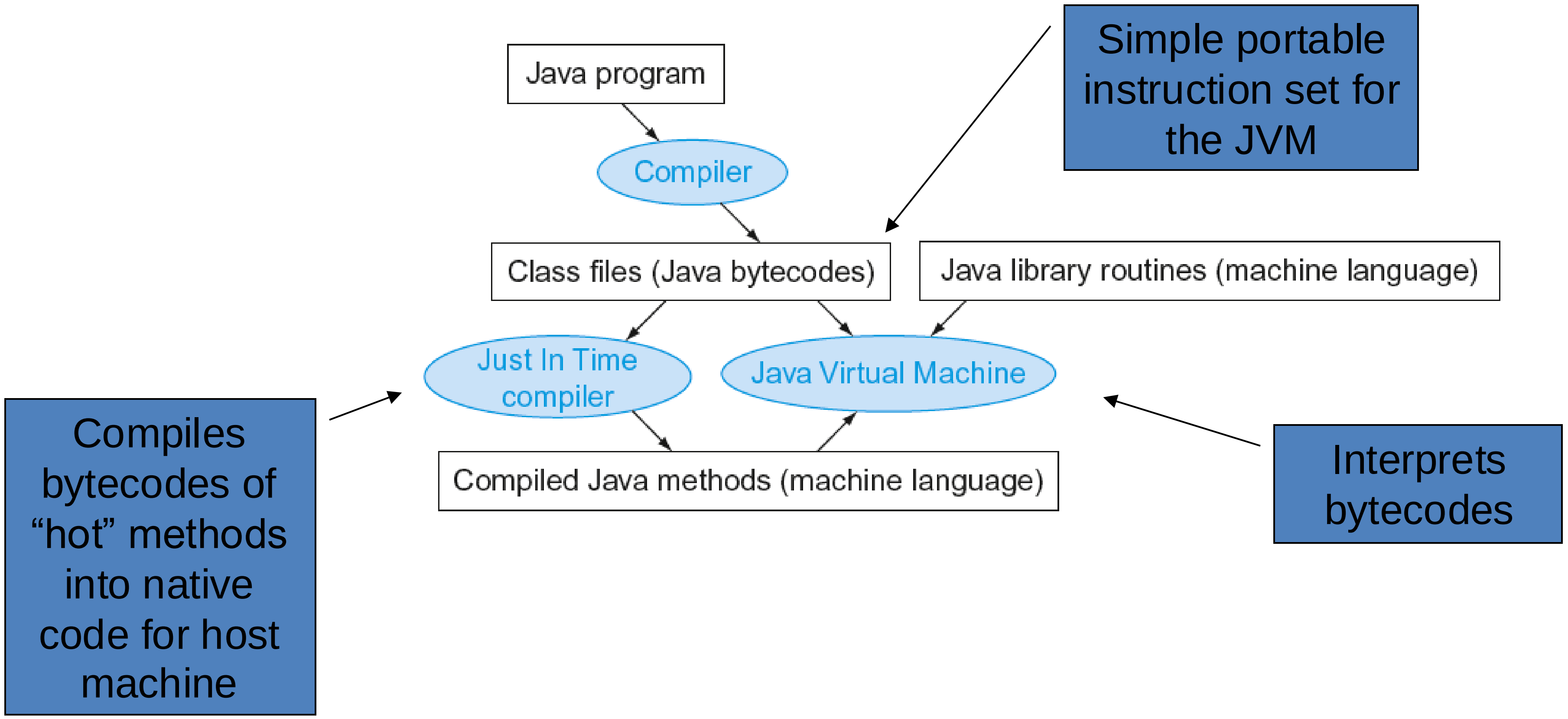
Linker/loader code

Dynamically
mapped code



(a) First call to DLL routine (b) Subsequent calls to DLL routine

Starting Java Applications


Java program
Compiler
Class files (Java bytecodes)
Java library routines (machine language)
Just In Time compiler
Java Virtual Machine
Compiled Java methods (machine language)
Simple portable instruction set for the JVM
Compiles bytecodes of "hot" methods into native code for host machine
Interprets bytecodes

2.13 A C Sort Example To Put it All Together

- **Three general steps for translating C procedures**
  - Allocate registers to program variables
  - Produce code for the body of the procedures
  - Preserve registers across the procedures invocation
- **Procedure *swap***
  - C code

```
void   swap ( long  long    v[  ] ,    size_t  k )
{
        long  long   temp ;
        temp  =  v[ k ] ;
        v[ k ] =  v[ k + 1 ] ;
        v[ k + 1 ]  =  temp ;
}
```

The Procedure Swap

- Register allocation for *swap*

  v ---- x10 k ---- x11 temp ---- x5

- *swap* is a leaf procedure, nothing to preserve
- RISC-V code for the procedure *swap*
  - **Procedure body**

```
swap:   slli   x6,  x11, 3        //  x6 = k * 8
        add    x6,  x10, x6       //  x6 = v + ( k * 8 )
        ld     x5, 0(x6)          //  x5 ← v[ k ]
        ld     x7, 8(x6)          //  x7 ← v[ k + 1 ]
        sd     x7, 0(x6)          //  v[k+1] → v[ k ]
        sd     x5, 8(x6)          //  v[k] → v[ k + 1 ]
```

  - **Procedure return**

```
      jalr   x0,   0(x1)          //   return to calling routine
```

The Sort Procedure in C

Procedure *sort*

- C code

```
void  sort (long  long    v[  ] ,    size_t    n )
{
        size_t    i ,  j ;
        for ( i  =  0 ; i  <  n ; i + =  1 ) {
              for ( j  =  i  -  1 ; j  >=  0  &&  v[j]  >  v[j+1] ; j -=  1 )
                     swap ( v ,  j ) ;
        }
}
```

- **Register allocation** for *sort*

  v ---- x10   n ---- x11   i ---- x19   j ---- x20

- **Passing parameters** in *sort*
- **Preserving registers** in *sort*

  x1 , x19, x20, x21, x22

The Outer Loop

- Skeleton of outer loop:
  - for (i = 0; i <n; i += 1) {

```
   li   x19,0         // i = 0
for1tst:
   bge  x19,x11,exit1   // go to exit1 if x19 ≥ x11 (i≥n)

   (body of outer for-loop)

   addi x19,x19,1           // i += 1
   j    for1tst             // branch to test of outer loop
exit1:
```

The Inner Loop

- Skeleton of inner loop:
  - for (j = i – 1; j >= 0 && v[j] > v[j + 1]; j – = 1) {

```
        addi x20,x19,-1     // j = i –1
  for2tst:
      blt  x20,x0,exit2   // go to exit2 if x20 < 0 (j < 0)
      slli x5,x20,3       // reg x5 = j * 8
      add  x5,x10,x5      // reg x5 = v + (j * 8)
      ld   x6,0(x5)       // reg x6 = v[j]
      ld   x7,8(x5)       // reg x7 = v[j + 1]
      ble  x6,x7,exit2    // go to exit2 if x6 ≤ x7
      mv   x21, x10       // copy parameter x10 into x21
      mv   x22, x11       // copy parameter x11 into x22
      mv   x10, x21       // first swap parameter is v
      mv   x11, x20       // second swap parameter is j
        jal  x1,swap        // call swap
        addi x20,x20,-1     // j -= 1
        j    for2tst        // branch to test of inner loop
   exit2:
//see p139 on textbook for entire code, place of MV is different, why?
```

Preserving Registers

- Saving registers

```
sort:   addi  sp,  sp, -40     // make room on stack for 5 registers
        sd    x1, 32(sp)       // save return address on stack
        sd    x22, 24(sp)      // save x22 on stack
        sd    x21, 16(sp)      // save x21 on stack
        sd    x20,  8(sp)      // save x20 on stack
        sd    x19,  0(sp)      // save x19 on stack
```

- Procedure body{Outer loop   {Inner loop}   }
- Restoring registers

```
exit1:  ld    x19,  0(sp)      // restore x19 from stack
        ld    x20,  8(sp)      // restore x20 from stack
        ld    x21,  16(sp)     // restore x21 from stack
        ld    x22, 24(sp)      // restore x22 from stack
        ld    x1, 32(sp)       // restore return address from stack
        addi  sp, sp, 40       // restore stack pointer
```

- Procedure return

```
        jalr   x0,   0(x0)     // return to calling routine
```

2.14 Arrays versus Pointers

- Array indexing involves
  - Multiplying index by element size
  - Adding to array base address
- Pointers correspond directly to memory addresses
  - Can avoid indexing complexity

Example: Clearing an Array

```c
clear1(int array[], int size) {
  int i;
  for (i = 0; i < size; i += 1)
    array[i] = 0;
}
```

```c
clear2(int *array, int size) {
  int *p;
  for (p = &array[0]; p < &array[size];
       p = p + 1)
    *p = 0;
}
```

```
   li    x5,0         // i = 0
loop1:
   slli x6,x5,3      // x6 = i * 8
   add  x7,x10,x6    // x7 = address
                     // of array[i]
   sd   x0,0(x7)     // array[i] = 0
   addi x5,x5,1      // i = i + 1
   blt  x5,x11,loop1   // if (i<size)
                       // go to loop1
```

```
   mv x5,x10         // p = address
                     // of array[0]
   slli x6,x11,3     // x6 = size * 8
   add x7,x10,x6     // x7 = address
                     // of array[size]
loop2:
   sd x0,0(x5)       // Memory[p] = 0
   addi x5,x5,8      // p = p + 8
   bltu x5,x7,loop2
                     // if (p<&array[size])
                     // go to loop2
```

Comparison of Array vs Pointers

- **Multiply "strength reduced" to shift**
- **Array version requires shift to be inside loop**
  - Part of index calculation for incremented i
  - c.f. incrementing pointer
- **Compiler can achieve same effect as manual use of pointers**
  - Induction variable elimination
  - Better to make program clearer and safer

2.16 Real Stuff: MIPS Instructions

- **MIPS: commercial predecessor to RISC-V**
- **Similar basic set of instructions**
  - 32-bit instructions
  - 32 general purpose registers, register 0 is always 0
  - 32 floating-point registers
  - Memory accessed only by load/store instructions
    - Consistent use of addressing modes for all data sizes
- **Different conditional branches**
  - For <, <=, >, >=
  - RISC-V: blt, bge, bltu, bgeu
  - MIPS: slt, sltu (set less than, result is 0 or 1)
    - Then use beq, bne to complete the branch

Instruction Encoding

Register-register

	31 25	24 20	19 15	14 12	11 7	6 0
RISC-V	funct7(7)	rs2(5)	rs1(5)	funct3(3)	rd(5)	opcode(7)
	31 26	25 21	20 16	15 11	10 6	5 0
MIPS	Op(6)	Rs1(5)	Rs2(5)	Rd(5)	Const(5)	Opx(6)

Load

	31 20	19 15	14 12	11 7	6 0
RISC-V	immediate(12)	rs1(5)	funct3(3)	rd(5)	opcode(7)

	31 26	25 21	20 16	15 0
MIPS	Op(6)	Rs1(5)	Rs2(5)	Const(16)

Store

	31 25	24 20	19 15	14 12	11 7	6 0
RISC-V	immediate(7)	rs2(5)	rs1(5)	funct3(3)	immediate(5)	opcode(7)

	31 26	25 21	20 16	15 0
MIPS	Op(6)	Rs1(5)	Rs2(5)	Const(16)

Branch

	31 25	24 20	19 15	14 12	11 7	6 0
RISC-V	immediate(7)	rs2(5)	rs1(5)	funct3(3)	immediate(5)	opcode(7)

	31 26	25 21	20 16	15 0
MIPS	Op(6)	Rs1(5)	Opx/Rs2(5)	Const(16)

2.17 Real Stuff: The Intel x86 ISA

- **Evolution with backward compatibility**
  - 8080 (1974): 8-bit microprocessor
    - Accumulator, plus 3 index-register pairs
  - 8086 (1978): 16-bit extension to 8080
    - Complex instruction set (CISC)
  - 8087 (1980): floating-point coprocessor
    - Adds FP instructions and register stack
  - 80286 (1982): 24-bit addresses, MMU
    - Segmented memory mapping and protection
  - 80386 (1985): 32-bit extension (now IA-32)
    - Additional addressing modes and operations
    - Paged memory mapping as well as segments

The Intel x86 ISA

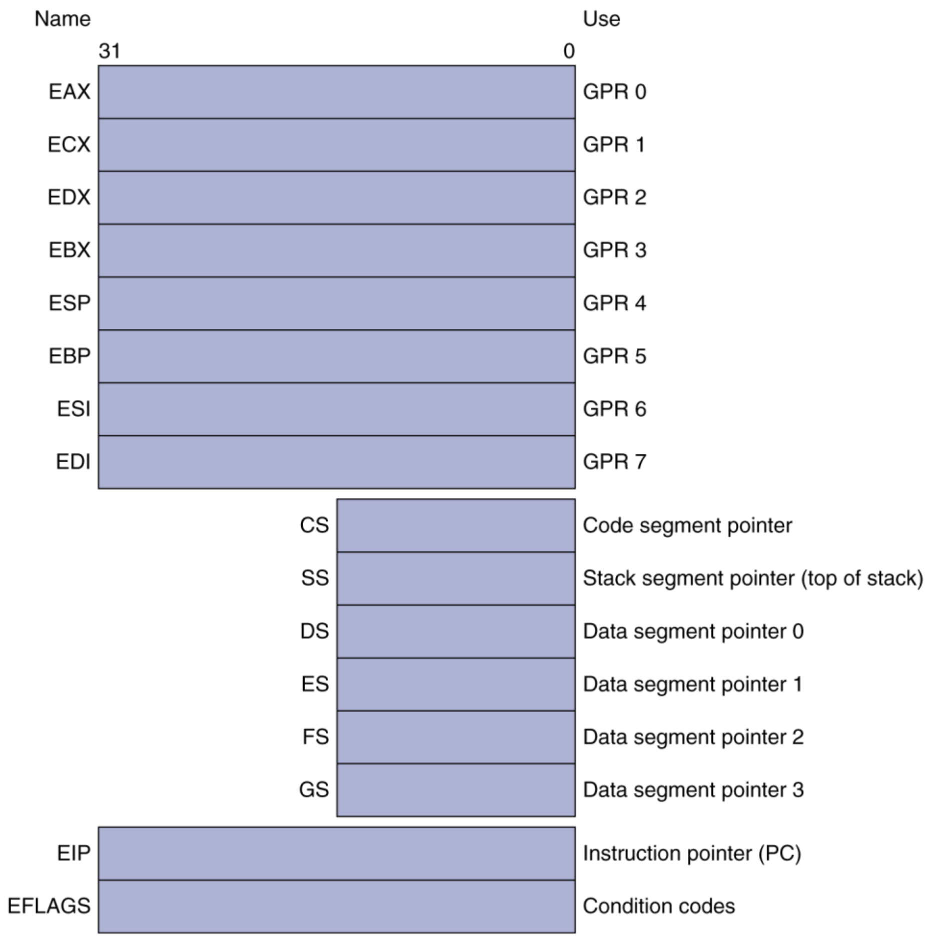
Further evolution…

- i486 (1989): pipelined, on-chip caches and FPU
  - Compatible competitors: AMD, Cyrix, …
- Pentium (1993): superscalar, 64-bit datapath
  - Later versions added MMX (Multi-Media eXtension) instructions
  - The infamous FDIV bug
- Pentium Pro (1995), Pentium II (1997)
  - New microarchitecture (see Colwell, *The Pentium Chronicles*)
- Pentium III (1999)
  - Added SSE (Streaming SIMD Extensions) and associated registers
- Pentium 4 (2001)
  - New microarchitecture
  - Added SSE2 instructions

The Intel x86 ISA

- **And further…**
  - AMD64 (2003): extended architecture to 64 bits
  - EM64T – Extended Memory 64 Technology (2004)
    - AMD64 adopted by Intel (with refinements)
    - Added SSE3 instructions
  - Intel Core (2006)
    - Added SSE4 instructions, virtual machine support
  - AMD64 (announced 2007): SSE5 instructions
    - Intel declined to follow, instead…
  - Advanced Vector Extension (announced 2008)
    - Longer SSE registers, more instructions
- **If Intel didn't extend with compatibility, its competitors would!**
  - Technical elegance ≠ market success

Basic x86 Registers



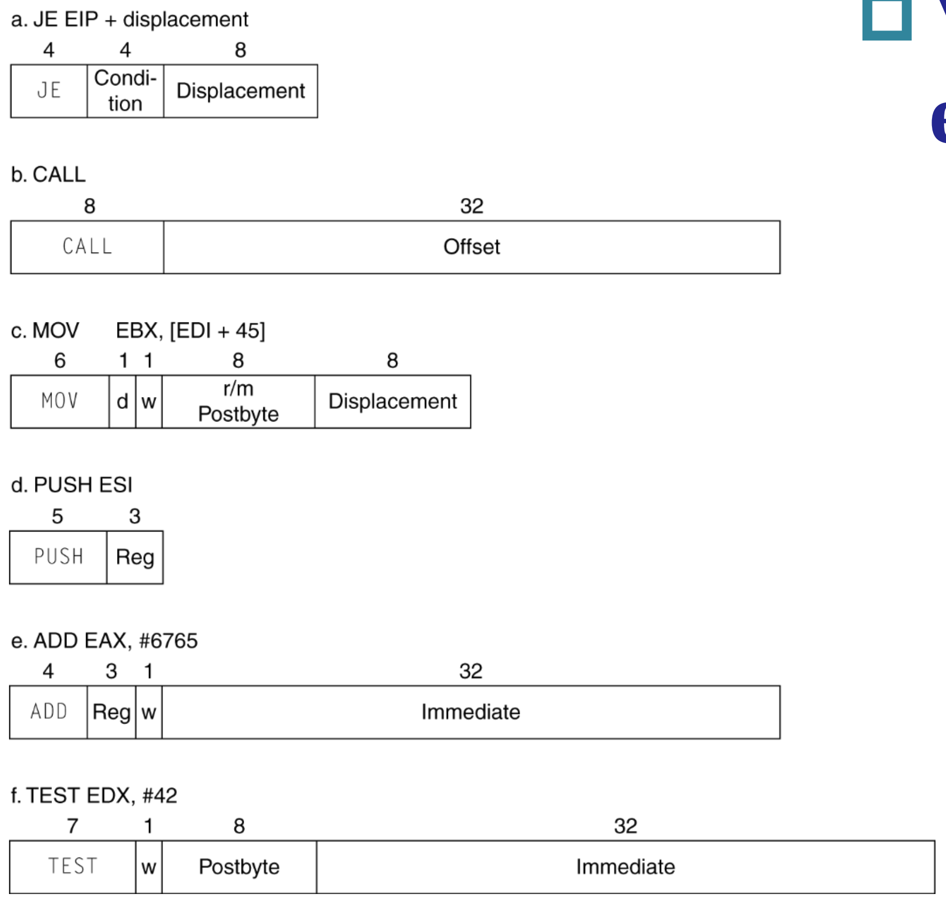
Basic x86 Addressing Modes

- **Two operands per instruction**

Source/dest operand	Second source operand
Register	Register
Register	Immediate
Register	Memory
Memory	Register
Memory	Immediate

- **Memory addressing modes**
  - Address in register
  - Address = R_{base} + displacement
  - Address = $R_{base} + 2^{scale} \times R_{index}$ (scale = 0, 1, 2, or 3)
  - Address = $R_{base} + 2^{scale} \times R_{index}$ + displacement

x86 Instruction Encoding



- **Variable length encoding**
  - Postfix bytes specify addressing mode
  - Prefix bytes modify operation
    - Operand length, repetition, locking, …

Implementing IA-32

- **Complex instruction set makes implementation difficult**
  - Hardware translates instructions to simpler microoperations
    - Simple instructions: 1–1
    - Complex instructions: 1–many
  - Microengine similar to RISC
  - Market share makes this economically viable
- **Comparable performance to RISC**
  - Compilers avoid complex instructions

2.18 Other RISC-V Instructions

- **Base integer instructions (RV64I)**
  - Those previously described, plus
  - auipc rd, immed // rd = (imm<<12) + pc
    - follow by jalr (adds 12-bit immed) for long jump
  - slt, sltu, slti, sltui: set less than (like MIPS)
  - addw, subw, addiw: 32-bit add/sub
  - sllw, srlw, srlw, slliw, srliw, sraiw: 32-bit shift
- **32-bit variant: RV32I**
  - registers are 32-bits wide, 32-bit operations

Instruction Set Extensions

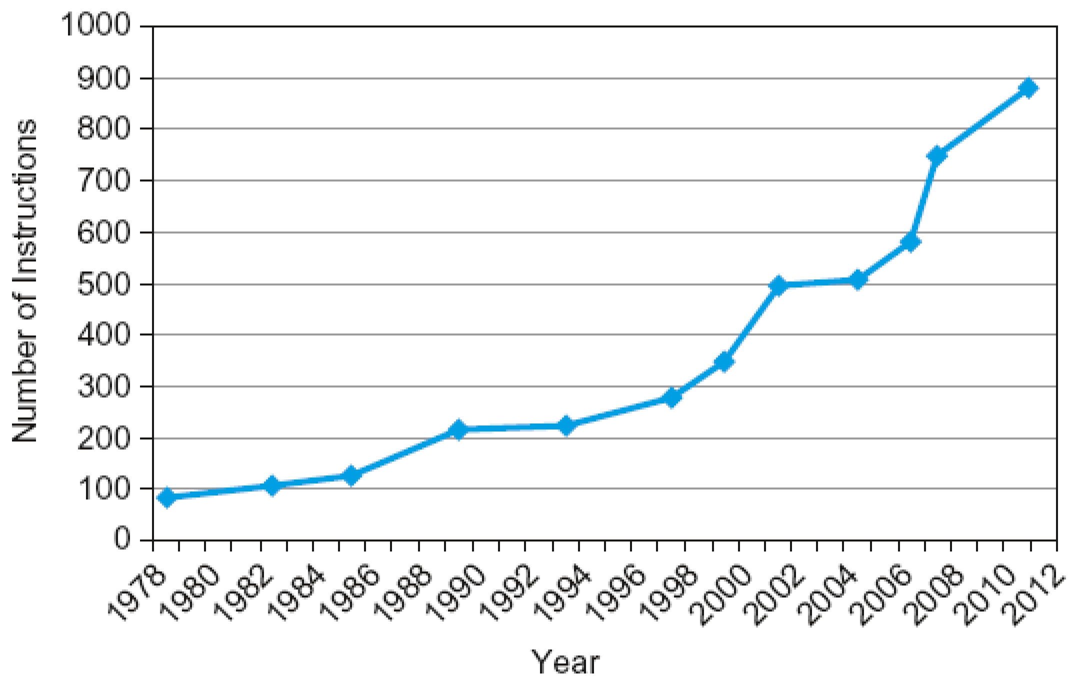
- **M: integer multiply, divide, remainder**
- **A: atomic memory operations**
- **F: single-precision floating point**
- **D: double-precision floating point**
- **C: compressed instructions**
  - 16-bit encoding for frequently used instructions

Fallacies

- **Powerful instruction ⇒ higher performance**
  - Fewer instructions required
  - But complex instructions are hard to implement
    - May slow down all instructions, including simple ones
  - Compilers are good at making fast code from simple instructions
- **Use assembly code for high performance**
  - But modern compilers are better at dealing with modern processors
  - More lines of code ⇒ more errors and less productivity

Fallacies

- **Backward compatibility ⇒ instruction set doesn't change**
  - But they do accrete more instructions



x86 instruction set

Pitfalls

- **Sequential words are not at sequential addresses**
  - Increment by 4, not by 1!
- **Keeping a pointer to an automatic variable after procedure returns**
  - e.g., passing pointer back via an argument
  - Pointer becomes invalid when stack popped

Summary

- **Design principles**
  1. Simplicity favors regularity
  2. Smaller is faster
  3. Good design demands good compromises
- **Make the common case fast**
- **Layers of software/hardware**
  - Compiler, assembler, hardware
- **RISC-V: typical of RISC ISAs**
  - c.f. x86

Homework

- 2.4, 2.8, 2.12, 2.14, 2.17, 2.22, 2.24, 2.29

END