# 计算机组成原理
# 第二章“指令系统”

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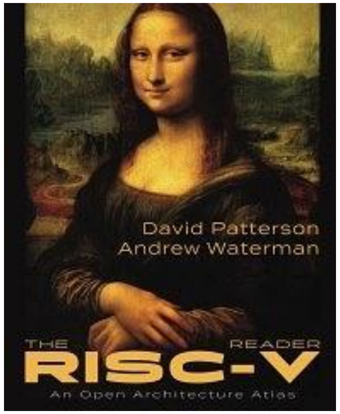
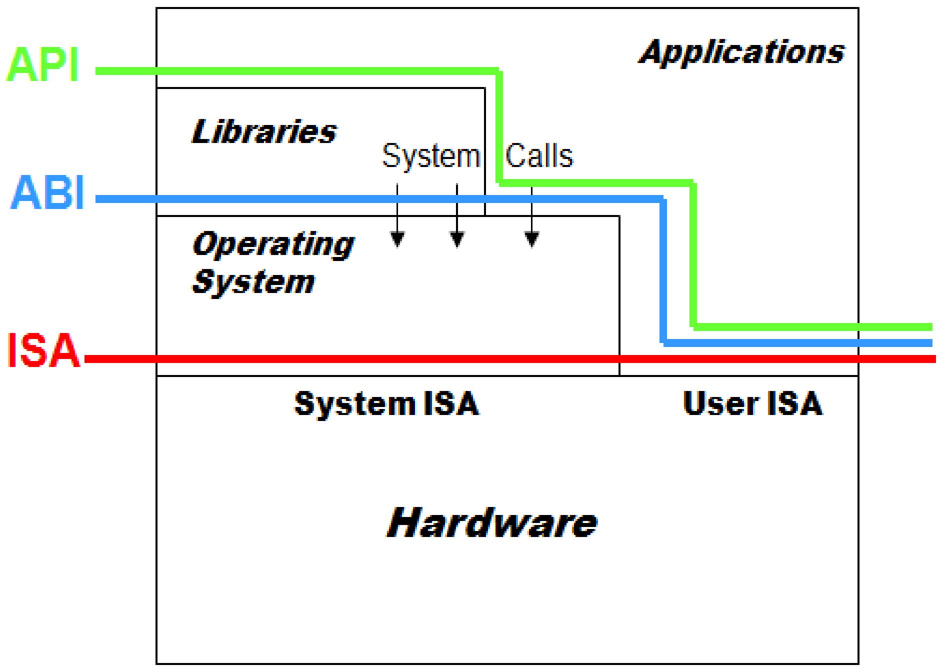
# 概要

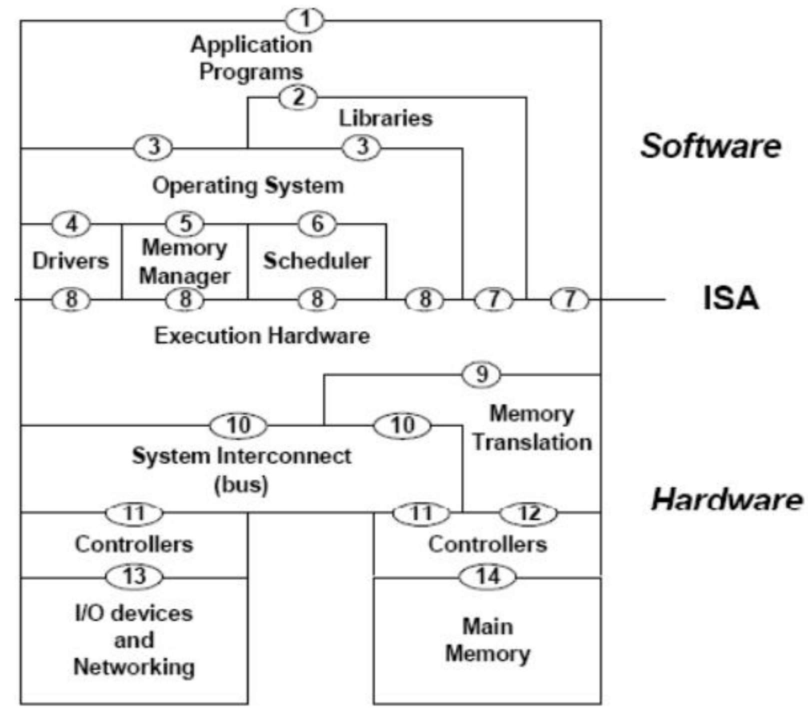
David Patterson，Andrew Waterman，*The RISC-V Reader: An Open Architecture Atlas*，2017




- 指令系统：机器指令的集合
  - “程序控制”
    - 程序=顺序执行的指令流
  - 机器语言，汇编语言（Assemble Language）
  - Instruction Set Architecture（ISA）
    - 分类：CISC、RISC、VLIW
    - 影响：处理器、C编译器、OS。。。
- 本章的内容
  - RV指令系统
    - 操作数：寄存器，存储器（大小尾端，对齐），常数/立即数；
    - 指令功能，指令格式与编码，寻址方式（操作数，下一条指令）
    - 分支指令$2.7，*大立即数处理$2.10*
    - 过程调用$2.8，$2.13
    - 汇编程序设计：COD4附录B
  - 指令系统特征
  - *编译过程：$2.12*
    - *可执行程序生成：编译，汇编，链接，加载*

# Architecture（ISA）& Interfaces

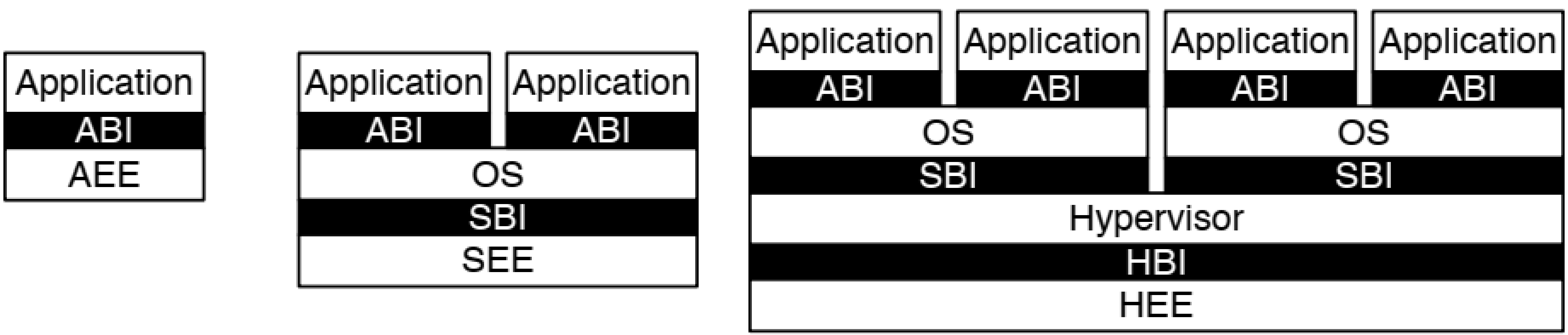



- **API** – application programming interface
- **ABI** – application binary interface = SysCall+UserISA（$1.4.3）
- **ISA** – instruction set architecture（$1.4.3）
  - 简称Architecture: formal specification of a system's interface and the logical behavior of its visible resources.

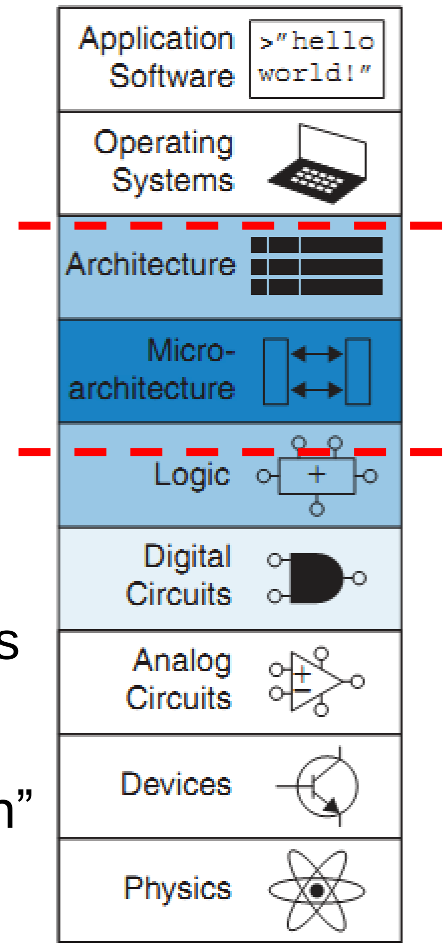
# RISC-V Privileged Software Stack

- application execution environment (AEE)
- application binary interface (ABI)
- supervisor execution environment (SEE)
- supervisor binary interface (SBI)
- hypervisor execution environment (HEE)
- hypervisor binary interface (HBI)

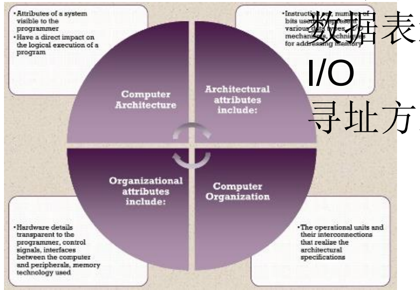


# Instruction-Set Processor Design

- Architecture (ISA) *programmer/compiler view*
  - "functional appearance to its immediate user/system programmer"
  - Opcodes, addressing modes, architected registers, IEEE floating point
  - 机器语言
- Implementation (µArch) *processor designer view*
  - "logical structure or organization that performs the architecture"
  - functional units, pipelining, caches, physical registers
- Realization (chip) *chip/system designer view*
  - "physical structure that embodies the implementation"
  - Gates, cells, transistors, wires



# 体系结构（ISA）的8种属性

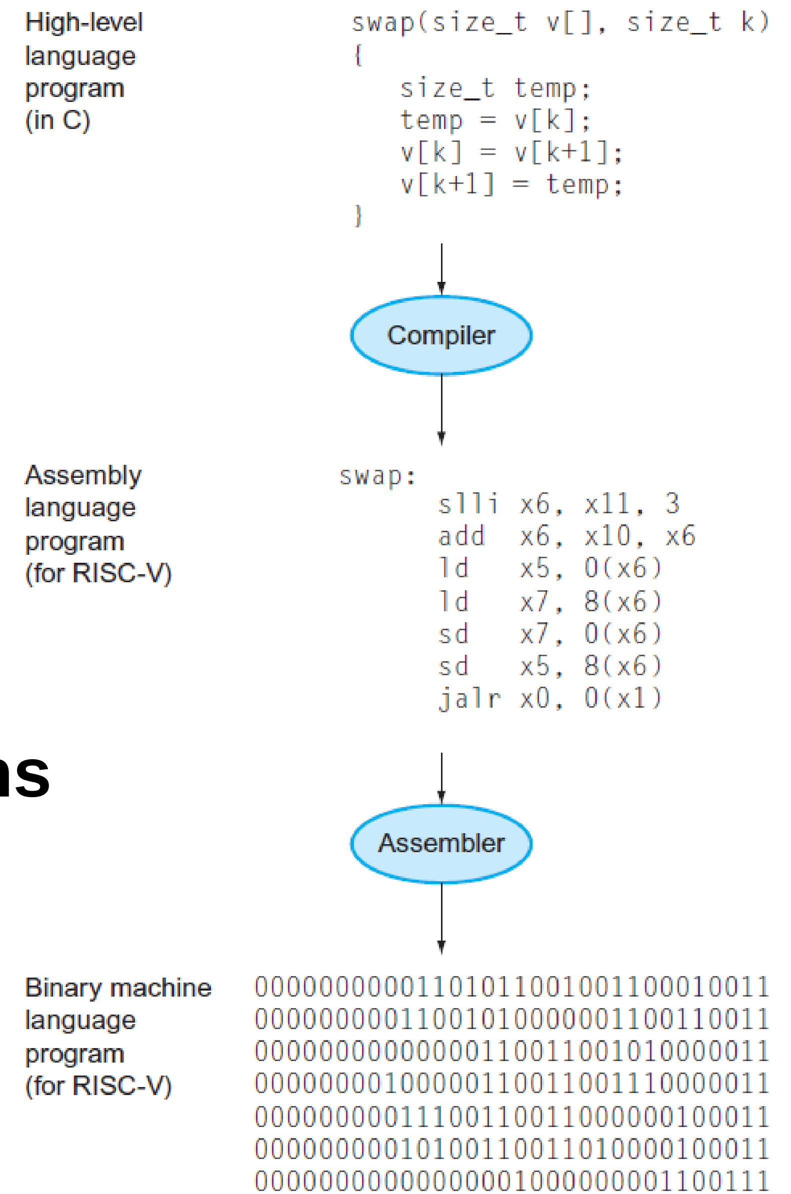



指令集
数据表示
I/O
寻址方式

- 数据表示
  - 硬件能直接辨识和操作的数据类型和格式
- 寻址方式
  - 最小可寻址单位、寻址方式的种类、地址运算
- 寄存器组织
  - 操作寄存器、变址寄存器、控制（专用）寄存器的定义、数量和使用规则
- 存储系统
  - 最小编址单位、编址方式、主存容量、最大可编址空间
- 指令系统
  - 机器指令的操作类型、格式，指令间排序和控制机构。【MCM？】
- 输入输出
  - I/O互连方式、处理机/存储器与I/O设备间的数据交换方式和过程控制
- 中断（异常）机构
  - 中断类型、中断级别，以及中断响应方式等
- *信息保护*
  - *信息保护方式、硬件信息保护机制*

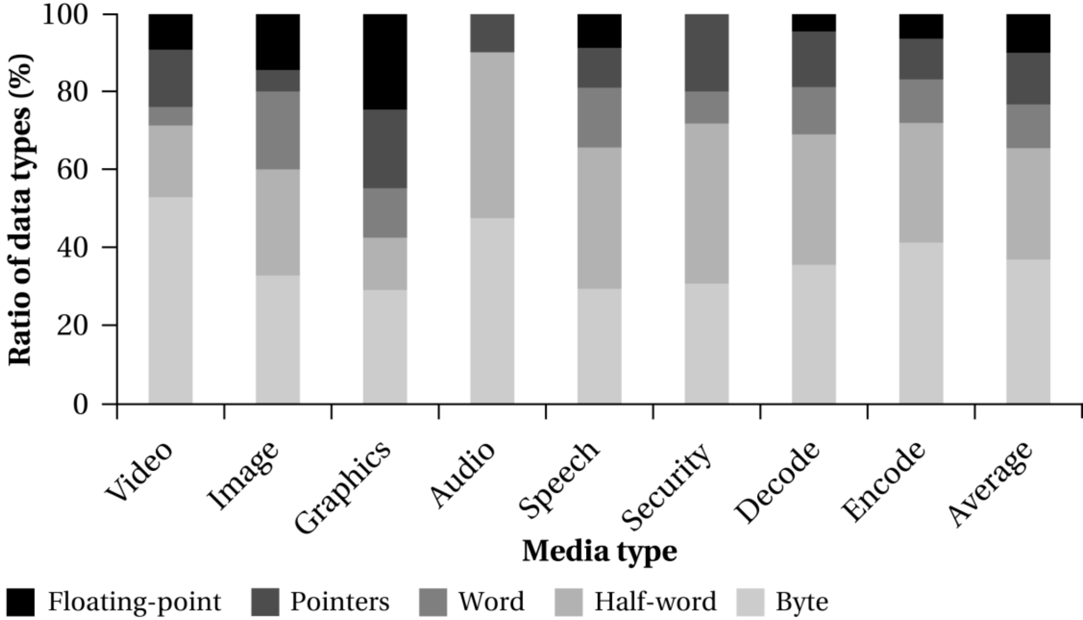
# High Level to Assembly，图1-4

- **High Level Lang (C, etc.)**
  - Statements
  - Variables
  - Operators
  - func, proc, methods
- **Assembly Language**
  - Instructions
  - Registers
  - Memory segments/sections
- **Data Representation**
- **Number Systems**



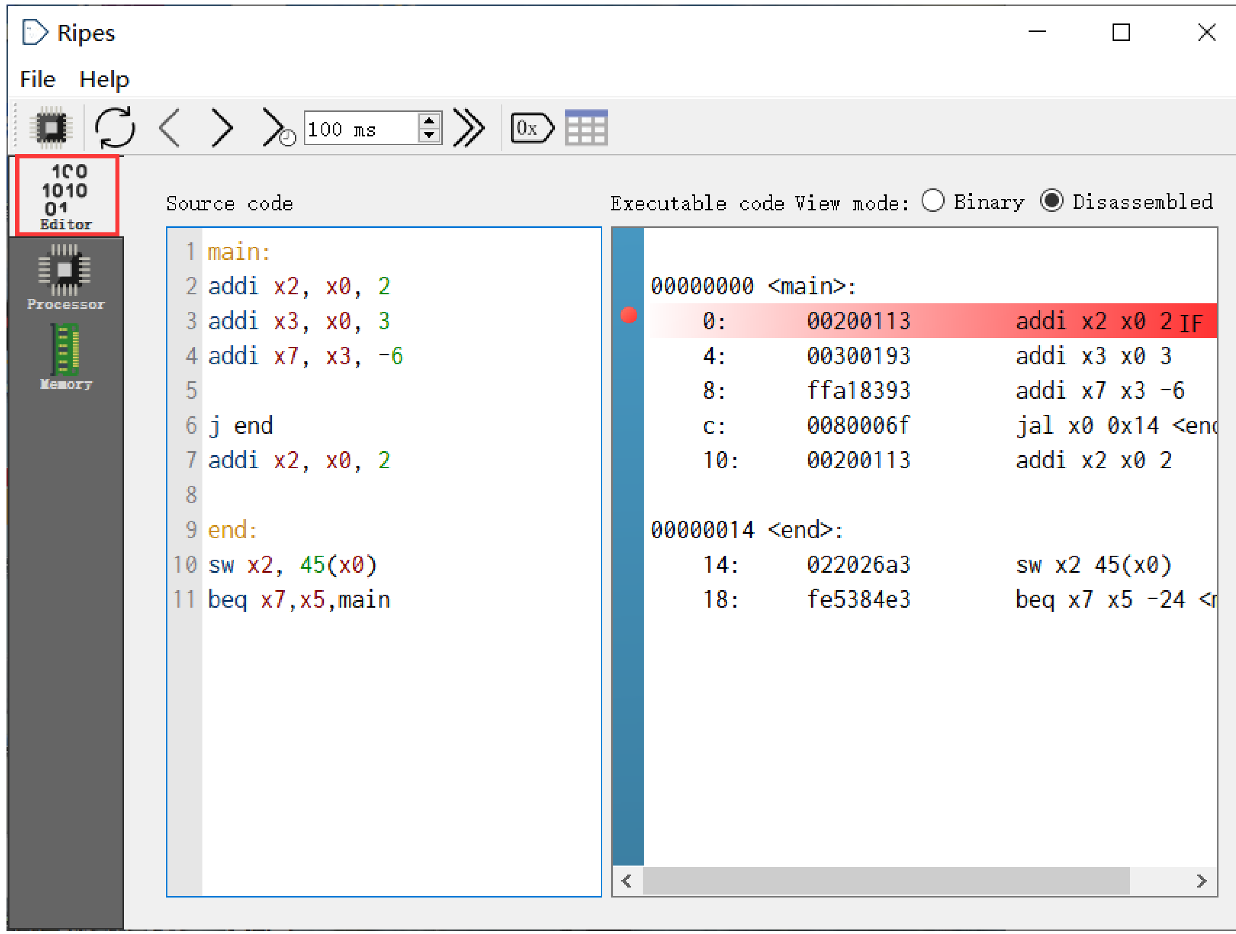
# 操作数（opr）： Data Representation，Number Systems

- 操作数类型：进制，编码，立即数（补码）
  - 地址：无符号整数。寄存器、内存、I/O端口ID
  - 数值：常数、定点数（有符号/无符号）、浮点数、逻辑值
  - 字符：ASCII、汉字内码
- 字长：“RV32I/*RV64*”：32位/*64位*，“大立即数”
  - 字节
  - 半字：2B
  - 字：4B
  - *双字：8B*
- 物理操作数：存放位置
  - 寄存器
  - 主存
  - I/O端口
  - 外存？



# 指令字中的操作数

- 寄存器
- 存储器
  - 内存地址
  - 字长：sw
- 立即数
  - 进制表示
    - 十进制：2
    - 十六进制
      - 0x12345
    - 二进制
      - 0b1101
- 标号/行号
  - main，end



# RV architected registers和ABI，图2-14

| Name | Register number | 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 |

ABI寄存器名，用途，过程调用时是否要保存到栈中

# RV典型内存地址空间分配：段式

- 段式
  - DATA
    - static
    - Stack/Heap
      - 栈：自高向低
      - 堆：自低向高
  - CODE/Text
- 地址格式
  - 绝对地址
  - 相对地址：基址+偏移
    - offset，displacement
    - 基址寄存器bp
- 外设地址
  - I/O port?
  - 硬盘
  - 网络

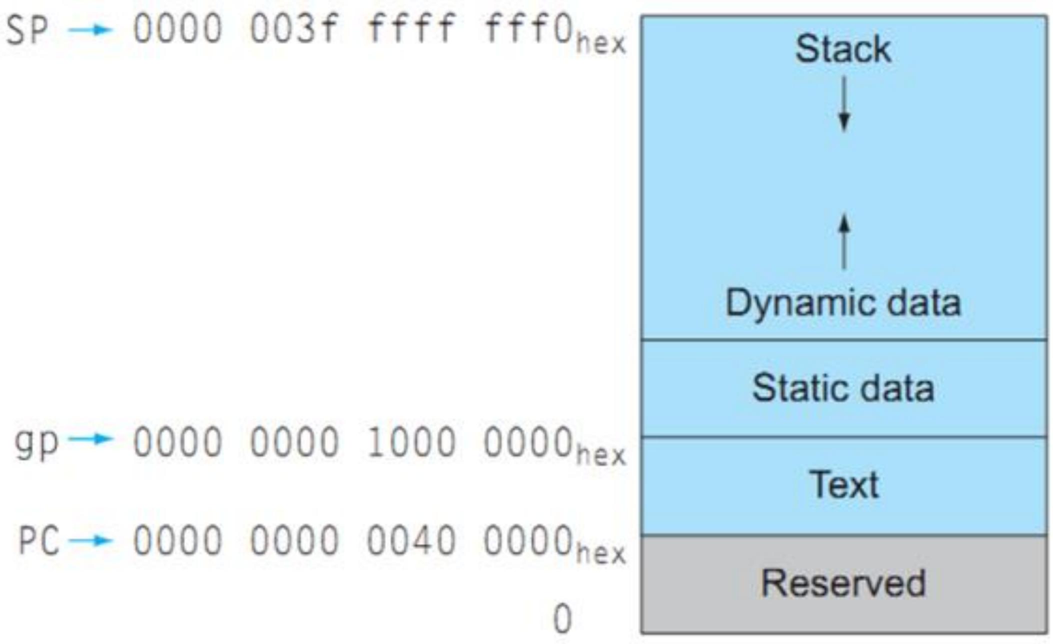



图2-13 Linux用户地址空间划分约定

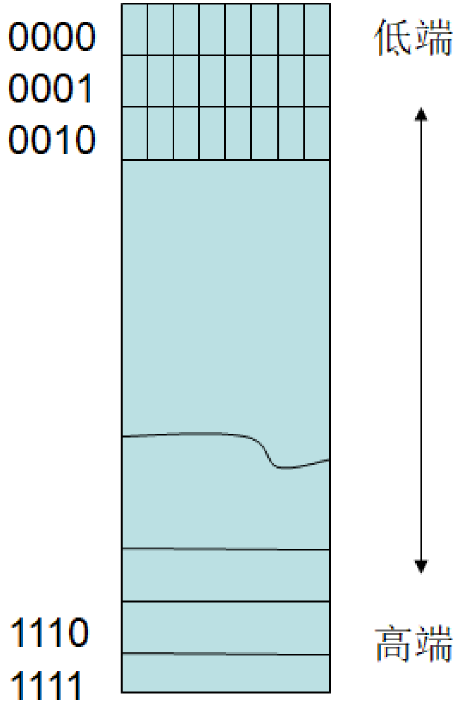
可寻址的总的内存空间大小？

各段空间大小？

# 字存储顺序（Byte Ordering）$2.3.1

- 字存储的顺序中，字节的次序有两种
  - 大端/大尾端（big endness）
    - 低地址，高字节
  - 小端/小尾端（little endness）
    - 低地址，低字节
- X86和RV都为小端，ARM可以自主设置

- 00000000 00000000 00000000 00000001
  - 00000000 00000111 00000011 00000001?




```
大尾端： 00000000 00000000 00000000 00000001
         addr+0   addr+1    addr+2   addr+3   //先存高有效位（在低地址）
小尾端： 00000001 00000000 00000000 00000000
         addr+0   addr+1    addr+2   addr+3   //先存低有效位（在低地址）
```

# 数据对齐（Memory Alignment），  $2.3.1

- 在数据不对准边界的计算机中，数据（例如一个字）可能在两个存储单元中。
  - 此时需要访问两次存储器，并对高低字节的位置进行调整后，才能取得一字。
- 边界对齐：RV/x86不要求，MIPS要求
  - 字对齐：地址左移两位，按字访问
  - 半字对齐：地址左移一位，按半字访问

| 存储器 | | | 地址（十进制） |
|---|---|---|---|
| 字（地址2） | | 半字（地址0） | 0 |
| 字节（地址7） | 字节（地址6） | 字（地址4） | 4 |
| 半字（地址10） | | 半字（地址8） | 8 |

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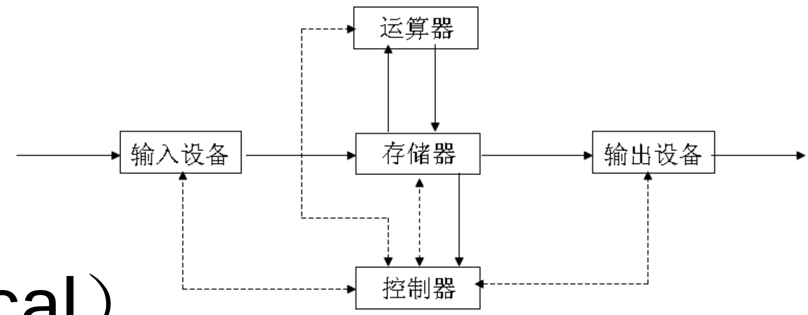
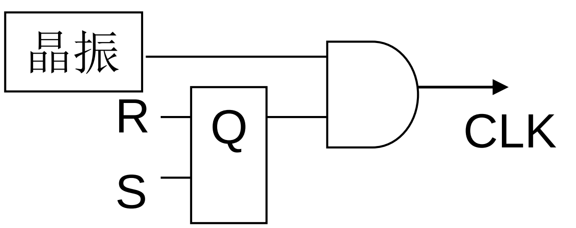
# 操作分类

- 数据传递（data movement）
  - 访存：load，store，*mov*
  - I/O：in，*out*

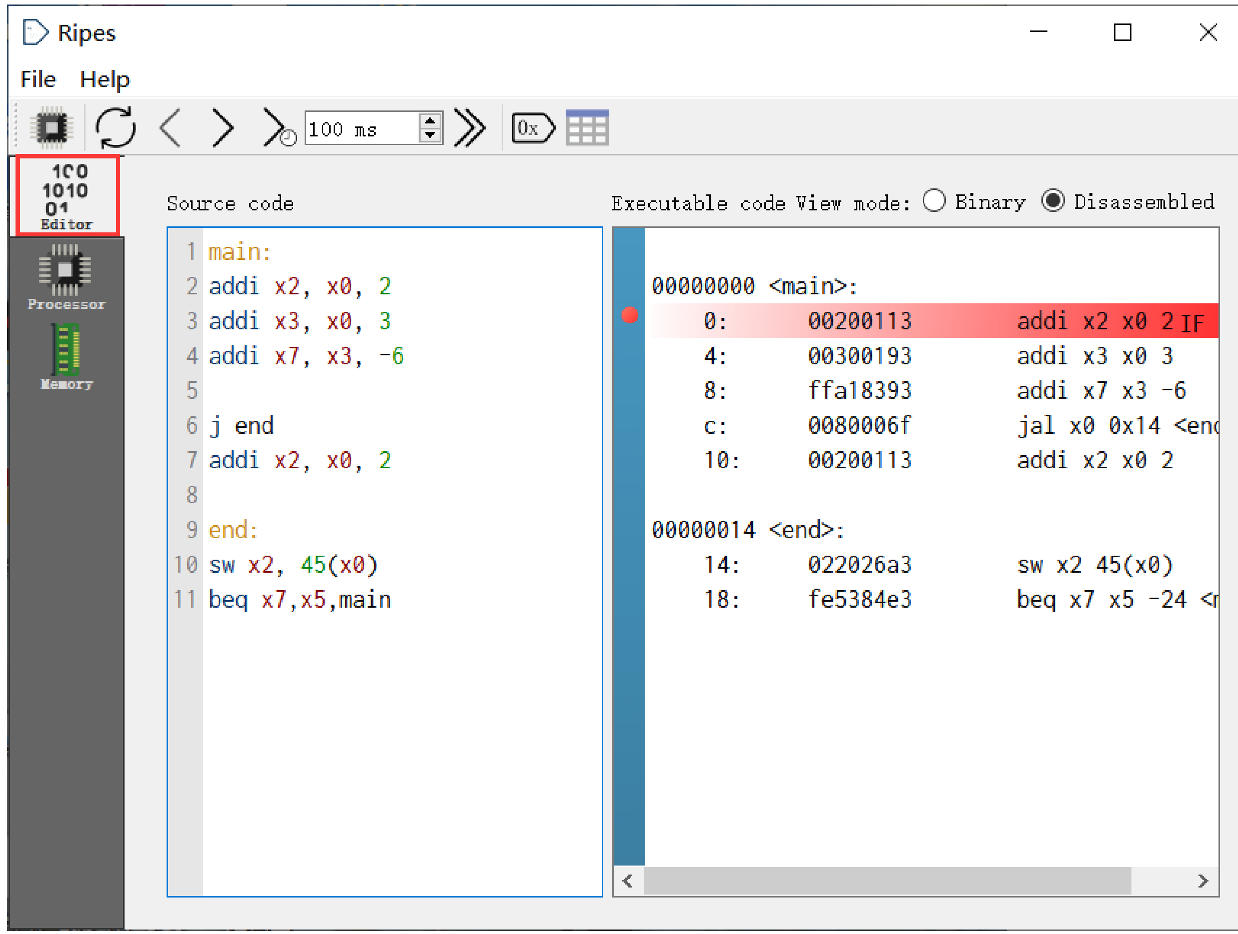



- 算逻运算（arithmetic & logical）
  - add，sub，and，not，or，xor，*dec*，*inc*，*cmp*
  - monadic & dyadic operations
- 移位操作
  - monadic operations：shl，shr，srl，srr
- 分支控制（tranfer of contral，Branch）
  - comparisons & conditional branches：beq，bnz
  - 无条件转移：jmp
  - procedure call：*call*，*ret*，*int*，*iret*
- 系统指令：nop，*sti*，*cli*，*lock*，*HLT*



# 指令示例

- ALU：addi
  - 源操作数
    - 寄存器
    - 立即数
  - 目的操作数
    - 寄存器
- 分支：j，beq
  - NPC
    - PC+1
    - 立即数
- 访存：sw
  - 内存地址
    - 基址+偏移



# 指令字格式Machine Instruction Layout

- von Neumann：“指令由**操作码**和**地址码**构成”
- 操作码：操作的性质
- 地址码：指令和操作数（operand）的存储位置

| 操作码域（op） | 地址码域（addr） |
|---|---|

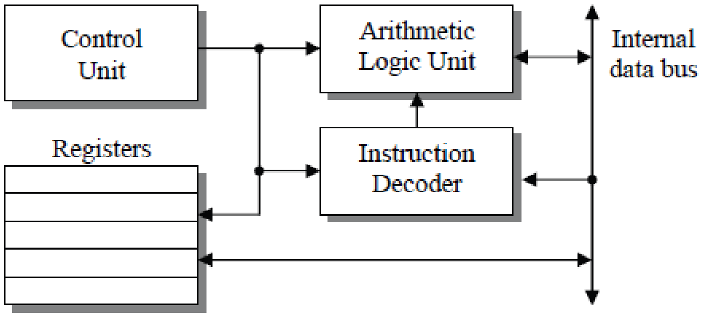
- 指令字长度固定vs.可变：RISC（RV/MIPS/ARM）一般32位
  - 固定：规则，浪费空间
- 操作码长度固定vs.可变
  - 固定：译码简单，指令条数有限，RISC（RV/MIPS/ARM）
  - 可变：指令条数和格式按需调整，CISC（x86），RV（16/32/…）
- “扩展操作码技术”：调整op与addr域
  - 如果指令字长固定，则操作码长度增加，地址码长度缩短

# 地址码：操作数，指令

- 源操作数、目的操作数、下一条指令地址
  - 地址：寄存器、主存、I/O端口
- 地址码域格式
  - 4地址指令：op rs1, rs2, rd, ni
  - 3地址指令：op rs1, rs2, rd； ni在PC中
  - 2地址指令：op rs1, rs2； rd=rs1 or ACC
  - 1地址指令：op rs2； rs1=ACC，rd=ACC
  - 0地址指令：op； 堆栈操作

# 寻址方式：指令的地址码域

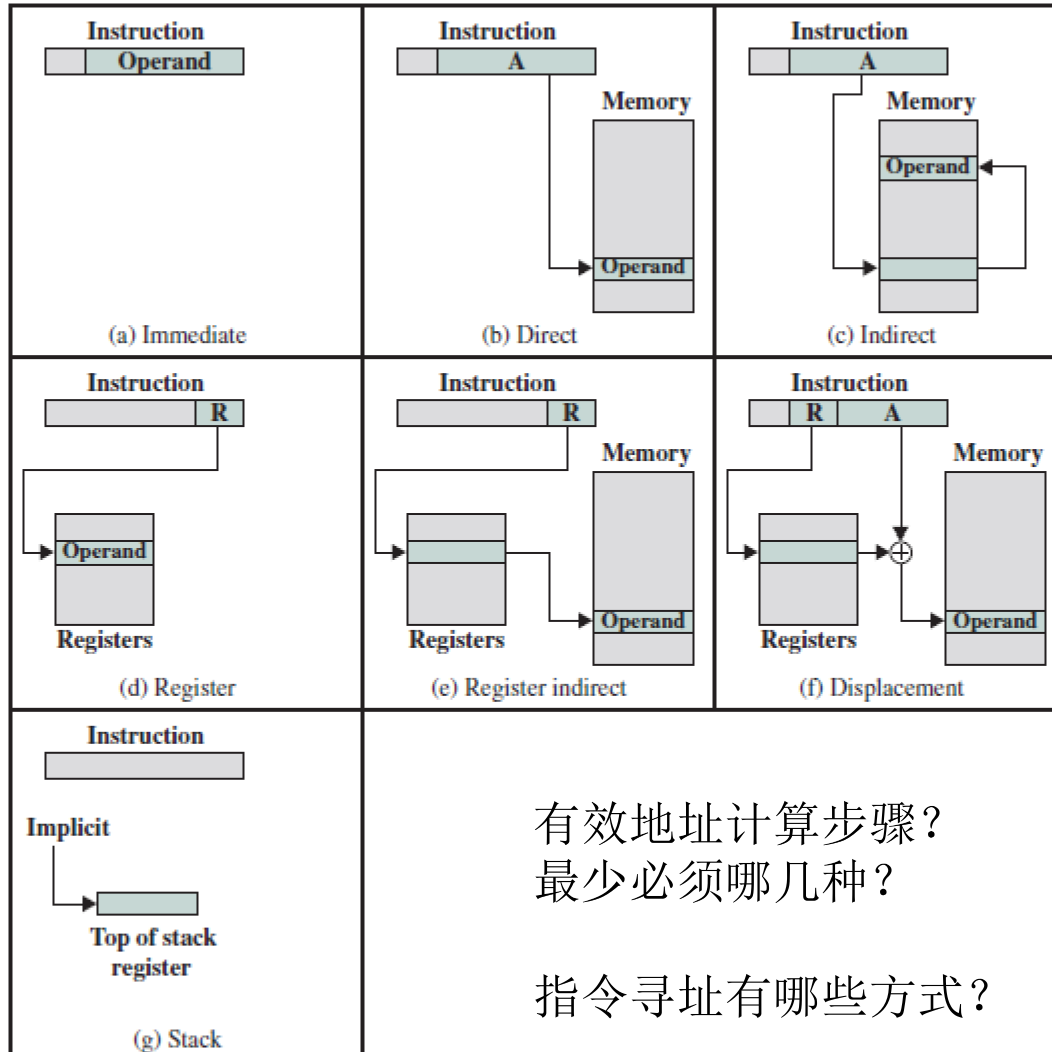
- 寻址方式：指令字和操作数的存放地址的计算方式
- 指令寻址：现代CPU利用PC
  - 顺序执行：每执行一条指令，PC自动1
  - 跳转：更新PC，转移到目的地址执行
- 操作数寻址
  - 指令中给出“形式地址”
  - 有效地址：操作数在寄存器/内存中的物理地址
    - EA＝寻址方式＋形式地址




| 操作码 | 形式地址 |
|---|---|

# 寻址方式：操作数，下一条指令

- 常见约10种
  - 立即寻址（a）
  - 直接寻址（b）
  - 间接寻址（c）
  - 寄存器寻址（d）
  - 寄存器间接寻址（e）
  - 基址寻址（f）
    - BP+offset
  - PC相对寻址（f）
    - PC+offset
  - 堆栈寻址（g）
  - *变址寻址（d+f）*
    - Index：x86的si/di
  - *隐含寻址（如堆栈）*



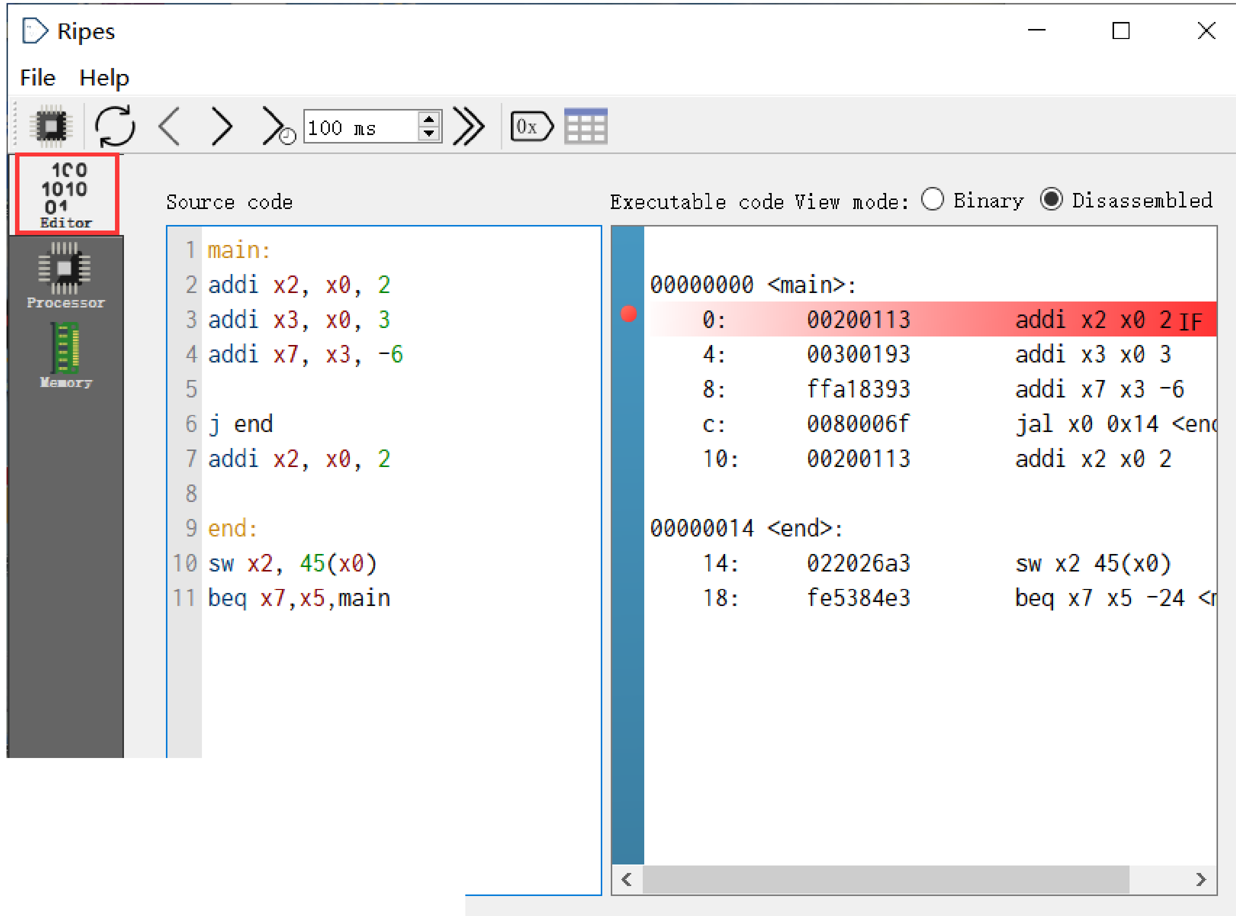

有效地址计算步骤？
最少必须哪几种？

指令寻址有哪些方式？

# 寻址方式示例：操作数，下一条指令

- addi
- j/jal
- sw
- beq

- C程序
  - 存储模型
    - 名，地址，寄存器？
  - 执行模型：控制流
    - 行号？

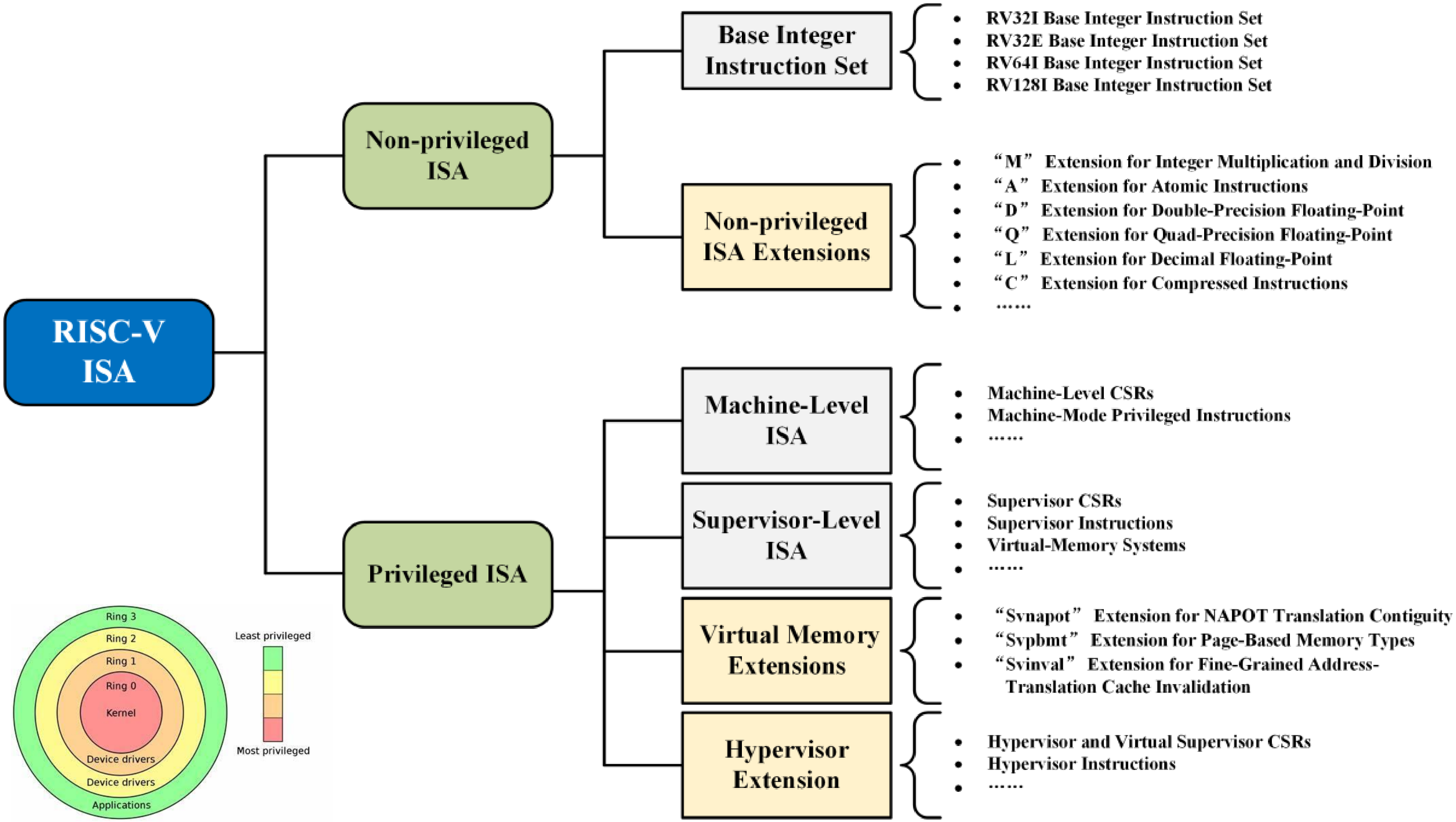



```
#include <stdio.h>

int
main (int argc, char *argv[])
{
    int i;
    int sum = 0;

    for (i = 0; i <= 100; i = i + 1) sum = sum + i * i;
    printf ("The sum from 0 .. 100 is %d\n", sum);
}
```

# The RISC-V ISA



# RISC-V ISA的特点

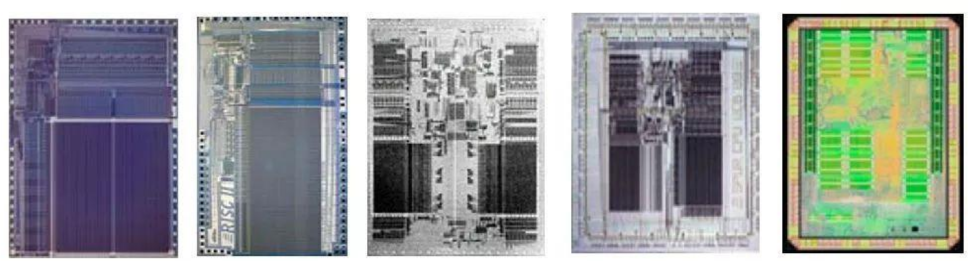
- 模块化
  - RV32I+系统指令：可运行Linux
    - RV32I：图2-18 + 图2-41，永远不变
    - 系统指令：同步，CSR，异常，图5-47
  - RV32IMFD指令集
  - RV32E
- 约束
  - 成本：芯片面积
  - 简洁
  - 性能：时间，功耗
  - 架构与实现分离
  - 扩展性：操作码域空间
  - 程序大小
  - 易于编程/编译/链接

图5-47

| Type | Mnemonic | Name |
|---|---|---|
| Mem. Ordering | FENCE.I | Instruction Fence |
| | FENCE | Fence |
| | SFENCE.VMA | Address Translation Fence |
| CSR Access | CSRRWI | CSR Read/Write Immediate |
| | CSRRSI | CSR Read/Set Immediate |
| | CSRRCI | CSR Read/Clear Immediate |
| | CSRRW | CSR Read/Write |
| | CSRRS | CSR Read/Set |
| | CSRRC | CSR Read/Clear |
| System | ECALL | Environment Call |
| | EBREAK | Environment Breakpoint |
| | SRET | Supervisor Exception Return |
| | WFI | Wait for Interrupt |

图2-42

| Mnemonic | Description | Insn. Count |
|---|---|---|
| I | Base architecture | 51 |
| M | Integer multiply/divide | 13 |
| A | Atomic operations | 22 |
| F | Single-precision floating point | 30 |
| D | Double-precision floating point | 32 |
| C | Compressed instructions | 36 |



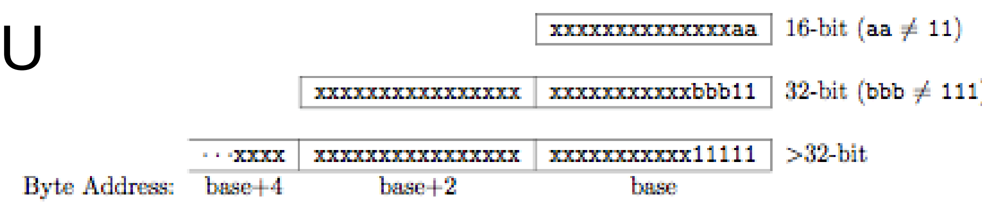
RISC-I 1981　RISC-II 1983　RISC-III (SOAR) 1984　RISC-IV (SPUR) 1988　RISC-V 2013

# RISC-V指令格式与操作码

图2-19，图4-16

| Name (Field size) | Field 7 bits | 5 bits | 5 bits | 3 bits | 5 bits | 7 bits | Comments |
|---|---|---|---|---|---|---|---|
| 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 | immed[12,10:5] | rs2 | rs1 | funct3 | immed[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 |

- 指令格式：6种，基本R/I/S/U
  - 规整：Reg和Imm位置固定
  - op码与指令类型和格式绑定




- B/J-type的立即数域（循环移位）【$4.4.2，图4-17，4-18】
  - “减少数据通路上的MUX数量和MUX端口数，改善时钟周期”，
- 变长指令字：Opcode的bbbaa
  - Can support variable-length instructions【当前仅RV16/RV32】

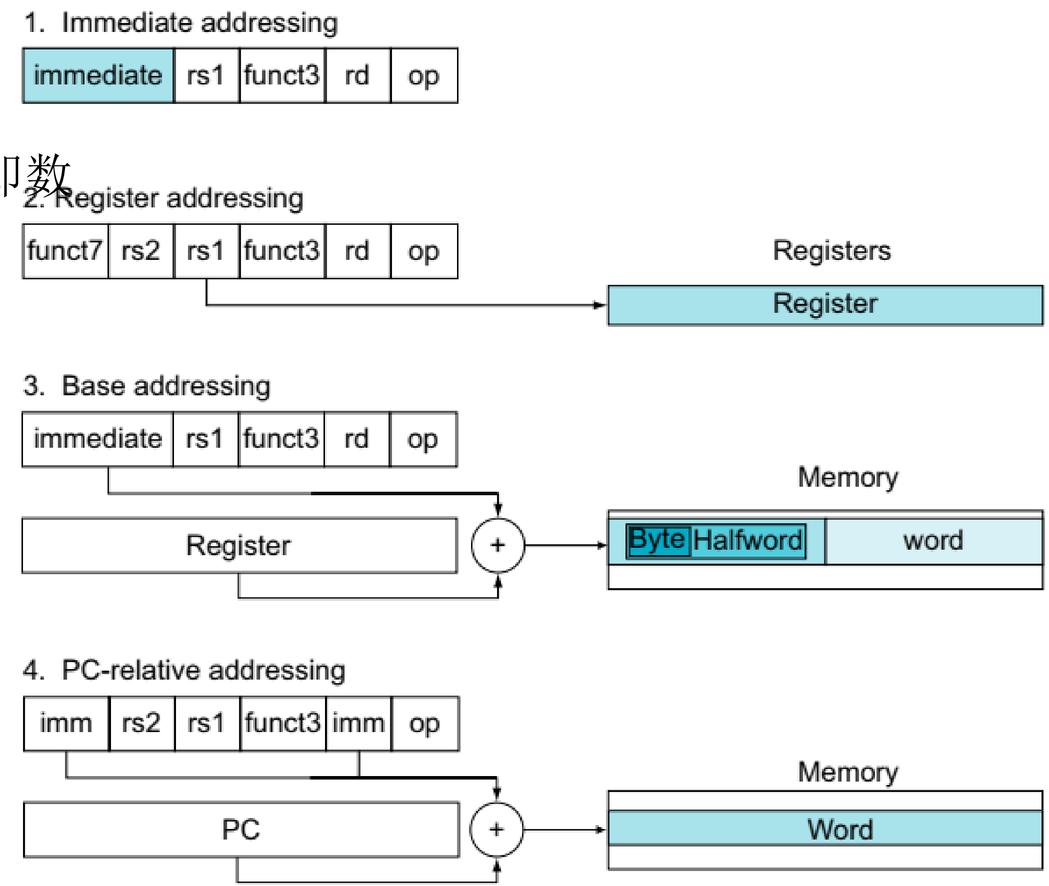
# RV指令操作码

- 常用，图2-18
  - 按字长分类：访存指令
    - b，h，w，d
  - 按数据类型分类
    - i，u
  - 按指令格式分类
- 典型：按功能分类
  - 同功能：op同，funct不同
  - 三类：ALU，访存，分支
    - add：R-type
    - addi：I-type
    - lw：load，I-type
    - sw：store，S-type
    - beq：SB-type
    - jal（UJ-type），jalr（I-type）
- *RV321指令示例：图3-12*

| 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 | 0000000 |
| | or | 0110011 | 110 | 0000000 |
| | and | 0110011 | 111 | 0000000 |
| | lr.d | 0110011 | 011 | 0001000 |
| | sc.d | 0110011 | 011 | 0001100 |
| 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. |
| 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. |

# RISC-V寻址方式，图2-17

- 4种：本质【HW】3种，Imm，Reg，Base
- opr寻址方式
  - 立即寻址
    - 一条指令只能有一个立即数
    - addi x1, x2, 1000
  - 寄存器寻址
  - 基址寻址
    - 一条指令只能有一个
    - lw x1, 1000(x2)
- 指令字寻址方式
  - PC相对寻址
    - beq，jal
  - 间接跳转：indirect
    - jalr x0，100(x1)



# 例：RV指令格式，寻址方式，图2-6

| R-type Instructions | funct7 | rs2 | rs1 | funct3 | rd | opcode | Example |
|---|---|---|---|---|---|---|---|
| add (add) | 0000000 | 00011 | 00010 | 000 | 00001 | 0110011 | add x1, x2, x3 |
| sub (sub) | 0100000 | 00011 | 00010 | 000 | 00001 | 0110011 | sub x1, x2, x3 |

| I-type Instructions | immediate | rs1 | funct3 | rd | opcode | Example |
|---|---|---|---|---|---|---|
| addi (add immediate) | 001111101000 | 00010 | 000 | 00001 | 0010011 | addi x1, x2, 1000 |
| lw (load word) | 001111101000 | 00010 | 010 | 00001 | 0000011 | lw x1, 1000 (x2) |

| S-type Instructions | immed -iate | rs2 | rs1 | funct3 | immed -iate | opcode | Example |
|---|---|---|---|---|---|---|---|
| sw (store word) | 0011111 | 00001 | 00010 | 010 | 01000 | 0100011 | sw x1, 1000(x2) |

- 汇编指令操作数寻址方式表示
  - 寄存器寻址【编号，别名】，立即寻址【二/十/16进制】，基址寻址【1000(x2)】
  - **算逻**指令均为寄存器寻址或立即寻址，load/store为基址寻址
- 机器指令与汇编指令中源操作数和目的操作数的位置对应关系
  - 汇编指令：x2/x3为源操作数rs1/rs2，x1为目的操作数rd
  - 注意S-type：rs2 = x1（待写入，源），rs1 = x2（基址），rs2 => mem[rs1+1000]
- **Load-Store架构**：ALU操作为Reg-Reg或Reg-Imm型，只能Load/Store访存（I/O）
  - add x1, x1, 1000(x2)    //非法

# $zero：x0寄存器，$2.3.2

| Name | Register number | 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 |

- x0固定为“0”（hardwired）
  - data move：reg-reg

```
add $v0,$s0,$zero # returns f ($v0 = $s0 + 0)
```

  - 寄存器赋值

```
addi  $v0,$zero,1 # return 1
```

  - Compare

```
beq   $t0,$zero,L1    # if n >= 1, go to L1
```

  - Goto

beq x0，x0，Exit    // ≠ jal？

# 分支指令寻址方式：跳转范围？

$2.7，2.8，2.10.2，4.4

- 条件分支：PC相对分支，12位offset，+/-
  - beq，bne，…

| | | |
|---|---|---|
| Branch if equal | beq x5, x6, 100 | if (x5 == x6) go to PC+100 |

| | | | | | | |
|---|---|---|---|---|---|---|
| SB-type | immed[12,10:5] | rs2 | rs1 | funct3 | immed[4:1,11] | opcode |

- 无条件分支，+/-，过程调用
  - jal：PC-relative分支， 20位offset，Calling，x1 = ra

| | | |
|---|---|---|
| Jump and link | jal x1, 100 | x1 = PC+4; go to PC+100 |

| | | | |
|---|---|---|---|
| UJ-type | immediate[20,10:1,11,19:12] | rd | opcode |

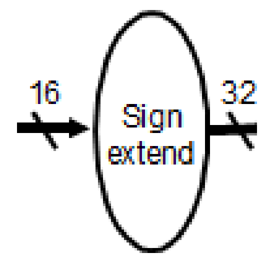
  - jalr：间接（indirect）跳转，12位offset，Return

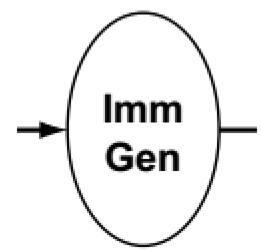
| | | |
|---|---|---|
| Jump and link register | jalr x1, 100(x5) | x1 = PC+4; go to x5+100 |

| | | | | | |
|---|---|---|---|---|---|
| I-type | immediate[11:0] | rs1 | funct3 | rd | opcode |

# 位扩展：短立即数=>32位立即数，$2.4

- 需求：I/S/SB/UJ-type，12位/20位短立即数=>32位
  - addi $s3,$s3,4；$s3 = $s3 + 4
  - lw $t1, offset($t2)；$t1=M[$t2+offset]
  - beq $1, $3, 7； if($1=$3)then goto nPC+7, else not taken
  - jal x0, 100；x0 = 0, goto PC+100
- 位扩展：高位填充
  - 无符号扩展（zero extension）：高位补0
    - 逻辑运算
  - 符号扩展（sign extension）：高位补1，补码
    - 算术运算，地址偏移

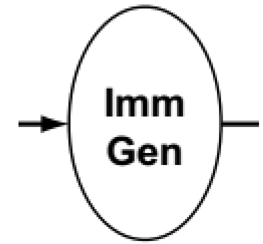



| | | | | | | |
|---|---|---|---|---|---|---|
| I-type | immediate[11:0] | | rs1 | funct3 | rd | opcode |
| S-type | immed[11:5] | rs2 | rs1 | funct3 | immed[4:0] | opcode |
| SB-type | immed[12,10:5] | rs2 | rs1 | funct3 | immed[4:1,11] | opcode |
| UJ-type | immediate[20,10:1,11,19:12] | | | | rd | opcode |

# 32位常数生成，“双指令序列”法，了解

- 计算：大立即数，$2.10.1
  - 取20位立即数：取左移12位后的20位立即数
    - lui：load upper immediate，U-type
      - 加载20位立即数到[31:12]，[11:0]=0
      - 例：lui x5，0x12345；x5=0x1234 5000，
  - +低12位
    - addi：I-type




- 长跳转：寻址32位地址空间，$2.10.2，——*$2.18的auipc？*
  - lui：取高20位
    - 例： lui x5，0x12345；
  - jalr：jump & link reg，I-type
    - 高20位+低12位，——基于x5间接跳转，不是PC相对寻址！
    - 例：jalr x1，100(x5)；x1=PC+4，goto x5+100

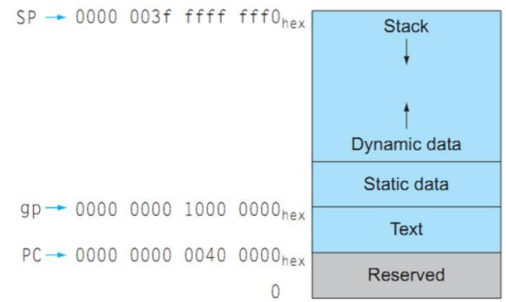
| | | | | | |
|---|---|---|---|---|---|
| U-type | immediate[31:12] | | | rd | opcode |
| I-type | immediate[11:0] | rs1 | funct3 | rd | opcode |

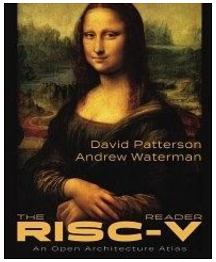
# RV汇编程序结构：段式，《P&W》例

对照图2-25：
sort函数

```
  .text                       # Directive: enter text section
  .align 2                    # Directive: align code to 2^2 bytes
  .globl main                 # Directive: declare global symbol main
main:                         # label for start of main
  addi sp,sp,-16              # allocate stack frame
  sw   ra,12(sp)              # save return address
  lui  a0,%hi(string1)        # compute address of
  addi a0,a0,%lo(string1)     #   string1
  lui  a1,%hi(string2)        # compute address of
  addi a1,a1,%lo(string2)     #   string2
  call printf                 # call function printf
  lw   ra,12(sp)              # restore return address
  addi sp,sp,16               # deallocate stack frame
  li   a0,0                   # load return value 0
  ret                         # return
  .section .rodata            # Directive: enter read-only data section
  .balign 4                   # Directive: align data section to 4 bytes
string1:                      # label for first string
  .string "Hello, %s!\n"      # Directive: null-terminated string
string2:                      # label for second string
  .string "world"             # Directive: null-terminated string
```

```c
#include <stdio.h>
int main()
{
   printf("Hello, %s\n", "world");
   return 0;
}
```



# 过程调用：参数传递，保存断点，保存现场

- 例，数组排序：sort()，swap()，$2.13.1
  - call/jal，return/jalr

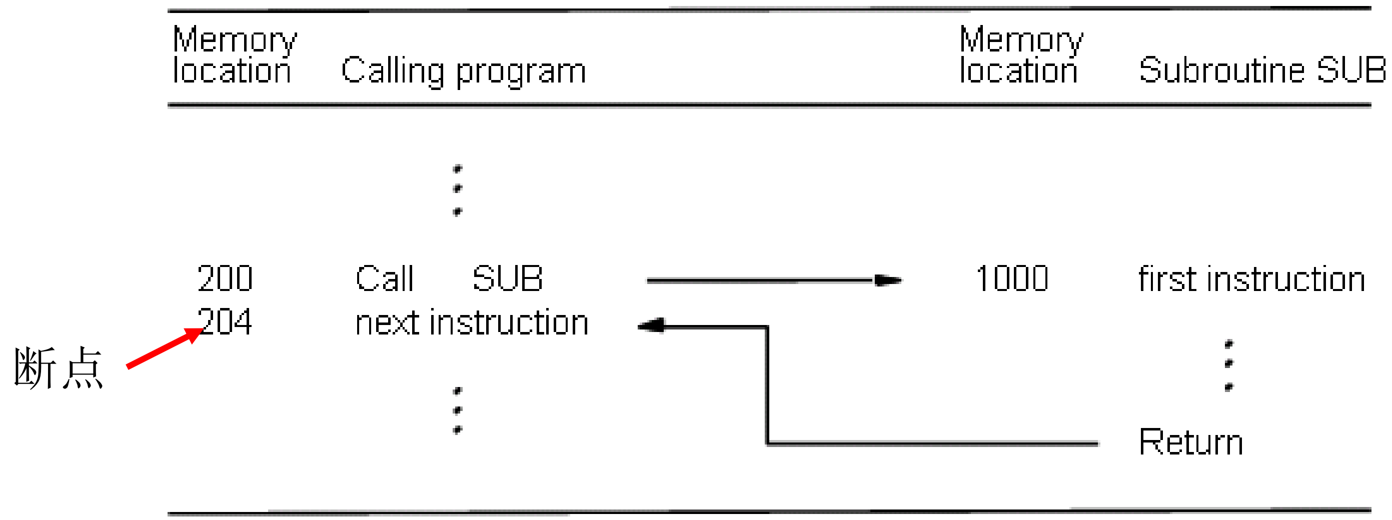
```
void sort (int v[], size_t int n)
{
   size_t i, j;
   for (i = 0; i < n; i += 1) {
        for (j = i - 1; j >= 0 && v[j] > v[j + 1]; j -= 1) {
             swap(v,j);
        }
   }
}
```

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

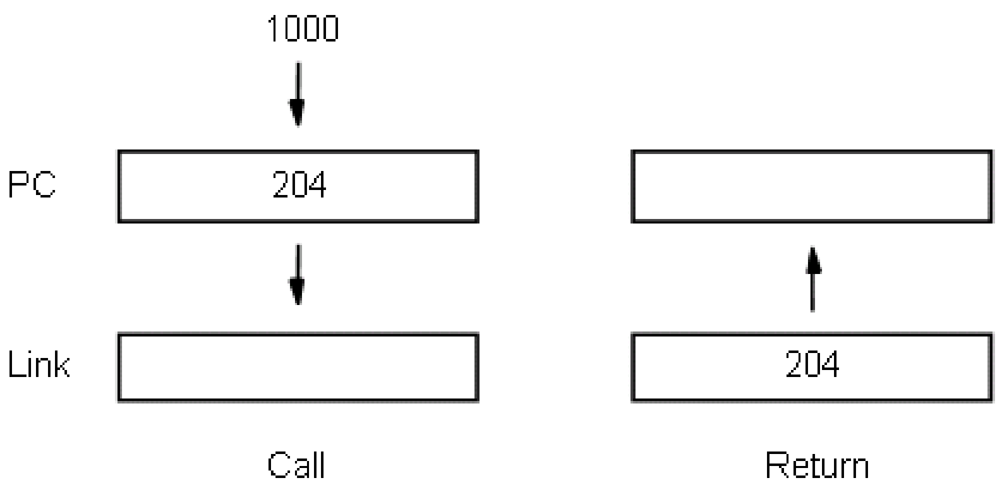
| | |
|---|---|
| Pass parameters and call | `addi x10, x21, 0    # first swap parameter is v`<br>`addi x11, x20, 0    # second swap parameter is j`<br>`jal x1, swap        # call swap` |

```
swap:
 slli   x6, x11, 2   // reg x6 = k * 4
 add    x6, x10, x6  // reg x6 = v + (k * 4)
 lw     x5, 0(x6)    // reg x5 (temp) = v[k]
 lw     x7, 4(x6)    // reg x7 = v[k + 1]
 sw     x7, 0(x6)    // v[k] = reg x7
 sw     x5, 4(x6)    // v[k+1] = reg x5 (temp)
 jalr   x0, 0(x1)    // return to calling routine
```

# 保存断点：单级call/return指令（伪）

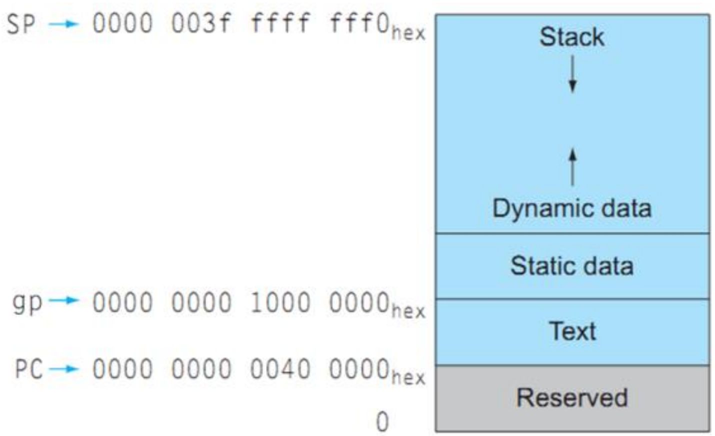


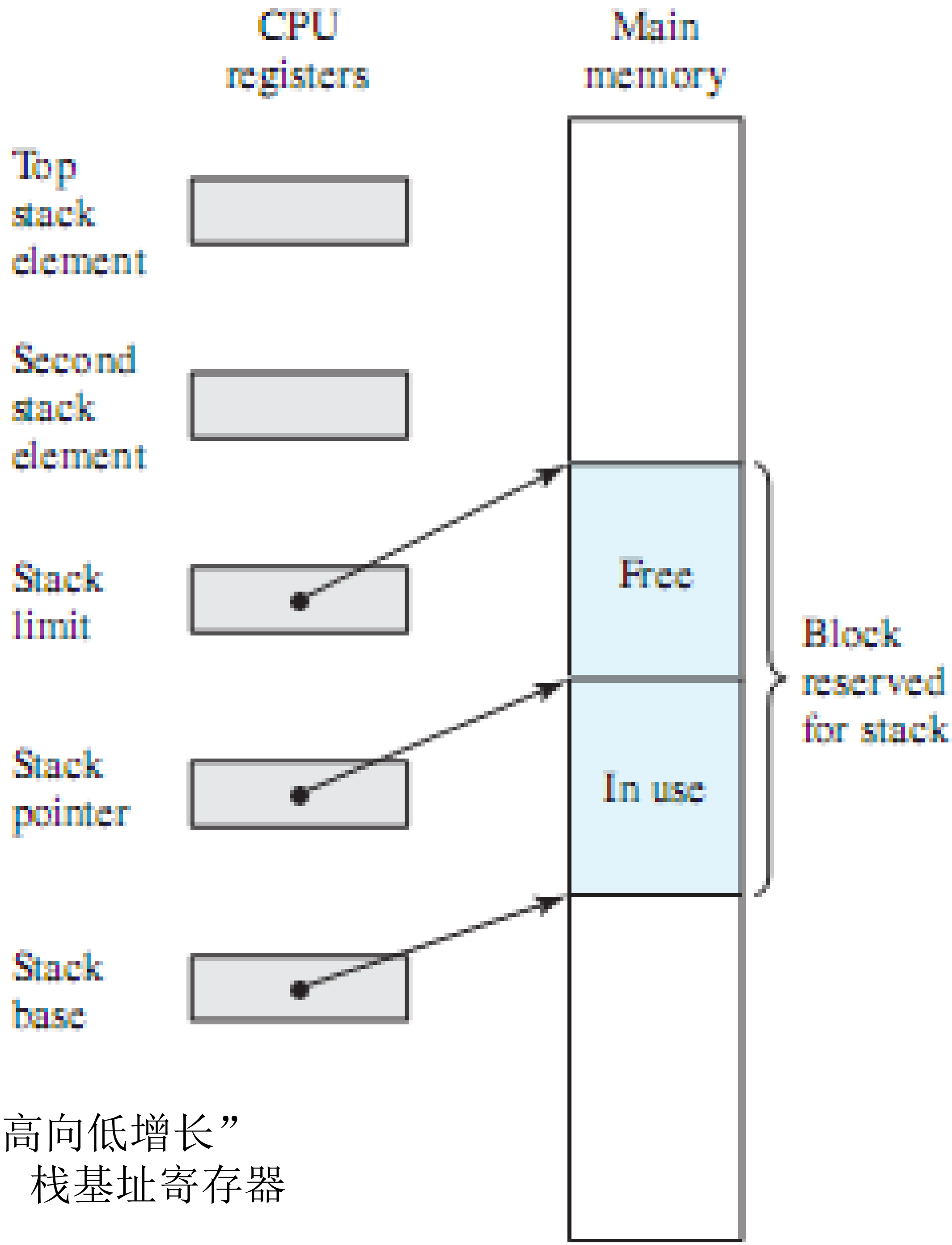

jal x1, 1000
jalr x0，0(x1)




链接寄存器x1 = npc = 返回地址ra

# stack

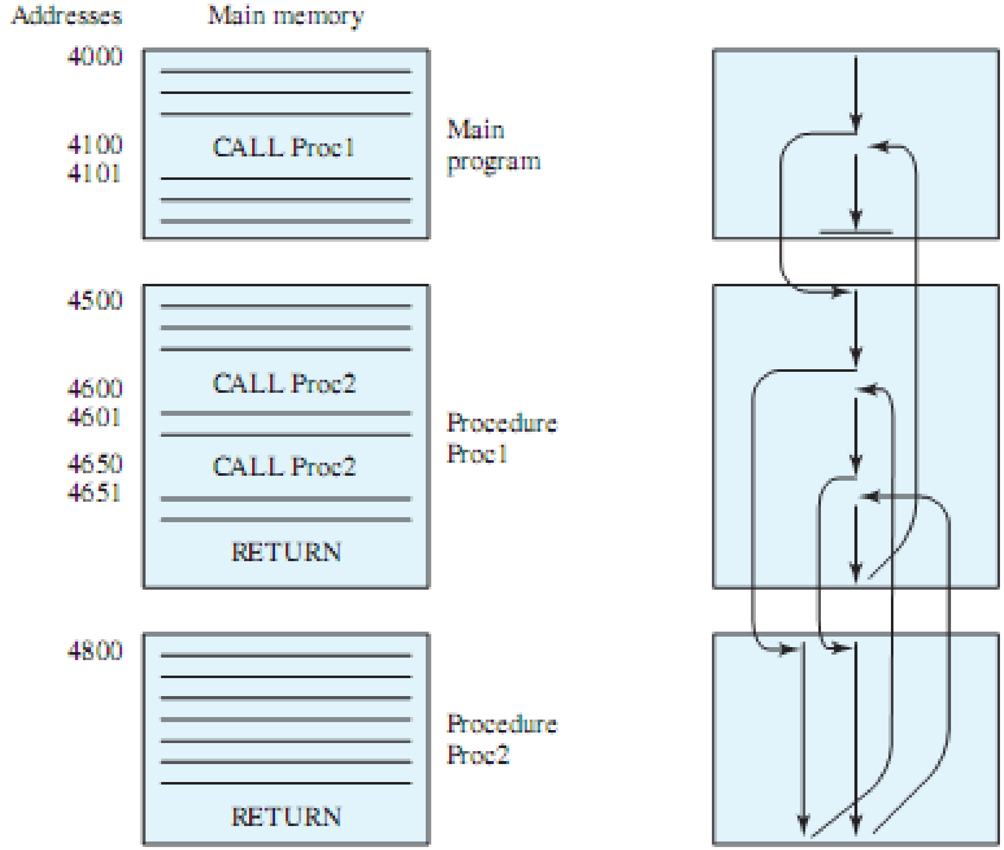


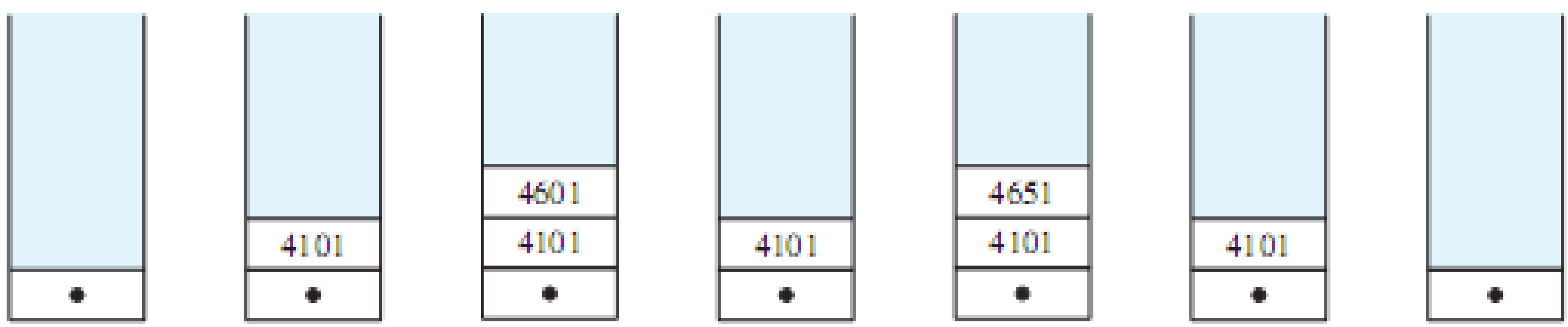

$2.8.1：“按照历史惯例，栈从高向低增长”
常见CPU寄存器：栈顶指针SP，栈基址寄存器

# Use of Stack to Implement Nested Procedures

注意：
示例仅保存了断点
空堆栈/满堆栈?




(a) Calls and returns (b) Execution sequence




(a) Initial stack contents (b) After CALL Proc1 (c) Initial CALL Proc2 (d) After RETURN (e) After CALL Proc2 (f) After RETURN (g) After RETURN

# 保存现场：RV保留寄存器

| Name | Register number | 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 |

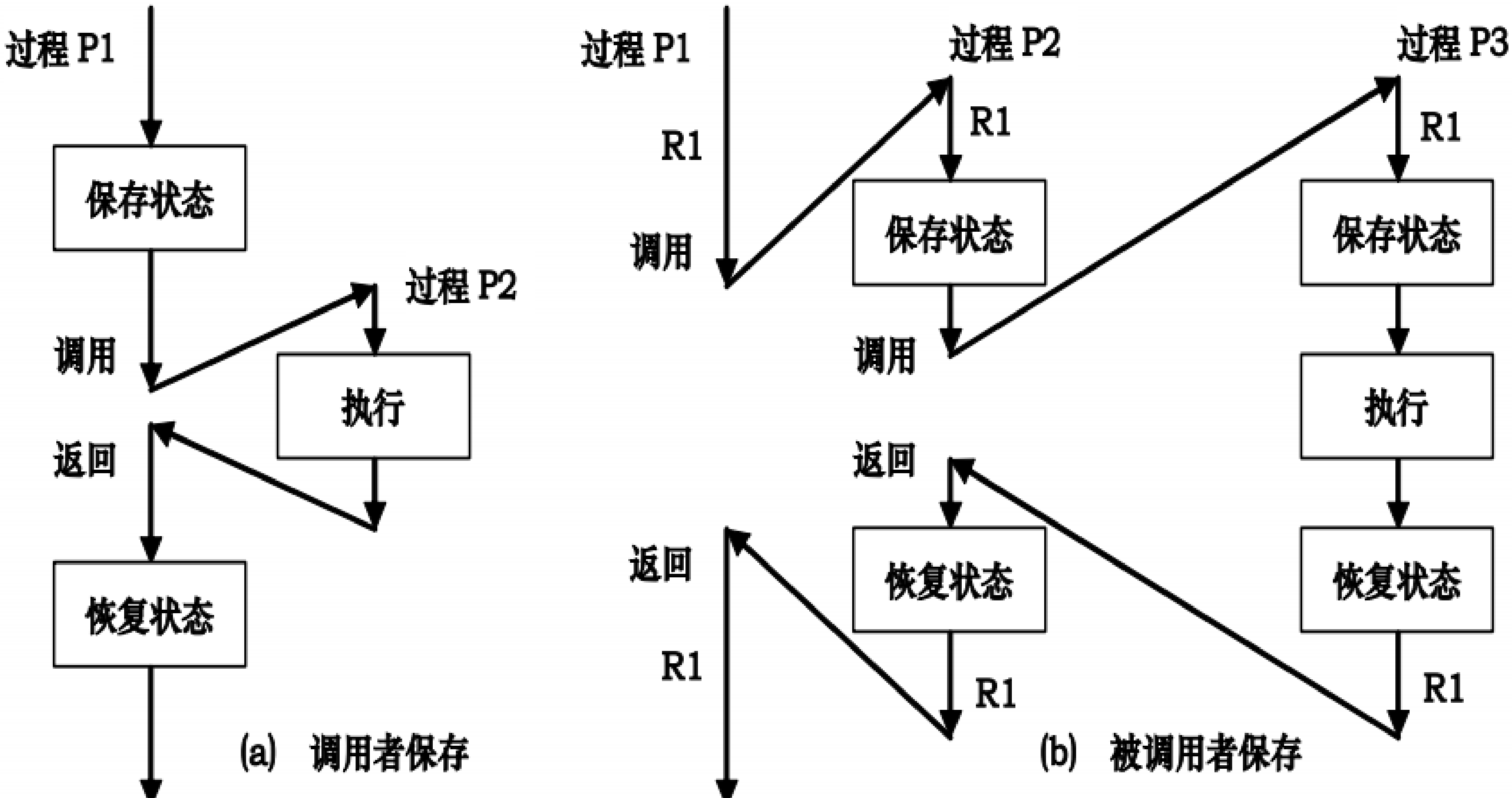
图2-14

- Preserved：在函数调用中应保持不变

# 过程调用：保存现场，两种保存模式，$2.8

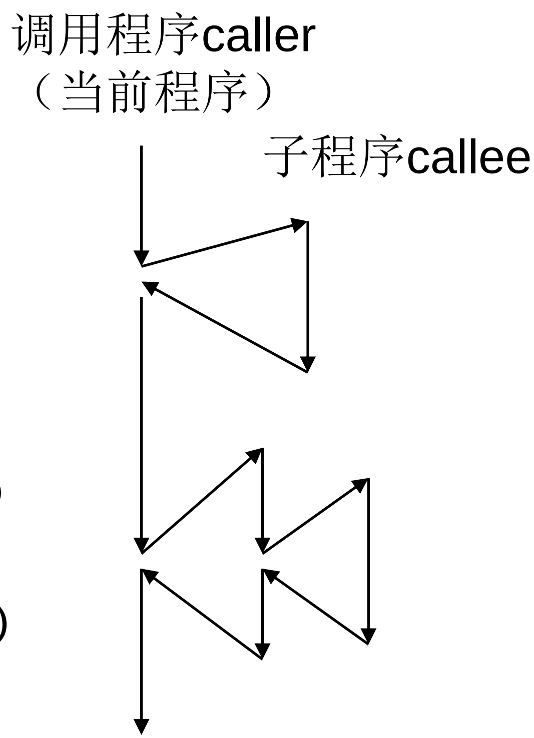
```
int leaf (int g, int h, int i, int j)
{           int f;
            f = (g + h) − (i + j);
            return f;
}
```

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



# 过程调用procedure calling

- 约定“由被调函数（子程序）保存状态（现场）”
  - Caller
    - 参数传递：将参数放在子过程可访问的位置：寄存器/栈/内存
    - 控制转移：Call子过程——原子操作（由一条指令完成）
      - 保存断点（nPC）：返回点
      - 将控制交给子过程：使PC指向子过程入口
  - Callee
    - 保存现场（状态）
      - 保留寄存器：将过程内将要使用的通用Reg入栈
      - 程序的内存数据区？
    - 计算，并将结果放在caller可以访问的位置
    - 恢复现场：出栈
    - 子过程Return：返回Caller的返回点（断点）
      - 将控制交回调用程序：PC = nPC
- 控制转移指令：call（jal）/return（jalr）
- 类型：叶子过程，嵌套过程，递归过程



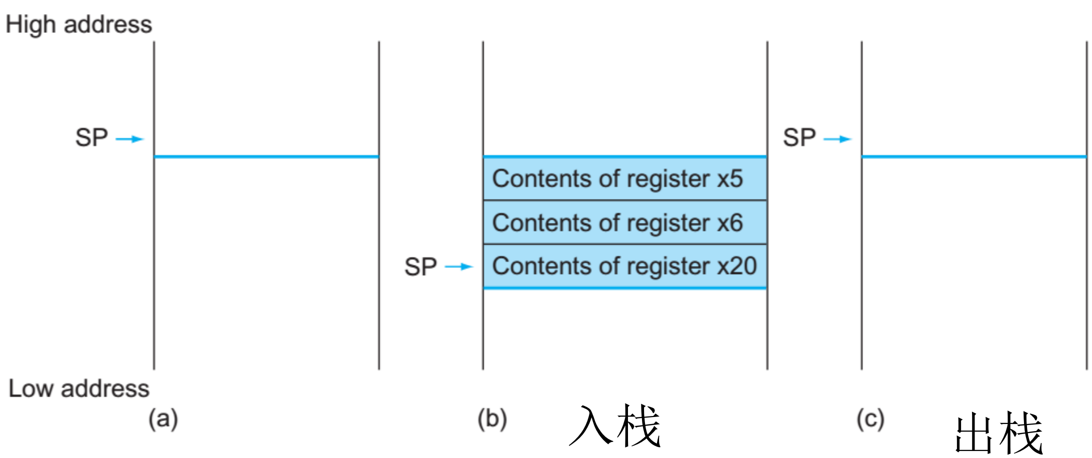
# RV32堆栈操作：push/pop，图2-10

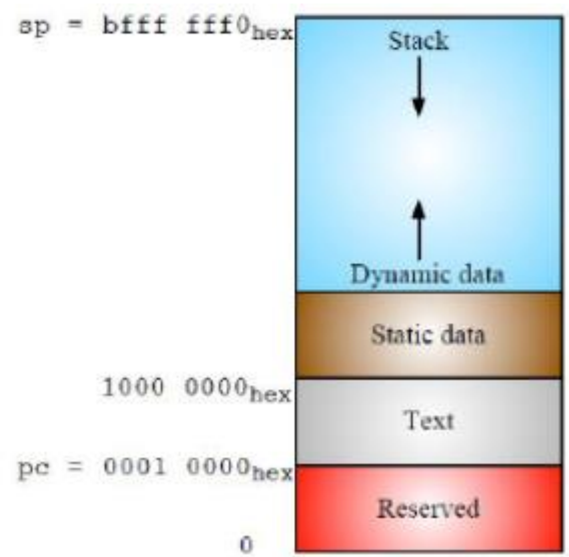
入栈

```
addi  sp, sp, -12        // adjust stack to make room for 3 items
sw    x5, 8(sp)     // save register x5 for use afterwards
sw    x6, 4(sp)          // save register x6 for use afterwards
sw    x20, 0(sp)         // save register x20 for use afterwards
```

出栈

```
lw x20, 0(sp)    // restore register x20 for caller
lw x6, 4(sp)     // restore register x6 for caller
lw x5, 8(sp)     // restore register x5 for caller
addi sp, sp, 12  // adjust stack to delete 3 items
```



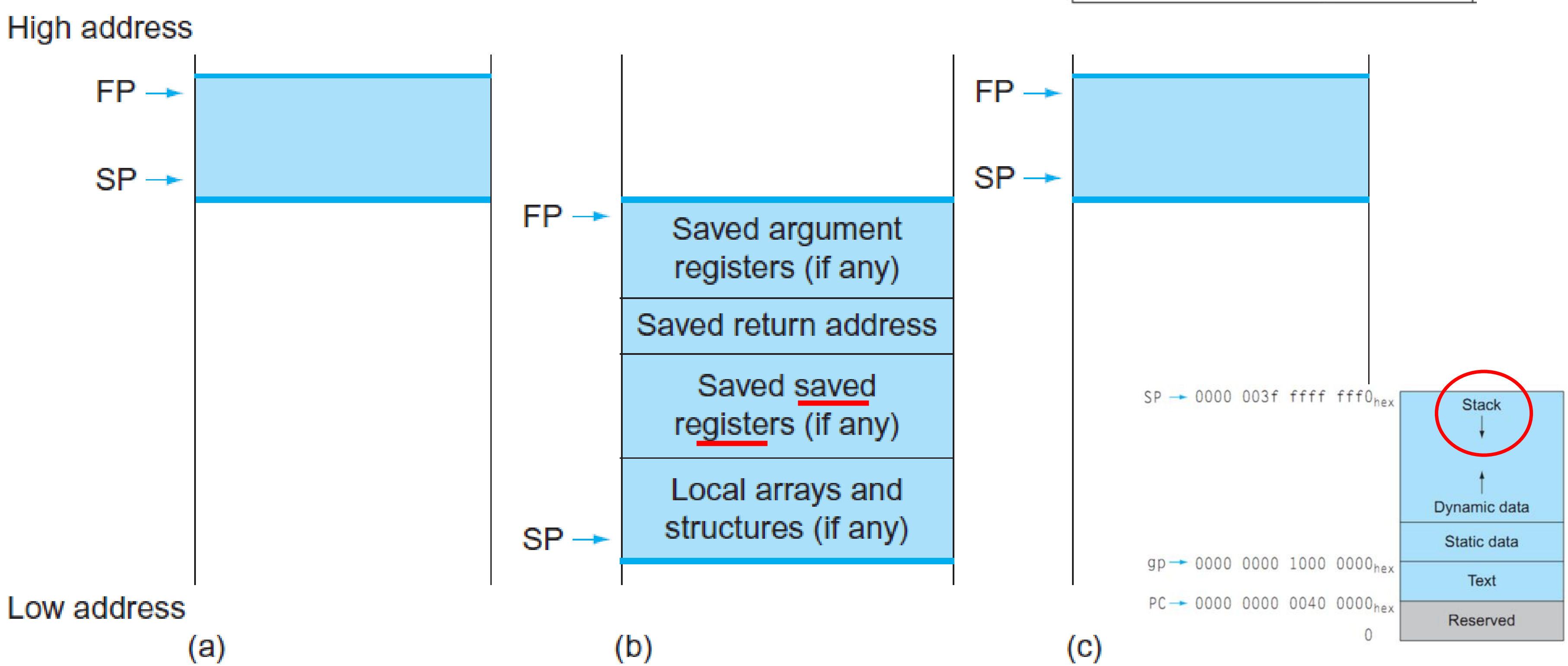
# RV的过程帧（栈帧，活动记录）

- 入栈顺序：参数，断点（返回地址），帧【保留寄存器，局部变量】
- 帧指针fp = 帧基址
  - 初始（a）：sp = fp
  - 结束（c）：sp = fp

图2-11

| |
|---|
| Saved registers: x8-x9, x18-x27 |
| Stack pointer register: x2(sp) |
| Frame pointer: x8(fp) |
| Return address: x1(ra) |
| Stack above the stack pointer |

图2-12

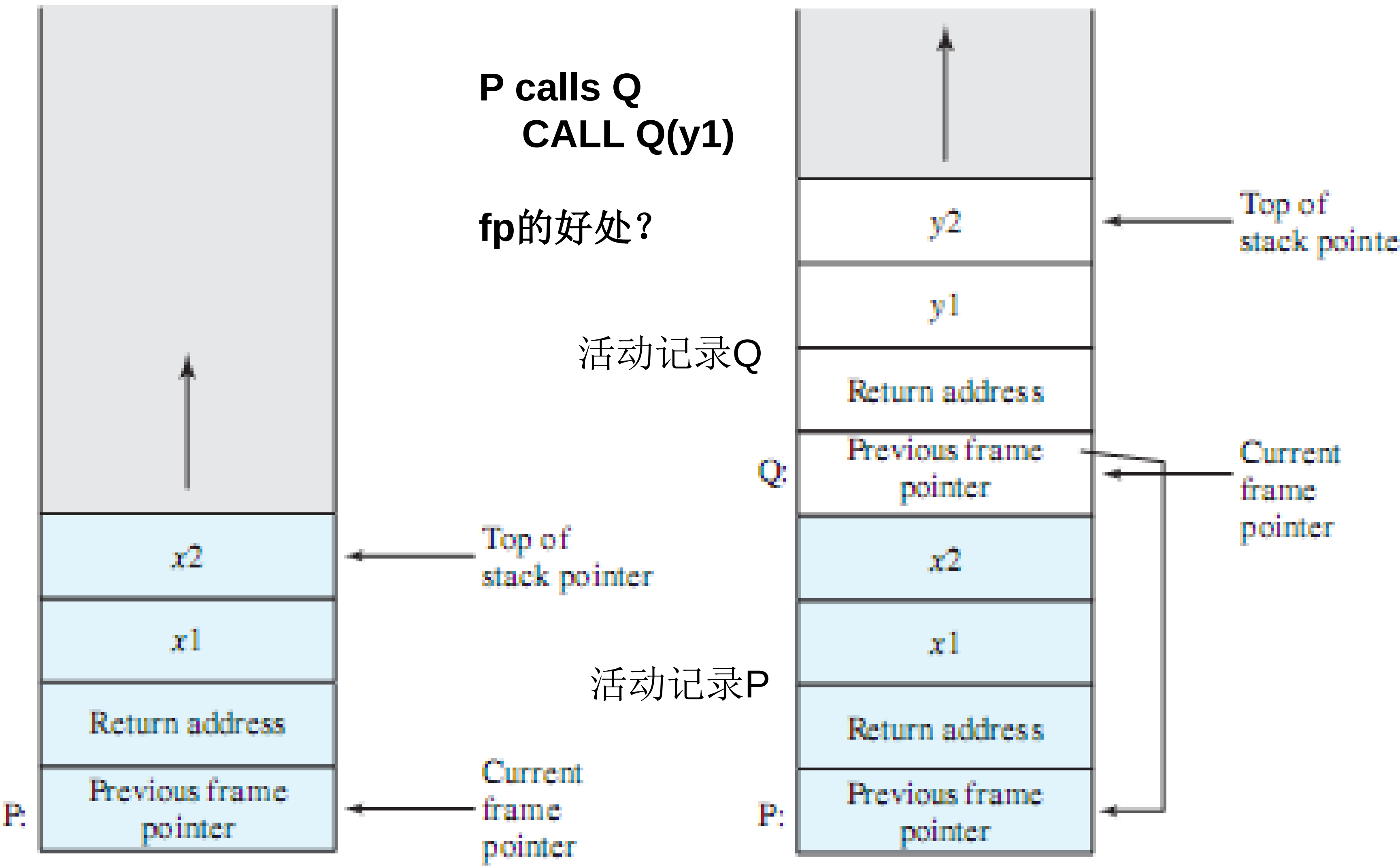


# stack frame：“活动”记录，帧指针fp

**P calls Q**

**CALL Q(y1)**

**fp的好处？**




(a) P is active

(b) P has called Q

# RV calling conventions，$2.8.2

- 传参和返回值：x10~x17【8个】
  - a0–a1: 函数变量或返回值
  - a2–a7：函数变量
- 断点ra：x1
- call
  - jal x1，ProcessAddress；PC相对寻址
    - jump-and-link：跳转，并自动保存断点（nPC）至$ra
- Return
  - jalr x0，0(ra)；间接跳转
    - jump-and-link register：返回ra。断点（当前子函数的nPC）保存于x0（被抛弃）
- 现场保存策略：preserved由callee保存，notPreserved由caller负责

| Name | Register number | 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 |

图2-14

| 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 |

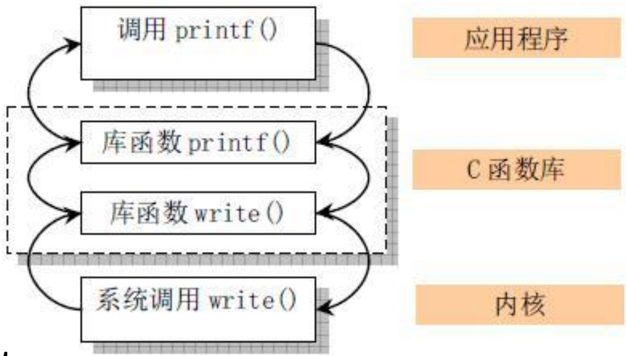
图2-11

| Register | ABI Name | Description | Saver |
|---|---|---|---|
| x0 | zero | Hard-wired zero | — |
| x1 | ra | Return address | Caller |
| x2 | sp | Stack pointer | Callee |
| x3 | gp | Global pointer | — |
| x4 | tp | Thread pointer | — |
| x5 | t0 | Temporary/alternate link register | Caller |
| x6–7 | t1–2 | Temporaries | Caller |
| x8 | s0/fp | Saved register/frame pointer | Callee |
| x9 | s1 | Saved register | Callee |
| x10–11 | a0–1 | Function arguments/return values | Caller |
| x12–17 | a2–7 | Function arguments | Caller |
| x18–27 | s2–11 | Saved registers | Callee |
| x28–31 | t3–6 | Temporaries | Caller |
| f0–7 | ft0–7 | FP temporaries | Caller |
| f8–9 | fs0–1 | FP saved registers | Callee |
| f10–11 | fa0–1 | FP arguments/return values | Caller |
| f12–17 | fa2–7 | FP arguments | Caller |
| f18–27 | fs2–11 | FP saved registers | Callee |
| f28–31 | ft8–11 | FP temporaries | Caller |

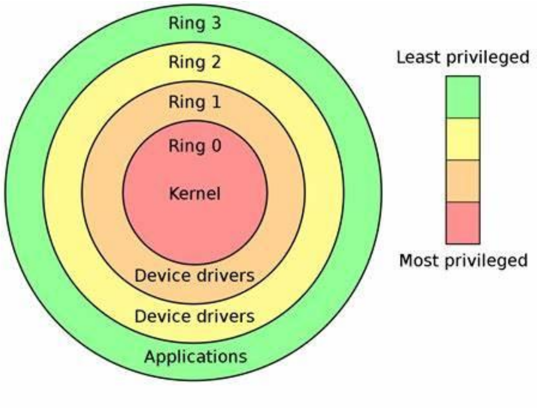
Table 25.1: Assembler mnemonics for RISC-V integer and floating-point registers, and their role in the first standard calling convention.

The RISC-V Instruction Set Manual，Volume I: Unprivileged ISA，2019
Ch25：RISC-V Assembly Programmer’s Handbook

# System calls



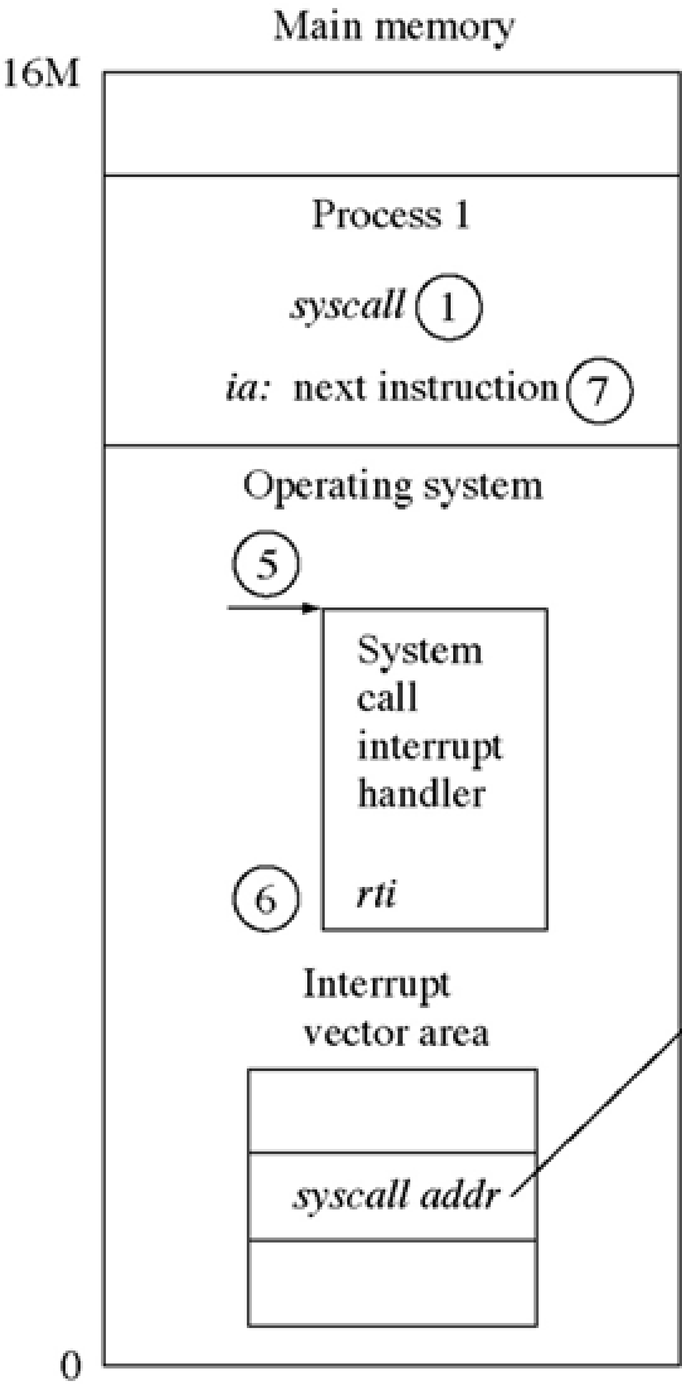

- OS服务：API
  - various names：trap/exception, svc, soft interrupt
- Why
  - 复用
  - Certain operations require specialized knowledge
    - I/O设备，PCIe总线，USB
  - protection：多任务共享

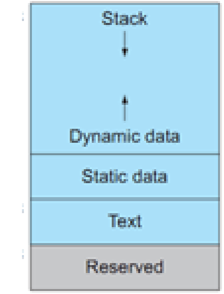



- What
  - A special machine instruction that causes an soft-interrupt/exception
    - 产生机器状态切换（protection）：用户态，内核态（系统态，supervisor，hypervisor）
    - 需保存PSW/CSR
  - RV：环境调用指令ecall
    - Ripes提供哪些API服务?
  - x86系统调用（system calls）：int16，int32
    - BIOS，Windows：显示、键盘、磁盘、文件、打印机、时间

COD-RV syscall指令，图5-47

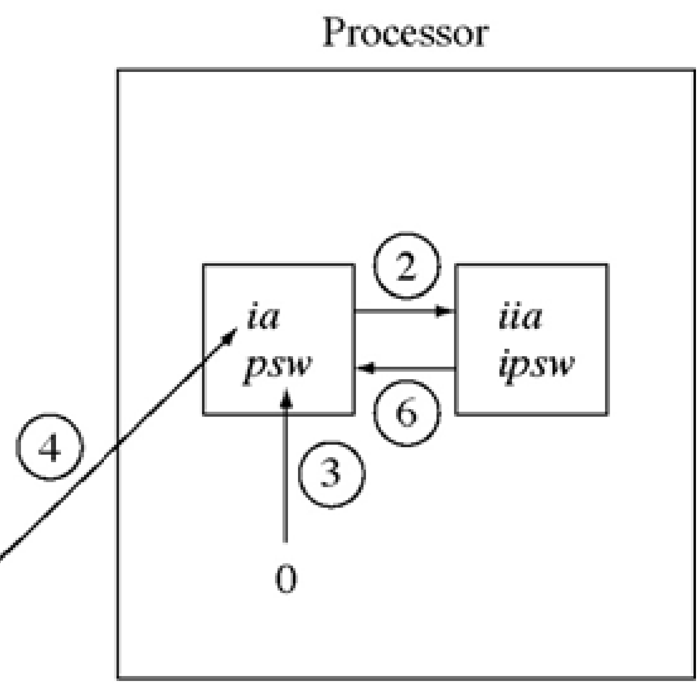
| | |
|---|---|
| ECALL | Environment Call |
| EBREAK | Environment Breakpoint |
| SRET | Supervisor Exception Return |
| WFI | Wait for Interrupt |




# System call flow of control

1. User program invokes system call. 用户态
2. Operating system code performs operation. 系统态
3. Returns control to user program. 用户态



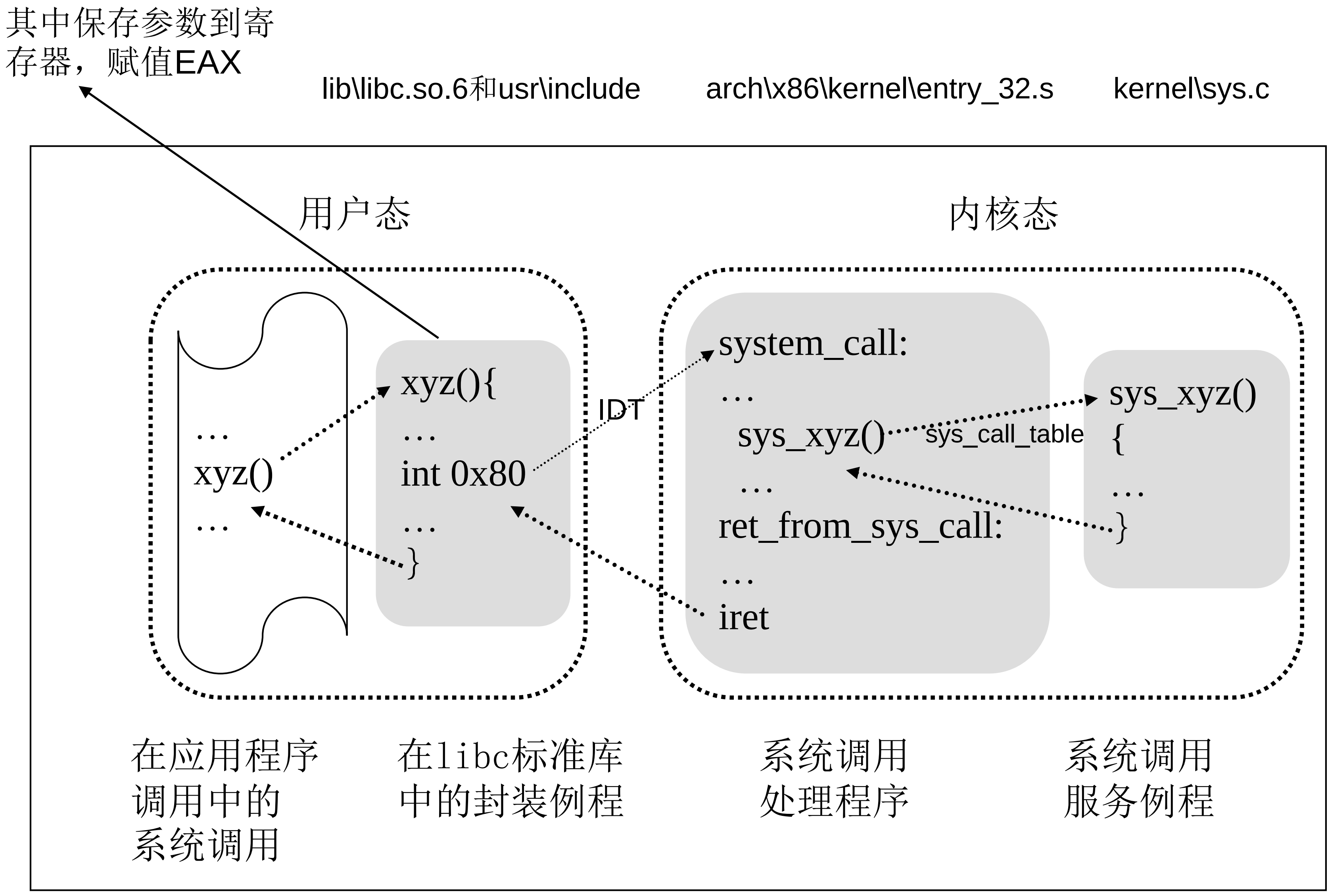

2/3/4由syscall指令完成！
2：保存断点和psw
3：psw赋0，进入内核态
4：syscall入口赋给PC

5：进入系统函数
6/7由中断返回指令iret完成
6：恢复调用前状态
7：从断点处继续执行

API存储位置：
sys_call_table（interrupt vector area）
sys_call_ISR（system call interrupt handler）

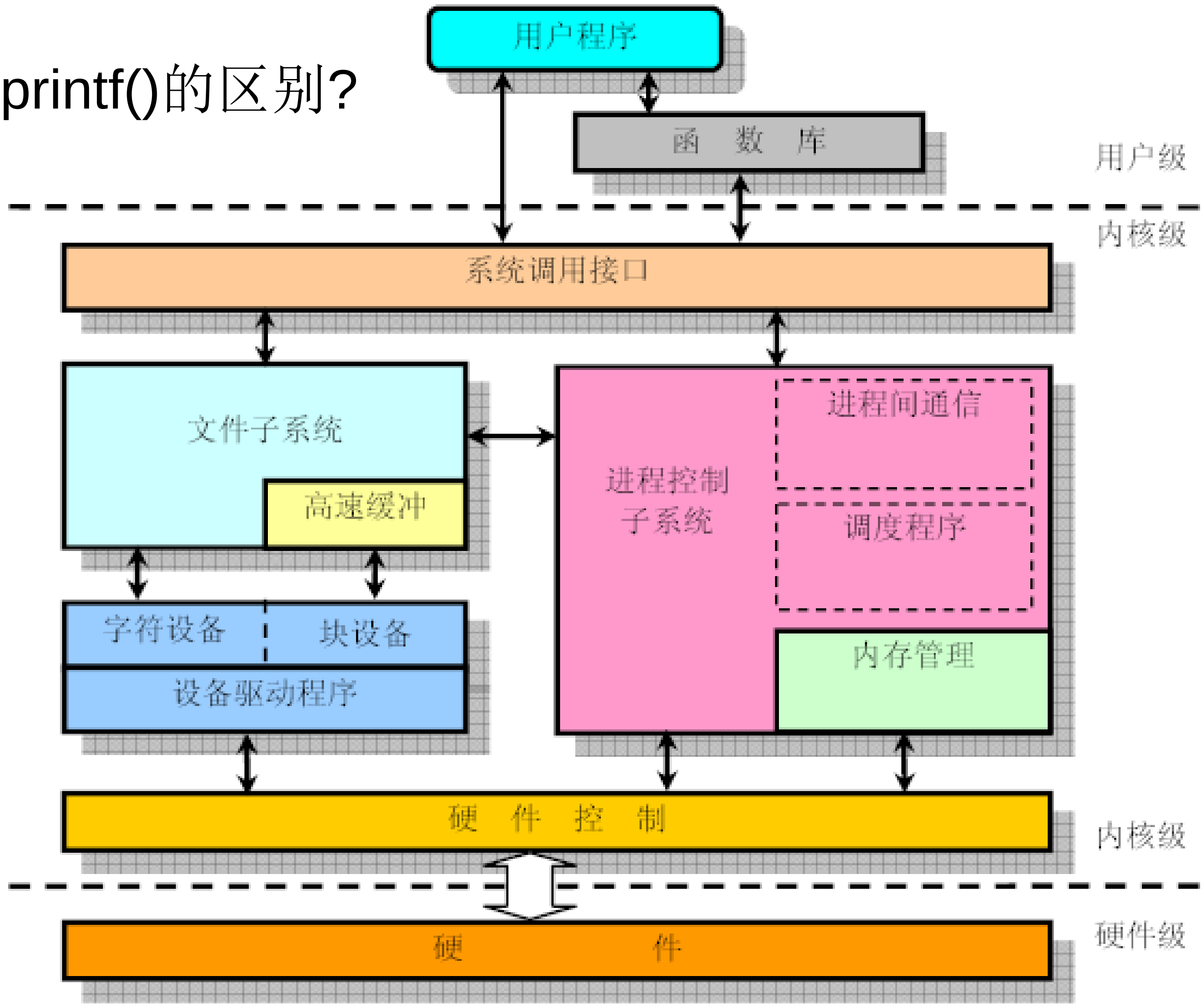
ia：指令地址寄存器，保存于iia寄存器
psw：程序状态字寄存器，保存于ipsw寄存器

# 系统调用：x86调用门

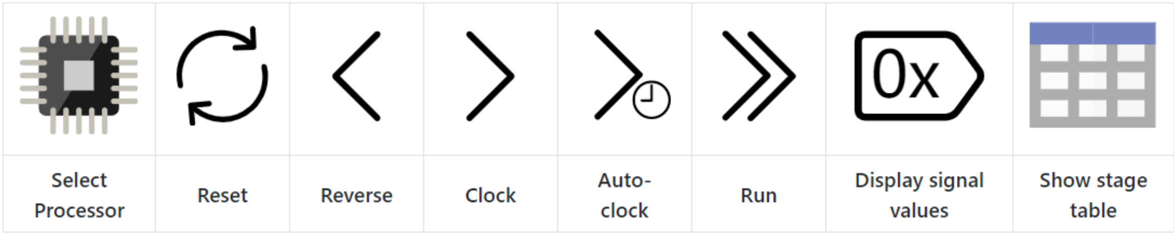

其中保存参数到寄
存器，赋值EAX
lib\libc.so.6和usr\include
arch\x86\kernel\entry_32.s
kernel\sys.c
用户态
内核态
…
xyz()
…
xyz(){
…
int 0x80
…
}
IDT
system_call:
…
sys_xyz()
sys_call_table
…
ret_from_sys_call:
…
iret
sys_xyz()
{
…
}
在应用程序
调用中的
系统调用
在libc标准库
中的封装例程
系统调用
处理程序
系统调用
服务例程

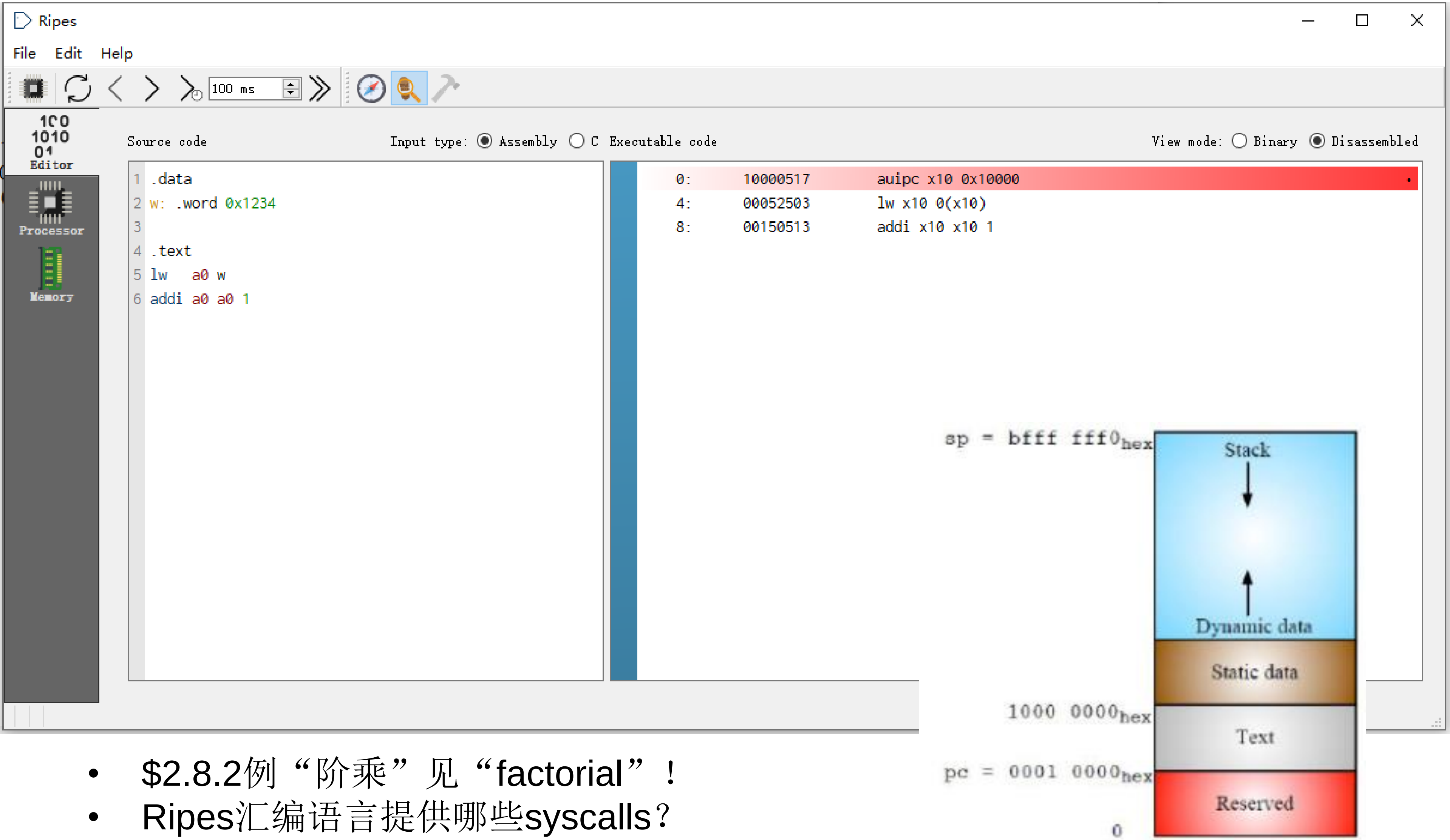
# C语言和OS服务：APIs、libc、syscalls?

abs()与printf()的区别?



# Ripes汇编




- $2.8.2例“阶乘”见“factorial”！
- Ripes汇编语言提供哪些syscalls？

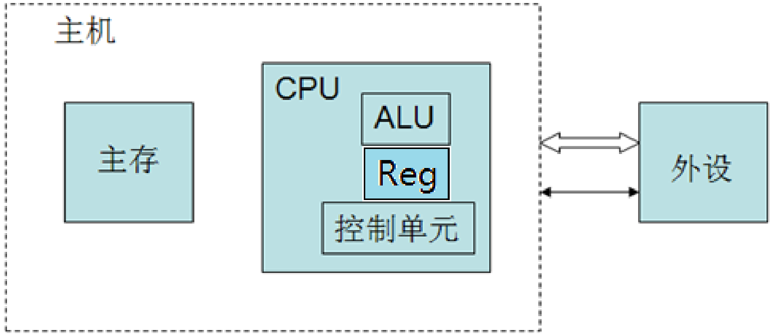
# SPIM的系统调用：COD4附录B.9

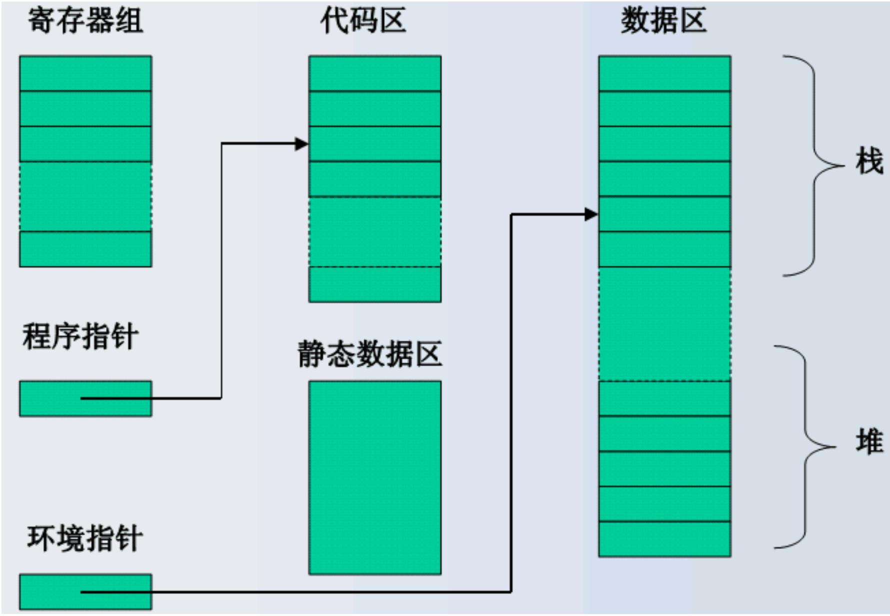
- SPIM：MIPS-32仿真器
  - 汇编程序调试、执行
  - 标准设备I/O服务
- SYSCALL Step
  - $v0=srv#
  - $a0~3=arg
  - syscall
  - $v0=返回值
- Ripes类似

| Service | System Call Code | Arguments | Result |
|---|---|---|---|
| print integer | 1 | $a0 = value | (none) |
| print float | 2 | $f12 = float value | (none) |
| print double | 3 | $f12 = double value | (none) |
| print string | 4 | $a0 = address of string | (none) |
| read integer | 5 | (none) | $v0 = value read |
| read float | 6 | (none) | $f0 = value read |
| read double | 7 | (none) | $f0 = value read |
| read string | 8 | $a0 = address where string to be stored<br>$a1 = number of characters to read + 1 | (none) |
| memory allocation | 9 | $a0 = number of bytes of storage desired | $v0 = address of block |
| exit (end of program) | 10 | (none) | (none) |
| print character | 11 | $a0 = integer | (none) |
| read character | 12 | (none) | char in $v0 |

# 汇编语言程序设计要点：显式与约定

- 机器模型：对程序员显式可见
- ISA
  - 指令集
    - 数据存储：reg， mem
    - Move，ALU，分支，I/O
    - 整数，*浮点*，伪指令（RV1图2-40）
  - 寻址方式：操作数，目标指令
- 程序
  - 段式内存分配：数据、代码、堆栈
  - 寄存器分配：寄存器使用约定
  - 过程调用/系统调用约定
    - » 堆栈，栈帧
- *可执行程序生成*



# Bubble sort (trace)

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | 4 | 10 | 5 | 3 |

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | 3 | 4 | 5 | 10 |

**Basic idea:**

① $j \leftarrow n-1$ (index of last element in $A$)
② If $A[j] < A[j-1]$, swap both elements
③ $j \leftarrow j-1$, goto ② if $j > 0$
④ Goto ① if a swap occurred

见$2.13.2，图2-25

①

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | 4 | 10 | 5 | ③ |

②

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | 4 | 10 | ③ ↔ | 5 |

③

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | 4 | 10 | ③ | 5 |

②

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | 4 | ③ ↔ | 10 | 5 |

③

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | 4 | ③ | 10 | 5 |

②

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | ③ ↔ | 4 | 10 | 5 |

③

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | ③ | 4 | 10 | 5 |

②

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| ③ ↔ | 3 | 4 | 10 | 5 |

④ Swap occured? (Yes, goto ①)

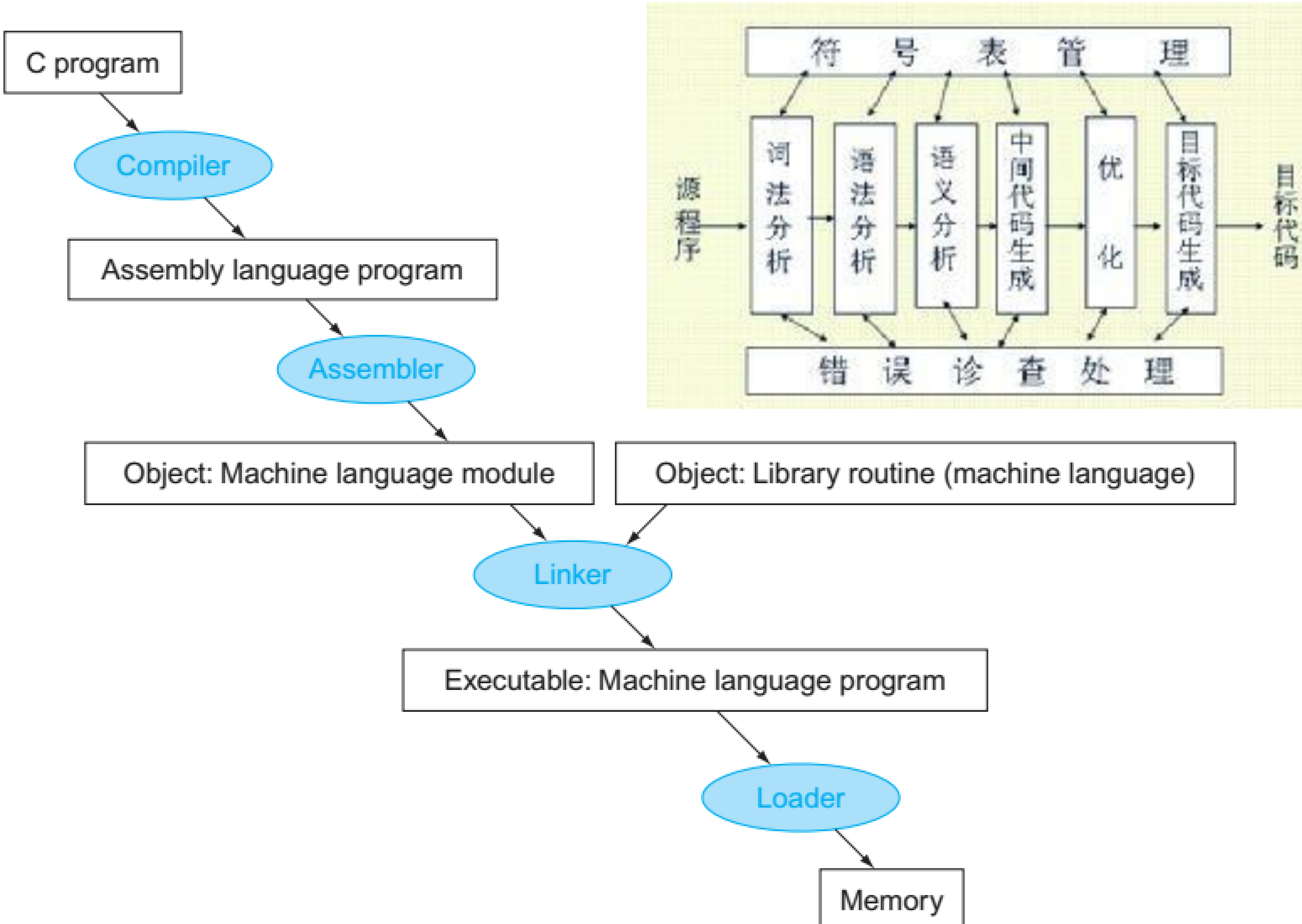
①

| $A[0]$ | $A[1]$ | $A[2]$ | $A[3]$ | $A[4]$ |
|---|---|---|---|---|
| 3 | 3 | 4 | 10 | ⑤ |

# 可执行程序格式、生成与执行

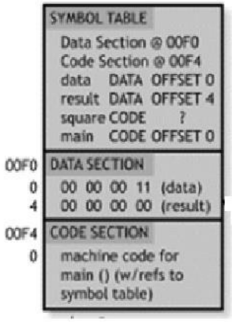
了解，自学

# A translation hierarchy for C，FIG 2.20

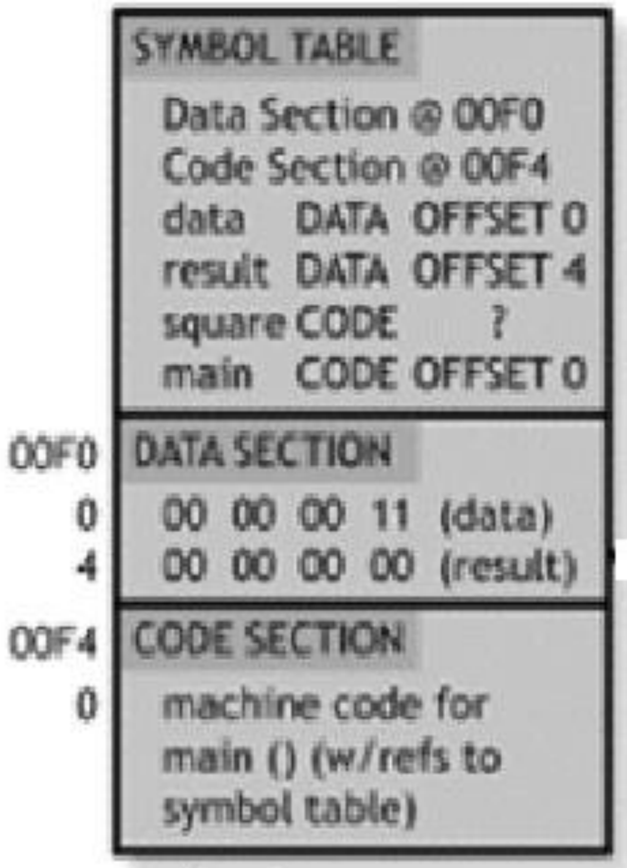


# The Assembly Process：生成.obj

- Assembler translates source file to *object code*（common object file format, COFF）
  - Recognizes *mnemonics* for OP codes
  - Interprets *addressing modes* for operands
  - Recognizes *directives* that define constants and allocate space in memory for data
  - *Labels* and *names* placed in symbol table
- 关键问题：Consider forward branch to label in program
  - Offset cannot be found without target address
- Let assembler make two passes over program
  - 1st pass: generate all machine instructions, and enter labels/addresses into symbol table
    - Some instructions incomplete but sizes known
  - 2nd pass: calculate unknown branch offsets using address information in symbol table



# .obj与Symbol Table




```
    .text
    .align 2
    .globl main
main:
    addi sp,sp,-16
    sw   ra,12(sp)
    lui  a0,%hi(string1)
    addi a0,a0,%lo(string1)
    lui  a1,%hi(string2)
    addi a1,a1,%lo(string2)
    call printf
    lw   ra,12(sp)
    addi sp,sp,16
    li   a0,0
    ret
    .section .rodata
    .balign 4
string1:
    .string "Hello, %s!\n"
string2:
    .string "world"
```

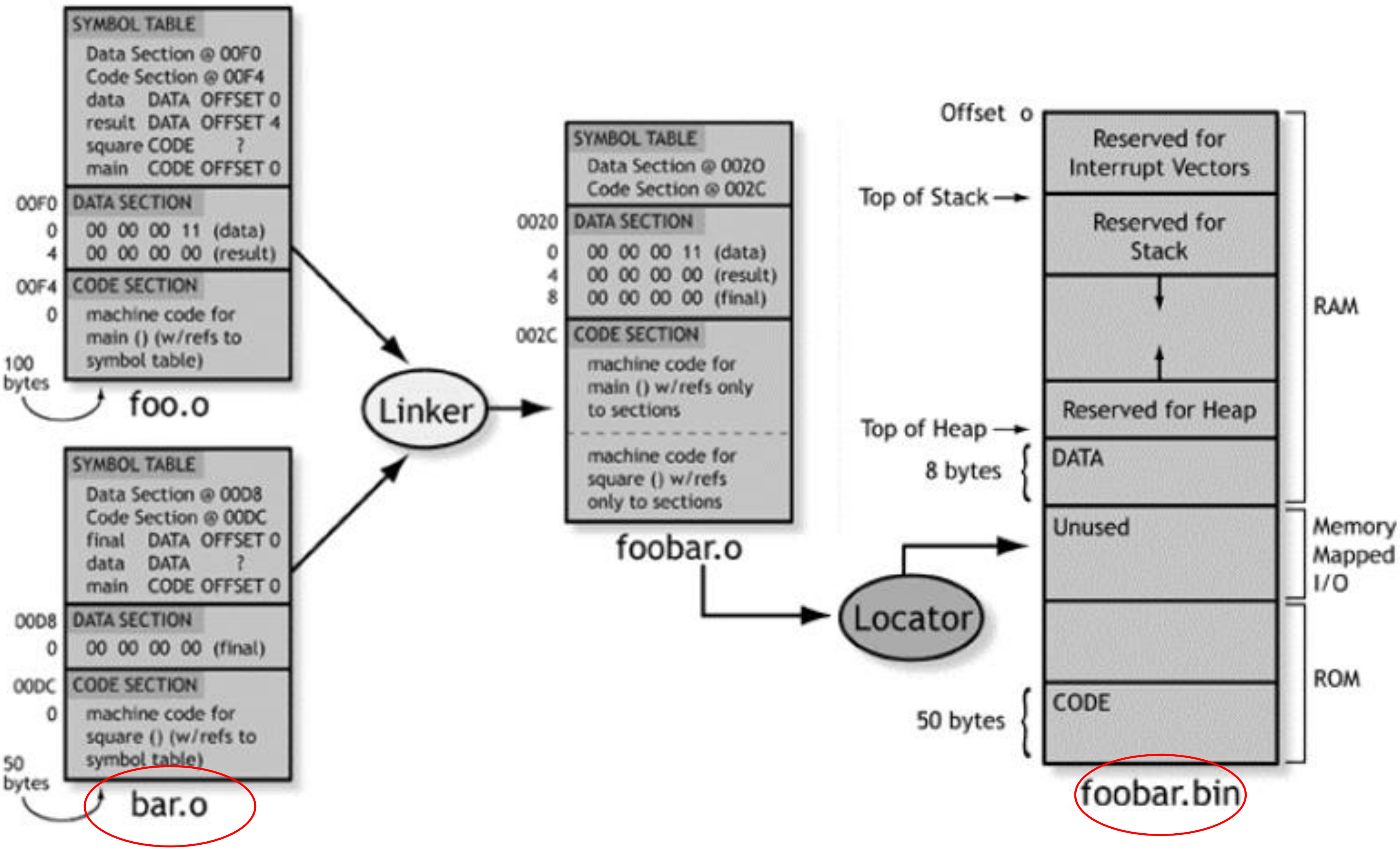
符号表：
全局定义和外部引用

*directives*： 内存地址指针
*Labels*： 程序地址标号
*names*： 段名，变量名

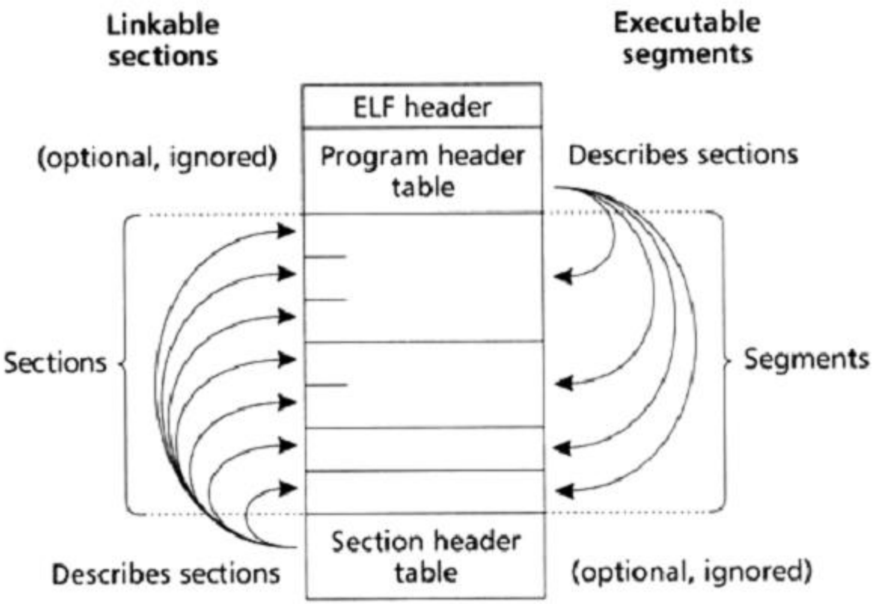
# The Linker：合并各段

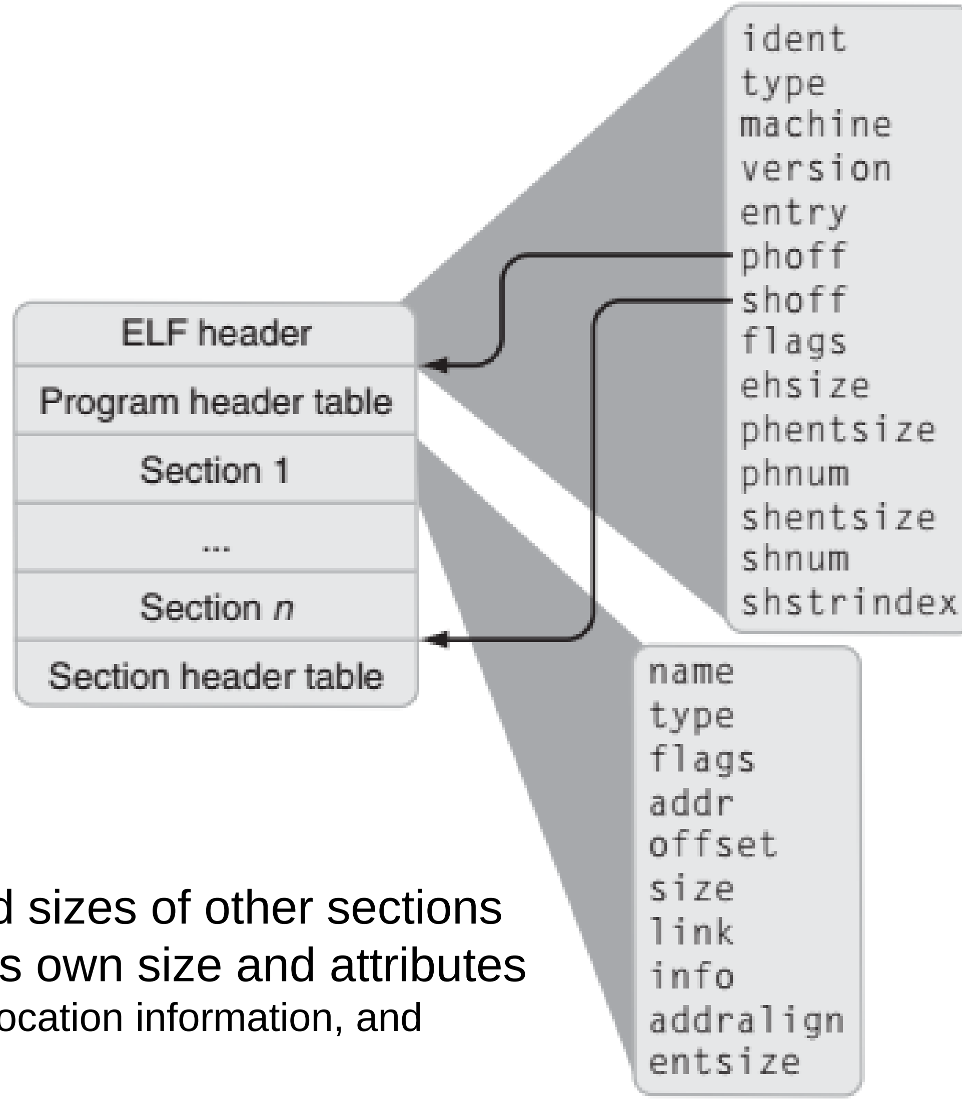
- Combines object files into object program （exe）
  - Constructs map of full program in memory using length information in each object file
    - Map determines addresses of all names
  - Instructions referring to external names are finalized with addresses determined by map
- Libraries：Subroutines
  - includes name information to aid in resolving references from calling program

# Linking and Locating



# ELF 格式目标文件结构



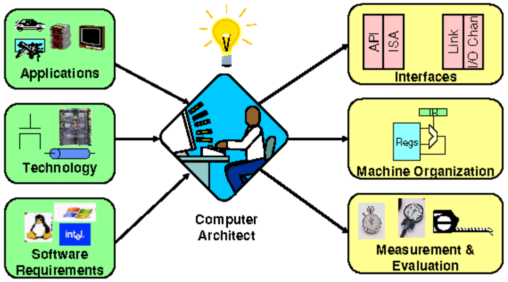

- the ELF specification
  - ELF header tell the offsets and sizes of other sections
  - Each section then describes its own size and attributes
    - symbol tables, string tables, relocation information, and dynamic linking information

# Loading/Executing Object Programs

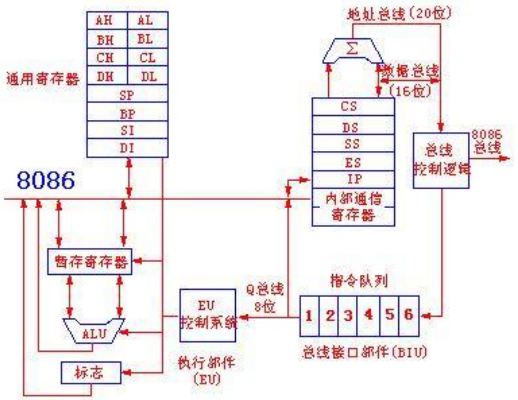
- 将映像文件从磁盘加载到内存
  - 读取文件头来确定各段大小
  - 创建虚拟地址空间
  - 将代码和初始化的数据复制到内存中
    - 或设置页表项来处理缺页
  - 在栈上建立参数
  - 初始化寄存器（包括sp、 fp、 gp）
  - 跳转到启动例程
    - 将参数复制到x10等等并调用main函数
    - 当main函数返回时，进行exit系统调用

# ISA分类与进化

# 影响早期ISA设计的因素




- 内存小而慢，能省则省
  - 某个完整系统只需几K字节
  - 指令长度不等、执行多个操作的指令
- 寄存器贵，少
  - 操作基于存储器
  - 多种寻址方式

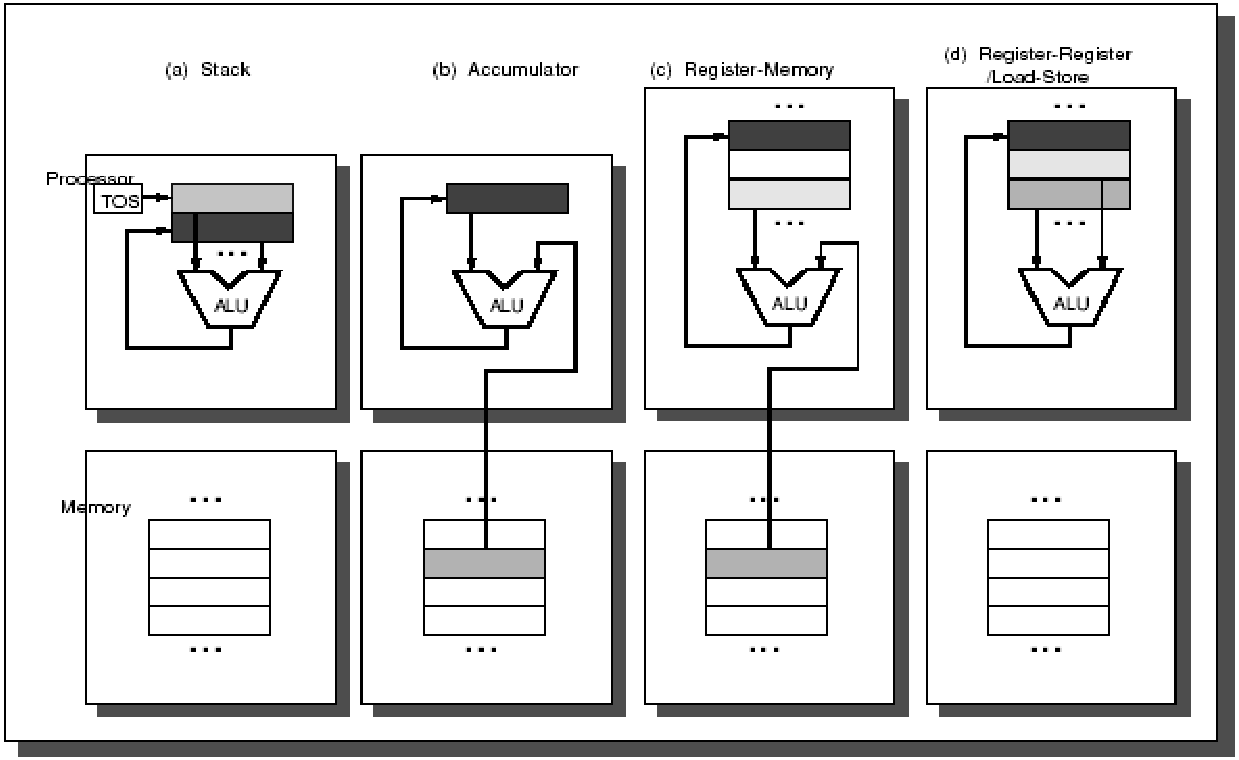



- 编译技术尚未出现
  - 程序是以机器语言或汇编语言设计
  - 当时的看法是硬件比编译器更易设计
    - 为了便于编写程序，计算机架构师造出越来越复杂的指令，完成高级程序语言直接表达的功能
    - 进化中的痕迹：X86中的串操作指令

# 机器结构与ISA分类

- 指令格式和寻址方式越复杂，则越灵活高效
  - 性能：操作数的存放位置（访存是瓶颈）
  - 权衡：硬件设计复杂度、指令系统的兼容性
- 机器结构：processor designer view
  - stack
  - Accumulator
  - register-mem
  - register-register
- ISA分类：programmer/compiler view
  - CISC：以机器指令实现高级语言功能（reg-mem）
  - RISC：采用load/store体系，运算基于寄存器（reg-reg）
  - VLIW：兼容性差，硬件简单，低功耗

# ISA Classes (processor designer view)

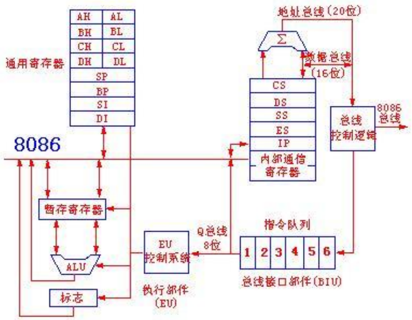



| Stack | Accumulator | Register (register-memory) | Register (load-store) |
|---|---|---|---|
| Push A | Load A | Load R1,A | Load R1,A |
| Push B | Add B | Add R3,R1,B | Load R2,B |
| Add | Store C | Store R3,C | Add R3,R1,R2 |
| Pop C | | | Store R3,C |

H&P第6版：附录A，图A.1，四类ISA中操作数的位置

# ISA分类（programmer prospective）

- CISC：硬件换性能！≈上千条指令
  - 以机器指令实现高级语言功能
  - 指令译码复杂
    - 指令格式、字长不一（x86从1byte～6bytes）
    - 寻址方式多
  - 访存开销大：寄存器少，任何指令都可以访存




- RISC：简化硬件，优化常用操作！≤ 两百条指令
  - 指令字长固定，格式规则，种类少，寻址方式简单
  - 减少访存，设置大量通用寄存器，运算基于寄存器
    - 为了提高性能，需要减少访存次数，因此寄存器寻址性能最高。
    - 采用load/store体系，只有load/store指令访存。
  - 采用Superscalar、Superpipeling等技术，提高IPC
- VLIW：空间换时间（SIMD），低功耗，兼容性差

# CISC例，X86指令格式，图2-39

a. JE EIP + displacement

| 4 | 4 | 8 |
|---|---|---|
| JE | Condition | Displacement |

b. CALL

| 8 | 32 |
|---|---|
| CALL | Offset |

c. MOV  EBX, [EDI + 45]

| 6 | 1 | 1 | 8 | 8 |
|---|---|---|---|---|
| MOV | d | w | r-m postbyte | Displacement |

d. PUSH ESI

| 5 | 3 |
|---|---|
| PUSH | Reg |

e. ADD EAX, #6765

| 4 | 3 | 1 | 32 |
|---|---|---|---|
| ADD | Reg | w | Immediate |

f. TEST EDX, #42

| 7 | 1 | 8 | 32 |
|---|---|---|---|
| TEST | w | Postbyte | Immediate |

# Growth of x86 instruction set over time

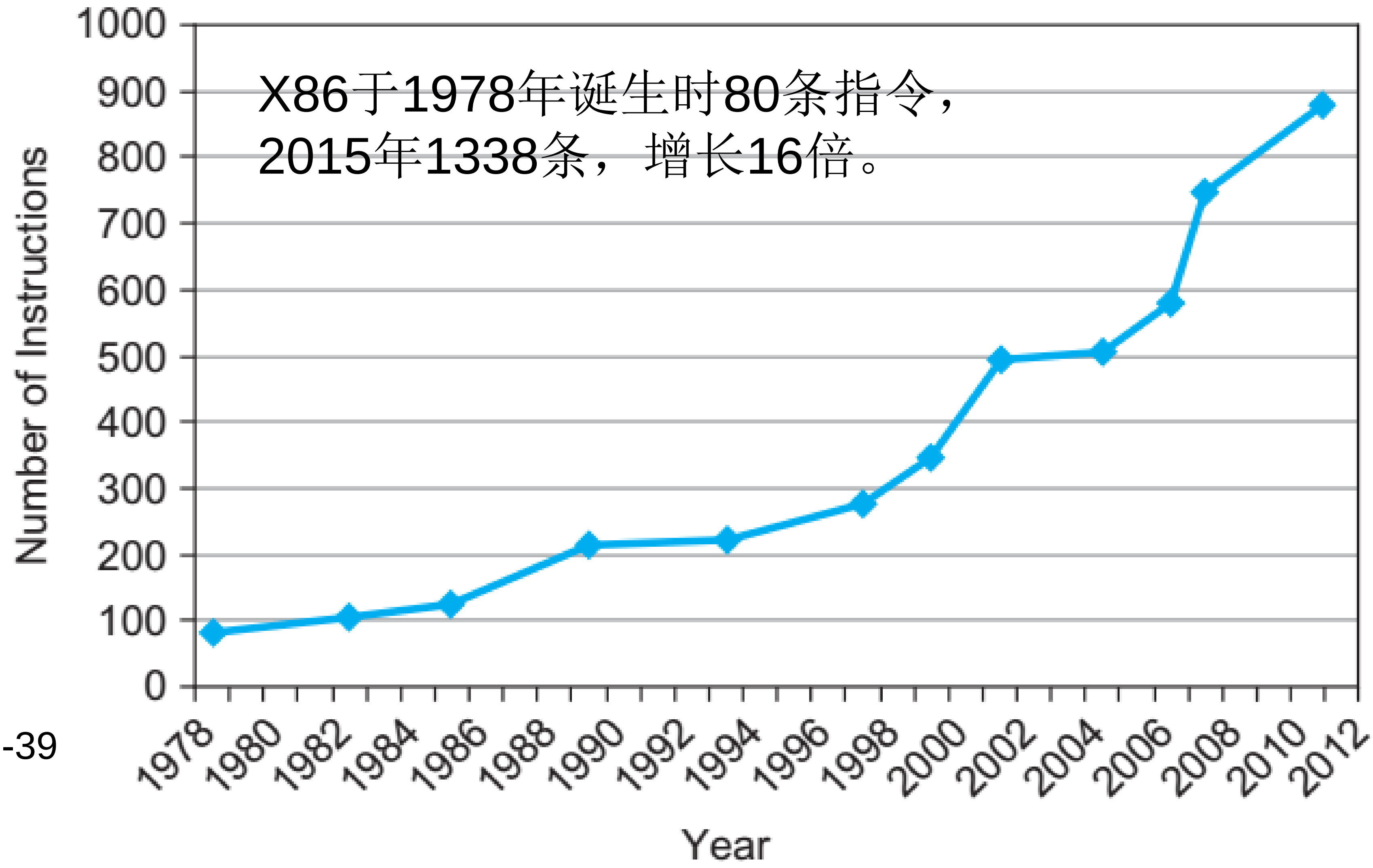



图2-39

# 指令分布：RV，x86

- SPEC CPU2006

图3-22

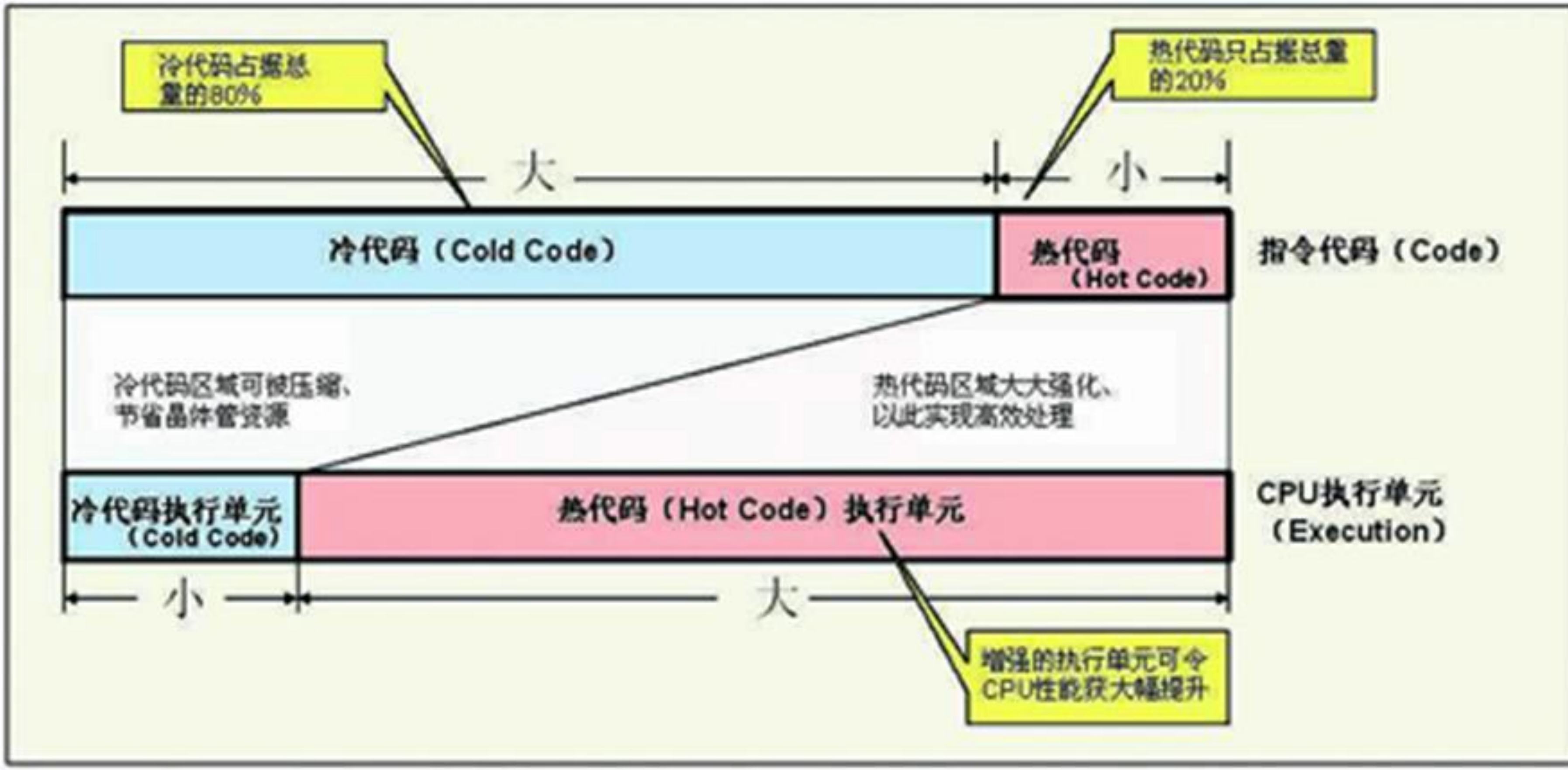
| RISC-V Instruction | Name | Frequency | Cumulative |
|---|---|---|---|
| Add immediate | addi | 14.36% | 14.36% |
| Load word | lw | 12.65% | 27.01% |
| Add registers | add | 7.57% | 34.58% |
| Load fl. pt. double | fld | 6.83% | 41.41% |
| Store word | sw | 5.81% | 47.22% |
| Branch if not equal | bne | 4.14% | 51.36% |
| Shift left immediate | slli | 3.65% | 55.01% |
| Fused mul-add double | fmadd.d | 3.49% | 58.50% |
| Branch if equal | beq | 3.27% | 61.77% |
| Add immediate word | addiw | 2.86% | 64.63% |
| Store fl. pt. double | fsd | 2.24% | 66.87% |
| Multiply fl. pt. double | fmul.d | 2.02% | 68.89% |

| Rank | 80x86 instruction | Integer average (% total executed) |
|---|---|---|
| 1 | load | 22% |
| 2 | conditional branch | 20% |
| 3 | compare | 16% |
| 4 | store | 12% |
| 5 | add | 8% |
| 6 | and | 6% |
| 7 | sub | 5% |
| 8 | move register-register | 4% |
| 9 | call | 1% |
| 10 | return | 1% |
| | Total | 96% |

图2-48

| Instruction class | RISC-V examples | HLL correspondence | Frequency | |
|---|---|---|---|---|
| | | | Integer | Fl. Pt. |
| Arithmetic | add, sub, addi | Operations in assignment statements | 16% | 48% |
| Data transfer | ld, sd, lw, sw, lh, sh, lb, sb, lui | References to data structures in memory | 35% | 36% |
| Logical | and, or, xor, sll, srl, sra | Operations in assignment statements | 12% | 4% |
| Branch | beq, bne, blt, bge, bltu, bgeu | *If* statements; loops | 34% | 8% |
| Jump | jal, jalr | Procedure calls & returns; *switch* statements | 2% | 0% |

# RISC的理论基础：二八定律




- 1975年IBM John Cocke（1987图灵奖）提出“二八定律”，应精简指令数量，一条复杂指令可用多条简单指令代替，且应放弃微程序技术。
  - 1980年完成了第一个采用RISC 架构【llxx：应称“精简指令集”架构，RISC是UCB提出的 】的计算机原型IBM ® 801。
- UCB David Patterson（2017图灵奖）和Carlo H. Sequin 1980年总结Cocke思想，提出“RISC”一词
  - 1982完成RISC-I处理器

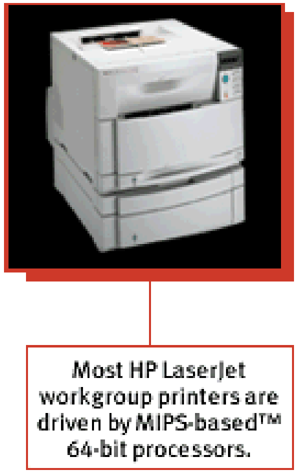
# CISC machine vs RISC machine

- Instructions are of variable format.
- There are multiple instructions and addressing modes.
- Complex instructions take many different cycles.
- Any instruction can reference memory.
- There is a single set of registers.
- No instructions are pipelined.
- A microprogram is executed for each native instruction.
- Complexity is in the microprogram and hardware.

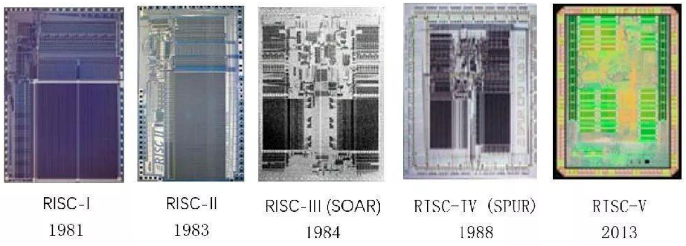
- Fixed-format instructions.
- Few instructions and addressing modes.
- Simple instructions taking one clock cycle.
- LOAD/STORE architecture to reference memory.
- Large multiple-register sets.
- Highly pipelined design.
- Instructions executed directly by hardware.
- Complexity handled by the compiler and software.

# MIPS is simple, elegant.

- "无互锁流水段微处理器"
  - **M**icroprocessor w/o **I**nterlocked **P**iped **S**tages
  - interlock单元：数据依赖问题
    - 互锁：检测，推迟后续指令执行（互锁状态）
    - 无互锁：尽量利用软件办法避免
    - 无互锁困难，低效：R4000以后使用interlock



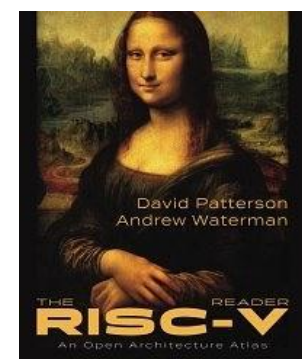

- Patterson总结Cocke思想，提出RISC指令集，1980
  - 4个Design PrinciplesSimplicity favors regularity
    - Smaller is faster
    - *Make the common case fast*
    - Good design demands good compromises
  - 1981/1982完成RISC-I处理器
- Hennessy完成MIPS，1983？



# RV vs. MIPS：指令格式，图2.29

| 31 | 30 25 | 24 21 | 20 | 19 15 | 14 12 | 11 8 | 7 | 6 0 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| funct7 | | rs2 | | rs1 | funct3 | rd | | opcode | R-type | 寄存器-寄存器操作 |
| imm[11:0] | | | | rs1 | funct3 | rd | | opcode | I-type | 短立即数和访存load |
| imm[11:5] | | rs2 | | rs1 | funct3 | imm[4:0] | | opcode | S-type | 访存store指令 |
| imm[12] | imm[10:5] | rs2 | | rs1 | funct3 | imm[4:1] | imm[11] | opcode | B-type | 条件跳转指令 |
| imm[31:12] | | | | | | rd | | opcode | U-type | 长立即数 |
| imm[20] | imm[10:1] | | imm[11] | imm[19:12] | | rd | | opcode | J-type | 无条件跳转 |

| | | | | | | |
|---|---|---|---|---|---|---|
| R-type *reg-reg* | op(6 bits) | rs(5 bits) | rt(5 bits) | rd(5 bits) | shamt(5 bits) | funct(6 bits) |
| | op(6 bits) | rs(5 bits) | rt(5 bits) | immediate(16 bits) | | |
| I-type *reg-mm* | op(6 bits) | rs(5 bits) | rt(5 bits) | addr(16 bits) | | |
| J-type | op(6 bits) | rs(5 bits) | rt(5 bits) | addr(16 bits) | | |
| | op(6 bits) | addr(26 bits) | | | | |

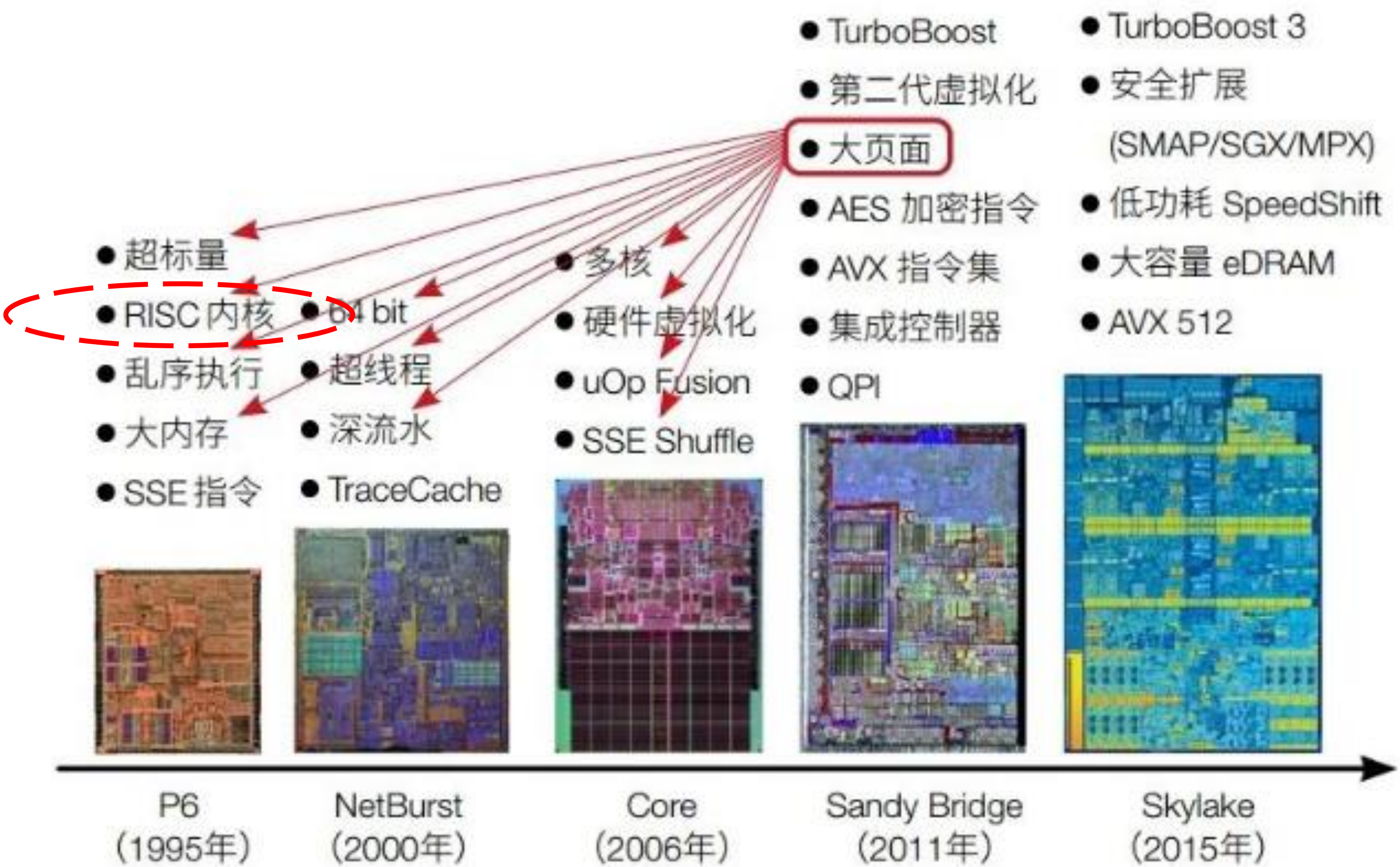



差别：1）操作码位数与位置；2）立即数位数与位置；2）rs/rd位置。

# LA32基础整数指令

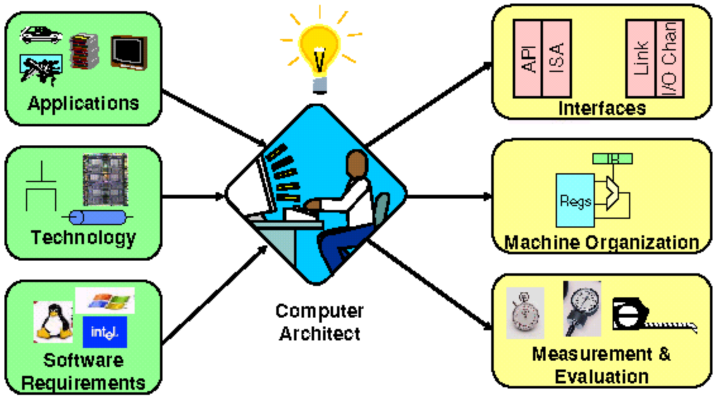
| | |
|---|---|
| 算术运算类指令 | ADD.W, SUB.W, ADDI.W, ALSL.W, LU12I.W, SLT, SLTU, SLTI, SLTUI,<br>PCADDI, PCADDU12I, PCALAU12I,<br>AND, OR, NOR, XOR, ANDN, ORN, ANDI, ORI, XORI,<br>MUL.W, MULH.W, MULH.WU, DIV.W, MOD.W, DIV.WU, MOD.WU |
| 移位运算类指令 | SLL.W, SRL.W, SRA.W, ROTR.W, SLLI.W, SRLI.W, SRAI.W, ROTRI.W |
| 位操作指令 | EXT.W.B, EXT.W.H, CLO.W, CLZ.W, CTO.W, CTZ.W, BYTEPICK.W,<br>REVB.2H, BITREV.4B, BITREV.W, BSTRINS.W, BSTRPICK.W, MASKEQZ, MASKNEZ |
| 转移指令 | BEQ, BNE, BLT, BGE, BLTU, BGEU, BEQZ, BNEZ, B, BL, JIRL |
| 访存指令 | LD.B, LD.H, LD.W, LD.BU, LD.HU, ST.B, ST.H, ST.W, PRELD |
| 原子访存指令 | LL.W, SC.W |
| 栅障指令 | DBAR, IBAR |
| 其它杂项指令 | SYSCALL, BREAK, RDTIMEL.W, RDTIMEH.W, CPUCFG |

# Intel处理器架构演化（1995—2015 年）



# ISA: A Minimalist Perspective

- ISA design decisions must take into account:
  - technology
  - machine organization
  - programming languages
  - compiler technology
  - operating systems



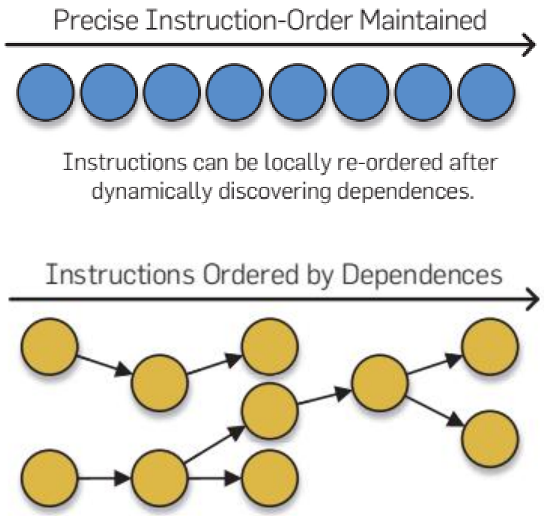

- “最小”处理器？——快速原型☺，ABC
  - A：由哪些部件构成？
  - B：需要哪几条指令？需要哪些寻址方式？执行过程？
  - C：CPI，IPC

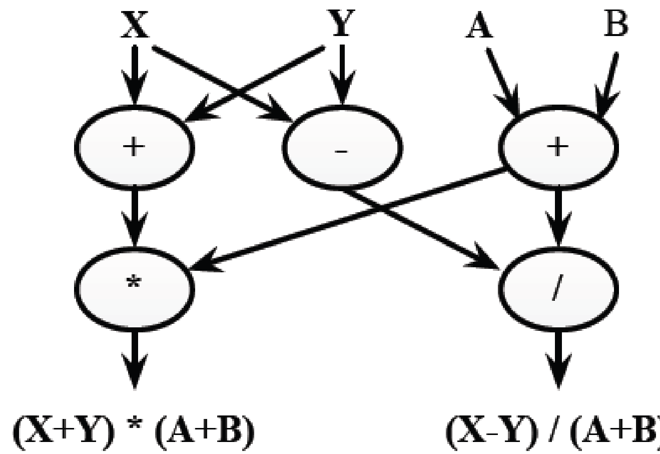
# OISC：the one instruction set computer

- OISC：the ultimate reduced instruction set computer
  - 一条SBN指令：substract and branch if negative
    - subleq *a*, *b*, *c*；Mem[*b*] = Mem[*b*] - Mem[*a*]，
      if (Mem[*b*] ≤ 0) goto *c*

- 应用：嵌入式处理器
  - 硬件极其简单
    - 程序员有充分的控制权
    - 优化由编译器完成
  - 灵活
    - 其他“指令”都可由该指令构造
    - 意味着用户可自定义指令集
    - 意味着可适用于任何领域
  - 低功耗

# Von Neumann vs. dataflow

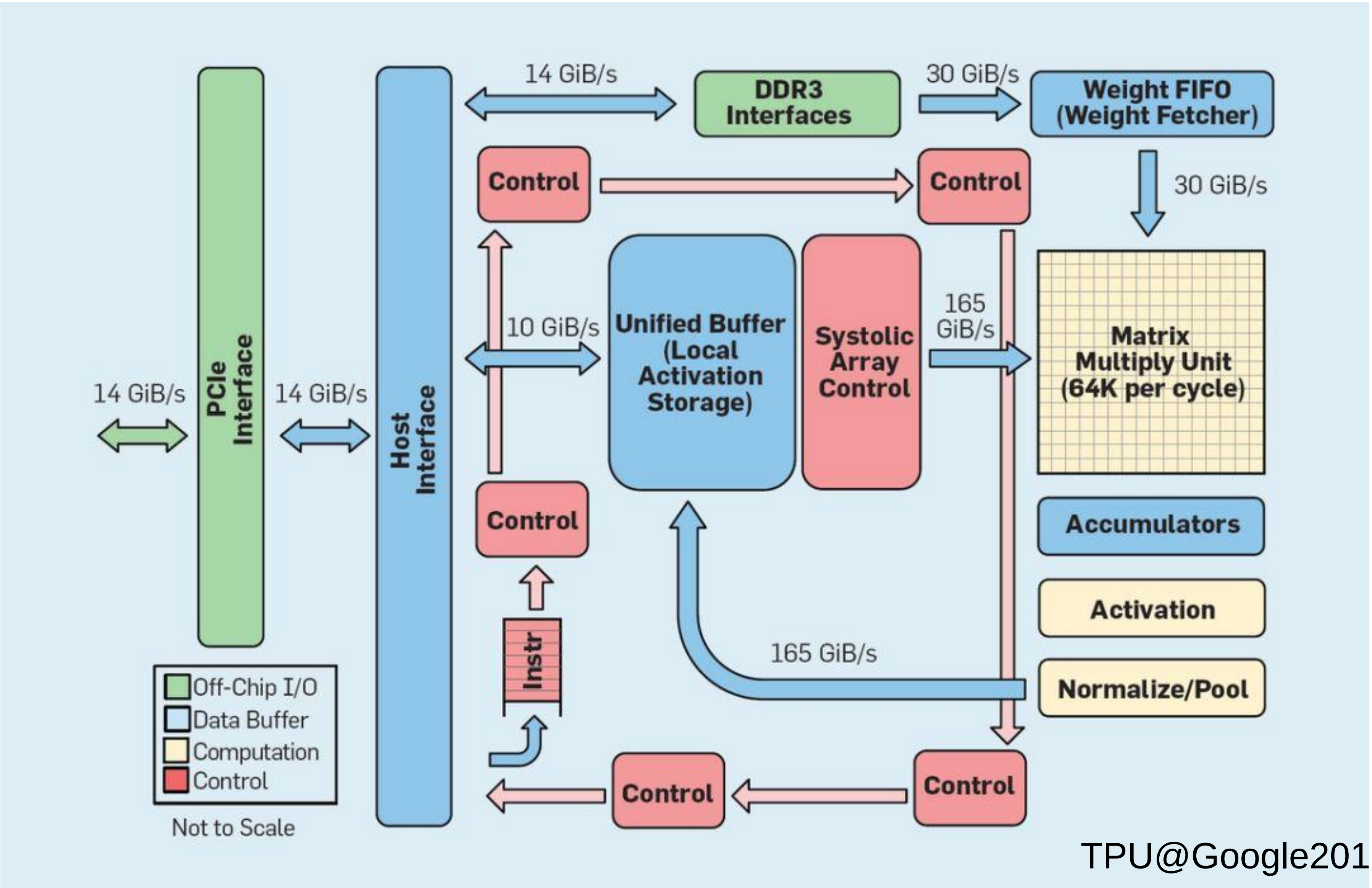



| | | | |
|---|---|---|---|
| 1. | LOAD | R2,A | ; load A into R2 |
| 2. | LOAD | R3,B | ; load B into R3 |
| 3. | ADD | R11,R2,R3 | ; R11 = A + B |
| 4. | LOAD | R4,X | ; load X into R4 |
| 5. | LOAD | R5,Y | ; load Y into R5 |
| 6. | ADD | R10,R4,R5 | ; R10 = X + Y |
| 7. | SUB | R12,R4,R5 | ; R12 = X - Y |
| 8. | MULT | R14,R10,R11 | ; R14 = (X+Y)*(A+B) |
| 9. | DIV | R15,R12,R11 | ; R15 = (X-Y)/(A+B) |
| 10. | STORE | VAL1,R14 | ; store first result to VAL1 |
| 11. | STORE | VAL2,R15 | ; store second result to VAL2 |

| | | | |
|---|---|---|---|
| 1. | INPUT | 3L | ; get A, send to instr 3, left input |
| 2. | INPUT | 3R | ; get B, send to instr 3, right input |
| 3. | ADD | 8R,9R | ; A + B, send to instrs 8, right and 9, right |
| 4. | INPUT | 6L,7L | ; get X, send to instrs 6, left and 7, left |
| 5. | INPUT | 6R,7R | ; get Y, send to instrs 6, right and 7, right |
| 6. | ADD | 8L | ; X+Y, send to instr 8, left |
| 7. | SUB | 9L | ; X - Y, send to instr 9, left |
| 8. | MULT | 10L | ; (X+Y)*(A+B), send to instr 10, left |
| 9. | DIV | 11L | ; (X-Y)/(A+B), send to instr 11, left |
| 10. | OUTPUT | VAL1 | ; output first result to destination |
| 11. | OUTPUT | VAL2 | ; output second result to destination |

# 计算机架构的未来：DSA，寒武纪、英伟达等

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# 小结

- 作业
  - 2.9，2.24，2.35，2.40
- 思考（选一）
  - CPU的ISA要定义哪些内容？见Yale Patt附录A
  - main()与swap()状态保存异同？
  - 过程调用时程序的内存数据是否需要保存？
  - Windows系统中可执行程序的格式？
- 实验报告：2周
  - 基于RV汇编，设计一个冒泡排序程序，并用Ripes工具调试执行。
  - 可选：测量冒泡排序程序的执行时间。CPI?