哈爾濱工業大學（深圳）
HARBIN INSTITUTE OF TECHNOLOGY

实验报告

开课学期：2022 春季

课程名称：计算机组成原理（实验）

实验名称：从 C 语言到机器码

实验性质：综合设计型

实验学时：2 地点：

学生班级：计算机类 4 班

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作业成绩：

实验与创新实践教育中心制

2022 年 3 月

1、实验结果截图

注：执行 make 会导致 out/main.s 原含有注释的代码被删除，请勿在检查前直接执行. 除此之外，本人默认选择 riscv64-linux-gnu-gcc 作为编译器，如需使用范例所给的 riscv64-unknown-elf-gcc，请执行 make unknown 命令

```
efjerryyang@LAPTOP-LMAMBQ2N:/mnt/d/Projects/GitHub/computer-system/comp-organ/lab1/lab-submit$ make
Checking..
mkdir -p out
riscv64-linux-gnu-gcc -static -E src/main.c -o out/main.i
riscv64-linux-gnu-gcc -static -S out/main.i -o out/main.s -Og
riscv64-linux-gnu-gcc -static -c out/main.s -o out/main.o -march=rv64g
riscv64-linux-gnu-objdump -D out/main.o > out/main.objdump.s
riscv64-linux-gnu-gcc -static src/main.c -o out/main -Og
command: spike $(which pk) ./out/main
command: cat ./out/main.objdump.s
efjerryyang@LAPTOP-LMAMBQ2N:/mnt/d/Projects/GitHub/computer-system/comp-organ/lab1/lab-submit$ spike $(which pk) ./out/main
bbl loader
21952
efjerryyang@LAPTOP-LMAMBQ2N:/mnt/d/Projects/GitHub/computer-system/comp-organ/lab1/lab-submit$ tree
.
├── 200110428-杨杰睿-实验1-实验报告.docx
├── 200110428-杨杰睿-实验1-实验报告.pdf
├── Makefile
├── out
│   ├── main
│   ├── main.i
│   ├── main.o
│   ├── main.objdump.s
│   └── main.s
└── src
    ├── main.c
    └── multiply.h

2 directories, 10 files
efjerryyang@LAPTOP-LMAMBQ2N:/mnt/d/Projects/GitHub/computer-system/comp-organ/lab1/lab-submit$
```

2、汇编代码注释（只需写主程序和子程序即可）

注：更为规整的格式请参见 out/main.s 代码行末注释.

```
    .file   "main.c"
    .option pic
    .text
    .align  1
    .globl  multiply
    .type   multiply, @function
multiply:
    mv  a5,a0
    # 将参数寄存器 a0 的值复制到参数寄存器 a5，即 x 保存到 a5
    li  a0,0
    # 加载立即数 0 到寄存器 a0，即 result 初始化为 0
    j   .L2
    # 无条件跳转到.L2 标签
.L3:
    addw    a0,a0,a4
    # 将参数寄存器 a4 与参数寄存器 a0 的值相加，结果复制到 a0 中，即计算 result 加上 a4 寄存器中的值，a4 寄存器的值取决于(y&1)的结果，详见.L2 标签
    slli    a0,a0,48
    # 将参数寄存器 a0 的值逻辑左移 48 位，结果复制到 a0 中，即丢弃寄存器 a0 从 17
```

```
位到 64 位的值，即保证下一步计算后 result 的结果是 uint16_t
    srli    a0,a0,48
    # 将参数寄存器 a0 的值逻辑右移 48 位，结果复制到 a0 中，即将寄存器 a0 的高 48
位写为 0，结果保存在低 16 位中，即保证 result 的结果是 uint16_t
    srli    a1,a1,1
    # 将参数寄存器 a1 的值逻辑右移 1 位，结果复制到 a1 中，即将 a1 寄存器的值整除 2，
即源代码中语句 y >>= 1
    slliw   a5,a5,1
    # 将参数寄存器 a5 的值逻辑左移 1 位，结果复制到 a5 中，即将 a5 寄存器的值乘以 2，
即源代码中语句 x <<= 1
    slli    a5,a5,48
    # 将参数寄存器 a5 的值逻辑左移 48 位，结果复制到 a5 中，即丢弃寄存器 a5 从 17
位到 64 位的值，即保证下一步计算后 x 的类型是 uint16_t
    srli    a5,a5,48
    # 将参数寄存器 a5 的值逻辑右移 48 位，结果复制到 a5 中，即将寄存器 a5 的高 48
位写为 0，结果保存在低 16 位中，即保证 x 的类型是 uint16_t
.L2:
    beqz    a1,.L6
    # 若参数寄存器 a1 的值等于 0，就跳转到.L6 标签，即 y 等于 0 的时候跳转到.L6
    andi    a4,a1,1
    # 将 a1 的值和立即数 1 进行“按位与”运算，将结果复制到 a4 寄存器中，即计算(y&1)
的值
    beqz    a4,.L3
    # 若寄存器 a4 的内容值等于 0，就直接跳转到.L3 标签，即(y&1)等于 0 的时候跳转
到.L3
    mv  a4,a5
    # 将寄存器 a5 的值复制到寄存器 a4 中，即将 x 的值保存到寄存器 a4
    j   .L3
    # 无条件跳转到.L3 标签
.L6:
    ret # 函数返回，跳转到上层调用者处，返回值在参数寄存器 a0 中，即返回值为 result
    .size   multiply, .-multiply
    .section    .rodata.str1.8,"aMS",@progbits,1
    .align  3           # 对齐为 8 bytes
.LC0:
    .string "%u\n"      # 字符串"%u\n"
    .text
    .align  1           # 对齐为 1 byte
    .globl  main
    .type   main, @function
main:
    addi    sp,sp,-16
    # 将堆栈指针寄存器 sp 与立即数(-16)相加，再存入堆栈指针寄存器 sp，即 sp = sp
+ (-16)
```

```
    sd  ra,8(sp)
    # 将 ra 寄存器的内容写入 sp 所指向地址加 8 的偏移量，即将上级调用者的返回地址写入方才分配的栈空间最高的双字中（栈空间总共分配了 2 个双字，当前最高位的空间写入了 ra）
    li  a1,28
    # 将立即数 28 加载到参数寄存器 a1 中，即本例源码中的调用 multiply(x ,x)的第 2 个 x 参数
    li  a0,28
    # 将立即数 28 加载到参数寄存器 a0 中，即本例源码中的调用 multiply(x ,x)的第 1 个 x 参数
    call    multiply
    # 将 main 部分下一条需要执行的指令地址写入 ra 寄存器，调用函数 multiply，返回值 y 保存在 a0 参数寄存器中
    li  a1,28
    # 将立即数 28 加载到参数寄存器 a1 中，即本例源码中的调用 multiply(y ,x)的第 2 个 x 参数，y 的值保存在 a0 中
    call    multiply
    # 将 main 部分下一条需要执行的指令地址写入 ra 寄存器，调用函数 multiply，返回值 result 保存在 a0 参数寄存器中
    sext.w  a1,a0
    # 将 a0 参数寄存器的值复制到 a1 中，进行 32 位符号扩展(sign extend word)，此处应该是打印时的格式化指示符%u 所致
    lla a0,.LC0
    # 将.LC0 标签地址加载到参数寄存器 a0 中，即将字符串"%u\n"地址复制到 a0 中
    call    printf@plt
    # 将 main 部分下一条需要执行的指令地址写入 ra 寄存器，调用函数 printf@plt，返回值读取的参数个数保存在 a0 参数寄存器中
    li  a0,0
    # 将立即数 0 加载到参数寄存器 a0 中，即 main 返回值为 0，代表正常退出。
    ld  ra,8(sp)
    # 将堆栈指针寄存器 sp 所指向高 8 字节地址的值写入 ra 寄存器中，即将保存的上级调用者的返回地址从栈空间的最高双字取出复制到 ra 中
    addi    sp,sp,16
    # 将堆栈指针寄存器 sp 与立即数 16 相加，再存入堆栈指针寄存器 sp，即 sp = sp + 16
    jr  ra
    # 返回上级调用者，返回地址为 ra，返回值为 a0，即 main 函数返回上级并返回 0
    .size   main, .-main
    .ident  "GCC: (Ubuntu 9.4.0-1ubuntu1~20.04) 9.4.0"
    .section    .note.GNU-stack,"",@progbits
```

3、机器码注释（只需写主程序和子程序即可）

示例：

注：更便于查看的文本请参见 out/main.decoder.s 的内容.

```
Disassembly of section .text:

0000000000000000 <multiply>:
   0: 00050793           mv  a5,a0
bit-level representation:
  00000000000001010000011110010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 01010 |  000   | 01111 | 0010011 |
+--------------+-------+--------+-------+---------+

   4: 00000513           li  a0,0
bit-level representation:
  00000000000000000000010100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 00000 |  000   | 01010 | 0010011 |
+--------------+-------+--------+-------+---------+

   8: 0200006f           j 28 <.L2>
bit-level representation:
  00000010000000000000000001101111
+----------------------+-------+---------+
| imm[20|10:1|11|19:12] |   rd  |  opcode |
+----------------------+-------+---------+
|  00000010000000000000 | 00000 | 1101111 |
+----------------------+-------+---------+


000000000000000c <.L3>:
   c: 00e5053b           addw  a0,a0,a4
bit-level representation:
  00000000111001010000010100111011
+---------+-------+-------+--------+-------+---------+
|  funct7 |  rs2  |  rs1  | funct3 |   rd  |  opcode |
+---------+-------+-------+--------+-------+---------+
| 0000000 | 01110 | 01010 |  000   | 01010 | 0111011 |
+---------+-------+-------+--------+-------+---------+
```

```
  10: 03051513           slli  a0,a0,0x30
bit-level representation:
  00000011000001010001010100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000110000 | 01010 |  001   | 01010 | 0010011 |
+--------------+-------+--------+-------+---------+

  14: 03055513           srli  a0,a0,0x30
bit-level representation:
  00000011000001010101010100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000110000 | 01010 |  101   | 01010 | 0010011 |
+--------------+-------+--------+-------+---------+

  18: 0015d593           srli  a1,a1,0x1
bit-level representation:
  00000000000101011101010110010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000001 | 01011 |  101   | 01011 | 0010011 |
+--------------+-------+--------+-------+---------+

  1c: 0017979b           slliw a5,a5,0x1
bit-level representation:
  00000000000101111001011110011011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000001 | 01111 |  001   | 01111 | 0011011 |
+--------------+-------+--------+-------+---------+

  20: 03079793           slli  a5,a5,0x30
bit-level representation:
  00000011000001111001011110010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000110000 | 01111 |  001   | 01111 | 0010011 |
```

```
+--------------+-------+--------+-------+---------+

  24: 0307d793           srli  a5,a5,0x30
bit-level representation:
  00000011000001111101011110010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000110000 | 01111 |  101   | 01111 | 0010011 |
+--------------+-------+--------+-------+---------+


0000000000000028 <.L2>:
  28: 00058a63           beqz  a1,3c <.L6>
bit-level representation:
  00000000000001011000101001100011
+--------------+-------+-------+--------+-------------+---------+
| imm[12|10:5] |  rs2  |  rs1  | funct3 | imm[4:1|11] |  opcode |
+--------------+-------+-------+--------+-------------+---------+
|   0000000    | 00000 | 01011 |  000   |    10100    | 1100011 |
+--------------+-------+-------+--------+-------------+---------+

  2c: 0015f713           andi  a4,a1,1
bit-level representation:
  00000000000101011111011100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000001 | 01011 |  111   | 01110 | 0010011 |
+--------------+-------+--------+-------+---------+

  30: fc070ee3           beqz  a4,c <.L3>
bit-level representation:
  11111100000001110000111011100011
+--------------+-------+-------+--------+-------------+---------+
| imm[12|10:5] |  rs2  |  rs1  | funct3 | imm[4:1|11] |  opcode |
+--------------+-------+-------+--------+-------------+---------+
|   1111110    | 00000 | 01110 |  000   |    11101    | 1100011 |
+--------------+-------+-------+--------+-------------+---------+

  34: 00078713           mv  a4,a5
bit-level representation:
  00000000000001111000011100010011
+--------------+-------+--------+-------+---------+
```

```
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 01111 |  000   | 01110 | 0010011 |
+--------------+-------+--------+-------+---------+

  38: fd5ff06f           j c <.L3>
bit-level representation:
  11111101010111111111000001101111
+----------------------+-------+---------+
| imm[20|10:1|11|19:12] |   rd  |  opcode |
+----------------------+-------+---------+
|  11111101010111111111 | 00000 | 1101111 |
+----------------------+-------+---------+


000000000000003c <.L6>:
  3c: 00008067           ret
bit-level representation:
  00000000000000001000000001100111
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 00001 |  000   | 00000 | 1100111 |
+--------------+-------+--------+-------+---------+


0000000000000040 <main>:
  40: ff010113           addi  sp,sp,-16
bit-level representation:
  11111111000000010000000100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 111111110000 | 00010 |  000   | 00010 | 0010011 |
+--------------+-------+--------+-------+---------+

  44: 00113423           sd  ra,8(sp)
bit-level representation:
  00000000000100010011010000100011
+-----------+-------+-------+--------+----------+---------+
| imm[11:5] |  rs2  |  rs1  | funct3 | imm[4:0] |  opcode |
+-----------+-------+-------+--------+----------+---------+
|  0000000  | 00001 | 00010 |  011   |  01000   | 0100011 |
+-----------+-------+-------+--------+----------+---------+
```

```
  48: 01c00593           li  a1,28
bit-level representation:
  00000001110000000000010110010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000011100 | 00000 |  000   | 01011 | 0010011 |
+--------------+-------+--------+-------+---------+

  4c: 01c00513           li  a0,28
bit-level representation:
  00000001110000000000010100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000011100 | 00000 |  000   | 01010 | 0010011 |
+--------------+-------+--------+-------+---------+

  50: 00000097           auipc ra,0x0
bit-level representation:
  00000000000000000000000010010111
+----------------------+-------+---------+
|      imm[31:12]      |   rd  |  opcode |
+----------------------+-------+---------+
| 00000000000000000000 | 00001 | 0010111 |
+----------------------+-------+---------+

  54: 000080e7           jalr  ra # 50 <main+0x10>
bit-level representation:
  00000000000000001000000011100111
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 00001 |  000   | 00001 | 1100111 |
+--------------+-------+--------+-------+---------+

  58: 01c00593           li  a1,28
bit-level representation:
  00000001110000000000010110010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000011100 | 00000 |  000   | 01011 | 0010011 |
+--------------+-------+--------+-------+---------+
```

```
  5c: 00000097           auipc ra,0x0
bit-level representation:
  00000000000000000000000010010111
+----------------------+-------+---------+
|      imm[31:12]      |   rd  |  opcode |
+----------------------+-------+---------+
| 00000000000000000000 | 00001 | 0010111 |
+----------------------+-------+---------+

  60: 000080e7           jalr  ra # 5c <main+0x1c>
bit-level representation:
  00000000000000001000000011100111
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 00001 |  000   | 00001 | 1100111 |
+--------------+-------+--------+-------+---------+

  64: 0005059b           sext.w  a1,a0
bit-level representation:
  00000000000001010000010110011011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 01010 |  000   | 01011 | 0011011 |
+--------------+-------+--------+-------+---------+

  68: 00000517           auipc a0,0x0
bit-level representation:
  00000000000000000000010100010111
+----------------------+-------+---------+
|      imm[31:12]      |   rd  |  opcode |
+----------------------+-------+---------+
| 00000000000000000000 | 01010 | 0010111 |
+----------------------+-------+---------+

  6c: 00050513           mv  a0,a0
bit-level representation:
  00000000000001010000010100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 01010 |  000   | 01010 | 0010011 |
```

```
+--------------+-------+--------+-------+---------+

  70: 00000097           auipc ra,0x0
bit-level representation:
  00000000000000000000000010010111
+----------------------+-------+---------+
|      imm[31:12]      |   rd  |  opcode |
+----------------------+-------+---------+
| 00000000000000000000 | 00001 | 0010111 |
+----------------------+-------+---------+

  74: 000080e7           jalr  ra # 70 <main+0x30>
bit-level representation:
  00000000000000001000000011100111
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 00001 |  000   | 00001 | 1100111 |
+--------------+-------+--------+-------+---------+

  78: 00000513           li  a0,0
bit-level representation:
  00000000000000000000010100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 00000 |  000   | 01010 | 0010011 |
+--------------+-------+--------+-------+---------+

  7c: 00813083           ld  ra,8(sp)
bit-level representation:
  00000000100000001001100010000011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000001000 | 00010 |  011   | 00001 | 0000011 |
+--------------+-------+--------+-------+---------+

  80: 01010113           addi  sp,sp,16
bit-level representation:
  00000001000000010000000100010011
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
```

```
| 000000010000 | 00010 |  000   | 00010 | 0010011 |
+--------------+-------+--------+-------+---------+

  84: 00008067           ret
bit-level representation:
  00000000000000001000000001100111
+--------------+-------+--------+-------+---------+
|  imm[11:0]   |  rs1  | funct3 |   rd  |  opcode |
+--------------+-------+--------+-------+---------+
| 000000000000 | 00001 |  000   | 00000 | 1100111 |
+--------------+-------+--------+-------+---------+
```