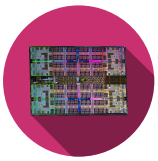


Befehlssatzarchitektur

Studentenlösungen
Übungen Computerarchitektur

1 Instruction-Set Architecture

1.1 Einfach C-Code zu RISC-V Assembler

1.1.1 Lösungsunterstützung

a) You need the instruction: `add`
b) You need the instructions: `add`, `sub`
c) You need the instruction: `addi`
d) You need the instruction: `addi`
e) You need the instructions: `lui`, `addi`. Beware immediates overflow.
f) You need the instructions: `lui`, `addi`. Beware immediates overflow.

isa/c-to-riscv-01

1.2 Algorithmik C-Code zu RISC-V Assembler

1.2.1 Lösungsunterstützung

a) One variant is with: `bne`, `add`, `sub`
b) One variant is with: `bne`, `add`, `j`, `sub`
c) One variant is with: `addi`, `bne`, `add`, `j`
d) One variant is with: `addi`, `bge`, `add`, `slli`, `j`
e) One variant is with: `lui`, `addi`, `lw`, `slli`, `sw`
f) One variant is with: `lui`, `ori`, `addi`, `bge`, `slli`, `add`, `lw`, `sw`, `j`
g) One variant is with: `addi`, `add`, `lb`, `beq`, `j`

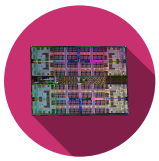
isa/c-to-riscv-02

1.3 Maschinencode zu RISC-V Assembler

1.3.1 Lösungsunterstützung

a)
```
0x41FE 83B3 = 0100 0001 1111 1110 1000 0011 1011 0011
```

op $= 51$, funct3 $= 0$ ⇨ `add` or `sub` (R-Type Command)



funct7 = 01000000 ⇨ **sub**

funct7	rs2	rs1	funct3	rd	op
0100 000	11111	11101	000	00111	0110011
32	31	29	0	7	51

```
sub t2, t4, t6
```

b) I-Type

isa/machinecode-to-riscv-01

1.4 Logische Operationen mit Registern

1.4.1 Lösungsunterstützung

a) **s3 = 0x46A1 0000**
b) **s4 = 0xFFFF 01B7**
c) **s5 = 0xB95E F1B7**

isa/riscv-execution-01

1.5 Logische Operationen mit Werten

1.5.1 Lösungsunterstützung

a) **s3 = 0x3A75 0824**
b) •
c) •

isa/riscv-execution-02

1.6 Multiplikationen in RISC-V

1.6.1 Lösungsunterstützung

s4 = 0xE000 0000
s3 = 0x0000 0000

isa/riscv-execution-03

1.7 Division und Modulo

1.7.1 Lösungsunterstützung

s3 = 0x0000 0005

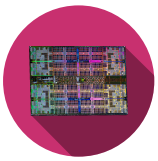
s4 = 0x0000 0002

isa/riscv-execution-04

1.8 R-Typ zu Maschinencode

1.8.1 Lösungsunterstützung

a)



```
add x18, x18, x20
```

R-Type Command

funct7	rs2	rs1	funct3	rd	op
0	20	19	0	18	51
0000000	10100	10011	000	10010	0110011

```
0x0149 8933
```

b) •
c) **0x0092 9BB3**
d) •
e) •

isa/riscv-to-machinecode-01

1.9 I-Typ zu Maschinencode

1.9.1 Lösungsunterstützung

a)
```
addi x8, x9, 12
```

I-Type Command

$imm_{11:0}$	rs1	funct3	rd	op
12	9	0	8	19
0000 0000 1100	01001	000	01000	001 0011

```
0x00C4 8413
```

b) •
c) •
d) **0x01B0 1483**
e) •

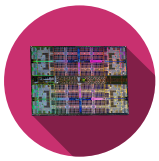
isa/riscv-to-machinecode-02

1.10 S-Typ zu Maschinencode

1.10.1 Lösungsunterstützung

a) **0xFE79 AD23**
b) •
c)
```
sb x30, 0x2D(x0)
```

S-Type Command



$imm_{11:5}$	rs2	rs1	funct3	$imm_{4:0}$	op
0000 001	30	0	0	01101	35
0000 001	11110	00000	000	01101	010 0011

```
0x03E0 06A3
```

isa/riscv-to-machinecode-03

1.11 Realzeitsystem

Was ist der Hauptunterschied zwischen einem „harten“ und einem „weichen“ Echtzeitsystem?

1.11.1 Lösungsunterstützung

One of those system types is considered as failed if it misses any timing. When/Why is it necessary to be so strict ?

isa/riscv-to-machinecode-04

1.12 U-Typ zu Maschinencode

1.12.1 Lösungsunterstützung

`0x8CDE FAB7`

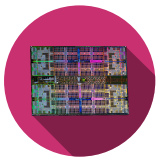
isa/riscv-to-machinecode-05

1.13 J-Typ zu Maschinencode

1.13.1 Lösungsunterstützung

`0x0FF8A 60EF`

isa/riscv-to-machinecode-06



2 Laborergänzung

Um Ihnen zu helfen können Sie gerne der RISC-V-Interpreter auf https://course.hevs.io/car/riscv-interpreter/ sowie Ripes verwenden.

Achten Sie sich auf die Typen der Variablen!

- Der Typ **int** wird als vorzeichenbehaftete 32-Bit-Größe betrachtet.
- Der Typ **unsigned int** wird als unsignierter 32-Bit-Typ betrachtet.
- Wenn eine Zahl dahinter steht (z. B. **int16_t**), bedeutet dies, dass die Variable x-Bit lang ist (hier 16). Wenn ein **u** vorangestellt ist, ist er unsigniert.

uint8_t ist also ein vorzeichenloses Byte, während **int8_t** ein vorzeichenbehaftetes Byte ist.

2.1 Grundrechenarten

2.1.1 Lösungsunterstützung

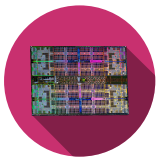
a)

```
# a = b + c;
# s0 = a, s1 = b, s2 = c

# b = 1, c = 2
addi s1, zero, 1
addi s2, zero, 2
add s0, s1, s2      # a = b + c
# s0 = 0x00000003
# s1 = 0x00000001
# s2 = 0x00000002

# b = -1, c = 2

...

# s0 = 0x00000001
# s1 = 0xffffffff
# s2 = 0x00000002

# b = -12, c = 2032

...

# s0 = 0x000007db
# s1 = 0xfffffff4
# s2 = 0x000007e7
```

b)

```
# a = b - c;
# d = (e + f) - (g + h);
# s0-s7 = a-h

...

# t0 = 0xffffffb1
# t1 = 0x000007db
# s0 = 0xffffffff
# s1 = 0x00000002
# s2 = 0x00000003
# s3 = 0xfffff7d6
# s4 = 0xffffffff
# s5 = 0xffffffb2
# s6 = 0x000007e7
# s7 = 0xfffffff4
```

isa/lab-basic-calc



2.2 Speicherzugriff

2.2.1 Lösungsunterstützung

```
# Check for sign extension comprehension

# uint16_t a = mem[3];
# mem[4] = a;
# t0 is a
lhu t0, 3(zero) # if lh, the last bit may be 1 -> extended -> wrong number
sw  t0, 4(zero)


# int16_t a = mem[3];
# mem[4] = a;
# t0 is a
??? t0, 3(zero) # if lh, the last bit may be 1 -> ???
??? t0, 4(zero)
```

isa/lab-memory

2.3 Grundlegende Algorithmen

1. Übertrage den 8Bit Wert des Speichers an Addresse 0x0000´1000 seriell Bit für Bit im Least Significant Bit (LSB) des Speichers in der Addresse 0x0000´1001. Die restlichen Bits der Speicheraddresse 0x0000´1001 müssen ‚0' betragen. Berechnen sie die BaudRate in $\frac{\text{Instructions}}{\text{Bit}}$ für die gesamte Übertragung?

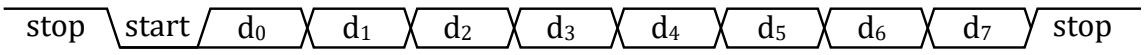


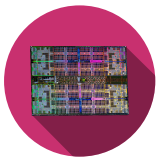
Abbildung 5 - UART Serielle Übertragung

2. Multipliziere zwei 4-bit Zahlen zusammen benutzte hierzu zusätzlich einen der Befehle **bne**, **bge**. Der Algorithmus funktioniert folgendermassen: Eine Multiplikation ist das gleiche wie die x-fache Addition der gleichen Zahl. Zum Beispiel: $2 * 9 = 9 + 9 = 18$.

2.3.1 Lösungsunterstützung

1. UART transmission idea:

```
# Serial UART Transmisstion
# setup
lui s2, 0x00001      # store UART base address
addi t0, zero, 0xA   # value to be send for testing
sb   t0, 0(s2)       # save to memory

# start
lui s2, 0x00001      # store UART base address
addi s1, zero, 0x1   # store mask bit
lb s0, 0(s2)         # get value from memory

# send stopbit
sb s1, 1(s2)         # send stopbit to memory
addi zero, zero, 0   # nop
```



```
addi zero, zero, 0   # nop

# send startbit
...

# algorithm iteration #1 to #8
...

# send stopbit
addi zero, zero, 0   # nop
sb s1, 1(s2)         # send stopbit to memory
```

2. Two numbers basic multiplication with loops idea:

```
# Input values
# a0, a1 = input, a2 = output
addi a0, zero, 9
addi a1, zero, 2

# init output to zero
addi a2, zero, 0

# check if a1 is zero
if a1 == 0 => goto end
decrement a1

accumulate:
  accumulate into a2
  decrement a1
  continue if not 0
```

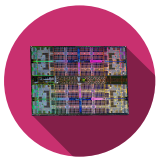
isa/lab-basic-algos

2.4 Branching

2.4.1 Lösungsunterstützung

If / else

```
addi s0, zero, 1 # int a = 1
addi s1, zero, 2 # int b = 2

# if(a == b)
test1:
  bne s0, s1, test2 # imm = 12
# a == b
equal:
  c = 0
  goto end
# else if b > a
test2: # a < b === b >= a
  if a < b => goto a_smaller
# a > b
a_bigger:
  addi s2, zero, 1
```



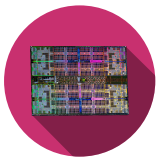
```
  jal end # imm = 8
# a < b
a_smaller:
  addi s2, zero, 2

end:
# ...
```

2.4.2 Switch case

```
# a = s0, mem[2] = s1
lw s1, 2(zero)

# if(b == 0)
bne s1, zero, not0 # imm = 12

# b == 0
li s0, 17
jal end # imm = 48

# b != 0
not0:
  li t1, 3
  # if(b == 3)
  bne s1, t1, not3 # imm = 12

# b == 3
li s0, 33
jal end # imm = 32

# b != 3
not3:
  ...
  # if(b == 8)
  if(b == 8) goto is8_or_12 # imm = 20
  ...
  # if(b == 12)
  if(b == 12) goto is8_or_12 # imm = 12

# b != 8 | 12 (others)
li s0, 99
jal end # imm = 8

# b == 8 | 12
is8_or_12:
  li s0, 10

end:
# ...
```

2.4.3 While / Do While

```
// A : simple do-while
addi a5, zero, 10 # int a = 10;
while_entry:
```

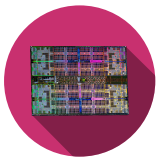


```
  addi a5, a5, -1 # a--
  bne zero, a5, while_entry # imm = -4

// B : similar
addi a5, zero, 10 # int a = 10;
while_entry:
  addi a5, a5, -1 # a--
  if a >= 0 => goto while_entry

// C : uint32_t instead of int
...
```

2.4.4 For

```
# a is s0, i is s1, mem[0] = s2
lw s2, 0(zero) # loop target

# For the for to work, blte does not exist.
# Thus, since the loop decreases, a > b
#  === a-1 >= b (for signed only, else infinite loop)
# so better a >= b + 1
addi s2, s2, 1  # target + 1
li s1, 4        # i = 4
mv s0, zero     # a = 0

jal for_test # imm = 8

for_do:
  add s0, s0, s1
  addi s1, s1, -1 # MUST be at the end of for

for_test:
  bge  s1, s2, for_do # imm = -8
```

isa/lab-branch



2.5 Functions

2.5.1 Lösungsunterstützung

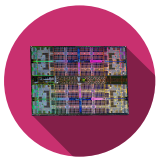
a) A function with context saving which can be optimized

```
# a is s0, b is s1
li s0, 1 # a = 1
mv a0, s0 # copy into a0 as funct. arg
jal ra, doubleIt # imm = undef.
mv s1, a0 # b = result

# DO NOT FORGET THE FOLLOWING
# a0 is a scratch register, and we
called a function
# so we are not sure if a0 is still s0
mv a0, s0
jal ra, doubleItOpti # imm = undef.
mv s1, a0 # b = result

# ...

doubleIt:
  # save context
  addi sp, sp, -4
  sw s0, 0(sp)
  # do a = a * 2
  mv s0, a0
  sll s0, s0, 1
  mv a0, s0
  # restore context
  lw s0, 0(sp)
  addi sp, sp, 4
  jalr zero, ra, 0 # or pseudo jr ra

# If 'a' should be a register
doubleItOpti:
  mv t0, a0
  sll t0, t0, 1
  mv a0, t0
  jalr zero, ra, 0 # or pseudo jr ra

# Most opti version
doubleItOpti2:
  # nothing to save since we can do it
with a0 directly
  sll a0, a0, 1
  jalr zero, ra, 0 # or pseudo jr ra
```

b) A function with too many arguments

```
# a to j in s0-s10
# res in s11
li s0 1
li s1 2
...
li s10 10

# prepare arguments
mv a0, s0
mv a1, s1
...
mv a7, s7
# still two args to pass -> stack
addi sp, sp, -8
# It is important that the caller
# reserves the space. Also, note
# the order in stack.
sw s8, 4(sp)
sw s9, 0(sp)
# call
jal ra, sum
# stack not needed anymore
addi sp, sp, 8

mv s1, a0 # b = result

# ...

sum:
  # do add with aX regs
  add a0, a0, a1
  add a0, a0, a2
  ...
  add a0, a0, a7
  # load i from over sp
  lw t0, 4(sp)
  add a0, a0, t0
  # load j from over sp
  lw t0, 0(sp)
  add a0, a0, t0
  jr ra
```

isa/lab-fcts



2.5.2 Lösungsunterstützung

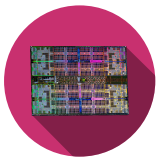
2.5.2.1 Modulo

```
# RV32IM
# a is s0, b is s1, c is s2
li s0, 9
li s1, 7
remu s2, s0, s1

# RV32I
# Call a div algorithm and take remainder
# Or call a sub loop

# Modulo of power of 2
li s0, 9
li s1, 8
addi t0, s2, -1 # pow 2 - 1
and s2, t0, s0
```

2.5.2.2 °F -> °C

The main algorithm is:

```
begin:
    li s0, 550 # degrees farenheit

    li s1, 466034 # magic number
    mv s2, s0 # c = f

    # A: c = f - 32
    addi s2, s2, -32

    # B: c = c * 5
    # Variante 1 c*5 with shift
    # slli s3, s2, 2 # c * 4
    # add s2, s3, s2 # c + c (== * 5)
    # Variante 2 c*5 with function
    mv a0, s2
    li a1, 5
    # jal ra, mulFunct   # func variant malFunct
    # jal ra, sfmulFunct # func variant sfmulFunct
    jal ra, fmulFunct    # func variant fmulFunct
    mv s2, a0

    # C: c = c * 2^n / 9
    mv a0, s2
    mv a1, s1
    # jal ra, mulFunct   # func variant malFunct
    # jal ra, sfmulFunct # func variant sfmulFunct
    jal ra, fmulFunct    # func variant fmulFunct
    mv s2, a0

    # D: c >>= n
    srli s2, s2, 22

# End
```



```
nop
    j begin
```

The multiplication functions (from worst to best):

a)

```
# bad O(n_b)
mulFunct: # mulFunct(int a, int b)
    # add itself each time
    mv t0, a0
    addi a1, a1, -1

    mul_beg:
    bgeu zero, a1, mul_end # if 1 > b
    add a0, a0, t0
    addi a1, a1, -1
    j mul_beg

    mul_end:
    jr ra

# better O(n_min[a,b])
sfmulFunct: # sfmulFunct(int a, int b)
    swap a and b to loop less times
    loop to multiply
```

b)

```
# best
fmulFunct: # fmulFunct(int a, int b)
    swap a and b to loop less times

    mul_is_done:
        if b is 0 => goto fmul_end

        if b[0] is 0 => goto shift
    add:
        add t0, a0, t0
    shift:
        shift a0 left once
        shift a1 right once
        goto mul_is_done

    fmul_end:
        mv a0, t0
        jr ra
```

The test with n = 23 should work for small numbers but overflow with bigger:

- 100F = 37C; 400F = 204C
- 1000F = 25C -> WRONG

$$\begin{aligned} \text{nbBits}_{\text{max}_{\text{fahrenheit}}} + \text{nbBits}_{\text{mult5}} + \text{nbBits}_{\text{magicNumber}} = \\ 10(\text{max. 1000-32}) + 3 + (n - \text{nbBits}_{\text{div9}} + 1) = \\ 10 + 3 + (16 - 4 + 1) = \\ = 26 \text{ bits} \end{aligned} \tag{1}$$

Because, following Gleichung 1, if n is 23 → equation gives 33 bits, but we are on 32.

isa/lab-adv-algos