



Alle Übungen CAR

Studentenlösungen Übungen Computerarchitektur

1 | Chip & Silikon Herstellung

1.1 Fabrikation

- a) 71.8%
- b) 235.5 dies
- c) 169.1 good_dies
- d) 1.18 CHF

fun/fabrication-01

1.2 Fabrikation

- a) $120 \frac{\text{wafers}}{\text{ingot}}$
- b) 250CHF
- c) 0.796CHF
- d) 209.3 dies
- e) 158.23 dies
- f) 2.05CHF

fun/fabrication-02

1.3 Fabrikation

- a) 200CHF
- b) $\approx 600 \frac{\text{dies}}{\text{wafer}}$
- c) $1.06 \frac{\text{CHF}}{\text{die}}$

fun/fabrication-03



2 | Moore'sches Gesetz & Denard-Skalierung

2.1 Dennard-Skalierung

- a) $1.414 = \sqrt{2}$
- b) 406pm equals to 16601 times smaller

fun/dennardscaling-01

2.2 Die dynamische Leistungsaufnahme einer CMOS Schaltung ist:

Two statements are true, one is false.

fun/dennardscaling-02

3 | Stromverbrauch

3.1 Lebensdauer des Handy-Akkus

- a) 112.6h
- b) 9.19h

fun/powerconsumption-01

1 | Prozessor Benchmark & Leistung

1.1 Welche der folgenden Aussagen sind richtig?

Three statements are true one is false.

per/benchmark-01

1.2 Was ist der Durchsatz (throughput)?

One statement is true and three are false.

per/benchmark-02

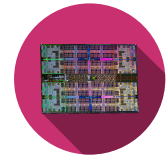
1.3 Was ist der SPEC?

One statement is true and three are false.

per/benchmark-03

1.4 Was ist das Ziel der EEMBC-Benchmark?

One statement is correct and three are false

*per/benchmark-04***1.5 Welche der folgenden Kennzahlen ist eine Energieeffizienzkennzahl?**

One statement is correct and three are false.

*per/benchmark-05***1.6 Bei einem eingebetteten System sind sowohl der Stromverbrauch als auch die Leistung pro Watt wichtig.**

50/50 change. Think.

*per/benchmark-06***1.7 Prozessorleistung**

- a) $30\mu s$
- b) $2 \frac{\text{cycles}}{\text{instruction}}$
- c) $5 \frac{\text{cycles}}{\text{instruction}}$
- d) $292\mu s$
- e) Processor B is 1.29 times faster than processor A.

*per/performance-01***1.8 Prozessorleistung**

- a) $\text{CPI}_{\text{Avg}_A} = 3.775 \frac{\text{cycle}}{\text{instr}}$ & $\text{CPI}_{\text{Avg}_A} = 2.52 \frac{\text{cycle}}{\text{instr}}$
- b) Computer B is 1.35 times faster than Computer A.
- c) 2.69GHz

*per/performance-02***1.9 Prozessorleistung**

Execution_time = 8.75ms

*per/performance-03***1.10 Prozessorleistung**

Variant 2

*per/performance-04***1.11 Prozessorleistung**

- a) CPU_A is better when
 - a) $w_{p_1} > 90.90\%$
 - b) $w_{p_2} < 9.09\%$
- b) CPU_B is better when
 - a) $w_{p_1} > 90\%$
 - b) $w_{p_2} < 10\%$
- c) CPU_C is better when
 - a) $w_{p_1} > 50\%$



b) $w_{p_2} < 50\%$

per/performance-05

1.12 Prozessorleistung

Central-Processing-Unit (CPU) A is the fastest!

per/performance-06

1.13 Prozessorleistung

Die Clockfrequenz des CPU beträgt 2 GHz

4.65

per/performance-07

1.14 Welches ist die beste Messgröße für einen Leistungsvergleich?

One statement is true the others are false.

per/performance-08

1.15 Prozessorleistung

$$T = 3.2\overline{3}\text{ms}$$

per/performance-09

1.16 Amdahlsches Gesetz

$$S = 5.263\%$$

per/amdahls-law-01

1.17 Amdahlsches Gesetz

$$f = 66.\overline{6}\%$$

per/amdahls-law-02

1.18 Amdahlsches Gesetz

Optimization A is 1.28 times better than Optimization B.

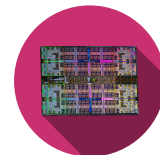
per/amdahls-law-03

1 | Implementierung

1.1 Was ist der Hauptunterschied zwischen einem harten und einem weichen Echtzeitsystem?

One statement is correct the other one is false.

imp/implementation-01



1.2 Was ist ein eingebettetes System?

One statement is correct all others are false.

imp/implementation-02

1.3 Schnellere Ausführungszeit bedeutet weniger Energie.

One statement is correct the other false.

imp/implementation-03

1.4 Warum werden immer mehr SOC's anstelle von CPU's entwickelt?

All statements are either correct or false.

imp/implementation-04

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 \Rightarrow **add** or **sub** (R-Type Command)

funct7 = 01000000 \Rightarrow **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 unsigned 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 unsigned.

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 = 0xffffffff4
# s2 = 0x000007e7
```

b)

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

...

# t0 = 0xffffffffb1
# t1 = 0x000007db
# s0 = 0xffffffff
# s1 = 0x00000002
# s2 = 0x00000003
# s3 = 0xfffff7d6
# s4 = 0xfffffffff
# s5 = 0xffffffb2
# s6 = 0x000007e7
# s7 = 0xffffffff4
```

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

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

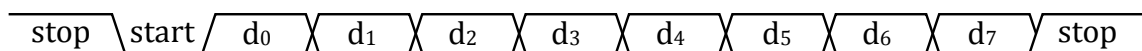


Abbildung 5 - UART Serielle Übertragung

- 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

- UART transmission idea:

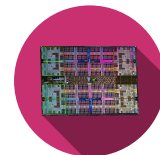
```
# Serial UART Transmission
# setup
lui s2, 0x00001 # store UART base address
addi t0, zero, 0xA # value to be send for testing
sb t0, 0(s2) # save to memory

# 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

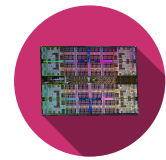
# For the for to work, blte does not exist.
# Thus, since the loop decreases, a > b
# == a-1 >= b (for signed only, else infinite loop)
# so better a >= b + 1
addi s2, s2, 1 # target + 1
li s1, 4      # i = 4
mv s0, zero   # a = 0

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 b) A function with too many arguments

```
# 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
```

```
# 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 fahrenheit

    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)
mulFunc: # mulFunc(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])
sfmulFunc: # sfmulFunc(int a, int b)
swap a and b to loop less times
loop to multiply
```

b)

```
# best
fmulFunc: # fmulFunc(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

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

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

isa/lab-adv-algos

1 | Architektur

1.1 Stack-Architektur

- a) -
- b) 7 explicit fetch and none implicit
- c) 7 explicit fetch, 4 implicit fetch, 4 implicit store

arc/stack-01



1.2 Stack-Architektur

- a) -
- b) 7 explicit fetch
- c) 7 explicit fetch (with compiler optimizations)
7 explicit fetch, 1 implicit store, 1 implicit fetch (without compiler optimizations)
- d) 7 explicit fetch, 3 implicit store, 3 implicit fetch (without compiler optimizations)

arc/stack-02

2 | Single-Cycle RISC-V

2.1 Single-Cycle-Prozessorbetrieb

```
PCScr = '0'  
RegWrite = '1'  
ImmScr[1:0] = "xx"  
ALUSrc = '0'  
ALUControl[2:0] = "010"  
MemWrite = '0'  
ResultScr = '0'
```

arc/scr-01

2.2 Einzelzyklus mit Anweisung **jal** verlängern

```
PCScr = '0'  
RegWrite = '1'  
ImmScr[1:0] = "xx"  
ALUSrc = '0'  
ALUControl[2:0] = "010"  
MemWrite = '0'  
ResultScr = '0'
```

arc/scr-02

2.3 Einzelzyklus-Prozessorleistung

$$T_{\text{program_single_cycle}} = 75\text{sec} \quad (2)$$

arc/scr-03



3 | Multi-Cycle RISC-V

3.1 Mehrzyklus-Prozessorleistung

$$\begin{aligned} \text{CPI}_{\text{load}} &= 5 \text{ cycles} \\ \text{CPI}_{\text{store}} &= 4 \text{ cycles} \\ \text{CPI}_{\text{branch}} &= 3 \text{ cycles} \\ \text{CPI}_{\text{jump}} &= 4 \text{ cycles} \\ \text{CPI}_{\text{alu}} &= 4 \text{ cycles} \\ \text{CPI}_{\text{average}} &= 4.14 \text{ cycles} \end{aligned} \tag{3}$$

arc/mcr-01

3.2 Multi-Zyklus-Prozessorleistung

$$T_{\text{program_single_cycle}} = 155.25\text{sec} \tag{4}$$

arc/mcr-02