Project 1: Optimizing the Performance of a Pipelined Processor

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April 30, 2023

1 Introduction

In this project,we need to solve questions of three parts including Part A, Part B, Part C.

In Part A, to improve our understanding of y86 assembly language and better prepare ourselves for Part C, we should write Y86 programs using y86 assembly language to simulate example.c file. Specifically, we need to write three programs: sum.ys, rsum.ys, and copy.ys. The sum.ys program iteratively sums linked list elements in a non-recursive form, rsum.ys recursively sums linked list elements, and copy.ys copies a source block to a destination block. To solve these problems, we should first learn the y86 assembly language and then read asum.ys in the $y86 - code$ directory. After that, we can sequentially use appropriate instructions to write sum.ys, rsum.ys, and copy.ys.

In Part B, we are required to extend an instruction named *iaddl* to the ISA by modifying the seq-full.hcl, in order to gain a better understanding of the hardware description language. To achieve this goal, we should first learn the fundamental knowledge about HCL. Then we need to carefully read the seq-full.hcl to understand how to add corresponding codes for *iaddl*. After that, we should write out the description of *iaddl* and add the necessary codes to the seq-full.hcl file.

In Part C, we are provided with a file called ncopy.ys, which can copy *len* elements from the array *src* to the array *dst*. Our task is to reduce the average CPE (cycles per element) as much as possible, and if we can achieve an average CPE less than 10, we will get full grades for Part C. To reduce the CPE, we should try our best to avoid load/use cases in the code, add *iaddl* instruction, and use loop unrolling strategy, which should be considered carefull .

The arrangement of our group members: student Cai finishes part A,part B.**Student Zhang** finishes part C and finally writes the report of this project.

2 Experiments

2.1 Part A

2.1.1 Analysis

We are required to write Y86 programs to simulate the example.c file. Specifically, we need to write three programs: sum.ys, rsum.ys, and copy.ys. The sum.ys program iteratively sums linked list elements in a non-recursive form, rsum.ys recursively sums linked list elements, and copy.ys copies a source block to a destination block. Moreover, in sum.ys and rsum.ys, we should return the result of 0x*cba* in register $\%eax$, while in copy.ys, we need to return the checksum (xor value) of all the words copied in the register $\%eax$.

To successfully complete this part, we must have a basic understanding of the Y86 assembly language. The difficulties in this part include understanding the basic logic of assembly programs, such as the use of *push* and *pop* operations when calling functions, knowing the method for passing parameters in assembly programs, and being familiar with related instructions and using them correctly. By using *jmp*, various kinds of *mov*, logical instructions, and so on, we can easily solve this part. The core technique here is to understand the meaning of instructions well and to organize our code carefully.

2.1.2 Code

sum.ys

```
# name:
# ID  :
# sum.ys
    .pos 0
# init...
# Sample linked list...

Main:   pushl %ebp
    rrmovl %esp, %ebp

    irmovl ele1,%edx
    pushl %edx
    call sum                 # sum(*head)
    rrmovl %ebp,%esp
    popl %ebp
    ret

sum:   pushl %ebp
    rrmovl %esp, %ebp
    mrmovl 8(%ebp), %ecx     # %ecx <- head
    xorl %eax, %eax
    andl %ecx, %ecx          # check if %ecx == NULL
    je End
Loop:   mrmovl (%ecx), %esi # %esi <- *head
    addl %esi, %eax          # %eax = %eax + %esi
    mrmovl 4(%ecx), %ecx     # *head = head->next
    andl %ecx, %ecx
```

```
    jne Loop
End:    rrmovl %ebp, %esp
    popl %ebp
    ret

    .pos 0x100
Stack:
```

rsum.ys

```
# name: Zhang Xiangdong
# ID  : 521030910206
# rsum.ys
    .pos 0
# init...
# Sample linked list...

Main:   pushl %ebp
    rrmovl %esp, %ebp
    irmovl ele1,%edx
    pushl %edx
    call rsum                   # rsum(*head)
    rrmovl %ebp,%esp
    popl %ebp
    ret


rsum:   pushl %ebp
    rrmovl %esp, %ebp
    mrmovl 8(%ebp), %ecx        # %ecx <- head
    xorl %edx, %edx             # set zero
    andl %ecx, %ecx
    je ZERO

    mrmovl (%ecx), %edx         # %edx <- *head
    pushl %edx                  # store the value

    pushl %ebp
    rrmovl %esp,%ebp
    mrmovl 4(%ecx), %ecx
    pushl %ecx
    call rsum                   # rsum(head->next)
    rrmovl %ebp, %esp
    popl %ebp

    popl %edx                   # get the previous value
ZERO:   rrmovl %ebp, %esp
    popl %ebp
    addl %edx, %eax             # add the value to the return
        value,namely %eax
    ret
    .pos 0x200
Stack:
```

copy.ys

```
# name:
# ID  :
# copy.ys
```

```
    .pos 0
# init...
# Source block...
# Destination...

Main:   pushl %ebp
    rrmovl %esp, %ebp
    irmovl $3,%edx
    pushl %edx              # push parameters
    irmovl dest, %edx
    pushl %edx
    irmovl src, %edx
    pushl %edx
    call copy_block         # copy_block(*src, *dest, len)
    rrmovl %ebp,%esp
    popl %ebp
    ret

copy_block:   pushl %ebp
    rrmovl %esp, %ebp

    mrmovl 8(%ebp), %esi    # %esi = src
    mrmovl 12(%ebp), %edi   # %edi = dst
    mrmovl 16(%ebp), %ecx   # %ecx = len
    xorl %eax, %eax         # store the return value
    andl %ecx, %ecx
    je ZERO
Loop:   mrmovl (%esi), %ebx # %ebx <- *(src)
    irmovl $4, %edx
    addl %edx, %esi         # src++

    rmmovl %ebx, (%edi)     # *(dst) <- %ebx
    addl %edx, %edi
    xorl %ebx, %eax         # %eax <- %ebx ^ %eax
    irmovl $1, %edx
    subl %edx, %ecx         # len--
    jne Loop

ZERO:   rrmovl %ebp, %esp
    popl %ebp
    ret


    .pos 0x400
Stack:
```

2.1.3 Evaluation

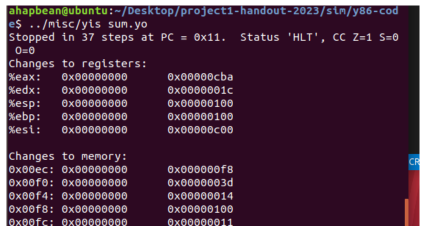


Figure 1: the running result of sum.ys

We write a Y86 program sum.ys that iteratively sums the elements of a linked list.When testing our program,the graders do not spot any errors in our codes. And we can see that the summatiom 0xcba is correctly calculated and is stored in the register $\%eax$.

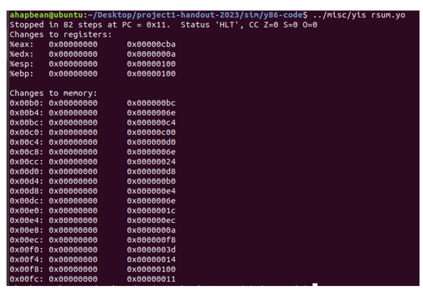


Figure 2: the running result of sum.ys

We write a Y86 program rsum.ys that recursively sums the elements of a linked list. We use a recursive way to solve this question and we get the right result 0xcba in the register $\%eax$. And when testing our program,the graders do not spot any errors in our codes.

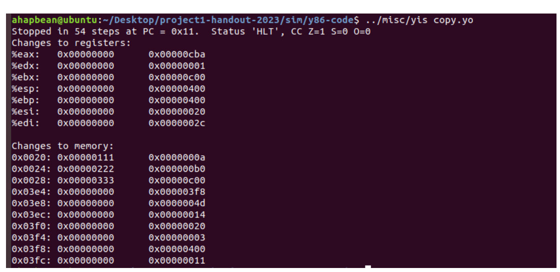


Figure 3: the running result of sum.ys

We write a Y86 program copy.ys that copies a block of words from one part of memory to another area of memory, computing the checksum (Xor) of all the words copied. We successfully get the checksum 0x*cba* in %*eax* and we can see the previous 0x111 0x222 0x333 in *dst* array are changed to be 0x00*a* 0x0*b*0 0x*c*00 which showing that we achieving copying the *src* to the *dst*. And when testing our program,the graders do not spot any errors in our codes.

2.2 Part B

2.2.1 Analysis

We need to extend a instruction to the ISA named *iaddl* by modifying the seq-full.hcl.To accomplete this,first we should know what is HCL and how does it work.Then we need to figure out the detailed process of *iaddl*.Finally we need to modify the seq-full.hcl. The difficulties here include understanding hcl file, correctly writing the description of *iaddl*.

2.2.2 Code

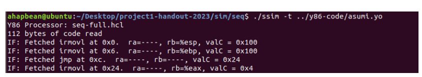
The code that is changed in seq-full.hcl is displayed here.

```
################ Fetch Stage     ##########

bool instr_valid = icode in
    { INOP, IHALT, IRRMOVL, IIRMOVL, IRMMOVL, IMRMOVL,
        IOPL, IJXX, ICALL, IRET, IPUSHL, IPOPL, IIADDL };

# Does fetched instruction require a regid byte?
bool need_regids =
    icode in { IRRMOVL, IOPL, IPUSHL, IPOPL,
            IIRMOVL, IRMMOVL, IMRMOVL, IIADDL };

# Does fetched instruction require a constant word?
bool need_valC =
    icode in { IIRMOVL, IRMMOVL, IMRMOVL, IJXX, ICALL, IIADDL};


################ Decode Stage    ##########

## What register should be used as the B source?
int srcB = [
    icode in { IOPL, IRMMOVL, IMRMOVL, IIADDL } : rB;
    icode in { IPUSHL, IPOPL, ICALL, IRET } : RESP;
    1 : RNONE;  # Don't need register
];

## What register should be used as the E destination?
int dstE = [
    icode in { IRRMOVL } && Cnd : rB;
    icode in { IIRMOVL, IOPL, IIADDL} : rB;
    icode in { IPUSHL, IPOPL, ICALL, IRET } : RESP;
    1 : RNONE;  # Don't write any register
];
```

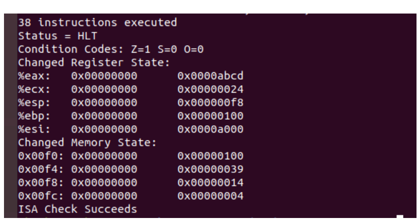
```
################ Execute Stage    ##########

## Select input A to ALU
int aluA = [
    icode in { IRRMOVL, IOPL } : valA;
    icode in { IIRMOVL, IRMMOVL, IMRMOVL, IIADDL } : valC;
    icode in { ICALL, IPUSHL } : -4;
    icode in { IRET, IPOPL } : 4;
    # Other instructions don't need ALU
];

## Select input B to ALU
int aluB = [
    icode in { IRMMOVL, IMRMOVL, IOPL, ICALL,
            IPUSHL, IRET, IPOPL, IIADDL } : valB;
    icode in { IRRMOVL, IIRMOVL } : 0;
    # Other instructions don't need ALU
];

## Set the ALU function
int alufun = [
    icode in {IOPL, IIADDL}  : ifun;
    1 : ALUADD;
];

## Should the condition codes be updated?
bool set_cc = icode in { IOPL, IIADDL};
```

2.2.3 Evaluation

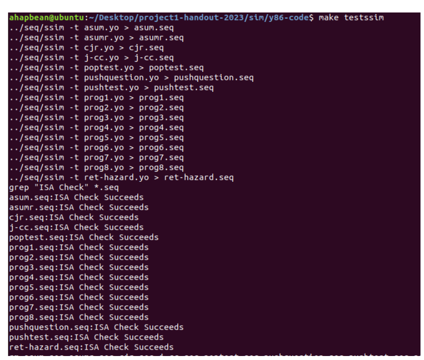
Evaluation1: we've written a description of the computations required for the iaddl instruction.



(a) evaluation2_1



(b) evaluation2_2



(c) evaluation2_3

Figure 4: evaluation2 results

Evaluation2: we pass the benchmark regression tests in y86-code.

(a) evaluation3_1

(b) evaluation3_2

Figure 5: evaluation3 results

Evaluation3: we pass the regression tests in ptest for iaddl.

2.3 Part C

2.3.1 Analysis

In this part,we need to modify the *ncopy.ys* and the $pipe - full.hcl$ with the goal of making ncopy.ys run as fast as possible.For evaluation,we run the *./correctness.pl* for checking correctness and run *./benchmark.pl* for getting CPE and grades.

The difficulties lie in many ascpects including properly modifying the $pipe - full.hcl$ file to get better performance while maintaining normal running standard and we need to be familiar with pipeline to find out which cases could bring bubbles to the pipeline and then try our best to change them.**We get** 9.09 **CPE for the final test**. We complete our work with several steps:

- Try our best to do code scheduling to prevent load/use case that bring bubbles to pipeline.
- Add *iaddl* instruction to the pipeline by modifying the $pipe - full.hcl$.
- Do loop unrolling of 5 cases including 8 4 3 2 1 *times*.
- Take advantage of the two registers $\%esi$, $\%edi$ to improve CPE to prevent load/use case To the fullest extent.

2.3.2 Code

1.pipe-full.hcl Code(only show the modified part)

```
## instruction fetch
# Is instruction valid?
bool instr_valid = f_icode in
    { INOP, IHALT, IRRMOVL, IIRMOVL, IRMMOVL, IMRMOVL,
    IOPL, IJXX, ICALL, IRET, IPUSHL, IPOPL, IIADDL };

# Does fetched instruction require a regid byte?
bool need_regids =
    f_icode in { IRRMOVL, IOPL, IPUSHL, IPOPL,
```

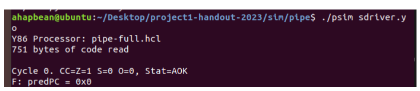
```
            IIRMOVL, IRMMOVL, IMRMOVL, IIADDL };

# Does fetched instruction require a constant word?
bool need_valC =
    f_icode in { IIRMOVL, IRMMOVL, IMRMOVL, IJXX, ICALL,
        IIADDL };

## Decode stage
## What register should be used as the B source?
int d_srcB = [
    D_icode in { IOPL, IRMMOVL, IMRMOVL, IIADDL } : D_rB;
    D_icode in { IPUSHL, IPOPL, ICALL, IRET } : RESP;
    1 : RNONE;  # Don't need register
];

## What register should be used as the E destination?
int d_dstE = [
    D_icode in { IRRMOVL, IIRMOVL, IOPL, IIADDL } : D_rB;
    D_icode in { IPUSHL, IPOPL, ICALL, IRET } : RESP;
    1 : RNONE;  # Don't write any register
];

## execute stage
## Select input A to ALU
int aluA = [
    E_icode in { IRRMOVL, IOPL } : E_valA;
    E_icode in { IIRMOVL, IRMMOVL, IMRMOVL, IIADDL } : E_valC;
    E_icode in { ICALL, IPUSHL } : -4;
    E_icode in { IRET, IPOPL } : 4;
    # Other instructions don't need ALU
];

## Select input B to ALU
int aluB = [
    E_icode in { IRMMOVL, IMRMOVL, IOPL, ICALL,
            IPUSHL, IRET, IPOPL, IIADDL } : E_valB;
    E_icode in { IRRMOVL, IIRMOVL } : 0;
    # Other instructions don't need ALU
];

## Should the condition codes be updated?
bool set_cc = (E_icode == IOPL || E_icode == IIADDL) &&
    # State changes only during normal operation
    !m_stat in { SADR, SINS, SHLT } && !W_stat in { SADR,
        SINS, SHLT };
```

2.ncopy.ys Code(only show the core part)

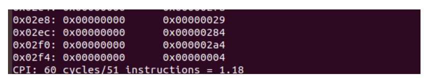
```
    xorl %eax,%eax                  # count = 0;
    iaddl $-8, %edx
    jl pre_len4
len8:
    mrmovl (%ebx), %esi          # loop unrolling with len=8
    mrmovl 4(%ebx), %edi    # use two registers to reduce data
        hazard
    rmmovl %esi, (%ecx)
    andl %esi, %esi
    rmmovl %edi, 4(%ecx)
```

```
    jle len8_1
    iaddl $1, %eax              # count++
len8_1:
    andl %edi, %edi
    jle len8_2
    iaddl $1, %eax

len4:
    mrmovl (%ebx), %esi     # loop unrolling with len = 4
    mrmovl 4(%ebx), %edi
    rmmovl %esi, (%ecx)
    andl %esi, %esi
    rmmovl %edi, 4(%ecx)
    jle len4_1
    iaddl $1, %eax                  # count++
len4_1:
    andl %edi, %edi
    jle len4_2
    iaddl $1, %eax

    # loop unrolling with len = 3,len = 2,len = 1 ...
```

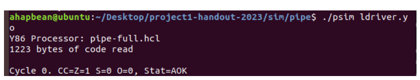
2.3.3 Evaluation



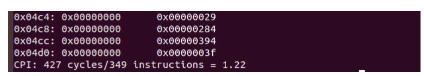
(a) evalutaion1_1



(b) evalutaion1_2



(c) evalutaion1_3



(d) evalutaion1_4

Figure 6: evaluation1 results

Evaluation1: We successfully pass the sdriver and the ldriver test.

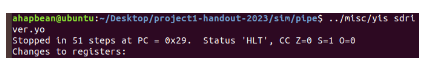
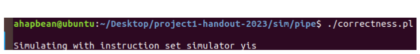
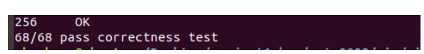


Figure 7: evaluation2 results

Evaluation2: Our function ncopy works properly with YIS.



(a) evalutaion3_1



(b) evalutaion3_2

Figure 8: evaluation3 results

Evaluation3: Our code run correctly with correctness.pl.

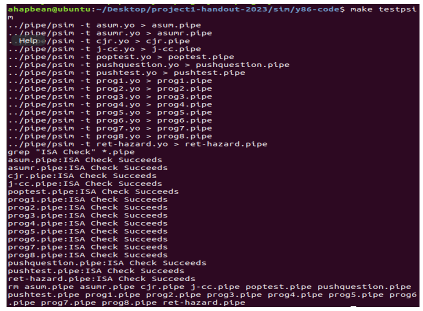
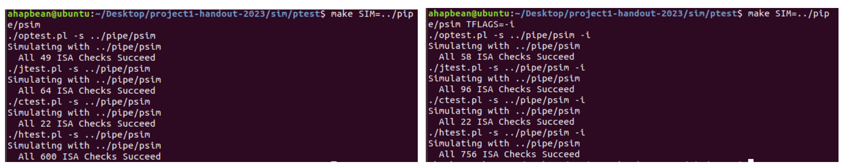


Figure 9: evaluation4 results

Evaluation4: We test our simulator against the Y86 benchmark programs and pass all test.

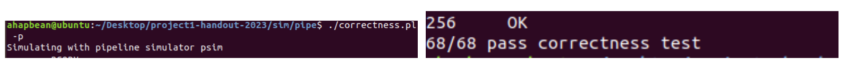


(a) evalutaion5_1

(b) evalutaion5_2

Figure 10: evaluation5 results

Evalutaion5: Our pipeline simulator pass ../ptest (-i).

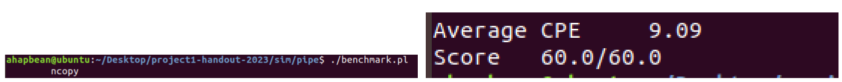


(a) evalutaion6_1

(b) evalutaion6_2

Figure 11: evaluation6 results

Evaluation6: We pass ./correctness.pl -p.



(a) evalutaion7_1

(b) evalutaion7_2

Figure 12: evaluation7 results

Evaluation7: Our code get 9.09 CPE by running the benchmark.pl.
Evaluation8: Our codes are 602 bytes long namely less than 1000 bytes.

3 Conclusion

3.1 Problems

- Question: Do not know how the *.hcl* file work when doing part B. We solve this by reading corresponding chapters in CSAPP and search some internet information.Finally,we learn this well and solve part B successfully.

- Question: After loop unrolling,our CPE only reduce to 11.49 but all strategies seem to have been applied. After thinking for a relatively long time,we find that we do loop unrolling in a bad manner because we add the pointer with 4 each time.Actually,most of them can be deleted by knowing the concrete offset value.Through this improvement, we improve our codes and reduce the CPE to less than 10.

3.2 Achievements

- We code our part A code in a relatively clear manner because we add comments in detail in our codes.

- We make the *iaddl* run correctly in part B.

- After many times of improvement to the ncopy.ys and the pipe-full.hcl,we make our CPE to 9.92 in part C.

- We think actively and try our best to improve our code.Finally we reduce the CPE to 9.09 which turns out to be a great breakthrough for us.