

# Computer Organization Principle

## Arch Lab: Optimizing the Performance of a Pipelined Processor

### 1 Introduction

In this lab, you will learn about the design and implementation of a pipelined Y86-64 processor, optimizing both it and a benchmark program to maximize performance. You are allowed to make any semantics-preserving transformation to the benchmark program, or to make enhancements to the pipelined processor, or both. When you have completed the lab, you will have a keen appreciation for the interactions between code and hardware that affect the performance of your programs.

The lab is organized into three parts, each with its own handin. In Part A you will write some simple Y86-64 programs and become familiar with the Y86-64 tools. In Part B, you will extend the SEQ simulator with a new instruction. These two parts will prepare you for Part C, the heart of the lab, where you will optimize the Y86-64 benchmark program and the processor design.

### 2 Logistics

You will work on this lab alone. Any clarifications and revisions to the assignment will be posted on the course Web page.

### 3 Handout Instructions

1. Start by copying the file `archlab-handout.tar` to a Linux directory in which you plan to do your work.
2. Then give the command: `tar xvf archlab-handout.tar`. This will cause the following files to be unpacked into the directory: `README`, `Makefile`, `sim.tar`, `archlab.pdf`, and `simguide.pdf`.
3. Next, give the command `tar xvf sim.tar`. This will create the directory `sim`, which contains your personal copy of the Y86-64 tools. You will be doing all of your work inside this directory.
4. Finally, change to the `sim` directory and build the Y86-64 tools:

```
unix> cd sim  
unix> make clean; make
```

## 4 Part A

You will be working in directory `sim/misc` in this part.

Your task is to write and simulate the following three Y86-64 programs. The required behavior of these programs is defined by the example C functions in `examples.c`. Be sure to put your name and ID in a comment at the beginning of each program. You can test your programs by first assembling them with the program `YAS` and then running them with the instruction set simulator `YIS`.

In all of your Y86-64 functions, you should follow the x86-64 conventions for passing function arguments, using registers, and using the stack. This includes saving and restoring any callee-save registers that you use.

### **sum.ys: Iteratively sum linked list elements**

Write a Y86-64 program `sum.ys` that iteratively sums the elements of a linked list. Your program should consist of some code that sets up the stack structure, invokes a function, and then halts. In this case, the function should be Y86-64 code for a function (`sum_list`) that is functionally equivalent to the C `sum_list` function in Figure 1. Test your program using the following three-element list:

```
# Sample linked list
.align 8
ele1:
    .quad 0x00a
    .quad ele2
ele2:
    .quad 0x0b0
    .quad ele3
ele3:
    .quad 0xc00
    .quad 0
```

### **rsum.ys: Recursively sum linked list elements**

Write a Y86-64 program `rsum.ys` that recursively sums the elements of a linked list. This code should be similar to the code in `sum.ys`, except that it should use a function `rsum_list` that recursively sums a list of numbers, as shown with the C function `rsum_list` in Figure 1. Test your program using the same three-element list you used for testing `list.ys`.

### **copy.ys: Copy a source block to a destination block**

Write a program (`copy.ys`) that copies a block of words from one part of memory to another (non-overlapping area) area of memory, computing the checksum (Xor) of all the words copied.

```

1 /* linked list element */
2 typedef struct ELE {
3     long val;
4     struct ELE *next;
5 } *list_ptr;
6
7 /* sum_list - Sum the elements of a linked list */
8 long sum_list(list_ptr ls)
9 {
10     long val = 0;
11     while (ls) {
12         val += ls->val;
13         ls = ls->next;
14     }
15     return val;
16 }
17
18 /* rsum_list - Recursive version of sum_list */
19 long rsum_list(list_ptr ls)
20 {
21     if (!ls)
22         return 0;
23     else {
24         long val = ls->val;
25         long rest = rsum_list(ls->next);
26         return val + rest;
27     }
28 }
29
30 /* copy_block - Copy src to dest and return xor checksum of src */
31 long copy_block(long *src, long *dest, long len)
32 {
33     long result = 0;
34     while (len > 0) {
35         long val = *src++;
36         *dest++ = val;
37         result ^= val;
38         len--;
39     }
40     return result;
41 }

```

Figure 1: **C versions of the Y86-64 solution functions.** See `sim/misc/examples.c`

Your program should consist of code that sets up a stack frame, invokes a function `copy_block`, and then halts. The function should be functionally equivalent to the C function `copy_block` shown in Figure Figure 1. Test your program using the following three-element source and destination blocks:

```
.align 8
# Source block
src:
    .quad 0x00a
    .quad 0x0b0
    .quad 0xc00

# Destination block
dest:
    .quad 0x111
    .quad 0x222
    .quad 0x333
```

## 5 Part B

You will be working in directory `sim/seq` in this part.

Your task in Part B is to extend the SEQ processor to support the `iaddq`, described in Homework problems 4.51 and 4.52. To add this instructions, you will modify the file `seq-full.hcl`, which implements the version of SEQ described in the CS:APP3e textbook. In addition, it contains declarations of some constants that you will need for your solution.

Your HCL file must begin with a header comment containing the following information:

- Your name and ID.
- A description of the computations required for the `iaddq` instruction. Use the descriptions of `irmovq` and `OPq` in Figure 4.18 in the CS:APP3e text as a guide.

### Building and Testing Your Solution

Once you have finished modifying the `seq-full.hcl` file, then you will need to build a new instance of the SEQ simulator (`ssim`) based on this HCL file, and then test it:

- *Building a new simulator:* You can use `make` to build a new SEQ simulator:

```
unix> make VERSION=full
```

This builds a version of `ssim` that uses the control logic you specified in `seq-full.hcl`. To save typing, you can assign `VERSION=full` in the Makefile.

- *Testing your solution on a simple Y86-64 program.* For your initial testing, we recommend running simple programs such as `asumi.yo` (testing `iaddq`) in TTY mode, comparing the results against the ISA simulation:

```
unix> ./ssim -t ../y86-code/asumi.yo
```

If the ISA test fails, then you should debug your implementation by single stepping the simulator in GUI mode:

```
unix> ./ssim -g ../y86-code/asumi.yo
```

- *Retesting your solution using the benchmark programs.* Once your simulator is able to correctly execute small programs, then you can automatically test it on the Y86-64 benchmark programs in `../y86-code`:

```
unix> (cd ../y86-code; make testssim)
```

This will run `ssim` on the benchmark programs and check for correctness by comparing the resulting processor state with the state from a high-level ISA simulation. Note that none of these programs test the added instructions. You are simply making sure that your solution did not inject errors for the original instructions. See file `../y86-code/README` file for more details.

- *Performing regression tests.* Once you can execute the benchmark programs correctly, then you should run the extensive set of regression tests in `../ptest`. To test everything except `iaddq`:

```
unix> (cd ../ptest; make SIM=../seq/ssim)
```

To test your implementation of `iaddq`:

```
unix> (cd ../ptest; make SIM=../seq/ssim TFLAGS=-i)
```

For more information on the SEQ simulator refer to the handout *CS:APP3e Guide to Y86-64 Processor Simulators* (`simguide.pdf`).

## 6 Part C

You will be working in directory `sim/pipe` in this part.

The `ncpy` function in Figure 2 copies a `len`-element integer array `src` to a non-overlapping `dst`, returning a count of the number of positive integers contained in `src`. Figure 3 shows the baseline Y86-64 version of `ncpy`. The file `pipe-full.hcl` contains a copy of the HCL code for PIPE, along with a declaration of the constant value `IIADDQ`.

Your task in Part C is to modify `ncpy.ys` and `pipe-full.hcl` with the goal of making `ncpy.ys` run as fast as possible.

You will be handing in two files: `pipe-full.hcl` and `ncpy.ys`. Each file should begin with a header comment with the following information:

```

1  /*
2   * ncopy - copy src to dst, returning number of positive ints
3   * contained in src array.
4   */
5 word_t ncopy(word_t *src, word_t *dst, word_t len)
6 {
7     word_t count = 0;
8     word_t val;
9
10    while (len > 0) {
11        val = *src++;
12        *dst++ = val;
13        if (val > 0)
14            count++;
15        len--;
16    }
17    return count;
18 }

```

Figure 2: **C version of the ncopy function.** See `sim/pipe/ncopy.c`.

- Your name and ID.
- A high-level description of your code. In each case, describe how and why you modified your code.

## Coding Rules

You are free to make any modifications you wish, with the following constraints:

- Your `ncpy.ys` function must work for arbitrary array sizes. You might be tempted to hardwire your solution for 64-element arrays by simply coding 64 copy instructions, but this would be a bad idea because we will be grading your solution based on its performance on arbitrary arrays.
- Your `ncpy.ys` function must run correctly with YIS. By correctly, we mean that it must correctly copy the `src` block *and* return (in `%rax`) the correct number of positive integers.
- The assembled version of your `ncpy` file must not be more than 1000 bytes long. You can check the length of any program with the `ncpy` function embedded using the provided script `check-len.pl`:

```
unix> ./check-len.pl < ncopy.yo
```

- Your `pipe-full.hcl` implementation must pass the regression tests in `../y86-code` and `../ptest` (without the `-i` flag that tests `iaddq`).

Other than that, you are free to implement the `iaddq` instruction if you think that will help. You may make any semantics preserving transformations to the `ncpy.ys` function, such as reordering instructions, replacing groups of instructions with single instructions, deleting some instructions, and adding other instructions. You may find it useful to read about loop unrolling in Section 5.8 of CS:APP3e.

```

1 ##########
2 # ncopy.ys - Copy a src block of len words to dst.
3 # Return the number of positive words (>0) contained in src.
4 #
5 # Include your name and ID here.
6 #
7 # Describe how and why you modified the baseline code.
8 #
9 #####
10 # Do not modify this portion
11 # Function prologue.
12 # %rdi = src, %rsi = dst, %rdx = len
13 ncopy:
14
15 #####
16 # You can modify this portion
17         # Loop header
18         xorq %rax,%rax          # count = 0;
19         andq %rdx,%rdx          # len <= 0?
20         jle Done                 # if so, goto Done:
21
22 Loop:    mrmovq (%rdi), %r10      # read val from src...
23         rmovq %r10, (%rsi)      # ...and store it to dst
24         andq %r10, %r10          # val <= 0?
25         jle Npos                 # if so, goto Npos:
26         irmovq $1, %r10
27         addq %r10, %rax          # count++
28 Npos:    irmovq $1, %r10
29         subq %r10, %rdx          # len--
30         irmovq $8, %r10
31         addq %r10, %rdi          # src++
32         addq %r10, %rsi          # dst++
33         andq %rdx,%rdx          # len > 0?
34         jg Loop                  # if so, goto Loop:
35 #####
36 # Do not modify the following section of code
37 # Function epilogue.
38 Done:
39         ret
40 #####
41 # Keep the following label at the end of your function
42 End:

```

Figure 3: **Baseline Y86-64 version of the ncopy function.** See `sim/pipe/ncopy.ys`.

## Building and Running Your Solution

In order to test your solution, you will need to build a driver program that calls your `ncopy` function. We have provided you with the `gen-driver.pl` program that generates a driver program for arbitrary sized input arrays. For example, typing

```
unix> make drivers
```

will construct the following two useful driver programs:

- `sdriver.yo`: A *small driver program* that tests an `ncopy` function on small arrays with 4 elements. If your solution is correct, then this program will halt with a value of 2 in register `%rax` after copying the `src` array.
- `ldriver.yo`: A *large driver program* that tests an `ncopy` function on larger arrays with 63 elements. If your solution is correct, then this program will halt with a value of 31 (`0x1f`) in register `%rax` after copying the `src` array.

Each time you modify your `ncopy.ys` program, you can rebuild the driver programs by typing

```
unix> make drivers
```

Each time you modify your `pipe-full.hcl` file, you can rebuild the simulator by typing

```
unix> make psim VERSION=full
```

If you want to rebuild the simulator and the driver programs, type

```
unix> make VERSION=full
```

To test your solution in GUI mode on a small 4-element array, type

```
unix> ./psim -g sdriver.yo
```

To test your solution on a larger 63-element array, type

```
unix> ./psim -g ldriver.yo
```

Once your simulator correctly runs your version of `ncopy.ys` on these two block lengths, you will want to perform the following additional tests:

- *Testing your driver files on the ISA simulator.* Make sure that your `ncopy.ys` function works properly with YIS:

```
unix> make drivers
unix> ../misc/yis sdriver.yo
```

- *Testing your code on a range of block lengths with the ISA simulator.* The Perl script `correctness.pl` generates driver files with block lengths from 0 up to some limit (default 65), plus some larger sizes. It simulates them (by default with YIS), and checks the results. It generates a report showing the status for each block length:

```
unix> ./correctness.pl
```

This script generates test programs where the result count varies randomly from one run to another, and so it provides a more stringent test than the standard drivers.

If you get incorrect results for some length  $K$ , you can generate a driver file for that length that includes checking code, and where the result varies randomly:

```
unix> ./gen-driver.pl -f ncopy.ys -n K -rc > driver.ys
unix> make driver.yo
unix> ../misc/yis driver.yo
```

The program will end with register `%rax` having the following value:

**0xaaaa** : All tests pass.

**0xbbbb** : Incorrect count

**0xcccc** : Function `ncpy` is more than 1000 bytes long.

**0xdddd** : Some of the source data was not copied to its destination.

**0xeeee** : Some word just before or just after the destination region was corrupted.

- *Testing your pipeline simulator on the benchmark programs.* Once your simulator is able to correctly execute `sdriver.ys` and `ldriver.ys`, you should test it against the Y86-64 benchmark programs in `../y86-code`:

```
unix> (cd ../y86-code; make testpsim)
```

This will run `psim` on the benchmark programs and compare results with YIS.

- *Testing your pipeline simulator with extensive regression tests.* Once you can execute the benchmark programs correctly, then you should check it with the regression tests in `../ptest`. For example, if your solution implements the `iaddq` instruction, then

```
unix> (cd ../ptest; make SIM=../pipe/psim TFLAGS=-i)
```

- *Testing your code on a range of block lengths with the pipeline simulator.* Finally, you can run the same code tests on the pipeline simulator that you did earlier with the ISA simulator

```
unix> ./correctness.pl -p
```

**Note: The tests above only check the correctness of your implementation (worth 40 points). In addition, you also need to improve the CPE performance of your program (worth 60 points), read Evaluation part for details.**

## 7 Evaluation

The lab is worth 100 points: 20 points for Part A, 30 points for Part B, and 50 points for Part C.

### Part A

Part A is worth 20 points, with the following breakdown:

- 15 points for correctness of output, 5 points each for the three tasks.
- 5 points for valid translation and implementation of the original C code into Y86-64 assembly, ensuring that the logical behavior of the code is retained.

### Part B

This part of the lab is worth 30 points:

- 10 points for your description of the computations required for the `iaddq` instruction (included in the report).
- 5 points for passing the benchmark regression tests in `y86-code`, to verify that your simulator still correctly executes the benchmark suite.
- 15 points for passing the regression tests in `ptest` for `iaddq`.

### Part C

This part of the Lab is worth 50 points: **You will not receive any credit if either your code for `ncopy.ys` or your modified simulator fails any of the tests described earlier.**

- 10 points each for your descriptions of `ncopy.ys` and `pipe-full.hcl`(included in the report).
- 30 points for performance. To receive credit here, your solution must be correct, as defined earlier. That is, `ncopy` runs correctly with `YIS`, and `pipe-full.hcl` passes all tests in `y86-code` and `ptest`.

We will express the performance of your function in units of *cycles per element* (CPE). That is, if the simulated code requires  $C$  cycles to copy a block of  $N$  elements, then the CPE is  $C/N$ . The PIPE simulator displays the total number of cycles required to complete the program. The baseline version of the `ncopy` function running on the standard PIPE simulator with a large 63-element array requires 897 cycles to copy 63 elements, for a CPE of  $897/63 = 14.24$ .

Since some cycles are used to set up the call to `ncpy` and to set up the loop within `ncpy`, you will find that you will get different values of the CPE for different block lengths (generally the CPE will drop as  $N$  increases). We will therefore evaluate the performance of your function by computing the average of the CPEs for blocks ranging from 1 to 64 elements. You can use the Perl script `benchmark.pl` in the `pipe` directory to run simulations of your `ncpy.ys` code over a range of block lengths and compute the average CPE. Simply run the command

```
unix> ./benchmark.pl
```

to see what happens. For example, the baseline version of the `ncpy` function has CPE values ranging between 29.00 and 14.27, with an average of 15.18. Note that this Perl script does not check for the correctness of the answer. Use the script `correctness.pl` for this.

You should be able to achieve an average CPE of less than 9.00. Our best version averages 7.48. If your average CPE is  $c$ , then your score  $S$  for this portion of the lab will be:

$$S = \begin{cases} 0, & c > 10.5 \\ 10 \cdot (10.5 - c), & 7.50 \leq c \leq 10.50 \\ 30, & c < 7.50 \end{cases}$$

By default, `benchmark.pl` and `correctness.pl` compile and test `ncpy.ys`. Use the `-f` argument to specify a different file name. The `-h` flag gives a complete list of the command line arguments.

## 8 Handin Instructions

- You will be handing in three sets of files:
  - Part A: `sum.ys`, `rsum.ys`, and `copy.ys`.
  - Part A: reports which provide a brief explanation of your translations, and a screenshot of your output.
  - Part B: `seq-full.hcl`.
  - Part B: reports which include the description of the instructions you implemented, the difficulties you faced, what you learned in the lab, etc.
  - Part C: `ncpy.ys` and `pipe-full.hcl`.
  - Part C: reports which include the description of the instructions you implemented, how you modified the simulator and your analysis, the difficulties you faced, what you learned in the lab, etc.

- The structure of your submission should look as follows:

```
+-----  
name_ID_archlab/  
  +- PartA/  
    |   +- sum.ys  
    |   +- rsum.ys  
    |   +- copy.ys  
  +- PartB/  
    |   +- seq-full.hcl  
  +- PartC/  
    |   +- ncopy.ys  
    |   +- pipe-full.hcl  
  +- report/  
    |   +- report.pdf  
+-----
```