CSCI 2021, Fall 2012
Optimizing the Performance of a Pipelined Processor
Assigned: 11/06, Due: 11/16, 11:59PM

1 Introduction

In this lab, you will learn about the design and implementation of a pipelined Y86 processor, optimizing both it and a benchmark program to maximize performance. 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 two parts, each with its own handin. In Part A you will write some simple Y86 programs and become familiar with the Y86 tools. In Part B, you will modify the Y86 benchmark program and the processor design.

2 Logistics

As usual, you may work in pairs on this assignment. Groups of greater than two are not permitted.

Any clarifications and revisions to the assignment will be posted on the assignment's forum. *First tip: Get started as soon as possible (Immediately).*

Please consult the simulation guide in the handout right away in order to understand how the simulator work and prevent later frustrations in an attempt to get anything working.

3 Handin Instructions

- You will use Moodle to turn in your code.
- You will be handing in two sets of files through *2 submissions*, one per part:
  - Part A: `sum.ys`, `rsum.ys`, and `copy.ys`.
  - Part B: `ncopy.ys` and `pipe-full.hcl`.
- Make sure you have included your name(s) and ID(s) in a comment at the top of each of your handin files.

- Failure to follow these submission instructions may result in penalty points and worse yet, no grade.

4 Handout Instructions

You will obtain the architecture lab under the download named ”archlab-handout.tar”.

1. Start by copying the file `archlab-handout.tar` to a (protected) 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.ps`, `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 tools. You will be doing all of your work inside this directory.
4. Finally, change to the `sim` directory and build the Y86 tools:

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

5 Part A

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

Your task is to write and simulate the following three Y86 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 assemblying them with the program YAS and then running them with the instruction set simulator YIS.

In all of your Y86 functions, you should follow the IA32 conventions for the structure of the stack frame and for register usage instructions, including saving and restoring any callee-save registers that you use.

`sum.ys`: Iteratively sum linked list elements

Write a Y86 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 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 4
ele1:
        .long 0x00a
        .long ele2
ele2:
        .long 0x0b0
        .long ele3
ele3:
        .long 0xc00
        .long 0
```

`rsum.ys`: Recursively sum linked list elements

Write a Y86 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.

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 4
# Source block
src:
        .long 0x00a
        .long 0x0b0
        .long 0xc00

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

```c
/* linked list element */
typedef struct ELE {
    int val;
    struct ELE *next;
} *list_ptr;

/* sum_list - Sum the elements of a linked list */
int sum_list(list_ptr ls)
{
    int val = 0;
    while (ls) {
        val += ls->val;
        ls = ls->next;
    }
    return val;
}

/* rsum_list - Recursive version of sum_list */
int rsum_list(list_ptr ls)
{
    if (!ls)
        return 0;
    else {
        int val = ls->val;
        int rest = rsum_list(ls->next);
        return val + rest;
    }
}

/* copy_block - Copy src to dest and return xor checksum of src */
int copy_block(int *src, int *dest, int len)
{
    int result = 0;
    while (len > 0) {
        int val = *src++;
        *dest++ = val;
        result ^= val;
        len--;
    }
    return result;
}
```

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

```
/*
 * ncopy - copy src to dst, returning number of positive ints
 * contained in src array.
 */
int ncopy(int *src, int *dst, int len)
{
    int count = 0;
    int val;

    while (len > 0) {
        val = *src++;
        *dst++ = val;
        if (val > 0)
            count++;
        len--;
    }
    return count;
}
```

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

6 Part B

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

The `ncopy` 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 version of `ncopy`. The file `pipe-full.hcl` contains a copy of the HCL code for PIPE, along with a declaration of the constant value `IIADDL`.

Your task is Part B is to:

- modify `pipe-full.hcl` by adding `IIADDL` to the set of instruction that the pipeline simulator can execute. As mentioned above, note `IIADDL` is already declared.
- modify `ncopy.ys` by replacing a number of instructions with `IIADDL`.

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

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

```
#################################################################
# ncopy.ys - Copy a src block of len ints to dst.
# Return the number of positive ints (>0) contained in src.
#
# Include your name and ID here.
#
# Describe how and why you modified the baseline code.
#
#################################################################
# Do not modify this portion
# Function prologue.
ncopy:  pushl %ebp              # Save old frame pointer
        rrmovl %esp,%ebp        # Set up new frame pointer
        pushl %esi              # Save callee-save regs
        pushl %ebx
        pushl %edi
        mrmovl 8(%ebp),%ebx     # src
        mrmovl 16(%ebp),%edx    # len
        mrmovl 12(%ebp),%ecx    # dst

#################################################################
# You can modify this portion
        # Loop header
        xorl %eax,%eax          # count = 0;
        andl %edx,%edx          # len <= 0?
        jle Done                # if so, goto Done:

Loop:   mrmovl (%ebx), %esi     # read val from src...
        rmmovl %esi, (%ecx)     # ...and store it to dst
        andl %esi, %esi         # val <= 0?
        jle Npos                # if so, goto Npos:
        irmovl $1, %edi
        addl %edi, %eax         # count++
Npos:   irmovl $1, %edi
        subl %edi, %edx         # len--
        irmovl $4, %edi
        addl %edi, %ebx         # src++
        addl %edi, %ecx         # dst++
        andl %edx,%edx          # len > 0?
        jg Loop                 # if so, goto Loop:
#################################################################
# Do not modify the following section of code
# Function epilogue.
Done:
        popl %edi               # Restore callee-save registers
        popl %ebx
        popl %esi
        rrmovl %ebp, %esp
        popl %ebp
        ret
#################################################################
# Keep the following label at the end of your function
End:
```

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

Coding Rules

You are free to make any modifications you wish, with the following constraints (while they may appear unreasonable, we have them anyway):

- Your `ncopy.ys` function must work for arbitrary array sizes.
- Your `ncopy.ys` function must run correctly with YIS. By correctly, we mean that it must correctly copy the `src` block *and* return (in `%eax`) the correct number of positive integers.
- The assembled version of your `ncopy` file must not be more than 1000 bytes long. You can check the length of any program with the `ncopy` 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` flags that test `iaddl`).

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 `%eax` 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 `%eax` 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 `%eax` having the following value:

  `0xaaaa` : All tests pass.

  `0xbbbb` : Incorrect count

  `0xcccc` : Function ncopy 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 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, since your solution implements the `iaddl` 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
```

7 Evaluation

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

Part A

Part A is worth 30 points, 10 points for each Y86 solution program. Each solution program will be evaluated for correctness, including proper handling of the stack and registers, as well as functional equivalence with the example C functions in `examples.c`.

The programs `sum.ys` and `rsum.ys` will be considered correct if the graders do not spot any errors in them, and their respective `sum_list` and `rsum_list` functions return the sum `0xcba` in register `%eax`.

The program `copy.ys` will be considered correct if the graders do not spot any errors in them, and the `copy_block` function returns the sum `0xcba` in register `%eax`, copies the three words `0x00a`, `0x0b`, and `0xc` to the 12 contiguous memory locations beginning at address `dest`, and does not corrupt other memory locations.

Part B

This part of the Lab is worth 20 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.**

- 15 points for your implementation of `IIADDL` in the pipeline simulator.
- 5 points for correctly modifying `ncopy.ys` to use `IIADDL`.
- That is, `ncopy` must run correctly with YIS, and `pipe-full.hcl` must pass all tests in `y86-code` and `ptest`.

8 Performance metrics: YOU MAY SKIP THIS SECTION!

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 914 cycles to copy 63 elements, for a CPE of $914/63 = 14.51$.

Since some cycles are used to set up the call to `ncopy` and to set up the loop within `ncopy`, 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 `ncopy.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 `ncopy` function has CPE values ranging between 46.0 and 14.51, with an average of 16.44. Note that this Perl script does not check for the correctness of the answer. Use the script `correctness.pl` for this.

The performance of this code can be improved to an average CPE of less than 10.0. Our best version average is 9.27.

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

9 Hints

- By design, both `sdriver.yo` and `ldriver.yo` are small enough to debug with in GUI mode. We find it easiest to debug in GUI mode, and suggest that you use it.
- If you running in GUI mode on a Unix server, make sure that you have initialized the DISPLAY environment variable:

  ```
  unix>  setenv DISPLAY myhost.edu:0
  ```

- With some X servers, the "Program Code" window begins life as a closed icon when you run `psim` or `ssim` in GUI mode. Simply click on the icon to expand the window.
- With some Microsoft Windows-based X servers, the "Memory Contents" window will not automatically resize itself. You'll need to resize the window by hand.
- The `psim` and `ssim` simulators terminate with a segmentation fault if you ask them to execute a file that is not a valid Y86 object file.