

CS:APP Guide to Y86 Processor Simulators*

Randal E. Bryant
David R. O'Hallaron

November 4, 2004

*Copyright © 2002, R. E. Bryant, D. R. O'Hallaron. All rights reserved.

This document describes the processor simulators that accompany the presentation of the Y86 processor architectures in Chapter 4 of *Computer Systems: A Programmer's Perspective*. These simulators model three different processor designs: SEQ, SEQ+, and PIPE.

1 Installing

The code for the simulator is distributed as a Tar format file named `sim.tar`. You can get a copy of this file from the CS:APP Web site (`csapp.cs.cmu.edu`).

With the tar file in the directory you want to install the code, you should be able to do the following:

```
unix> tar xf sim.tar
unix> cd sim
unix> make clean
unix> make
```

By default, this generates GUI (graphic user interface) versions of the simulators, which require that you have Tcl/Tk installed on your system. If not, then you have the option to install TTY-only versions that emit their output as ASCII text on stdout. See file `README` for a description of how to generate the GUI and TTY versions.

The directory `sim` contains the following subdirectories:

- misc** Source code files for utilities such as YAS (the Y86 assembler), YIS (the Y86 instruction set simulator), and HCL2C (HCL to C translator). It also contains the `isa.c` source file that is used by all of the processor simulators.
- seq** Source code for the SEQ and SEQ+ simulators. Contains the HCL file for homework problems 4.34 and 4.35. See file `README` for instructions on compiling the different versions of the simulator.
- pipe** Source code for the PIPE simulator. Contains the HCL files for homework problems 4.37–4.42. See file `README` for instructions on compiling the different versions of the simulator.
- y86-code** Y86 assembly code for many of the example programs shown in the chapter. You can automatically test your modified simulators on these benchmark programs. See file `README` for instructions on how to run these tests. As a running example, we will use the program `asum.js` in this subdirectory. This program is shown as CS:APP Figure 4.6. The compiled version of the program is shown in Figure 1.
- pctest** Scripts that generate systematic regression tests of the different instructions, the different jump possibilities, and different hazard possibilities. These scripts are very good at finding bugs in your homework solutions. See file `README` for instructions on how to run these tests.

```

1      | # Execution begins at address 0
2      |
3      | .pos 0
4      | init:  irmovl Stack, %esp      # Set up Stack pointer
5      |      0x006: 308500010000      |      irmovl Stack, %ebp      # Set up base pointer
6      |      0x00c: 7024000000      |      jmp Main              # Execute main program
7      |
8      | # Array of 4 elements
9      |      0x014: .align 4
10     |      0x014: 0d000000      | array: .long 0xd
11     |      0x018: c0000000      |      .long 0xc0
12     |      0x01c: 000b0000      |      .long 0xb00
13     |      0x020: 00a00000      |      .long 0xa000
14     |
15     | Main:  irmovl $4,%eax
16     |      0x02a: a008          |      pushl %eax            # Push 4
17     |      0x02c: 308214000000  |      irmovl array,%edx
18     |      0x032: a028          |      pushl %edx            # Push array
19     |      0x034: 803a000000    |      call Sum              # Sum(array, 4)
20     |      0x039: 10           |      halt
21     |
22     | # int Sum(int *Start, int Count)
23     | Sum:   pushl %ebp
24     |      0x03a: a058          |      rrmovl %esp,%ebp
25     |      0x03c: 2045          |      mrmovl 8(%ebp),%ecx    # ecx = Start
26     |      0x03e: 501508000000  |      mrmovl 12(%ebp),%edx   # edx = Count
27     |      0x044: 50250c000000  |      irmovl $0, %eax        # sum = 0
28     |      0x04a: 308000000000  |      andl  %edx,%edx
29     |      0x050: 6222          |      je      End
30     |      0x052: 7374000000    |      Loop: mrmovl (%ecx),%esi # get *Start
31     |      0x057: 506100000000  |      addl %esi,%eax         # add to sum
32     |      0x05d: 6060          |      irmovl $4,%ebx         #
33     |      0x05f: 308304000000  |      addl %ebx,%ecx         # Start++
34     |      0x065: 6031          |      irmovl $-1,%ebx        #
35     |      0x067: 3083ffffff    |      addl %ebx,%edx         # Count--
36     |      0x06d: 6032          |      jne     Loop          # Stop when 0
37     |      0x06f: 7457000000    |      End:
38     |      0x074: b058          |      popl %ebp
39     |      0x076: 90           |      ret
40     |      0x100: .pos 0x100
41     |      0x100: Stack: # The stack goes here

```

Figure 1: **Sample object code file.** This code is in the file `asum.yo` in the `y86-code` subdirectory.

2 Utility Programs

Once installation is complete, the `misc` directory contains two useful programs:

YAS The Y86 assembler. This takes a Y86 assembly code file with extension `.ys` and generates a file with extension `.yo`. The generated file contains an ASCII version of the object code, such as that shown in Figure 1 (the same program as shown in CS:APP Figure 4.7). The easiest way to invoke the assembler is to use or create assembly code files in the `y86-code` subdirectory. For example, to assemble the program in file `asum.ys` in this directory, we use the command:

```
unix> make asum.yo
```

YIS The Y86 instruction simulator. This program executes the instructions in a Y86 machine-level program according to the instruction set definition. For example, suppose you want to run the program `asum.yo` from within the subdirectory `y86-code`. Simply run:

```
unix> ../misc/yis asum.yo
```

YIS simulates the execution of the program and then prints changes to any registers or memory locations on the terminal, as described in CS:APP Section 4.1.

3 Processor Simulators

For each of the three processors, SEQ, SEQ+, and PIPE, we have provided simulators SSIM, SSIM+, and PSIM respectively. Each simulator can be run in TTY or GUI mode:

TTY mode Uses a minimalist, terminal-oriented interface. Prints everything on the terminal output. Not very convenient for debugging but can be installed on almost any system and can be used for automated testing. The default mode for all simulators.

GUI mode Has a graphic user interface, to be described shortly. Very helpful for visualizing the processor activity and for debugging modified versions of the design. However, requires installation of Tcl/Tk on your system. Invoked with the `-g` command line option.

3.1 Command Line Options

You can request a number of options from the command line:

-h Prints a summary of all of the command line options.

-g Run the simulator in GUI mode (default TTY mode).

- t** Runs both the processor and the ISA simulators, comparing the resulting values of the memory, register file, and condition codes. If no discrepancies are found, it prints the message “ISA Check Succeeds.” Otherwise, it prints information about the words of the register file or memory that differ. This feature is very useful for testing the processor designs.
- l m** Sets the instruction limit, executing at most m instructions before halting (default 10000 instructions).
- v n** Sets the verbosity level to $0 \leq n \leq 2$ (default $n = 2$).

Simulators running in GUI mode must be invoked with the name of an object file on the command line. In TTY mode, the object file name is optional, coming from stdin by default.

Here are some typical invocations of the simulators (from the `y86-code` subdirectory):

```
unix> ../seq/ssim -h
unix> ../seq/ssim -t < asum.yo
unix> ../pipe/psim -t -g asum.yo
```

The first case prints a summary of the command line options for SSIM. The second case runs the SEQ simulator in TTY mode, reading object file `asum.yo` from stdin. The third case runs the PIPE simulator in GUI mode, executing the instructions object file `asum.yo`. In both the second and third cases, the results are compared with the results from the higher-level ISA simulator.

3.2 SEQ and SEQ+ Simulators

The GUI version of the SEQ processor simulator is invoked with an object code filename on the command line:

```
unix> ../seq/ssim -g asum.yo &
```

where the “&” at the end of the command line allows the simulator to run in background mode. The simulation program starts up and creates three windows, as illustrated in Figure 2–4.

The first window (Figure 2) is the main control panel. If the HCL file was compiled by HCL2C with the `-n name` option, then the title of the main control window will appear as “Y86 Processor: name” Otherwise it will appear as simply “Y86 Processor.”

The main control window contains buttons to control the simulator as well as status information about the state of the processor. The different parts of the window are labeled in the figure:

Control: The buttons along the top control the simulator. Clicking the **Quit** button causes the simulator to exit. Clicking the **Go** button causes the simulator to start running. Clicking the **Stop** button causes the simulator to stop temporarily. Clicking the **Step** button causes the simulator to execute one instruction and then stop. Clicking the **Reset** button causes the simulator to return to its initial state, with the program counter at address 0, the registers set to 0s, the memory erased except for the program, and the condition codes set with $ZF = 1$, $CF = 0$, and $OF = 0$.

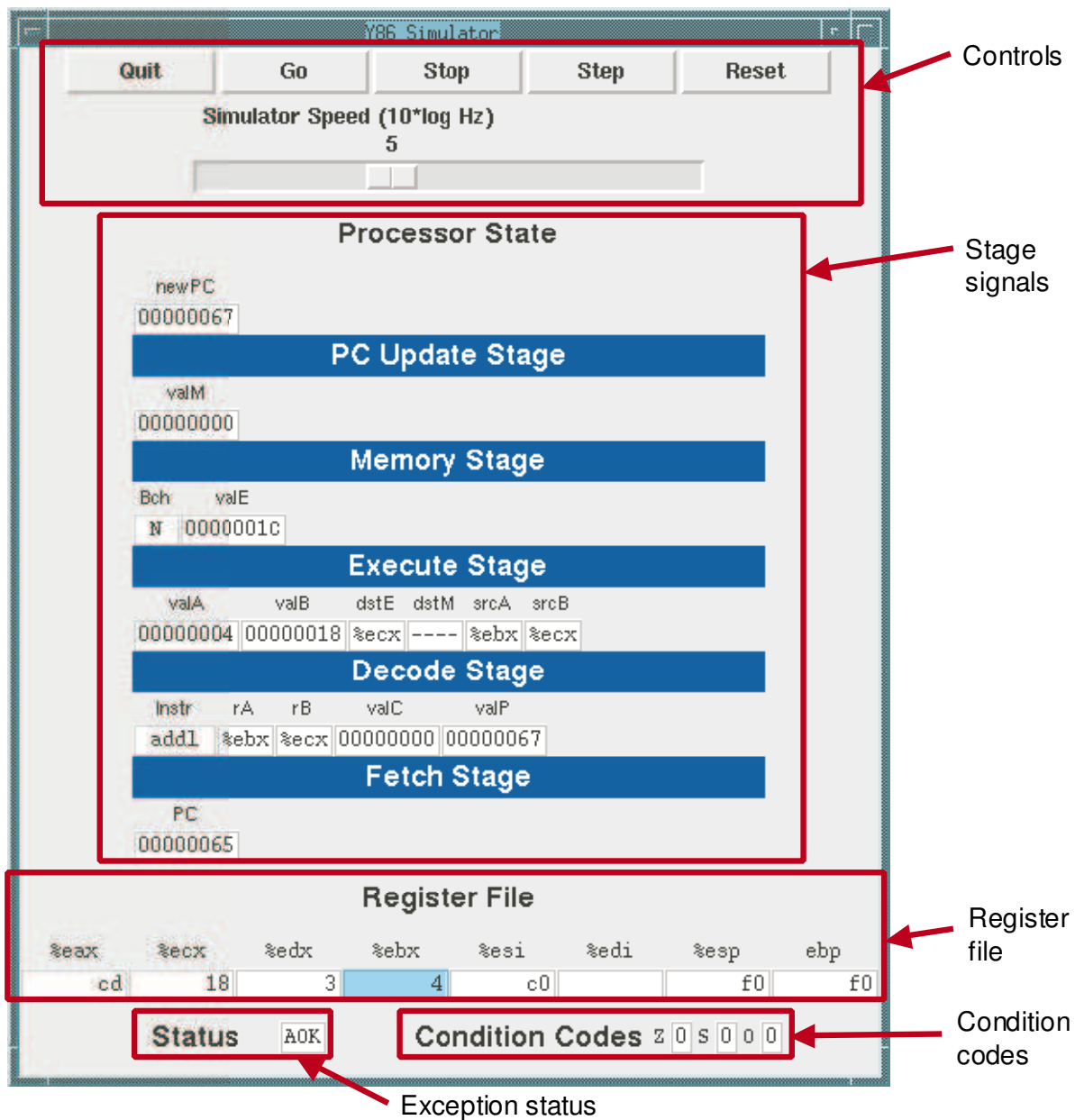


Figure 2: Main control panel for SEQ simulator

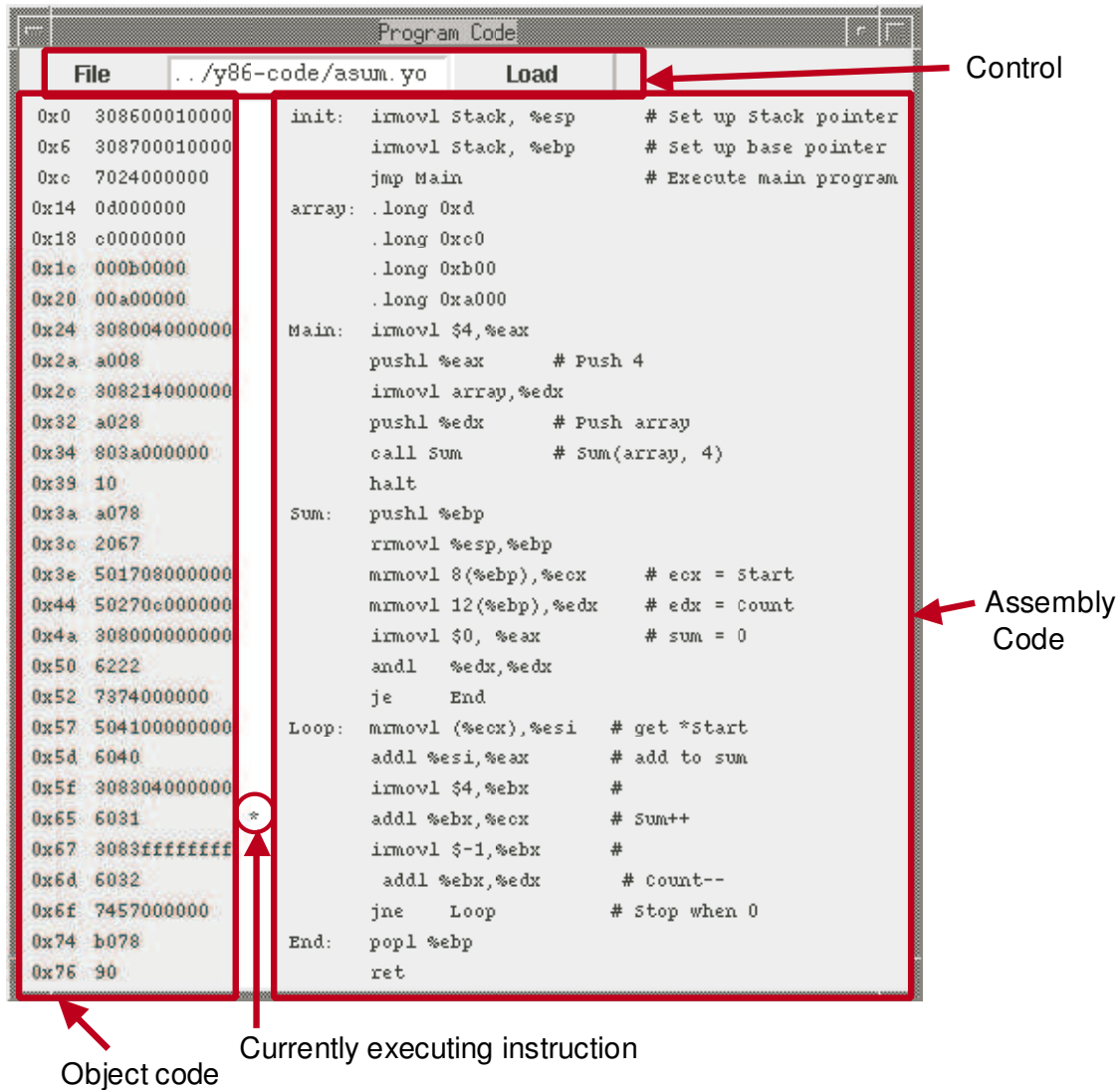


Figure 3: Code display window for SEQ simulator

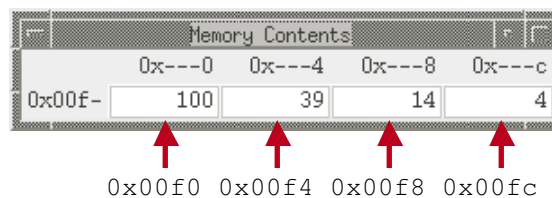


Figure 4: Memory display window for SEQ simulator

The slider below the buttons control the speed of the simulator when it is running. Moving it to the right makes the simulator run faster.

Stage signals: This part of the display shows the values of the different processor signals during the current instruction evaluation. These signals are almost identical to those shown in CS:APP Figure 4.21. The main difference is that the simulator displays the name of the instruction in a field labeled `Instr`, rather than the numeric values of `icode` and `ifun`. Similarly, all registers are shown using their names, with “----” indicating that no register access is required.

Register file: This section displays the values of the eight program registers. The register that has been updated most recently is shown highlighted in light blue. Register contents are not displayed until after the first time they are set to nonzero values.

Remember that when an instruction writes to a program register, the register file is not updated until the beginning of the next clock cycle. This means that you must step the simulator one more time to see the update take place.

Status: This shows the status of the current instruction being executed. The possible values are:

AOK: No problem encountered.

ADR: An addressing error has occurred either trying to read an instruction or trying to read or write data. Addresses cannot exceed `0xFFFF`.

INS: An illegal instruction was encountered.

HLT: A `halt` instruction was encountered.

Condition codes: These show the values of the three condition codes: `ZF`, `SF`, and `OF`.

Remember that when an instruction changes the condition codes, the condition code register is not updated until the beginning of the next clock cycle. This means that you must step the simulator one more time to see the update take place.

The processor state illustrated in Figure 2 is for the second execution of line 32 of the `asum.yo` program shown in Figure 1. We can see that the program counter is at `0x065`, that it has processed the instruction `addl %ebx, %ecx`, that register `%eax` holds `0xcd`, the sum of the first two array elements, and `%edx` holds 3, the count that is about to be decremented. Register `%ecx` still holds `0x18`, the address of the second array element, but there is a pending write of `0x01C` to this register (since `dstE` is set to `%ecx` and `valE` is set to `0x01C`). This write will take place at the start of the next clock cycle.

The window depicted in Figure 3 shows the object code file that is being executed by the simulator.¹ The edit box identifies the file name of the program being executed. You can edit the file name in this window and click the **Load** button to load a new program. The left hand side of the display shows the object code being executed, while the right hand side shows the text from the assembly code file. The center has an asterisk (*) to indicate which instruction is currently being simulated. This corresponds to line 32 of the `asum.yo` program shown in Figure 1.

¹On some windowing systems, this window begins life as a closed icon if the object file is large. If this happens, simply click on the icon to expand the window.

The window shown in Figure 4 shows the contents of the memory. It shows only those locations between the minimum and maximum addresses that have changed since the program began executing. Each row shows the contents of four memory words. Thus, each row shows 16 bytes of the memory, where the addresses of the bytes differ in only their least significant hexadecimal digits. To the left of the memory values is the “root” address, where the least significant digit is shown as “-”. Each column then corresponds to words with least significant address digits 0x0, 0x4, 0x8, and 0xc. The example shown in Figure 4 shows memory locations 0x00f0, 0x00f4, 0x00f8, and 0x00fc.

The memory contents illustrated in the figure show the stack contents of the `asum.yo` program shown in Figure 1 during the execution of the `Sum` procedure. Looking at the stack operations that have taken place so far, we see that `%esp` was first initialized to 0x100 (line 3), and then we pushed the values 4 (line 15) and 0x014, the address of `array` (line 17) before making the call to `Sum` (line 18). This call pushed the return address 0x039 onto the stack. The first instruction of `Sum` pushes `%ebp` onto the stack (line 22), having value 0x100. That accounts for all of the words shown in this memory display.

Figure 5 shows the control panel window for the SEQ+ simulator, when executing the same object code file and when at the same point in this program. We can see that the only difference is in the ordering of the stages and the different signals listed. These signals correspond to those in CS:APP Figure 4.31. The SEQ+ simulator also generates code and memory windows. These have identical format to those for the SEQ simulator.

3.3 PIPE Simulator

The PIPE simulator also generates three windows. Figure 6 shows the control panel. It has the same set of controls, and the same display of the register file and condition codes. The middle section shows the state of the pipeline registers. The different fields correspond to those in CS:APP Figure 4.53. At the bottom of this panel is a display showing the number of cycles that have been simulated (not including the initial cycles required to get the pipeline flowing), the number of instructions that have completed, and the resulting CPI.

As illustrated in the close-up view of Figure 7, each pipeline register is displayed with two parts. The upper values in white boxes show the current values in the pipeline register. The lower values with a gray background show the inputs to pipeline register. These will be loaded into the register on the next clock cycle, unless the register bubbles or stalls.

The flow of values through the PIPE simulator is quite different from that for the SEQ or SEQ+ simulator. With SEQ and SEQ+, the control panel shows the values resulting from executing a single instruction. Each step of the simulator performs one complete instruction execution. With PIPE, the control panel shows the values for the multiple instructions flowing through the pipeline. Each step of the simulator performs just one stage’s worth of computation for each instruction.

Figure 8 shows the code display for the PIPE simulator. The format is similar to that for SEQ and SEQ+, except that rather than a single marker indicating which instruction is being executed, the display indicates which instructions are in each state of the pipeline, using characters F, D, E, M, and W, for the fetch, decode, execute, memory, and write-back stages.

The PIPE simulator also generates a window to display the memory contents. This has an identical format to the one shown for SEQ (Figure 4).

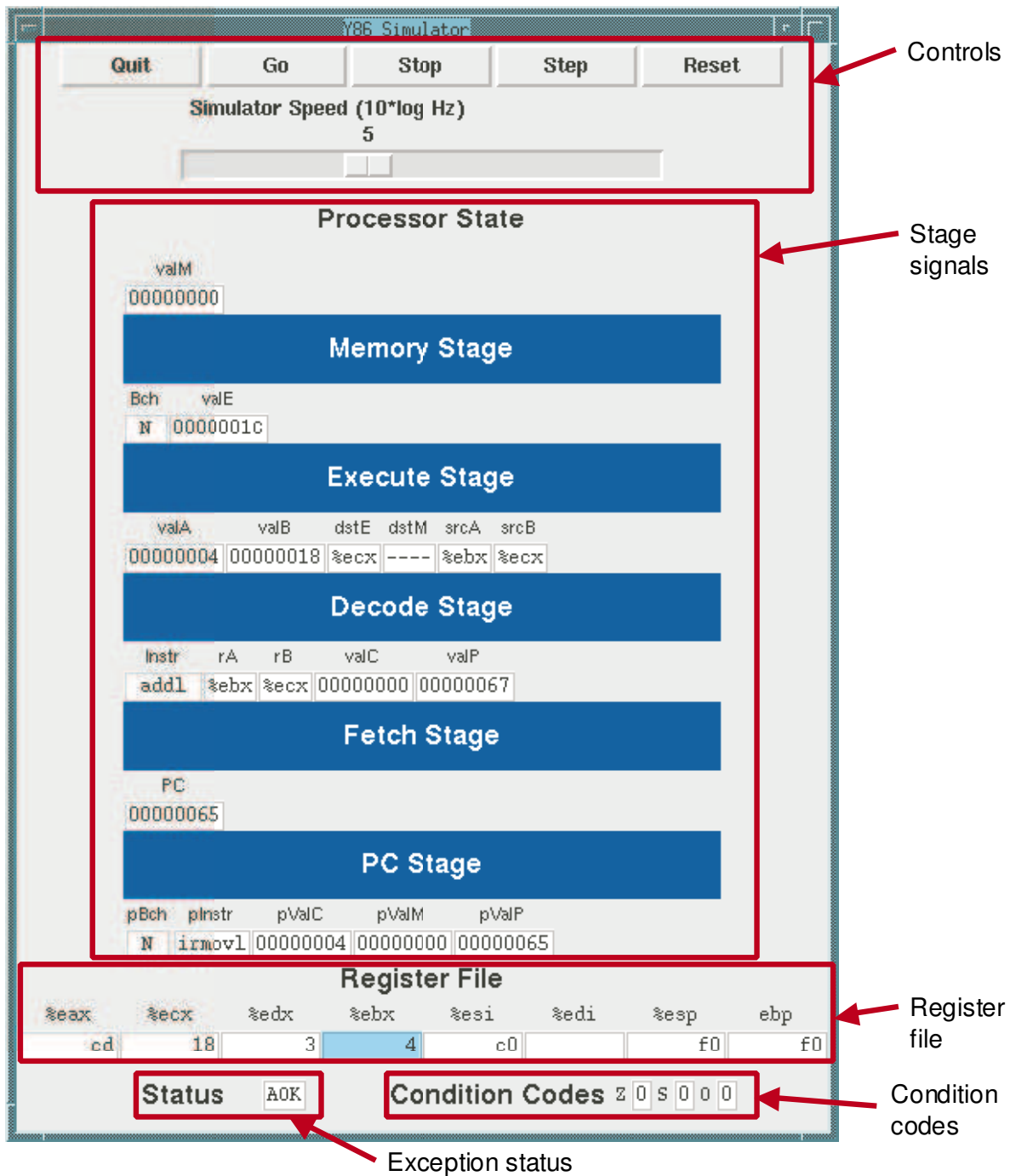


Figure 5: Main control panel for SEQ+ simulator

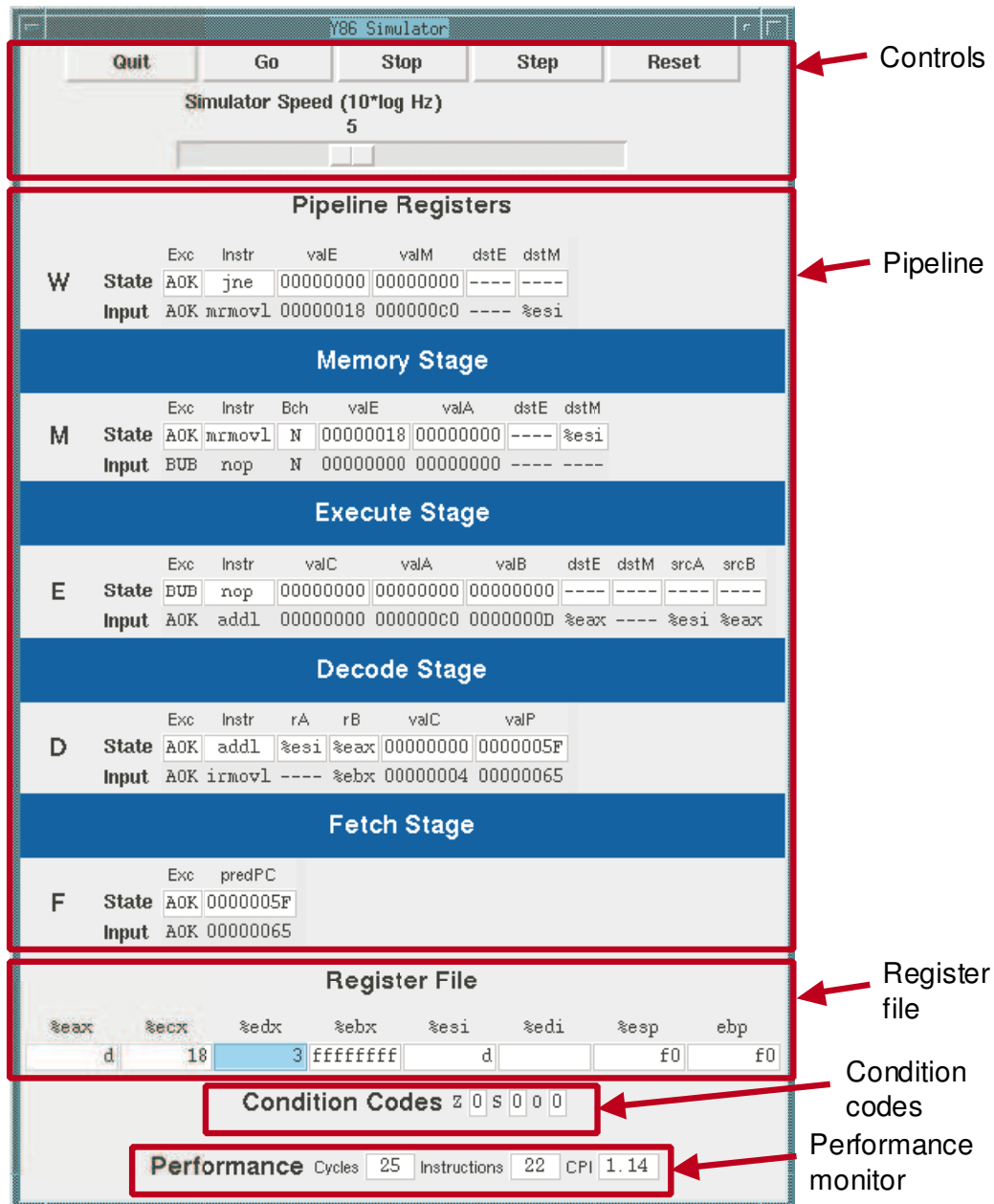


Figure 6: Main control panel for PIPE simulator

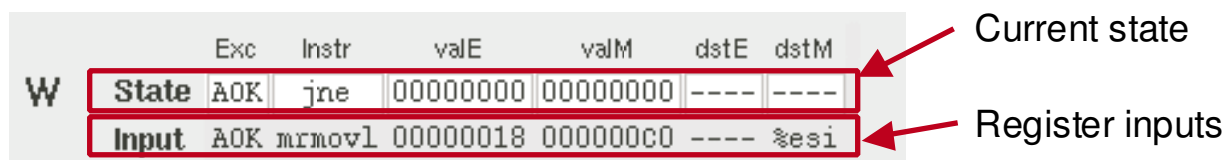


Figure 7: View of single pipe register in control panel for PIPE simulator

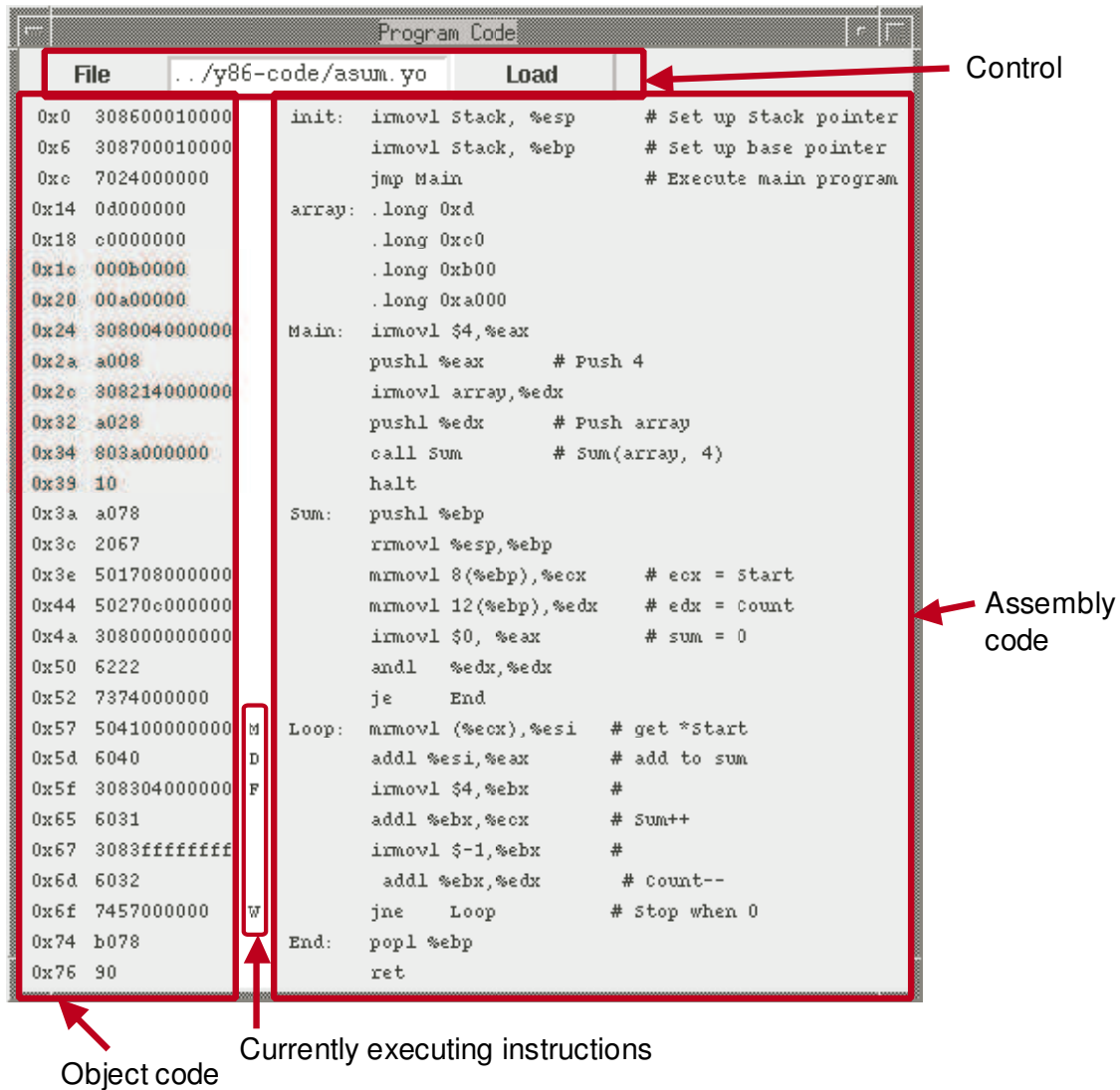


Figure 8: Code display window for PIPE simulator

The example shown in Figures 6 and 8 show the status of the pipeline when executing the loop in lines 29–35 of Figure 1. We can see that the simulator has begun the second iteration of the loop. The status of the stages is as follows:

Write back: The loop-closing `jne` instruction (line 35) is finishing.

Memory: The `mrmovl` instruction (line 29) has just read `0x0C0` from address `0x018`. We can see the address in `valE` of pipeline register `M`, and the value read from memory at the input of `valM` to pipeline register `W`.

Execute: This stage contains a bubble. The bubble was inserted due to the load-use dependency between the `mrmovl` instruction (line 29) and the `addl` instruction (line 30). It can be seen that this bubble acts like a `nop` instruction. This explains why there is no instruction in Figure 8 labeled with “E.”

Decode: The `addl` instruction (line 30) has just read `0x00D` from register `%eax`. It also read `0x00D` from register `%esi`, but we can see that the forwarding logic has instead used the value `0x0C0` that has just been read from memory (seen as the input to `valM` in pipeline register `W`) as the new value of `valA` (seen as the input to `valA` in pipeline register `E`).

Fetch: The `irmovl` instruction (line 31) has just been fetched from address `0x05f`. The new value of the PC is predicted to be `0x065`.

Associated with each stage is an *exception status* field `Exc`. This field shows the status of the instruction in that stage of the pipeline. Status “AOK” means that no exception has been encountered. Status “BUB” indicates that a bubble is in this stage, rather than a normal instruction. Other possible status values are “ADR” when an invalid memory location is referenced, “INS” when an illegal instruction code is encountered, “PIP” when a problem arose in the pipeline (this occurs when both the stall and the bubble signals for some pipeline register are set to 1), and “HLT” when a halt instruction is encountered. The simulator will stop when any of these last four cases reaches the write-back stage.

Carrying the exception status for an individual instruction through the pipeline along with the rest of the information about that instruction enables precise handling of the different exception conditions, as described in CS:APP Section 4.5.11.

4 Some Advice

The following are some miscellaneous tips, learned from experience we have gained in using these simulators.

- *Get familiar with the simulator operation.* Try running some of the example programs in the `y86-code` directory. Make sure you understand how each instruction gets processed for some small examples. Watch for interesting cases such as mispredicted branches, load interlocks, and procedure returns.
- *You need to hunt around for information.* Seeing the effect of data forwarding is especially tricky. There are seven possible sources for signal `valA` in pipeline register `E`, and six possible sources for

signal **valB**. To see which one was selected, you need to compare the input to these pipeline register fields to the values of the possible sources. The possible sources are:

R[d_srcA] The source register is identified by the input to **srcA** in pipeline register E. The register contents are shown at the bottom.

R[d_srcB] The source register is identified by the input to **srcB** in pipeline register E. The register contents are shown at the bottom.

D_valP This value is part of the state of pipeline register D.

e_valE This value is at the input to field **valE** in pipeline register M.

M_valE This value is part of the state of pipeline register M.

m_valM This value is at the input to field **valM** in pipeline register W.

W_valE This value is part of the state of pipeline register W.

W_valM This value is part of the state of pipeline register M.

- *Do not overwrite your code.* Since the data and code share the same address space, it is easy to have a program overwrite some of the code, causing complete chaos when it attempts to execute the overwritten instructions. It is important to set up the stack to be far enough away from the code to avoid this.
- *Avoid large address values.* The simulators do not allow any addresses greater than 0x0FFF. In addition, the memory display becomes unwieldy if you modify memory locations spanning a wide range of addresses.
- *Be aware of some “features” of the GUI-mode simulators (PSIM and SSIM).*
 - If you are running in GUI mode on a Unix box, remember to initialize the **DISPLAY** environment variable:

```
unix> setenv DISPLAY myhost.edu:0
```
 - With some Unix X Window managers, the “Program Code” window begins life as a closed icon. If you don’t see this window when the simulator starts, you’ll need to expand the window manually by clicking on it.
 - With some Microsoft Windows X servers, the “Memory Contents” window does not automatically resize itself when the memory contents change. In these cases, you’ll need to resize the window manually to see the memory contents.
 - The simulators will terminate with a segmentation fault if you ask them to execute a file that is not a valid Y86 object file.
 - When running in GUI mode, the simulators will single-step past a **halt** instruction.