

Hardware Project #4

Single-Cycle CPU

due at 5pm, Thu 9 Nov 2017

1 Purpose

In this project, you will implement a single-cycle CPU. One of the keys of this project is understanding how the control bits are used to direct the rest of the processor - so most of your code will be finding (and then using) the various control bits.

Unfortunately, in order to test that you are doing this correctly (without having the TAs spend hours looking at your code), I had to break the CPU down into a fairly large number of relatively small pieces. You will implement a number of functions - most will be fairly small - and my testcases will join all of the little pieces together into a larger system.

You'll be happy to learn that in this project, I have **removed the restrictions!** Now, if you want to add, multiply, or whatever, you are allowed to do it. We can allow this now because now you know what it takes - something as simple as the `+` operator in C actually represents a non-trivial component in hardware.

We'll be writing this project entirely in C.

1.1 “Extra” Instructions and Their Testcases

There are a certain set of instructions which all students must implement - basically, these are the set which can be easily implemented by the basic processor design that we've provided for you.

However, you will also be expected to **expand** on this design a bit. We have provided a set of “extra” instructions, which can also be implemented with (relatively) small changes to the processor. You must choose three of these instructions, and update your design to support them (details below).

When you download the testcases for your program, you should download the “ordinary” testcases (they are all numbered), and then download the “extra” testcases for the instructions that you have chosen. These them all using the grading script.

1.2 Required Filenames to Turn in

Name your C file `proj_hw04.c`.

Also, upload a README file (name it either `README` or `README.txt` - please, make it a plain text file). The first paragraph of this file should **simply list the “extra” instructions you have chosen to implement**¹. The rest of

¹If you didn't have time to implement this, then say so.

the README file should describe how you changed the processor to support them.

We'll use this README file to (manually) configure the grading script for you - so please, follow the instructions. I don't want to have to search through 100 different student directories for hard-to-read README files!

1.3 More Complex Testcases

Because the testcases have a lot of C code that they share, I now have some "common code" which is shared across all of them. This is contained in a header file `proj_hw04_test_commonCode.h` and the matching source file `proj_hw04_test_commonCode.c`. Each testcase will include the header, and link with the shared code.

While you are allowed to include the test-common-code header if you want, I don't think that you will need it. Feel free to poke around the code, however.

1.4 Random Numbers

Please note that testcase 07 uses C's `rand()` function to generate inputs. The `.out` file that I have provided works when running on Lectura, but it may or may not work on your machine. If you are failing testcase 07, try running it on Lectura instead.

2 "Ordinary" Instructions

Your CPU must support all of the following instructions:

- `add`, `addu`, `sub`, `subu`, `addi`, `addiu`
(Treat the 'u' instructions exactly the same as their more ordinary counterparts. Just use C addition and subtraction, using signed integers. Ignore overflow.)
- `and`, `or`
- `slt`, `slti`
- `lw`, `sw`
- `beq`, `j`

The testcases will handle the `syscall` instruction on your behalf - you don't have to write any code to make it work.

Your implementation for these instructions must match the book - and the slides we've been going over in lecture. You must use the same control wires, with the same meanings.² Your "extra" control wires (if any) must all be **zero** for these instructions.

²The only exception - as I've said in class, is that we don't use a separate "ALU Control" in our processor. Instead, you will set the ALU operation directly, in your control logic.

2.1 “Extra” Instructions

Choose three instructions from the following list, and implement them as well in your CPU:

- `andi, ori, nor`
- `lui`
- `sra, srl, sll`
- `bne`
- `lb, sb`

Your implementation for these instructions must match the MIPS architecture; you can look each of these up, in Appendix A, to find out exactly how they work. **You must use the opcode that MIPS requires, and do exactly what the MIPS architecture says these instructions do.**

However, none of these can be implemented with the standard CPU design that we’ve discussed. Each one needs some sort of small change. Some can be implemented by adding a new ALU operation, or by adding a new input to an existing MUX; others will require that you add a new MUX, or new logic somewhere in the processor.

2.2 New Control Bits

To support your extra features, you must set new control bits in the CPU design. One option is to simply add new values to a multi-bit field; for instance, you could add an ALU operation 4 (the standard processor only supports 0-3), which did something new. Likewise, you might add a new input to the `ALUsrc` MUX (which feeds into ALU input 2).

Alternatively, you might add entirely new control lines. For instance, you might add a new control wire which means “invert the Zero output from the ALU.” To support these, the `CPUControl` struct (see below) includes 3 different “extra” fields. **You get to decide what these mean - in theory you could have 96 new control wires!** Or, you may ignore them, if you don’t need them.

I have just one limitation: you must **not** simply copy the instruction, opcode, or funct fields into the `extra` fields. Instead, you must **decode** the opcode/funct, and **set control wires**. It’s just that you get to decide what the new control wires mean.³

2.3 “Don’t Cares”

In some instructions, there are control bits which don’t matter. For instance, in any instruction which sets `regWrite=0`, the control bits `regDst` and `memToReg` don’t matter, since they can’t possibly affect what happens this clock cycle.

³For the same reason, global variables are forbidden!

In real hardware, these are called “don’t cares,” and thus we can set these to **whatever** value - basically, we choose arbitrary values for them - whatever makes the hardware implementation cheaper.

But in our code, we will be dumping these values in the testcase, and comparing them against a standard output - so we need a standard value for each one. So our rule is: **if you don’t care about a control wire, always set it to zero.**

2.4 Invalid Instructions

In real hardware, if your code includes an instruction with a bad opcode, the program will crash. That is, the CPU has special circuits which force an “exception” if an invalid opcode is found; this forces the software into the Operating System - and normally results in the OS killing your program.

To simplify things, you won’t implement any of this, with one exception: if the opcode is invalid (or if the opcode indicates “R-format” but the funct field is invalid), then you will set an **err** field in the control bits. See the header file for a detailed description - but make sure that, in this case, you don’t set additional fields (after **err**) to nonzero values.

2.5 Not-Required Instructions

Some students like to implement some additional instructions that I don’t require. This is fine, but they **must be standard MIPS instructions**, using the normal opcodes. For instance, you could implement `jal` - but if so, it **must** use opcode `0x3`.

Our testcases will check to see if your Control component sets the **err** field as required. But since we don’t know which students may have supported additional (normal) MIPS instructions, we will **only test opcodes that are not valid in standard MIPS**.

Remember, only instructions from the **approved list above** count towards your grade. (Sorry, but those are the only ones for which we have testcases.)

3 Typedefs, Structures, and Utility Functions

I have provided `proj_hw04.h`, which defines several types for you and the prototypes for each of the functions which you must implement.

You must not change this header. If you do, your code won’t compile when I test it.

3.1 WORD

`WORD` is a typedef that will be 32 bits in size. I use it for parameters and return values which need to be exactly 32 bits, and I encourage you to use it for your

variables (when they are 32 bits as well). Bit fields (from single bits, all the way up to huge ones) are represented by simple `int` variables.

So yes, there are some `ints` in the data structures that represent a single bit (such as `bNegate`). There are others (such as `funct`) that represent 5 or 6 bits, and some (such as `imm16`) that even represent 16 bits!

3.2 `WORD signExtend16to32(int)`

This utility function is already provided by me; you don't have to write it. It takes a 16-bit input, sign extends it to a full word, and then returns the value.

3.3 `struct InstructionFields`

This struct is initialized by the `extract_instructionFields()` function, which you will write.

This struct represents all of the fields in the instruction. When you fill this struct, set **all** of the fields, with **no intelligence at all**. So, for instance, you should always set the `address` field - even if this is not a J instruction; the `address` field just represents the 26 wires, which can be then connected to other places.

3.4 `struct CPUControl`

This struct is initialized by the `fill_CPUControl()` function, which you will write. (This function will make up most of your code for this project.)

This struct represents all of the control bits. Your code will read the function fields (out of an `InstructionFields` struct), decode the opcode and funct fields, and set all of the control bits that are required.

We will describe `fill_CPUControl()` in detail later in this spec. For now, remember two rules:

- You must fill in **all** of the fields in this struct, in `fill_CPUControl()`.
- You must never modify any of these fields later in your program.

3.5 `struct ALUResult`

This tiny struct has two fields: `result` (32 bits, stored in a `WORD` variable) and `zero` (1 bit, although we store it in an `int`). It simply represents the output from the ALU; you will fill in both fields in `execute_ALU()`.

Always set the `zero` output (to either 0 or 1), no matter what ALU operation you perform.

3.6 struct MemResult

This tiny struct only has a single field - `readVal`. But I placed it inside a struct so that `execute_MEM()` will work roughly like `execute_ALU()`.⁴

4 The Fields of CPUControl

The `CPUControl` struct has many fields. You need to set all of them in `fill_CPUControl()`.

4.1 The Real Control Bits

`CPUControl` has fields for every one of the control bits that we’ve discussed in class and in the book - except for the `ALUop` that goes from the main Control using to the ALU Control. (In this struct, we’ll simply set the proper ALU operation directly, in the field named `ALU.op`.)

See above for the discussion of “ordinary” and “extra” instructions (those that can be implemented by the processor design shown in the book, and those that need additional control bits). For the “ordinary” instructions, you must implement the control bits **exactly as described in the book and slides**. For the “extra” instructions, you must either define new control bits (which are zero for the “ordinary” instructions, but which you turn on for certain “extra” instructions), or define new values (such as adding new ALU operations, or adding more inputs to a MUX).

As noted above, there are some situations where a bit may be a “don’t care” - meaning it can have no effect on the operation of the CPU for this clock cycle (because other bits make it pointless). Always set “don’t cares” to zero.

4.2 Extra Words

Finally, `CPUControl` has three extra WORDs provided for you. These fields must all be zero for all “ordinary” instructions. However, if you want, you can use these to store up to 96 additional control bits, to make the “extra” instructions work.

It is not required that you use these fields. Some designs may support the “extra” fields simply by adding new legal values to existing fields (such as the ALU operation). But I’ve provided these for you **just in case you find them handy**.

5 The Functions

You must implement all of the following functions. **I strongly recommend that you implement these one at a time, and test them individually.** The first several testcases are designed to test these one at a time - sometimes

⁴Maybe I’m being silly. But I like symmetry!

in isolation, and sometimes in concert with other pieces. After the intro test-cases, we will then test complete instructions, all as one pack - and then small programs.

As you are writing your solution, start by “stubbing out” all of the required functions. That is, cut-n-paste the declarations from `proj_hw04.h` into your file, and give them (empty) bodies. That way, the code will compile - and you can start testing - long before the rest of your code is written.

5.1 `WORD getInstruction(WORD curPC, WORD *instructionMemory)`

You must read the proper word out of instruction memory, given the current Program Counter. Return the value. Remember that the Program Counter gives the address of the current instruction in **bytes** but that this is an **array of words**.

5.2 `void extract_InstructionFields(WORD, InstructionFields *fieldsOut)`

This function is passed an instruction as input; it must read all of the fields out of the instruction, and store them into the fields in the `InstructionFields` struct.

No other function in your code may modify any field in this struct!

5.3 `int fill_CPUControl(InstructionFields*, CPUControl*)`

The first parameter is an **in** parameter: it is the `InstructionFields` struct that you fill. The second is a `CPUControl*` struct. Read the opcode and funct from the Fields struct, and then set all of the correct controls in the Control struct.

This function returns 1 if the instruction is recognized, and 0 if the opcode or funct is invalid.

No other function in your code may modify any field in this struct!

5.4 `WORD getALUinput*(...)`

There are two of these functions, one for each of the ALU inputs. These functions have several input parameters:

- The `CPUControl` for this instruction
- The `InstructionFields` for this instruction
- The value of the two registers read from the register file (based on the `rs,rt` fields you set in `InstructionFields`)

Note that you might not need all of these inputs for your implementation - but we’ve designed this project with flexibility. If (for instance) you wanted to

add a MUX in front of ALU input 1 (like we already have one in front of ALU input 2), you should be able to do that with the parameters we've provided.

5.5 void execute_ALU(CPUControl*, WORD,WORD, ALUResult*)

This function implements the ALU. Remember, we've **removed the limitations** - so I fully expect you to use the C addition and subtraction operators (or anything else that might be handy). However, you must choose **what** you do only by reading the various control fields in the `CPUControl` struct. (You will notice that you don't have access to the instruction itself in this function!)

The second and third parameters are the ALU inputs 1 and 2 (see the functions above).

The fourth parameter is an **out** parameter: set **all** of its fields, every time that this function is called!

5.6 void execute_MEM(CPUControl*,ALUResult*, WORD,WORD, WORD*, MEMResult*)

This function implements the data memory unit. The first parameter is the CPU control; check for the memory control bits inside it to see what you need to do (if anything). Most of the time, you will do nothing - but even in that case, you must set the output bits (to zero).

The second parameter is the `ALUResult` struct, which you set in a previous call to `execute_ALU()`. You must not change anything inside this struct, but you can read the fields.

The third and fourth parameters are the two registers that were read for this instruction - based on the `rs,rt` values you set in the `InstructionFields` struct.

The fifth parameter is an array of `WORDS`, representing the data memory. (Remember: all memory addresses are given in bytes, but the array is an array of words.)

The final parameter is an **out** parameter: it is the "Read data" field, coming out of the memory unit. If you read a value from memory, then this field must have that value. If not (if you write, or if you do nothing), then you must **set this to zero**.

5.7 WORD getNextPC(...)

This function implements the logic which decides what the next PC will be. The first parameter is the `InstructionFields` for this instruction, and the second is the `CPUControl`. The third is the `aluZero` output from the ALU. The next two are the two registers read for this instruction; the fifth is the previous PC.

Return the new PC.

5.8 void execute_updateRegs(...)

This represents the final stage of the processor: writing to a register (if required). The first parameter is the fields of the instruction, followed by the control bits; the third and fourth are the results from the ALU and Memory, respectively.

The last parameter is a pointer to the current set of registers, which you may have to write to.

6 Data and Instruction Memory Sizes; Number of Registers

I will ensure (in my testcases) that any address we use (any PC or data address) will be small enough to fit into the memory that I provide you. So you don't have to check for any address is that is "too large." (I will also not ever use unaligned memory addresses.)

When I pass you registers (`getALUInput*`), `execute_updateRegs()`, I will always pass you an array of 34 registers. This is to represent the 32 ordinary registers, plus the `lo`, `hi` registers which are used for multiplication and division. You are **not** expected to implement multiplication and division, but I wanted to make it possible for the students who were interested.

6.1 Register Zero

I'm not sure, in the official MIPS specification, what happens when you try to write to register `$zero`. (I'm sure that it doesn't actually change anything - but I don't know if there are any errors or other side-effects that are required.)

So, in our testcases, **we will never try to write to it** - meaning that you don't need to write any special code to handle it. Moreover, you may assume, any time I pass you the array of registers, that element `[0]` of the array contains 0.

7 A Note About Grading

Your code will be tested automatically. Therefore, your code must:

- Use exactly the filenames that we specify (remember that names are case sensitive).
- **Not** use any other files (unless allowed by the project spec) - since our grading script won't know to use them.
- Follow the spec precisely (don't change any names, or edit the files I give you, unless the spec says to do so).
- (In projects that require output) match the required output **exactly!** Any extra spaces, blank lines misspelled words, etc. will cause the testcase to fail.

To make it easy to check, I have provided the grading script. I **strongly recommend** that you download the grading script and all of the testcases, and use them to test your code from the beginning. You want to detect any problems early on!

7.1 Testcases

You can find the project files for this project (including any testcases I've provided) at:

`http://lecturer-russ.appspot.com/classes/cs252/fall17/projects/proj_hw04/`

You can also find them on Lectura at

`/home/russell11/cs252.website/projects/proj_hw04/`

For assembly language programs, the testcases will be named `test*.s`. For C programs, the testcases will be named `test*.c`. For Java programs, the testcases will be named `Test*.java`. (You will only have testcases for the languages that you have to actually write for each project, of course.)

Each testcase has a matching output file, which ends in `.out`; our grading script needs to have both files available in order to test your code.

For many projects, we will have “secret testcases,” which are additional testcases that we do not publish until after the solutions have been posted. These may cover corner cases not covered by the basic testcase, or may simply provide additional testing. **You are encouraged to write testcases of your own, in order to better test your code.**

7.2 Automatic Testing

We have provided a testing script (in the same directory), named `grade_proj_hw04`. Place this script, all of the testcase files (including their `.out` files if assembly language), and your program files in the same directory. (I recommend that you do this on Lectura, or a similar department machine. It **might** also work on your Mac, but no promises!)

7.3 Writing Your Own Testcases

The grading script will grade your code based on the testcases it finds in the current directory. Start with the testcases I provide - however, I encourage you to write your own as well. If you write your own, simply name your testcases using the same pattern as mine, and the grading script will pick them up.

While you normally cannot share code with friends and classmates, **testcases are the exception**. We encourage you to share your testcases - ideally by posting them on Piazza. Sometimes, I may even pick your testcase up to be part of the official set, when I do the grading!

8 Turning in Your Solution

You must turn in your code using D2L, using the Assignment folder for this project. Turn in only your program; do not turn in any testcases or other files.