MP 3: A Pipelined Implementation of the LC-3b Processor

Version 2.0.2

1 Overview

This machine problem involves the design of a pipelined microprocessor. You are required to implement the LC-3b instruction set in its entirety (with the exception of RTI) using the pipelining techniques described in class. This handout is an incomplete specification to get you started with your design; a portion of this machine problem is left open ended for you to explore design options that interest you.

You will begin your design by creating a basic pipeline that can execute several basic LC-3b instructions. Then, as the project progresses, you will add support for the rest of the LC-3b ISA, a cache hierarchy consisting of split L1 caches and a unified L2 cache, hazard detection, and data forwarding. Toward the end of the project, you will have the opportunity to expand your design with advanced design options of your choosing. For groups which correctly implement an MP 3 design, a competition will be held to find which design can execute our benchmark program in the least amount of simulated time.

2 Getting started

2.1 Working as a group

For this assignment, you must work in a group of three people. It will be your responsibility to work on the assignment as a team. Every member should be knowledgeable about all aspects of your design, so don’t silo responsibilities and expect everything to work when you put the parts together. Good teams will communicate often and discuss issues (either with the design or with team members) that arise in a timely manner.

To aid collaboration, we provide a private GitLab repository for class that you can use to share code within your team and with your TA. We will add you to our class account on GitLab, within which you will be able to create a repository to share with your group.

2.2 Mentor TAs

Given that every group’s design will be different in MP 3, it is often difficult for a TA unfamiliar with your group to answer all of your questions. In order to make sure that each group has someone who is knowledgeable about their design, each group will be assigned a mentor TA. You will have regular meetings with your mentor TA so that they know how your project is doing and any major hurdles you have encountered along the way. You should meet with your mentor TA at least once every checkpoint. Scheduling these meetings is your responsibility. In the past some teams have (foolishly) blown these meetings off, and we’ve received course feedback asking that they be made mandatory.

Your first meeting with your mentor TA will be not only to review your paper design for your basic pipeline, but also to discuss your goals for the project. Before meeting with your mentor TA you should have discussed in detail with your team about what design options you plan to explore. Your mentor TA may advise against certain

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1 The only exception to form a group of two or an individual person is when the class is not a multiple of three.

2 https://gitlab-beta.engr.illinois.edu
options, but you are free to work on whatever you like. As the project progresses, you may find that your goals and your design change. This is normal and you are free to take the project in a direction that interests you. However, you must keep your mentor TA up to date about any changes you have made or plan to make.

In order to get the most out of your relationship with your mentor TA, you should approach the relationship as if your group has been hired into a company and given the MP 3 design as a job assignment. A senior engineer has been assigned to help you stay on schedule and not get overwhelmed by tool problems or design problems. Do not think of the TA as an obstacle or hostile party. Do not try to “protect” your design from the TA by not allowing him or her to see defects or problem areas. Do not miss appointments or engage in any other unprofessional conduct. Do not hand in submissions past the deadline unless you have discussed extenuating circumstances with your TA. Your mentor TA should be a consulting member of your team, not an external bureaucrat.

2.3 Testing

Throughout the MP, you will need to generate your own test code. This is extremely important as untested components may lead to failing the final test code and competition benchmark altogether. Remember that in many of your components, such as the register bypassing unit, the order of the instructions as well as what operands are used is crucial. You cannot just test that your processor executes each of the instructions correctly in isolation. You should try to generate test code to test as many corner cases as you can think of.

3 The pipeline

3.1 Pipeline control

In this pipelined design, you will be using a simple control memory to generate control signals. No state diagrams will be allowed for pipeline control (state diagrams are still allowed for cache controllers). The control memory behaves similar to a ROM (read only memory). When an instruction is ready to be decoded, the opcode, (and possibly some other fields of the instruction word) are sent to a logic block, which then outputs a control word containing the signals necessary to control all the pipeline stages of the particular instruction. This control word (which is not necessarily 16 bits long) is then passed down the pipeline along with the other operands needed for the instruction. To assist in debugging, please pass the entire control word as well as the instruction's opcode down the pipeline. This allows the logic in each stage to be set correctly for that specific instruction.

One way to implement the control memory discussed above is using a SystemVerilog case statement. You can implement the control word as a struct containing the signals that you need. The following code blocks contain examples for the control word struct and control ROM.

Listing 1: Example control word definition (place in lc3b_types.sv)

```verilog
typedef struct packed {  
    lc3b_opcode opcode;  
    lc3b_aluop aluop;  
    logic load_cc;  
    logic load_regfile;  
    /* ... other signals ... */
} lc3b_control_word;
```

Listing 2: Example control memory module

```verilog
import lc3b_types::*;

module control_rom  
(  
    input lc3b_opcode opcode,  
    output lc3b_control_word ctrl  
);
```
always_comb
begin
    /* Default assignments */
    ctrl.opcode = opcode;
    ctrl.load_cc = 1'b0;
    /* ... other defaults ... */

    /* Assign control signals based on opcode */
    case(opcode)
        op_add: begin
            ctrl.aluop = alu_add;
            end
        
        op_and: begin
            ctrl.aluop = alu_and;
            end

        /* ... other opcodes ... */
        default: begin
            ctrl = 0; /* Unknown opcode, set control word to zero */
            end
    endcase
end
endmodule : control_rom

You should only use the opcode concatenated with at most three other bits of the instruction as the inputs to this ROM (you should use only 4-7 bits to generate the control word). Also, you must not do any sort of computation in this ROM. The ROM is meant exclusively for generating simple control signals such as mux selects, etc. Do not use the control ROM to perform computations (such as addition, branch condition comparisons, etc).

### 3.2 Pipeline datapath

Regardless of your design, you will have to do things in a considerably different manner compared to your previous MP datapath designs. When you start entering your design into the software tools, start from scratch. Do not try to copy over your old MP 2 datapath design and then edit it.

Between each pipeline stage, you will need a set of registers to hold the values from the previous stage. Unlike the design shown in the textbook, you do not need to implement those registers as one colossal box. You are permitted to break the pipeline registers up into many smaller registers each containing one value (e.g., the ALU output, or a control word). Pick a style that fits your group.

### 3.3 Things to think about

A couple features of the LC-3b ISA present challenges for pipelining. The indirect memory instructions (LDI, STI) require two memory accesses and therefore require special attention in the pipeline. Also, conditional branches require special care to be resolved correctly. Your group should discuss these issues while working on your paper design.

### 4 Project milestones

MP 3 is divided into several submissions to help you manage your progress. The dates for submissions are provided in the class schedule. Late work will not be accepted for MP 3 unless you have discussed extenuating circumstances with your mentor TA before the deadline.
Figure 1: Overview of pipeline datapath and cache hierarchy. Note the location of pipeline stages, stage registers, and arbiter. Your paper designs should be much more detailed than this.
4.1 Basic pipeline paper design

The first submission for this project will be a paper design of your pipelined datapath. The design should be detailed enough for the TAs to trace the execution of all the LC-3b instructions through your datapath. The paper design should map out the entire pipeline, including components in all the stages (e.g., registers, muxes, ALU, register file), stage registers, and control signals. In other words, with the paper design in hand, you should be able to easily translate your design into code.

We will not require your design to handle data forwarding at this point, but you may still want to design for it to avoid having to change your design down the road. If completed, designs for advanced features such as branch prediction can also be included.

A good way to start the pipeline design is to first determine the number of stages and the function of each stage. Then, go through the LC-3b ISA, e.g., ADD, LDR, STR, BR, etc, to see what components need to be added to each stage for a given instruction. Use the book and lecture notes as references.

4.2 Checkpoints

There will be three checkpoints to keep you on track for this MP. For each checkpoint, you will be required to have implemented a certain amount of the functionality for your pipelined LC-3b design. In addition, at each checkpoint, you should meet, as a team, with your mentor TA and provide him or her with the following information in writing:

- A brief report detailing progress made since the previous checkpoint. This should include what functionality you implemented and tested as well as how each member of the group contributed.
- A roadmap for what you will be implementing for the following checkpoint. The roadmap should include a breakdown of who will be responsible for what and paper designs for all design options that you are planning to implement for the next checkpoint.

Besides helping the TAs check your progress on the MP, the checkpoints are an opportunity for you to get answers to any questions that may have come up during the design process. You should use this time to get clarifications or advice from your mentor TA.

Note that the checkpoint requirements outline the minimum amount of work that should have been completed since the start of the project. You should work ahead where possible to have more time to complete advanced design options.

4.2.1 Checkpoint 1: Basic instructions

By checkpoint 1, you should have a basic pipeline that can handle ADD, AND, NOT, LDR, STR, and BR instructions. You do not need to handle any control hazards or data hazards. The test code will contain NOPs to allow the processor to work without hazard detection. For this checkpoint you can use a “magic” memory that always sets mem_resp high immediately so that you don't have to handle cache misses or memory stalls.

Also, you should provide your mentor TA with an overview of your cache hierarchy (showing how your L1 caches, arbiter, and L2 cache interface with each other) as well as detailed designs for your arbiter and L2 cache.

4.2.2 Checkpoint 2: Complete LC-3b ISA and cache arbiter

By checkpoint 2, your pipeline should be able to handle all of the LC-3b instructions. You should also have your cache arbiter implemented and integrated such that the datapath connects to your split L1 caches, which connect to the arbiter, which connects to physical memory (or the L2 cache if that is completed). You must implement multi-cycle L2 accesses at this time. This can be done by adding something like the MAR and MDR registers from your MP0 CPU to your cache datapath, or by adding some registers and control logic to the arbiter. On an L1 miss, the read should not be seen by L2 until the next cycle. This should mean that your critical path does not span all the way from your memory pipeline stage to the L2 cache. At this point, if you have not done so already, you should provide your mentor TA with paper designs for data forwarding.

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4.2.3 Checkpoint 3: Data forwarding and L2 cache

By checkpoint 3, your pipeline should be able to do hazard detection and forwarding. Furthermore, your L2 cache should be completed and integrated into your cache hierarchy.

4.2.4 Checkpoint 4: Advanced design part 1

4.3 Final submission

For the final demo, your design should have all proposed features working correctly. You should be able to demonstrate with your own test code any advanced features that you expect to get design points for. You should also know how each feature impacts the performance of your pipeline.

4.4 Presentation and report

At the conclusion of the project, you will give a short presentation to the course staff (and fellow students) about your design. In addition, you will need to collect your checkpoint progress reports and paper designs together as a final report that documents your accomplishments. More information about both the presentation and report will be released at a later date.

5 Grading

MP 3 will be graded out of 140 points. Out of the 140 points, 60 points are allocated for regularly meeting with your TA, for submitting paper designs of various parts of your design, for a final presentation given to the course staff, and for documenting your design within a final report.

A breakdown of points for MP 3 is given in Table 1. Points are organized into two categories across five submissions. Note that the number of points you can attain depends on what advanced design options you wish to pursue.

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Table 1: MP 3 points breakdown. Points for each item are enclosed in brackets.
5.1 Advanced design options

Of the 80 implementation points, 45 will come from the implementation of the basic pipeline and required advanced features. The other 25 points will be given for the implementation of advanced design options. For each advanced design option, points will be awarded based on the three criteria below:

- Design and implementation: Your group has a clear understanding of what is to be built and how to go about building it, and is able to produce a working implementation.
- Testing strategy: The design is thoroughly tested with test code and/or test benches that you have written. Corner cases are considered and accounted for and you can prove that your design works as expected.
- Performance analysis: A summary of how the advanced design impacts the performance of your pipelined processor. Does it improve or degrade performance? How is the performance impact vary across different workloads? Why does the design improve or degrade performance?

A list of advanced design options along with their point values are provided in Section 6.2.

5.2 Group evaluations

At the end of the project, each group member will submit feedback on how well the group worked together and how each member contributed to the project. The evaluation, along with feedback provided at TA meetings throughout the semester, will be used to judge individual contribution to the project. Up to 30 points may be deducted from a group member’s score if it is evident that he or she did not contribute to the project.

Although the group evaluation occurs at the end of the project, this should not be the first time your mentor TA hears about problems that might be occurring. If there are major problems with collaboration, the problems should be reflected in your TA meetings and progress reports. The responses on the group evaluation should not come as a surprise to anyone.

6 Design guidelines

6.1 Basic design

Every group must complete the basic pipelined LC-3b design which consists of the following:

- **Datapath**
  - 5-stage pipeline which implements the full LC-3b ISA (except RTI) [10]
  - Hazard detection and data forwarding (EX→EX, MEM→EX, MEM→MEM, transparent register file, memory stalling) [5]

- **Cache**
  - Split L1 caches [2]
  - L1 cache request arbiter [3]
  - Unified L2 cache [5]

6.2 Advanced design options

- Detail about advanced design options will be released after checkpoint 3.
7 FAQs

• Can we use state machines for our MP 3 design?
  Only in the cache hierarchy, nowhere else. A non-pipelined cache may use a state machine as its controller.

• Can we change the bandwidth of physical memory?
  By default, physical memory has a bandwidth of 128-bits (per direction) and a delay of 200 ns. You may widen this to 256-bits (per direction), but you must set the delay to be 250 ns.

• What does “no artificial stalls” mean?
  Note: This question is only relevant if you are pursuing the memory stage leapfrogging design option.
  A better phrasing would probably be “no unnecessary stalls.” It means that non-dependent, non-memory instructions which follow a memory operation must not be stalled by the memory operation. This is true even if the memory instruction encounters a cache miss. (Note: For the purposes of this requirement, WAW (write after write) dependencies are considered valid dependencies.) Some examples might help clarify.

Example 1:

```
| LDI R1, R0, 5   ; A
| ADD R4, R4, R3  ; B
```

In this example, instruction B is not dependent on instruction A. It should not be stalled by the fact that instruction A will be in the MEM stage for at least 2 cycles. Instruction B should “go around” the MEM stage and proceed down the pipeline.

Example 2:

```
| LDI R1, R0, 5   ; A
| ADD R3, R1, R5  ; B
```

Here instruction B must stall because it is dependent on instruction A.

Example 3:

```
| LDI R1, R0, 5   ; A
| LDR R4, R2, label ; B
```

Instruction B must stall because it is a memory instruction.

Example 4:

```
| LDB R1, R0, 7   ; A
| ADD R4, R4, R5  ; B
| AND R3, R1, R6  ; C
| LSHF R2, R2, 2  ; D
```

Instruction B should not stall (independent). Instruction C must stall. Instruction D is independent, but may stall because the instruction before it is stalling. This illustrates that you can stop letting instructions “go around” the MEM stage once you encounter a dependent instruction.

Example 5:

```
| LDI R1, R0, 10  ; A
| BRz label       ; B
```

Instruction B is dependent on instruction A. (It needs the condition codes that will be set by A.) Instruction B must stall.

Example 6:
Assume A misses in the cache. Instruction B is independent of A, and should continue on to writeback. C depends only on the condition codes set by B, and should also continue on to writeback.

8 Advice from past students

- On starting early:
  - “Start early. Have everything that you have implemented also in a diagram, updating while you go.”
  - “START EARLY. take the design submission for next checkpoint during TA meetings seriously. it will save you a lot of time. Front-load your advanced design work or sufferrrrr”
  - “start early and ask your TA for help.”
  - “Finish 3 days before it’s due. You will need those 3 days (at least) to debug, which should involve the creation and execution of your own tests!”
  - “Make the work you do in the early checkpoints bulletproof and it will make your life WAY easier in the later stages of MP3.”
  - Don’t let a passed checkpoint stop you from working ahead. The checkpoints aren’t exactly a perfect balance of work. There’s always more you can add for extra credit.
  - (In an end-of-semester survey, most students responded that they spent 10-20 hours per week working on ECE 411 assignments.)

- Implementation tips:
  - “Don't trust the TA provided hazard test code, just because it works doesn't mean your code can handle all data and control hazards.”
  - “Also, it was very good to test the cache interface with the MP 2 cache, and test the bigger cache you do (L2 cache, more ways, 8-way pseudo LRU) on the MP 2 datapath. This just makes it easier to stay out of each other's hair.”
  - “Run timing analyses along the way so you're not trying to meet the 100 MHz requirement on the last night.”
  - “Write your own test code for every case. Check for regressions.”
  - “Don't pass the control bits down the pipeline separately, pass the entire control word down the pipeline. Also, pass the opcode and PC down. These are essential when debugging.”
  - “Check your sensitivity lists!!”

- Possible difficulties:
  - “Implement forwarding from the start, half of our bugs were in this. Take the paper design seriously, we eliminated a lot of bugs before we started. Use the test-o-matic.”
  - “Integration is by far the most difficult part of this MP. Just because components work on their own does not mean they will work together.”
  - “The hard part about mp3 is 1) integrating components of your design together and 2) edge cases. Really try to think of all edge cases/bugs before you starting coding. Also, be patient when debugging.”

- On teamwork:
  - “Try to split up the work into areas you like – cache vs datapath, etc. You will be in the lab a lot, so you might as well be doing a part of the project you enjoy more than other parts”
“Don’t get overwhelmed, it is a lot of work but not as much as it seems actually. As long as you start at least a paper design ASAP, you should finish each checkpoint with no problems.”

“Come up with a naming convention and stick to it. Don’t just name signals opcode1, opcode2, etc. For example, prepend every signal for a specific stage with a tag to specify where that signal originates from (EX_Opcode, MEM_Opcode).”

“Label all your components and signals as specific as possible, your team will thank you and you will thank yourself when you move into the debugging stages!”

“If you know how to use any version control, use it. If you don’t, it’s probably a good thing to learn it anyway. We used git and it was super useful.”

“Learn how to use Github well! It is very difficult to get through MP3 without this knowledge.”

“If you put in the work, you’ll get results. All the tools you need for debugging are at your disposal, nothing is impossible to figure out.”