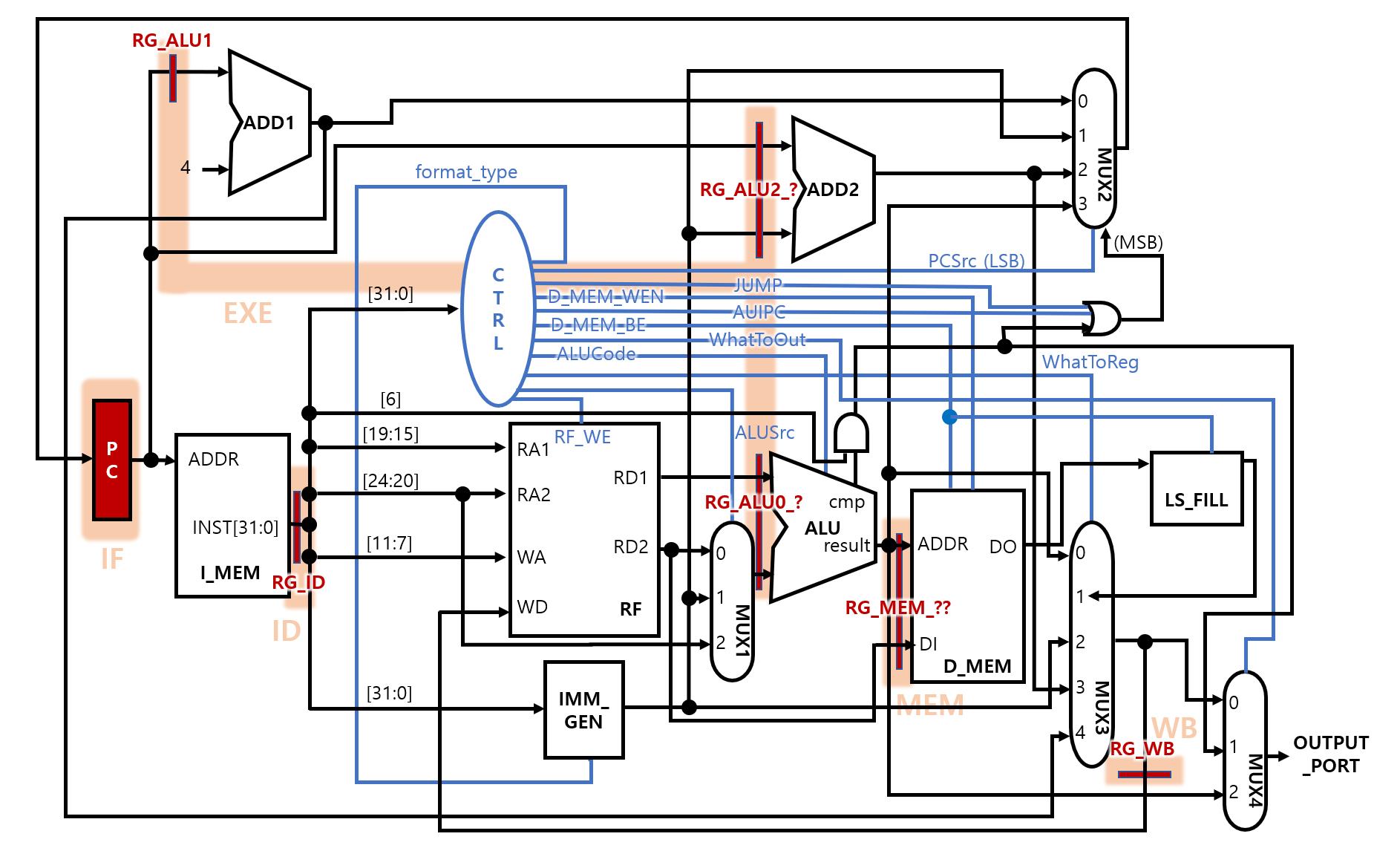
**EE312 Lab Report – Lab 4. Multi Cycle CPU**

**20160030 고은석, 20160680 추헌호**

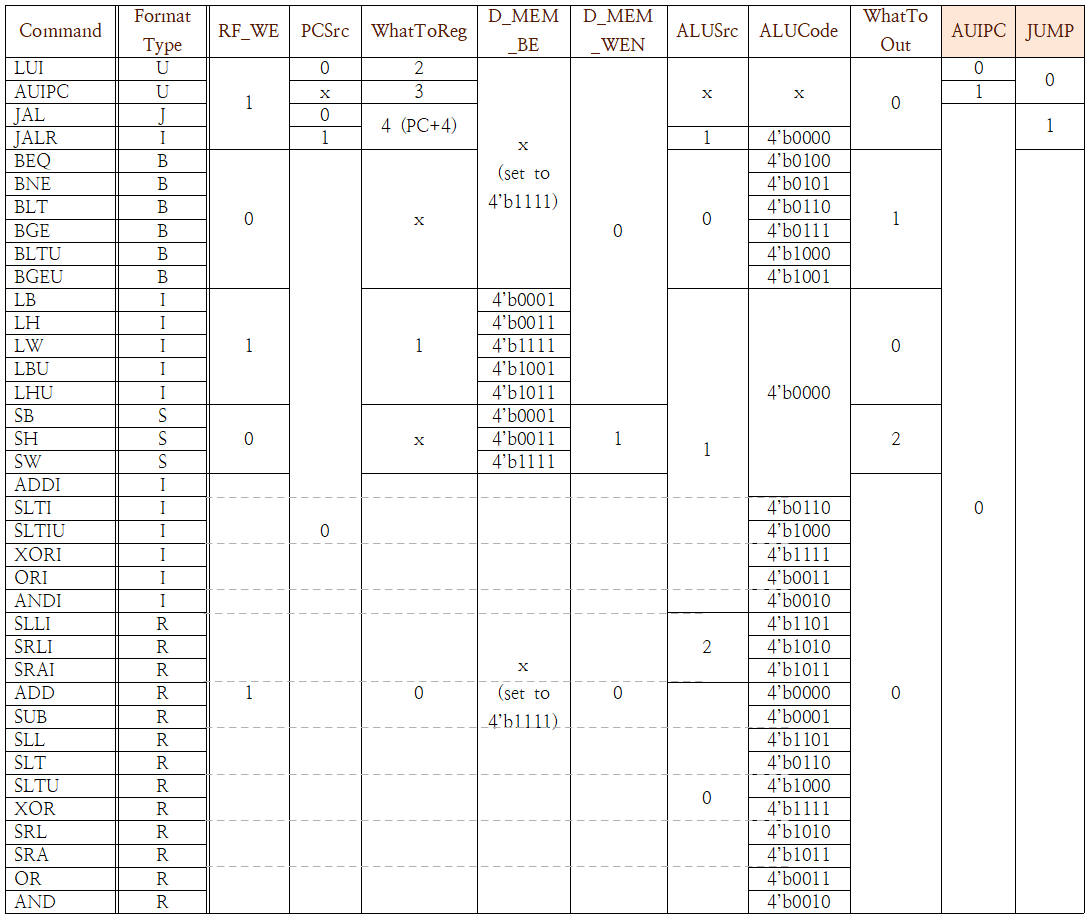
**1. Introduction**

본 과제에서는 Verilog HDL을 통해 RV32I 기반의 Multi Cycle CPU를 구현한다. Single Cycle CPU는 가장 오래 걸리는 instruction에 맞춰 CLK 주기를 설정해야 하기 때문에, 그보다 짧은 instruction을 실행할 때는 버려지는 시간이 발생한다. 따라서 CPU의 처리 속도를 높이기 위해, 전체 실행을 5개의 stage(IF, ID, EXE, MEM, WB)로 나눈 후 CLK 주기마다 하나의 stage를 처리하는 방식을 사용하면 CPU의 처리 속도를 가속할 수 있다. 이 방식을 사용하는 CPU를 Multi Cycle CPU라고 한다.

**2. Design**

Multi Cycle CPU의 기본적인 구조는 Figure 1과 같다. 기본적으로 Single Cycle CPU의 구조를 그대로 차용하였으며, 다만 각 stage별로 register를 추가해 CLK에 따라 적절한 register가 update 되도록 설계하였다. Figure 1에서 새로 추가된 register는 붉은색으로 표시되어 있으며, 편의를 위해 각 register가 어떤 stage에 속하는지 연한 붉은색으로 표시되어 있다. ㅇ 

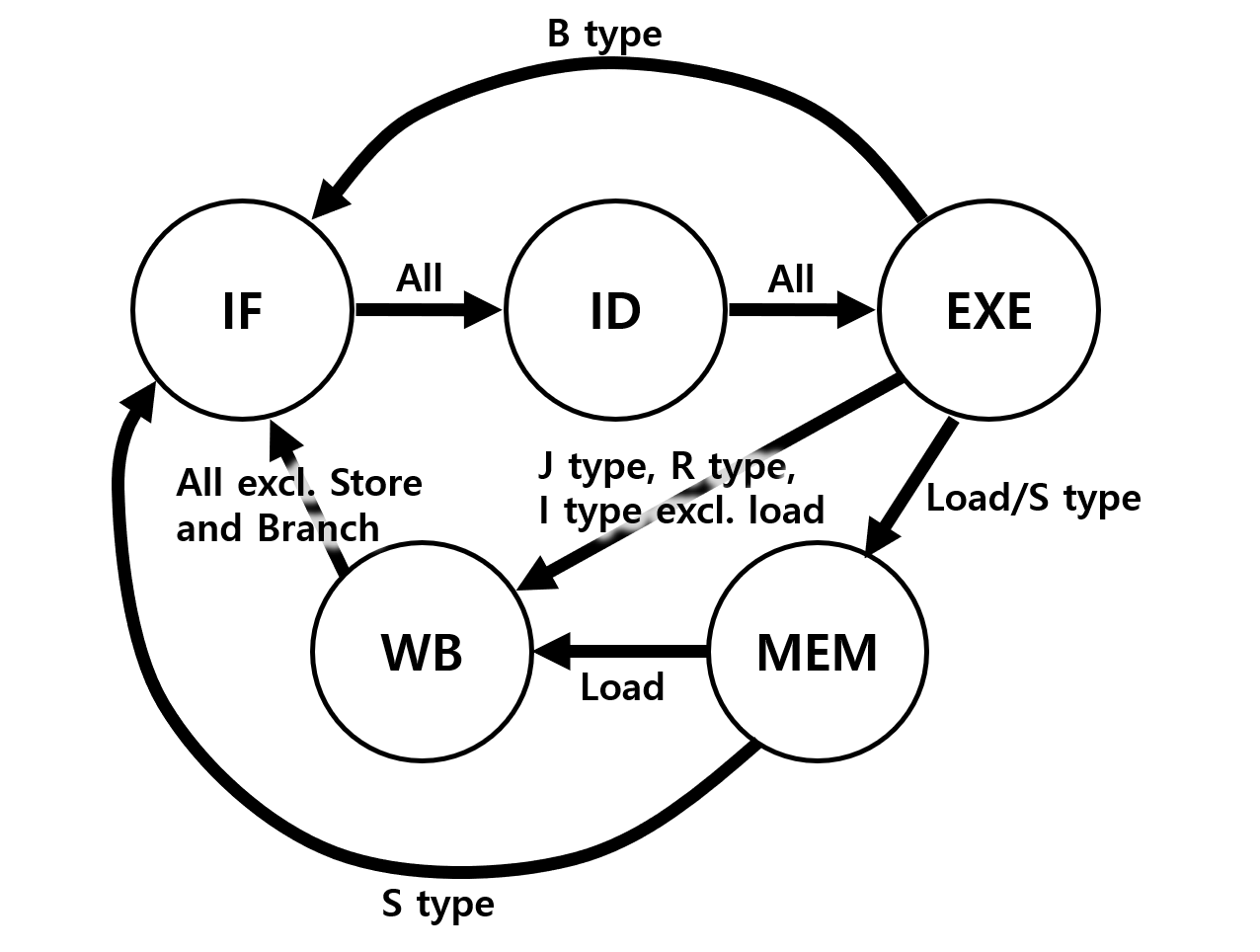
**Figure 1. Datapath and Control Unit of Single Cycle CPU**



**Table 1. Generation of signals at CTRL unit**

CTRL 모듈로부터 발생되는 신호 역시 Single Cycle CPU 때와 동일하다. 본 과제의 경우 사용되지 않는 instruction이 있지만, 그대로 두어도 문제가 발생하지 않기 때문에 Lab 3의 CTRL 모듈을 그대로 차용하였다.

Instruction type에 따라 각 stage에서 어떤 stage로 이동할 것인가에 대한 FSM은 Figure 2에 나타나 있다. 이는 과제 가이드인 ‘EE312 Assigment4.pdf’의 Figure 3과 유사하지만, JUMP가 없고 JAL, JALR이 추가되어 있다는 차이가 있다.

 **Figure 2. FSM of Multi Cycle CPU**

**3. Implementation**

1. Template 구성

REG\_FILE.v, Mem\_Model.v, RISCV\_CLKRST.v은 수정하지 않고 주어진 그대로 사용했다. 주어진 파일인 RISCV\_TOP.v를 수정하였고, Lab 3와 같이 추가로 ALU\_RISCV.v와 CTRL.v를 추가했다. 추가된 파일 각각은 ALU와 CTRL unit 모듈을 담당한다. ALU\_RISCV.v는 Lab. 1에서 구현했던 것을 수정하여 사용하였으며, Opcode에 따른 실행 내용은 Table 2에 나와 있다.

1. 모듈 설명

RISCV\_TOP에는 Figure 1에서 나타낸 wire와 register들이 모두 구현되어 있다. 그래서 CTRL 모듈, ALU 모듈이 전부 여기에서 사용된다. Figure 2에서 나타낸 FSM은 negedge CLK일 때 if문을 통해 구현된다. 이는 Lab 2에서 vending machine의 FSM을 구현했던 것과 기본적으로 같은 방식이다.

추가로 RISCV\_TOP.v에는 IMM\_GEN과 LS\_FILL이라는 간단한 모듈 두 개가 추가로 구현되어 있는데, 너무 간단한 모듈이라 따로 문서를 분리하지 않고 RISCV\_TOP.v 안에 포함시켰다. IMM\_GEN은 immediate generator라는 뜻으로 기본적인 sign extension을 수행하는 모듈이다. LS\_FILL은 load 명령을 수행할 때 D\_MEM\_BE에 따라 D\_MEM의 output에 sign/unsigned extension을 수행하는 모듈이다.

테이블이(가) 표시된 사진

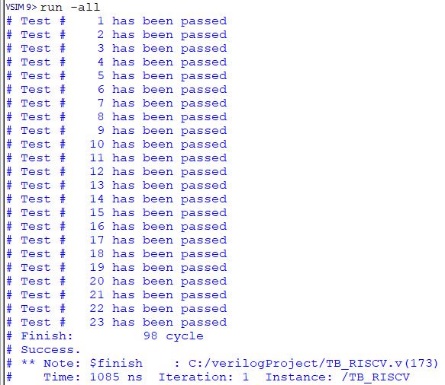
자동 생성된 설명 CTRL.v는 fetch된 instruction을 통해 Table 1에 나오는 11가지 신호를 발생시키는 모듈이다. 이 신호에 따라 CPU 내에서 어떤 루트를 따르게 될지 자동으로 결정된다.

ALU\_RISCV.v는 ALU를 담당하는 모듈이며, 단 이 때 branch를 위해 compare 기능이 추가되어 있다. 교재의 경우 단순히 두 input의 subtraction을 통해 zero를 ALU의 output으로 두고 이를 branch에 활용하지만, 어차피 ALU 밖에서 구현되어야 할 로직이기 때문에 그냥 ALU 안에 포함시켰다. 그래서 zero를 사용하는 대신, opcode에 따라 comparison condition을 만족할 경우 cmp가 1이 되도록 구현되어 있다.

**Table 2. Action of ALU depending on opcode**

**4. Evaluation**

작성한 코드의 평가는 주어진 3개의 testbench 파일을 통해 하였으며, 각각의 경우에 포함된 모든 테스트를 통과하였다. 이는 Figure 3~5에 나타나 있다. 또한 cycle 수의 경우 forloop는 309, sort는 41477로 두 경우 모두 reference cycle과 같았다. 또한 Figure 6에 나타난 바와 같이, waveform을 통해 확인한 결과 instruction type에 따른 cycle 수도 과제 지침에 부합했다. (Branch는 3 cycle, Load는 5 cycle, 나머지는 4 cycle)

![텍스트이(가) 표시된 사진

자동 생성된 설명](data:image/jpeg;base64,/9j/4AAQSkZJRgABAQEAYABgAAD/4RDuRXhpZgAATU0AKgAAAAgABAE7AAIAAAAMAAAISodpAAQAAAABAAAIVpydAAEAAAAYAAAQzuocAAcAAAgMAAAAPgAAAAAc6gAAAAgAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAEhlb25obyBDaG9vAAAFkAMAAgAAABQAABCkkAQAAgAAABQAABC4kpEAAgAAAAMyMQAAkpIAAgAAAAMyMQAA6hwABwAACAwAAAiYAAAAABzqAAAACAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA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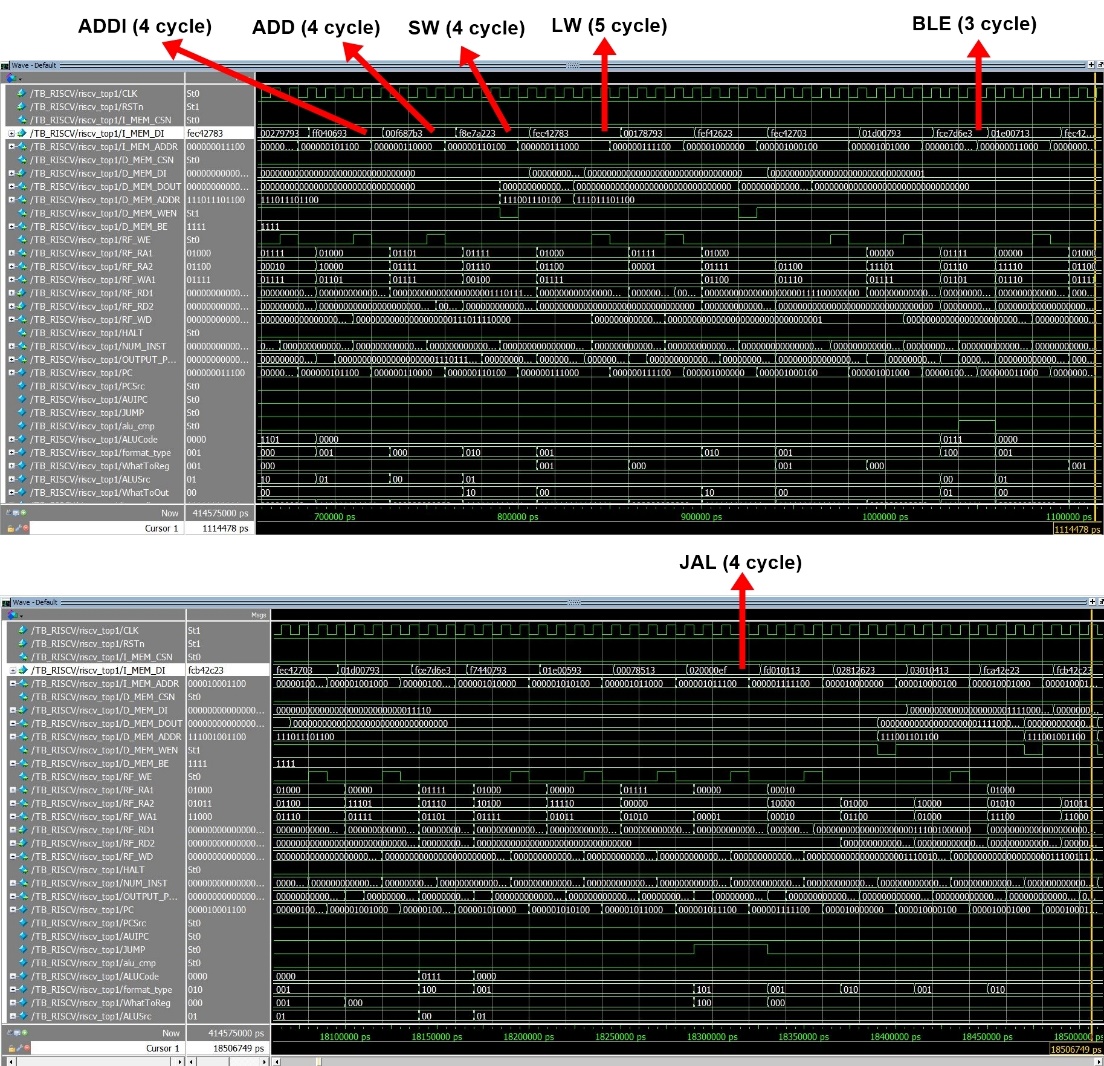
**Figure 4. Result of simulation when ‘TB\_RISCV\_forloop.v’ was used**

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자동 생성된 설명

**Figure 5. Result of simulation when ‘TB\_RISCV\_sort.v’ was used**

**Figure 3. Result of simulation when ‘TB\_RISCV\_inst.v’ was used**

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**Figure 6. Part of waveform of riscv\_top1 when TB\_RISCV\_sort.v was used as a testbench**

**5. Discussion**

본 과제에서 어려웠던 점은 디버깅이었다. 테스트벤치는 테스트케이스의 Pass/Fail이 결정되는 지점에서 모든 요소를 다 판단하지 못하고, 단지 output port로 나오는 값만으로 성공 여부를 출력하기 때문에 우연히도 잘못된 지점부터 몇 개의 테스트는 성공으로 뜨는 경우가 있었다. (예컨대 load는 단순히 target address만을 output으로 내보내므로, 잘못된 값이 대입되더라도 테스트를 pass한 것으로 뜬다.) 그래서 디버깅을 할 때 실패 지점만이 아니라 그 전 몇 개의 instruction도 같이 검토해야 했고, 그래서 더 복잡하게 느껴졌던 것 같다.

**6. Conclusion**

작성한 코드를 이용하여 확인해본 결과 실패한 testcase가 없었고 cycle per instruction도 적절했기에 Multi Cycle CPU가 성공적으로 구현되었다고 판단했다. 본 과제를 통해 강의를 통해 배운 Multi Cycle CPU의 구조에 대해 확실히 이해할 수 있게 되었고, Pipelined CPU 구현에도 큰 도움이 되리라 생각한다.