

6.823 Computer System Architecture
Bus-Based MIPS Implementation

<http://csg.csail.mit.edu/6.823/>

General Overview

Figure H14-A shows a diagram of a bus-based implementation of the MIPS architecture. In this architecture, the different components of the machine share a common 32-bit bus through which they communicate. Control signals determine how each of these components is used and which components get to use the bus during a particular clock cycle. These components and their corresponding control signals are described below.

For this handout, we shall use a positive logic convention. Thus, when we say signal X is “asserted”, we mean that signal X is a logical 1, and that the wire carrying signal X is raised to the “HIGH” voltage level.

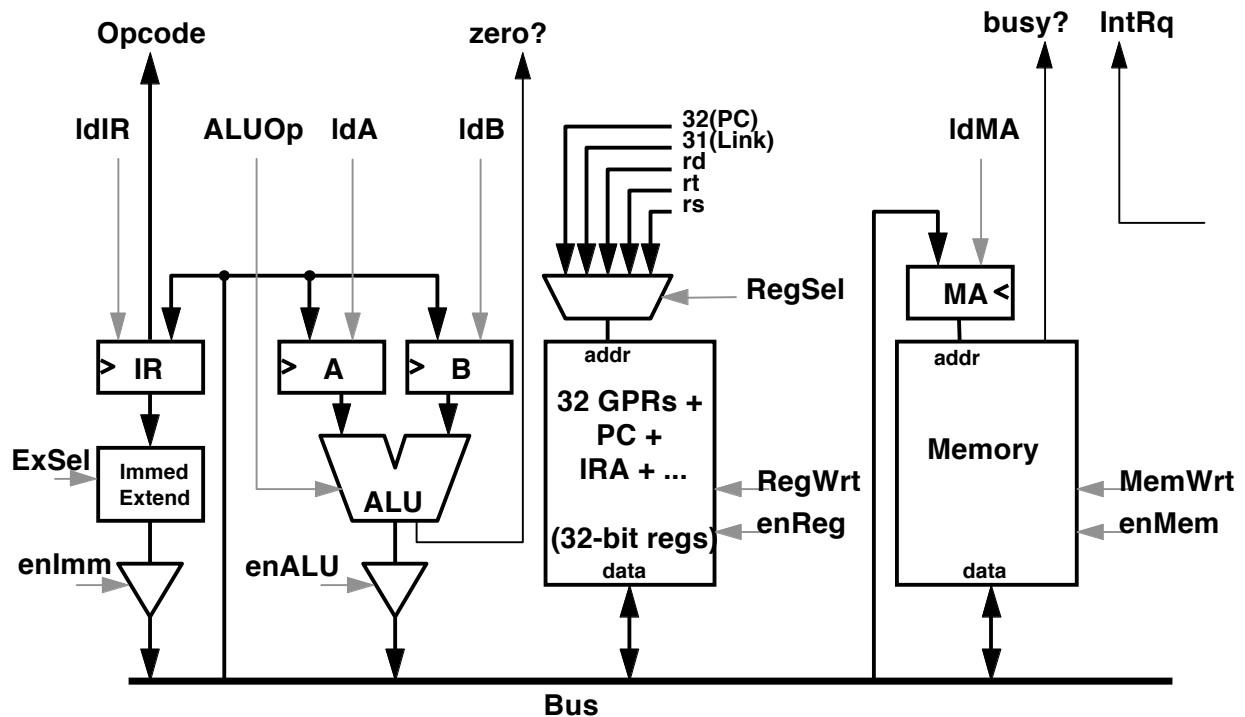


Figure H14-A: A bus-based datapath for MIPS.

The Enable Signals

Since the bus is shared by different components, there is a need to make sure that only one component is driving (“writing”) the bus at any point in time. We do this by using tri-state buffers at the output of each component that can write to the bus. A tri-state buffer is a simple combinational logic buffer with enable control. When enable is 1, then the output of the buffer simply follows its input. When enable is 0, then the output of the buffer “floats” -- i.e., regardless of its input, the tri-state buffer will not try to drive any voltage on the bus. Floating the buffer’s output allows some other component to drive the bus.¹

In the bus-based MIPS, we have four enable signals: enImm, enALU, enReg, and enMem. As shown, enImm and enALU are connected directly to the enable of a tri-state buffer. On the other hand, enReg and enMem are used in more complex circuitry to be explained later in the section on the register file. When setting these signals, it is important to make sure that at any one time, *at most one* device should be driving the bus. It is possible not to assert any of the four signals. In this case, the bus will float and will have an undefined value.

Special Registers and Load Signals

In addition to the registers in the register file, the bus-based MIPS has four other special internal registers: IR, A, B, and MA. These registers are 32-bit *edge triggered* registers with load enable control. As shown, these registers take their data inputs from the bus. If a register’s enable is asserted during a particular cycle, then the value on the bus during that cycle will be copied into the register at the *next* clock edge. If the enable control is 0, then register’s value is not changed.

We call these register enable signals *load* signals, and give them names of the form “ldXX” (i.e., ldIR, ldA, ldB, and ldMA). In addition, the RegWrt and MemWrt signals are also load signals, but their exact functionality will be discussed later. It is possible to assert more than one load signal at a time. In this case, the value on the bus will be loaded to all registers whose load signals are asserted.

The Instruction Register

The instruction register is used to hold the current 32-bit instruction word. As explained in the Handout #14 (RISC ISA- MIPS64), the opcode and function fields (see the MIPS64 instruction format) are used by the microcode control hardware to identify the instruction and run the appropriate microcode. As shown in Figure H14-A, the immediate field is connected to a sign

¹ You can also think of a tri-state buffer as an electronically controlled switch. If enable is 1, then the switch connects the input and the output as if they were connected by a wire. If enable is 0, then the input is electrically disconnected from the output. Note that the tri-state buffer is a memoryless device, and is *not* the same as a latch or a flip-flop.

extender and then to the bus. Finally, as described below, the register specifier fields go to a multiplexer connected to the register file address input.

The Sign Extender

The box named “Immed Extend” in the diagram is a sign extender module that extends a number (16 bits or 26 bits) to a 32-bit number. The sign extender can have one of four possible values. If ExSel is uExt16, then no sign extension is performed, and the most significant bits are just padded with 0’s. In this case, the input to the sign extender must be a 16-bit number. If ExSel is uExt26, then no sign extension is performed either, but the input to the sign extender must be a 26-bit number. If ExSel is sExt16, then the number is sign extended by taking its MSB and using it to pad the most significant bits of the 32-bit value. (Note: we use 2’s complement to represent negative numbers.) In this case, the input to the sign extender must be a 16-bit number. If ExSel is sExt26, then the input must be a 26-bit number, and it is sign extended by taking its MSB and using it to pad the most significant bits of the 32-bit value.

The ALU

The ALU takes 3 inputs: two 32-bit operand inputs, connected to the A and B registers, and an ALUOp input. ALUOp selects the operation to be performed on the operands. Assume that the ALU can perform the following operations by default, if not explicitly stated otherwise:

ALUOp	ALU Result Output
COPY_A	A
COPY_B	B
INC_A_1	A+1
DEC_A_1	A-1
INC_A_4	A+4
DEC_A_4	A-4
ADD	A+B
SUB	A-B

Table H14-1: ALU Operations for Handout #14.

In order to implement the entire MIPS ISA, we will need a few more ALU operations.

The ALU is purely combinational logic. It has two outputs, a 32-bit main result output, and 1-bit zero flag output, *zero*. The result output is computed as in Table H14-1. The zero flag simply indicates if the ALU result output equals to zero. If the result is 0 then *zero* is 1, otherwise *zero* is 0. For example, if A=2, B=2, and ALUOp=SUB, then the ALU result will be 0, and *zero* will be 1. This flag is used to do conditional branches in microcode.

The Register File

The register file contains the 32 general-purpose registers (GPRs), the PC, and a few other special-purpose registers. The register file itself has a 6-bit address input (*addr*) and a 32-bit data port. The address input determines which register is to be read or written to.

Two control signals determine how the register file is used during a certain cycle: *RegWrt* and *enReg*. *RegWrt* determines whether the operation to be performed, if any, is a read or a write. If *RegWrt* is 1, then it is a write, otherwise it's a read. *enReg* is a general enable control for the register file. If *enReg* is 1, then the register reads or writes depending on *RegWrt*. If *enReg* is 0, then nothing is done, regardless of the value of *RegWrt*. Figure H14-B shows exactly how *enReg* and *RegWrt* are wired to the register controls.

The address input (*addr*) determines which register in the file is to be used. Read operations are assumed to be combinational. That is, if you change the value at the *addr* input, then the value at the data output will change appropriately (after some delay), *even if* no clock edge occurs. Write operations, on the other hand, are edge triggered, such that data from the register's data input is only stored in the selected address at the next clock edge.

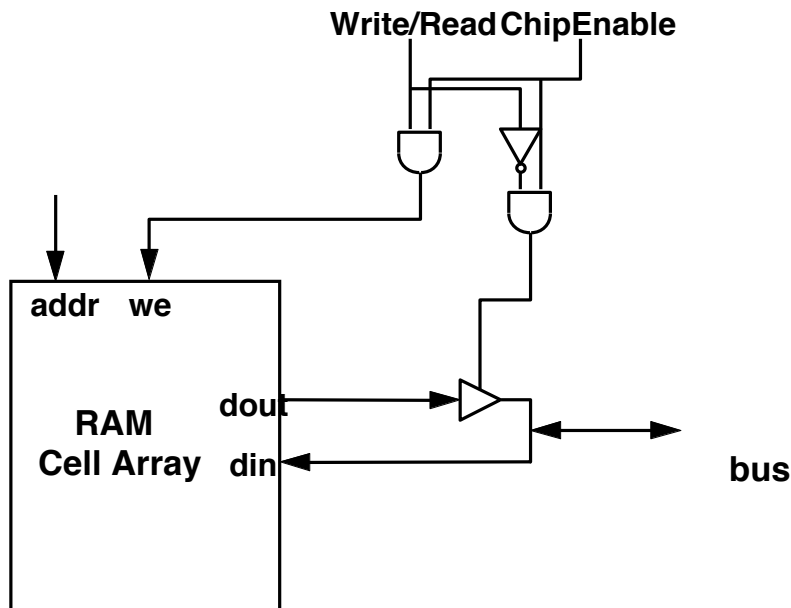


Figure H14-B: Control signals and bus connections for the register file and the memory.

While the *addr* input selects which register is used, the *RegSel* control signal selects what value is used as the *addr* input. As shown, *RegSel* controls a multiplexer that chooses between (at least) 5 possible values. The first two are the hardwired values 32 and 31, corresponding to the PC and the Link register respectively. The next three, *rs*, *rt*, and *rd*, are taken from the register specifier fields of the IR. The following figure shows which fields *rs*, *rt*, and *rd* correspond to:

6 bits	5 bits	5 bits	5 bits	11 bits
Opcode	<i>rs</i>	<i>rt</i>	<i>rd</i>	...

The exact meaning of these fields depends on the instruction and instruction-type. Please refer to H&P and the lecture notes. Note that these fields are 5 bits wide, while `addr` is 6 bits wide. This is because our register file here contains more than just the 32 GPR's. Just assume that the 5-bit fields are converted to a 6-bit address by padding the MSB with a 0. When specifying the value of `RegSel`, you should just use the symbols `PC`, `Link`, `rs`, `rt`, and `rd`.

The Memory

The memory module is very similar to the register file except that the address input is taken from an edge triggered register, `MA`. Thus, it takes two steps to access a particular memory location. First, you load the `MA` with the desired memory address. Then, you perform the desired memory operation. The `MemWrt` and `enMem` controls work just like `RegWrt` and `enReg`. Any operations to be performed on memory are performed on the location specified by the current value of `MA`. As in the register file, we assume that reads are combinational, while writes are edge triggered.

The main difference between memory module and the register file is the busy signal. Unlike the register file, the memory may take more than one cycle to complete a read or write (e.g., if you get a cache miss). The busy signal indicates that the memory isn't done reading or writing yet. The microcode can then respond to the busy signal appropriately.

The Clock Period and Timing Issues

We will assume that the clock period is long enough to guarantee that the results of all *combinational* logic paths are valid and stable before the setup time of any edge triggered components attempting to latch these results.

Remember that these combinational paths include not only computational elements like the sign extender, and the ALU, but also the register file and the memory during *read* operations. Specifically, the path from `addr` to the data output in both the register file and the memory is purely combinational. As mentioned above, if you change the value at the `addr` input, then the value at the data output will change appropriately (after some delay), *even if* no clock edge occurs.

Also remember that the path from *data input* to data output is *not* combinational. This applies not only to the register file and memory, but also to other edge triggered registers (i.e., `IR`, `A`, `B`, and `MA`). When performing a write to any of these components, the value at the data input is not stored until the *next* clock edge, and can thus only be read during the next clock cycle.

Finally, we will assume that there are no hold time violation problems.

Microprogramming on the Bus-Based MIPS Implementation

In the past, simple CISC machines employed a bus-based architecture wherein the different components of the machine (ALU, memory, etc.) communicated through a common bus. This type of architecture is easy and inexpensive to implement, but has the disadvantage of requiring all data movement between components to use the bus. Because of this bottleneck, an instruction on such an architecture typically took several cycles to execute.

Microprogramming makes it easy to generate the control signals for such multi-cycle instructions. A microcode program is basically a finite state machine description. Each line of microcode corresponds to some state of the machine, and contains a “microinstruction” which specifies the outputs for that state, and the next state. The outputs are used to control the different components in the datapath. The next state depends on the current state and possibly on certain other signals (e.g., condition flags). As we shall see, this simple FSM model proves to be very powerful, allowing complex operations like conditional branches and loops to be performed.

Table H14-3 in Appendix B shows a microcode table for the bus-based MIPS implementation. Some lines have been filled in as examples. The first column in the microcode table contains the state label of each microinstruction. For brevity, we assume that the states are listed in increasing numerical order, and we only label important states. For example, we label state FETCH0, and assume that the unlabeled line immediately following it corresponds to state (FETCH1). The second column contains a pseudo-code explanation of the microinstruction in RTL-like notation. The rest of the columns, except the last two, represent control signals that are asserted during the current cycle. ‘Don’t care’ entries are marked with a ‘*’.

The last two columns specify the next state. The μ Br (*microbranch*) column represents a 2-bit field with four possible values: N, J, Z, and D. If μ Br is N (next), then the next state is simply (*current state* + 1). If it is J (jump), then the next state is *unconditionally* the state specified in the Next State column (i.e., it’s an unconditional microbranch). If it is Z (branch-if-zero), then the next state depends on the value of the ALU’s *zero* output signal (i.e., it’s a conditional microbranch). If *zero* is asserted ($== 1$), then the next state is that specified in the Next State column, otherwise, it is (*current state* + 1). If μ Br is D (dispatch), then the FSM looks at the opcode and function fields in the IR and goes into the corresponding state. In this handout, we assume that the dispatch goes to the state labeled (MIPS-instruction-name + “0”). For example, if the instruction in the IR is SW, then the dispatch will go to state SW0.

The first three lines in the table (starting at FETCH0) form the *instruction fetch* stage. These lines are responsible for fetching the next instruction opcode, incrementing the PC, and then going to the appropriate microcode line based on the particular opcode fetched. The instruction fetch stage is performed for every instruction, and every instruction’s microcode should always end by executing an instruction fetch for the next instruction. The easiest way to do this is by having the last microinstruction of an instruction’s microcode do a microbranch to FETCH0. The microcode for NOP provides a simple example. For the rest of the instructions, their microcodes were not given intentionally; we expect students to fill out the table themselves.

Appendix A. A Cheat Sheet for the Bus-based MIPS Implementation

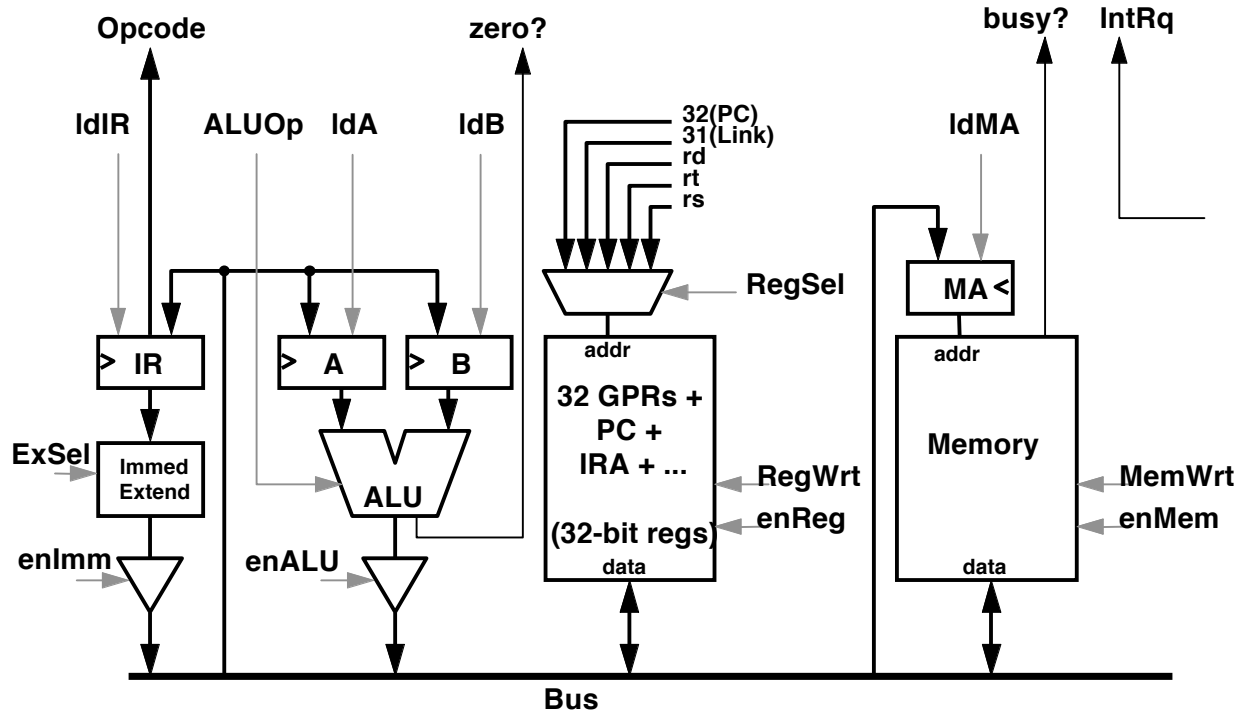
For your reference, we've also included the actual bus-based datapath as well as rehash of some important information about microprogramming in the bus-based architecture.

Remember that you can use the following ALU operations:

ALUOp	ALU Result Output
COPY_A	A
COPY_B	B
INC_A_1	A+1
DEC_A_1	A-1
INC_A_4	A+4
DEC_A_4	A-4
ADD	A+B
SUB	A-B

Table H14-2: Available ALU operations

Also remember that μBr (*microbranch*) column in Table H14-3 represents a 2-bit field with four possible values: N, J, Z, and D. If μBr is N (next), then the next state is simply (*current state* + 1). If it is J (jump), then the next state is *unconditionally* the state specified in the Next State column (i.e., it's an unconditional microbranch). If it is Z (branch-if-zero), then the next state depends on the value of the ALU's *zero* output signal (i.e., it's a conditional microbranch). If *zero* is asserted ($== 1$), then the next state is that specified in the Next State column, otherwise, it is (*current state* + 1). If μBr is D (dispatch), then the FSM looks at the opcode and function fields in the IR and goes into the corresponding state.



Appendix B. Microcode Table for the Bus-based MIPS Implementation

State	PseudoCode	ld IR	Reg Sel	Reg W	en Reg	ld A	ld B	ALUOp	en ALU	ld MA	Mem W	en Mem	Ex Sel	en Imm	μB r	Next State
FETCH0:	MA ← PC; A ← PC	0	PC	0	1	1	*	*	0	1	*	0	*	0	N	*
	IR ← Mem	1	*	*	0	0	*	*	0	0	0	1	*	0	N	*
	PC ← A+4	0	PC	1	1	0	*	INC_A_4	1	*	*	0	*	0	D	*
...																
NOP0:	microbranch back to FETCH0	0	*	*	0	*	*	*	0	*	*	0	*	0	J	FETCH0
ADDM0:																

Table H14-3 (Worksheet 1)