
Raisin64 Documentation

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Raisin64 (*RISC Architecture with In-order Superscalar Interlocked-pipeline*) is a pure 64-bit CPU design created as part of an educational project. Inspired by the architecture of the [MIPS R10000](#) and [POWER3](#), Raisin64 employs multiple specialized pipelines for integer operations, branching, load/store, etc. presently using a simplified issue system appropriate for the scope of a semester-long project.

Unlike most superscalar designs, Raisin64 does not re-order instructions or use register renaming¹ but instead provides a larger architectural register file of 63x64-bit registers.

Major features of the Raisin64 include:

Bits 64-bit

Instructions 50 Opcodes (with 16, 32, and 64-bit formats)

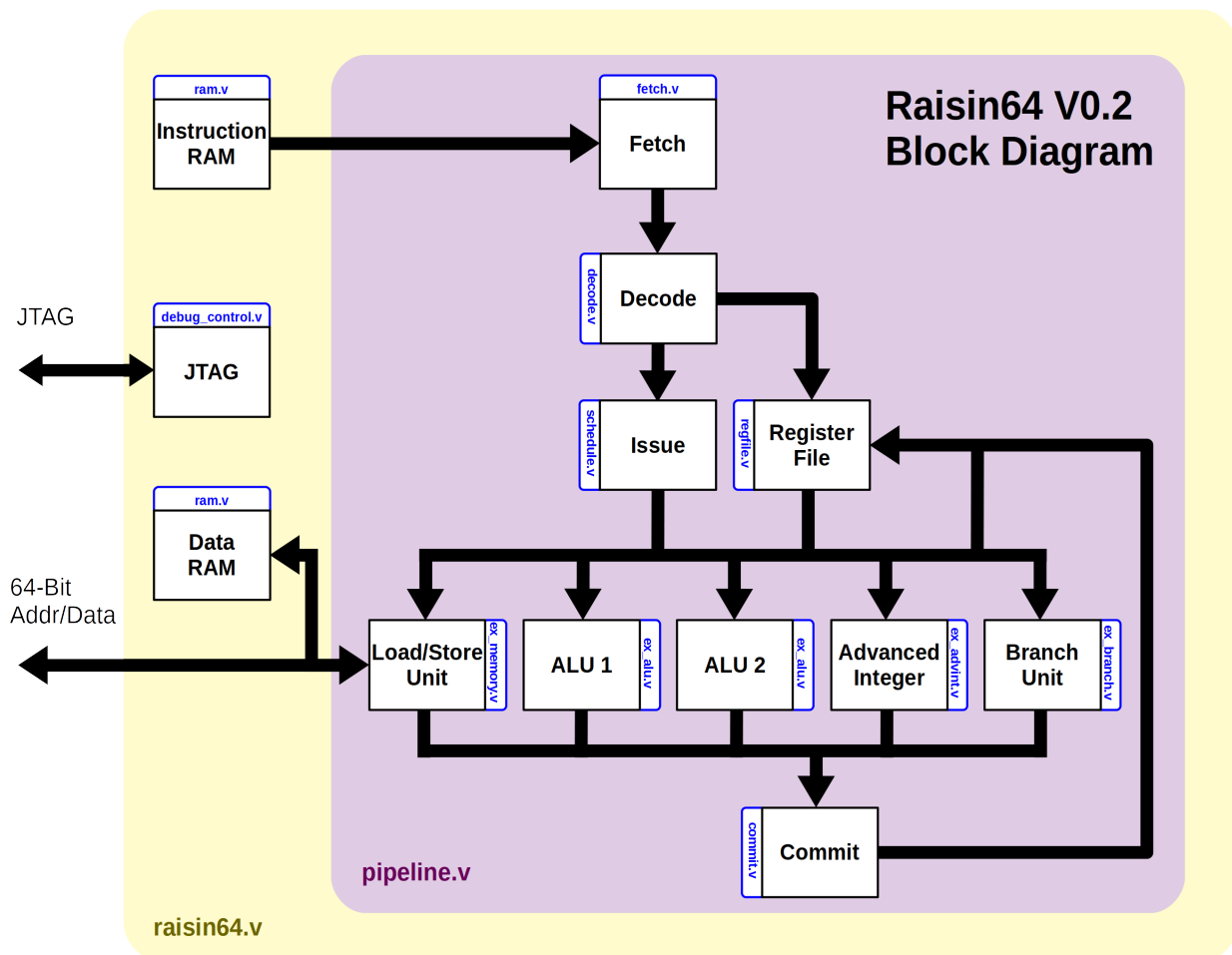
Design RISC (Harvard Architecture²)

Type Register-Register

Branching Compare and Branch

Endianness Big

Registers 63 (R0 = 0)



¹ Raisin64 will always issue instructions in-order but may do so before previous ones have finished executing provided they are dependency-free and the appropriate execution unit is available.

² Split-Cache Modified Harvard when *proposed caches and MMU* are introduced.

The various repositories hosting the source-code described in this document are available here:

Metaproject	https://github.com/ChrisPVille/raisin64
CPU RTL	https://github.com/ChrisPVille/raisin64-cpu
Binutils	https://github.com/ChrisPVille/raisin64-binutils
Nexys4DDR Example	https://github.com/ChrisPVille/raisin64-nexys4ddr
Binutils	https://github.com/ChrisPVille/raisin64-binutils
OpenOCD	https://github.com/ChrisPVille/raisin64-openocd
Docs Source	https://github.com/ChrisPVille/raisin64-docs
PDF Documentation	https://raisin64.fsys.io/_build/latex/Raisin64.pdf

RAISIN64 CPU

1.1 Purpose

The Raisin64, like most computer processors, is a collection of various processing elements and memories, creating what is presently a pipelined 64-bit Harvard RISC architecture. While the initial semester of work focused on getting the design off the ground: designing the instruction set, laying out the execution pipeline, preparing the tools, etc., the eventual goal is to create a CPU capable of running a modern general purpose operating system. This also includes porting all the required debug utilities, assembler, compiler, and other tools necessary to accomplish that goal.

Given the relative paucity of new ISAs, there seems to be little in the way of academic coursework and technical documentation on the bootstrapping process which must occur to make a new architecture useful. This project is the result of those observations, and provides me with experience beyond just computer architecture, including those software and hardware tasks necessary to actually do something useful with a CPU.

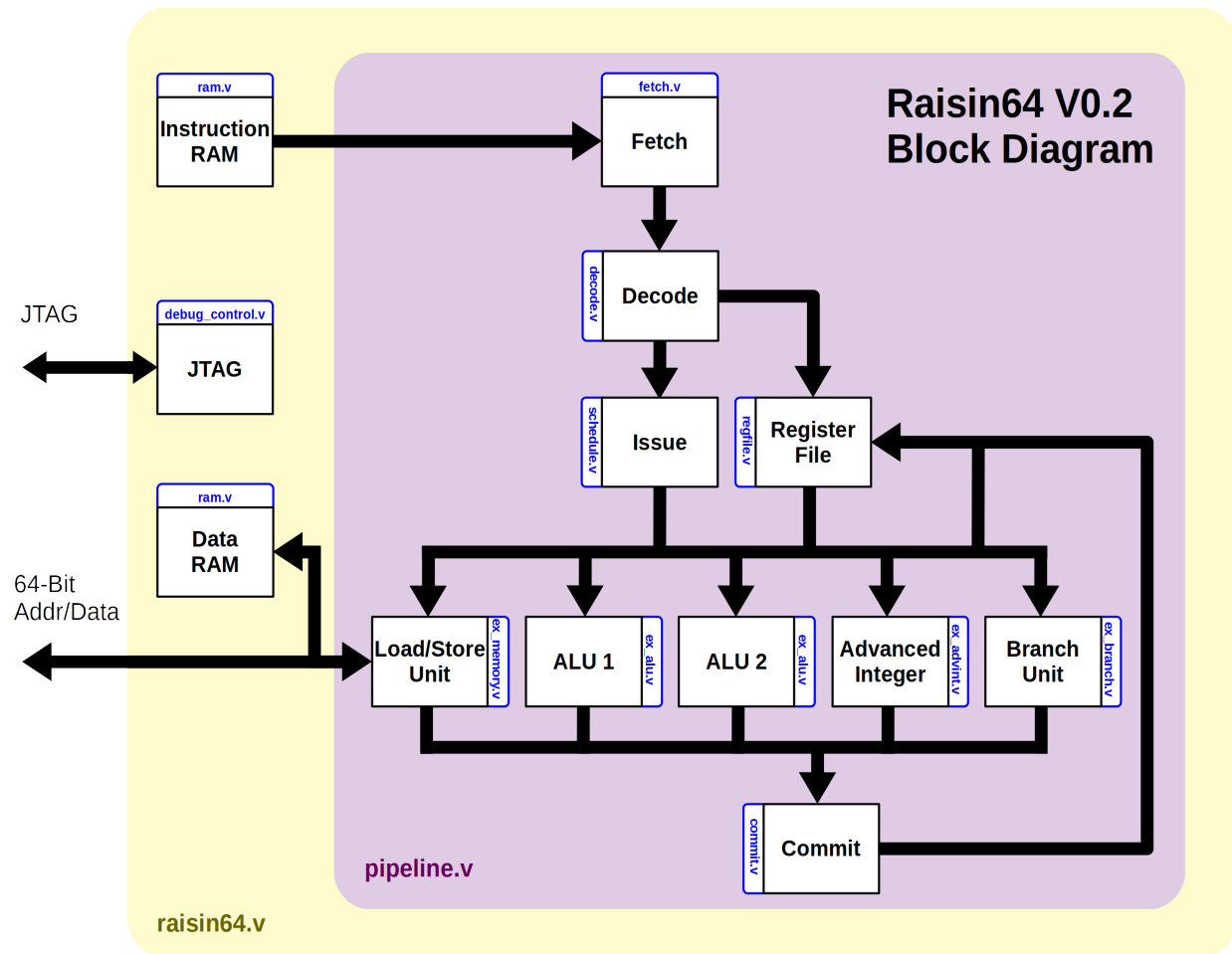
All of that said, the Raisin64 is an initial attempt at understanding pipelined processors, the trades between register count, opcode density, and speed, as well as being a platform for further experimentation. Envisioned as a pure 64-bit machine, the Raisin64 has no legacy instruction set to support and can start as a clean slate.

Anticipating that an out-of-order design with register renaming would be too much work for a semester long project, the Raisin64 ISA has a large architectural register set with 63 64-bit registers instead (Register 0 is always 0). These additional registers have consequences for the instruction format, requiring 6 bits to represent. While a 64-bit instruction word can easily store that, a fixed 64-bit instruction size would be immensely wasteful in terms of memory and cache utilization.

I decided to create a compact instruction format that allows certain instructions to have 16-bit representations and nearly all to have 32-bit representations, with only a few actually requiring the full 64-bit word (such as *Jump Immediate*). Of course, a fixed instruction word is convenient, so the Raisin64's decode stage is designed to expand the 16 and 32-bit instructions into the full 64-bit canonical form as it arrives. This also allows savings on cache and memory while having a simpler internal processing pipeline.

Full details on the instruction word formatting are documented in the *Raisin64 Instruction Set* section.

1.2 Pipeline Stages



The Raisin64 pipeline connects together the processing elements detailed in later sections. Having seen several academic and open-source processor designs, the processing pipeline tends to be one of the more confusing modules to look at, not because of algorithmic complexity but due to the large number of signals moving around the design.

Special effort was made to minimize the number of delay registers and extraneous signals between the various pipeline stages, keeping the design understandable and relatively easy to debug.

Below is an example of the Raisin64's pipeline executing the *VGA Demo Program*:

Stage:	Prefix:
Fetch	fe_*
Decode	de_*
Register File	rf_*
Scheduler	sc_*
Execution Unit	ex_unitName_*

The *fetch unit* is responsible for maintaining the program counter, calculating the next linear instruction's address based on the size of the present instruction, and muxing in the jump/branch destination address.

1.2.2 Decode Unit

Presently, the decode unit decodes a single instruction at a time, limiting the issue rate of the processor to 1 at most. Given the overall complexity of the design for a single semester project, it was decided to defer the multi-issue capability until next semester when the caches and fetch system will be written and adapted to wider access.

1.2. Pipeline Stages

There is no scenario where more than two registers are loaded, so the decode unit publishes zero, one, or two register numbers for the register file to load in the next stage.

1.2.3 Register File

The *register file* is a 63 entry, 64-bit dual read-port, single write-port RAM. The processing pipeline was architected to allow for a single cycle of read latency from the register file. This allows the otherwise large register file to map to higher density memories like distributed RAM or block RAM in FPGA implementations.

The register file is also designed to allow write values to fall through to the read port should another instruction be requesting the same register value. This data forwarding can save an otherwise wasted cycle.

1.2.4 Schedule Unit

The *scheduler*, or issue unit as it is conventionally known, runs concurrent to the register file on a given time-step. This allows the register file time to gather the data required for an operation while the scheduler is making a decision whether or not to issue that instruction.

As execution units are allowed to take more than one cycle to complete, the scheduler tries to issue instructions up to the point where there are either no free execution resources or one of the source operands is going to be written by an in-progress instruction that hasn't finished.

This is accomplished by marking those destination register numbers busy when they are issued and unmarking them when they are written back to the register file. A limited non-speculating in-order issue with out-of-order execution is a side-effect of the arrangement assuming register numbers don't overlap. Consider the following:

```
lw $r2, ($r1)      #Load data at address $r1 into $r2
add $r3, $r4, $r5  #Add $r4 and $r5, storing in $r3
add $r4, $r5, $r6
```

It is very likely that the ADD instructions will finish executing before the LW. The scheduler will identify LW affects only \$r2, and that it is not used in the subsequent instructions. Because instructions are always *issued* in order, the re-use of \$r4 is not a problem here either. It will always be read from the register file before the final ADD instruction is issued.

1.2.5 Execution Units

The execution units in the Raisin64 are entirely independent modules with a standard set of control signals:

```
input[63:0] in1,      //Input data A
input[63:0] in2,      //Input data B
output[63:0] out,     //Output data

input ex_enable,      //Execute now
output ex_busy,       //We are busy and cannot accept data
input[5:0] rd_in_rn,  //Destination Register Number
input[2:0] unit,      //Unit field from the instruction
input[1:0] op,        //Op field from the instruction

output[5:0] rd_out_rn, //Register Number to the commit unit
output valid,         //Output data is valid
input stall           //Commit unit is stalling us
```

The Raisin64 does allow execution units to have two output registers (which is used notably by the *Advanced Integer Unit*), but most only have one.

1.2.5.1 Integer Unit

The *integer unit*/ALU is the registering wrapper around the *combinational ALU implementation*. As this project was not focused on computer arithmetic and with the knowledge that the design would generally target FPGAs, it was decided to leave the Verilog operators for addition and subtraction. Synthesizers can be quite good at using dedicated hardware IP or putting down whatever adder implementation will best satisfy the speed and area constraints.

1.2.5.2 Advanced Integer Unit

The *advanced integer unit* is the registering wrapper around the *combinational advanced integer unit implementation*. Again, for similar reasons, the math operations were left as Verilog operators in the hopes that they would map nicely to onboard hard-IP present in the FPGA. The multiplier did so, mapping to a DSP block containing a multiply-accumulate unit. Unfortunately, there is no division hardware present on the FPGA family used for evaluation of the Raisin64.

Future Work

This will need to be converted to a pipelined division unit (or reciprocal/multiplication) at some point in the future, but for now division is disabled as execution pipeline stalls are already proven and the division instruction is ancillary to the project's goals.

1.2.5.3 Branch Unit

The *branch unit* itself is internally simple although the implications for the pipeline are complicated. The branch unit operates in either branch or jump mode, with jump being a trivial distillation of the branching mode. The unit accepts two input words and an immediate displacement value as well as a delayed version of the next linear program counter from the fetch unit. If the two words are equal, the branch unit adds the displacement to the program counter during its execution cycle.

On the next cycle, when results are typically presented to the commit unit, the branch unit will present `$r63` if appropriate for linking, and it will also signal the pipeline via `do_jump` that a jump is being issued. This causes the pipeline to flush currently fetched and decoded instructions to a NOP value, canceling any unissued instructions.

Because it is desirable to allow the branch unit to take an arbitrary length of time calculating whether or not to jump, the scheduler avoids issuing any instructions after a jump until it has completely resolved. The scheduler can be changed to take advantage of the present guaranteed one-cycle branch calculation, but this approach allows for easier experimentation.

1.2.5.4 Memory Unit

The *memory unit* is the pipeline's only window into the data space. Having a separate memory interface, the memory unit handles all load and store operations, calculating the effective address after adding the offsets, presenting the addresses on the bus, waiting for a response, and masking/sign-extending as required by the instruction. It then returns the result to the commit unit.

Future Work

Currently designed with a minimum execution time of 3 cycles, the memory unit could be further optimized to reduce latency given more analysis. The offset calculation and masking/sign-extension were intentionally put in their own stages preemptively for performance reasons which may ultimately be unnecessary.

1.2.6 Commit Unit

As results can arrive from many (possibly all) execution units simultaneously, the *commit unit* serves as a buffer between those results and the register file. This eliminates the need for a multi-ported write into the register file. The exact order of the writes is non-deterministic based on the present state of the commit unit's writeback engine. This does not present data consistency problems given that the scheduler has already taken care of resolving dependencies between the registers.

While the commit unit can only write back one register per cycle, it will continue to do so every cycle until empty, allowing it to drain faster than it will fill.

Future Work

More analysis could be done on whether this is provably the case, but the commit unit will need to be rewritten to support precise interrupts and exceptions, allowing for an orderly (or at least traceable) change of processor state.

1.3 Debug Controller

The *JTAGlet* is a JTAG TAP written from scratch to allow for easy interfacing between a parallel interface (such as a processor bus) and hardware debug probes. Sitting between Raisin64 and the JTAGlet JTAG TAP is *debug_control.v*. This debug controller exposes JTAG registers from the TAP to the rest of the processor, allowing the debug controller to take over main memory for programming and inspection as well as halt and reset the CPU.

This capability has several advantages. First, it allows for reprogramming the Raisin64 while it's running on an FPGA without waiting for re-synthesis due to a software change. Second, it prevents the synthesizer from optimizing out parts of the processor design that are not reachable with the program preloaded in the instruction RAM.

1.4 Proposed Extensions

Future Work

While out-of-scope for the present period of the project, some initial development was done on *Caches*, an *MMU*, and *Interrupt Unit*, primarily to ensure that they can be integrated into the design without significant modification to the processing pipeline.

These extensions will make the processor capable of running a general purpose operating system (such as Linux) without resorting to software emulation of customarily present hardware.

1.4.1 MMU

Nearly all general purpose operating systems depend on a *Memory Management Unit* to provide the virtual addressing used by userspace processes¹². The MMU presents each process with an illusory linear address space potentially overlapping with many other processes. Along with the *Translation Lookaside Buffer*, an MMU critically allows processes to be placed at arbitrary physical addresses (wherever the RAM happens to be free), with pages of that memory mapped at the virtual addresses the process expects.

¹ <https://www.kernel.org/doc/Documentation/nommu-mmmap.txt>

² <https://wiki.netbsd.org/projects/project/mmu-less/>

In the Raisin64, the MMU also acts as the first point where the instruction and data caches have a unified window into physical memory, making the processor a split-cache Modified Harvard architecture. Beyond the [page tables](#), which are conventionally placed in main memory, the MMU control registers will be present in the machine's memory-map and will be accessible in a kernel-mode unmapped region (that is, the memory addresses used to access the registers will never be mapped by the MMU and will always be passed through without translation).

Proposed MMU Specs:

Page Size 16KB Fixed

VA Width 47-Bits sign-extended

Page Table Three Level (3x 11-bit entries and 15-bit offset)

The virtual addressing scheme takes inspiration from several modern processor designs as a way to constrain the number of legal virtual addresses while not inhibiting the physical address space available to the MMU. While the virtual addresses are 64-bits, bits 63:47 must be sign-extended (i.e. replicated) from bit 46. This breaks the address space into several proposed regions:

Address	Purpose
0xFFFFFFFF_FFFFFFFF - 0xFFFFE000_00000000	Kernel-Mode Mapped
0xFFFFDFFF_FFFFFFFF - 0xFFFFC000_00000000	Kernel-Mode Unmapped
0xFFFFBFFF_FFFFFFFF - 0x00004000_00000000	Invalid
0x00003FFF_FFFFFFFF - 0x00000000_00000000	User-Mode Mapped

The following figure from ARM on the MIPS processor's memory map conveys the general principle of using the kernel-mode unmapped segment to allow access to IO registers (MMU configuration included) which are present at a fixed physical address:

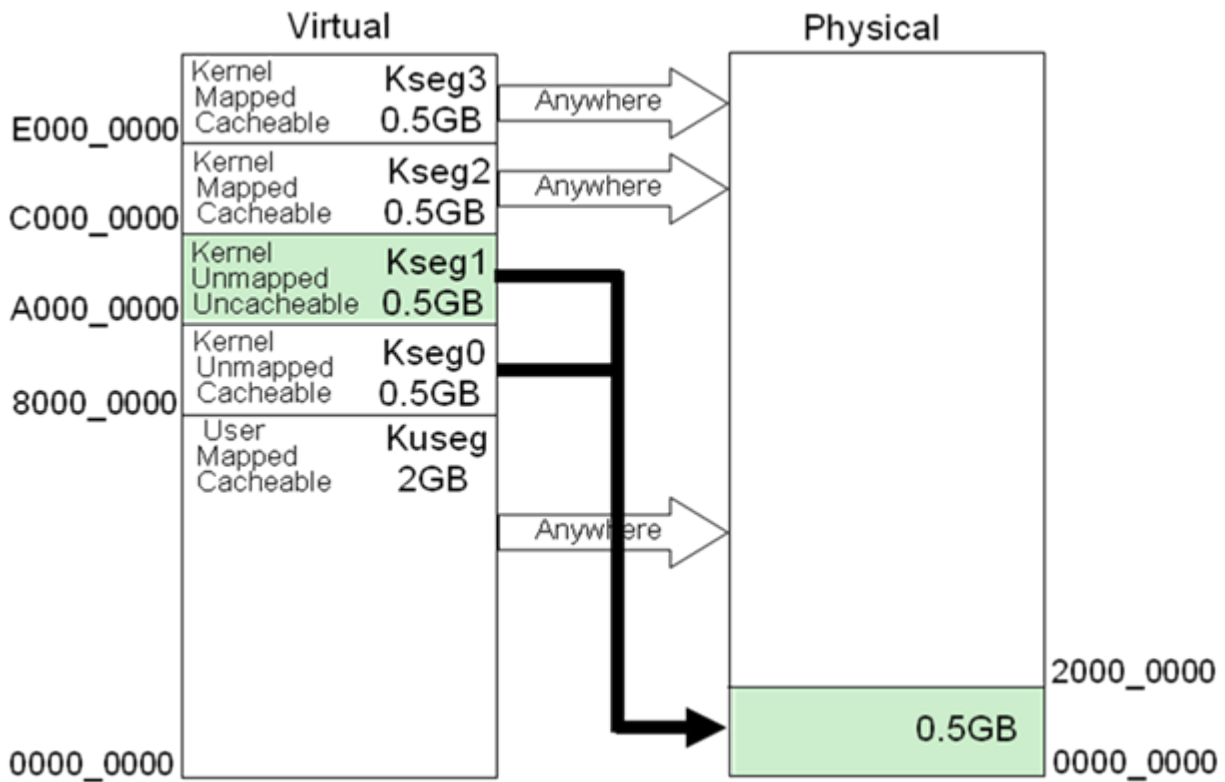


Fig. 1: From ARM AN235 Section 3.4³

1.4.2 Interrupt Unit

An Interrupt/Exception unit will be necessary to properly implement virtual memory. Attempting to access an unmapped, evicted, or privileged page from a userspace process should cause the operating system to take over and mitigate the situation (either by loading the page or terminating the process).

The Raisin64's processing pipeline will need some modifications to the *Commit Unit*. Although first steps have already been taken to add a mechanism allowing register and memory writes to be re-ordered, this can be expanded with program counter tracking information to ensure that the precise location of an interrupt can be recovered and the processor will not commit the pending results of an issued instruction later in the (now aborted) instruction stream.

1.4.3 Caches

Relatively simple compared to the MMU or Interrupt Unit, caches will likely have the largest impact on the performance of the processor. As the processing pipeline uses a Harvard architecture, the first level of caching is made up of a separate Instruction and Data cache. Each will sit on their respective data ports and provide a small number of highly/fully associative entries that are *virtually indexed and virtually tagged*.

This scheme will necessitate the flushing of the cache on a context-switch, but as the only known implementations of the Raisin64 are on FPGAs (without the benefit of hardware content-addressable memory), the caches need to be small and flushing their content on a context-switch will only affect a small number of entries.

Proposed Cache Specs:

- L1 Cache** Split Instruction/Data
- L1 Data** Small N-Way/Fully Associative
- L1 Instruction** Small N-Way/Fully Associative
- L1 Tag Scheme** Virtually Indexed, Virtually Tagged
- L2 Cache** Large Unified 2-Way Set Associative
- L2 Tag Scheme** Physically Indexed, Physically Tagged

While a second level cache between the MMU and main memory may be advantageous, the (comparatively) slow clock rates but high speed memory available on an FPGA may eliminate any benefit of another cache.

1.4.4 References

³ http://infocenter.arm.com/help/topic/com.arm.doc.dai0235c/index.html#arm_toc13

CODE SNIPPETS AND SOFTWARE

Each [instruction](#) detail page contains an example of how to use that specific opcode which will not be repeated here. Instead, a few simple programs will be presented that work with the [Nexys 4 DDR Reference Implementation](#), demonstrating aspects of the ISA or use of the hardware.

While containing a completely different opcode format and compact instruction support, the Raisin64 drew inspiration from MIPS for its instruction set and mnemonics. As a result, several programs I created for a previous academic MIPS design were easily ported to the Raisin64.

2.1 Switch to LED

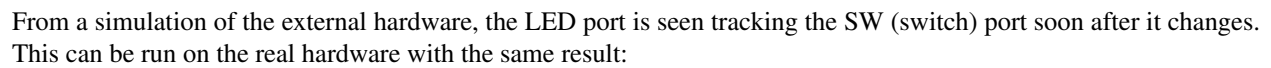
The Switch to LED program is the simplest proof-of-life for the Nexys 4 DDR board, reading the present position of the switches, and mirroring them onto the array of LEDs located immediately above.

```
.set SW_LADR, 0x00008000
.set LED_LADR, 0x00004000

.text
#Load the sign-extended upper portion of the IO space in R1
lui $r1, 0xFFFFC000

sw_loop:
ori $r2, $r1, SW_LADR #Load the switch address in R2
lw $r3, ($r2)         #and read into R3
ori $r2, $r1, LED_LADR #Now load LED address into R2
sw $r3, ($r2)         #And store R3 into *R2
ji sw_loop            #Repeat

add $r0, $r0, $r0      #NOP (not a delay slot) TODO Fix for assembler frag_
↪misalignment
```



Chapter 2. Code Snippets and Software

The assembly demonstrates the use of a stack, as well as useful GNU assembler syntax like defines, macros, data labels, alignment, etc. Also available at: <https://github.com/ChrisPVille/raisin64-nexys4ddr/blob/master/software/demo.S>

```

1  #-----
2  #Macros and defines to make life easier
3
4  .set IO_HADR,  0xFFFFC000
5  .set SW_LADR,  0x00008000
6  .set LED_LADR, 0x00004000
7  .set VGA_LADR, 0x00040000
8
9  .set COLOR_W,  0xF
10 .set COLOR_R,  0xC
11 .set COLOR_G,  0xA
12 .set COLOR_B,  0x9
13 .set COLOR_Y,  0xE
14
15 .set COL, 240
16 .set ROW, 68
17
18 #Loads the character and calls printChar (increments R16; R18 needs to be set)
19 .macro printCharImm char
20     addi $r17, $zero, \char
21     jali printChar
22     addi $r16, $r16, 1
23 .endm
24
25 .macro friendly_print col, row, attrib_byte, str_ptr
26     addi $r16, $zero, \col
27     addi $r17, $zero, \row
28     addi $r18, $zero, \attrib_byte
29     addi $r19, $zero, \str_ptr
30     jali printStr
31 .endm
32
33 .macro fn_enter
34     addi $sp, $sp, -8 #Allocate 1 word on the stack
35     sw    $lr, ($sp) #Store the current lr on the stack
36 .endm
37
38 .macro fn_exit
39     lw    $lr, ($sp) #Restore the original lr
40     addi $sp, $sp, 8 #Free the stack space we used
41     j     $lr #Return
42 .endm
43
44 #-----
45 #Data segment (for the data RAM)
46 .data
47
48 #Stack space (grows down towards zero)
49 stack: .space 8*8
50 stack_init_head:
51
52 #String storage
53 hello_str: .asciz "Hello, World!"
54 greet_str: .asciz "Greetings from "
55

```

(continues on next page)

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```

56 .align 9 #Fill 512
57
58 #-----
59 #Text segment (for the instruction ROM/RAM)
60 .text
61
62 reset:
63     #Setup the stack
64     addi $sp, $zero, stack_init_head
65
66     #Load the sign-extended upper portion of the IO space in R1
67     lui  $r1, IO_HADR
68     ori  $r2, $zero, 0xFFFF
69     ori  $r3, $r1, LED_LADR #Now load LED address into R3
70     sw   $r2, ($r3)        #And store R2 into *R3
71
72     #Clear the display
73     jali clearDisp
74
75     #Write the plain strings
76     friendly_print 115 20 0x0f hello_str
77     friendly_print 110 21 0x0f greet_str
78
79     #Write the colorful Raisin64
80     addi $r16, $zero, (21*COL)+125 #Row 21, Col 125
81     addi $r18, $zero, COLOR_B
82     printCharImm 'R'
83     addi $r18, $zero, COLOR_G
84     printCharImm 'a'
85     addi $r18, $zero, COLOR_Y
86     printCharImm 'i'
87     addi $r18, $zero, COLOR_R
88     printCharImm 's'
89     addi $r18, $zero, COLOR_B
90     printCharImm 'i'
91     addi $r18, $zero, COLOR_G
92     printCharImm 'n'
93     addi $r18, $zero, COLOR_Y
94     printCharImm '6'
95     addi $r18, $zero, COLOR_R
96     printCharImm '4'
97
98     jali reset_finloop
99     addi $r5, $zero, COL*ROW #Final character
100 fin_loop:
101     ori  $r4, $r1, SW_LADR #Load the switch address in R4
102     lw   $r3, ($r4)        #and read into R3
103     ori  $r4, $r1, LED_LADR #Now load LED address into R4
104     sw   $r3, ($r4)        #And store R3 into *R4
105     jali printChar
106     addi $r17, $r17, 1
107     addi $r18, $r18, 3
108     addi $r16, $r16, 1
109     beqal $r16, $r5, reset_finloop
110     ji    fin_loop         #Repeat
111 reset_finloop:
112     addi $r16, $zero, COL*40 #Start at row 40

```

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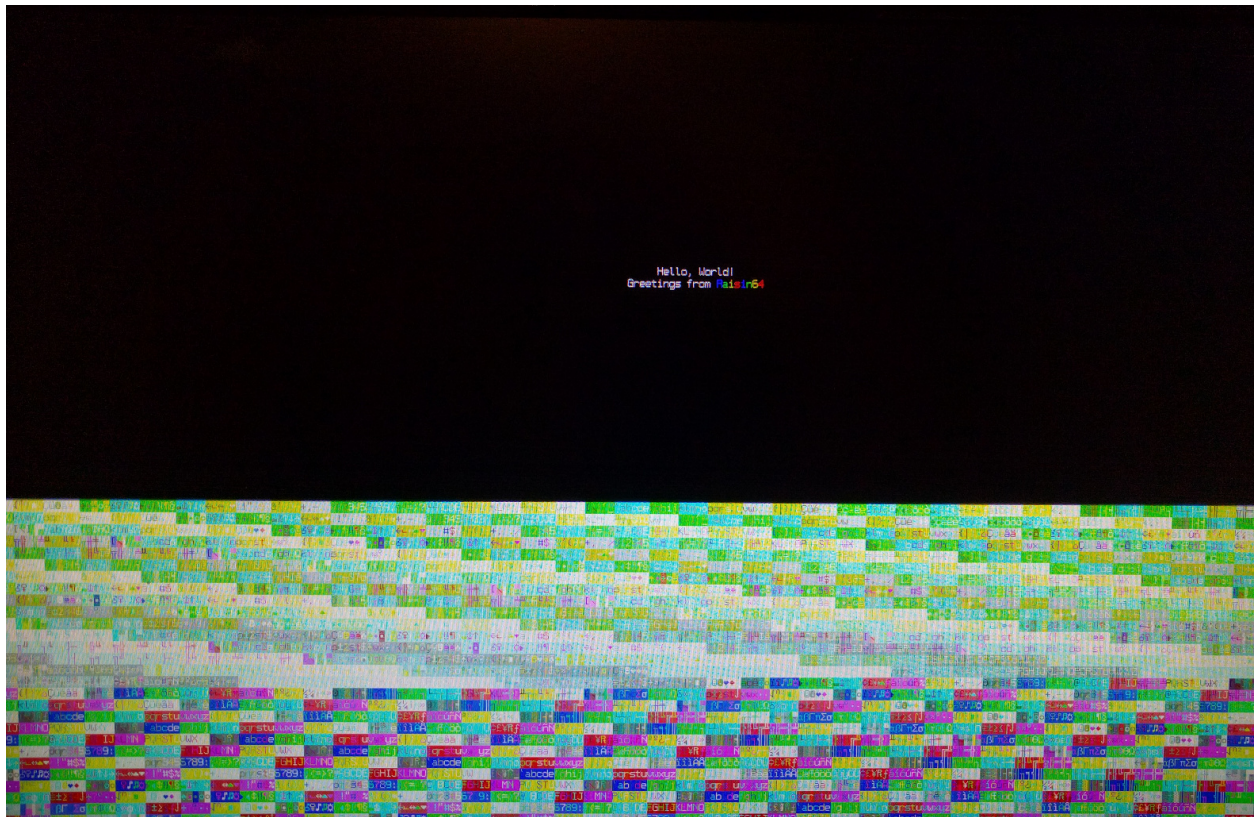
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```

113     j      $lr
114
115 #Clears display
116 clearDisp:
117     fn_enter
118     addi $r16, $zero, ROW*COL
119     add  $r17, $zero, $zero
120     add  $r18, $zero, $zero
121 clearDisp_loop:
122     beq  $r16, $zero, clearDisp_done
123     jali printChar
124     subi $r16, $r16, 1
125     ji   clearDisp_loop
126 clearDisp_done:
127     fn_exit
128
129 #Print ASCII string
130 # R16: Col
131 # R17: Row
132 # R18: Attribute
133 # R19: ASCII String (reference)
134 printStr:
135     fn_enter
136     addi $r4, $zero, COL          #R4 gets Number of Characters in Row
137     mul  $r17, $zero, $r17, $r4  #R17 = NumItemsInCol*RowNum
138     add  $r16, $r17, $r16        #R16 = Buffer "Character" number
139
140 printStr_nextChar:
141     lb   $r17, ($r19)            #R17 = Byte in string
142     beq  $r17, $zero, printStr_done #Null-Terminator
143     jali printChar              #Print the character
144     addi $r19, $r19, 1          #Increment pointers
145     addi $r16, $r16, 1
146     ji   printStr_nextChar
147 printStr_done:
148     fn_exit
149
150 #Sends character to video display
151 # R16: Display Buffer Offset
152 # R17: ASCII Character
153 # R18: Packed Attribute
154 printChar:
155     #We are a leaf function (calls no others).
156     #Don't bother putting ra on the stack as we
157     #won't overwrite it with function calls.
158     slli $r20, $r18, 8
159     or   $r20, $r20, $r17      #Prepare the packed VGA control word
160     andi $r20, $r20, 0xFFFF   #and mask it
161
162     #Prepare the base VGA address in R2
163     ori  $r2, $r1, VGA_LADR
164     slli $r21, $r16, 3         #Shift the buffer "cell" number
165     add  $r2, $r21, $r2        #Add the cell number to the address
166     sw   $r20, ($r2)          #Store the result
167     j    $lr
168
169 .align 11 #Fill 2K

```


Given the repetitive nature of drawing characters, the simulation is simultaneously un-interesting and overwhelming. Suffice it to say, it leads to a colorful demo.



TOOLS

As a completely new computer architecture and instruction set, there were no ready-made tools available for assembly, disassembly, linking, debugging, etc. In the spirit of bootstrapping a new system, it was decided early that given the eventual goal to run a general purpose operating system, GCC will be required. GCC leverages [binutils](#), a collection of assembly tools, object file manipulation utilities, as well as a powerful linker.

Using the preliminary instruction set defined early in the semester, binutils was ported to the Raisin64 ISA while the processor was still being developed. With an existing target (the [moxie](#)) as a template, the initial port of binutils was made functional by creating/modifying 26 files across the source.

Future Work

The current Raisin64 GNU Assembler port only constructs the 64-bit version of the instruction set. While the linker, disassembler, and other infrastructure tools should support the smaller instruction words (with some testing done to that effect), the assembler will require significant work outside the scope of the present semester.

The software architecture of the template was noted for it's reasonable size (ISA definitions and assembler were in the many-hundred-line range instead of the tens-of-thousands range for MIPS and x86), the Raisin64 is quite dissimilar being 64-bit with an entirely different instruction scheme. The [actual assembler core](#) was largely rewritten in what became a deep exploration of the binutils architecture.

3.1 Assembler

Being a port of binutils, the Raisin64 assembler should be familiar to an assembly language programmer, supporting the full set of [GNU As](#) features. An effort was made to support MIPS-like syntax with `$r0` or `$zero` style register numbering and a opcode `$dest, $src1, $src2` instruction format.

Named Registers:

Number	Name	Purpose
<code>\$r0</code>	<code>\$zero</code>	Zero Register
<code>\$r62</code>	<code>\$sp</code>	Stack Pointer (no special meaning to processor/convention only)
<code>\$r63</code>	<code>\$lr</code>	Link Register (Destination for JAL/BEQAL /etc.)

The assembler can be invoked as usual for GNU As:

```
raisin64-elf-as <input file> -o <output.elf>
```

This will produce an ELF that can be manipulated with `objdump`, `objcopy`, etc.

An example of the assembly process is in `assemble.sh` which takes an input assembly file, produces the assembled ELF, prints, and extracts the `.text` and `.data` sections (containing the instruction and data memories respectively). Finally, it converts the converting the output files from hex to ASCII using the `xxd` utility. The result is suitable for the `$readmemh Verilog` command:

```
raisin64-elf-as $1 -o prog.elf &&
raisin64-elf-objdump -s -j .data prog.elf &&
raisin64-elf-objdump -d -j .text prog.elf &&
raisin64-elf-objcopy -O binary -j .text prog.elf imem.bin &&
raisin64-elf-objcopy -O binary -j .data prog.elf dmem.bin &&
xxd -c 8 -ps imem.bin > imem.hex &&
xxd -c 8 -ps dmem.bin > dmem.hex
```

3.1.1 Binary Release

A binary release of the Raisin64 binutils was prepared, compatible with most 64-bit linux systems: <https://github.com/ChrisPVille/raisin64-binutils/releases>

3.1.2 Building from Source

The Raisin64 port can be obtained here: <https://github.com/ChrisPVille/raisin64-binutils>.

Binutils is mostly free from external dependencies out of necessity, so it should build without too much drama. Just be sure to configure it for the `raisin64-elf` target. i.e.:

```
./configure --target=raisin64-elf --prefix=<install directory>
make -j<threads>
```

3.2 Debugging

As the Raisin64 was designed with a home grown JTAG controller (the `JTAGlet`), there was no existing support in any tools. Not that JTAG core support would help much given the new ISA, but keeping with the bootstrap theme, a custom configuration script for `OpenOCD` was created that uses/misuses the scripting interface to provide communication with the processor's JTAG interface, program the memories, and examine the state of the machine.

Future Work

While the scripting interface was a quick way to support my target, the conventional approach is to write support for the target and JTAG controller in C, releasing a new version of `OpenOCD` (much like I did with `binutils`). This will be necessary to support remote debugging (via `GDB`) and will make future development easier.

The configuration script is accessible at https://github.com/ChrisPVille/raisin64-cpu/blob/master/support/jtag/raisin64_nodeps_openocd.cfg. Although it is currently configured for a `Bus Blaster v3`, it can be easily reconfigured for other JTAG probes.

This script is invoked by the adjacent `programImemDmem.sh` `<imem.hex>` `<optional dmem.hex>` or as:

```
openocd -f "raisin64_nodeps_openocd.cfg" -c "init; raisin64_program <imem.hex>
↪<optional dmem.hex>; exit"
```


The full set of implemented functions are:

Name	Arguments	Purpose
raisin64_halt	none	Halts the CPU (Required before dumping memory)
raisin64_resume	none	Un-Halts the CPU
raisin64_reset	none	Resets the CPU
raisin64_program	<imem.hex> <dmem.hex>	Programs Instruction and Data memory, resetting CPU
raisin64_dump_dmem	<addr> <size>	Dumps the contents of Data memory
raisin64_dump_imem	<addr> <size>	Dumps the contents of Instruction memory

3.2.1 Getting OpenOCD

As the present time, any modern version of OpenOCD can be used along with the script file for the Raisin64.

Official releases are at: <http://openocd.org/getting-openocd/> The future Raisin64 version will be located: <https://github.com/ChrisPVille/raisin64-openocd>

NEXYS 4 DDR REFERENCE IMPLEMENTATION

The Nexys 4 DDR (Using a [Xilinx Artix-7](#) series XC7A100T-1CSG324C) was chosen as the reference implementation due to its copious hardware resources, interactive IO, and sufficient memory for a general purpose operating system using the onboard resources. The Raisin64 was connected to memory-mapped peripherals providing access to the LEDs, Switches, and a custom written character oriented VGA controller.

The example project is accessible at <https://github.com/ChrisPVille/raisin64-nexys4ddr>

4.1 SoC Peripherals

Included are several trivial IO devices such as the switch and LED interface. These wait to be enabled based on the current address and a simple memory map decoder, carrying out the input or output as dictated by the processor's output enable and write signals.

IO Memory Map:

Name	Base Address
LED Output	0xFFFFC000_00004000
Switch Input	0xFFFFC000_00008000
VGA Character/Attribute RAM	0xFFFFC000_00040000

Simple IO Control:

```
////////// IO ////////////
wire led_en, sw_en, vga_en;
memory_map memory_map_external(
    .addr(mem_addr_valid ? mem_addr : 64'h0),
    .led(led_en),
    .sw(sw_en),
    .vga(vga_en)
);

//As noted in raisin64.v because our IO architecture will need to be completely
//re-written with the introduction of caches, we only support 64-bit aligned
//access to IO space for now.
reg[15:0] led_reg;
always @(posedge clk_dig or negedge rst_n) begin
    if(~rst_n) led_reg <= 16'h0;
    else if(led_en & mem_from_cpu_write) led_reg <= mem_from_cpu;
end

assign LED = led_reg;
```

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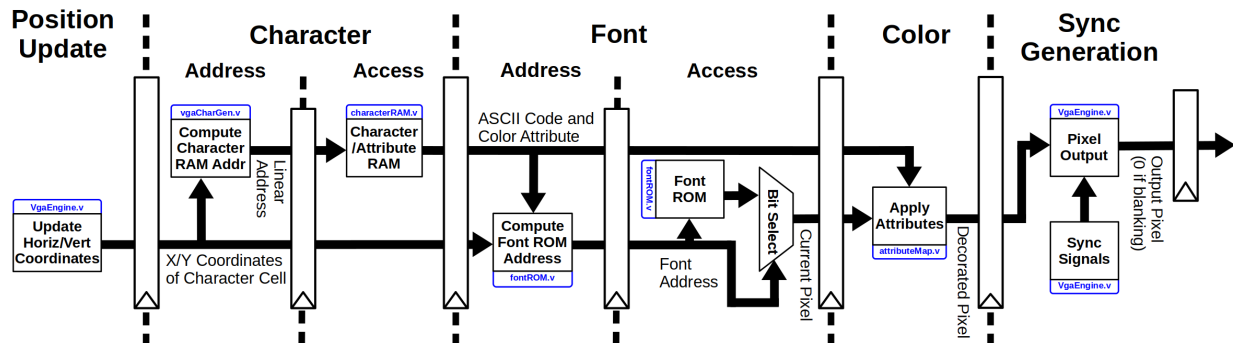
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```
//SW uses a small synchronizer
reg[15:0] sw_pre0, sw_pre1;
always @(posedge clk_dig or negedge rst_n) begin
    if(~rst_n) begin
        sw_pre0 <= 16'h0;
        sw_pre1 <= 16'h0;
    end else begin
        sw_pre0 <= sw_pre1;
        sw_pre1 <= SW;
    end
end

//Data selection
assign mem_to_cpu_ready = mem_addr_valid;
assign mem_to_cpu = sw_en ? sw_pre0 :
                    vga_en ? vga_dout :
                    64'h0;
```

The VGA controller is a much more complicated device, although it presents a simple interface to the CPU. Each “cell” in the video memory is a combined 16-bit character/attribute word, with the least significant 8-bits containing the ASCII character to draw and the most significant 8-bits containing the character’s color attributes.

VGA Controller Block Diagram:



More information is available at <https://github.com/ChrisPville/VGA-CharGen>

4.2 Required Hardware

- Nexys 4 DDR (Also known as Nexys A7)
- Bus Blaster (or another OpenOCD compatible JTAG Probe)
- VGA Monitor/Adapter

4.3 Synthesizing the Core

The Vivado 2018.2 project can either be cloned from the [project repository](#) (don’t forget to use the recursive flag), or a pre-packaged release can be downloaded from the [release page](#).

When opening the .xpr in Vivado, it should re-scan the source directories and update its module hierarchy. The project is configured for default non-aggressive implementation options to speed synthesis and place/route. With these

defaults, it should only take one or two minutes to get through implementation on a reasonably fast machine. The resulting utilization should be similar or less than:

Site Type	Used	Fixed	Available	Util%
Slice LUTs	4109	0	63400	6.48
• LUT as Logic	3910	0	63400	6.17
• LUT as Memory	199	0	19000	1.05
• LUT as Distributed RAM	176	0		
• LUT as Shift Register	23	0		
Slice Registers	2363	0	126800	1.86
• Register as Flip Flop	2363	0	126800	1.86
• Register as Latch	0	0	126800	0.00
F7 Muxes	73	0	31700	0.23
F8 Muxes	0	0	15850	0.00
Block RAM Tile	13	0	135	9.63
• RAMB36E1	13	0	135	9.63
• RAMB18	0	0	270	0.00
DSPs	16	0	240	6.67
• DSP48E1 only	16			

REFERENCE INDEX

5.1 Raisin64 Instruction Set

5.1.1 Overview

The Raisin64's instruction set draws heavily from MIPS with some concepts graciously borrowed from ARM as well. While the programmer's model and instruction set are decoupled from the underlying microarchitecture of the specific implementation, it was nonetheless decided to design the instructions such that a hardwired control unit (see *Decode Unit*) could process and set the appropriate signals.

Instructions are variable length (16-64) bit, and some have multiple forms like the *ADD Instruction*. When an instruction has multiple encodings, the opcode is usually the same between the alternate length versions of that instruction, but in all cases the processor expands the 16 and 32-bit versions of the instruction into their canonical 64-bit form, which has a regular encoding. The general instruction formats and opcodes are described below.

But Why?

There is a natural appeal to 64 registers on a 64-bit machine. This means 6 bits are needed in the instruction format to address each register. While 64-bit instructions allow this and efficient loading of immediate values, they waste program space more often than not. Variable length instructions are a good compromise to avoid the size penalty when not necessary.

5.1.2 Instruction Format

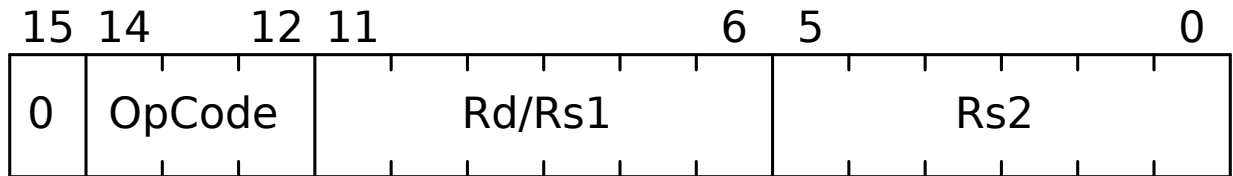
There are 6 instruction formats in Raisin64, register and immediate type 16-bit formats (16R and 16I), register and immediate type 32-bit formats (32R and 32I), and a combined register and immediate 64-bit format (64S) as well as a jump format (64J).

Comparing the 16, 32, and 64-bit formats, the smaller instructions contain those instructions which will fit in the reduced number of bits. The larger instruction formats are a super-set of the smaller ones, and whenever an instruction is available in a smaller format, it is available in all larger formats. For example, ADDI is available in 16, 32, and 64-bit instruction size, with the permitted size of the immediate growing as the instruction grows.

The 32 and 64-bit instruction formats share the same Unit/Op numbers, which are effectively the OpCode. The Unit number represents the type of operation while the Op indicates the specific operation requested. This conveniently fits into the first 8 bits of the instruction, making the opcode easier to view and manipulate.

5.1.3 16-bit formats

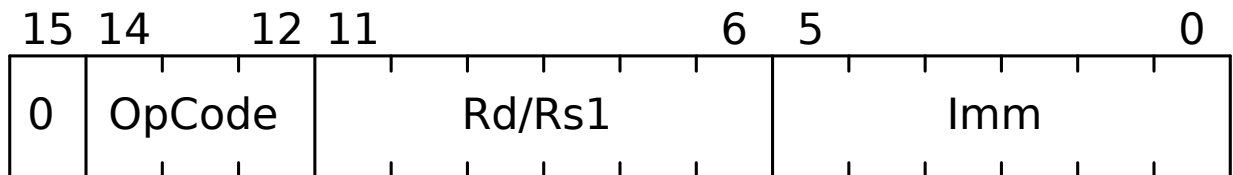
5.1.3.1 16R - 16-bit Register Format



Size

The 16-bit register format is a compact expression of select instructions operating with one source and one destination register. Instructions normally operating on three registers, such as ADD, instead operate in 2-register mode (i.e. $\$rd = \$rd + \$rs$).

5.1.3.2 16I - 16-bit Immediate Format



Size

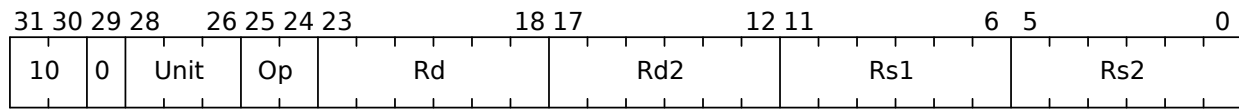
The 16-bit immediate format is used only for ADDI and SUBI, allowing for small increment and decrement operations in a compact format.

5.1.3.3 16-bit OpCode Table

OpCode	Type
0 - ADD	16R
1 - SUB	16R
2 - ADDI	16I
3 - SUBI	16I
4 - SYSCALL	16R
5 - J	16R
6 - JAL	16R
7 - Reserved	

5.1.4 32/64-bit Formats

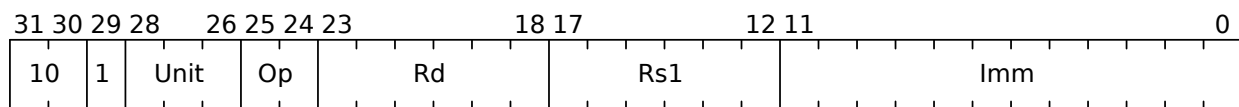
5.1.4.1 32R - 32-bit Register Format



Size Type

All register type instructions in the Raisin64 are available in 32R format. The only exception of this is the F* FPU call, which also uses the immediate field of the 64S format.

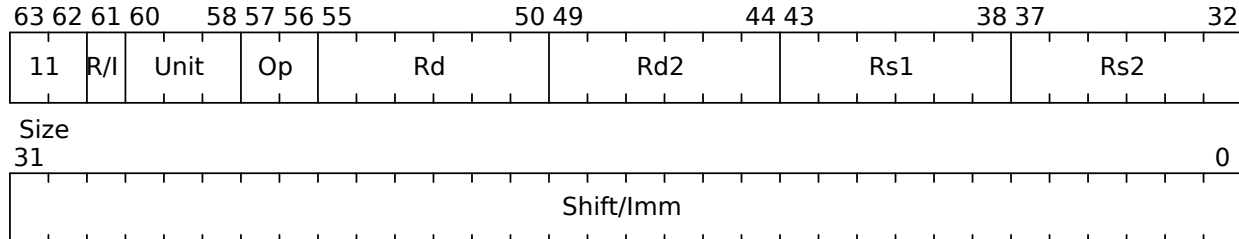
5.1.4.2 32I - 32-bit Immediate Format



Size Type

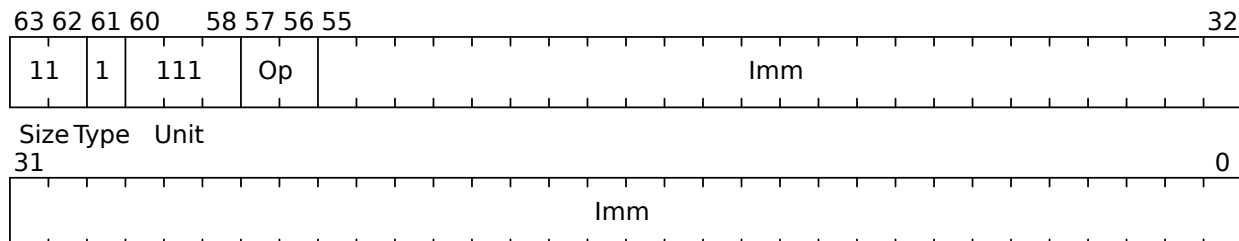
With the exception of JI, JALI, and LUI, all immediate type instructions in the Raisin64 are available in the 32I format with a 12-bit immediate value.

5.1.4.3 64S - 64-bit Standard Format



All register and immediate type instructions (except the immediate type branch and jump instructions) are available in the unified 64S format. When smaller width instructions are encountered by the Raisin64, they are internally expanded into canonical 64S format before being passed onto the rest of the processor. This 64-bit format has space for 4 registers (allowing for instructions like MUL) in addition to 32-bits of immediate data for shifting, bitwise, and ordinary immediate operations).

5.1.4.4 64J - 64-bit Jump Format



A special jump format for large displacement JI and JALI, the 64J format allows for a full 56-bit unsigned jump, more than sufficient to cover the entire virtual address space of the Raisin64.

5.1.4.5 32 and 64-bit Unit/Op Table

R/I	Unit	Op
0	0 - Basic Integer Math	0 - ADD
		1 - SUB
	1 - Compare/Set	0 - SLT
		1 - SLTU
		2 - SGT
		3 - SGTU
	2 - Shift	0 - SLL
		1 - SRA
		2 - SRL
	3 - Bitwise Op	0 - AND
		1 - NOR
		2 - OR
		3 - XOR
	4 - Advanced Integer Math	0 - MUL
		1 - MULU
		2 - DIV
		3 - DIVU
1	5 - Reserved	
	6 - Reserved	
	7 - Jump/Special	0 - SYSCALL
		1 - F* (FPU Call) ¹²
		2 - J
		3 - JAL
	0 - Basic Integer Math	0 - ADDI
		1 - SUBI
	1 - Compare/Set	0 - SLTI
		1 - SLTIU
		2 - SGTI
		3 - SGTIU
	2 - Shift	0 - SLLI
		1 - SRAI
		2 - SRLI
	3 - Bitwise Op	0 - ANDI
		1 - NORI

Continued on next page

Table 1 – continued from previous page

R/I	Unit	Op
		2 - ORI
		3 - XORI
	4 - Regular Load	0 - LW
		1 - L32
		2 - L16
		3 - L8
	5 - Sign-Extend Load	0 - LUI ¹
		1 - L32S
		2 - L16S
		3 - L8S
	6 - Store	0 - SW
		1 - S32
		2 - S16
		3 - S8
	7 - Jump Immediate	0 - BEQ
		1 - BEQAL
		2 - JI ¹
		3 - JALI ¹

¹ 64-bit format only² The F* instruction uses the immediate field of 64S to request a specific enumerated service from the FPU. These instructions (and FPU) do not yet exist.

5.1.5 Instructions

5.1.5.1 ADD - Integer Add

Adds registers `$rs1` and `$rs2`, placing the result in `$rd`.

Usage

```
add $rd, $rs1, $rs2
```

Operation

```
rd = rs1 + rs2;  
advance_pc();
```

Encoding

Type 0

Unit 0

Op 0

16-bit Opcode 0x0

32-bit Opcode 0x80

64-bit Opcode 0xC0

5.1.5.2 ADDI - Integer Add Immediate

Adds registers `$rs1` and a sign-extended immediate value, placing the result in `$rd`.

Usage

```
addi Rd, Rs1, imm
```

Operation

```
Rd = Rs1 + sign_extend(imm);  
advance_pc();
```

Encoding

Type 1

Unit 0

Op 0

16-bit Opcode 0x2

32-bit Opcode 0xA0

64-bit Opcode 0xE0

5.1.5.3 AND - Bitwise AND

ANDs `$rs1` with `$rs2`, placing the result in `$rd`.

Usage

```
and $rd, $rs1, $rs2
```

Operation

```
rd = rs1 & rs2;  
advance_pc();
```

Encoding

Type 0

Unit 3

Op 0

16-bit Opcode NONE

32-bit Opcode 0x8C

64-bit Opcode 0xCC

5.1.5.4 ANDI - Bitwise AND Immediate

ANDs `$rs1` with an immediate value, placing the result in `$rd`.

Usage

```
and $rd, $rs1, imm
```

Operation

```
rd = rs1 & imm;  
advance_pc();
```

Encoding

Type 1

Unit 3

Op 0

16-bit Opcode NONE

32-bit Opcode 0xAC

64-bit Opcode 0xEC

5.1.5.5 BEQ - Branch if Equal

If the `$rs1` register is equal to the `$rd` register, the program branches by the signed immediate displacement. As instructions must be aligned to 16-bit boundaries, the immediate value is left shifted by 1 before the jump.

Tip: An unconditional branch can be accomplished by comparing `$zero` with itself.

Usage

```
beq $rd, $rs1, imm
```

Operation

```
if(rd == rs)
    pc = pc+(imm<<1);
else
    advance_pc();
```

Encoding

Type 1

Unit 7

Op 0

16-bit Opcode NONE

32-bit Opcode 0xBC

64-bit Opcode 0xFC

5.1.5.6 BEQAL - Branch if Equal And Link

If the `$rs1` register is equal to the `$rd` register, the program branches by the signed immediate displacement. The address of the next linear instruction is placed as a return address in `r63`. As instructions must be aligned to 16-bit boundaries, the immediate value is left shifted by 1 before the jump.

Tip: An unconditional branch can be accomplished by comparing `$zero` with itself.

Usage

```
beqal $rd, $rs1, imm
```

Operation

```
if (Rd == Rs)
    r63 = next_pc();
    pc = pc + (imm << 1);
else
    advance_pc();
```

Encoding

Type 1

Unit 7

Op 1

16-bit Opcode NONE

32-bit Opcode 0xBD

64-bit Opcode 0xFD

5.1.5.7 DIV - Integer Divide

Divides registers `$rs1` by `$rs2`, and places the quotient in `$rd` and the remainder in `$rd2`, treating operands as 2's complement signed.

Usage

```
div $rd, $rd2, $rs1, $rs2
```

Operation

```
rd = rs1 / rs2;  
rd2 = rs1 % rs2;  
advance_pc();
```

Encoding

Type 0

Unit 4

Op 2

16-bit Opcode NONE

32-bit Opcode 0x92

64-bit Opcode 0xD2

5.1.5.8 DIVU - Unsigned Integer Divide

Divides registers `$rs1` by `$rs2`, and places the quotient in `$rd` and the remainder in `$rd2`, treating operands as unsigned.

Usage

```
divu $rd, $rd2, $rs1, $rs2
```

Operation

```
rd = rs1 / rs2;  
rd2 = rs1 % rs2;  
advance_pc();
```

Encoding

Type 0

Unit 4

Op 3

16-bit Opcode NONE

32-bit Opcode 0x93

64-bit Opcode 0xD3

5.1.5.9 F* - FPU Call

FPU Call (unimplemented)

Usage

```
todo
```

Operation

```
todo;  
advance_pc();
```

Encoding

Type 0

Unit 7

Op 1

16-bit Opcode NONE

32-bit Opcode NONE

64-bit Opcode 0xDD

5.1.5.10 J - Jump

Unconditional jump to the instruction in `$rs1`.

Usage

```
j $rs1
```

Operation

```
pc = rs1;
```

Encoding

Type 0

Unit 7

Op 2

16-bit Opcode 0x5

32-bit Opcode 0x9E

64-bit Opcode 0xDE

5.1.5.11 JAL - Jump and Link

Unconditional jump to the instruction in `$rs1`, placing the return address in `$r63`.

Usage

```
jal $rs1
```

Operation

```
r63 = next_pc();  
pc = rs;
```

Encoding

Type 0

Unit 7

Op 3

16-bit Opcode 0x6

32-bit Opcode 0x9F

64-bit Opcode 0xDF

5.1.5.12 JALI - Jump and Link Immediate

Unconditional jump to the immediate value, placing the return address in `$r63`. The top 8 bits of the jump destination address are taken from the current program counter. As instructions must be aligned to 16-bit boundaries, the immediate value is left shifted by 1 before the jump. Due to the size of the immediate value, JALI is only available in 64J format.

Usage

```
jali imm
```

Operation

```
r63 = pc + 8;  
pc = (pc & 0xff00000000000000) | imm<<1;
```

Encoding

Type 1

Unit 7

Op 3

16-bit Opcode NONE

32-bit Opcode NONE

64-bit Opcode 0xFF

5.1.5.13 JI - Jump Immediate

Unconditional jump to the immediate value. The top 8 bits of the jump destination address are taken from the current program counter. As instructions must be aligned to 16-bit boundaries, the immediate value is left shifted by 1 before the jump. Due to the size of the immediate value, JI is only available in 64J format.

Usage

```
ji imm
```

Operation

```
pc = (pc & 0xff00000000000000) | imm<<1;
```

Encoding

Type 1

Unit 7

Op 2

16-bit Opcode NONE

32-bit Opcode NONE

64-bit Opcode 0xFE

5.1.5.14 L16 - Load 16-bit

Loads 16-bit word from address `$rs1` offset by a signed immediate value and places it into `$rd`.

Usage

```
l16 $rd, imm($rs1)
```

Operation

```
rd[63:16] = 0;  
rd[15:8]  = *(rs+imm);  
rd[7:0]   = *(rs+imm+1);  
advance_pc();
```

Encoding

Type 1

Unit 4

Op 2

16-bit Opcode NONE

32-bit Opcode 0xB2

64-bit Opcode 0xF2

5.1.5.15 L16S - Load 16-bit Sign-Extend

Loads 16-bit word from address `$rs1` offset by a signed immediate value and places it into `$rd`.

Usage

```
l16s $rd, imm($rs1)
```

Operation

```
rd[63:16] = sign_bit(*(rs+imm));  
rd[15:8]  = *(rs+imm);  
rd[7:0]   = *(rs+imm+1);  
advance_pc();
```

Encoding

Type 1

Unit 5

Op 2

16-bit Opcode NONE

32-bit Opcode 0xB6

64-bit Opcode 0xF6

5.1.5.16 L32 - Load 32-bit

Loads 32-bit word from address `$rs1` offset by a signed immediate value and places it into `$rd`.

Usage

```
l32 $rd, imm($rs1)
```

Operation

```
rd[63:32] = 0;
rd[31:24] = *(rs+imm);
rd[23:16] = *(rs+imm+1);
rd[15:8]  = *(rs+imm+2);
rd[7:0]   = *(rs+imm+3);
advance_pc();
```

Encoding

Type 1

Unit 4

Op 1

16-bit Opcode NONE

32-bit Opcode 0xB1

64-bit Opcode 0xF1

5.1.5.17 L32S - Load 32-bit Sign-Extend

Loads 32-bit word from address `$rs1` offset by a signed immediate value and places it into `$rd`.

Usage

```
l32s $rd, imm($rs1)
```

Operation

```
rd[63:32] = sign_bit(*(rs+imm));  
rd[31:24] = *(rs+imm);  
rd[23:16] = *(rs+imm+1);  
rd[15:8]  = *(rs+imm+2);  
rd[7:0]   = *(rs+imm+3);  
advance_pc();
```

Encoding

Type 1

Unit 5

Op 1

16-bit Opcode NONE

32-bit Opcode 0xB5

64-bit Opcode 0xF5

5.1.5.18 L8 - Load 8-bit

Loads 8-bit word from address `$rs1` offset by a signed immediate value and places it into `$rd`.

Usage

```
l8 $rd, imm($rs1)
```

Operation

```
rd[63:8] = 0;  
rd[7:0]  = *(rs+imm);  
advance_pc();
```

Encoding

Type 1

Unit 4

Op 3

16-bit Opcode NONE

32-bit Opcode 0xB3

64-bit Opcode 0xF3

5.1.5.19 L8S - Load 8-bit Sign-Extend

Loads 8-bit word from address `$rs1` offset by a signed immediate value and places it into `$rd`.

Usage

```
l8s $rd, imm($rs1)
```

Operation

```
rd[63:8] = sign_bit(*(rs+imm));  
rd[7:0]  = *(rs+imm);  
advance_pc();
```

Encoding

Type 1

Unit 5

Op 3

16-bit Opcode NONE

32-bit Opcode 0xB7

64-bit Opcode 0xF7

5.1.5.20 LUI - Load Upper Immediate

Loads the immediate value into the upper 32 bits of `$rd`.

Usage

```
lui $rd, imm
```

Operation

```
rd = imm << 32;  
advance_pc();
```

Encoding

Type 1

Unit 5

Op 0

16-bit Opcode NONE

32-bit Opcode NONE

64-bit Opcode 0xF4

5.1.5.21 LW - Load 64-bit Word

Loads 64-bit word from address `$rs1` offset by a signed immediate value and places it into `$rd`.

Usage

```
lw $rd, imm($rs1)
```

Operation

```
rd[63:56] = *(rs+imm);
rd[55:48] = *(rs+imm+1);
rd[47:40] = *(rs+imm+2);
rd[39:32] = *(rs+imm+3);
rd[31:24] = *(rs+imm+4);
rd[23:16] = *(rs+imm+5);
rd[15:8]  = *(rs+imm+6);
rd[7:0]   = *(rs+imm+7);
advance_pc();
```

Encoding

Type 1

Unit 4

Op 0

16-bit Opcode NONE

32-bit Opcode 0xB0

64-bit Opcode 0xF0

5.1.5.22 MUL - Integer Multiply

Multiplies registers `$rs1` and `$rs2`, and places the results in `$rd` and `$rd2`, treating operands as 2's complement signed.

Usage

```
mul $rd, $rd2, $rs1, $rs2
```

Operation

```
rd = bottom_64bits(rs1 * rs2);  
rd2 = upper_64bits(rs1 * rs2);  
advance_pc();
```

Encoding

Type 0

Unit 4

Op 0

16-bit Opcode NONE

32-bit Opcode 0x90

64-bit Opcode 0xD0

5.1.5.23 MULU - Unsigned Integer Multiply

Multiplies registers `$rs1` and `$rs2`, and places the results in `$rd` and `$rd2`, treating operands as unsigned.

Usage

```
mulu $rd, $rd2, $rs1, $rs2
```

Operation

```
rd = bottom_64bits(rs1 * rs2);  
rd2 = upper_64bits(rs1 * rs2);  
advance_pc();
```

Encoding

Type 0

Unit 4

Op 1

16-bit Opcode NONE

32-bit Opcode 0x91

64-bit Opcode 0xD1

5.1.5.24 NOR - Bitwise NOR

NORs `$rs1` with `$rs2`, placing the result in `$rd`.

Usage

```
nor $rd, $rs1, $rs2
```

Operation

```
rd = ~(rs1|rs2);  
advance_pc();
```

Encoding

Type 0

Unit 3

Op 1

16-bit Opcode NONE

32-bit Opcode 0x8D

64-bit Opcode 0xCD

5.1.5.25 NORI - Bitwise NOR Immediate

NORs `$rs1` with an immediate value, placing the result in `$rd`.

Usage

```
nori $rd, $rs1, imm
```

Operation

```
rd = ~(rs1|imm);  
advance_pc();
```

Encoding

Type 1

Unit 3

Op 1

16-bit Opcode NONE

32-bit Opcode 0xAD

64-bit Opcode 0xED

5.1.5.26 OR - Bitwise OR

ORs `$rs1` with `$rs2`, placing the result in `$rd`.

Usage

```
or $rd, $rs1, $rs2
```

Operation

```
rd = rs1 | rs2;  
advance_pc();
```

Encoding

Type 0

Unit 3

Op 2

16-bit Opcode NONE

32-bit Opcode 0x8E

64-bit Opcode 0xCE

5.1.5.27 ORI - Bitwise OR Immediate

ORs `$rs1` with an immediate value, placing the result in `$rd`.

Usage

```
ori $rd, $rs1, imm
```

Operation

```
rd = rs1 | imm;  
advance_pc();
```

Encoding

Type 1

Unit 3

Op 2

16-bit Opcode NONE

32-bit Opcode 0xAE

64-bit Opcode 0xEE

5.1.5.28 S16 - Store 16-bit

Store least significant 16 bits of `$rd` into the address located in `$rs1` offset by a signed immediate value.

Usage

```
s16 $rd, imm($rs1)
```

Operation

```
*(rs+imm)    = rd[15:8];  
*(rs+imm+1)  = rd[7:0];  
advance_pc();
```

Encoding

Type 1

Unit 6

Op 2

16-bit Opcode NONE

32-bit Opcode 0xBA

64-bit Opcode 0xFA

5.1.5.29 S32 - Store 32-bit

Store least significant 32 bits of `$rd` into the address located in `$rs1` offset by a signed immediate value.

Usage

```
s32 $rd, imm($rs1)
```

Operation

```
*(rs+imm)    = rd[31:24];
*(rs+imm+1)  = rd[23:16];
*(rs+imm+2)  = rd[15:8];
*(rs+imm+3)  = rd[7:0];
advance_pc();
```

Encoding

Type 1

Unit 6

Op 1

16-bit Opcode NONE

32-bit Opcode 0xB9

64-bit Opcode 0xF9

5.1.5.30 S8 - Store 8-bit

Store least significant 8 bits of `$rd` into the address located in `$rs1` offset by a signed immediate value.

Usage

```
s8 $rd, imm($rs1)
```

Operation

```
*(rs+imm) = rd[7:0];  
advance_pc();
```

Encoding

Type 1

Unit 6

Op 3

16-bit Opcode NONE

32-bit Opcode 0xBB

64-bit Opcode 0xFB

5.1.5.31 SGT - Set 1 if Greater Than

Sets `$rd` as 1 if the signed representation of `$rs1` is greater than than the signed representation of `$rs2`, 0 otherwise.

Usage

```
sgt $rd, $rs1, $rs2
```

Operation

```
if((signed)rs1 > (signed)rs2)
    rd = 1;
else
    rd = 0;
advance_pc();
```

Encoding

Type 0

Unit 1

Op 2

16-bit Opcode NONE

32-bit Opcode 0x86

64-bit Opcode 0xC6

5.1.5.32 SGTI - Set 1 if Greater Than Immediate

Sets `$rd` as 1 if the signed representation of `$rs1` is greater than the signed immediate field, 0 otherwise.

Usage

```
sgti $rd, $rs1, imm
```

Operation

```
if((signed)rs1 > (signed)imm)
    rd = 1;
else
    rd = 0;
advance_pc();
```

Encoding

Type 1

Unit 1

Op 2

16-bit Opcode NONE

32-bit Opcode 0xA6

64-bit Opcode 0xE6

5.1.5.33 SGTIU - Set 1 if Greater Than Immediate Unsigned

Sets `$rd` as 1 if the unsigned representation of `$rs1` is greater than the unsigned immediate field, 0 otherwise.

Usage

```
sgtiu $rd, $rs1, imm
```

Operation

```
if ((unsigned) rs1 > (unsigned) imm)
    rd = 1;
else
    rd = 0;
advance_pc();
```

Encoding

Type 1

Unit 1

Op 3

16-bit Opcode NONE

32-bit Opcode 0xA7

64-bit Opcode 0xE7

5.1.5.34 SGTU - Set 1 if Greater Than Unsigned

Sets `$rd` as 1 if the unsigned representation of `$rs1` is greater than the unsigned representation of `$rs2`, 0 otherwise.

Usage

```
sgtu $rd, $rs1, $rs2
```

Operation

```
if((unsigned)rs1 > (unsigned)rs2)
    rd = 1;
else
    rd = 0;
advance_pc();
```

Encoding

Type 0

Unit 1

Op 3

16-bit Opcode NONE

32-bit Opcode 0x87

64-bit Opcode 0xC7

5.1.5.35 SLL - Shift Left Logical

Shift the contents of register `$rs1` left by a number of bits specified in `$rs2`, storing the result in `$rd`

Usage

```
sll $rd, $rs1, $rs2
```

Operation

```
rd = rs1<<rs2;  
advance_pc();
```

Encoding

Type 0

Unit 2

Op 0

16-bit Opcode NONE

32-bit Opcode 0x88

64-bit Opcode 0xC8

5.1.5.36 SLLI - Shift Left Logical Immediate

Shift the contents of register `$rs1` left by a number of bits specified in the immediate field, storing the result in `$rd`

Usage

```
slli $rd, $rs1, imm
```

Operation

```
rd = rs1<<imm;  
advance_pc();
```

Encoding

Type 1

Unit 2

Op 0

16-bit Opcode NONE

32-bit Opcode 0xA8

64-bit Opcode 0xE8

5.1.5.37 SLT - Set 1 if Less Than

Sets `$rd` as 1 if the signed representation of `$rs1` is less than the signed representation of `$rs2`, 0 otherwise.

Usage

```
slt $rd, $rs1, $rs2
```

Operation

```
if((signed)rs1 < (signed)rs2)
    rd = 1;
else
    rd = 0;
advance_pc();
```

Encoding

Type 0

Unit 1

Op 0

16-bit Opcode NONE

32-bit Opcode 0x84

64-bit Opcode 0xC4

5.1.5.38 SLTI - Set 1 if Less Than Immediate

Sets `$rd` as 1 if the signed representation of `$rs1` is less than the signed immediate field, 0 otherwise.

Usage

```
slti $rd, $rs1, imm
```

Operation

```
if((signed)rs1 < (signed)imm)
    rd = 1;
else
    rd = 0;
advance_pc();
```

Encoding

Type 1

Unit 1

Op 0

16-bit Opcode NONE

32-bit Opcode 0xA4

64-bit Opcode 0xE4

5.1.5.39 SLTIU - Set 1 if Less Than Immediate Unsigned

Sets `$rd` as 1 if the unsigned representation of `$rs1` is less than the unsigned immediate field, 0 otherwise.

Usage

```
sltiu $rd, $rs1, imm
```

Operation

```
if ((unsigned) rs1 < (unsigned) imm)
    rd = 1;
else
    rd = 0;
advance_pc();
```

Encoding

Type 1

Unit 1

Op 1

16-bit Opcode NONE

32-bit Opcode 0xA5

64-bit Opcode 0xE5

5.1.5.40 SLTU - Set 1 if Less Than Unsigned

Sets `$rd` as 1 if the unsigned representation of `$rs1` is less than the unsigned representation of `$rs2`, 0 otherwise.

Usage

```
sltu $rd, $rs1, $rs2
```

Operation

```
if((unsigned)rs1 < (unsigned)rs2)
    rd = 1;
else
    rd = 0;
advance_pc();
```

Encoding

Type 0

Unit 1

Op 1

16-bit Opcode NONE

32-bit Opcode 0x85

64-bit Opcode 0xC5

5.1.5.41 SRA - Shift Right Arithmetic

Shift the contents of register `$rs1` right by a number of bits specified in `$rs2`, sign-extending the value from `$rs1` and storing the result in `$rd`

Usage

```
sra $rd, $rs1, $rs2
```

Operation

```
rd = sign_extend(rs1)>>rs2;  
advance_pc();
```

Encoding

Type 0

Unit 2

Op 1

16-bit Opcode NONE

32-bit Opcode 0x89

64-bit Opcode 0xC9

5.1.5.42 SRAI - Shift Right Arithmetic Immediate

Shift the contents of register `$rs1` right by a number of bits specified in the immediate field, sign-extending the value from `$rs1` and storing the result in `$rd`

Usage

```
srai $rd, $rs1, imm
```

Operation

```
rd = sign_extend(rs1)>>imm;  
advance_pc();
```

Encoding

Type 1

Unit 2

Op 1

16-bit Opcode NONE

32-bit Opcode 0xA9

64-bit Opcode 0xE9

5.1.5.43 SRL - Shift Right Logical

Shift the contents of register `$rs1` right by a number of bits specified in `$rs2`, storing the result in `$rd`

Usage

```
srl $rd, $rs1, $rs2
```

Operation

```
rd = rs1>>rs2;  
advance_pc();
```

Encoding

Type 0

Unit 2

Op 2

16-bit Opcode NONE

32-bit Opcode 0x8A

64-bit Opcode 0xC8

5.1.5.44 SRLI - Shift Right Logical Immediate

Shift the contents of register `$rs1` right by a number of bits specified in the immediate field, storing the result in `$rd`

Usage

```
srli $rd, $rs1, imm
```

Operation

```
rd = rs1>>imm;  
advance_pc();
```

Encoding

Type 1

Unit 2

Op 2

16-bit Opcode NONE

32-bit Opcode 0xAA

64-bit Opcode 0xEA

5.1.5.45 SUB - Integer Subtract

Subtracts register `$rs2` from `$rs1`, placing the result in `$rd`.

Usage

```
sub $rd, $rs1, $rs2
```

Operation

```
rd = rs1 - rs2;  
advance_pc();
```

Encoding

Type 0

Unit 0

Op 1

16-bit Opcode 0x1

32-bit Opcode 0x81

64-bit Opcode 0xC1

5.1.5.46 SUBI - Integer Subtract Immediate

Subtracts a sign-extended immediate value from register `$rs1`, placing the result in `$rd`.

Usage

```
subi Rd, Rs1, imm
```

Operation

```
Rd = Rs1 - sign_extend(imm);  
advance_pc();
```

Encoding

Type 1

Unit 0

Op 1

16-bit Opcode 0x3

32-bit Opcode 0xA1

64-bit Opcode 0xE1

5.1.5.47 SW - Store 64-bit Word

Store 64-bit word `$rd` into the address located in `$rs1` offset by a signed immediate value.

Usage

```
sw $rd, imm($rs1)
```

Operation

```
* (rs+imm)    = rd[63:56];
* (rs+imm+1)  = rd[55:48];
* (rs+imm+2)  = rd[47:40];
* (rs+imm+3)  = rd[39:32];
* (rs+imm+4)  = rd[31:24];
* (rs+imm+5)  = rd[23:16];
* (rs+imm+6)  = rd[15:8];
* (rs+imm+7)  = rd[7:0];
advance_pc();
```

Encoding

Type 1

Unit 6

Op 0

16-bit Opcode NONE

32-bit Opcode 0xB8

64-bit Opcode 0xF8

5.1.5.48 SYSCALL - System Call

Request for kernel service (presently unimplemented pending addition of interrupts).

Usage

```
syscall
```

Operation

```
todo;  
advance_pc();
```

Encoding

Type 0

Unit 7

Op 0

16-bit Opcode 0x4

32-bit Opcode 0x9C

64-bit Opcode 0xDC

5.1.5.49 XOR - Bitwise XOR

XORs `$rs1` with `$rs2`, placing the result in `$rd`.

Usage

```
xor $rd, $rs1, $rs2
```

Operation

```
rd = rs1 ^ rs2;  
advance_pc();
```

Encoding

Type 0

Unit 3

Op 3

16-bit Opcode NONE

32-bit Opcode 0x8F

64-bit Opcode 0xCF

5.1.5.50 XORI - Bitwise XOR Immediate

XORs `$rs1` with an immediate value, placing the result in `$rd`.

Usage

```
xori $rd, $rs1, imm
```

Operation

```
rd = rs1 ^ imm;  
advance_pc();
```

Encoding

Type 1

Unit 3

Op 3

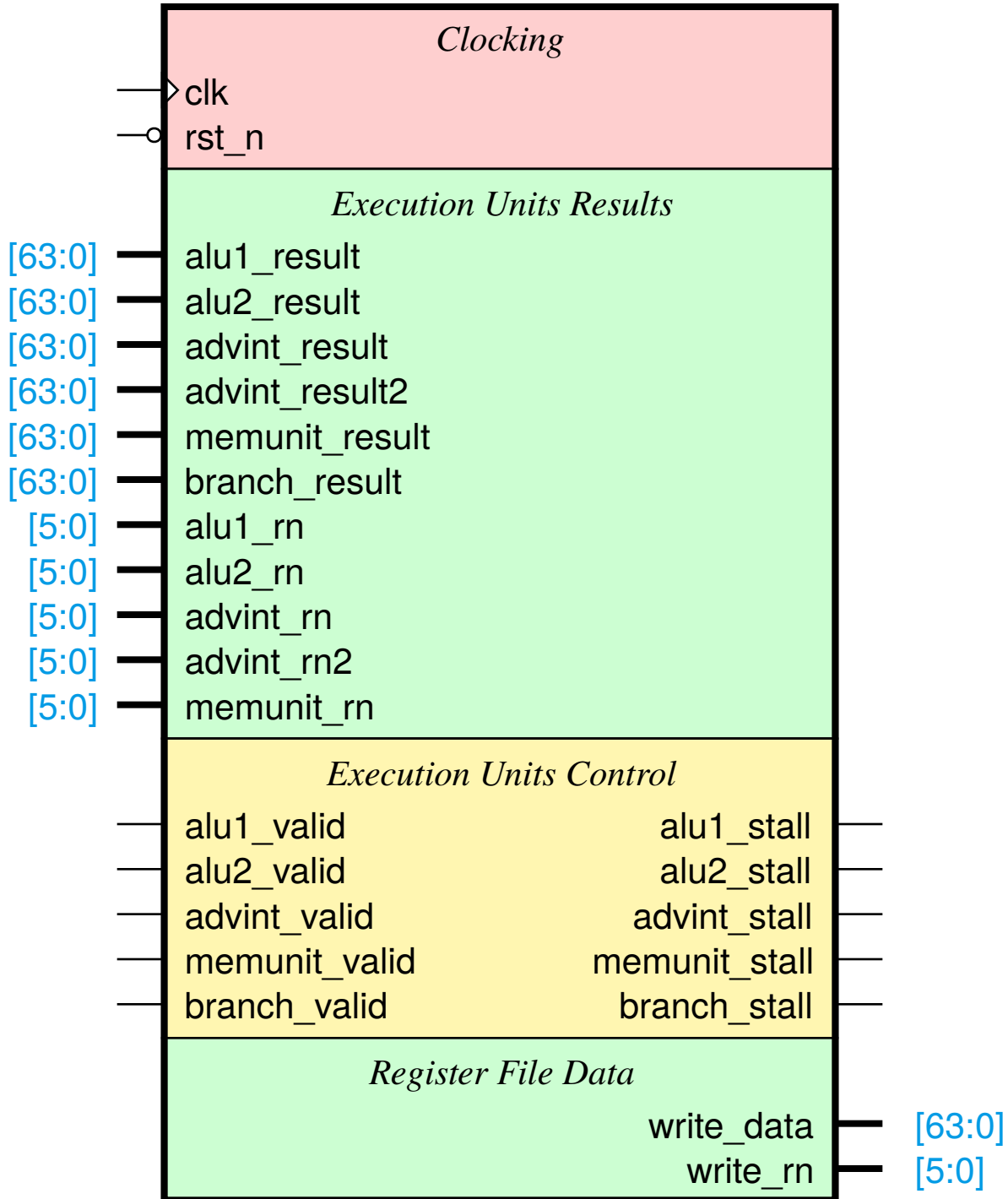
16-bit Opcode NONE

32-bit Opcode 0xAF

64-bit Opcode 0xEF

5.2 Verilog Module Index

5.2.1 commit.v



```

1 module commit (
2     // # {{clocks|Clocking}}

```

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```

3  input clk,
4  input rst_n,
5
6  /// {{data|Execution Units Results}}
7  input[63:0] alu1_result,
8  input[63:0] alu2_result,
9  input[63:0] advint_result,
10 input[63:0] advint_result2,
11 input[63:0] memunit_result,
12 input[63:0] branch_result,
13
14 input[5:0] alu1_rn,
15 input[5:0] alu2_rn,
16 input[5:0] advint_rn,
17 input[5:0] advint_rn2,
18 input[5:0] memunit_rn,
19
20 /// {{control|Execution Units Control}}
21 input alu1_valid,
22 input alu2_valid,
23 input advint_valid,
24 input memunit_valid,
25 input branch_valid,
26
27 output alu1_stall,
28 output alu2_stall,
29 output advint_stall,
30 output memunit_stall,
31 output branch_stall,
32
33 /// {{data|Register File Data}}
34 output[63:0] write_data,
35 output[5:0] write_rn
36 );
37
38 localparam STATE_IDLE = 3'h0;
39 localparam STATE_P1 = 3'h1;
40 localparam STATE_P2 = 3'h2;
41 localparam STATE_P3 = 3'h3;
42 localparam STATE_P4 = 3'h4;
43 localparam STATE_P5 = 3'h5;
44 localparam STATE_P6 = 3'h6;
45
46 reg[2:0] state, next_state;
47
48 reg[5:0] pending_rn[1:6];
49 reg[63:0] pending_data[1:6];
50 reg[6:1] pending_valid;
51
52 ///TODO Finish exception handling by un-stalling the ex units in strict order of_
↳issue (via external counting table)
53 ///For now, no exceptions are implemented.
54 assign alu1_stall = pending_valid[1] && state != STATE_P1;
55 assign alu2_stall = pending_valid[2] && state != STATE_P2;
56 assign advint_stall = (pending_valid[3] && state != STATE_P3) | (pending_valid[4] &
↳&& state != STATE_P4);
57 assign memunit_stall = pending_valid[5] && state != STATE_P5;

```

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```

58     assign branch_stall = pending_valid[6] && state != STATE_P6;
59
60     integer i;
61
62
63     //TODO A side-effect of the current implemtation is that a short running_
↳ instruction issued after a long running_
64     //one which affects the same destination register might get written/overwritten_
↳ in the wrong order. This will be
65     //fixed by the proposed PC instruction graduation control table necessary for_
↳ exceptions
66
67     //The *unit*_valid signals need to remain high for only one cycle per transaction_
↳ or all hell will break loose.
68     always @(posedge clk or negedge rst_n)
69     begin
70         if(~rst_n) begin
71             for(i = 1; i <= 6; i = i + 1) begin
72                 pending_data[i] <= 64'h0;
73                 pending_rn[i] <= 6'h0;
74                 pending_valid[i] <= 0;
75             end
76         end else begin
77             case(state)
78                 STATE_P1: pending_valid[1] <= 0;
79                 STATE_P2: pending_valid[2] <= 0;
80                 STATE_P3: pending_valid[3] <= 0;
81                 STATE_P4: pending_valid[4] <= 0;
82                 STATE_P5: pending_valid[5] <= 0;
83                 STATE_P6: pending_valid[6] <= 0;
84             endcase
85
86             if(alu1_valid & |alu1_rn) begin
87                 pending_data[1] <= alu1_result;
88                 pending_rn[1] <= alu1_rn;
89                 pending_valid[1] <= 1;
90
91             end if(alu2_valid & |alu2_rn) begin
92                 pending_data[2] <= alu2_result;
93                 pending_rn[2] <= alu2_rn;
94                 pending_valid[2] <= 1;
95
96             end if(advint_valid & (|advint_rn | |advint_rn2)) begin
97                 pending_data[3] <= advint_result;
98                 pending_rn[3] <= advint_rn;
99                 pending_valid[3] <= 1;
100                pending_data[4] <= advint_result2;
101                pending_rn[4] <= advint_rn2;
102                pending_valid[4] <= 1;
103
104            end if(memunit_valid & |memunit_rn) begin
105                pending_data[5] <= memunit_result;
106                pending_rn[5] <= memunit_rn;
107                pending_valid[5] <= 1;
108
109            end if(branch_valid) begin
110                pending_data[6] <= branch_result;

```

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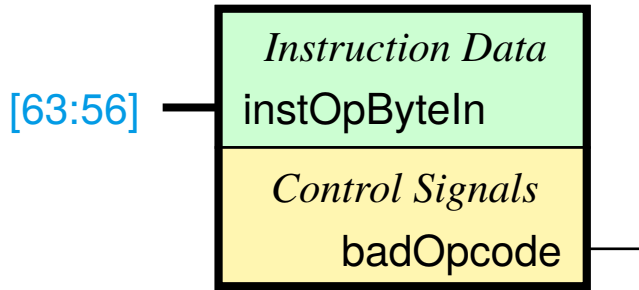
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```

111         pending_rn[6] <= 6'd63;
112         pending_valid[6] <= 1;
113     end
114 end
115 end
116
117 always @(posedge clk or negedge rst_n)
118 begin
119     if(~rst_n) state <= STATE_IDLE;
120     else state <= next_state;
121 end
122
123 always @(*)
124 begin
125     if((pending_valid[6] & state != STATE_P6) | branch_valid) next_state = STATE_
↪P6;
126     else if((pending_valid[5] & state != STATE_P5) | (memunit_valid & |memunit_
↪rn)) next_state = STATE_P5;
127     else if((pending_valid[4] & state != STATE_P4) | (advint_valid & |advint_
↪rn2)) next_state = STATE_P4;
128     else if((pending_valid[3] & state != STATE_P3) | (advint_valid & |advint_rn))_
↪next_state = STATE_P3;
129     else if((pending_valid[2] & state != STATE_P2) | (alu2_valid & |alu2_rn))_
↪next_state = STATE_P2;
130     else if((pending_valid[1] & state != STATE_P1) | (alu1_valid & |alu1_rn))_
↪next_state = STATE_P1;
131     else next_state = STATE_IDLE;
132 end
133
134 assign write_data = state == STATE_P1 ? pending_data[1] :
135                 state == STATE_P2 ? pending_data[2] :
136                 state == STATE_P3 ? pending_data[3] :
137                 state == STATE_P4 ? pending_data[4] :
138                 state == STATE_P5 ? pending_data[5] :
139                 state == STATE_P6 ? pending_data[6] :
140                 64'h0;
141
142 assign write_rn = state == STATE_P1 ? pending_rn[1] :
143                 state == STATE_P2 ? pending_rn[2] :
144                 state == STATE_P3 ? pending_rn[3] :
145                 state == STATE_P4 ? pending_rn[4] :
146                 state == STATE_P5 ? pending_rn[5] :
147                 state == STATE_P6 ? pending_rn[6] :
148                 6'h0;
149
150 endmodule

```

5.2.2 de_badDetect.v

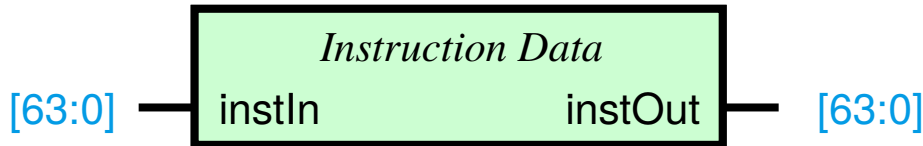


```

1  //Raisin64 Decode Unit - Bad Opcode Detector
2
3  module de_badDetect (
4      ## {{data|Instruction Data}}
5      input [63:56] instOpByteIn,
6
7      ## {{control|Control Signals}}
8      output badOpcode
9  );
10
11  `include "de_isa_def.vh"
12
13  reg badOpcode_pre;
14  wire is16, is32, is64;
15
16  assign badOpcode = badOpcode_pre;
17
18  assign is16 = ~instOpByteIn[63];
19  assign is32 = instOpByteIn[63:62] == 2'h2;
20  assign is64 = instOpByteIn[63:62] == 2'h3;
21
22  //Detects and flags invalid opcodes
23  always @(*)
24  begin
25      badOpcode_pre = 0;
26
27      if(is16 && instOpByteIn[62:60] == 3'h7) badOpcode_pre = 1;
28      else if(is32 | is64)
29      begin
30          case(instOpByteIn[61:56])
31              `OP_BAD_02, `OP_BAD_03, `OP_BAD_0B, `OP_BAD_14, `OP_BAD_15,
32              `OP_BAD_16, `OP_BAD_17, `OP_BAD_18, `OP_BAD_19, `OP_BAD_1A,
33              `OP_BAD_1B, `OP_BAD_22, `OP_BAD_23, `OP_BAD_2B: badOpcode_pre = 1;
34              `OP_FSTAR, `OP_LUI, `OP_JALI, `OP_JI: if(is32) badOpcode_pre = 1;
35          endcase
36      end
37  end
38  endmodule

```

5.2.3 de_canonicalize.v



```

1  //Raisin64 Decode Unit - Opcode Canonicalization
2  //Converts compact instructions into their true 64-bit native format
3
4  module de_canonicalize(
5      //# {{data/Instruction Data}}
6      input [63:0] instIn,
7      output [63:0] instOut
8  );
9
10     `include "de_isa_def.vh"
11
12     reg [63:0] instOut_pre;
13     assign instOut = instOut_pre;
14
15     //Expands input instruction into full 64-bit format
16     always @(*)
17     begin
18         instOut_pre = 64'h0;
19
20         //Set the output size field appropriately
21         instOut_pre[63:62] = 2'h3;
22
23         //16-Bit input instructions
24         if (~instIn[63])
25         begin
26             //Switch on Opcode field
27             case (instIn[62:60])
28                 `OP16_ADD:    instOut_pre[61:56] = `OP_ADD; //ADD Rd = Rd + Rs
29                 `OP16_SUB:    instOut_pre[61:56] = `OP_SUB; //SUB Rd = Rd - Rs
30                 `OP16_ADDI:   instOut_pre[61:56] = `OP_ADDI; //ADDI Rd = Rd + sign_
31                 `OP16_SUBI:   instOut_pre[61:56] = `OP_SUBI; //SUBI Rd = Rd - imm
32                 `OP16_SYSCALL: instOut_pre[61:56] = `OP_SYSCALL; //SYSCALL
33                 `OP16_J:      instOut_pre[61:56] = `OP_J; //J Rs
34                 `OP16_JAL:    instOut_pre[61:56] = `OP_JAL; //JAL Rs
35             endcase
36
37             instOut_pre[55:50] = instIn[59:54]; //Put the Rd/Rs1 into Rd
38             instOut_pre[49:44] = 6'h0; //Rd2 is not used in this format
39             instOut_pre[43:38] = instIn[59:54]; //Put the Rd/Rs1 into Rs1
40             instOut_pre[37:32] = instIn[53:48]; //Populate Rs2 (imm type instructions_
41             //ignore this)
42
43             //Sign extended immediate field and populate
44             instOut_pre[31:0] = {{26{instIn[53]}}, instIn[53:48]}; //reg type_
45             //instructions ignore this
46         end
47
48         //32-bit instructions

```

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```

47     else if (~instIn[62])
48     begin
49         instOut_pre[61:56] = instIn[61:56]; //Set Type/Unit/Op fields
50         instOut_pre[55:50] = instIn[55:50]; //Set Rd
51
52         //32I-Type instruction
53         if (instIn[61]) begin
54             instOut_pre[43:38] = instIn[49:44]; //Set Rs1
55
56             //Sign-Extended type
57             if (instIn[60] || //Most sign-extended Ops (remember, JALI and JI are
↳invalid for 32I)
58                 instIn[60:58] == 3'h0 || //ADDI/SUBI signed versions sign extend
59                 instIn[61:56] == `OP_SLTI || //SLTI and SGTI are signed and sign
↳extend
60                 instIn[61:56] == `OP_SGTI)
61                 instOut_pre[31:0] = {{20{instIn[43]}}, instIn[43:32]};
62             //Non Sign-extended type
63             else instOut_pre[11:0] = instIn[43:32];
64
65             //32R-Type instructions
66             end else begin
67                 //Set the other operands
68                 instOut_pre[49:32] = instIn[49:32];
69
70                 //No immediate
71             end
72         end
73         //64-bit instructions
74         else instOut_pre = instIn;
75     end
76 endmodule

```

5.2.4 debug_control.v

—	jtag_tck	jtag_tdo
—	jtag_tms	cpu_imem_addr
—	jtag_tdi	cpu_debug_to_imem_data
—	jtag_trst	cpu_imem_count
—	sys_rstn	cpu_imem_write
—	cpu_clk	cpu_dmem_addr
[63:0]	cpu_imem_to_debug_data	cpu_debug_to_dmem_data
—	cpu_imem_to_debug_data_ready	cpu_dmem_count
[63:0]	cpu_dmem_to_debug_data	cpu_dmem_write
—	cpu_dmem_to_debug_data_ready	cpu_halt_cpu
		cpu_resetsn_cpu

```

1  /* debug_control.v
2  *
3  * Example Debug Controller for a simple CPU using the JTAGlet interface
4  *
5  *-----
6  *
7  * Copyright 2018 Christopher Parish
8  *
9  * Licensed under the Apache License, Version 2.0 (the "License");
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11 * You may obtain a copy of the License at
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13 *   http://www.apache.org/licenses/LICENSE-2.0
14 *
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16 * distributed under the License is distributed on an "AS IS" BASIS,
17 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
18 * See the License for the specific language governing permissions and
19 * limitations under the License.
20 */
21
22 module debug_control(
23     input  jtag_tck,
24     input  jtag_tms,
25     input  jtag_tdi,
26     input  jtag_trst,
27     output jtag_tdo,
28
29     input sys_rstn, //System reset. Should NOT be externally tied to our cpu_resetsn_
    ↪cpu output
30
31     input cpu_clk,

```

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```

32
33     output reg[63:0] cpu_imem_addr,
34     output reg[63:0] cpu_debug_to_imem_data,
35     input [63:0] cpu_imem_to_debug_data,
36     input  cpu_imem_to_debug_data_ready,
37     output reg  cpu_imem_ce,
38     output reg  cpu_imem_we,
39
40     output reg[63:0] cpu_dmem_addr,
41     output reg[63:0] cpu_debug_to_dmem_data,
42     input [63:0] cpu_dmem_to_debug_data,
43     input  cpu_dmem_to_debug_data_ready,
44     output reg  cpu_dmem_ce,
45     output reg  cpu_dmem_we,
46
47     output reg  cpu_halt_cpu,
48     output  cpu_resetrn_cpu
49 );
50
51 //Signals from the JTAG TAP to the synchronizer
52 wire jtag_userOp_ready;
53
54 //Resulting signal in the CPU domain
55 wire cpu_userOp_ready;
56
57 //Requested operation/data from the TAP in the JTAG domain
58 wire[7:0] jtag_userOp;
59 wire[63:0] jtag_userData;
60
61 reg[63:0] cpu_userData;
62
63 //The Jtaglet JTAG TAP
64 jtaglet #(.ID_PARTVER(4'h1), .ID_PARTNUM(16'hCAFE), .ID_MANF(11'h035), .USERDATA_
↪LEN(64)) jtag_if
65     (.tck(jtag_tck), .tms(jtag_tms), .tdo(jtag_tdo), .tdi(jtag_tdi), .trst(jtag_
↪trst),
66     .userData_out(jtag_userData), .userData_in(cpu_userData), .userOp(jtag_
↪userOp),
67     .userOp_ready(jtag_userOp_ready));
68
69 //Synchronizer to take the userOp ready signal into the CPU clock domain
70 ff_sync #(.WIDTH(1)) userOpReady_toCPUDomain
71     (.clk(cpu_clk), .rst_p(~sys_rstn), .in_async(jtag_userOp_ready), .out(cpu_
↪userOp_ready));
72
73 //Stateless debug operations (which ignore debug register contents)
74 localparam DEBUGOP_NOOP_OP      = 8'h00;
75 localparam DEBUGOP_CPUHALT_OP   = 8'h01;
76 localparam DEBUGOP_CPURESUME_OP = 8'h02;
77 localparam DEBUGOP_CPURESET_OP  = 8'h03;
78
79 //Debug operations (use previously stored data to carry out an operation)
80 localparam DEBUGOP_READIMEM_OP  = 8'h04;
81 localparam DEBUGOP_WRITEIMEM_OP = 8'h05;
82 localparam DEBUGOP_READDMEM_OP  = 8'h06;
83 localparam DEBUGOP_WRITEDMEM_OP = 8'h07;
84

```

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```

85 //Load/store debug operations (have no side-effects apart from
86 //loading/storing the appropriate debug register)
87 localparam DEBUGOP_IADDR_REG    = 8'h80;
88 localparam DEBUGOP_IDATA_REG    = 8'h81;
89 localparam DEBUGOP_DADDR_REG    = 8'h82;
90 localparam DEBUGOP_DDATA_REG    = 8'h83;
91 localparam DEBUGOP_CPUFLAGS_REG = 8'h84;
92
93 reg cpu_userOp_ready_last;
94 wire execUserOp = ~cpu_userOp_ready_last & cpu_userOp_ready;
95
96 always @(posedge cpu_clk or negedge sys_rstn) begin
97     if(~sys_rstn) cpu_userOp_ready_last <= 0;
98     else cpu_userOp_ready_last <= cpu_userOp_ready;
99 end
100
101 always @(posedge cpu_clk or negedge sys_rstn) begin
102     if(~sys_rstn) begin
103         cpu_imem_we <= 0;
104         cpu_imem_ce <= 0;
105     end else begin
106         cpu_imem_we <= 0;
107         cpu_imem_ce <= 0;
108         if(execUserOp) case(jtag_userOp)
109             DEBUGOP_READIMEM_OP: cpu_imem_ce <= 1;
110             DEBUGOP_WRITEIMEM_OP: begin
111                 cpu_imem_we <= 1;
112                 cpu_imem_ce <= 1;
113             end
114         endcase
115     end
116 end
117
118 always @(posedge cpu_clk or negedge sys_rstn) begin
119     if(~sys_rstn) begin
120         cpu_dmem_we <= 0;
121         cpu_dmem_ce <= 0;
122     end else begin
123         cpu_dmem_we <= 0;
124         cpu_dmem_ce <= 0;
125         if(execUserOp) case(jtag_userOp)
126             DEBUGOP_READMEM_OP: cpu_dmem_ce <= 1;
127             DEBUGOP_WRITEDMEM_OP: begin
128                 cpu_dmem_we <= 1;
129                 cpu_dmem_ce <= 1;
130             end
131         endcase
132     end
133 end
134
135 always @(posedge cpu_clk) begin
136     if(execUserOp) case(jtag_userOp)
137         DEBUGOP_IADDR_REG: cpu_imem_addr <= jtag_userData;
138     endcase
139 end
140
141 always @(posedge cpu_clk) begin

```

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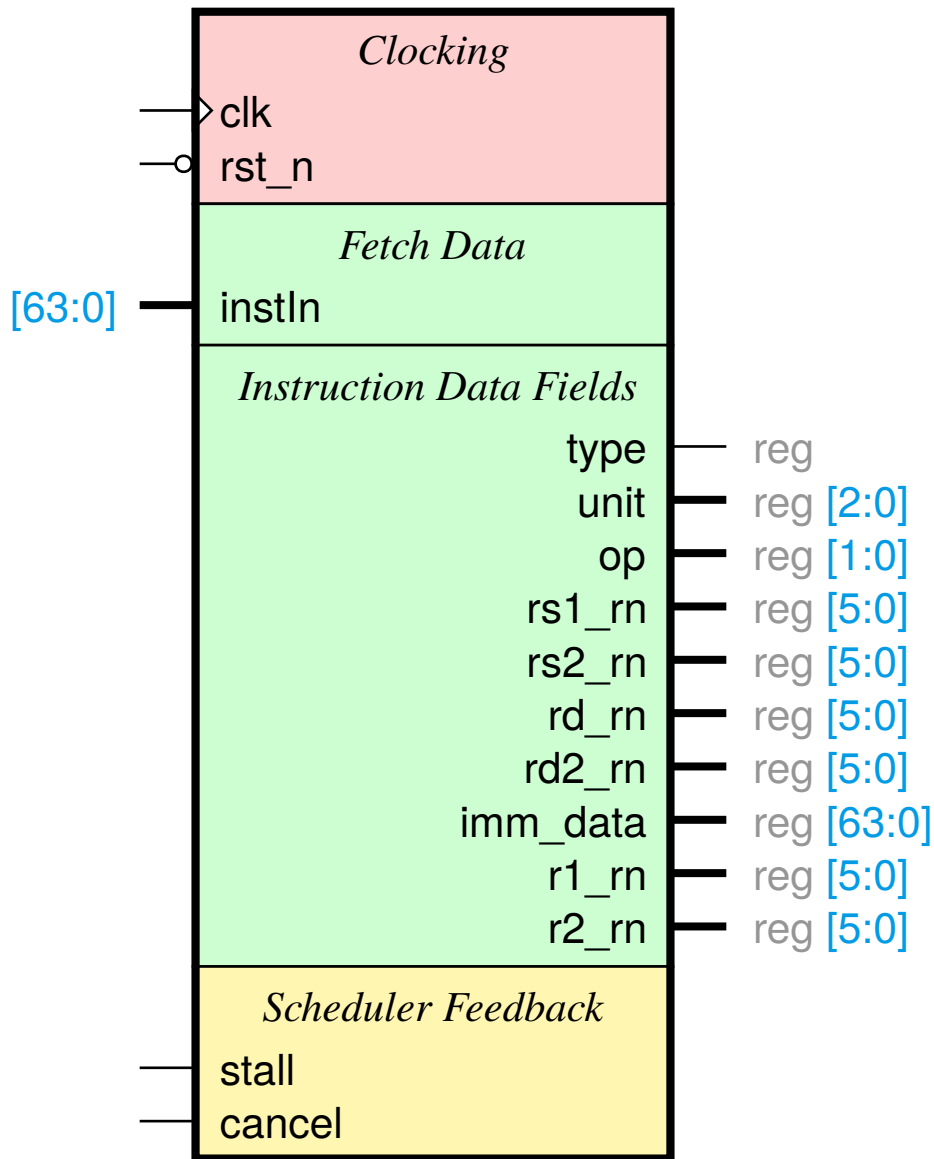
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```

142     if(execUserOp) case(jtag_userOp)
143         DEBUGOP_IDATA_REG: cpu_debug_to_imem_data <= jtag_userData;
144     endcase
145 end
146
147 always @(posedge cpu_clk) begin
148     if(execUserOp) case(jtag_userOp)
149         DEBUGOP_DADDR_REG: cpu_dmem_addr <= jtag_userData;
150     endcase
151 end
152
153 always @(posedge cpu_clk) begin
154     if(execUserOp) case(jtag_userOp)
155         DEBUGOP_DDATA_REG: cpu_debug_to_dmem_data <= jtag_userData;
156     endcase
157 end
158
159 always @(posedge cpu_clk or negedge sys_rstn) begin
160     if(~sys_rstn) begin
161         cpu_userData <= 0;
162     end else begin
163         if(cpu_imem_to_debug_data_ready) cpu_userData <= cpu_imem_to_debug_data;
164         else if(cpu_dmem_to_debug_data_ready) cpu_userData <= cpu_dmem_to_debug_
↪data;
165     end
166 end
167
168 //Reset Stretcher
169 reg requestReset;
170 reg[9:0] resetStretch;
171 assign cpu_resetsn_cpu = ~(|resetStretch);
172 always @(posedge cpu_clk or negedge sys_rstn) begin
173     if(~sys_rstn) resetStretch <= 10'b0;
174     else if(requestReset) resetStretch <= {10{1'b1}};
175     else if(resetStretch != 0) resetStretch <= resetStretch - 1;
176 end
177
178 always @(posedge cpu_clk or negedge sys_rstn) begin
179     if(~sys_rstn) begin
180         cpu_halt_cpu <= 0;
181         requestReset <= 0;
182     end else begin
183         requestReset <= 0;
184         if(execUserOp) case(jtag_userOp)
185             DEBUGOP_CPUHALT_OP: cpu_halt_cpu <= 1;
186             DEBUGOP_CPURESUME_OP: cpu_halt_cpu <= 0;
187             DEBUGOP_CPURESET_OP: begin
188                 cpu_halt_cpu <= 0;
189                 requestReset <= 1;
190             end
191         endcase
192     end
193 end
194
195 endmodule

```


5.2.5 decode.v



```

1  //Raisin64 Instruction Decode
2
3  module decode(
4      //# {{clocks|Clocking}}
5      input clk,
6      input rst_n,
7
8      //# {{data|Fetch Data}}
9      input [63:0] instIn,
10
11     //# {{data|Instruction Data Fields}}
12     output reg type,
13     output reg [2:0] unit,
14     output reg [1:0] op,

```

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```

15  output reg[5:0] rs1_rn,
16  output reg[5:0] rs2_rn,
17  output reg[5:0] rd_rn,
18  output reg[5:0] rd2_rn,
19  output reg[63:0] imm_data,
20
21  //Indicates which registers are loaded for this instruction
22  output reg[5:0] r1_rn,
23  output reg[5:0] r2_rn,
24
25  //# {{control|Scheduler Feedback}}
26  input  stall,
27  input  cancel
28  );
29
30  wire[63:0] canonInst;
31  wire badOpcode;
32
33  de_canonicalize de_canonicalize_1(
34      .instIn(instIn), .instOut(canonInst)
35  );
36
37  de_badDetect de_badDetect_1(
38      .instOpByteIn(instIn[63:56]), .badOpcode(badOpcode)
39  );
40
41  reg load_rs1, load_rs1_rs2, load_rs1_rd;
42
43  reg signedImm;
44
45  always @(*) begin
46      signedImm = 0;
47      casex(canonInst[60:56])
48          5'b000xx, //ADD, SUB
49          5'b001x0, //SLTI, SGTI
50          5'b10xxx, //LW, L32, L16, L8, LUI, L32S, L16S, L8S
51          5'b110xx, //SW, S32, S16, S8
52          5'b1110x: signedImm = 1; //BEQ, BEQAL
53      endcase
54  end
55
56  wire ji_type;
57  assign ji_type = &canonInst[61:57]; //Imm Type, Unit 7, JALI or JI
58
59  always @(*) begin
60      load_rs1 = 0;
61      load_rs1_rs2 = 0;
62      load_rs1_rd = 0;
63
64      if(~canonInst[61]) begin //R-Type
65          if(canonInst[60:58] < 3'h5 || //Units 0-4
66              (&canonInst[60:58] && canonInst[57:56] == 2'h1)) begin //F* Inst
67              load_rs1_rs2 = 1;
68          end else if(&canonInst[60:58] & canonInst[57]) begin //JAL, J
69              load_rs1 = 1;
70          end
71      end else begin //I-Type

```

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```

72     if(canonInst[60:58] < 3'h5 || //Units 0-4
73         canonInst[60:58] == 3'h5 && |canonInst[57:56]) begin //Unit 5 except LUI
74         load_rsl = 1;
75     end else if(canonInst[60:58] == 3'h6 | //Unit 6
76         &canonInst[60:58] & ~canonInst[57]) begin //BEQ, BEQAL
77         load_rsl_rd = 1;
78     end
79 end
80 end
81
82 always @(posedge clk or negedge rst_n)
83 begin
84     if(~rst_n) begin
85         type <= 0;
86         unit <= 0;
87         op <= 0;
88         rsl_rn <= 0;
89         rs2_rn <= 0;
90         rd_rn <= 0;
91         rd2_rn <= 0;
92         imm_data <= 0;
93         r1_rn <= 0;
94         r2_rn <= 0;
95     end else begin
96         if(cancel) begin
97             type <= 0;
98             unit <= 0;
99             op <= 0;
100             rsl_rn <= 0;
101             rs2_rn <= 0;
102             rd_rn <= 0;
103             rd2_rn <= 0;
104             imm_data <= 0;
105             r1_rn <= 0;
106             r2_rn <= 0;
107         end else if(~stall) begin
108             type <= canonInst[61];
109             unit <= canonInst[60:58];
110             op <= canonInst[57:56];
111             rsl_rn <= canonInst[43:38];
112             rs2_rn <= canonInst[37:32];
113             rd_rn <= canonInst[55:50];
114             rd2_rn <= canonInst[49:44];
115             imm_data <= ji_type ? {{7{1'b0}}, canonInst[55:0], 1'b0} : //TODO Need_
116             ↳to decide how upper bits are handled
117                 signedImm ? {{32{canonInst[31]}}, canonInst[31:0]} :
118                 {{32{1'b0}}, canonInst[31:0]};
119
120             r1_rn <= (load_rsl|load_rsl_rs2|load_rsl_rd) ? canonInst[43:38] : 6
121             ↳'h0;
122             r2_rn <= load_rsl_rd ? canonInst[55:50] :
123                 load_rsl_rs2 ? canonInst[37:32] :
124                 6'h0;
125         end
126     end
127 end

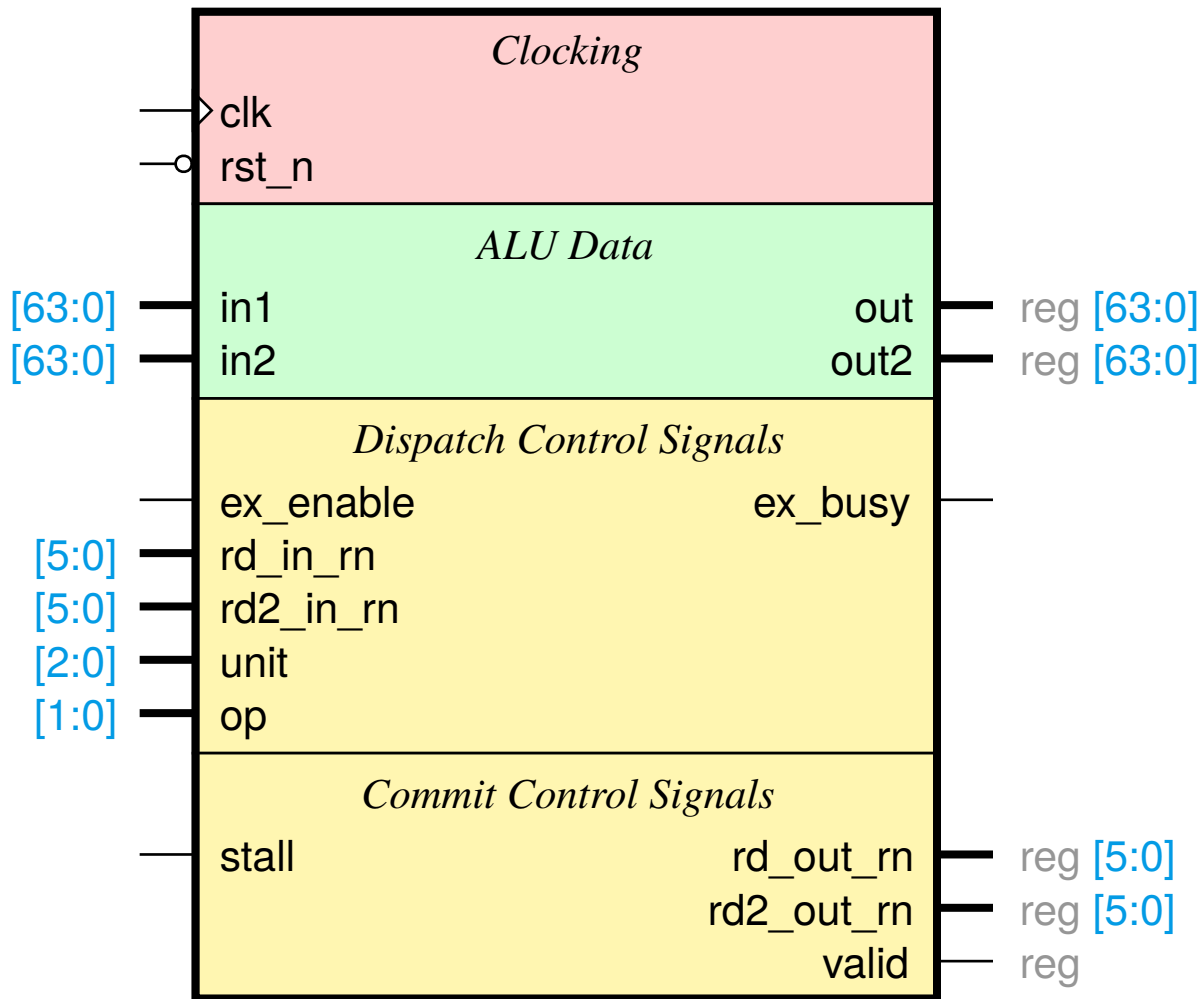
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127 `endmodule`

5.2.6 ex_advint.v



```

1  //Raisin64 Execute Unit - Advanced Integer Unit
2
3  module ex_advint(
4      //# {{clocks|Clocking}}
5      input clk,
6      input rst_n,
7
8      //# {{data|ALU Data}}
9      input [63:0] in1,
10     input [63:0] in2,
11     output reg [63:0] out,
12     output reg [63:0] out2,
13
14     //# {{control|Dispatch Control Signals}}
15     input ex_enable,
16     output ex_busy,
17     input [5:0] rd_in_rn,
18     input [5:0] rd2_in_rn,
19     input [2:0] unit,

```

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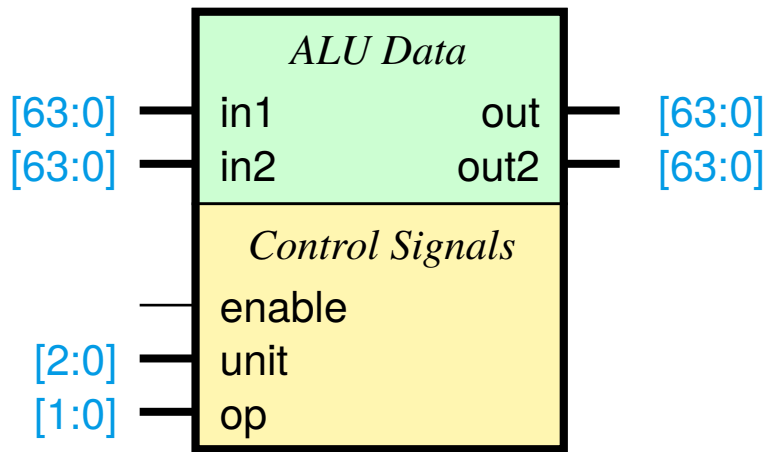
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```

20  input[1:0] op,
21
22  //# {{control|Commit Control Signals}}
23  output reg[5:0] rd_out_rn,
24  output reg[5:0] rd2_out_rn,
25  output reg valid,
26  input stall
27  );
28
29  wire[63:0] out_pre;
30  wire[63:0] out2_pre;
31
32  //We allow the next result to register when we aren't explicitly beign
33  //stalled by the next stage (i.e. our result has somewhere to go).
34  always @(posedge clk or negedge rst_n)
35  begin
36      if(~rst_n) begin
37          valid <= 0;
38          out <= 64'h0;
39          out2 <= 64'h0;
40          rd_out_rn <= 6'h0;
41          rd2_out_rn <= 6'h0;
42      end else begin
43          valid <= ex_enable;
44          out <= out_pre;
45          out2 <= out2_pre;
46          rd_out_rn <= rd_in_rn;
47          rd2_out_rn <= rd2_in_rn;
48      end
49  end
50
51  initial begin
52      if(stall&ex_enable) $error("Told to execute AdvInt when commit was stalled");
53  end
54
55  //As this is a one-cycle stage for now, busy is simple
56  assign ex_busy = stall;
57
58  ex_advint_s1 ex_advint_s1_1(
59      .in1(in1), .in2(in2), .out(out_pre), .out2(out2_pre),
60      .enable(ex_enable), .unit(unit), .op(op)
61  );
62
63  endmodule

```

5.2.7 ex_advint_s1.v



```

1  //Raisin64 Execute Unit - Advanced Integer Unit - Stage 1
2
3  //For now, we just use the intrinsic * and / operations. These do have the
4  //advantage of mapping to DSP hard-blocks on our example SoC design.
5
6  module ex_advint_s1(
7      //# {{data|ALU Data}}
8      input [63:0] in1,
9      input [63:0] in2,
10     output [63:0] out,
11     output [63:0] out2,
12
13     //# {{control|Control Signals}}
14     input enable,
15     input [2:0] unit,
16     input [1:0] op
17 );
18
19 reg [127:0] out_pre;
20 assign out = out_pre[63:0];
21 assign out2 = out_pre[127:64];
22
23 always @(*)
24 begin
25     out_pre = 128'h0;
26
27     if(enable & unit==3'h4) begin
28         case(op)
29             0: out_pre = $signed(in1) * $signed(in2); //MUL
30             1: out_pre = in1 * in2; //MULU
31             2,3: out_pre = {in2, in1}; //TODO div stubbed for now
32         //
33         //     out_pre[63:0] = $signed(in1) / $signed(in2);
34         //     out_pre[127:64] = $signed(in1) % $signed(in2);
35         //     end
36         //
37         3: begin //DIVU
38             //     out_pre[63:0] = in1 / in2;
39             //     out_pre[127:64] = in1 % in2;

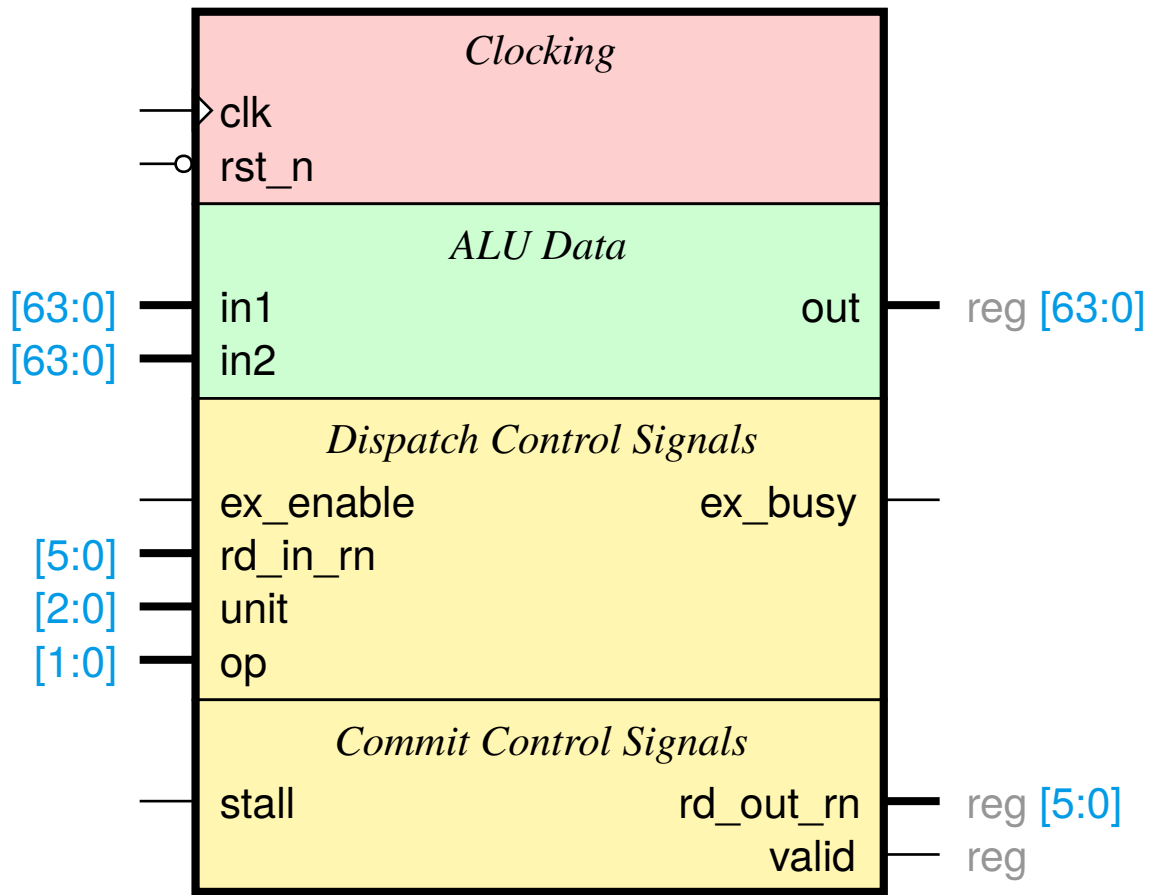
```

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```
39 //                               end
40         endcase
41     end
42 end
43 endmodule
```


5.2.8 ex_alu.v



```

1  //Raisin64 Execute Unit - Integer ALU
2
3  module ex_alu(
4      //# {{clocks|Clocking}}
5      input clk,
6      input rst_n,
7
8      //# {{data|ALU Data}}
9      input[63:0] in1,
10     input[63:0] in2,
11     output reg[63:0] out,
12
13     //# {{control|Dispatch Control Signals}}
14     input ex_enable,
15     output ex_busy,
16     input[5:0] rd_in_rn,
17     input[2:0] unit,
18     input[1:0] op,
19
20     //# {{control|Commit Control Signals}}
21     output reg[5:0] rd_out_rn,
22     output reg valid,
23     input stall

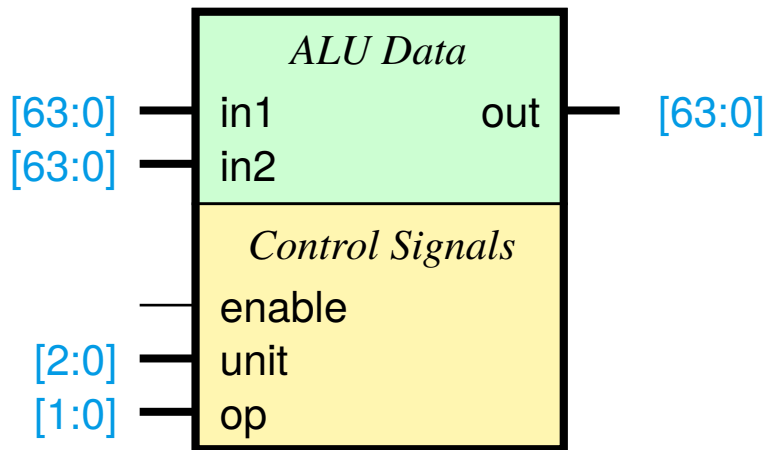
```

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```
24     );
25
26     wire[63:0] out_pre;
27
28     //We allow the next result to register when we aren't explicitly beign
29     //stalled by the next stage (i.e. our result has somewhere to go).
30     always @(posedge clk or negedge rst_n)
31     begin
32         if(~rst_n) begin
33             valid <= 0;
34             out <= 64'h0;
35             rd_out_rn <= 6'h0;
36         end else if(~stall) begin
37             valid <= ex_enable;
38             out <= out_pre;
39             rd_out_rn <= rd_in_rn;
40         end
41     end
42
43     initial begin
44         if(stall&ex_enable) $error("Told to execute ALU when commit was stalled");
45     end
46
47     //As this is a one-cycle stage, busy is simple
48     assign ex_busy = stall;
49
50     ex_alu_s1 ex_alu_s1_1(
51         .in1(in1), .in2(in2), .out(out_pre), .enable(ex_enable),
52         .unit(unit), .op(op)
53     );
54
55 endmodule
```

5.2.9 ex_alu_s1.v



```

1  //Raisin64 Execute Unit - Integer ALU Stage 1
2
3  module ex_alu_s1(
4      //# {{data|ALU Data}}
5      input [63:0] in1,
6      input [63:0] in2,
7      output [63:0] out,
8
9      //# {{control|Control Signals}}
10     input enable,
11     input [2:0] unit,
12     input [1:0] op
13 );
14
15     reg [63:0] out_pre;
16     assign out = out_pre;
17
18     always @(*)
19     begin
20         out_pre = 64'h0;
21         if(enable) case(unit)
22             3'h0: //Basic integer math
23                 case(op[0])
24                     0: out_pre = in1 + in2; //ADD
25                     1: out_pre = in1 - in2; //SUB
26                 endcase
27             3'h1: //Compare/Set
28                 case(op)
29                     0: out_pre = $signed(in1) < $signed(in2) ? 64'h1 : 64'h0; //SLT
30                     1: out_pre = in1 < in2 ? 64'h1 : 64'h0; //SLTU
31                     2: out_pre = $signed(in1) > $signed(in2) ? 64'h1 : 64'h0; //SGT
32                     3: out_pre = in1 > in2 ? 64'h1 : 64'h0; //SGTU
33                 endcase
34             3'h2: //Shift
35                 case(op)
36                     0: out_pre = in1 << {|in2[63:6], in2[5:0]}; //SLL
37                     1: out_pre = in1 >>> {|in2[63:6], in2[5:0]}; //SRA
38                     2,3: out_pre = in1 >> {|in2[63:6], in2[5:0]}; //SRL

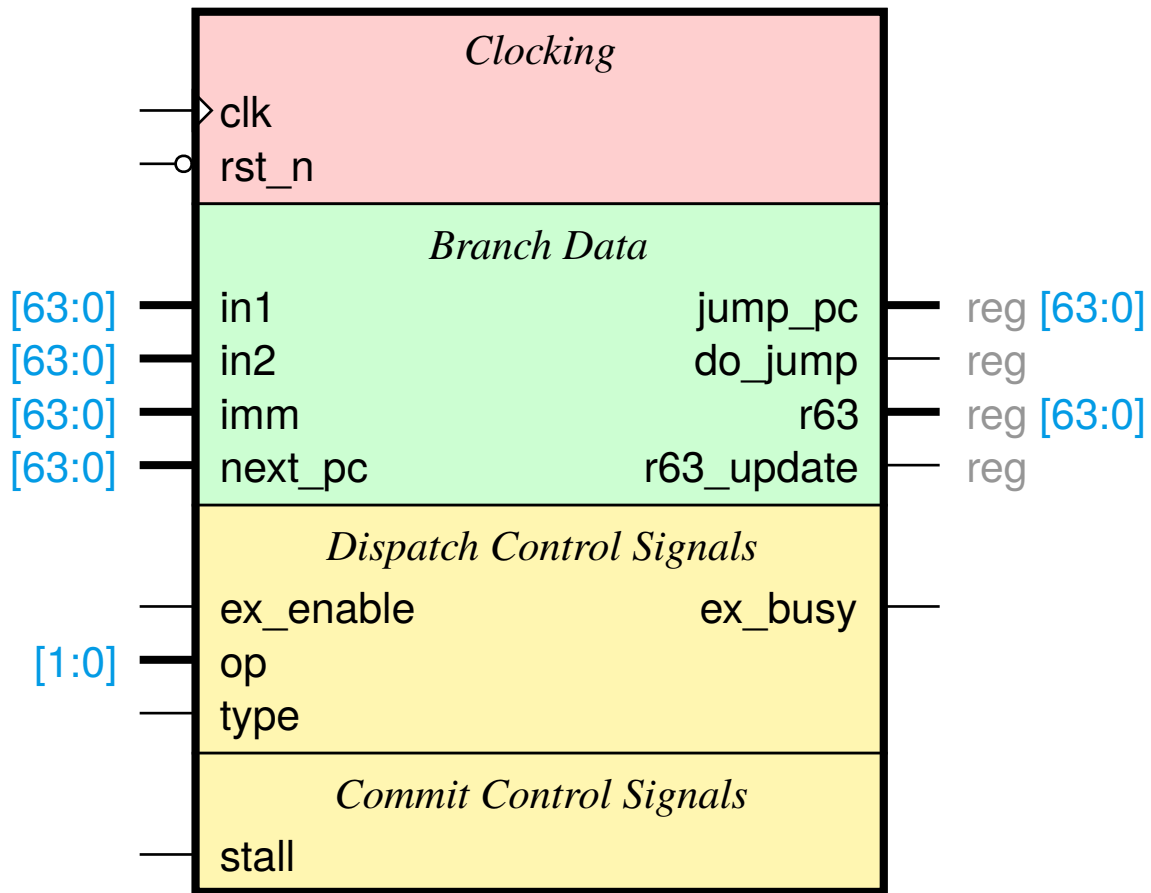
```

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```
39         endcase
40     3'h3: //Bitwise Operations
41         case (op)
42             0: out_pre = in1 & in2; //AND
43             1: out_pre = !(in1 | in2); //NOR
44             2: out_pre = in1 | in2; //OR
45             3: out_pre = in1 ^ in2; //XOR
46         endcase
47     endcase
48 end
49 endmodule
```

5.2.10 ex_branch.v



```

1  //Raisin64 Execute Unit - Branch and Jump Unit
2
3  module ex_branch(
4      //# {{clocks|Clocking}}
5      input clk,
6      input rst_n,
7
8      //# {{data|Branch Data}}
9      input [63:0] in1,
10     input [63:0] in2,
11     input [63:0] imm,
12     input [63:0] next_pc,
13     output reg [63:0] jump_pc,
14     output reg do_jump,
15
16     output reg [63:0] r63,
17     output reg r63_update,
18
19     //# {{control|Dispatch Control Signals}}
20     input ex_enable,
21     output ex_busy,
22     input [1:0] op,
23     input type,

```

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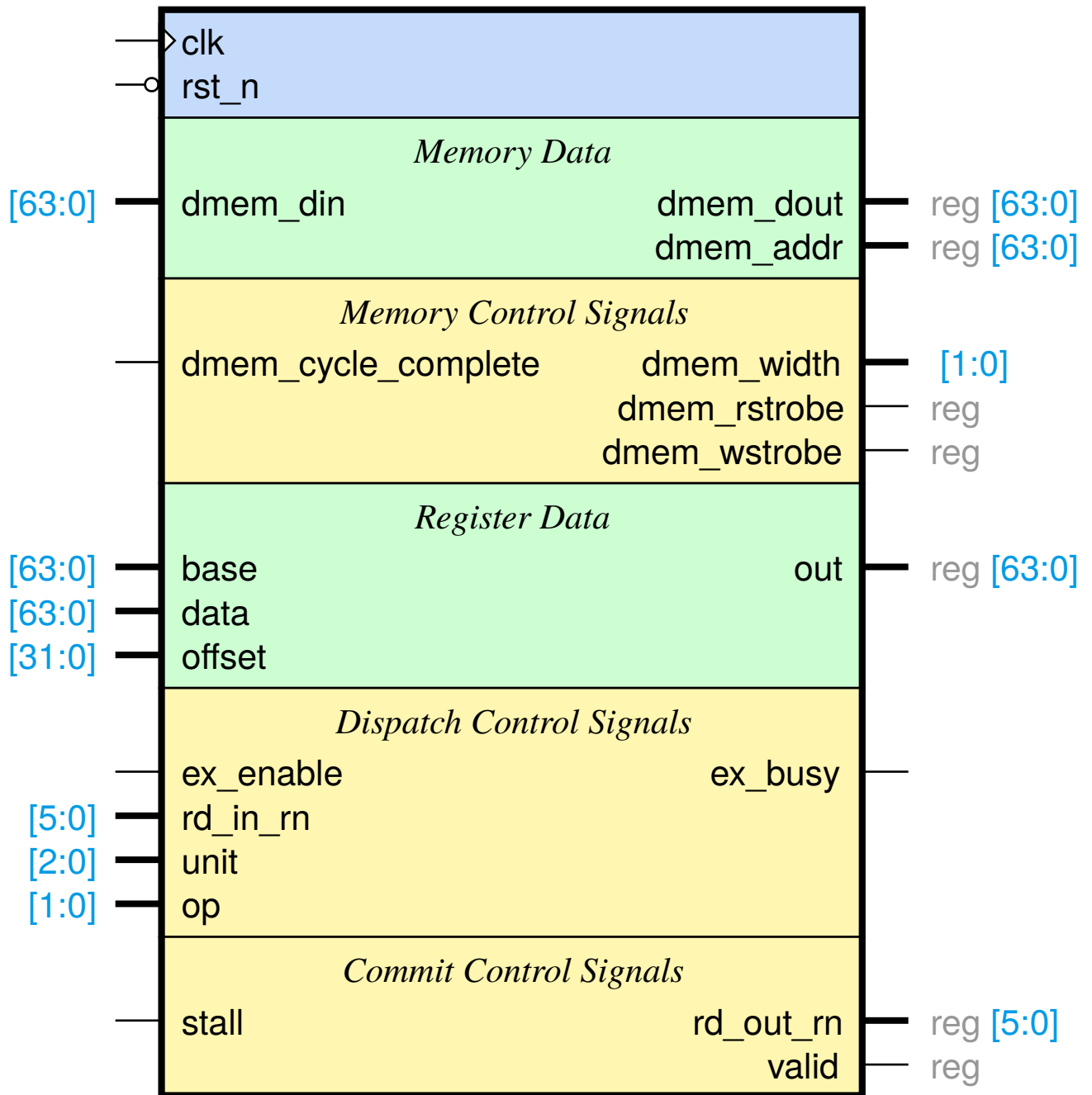
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```

24
25  //# {{control|Commit Control Signals}}
26  input stall
27  );
28
29  wire op_eq;
30  assign op_eq = (in1 == in2);
31
32  always @(posedge clk or negedge rst_n)
33  begin
34      if(~rst_n) begin
35          jump_pc <= 64'h0;
36          do_jump <= 0;
37          r63 <= 64'h0;
38          r63_update <= 0;
39      end else begin
40          jump_pc <= 64'h0;
41          do_jump <= 0;
42          r63 <= 64'h0;
43          r63_update <= 0;
44
45          if(ex_enable) begin
46              if(op[1]) begin //Jump
47                  //Input is already properly shifted by the time it gets here
48                  jump_pc <= type ? imm : in1;
49                  do_jump <= 1;
50                  if(op[0]) begin //And Link
51                      r63_update <= 1;
52                      r63 <= next_pc;
53                  end
54              end else if (~op[1] & op_eq) begin //Branch
55                  jump_pc <= next_pc + (imm<<1);
56                  do_jump <= 1;
57                  if(op[0]) begin //And Link
58                      r63_update <= 1;
59                      r63 <= next_pc;
60                  end
61              end
62          end
63      end
64  end
65
66  assign ex_busy = ex_enable | stall;
67
68  endmodule

```

5.2.11 ex_memory.v



```

1 //Raisin64 Execute Unit - Memory Unit
2
3 `include "io_def.vh"
4
5 module ex_memory(
6     input clk,
7     input rst_n,
8

```

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```

9      /// {{data|Memory Data}}
10     input [63:0] dmem_din,
11     output reg [63:0] dmem_dout,
12     output reg [63:0] dmem_addr,
13
14     /// {{control|Memory Control Signals}}
15     input dmem_cycle_complete,
16     output [1:0] dmem_width,
17     output reg dmem_rstrobe,
18     output reg dmem_wstrobe,
19
20     /// {{data|Register Data}}
21     input [63:0] base, //R1
22     input [63:0] data, //R2
23     input [31:0] offset,
24     output reg [63:0] out,
25
26     /// {{control|Dispatch Control Signals}}
27     input ex_enable,
28     output ex_busy,
29     input [5:0] rd_in_rn,
30     input [2:0] unit,
31     input [1:0] op,
32
33     /// {{control|Commit Control Signals}}
34     output reg [5:0] rd_out_rn,
35     output reg valid,
36     input stall
37 );
38
39 localparam START = 2'h0;
40 localparam READ_WAIT = 2'h1;
41 localparam WRITE_WAIT = 2'h2;
42
43 ////////////////////////////////////
44 //// Registering of control signals ////
45 ////////////////////////////////////
46
47 reg [5:0] rd_in_rn_reg;
48 reg [2:0] unit_reg;
49 reg [1:0] op_reg;
50
51 always @(posedge clk or negedge rst_n)
52 begin
53     if (~rst_n) begin
54         rd_in_rn_reg <= 6'h0;
55         unit_reg <= 3'h0;
56         op_reg <= 2'h0;
57     end else if (ex_enable) begin
58         rd_in_rn_reg <= rd_in_rn;
59         unit_reg <= unit;
60         op_reg <= op;
61     end
62 end
63
64 //Signals associated with the incoming instruction (and only valid at ex_enable)
65 wire load, store, lui;

```

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```

66     assign load = (unit == 3'h4 || //Regular load
67                   (unit == 3'h5 && op != 2'h0)); //Sign-Extend load except LUI
68
69     assign store = (unit == 3'h6); //Store
70     assign lui = (unit == 3'h5 && op == 2'h0); //LUI
71
72     //Signals using the registered control signals
73     wire sign_extend_reg;
74     assign sign_extend_reg = (unit_reg == 3'h5 && op_reg != 2'h0); //Sign-Extend load_
↳except LUI
75
76     assign dmem_width = op_reg;
77
78     //////////////////////////////////////
79     /// State machine control ///
80     //////////////////////////////////////
81
82     reg[1:0] state;
83
84     assign ex_busy = ex_enable || stall || (state != START && ~dmem_cycle_complete);
85
86     always @(posedge clk or negedge rst_n)
87     begin
88         if(~rst_n) begin
89             state <= START;
90             out <= 64'h0;
91             valid <= 1'b0;
92             rd_out_rn <= 6'h0;
93             dmem_dout <= 64'h0;
94             dmem_addr <= 64'h0;
95             dmem_rstrobe <= 1'b0;
96             dmem_wstrobe <= 1'b0;
97         end else begin
98
99             case(state)
100             START: begin
101                 valid <= 0;
102                 rd_out_rn <= 6'h0;
103                 dmem_rstrobe <= 0;
104                 dmem_wstrobe <= 0;
105
106                 if(ex_enable) begin
107                     if(load) begin
108                         state <= READ_WAIT;
109                         dmem_addr <= base + offset;
110                         dmem_rstrobe <= 1;
111                     end else if(store) begin
112                         dmem_addr <= base + offset;
113                         dmem_dout <= data;
114                         dmem_wstrobe <= 1;
115                         state <= WRITE_WAIT;
116                     end else if(lui) begin
117                         out <= {offset,{32{1'b0}}};
118                         valid <= 1;
119                         rd_out_rn <= rd_in_rn;
120                     end
121                 end

```

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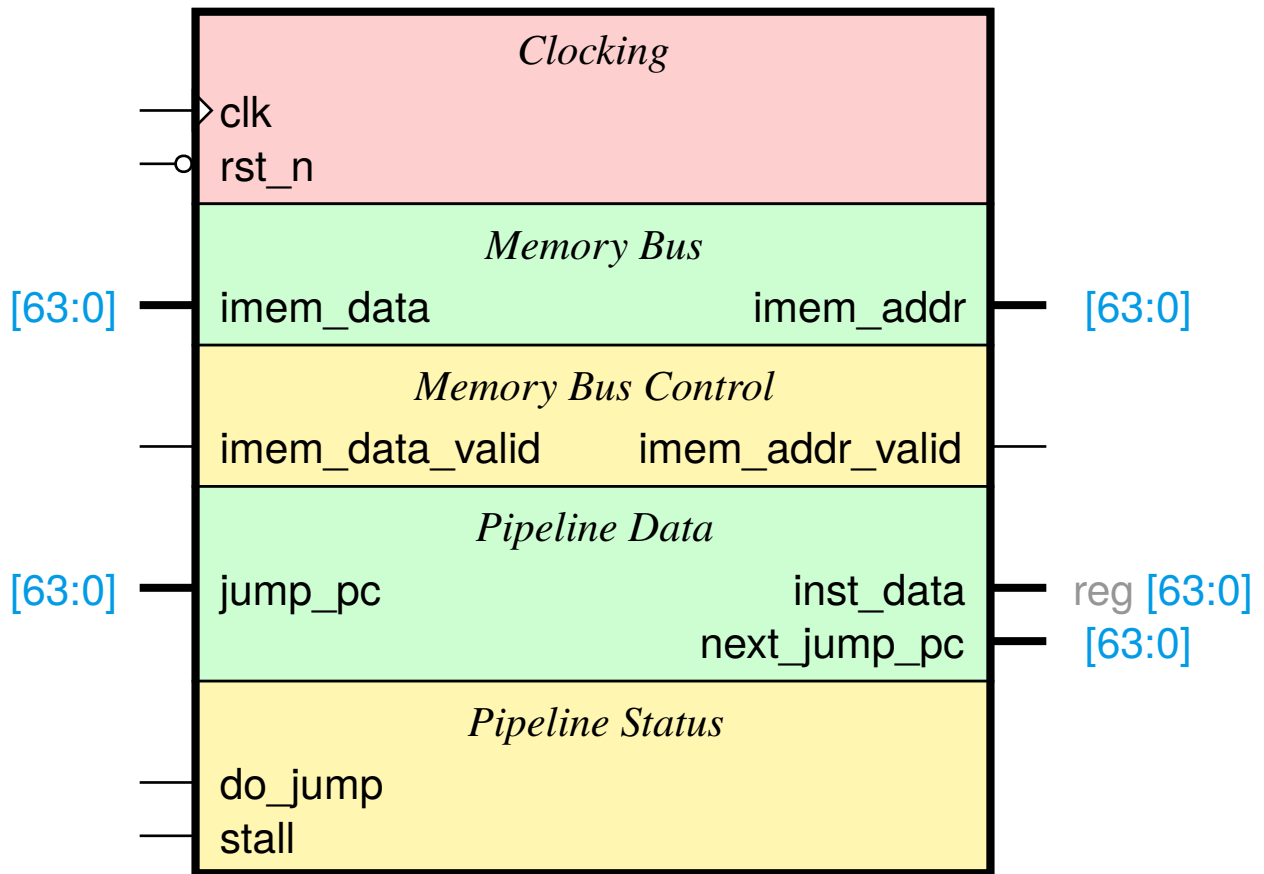
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```

122     end
123
124     READ_WAIT: begin
125         dmem_rstrobe <= 0;
126         if (dmem_cycle_complete) begin
127             valid <= 1;
128             rd_out_rn <= rd_in_rn_reg;
129             case (op_reg)
130                 //64-Bit load
131                 `RAM_WIDTH64: out <= dmem_din;
132
133                 //32-Bit load
134                 `RAM_WIDTH32: out <= sign_extend_reg ? {{32{dmem_din[63]}}}, dmem_
135                     ↳din[63:32]] :
136                     {{32{1'b0}}}, dmem_din[63:32]];
137
138                 //16-Bit load
139                 `RAM_WIDTH16: out <= sign_extend_reg ? {{48{dmem_din[63]}}}, dmem_
140                     ↳din[63:48]] :
141                     {{48{1'b0}}}, dmem_din[63:48]];
142
143                 //8-Bit load
144                 `RAM_WIDTH8: out <= sign_extend_reg ? {{56{dmem_din[63]}}}, dmem_
145                     ↳din[63:56]] :
146                     {{56{1'b0}}}, dmem_din[63:56]];
147             endcase
148             state <= START;
149         end
150     end
151
152     WRITE_WAIT: begin
153         dmem_wstrobe <= 0;
154         if (dmem_cycle_complete) begin
155             valid <= 1;
156             state <= START;
157         end
158     end
159
160     default: begin
161         state <= START; //TODO Throw exception
162     end
163 endcase
164 end
165 endmodule

```

5.2.12 fetch.v



```

1  //Raisin64 - Fetch Module
2  module fetch(
3      //# {{clocks|Clocking}}
4      input clk,
5      input rst_n,
6
7      //# {{data|Memory Bus}}
8      output [63:0] imem_addr,
9      input [63:0] imem_data,
10
11     //# {{control|Memory Bus Control}}
12     input imem_data_valid,
13     output imem_addr_valid,
14
15     //# {{data|Pipeline Data}}
16     output reg [63:0] inst_data,
17     output [63:0] next_jump_pc,
18     input [63:0] jump_pc,
19
20     //# {{control|Pipeline Status}}
21     input do_jump,
22     input stall
23 );
24

```

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```

25  reg[63:0] pc, next_pc, prev_pc;
26
27  always @(posedge clk or negedge rst_n)
28  begin
29      if(~rst_n) begin
30          //pc <= 64'h0;
31          prev_pc <= 64'h0;
32      end else begin
33          //pc <= next_pc;
34          prev_pc <= pc;
35      end
36  end
37
38  assign imem_addr = pc;
39
40  //Becuae the PC is "ahead" by a cycle and the data leaving the fetch
41  //module is "behind", our prev_pc will actually point at the next PC
42  //for any associated jumps.
43  assign next_jump_pc = prev_pc;
44
45  reg[63:0] next_seq_pc;
46  always @(*) begin
47      casex(imem_data[63:62])
48      2'b0x: next_seq_pc = prev_pc + 2;
49      2'b10: next_seq_pc = prev_pc + 4;
50      2'b11: next_seq_pc = prev_pc + 8;
51      endcase
52  end
53
54  always @(*) begin
55      pc = prev_pc;
56      if(do_jump) pc = jump_pc;
57      else if(stall) pc = prev_pc;
58      else if(imem_data_valid) begin
59          pc = next_seq_pc;
60      end
61  end
62
63  reg[63:0] next_data;
64  always @(*) begin
65      next_data = inst_data;
66      if(imem_data_valid) next_data = imem_data;
67  end
68
69  reg[63:0] prev_data;
70  reg just_stalled;
71  always @(posedge clk or negedge rst_n)
72  begin
73      if(~rst_n) begin
74          just_stalled <= 0;
75          inst_data <= 64'h0;
76      end else begin
77          just_stalled <= stall;
78          if(~imem_data_valid | do_jump) inst_data <= 64'h0;
79          else if(~stall) inst_data <= imem_data;
80      end
81  end

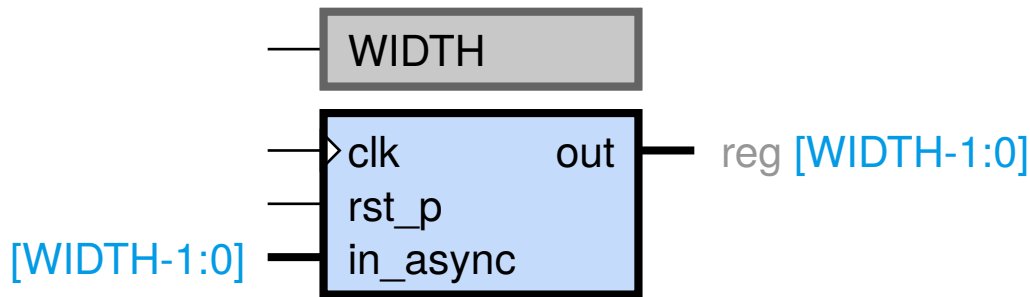
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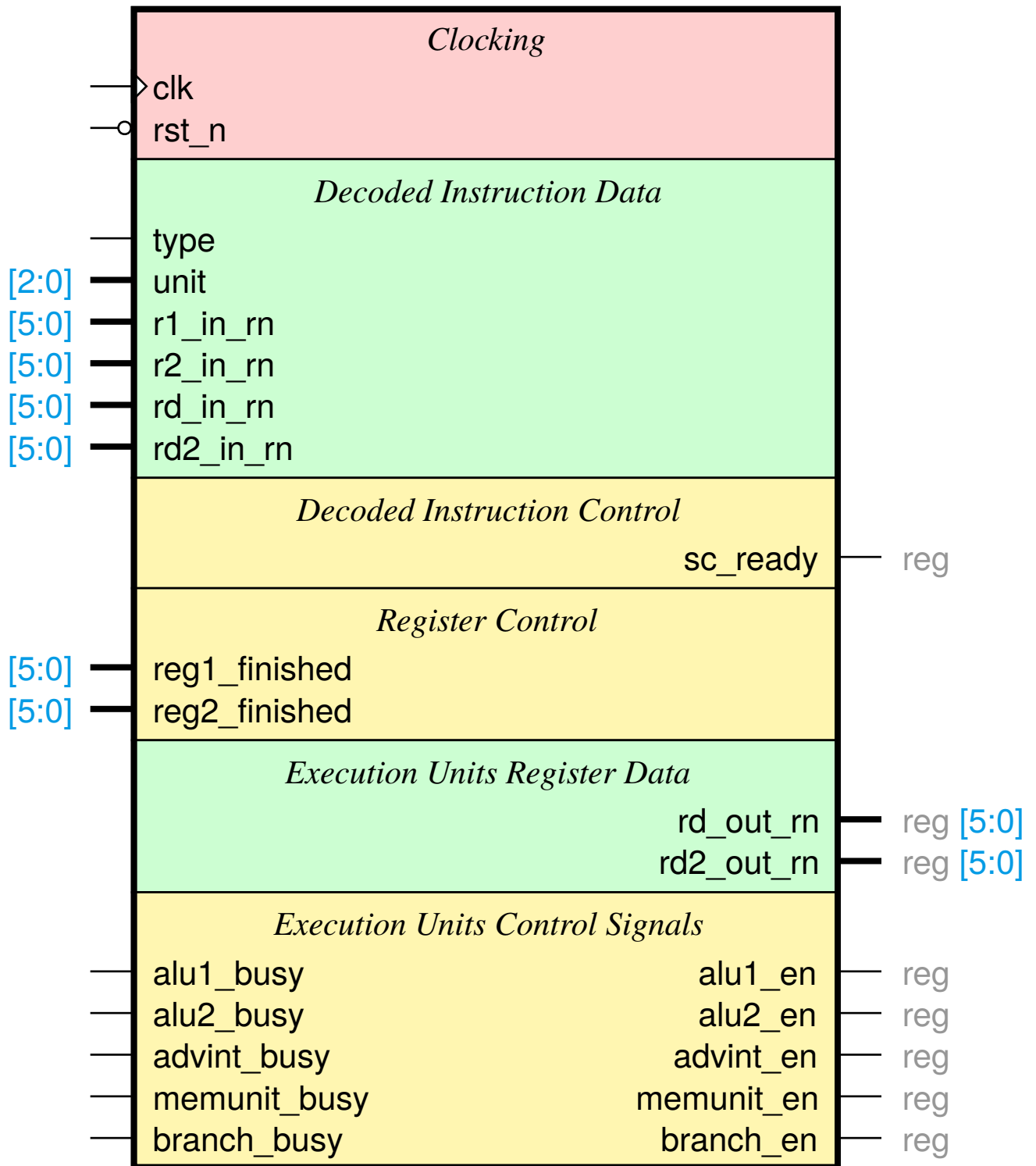
```
82      //assign inst_data = ~imem_data_valid ? 64'h0 :  stall/just_stalled ? prev_data :
83      ↪imem_data;
84      assign imem_addr_valid = 1;
85
86  endmodule
```

5.2.13 ff_sync.v



```
1  //Copyright 2017 Christopher Parish
2  //
3  //Licensed under the Apache License, Version 2.0 (the "License");
4  //you may not use this file except in compliance with the License.
5  //You may obtain a copy of the License at
6  //
7  // http://www.apache.org/licenses/LICENSE-2.0
8  //
9  //Unless required by applicable law or agreed to in writing, software
10 //distributed under the License is distributed on an "AS IS" BASIS,
11 //WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
12 //See the License for the specific language governing permissions and
13 //limitations under the License.
14
15 module ff_sync #(parameter WIDTH=1) (
16     input clk,
17     input rst_p,
18     input [WIDTH-1:0] in_async,
19     output reg [WIDTH-1:0] out);
20
21     (* ASYNC_REG = "TRUE" *) reg [WIDTH-1:0] sync_reg;
22     always @(posedge clk, posedge rst_p) begin
23         if(rst_p) begin
24             sync_reg <= 0;
25             out <= 0;
26         end else begin
27             {out, sync_reg} <= {sync_reg, in_async};
28         end
29     end
30
31 endmodule
```

5.2.14 schedule.v



```

1 //Raisin64 Instruction Scheduler
2 //Schedules a ready instruction to a free execution unit capable of servicing it

```

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```

3
4 module schedule(
5     //# {{clocks|Clocking}}
6     input clk,
7     input rst_n,
8
9     //# {{data|Decoded Instruction Data}}
10    input type,
11    input [2:0] unit,
12    input [5:0] r1_in_rn,
13    input [5:0] r2_in_rn,
14    input [5:0] rd_in_rn,
15    input [5:0] rd2_in_rn,
16
17    //# {{control|Decoded Instruction Control}}
18    output reg sc_ready,
19
20    //# {{control|Register Control}}
21    input [5:0] reg1_finished,
22    input [5:0] reg2_finished,
23
24    //# {{data|Execution Units Register Data}}
25    output reg [5:0] rd_out_rn,
26    output reg [5:0] rd2_out_rn,
27
28    //# {{control|Execution Units Control Signals}}
29    output reg alu1_en,
30    output reg alu2_en,
31    output reg advint_en,
32    output reg memunit_en,
33    output reg branch_en,
34
35    input alu1_busy,
36    input alu2_busy,
37    input advint_busy,
38    input memunit_busy,
39    input branch_busy
40 );
41
42 reg [63:0] reg_busy;
43
44 wire alu_type, advint_type, memunit_type, branch_type;
45 assign alu_type = ~unit[2];
46 assign advint_type = ~type && unit==3'h4;
47 assign memunit_type = type && (unit==3'h4 | unit==3'h5 | unit==3'h6);
48 assign branch_type = unit==3'h7;
49
50 wire instIssued;
51 assign instIssued = alu1_en | alu2_en | advint_en | memunit_en | branch_en;
52
53 reg operand_unavailable;
54
55 always @(*)
56 begin
57     operand_unavailable = 0;
58
59     //The register was previously busy

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```

60     if(reg_busy[r1_in_rn] && r1_in_rn!=reg1_finished && r1_in_rn!=reg2_finished)
↳operand_unavailable = 1;
61     else if(reg_busy[r2_in_rn] && r2_in_rn!=reg2_finished && r2_in_rn!=reg1_
↳finished) operand_unavailable = 1;
62
63     //We just issued something to an execution unit
64     else if(instIssued) begin
65         //The incoming source register is non-zero
66         if(|r1_in_rn) begin
67             //And it matches the previous destination register number. We
68             //will stall here until it is picked up by reg_busy next cycle
69             if(rd_out_rn==r1_in_rn) operand_unavailable = 1;
70             else if(rd2_out_rn==r1_in_rn) operand_unavailable = 1;
71
72         end
73         if(|r2_in_rn) begin
74             if(rd_out_rn==r2_in_rn) operand_unavailable = 1;
75             else if(rd2_out_rn==r2_in_rn) operand_unavailable = 1;
76         end
77     end
78 end
79
80 always @(*)
81 begin
82     sc_ready = 0;
83     if(~operand_unavailable & ~branch_busy) begin //TODO Branch busy condition_
↳can probably be moved outside the module via muxing of the unit_en lines with the_
↳operation cancel signal
84         if(alu_type & (~alu1_busy | ~alu2_busy)) sc_ready = 1;
85         else if(advint_type & ~advint_busy) sc_ready = 1;
86         else if(memunit_type & ~memunit_busy) sc_ready = 1;
87         else if(branch_type) sc_ready = 1;
88     end
89 end
90
91 always @(posedge clk or negedge rst_n)
92 begin
93     if(~rst_n) begin
94         alu1_en <= 0;
95         alu2_en <= 0;
96         advint_en <= 0;
97         memunit_en <= 0;
98         branch_en <= 0;
99         rd_out_rn <= 6'h0;
100        rd2_out_rn <= 6'h0;
101        reg_busy <= 64'h0;
102
103    end else begin
104        //Only allow the scheduling of instructions if the source registers
105        //aren't the destination of in-progress instructions.
106        alu1_en <= 0;
107        alu2_en <= 0;
108        advint_en <= 0;
109        memunit_en <= 0;
110        branch_en <= 0;
111
112        reg_busy[reg1_finished] <= 0;

```

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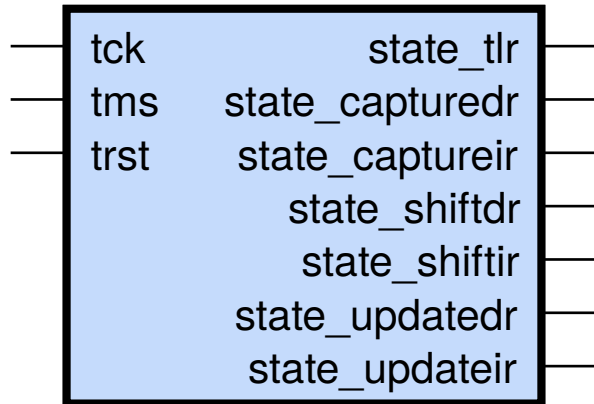
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```

113     reg_busy[reg2_finished] <= 0;
114
115     if(~operand_unavailable & ~branch_busy) begin
116         if(alu_type & ~alu1_busy) begin
117             alu1_en <= 1;
118             rd_out_rn <= rd_in_rn;
119             if(|rd_in_rn) reg_busy[rd_in_rn] <= 1;
120
121         end else if(alu_type & ~alu2_busy) begin
122             alu2_en <= 1;
123             rd_out_rn <= rd_in_rn;
124             if(|rd_in_rn) reg_busy[rd_in_rn] <= 1;
125
126         end else if(advint_type & ~advint_busy) begin
127             advint_en <= 1;
128             rd_out_rn <= rd_in_rn;
129             rd2_out_rn <= rd2_in_rn;
130             if(|rd_in_rn) reg_busy[rd_in_rn] <= 1;
131             if(|rd2_in_rn) reg_busy[rd2_in_rn] <= 1;
132
133         end else if(memunit_type & ~memunit_busy) begin
134             memunit_en <= 1;
135             rd_out_rn <= rd_in_rn;
136             if(|rd_in_rn && unit!=3'h6) reg_busy[rd_in_rn] <= 1;
137
138         end else if(branch_type) begin
139             branch_en <= 1;
140             rd_out_rn <= rd_in_rn;
141             //No need to mark R63 busy. If the branch is taken, other
142             //instructions in the pipeline are cancelled.
143         end
144     end
145 end
146 end
147
148 endmodule

```

5.2.15 jtag_state_machine.v



```

1  /* jtag_state_machine.v
2  *
3  * JTAG TAP State Machine
4  *
5  *-----
6  *
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8  *
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16 * distributed under the License is distributed on an "AS IS" BASIS,
17 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
18 * See the License for the specific language governing permissions and
19 * limitations under the License.
20 */
21
22 module jtag_state_machine(
23     input tck,
24     input tms,
25     input trst,
26
27     output state_tlr,
28     output state_capturedr,
29     output state_captureir,
30     output state_shiftdr,
31     output state_shiftir,
32     output state_updatedr,
33     output state_updateir
34
35 );
36
37 localparam TEST_LOGIC_RESET = 4'h0;
38 localparam RUN_TEST_IDLE   = 4'h1;
39 localparam SELECT_DR       = 4'h2;
40 localparam CAPTURE_DR      = 4'h3;

```

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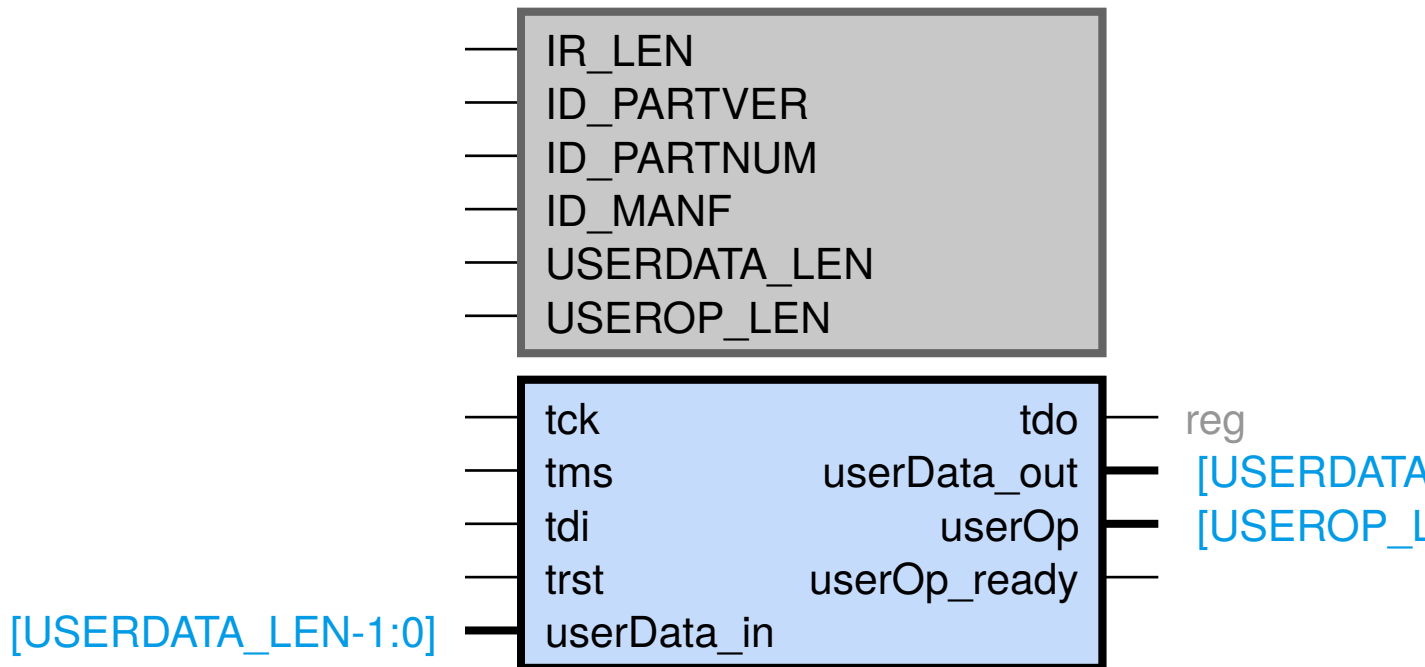
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```

41  localparam SHIFT_DR      = 4'h4;
42  localparam EXIT1_DR     = 4'h5;
43  localparam PAUSE_DR     = 4'h6;
44  localparam EXIT2_DR     = 4'h7;
45  localparam UPDATE_DR    = 4'h8;
46  localparam SELECT_IR    = 4'h9;
47  localparam CAPTURE_IR   = 4'hA;
48  localparam SHIFT_IR     = 4'hB;
49  localparam EXIT1_IR     = 4'hC;
50  localparam PAUSE_IR     = 4'hD;
51  localparam EXIT2_IR     = 4'hE;
52  localparam UPDATE_IR    = 4'hF;
53
54  reg[3:0] state;
55
56  always @(posedge tck or negedge trst) begin
57      if (~trst) begin
58          state <= TEST_LOGIC_RESET;
59      end else begin
60          case (state)
61              TEST_LOGIC_RESET: state <= tms ? TEST_LOGIC_RESET : RUN_TEST_IDLE;
62              RUN_TEST_IDLE:   state <= tms ? SELECT_DR : RUN_TEST_IDLE;
63              SELECT_DR :     state <= tms ? SELECT_IR : CAPTURE_DR;
64              CAPTURE_DR :    state <= tms ? EXIT1_DR : SHIFT_DR;
65              SHIFT_DR:      state <= tms ? EXIT1_DR : SHIFT_DR;
66              EXIT1_DR:      state <= tms ? UPDATE_DR : PAUSE_DR;
67              PAUSE_DR:      state <= tms ? EXIT2_DR : PAUSE_DR;
68              EXIT2_DR:      state <= tms ? UPDATE_DR : SHIFT_DR;
69              UPDATE_DR:     state <= tms ? SELECT_DR : RUN_TEST_IDLE;
70              SELECT_IR:     state <= tms ? TEST_LOGIC_RESET : CAPTURE_IR;
71              CAPTURE_IR:    state <= tms ? EXIT1_IR : SHIFT_IR;
72              SHIFT_IR :     state <= tms ? EXIT1_IR : SHIFT_IR;
73              EXIT1_IR:      state <= tms ? UPDATE_IR : PAUSE_IR;
74              PAUSE_IR:      state <= tms ? EXIT2_IR : PAUSE_IR;
75              EXIT2_IR:      state <= tms ? UPDATE_IR : SHIFT_IR;
76              UPDATE_IR:     state <= tms ? SELECT_DR : RUN_TEST_IDLE;
77          endcase
78      end
79  end
80
81  //I was going to use a function, but Vivado pooped itself when I tried. Typical...
82  assign state_tlr = (state == TEST_LOGIC_RESET);
83  assign state_capturedr = (state == CAPTURE_DR);
84  assign state_captureir = (state == CAPTURE_IR);
85  assign state_shiftdr = (state == SHIFT_DR);
86  assign state_shiftir = (state == SHIFT_IR);
87  assign state_updatedr = (state == UPDATE_DR);
88  assign state_updateir = (state == UPDATE_IR);
89
90  endmodule

```

5.2.16 jtaglet.v



```

1  /* jtaglet.v
2  *
3  * Top module for the JTAGlet JTAG TAP project
4  *
5  *-----
6  *
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16 * distributed under the License is distributed on an "AS IS" BASIS,
17 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
18 * See the License for the specific language governing permissions and
19 * limitations under the License.
20 */
21
22 module jtaglet #(
23     parameter IR_LEN = 4,
24     parameter ID_PARTVER = 4'h0,
25     parameter ID_PARTNUM = 16'h0000,
26     parameter ID_MANF = 11'h000,
27     parameter USERDATA_LEN = 32,
28     parameter USEROP_LEN = 8
29 ) (
30     input tck,
31     input tms,

```

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```

32  input tdi,
33  output reg tdo,
34  input trst,
35
36  input[USERDATA_LEN-1:0] userData_in,
37  output[USERDATA_LEN-1:0] userData_out,
38  output[USEROP_LEN-1:0] userOp,
39  output userOp_ready
40  );
41
42  localparam USERDATA_OP = 4'b1000;
43  localparam USEROP_OP = 4'b1001;
44  localparam IDCODE_OP = {(IR_LEN-1){1'b1}},1'b0}; //e.g. b1110
45  localparam BYPASS_OP = {IR_LEN{1'b1}}; // e.g. b1111 (required bit pattern per_
↳ spec)
46
47  wire[31:0] idcode = {ID_PARTVER, ID_PARTNUM, ID_MANF, 1'b1};
48
49  wire state_tlr, state_capturedr, state_captureir, state_shiftdr, state_shiftir,
50  state_updatedr, state_updateir;
51
52  jtag_state_machine jsm(.tck(tck), .tms(tms), .trst(trst), .state_tlr(state_tlr),
53  .state_capturedr(state_capturedr), .state_captureir(state_captureir),
54  .state_shiftdr(state_shiftdr), .state_shiftir(state_shiftir),
55  .state_updatedr(state_updatedr), .state_updateir(state_updateir));
56
57  reg[IR_LEN-1:0] ir_reg;
58
59  //USERDATA - DR becomes a USERDATA_LEN bit user data register passed out of the_
↳ module
60  wire userData_tdo;
61  jtag_reg #(.IR_LEN(IR_LEN), .DR_LEN(USERDATA_LEN), .IR_OPCODE(USERDATA_OP)) _
↳ userData_reg
62  (.tck(tck), .trst(trst), .tdi(tdi), .tdo(userData_tdo), .state_tlr(state_tlr),
63  .state_capturedr(state_capturedr), .state_shiftdr(state_shiftdr),
64  .state_updatedr(state_updatedr), .ir_reg(ir_reg), .dr_dataOut(userData_out),
65  .dr_dataIn(userData_in), .dr_dataOutReady());
66
67  //USEROPCODE - DR becomes an 8 bit operation select/initiate register passed out_
↳ of the module
68  wire userOp_tdo;
69  jtag_reg #(.IR_LEN(IR_LEN), .DR_LEN(USEROP_LEN), .IR_OPCODE(USEROP_OP)) userOp_reg
70  (.tck(tck), .trst(trst), .tdi(tdi), .tdo(userOp_tdo), .state_tlr(state_tlr),
71  .state_capturedr(state_capturedr), .state_shiftdr(state_shiftdr),
72  .state_updatedr(state_updatedr), .ir_reg(ir_reg), .dr_dataOut(userOp),
73  .dr_dataIn(8'b0), .dr_dataOutReady(userOp_ready));
74
75  //IDCODE - DR is pre-loaded with the 32 bit identification code of this part
76  wire idcode_tdo;
77  jtag_reg #(.IR_LEN(IR_LEN), .DR_LEN(32), .IR_OPCODE(IDCODE_OP)) idcode_reg
78  (.tck(tck), .trst(trst), .tdi(tdi), .tdo(idcode_tdo), .state_tlr(state_tlr),
79  .state_capturedr(state_capturedr), .state_shiftdr(state_shiftdr),
80  .state_updatedr(1'b0), .ir_reg(ir_reg), .dr_dataOut(),
81  .dr_dataIn(idcode), .dr_dataOutReady());
82
83  //BYPASS - DR becomes a 1 bit wide register, suitable for bypassing this part
84  wire bypass_tdo;

```

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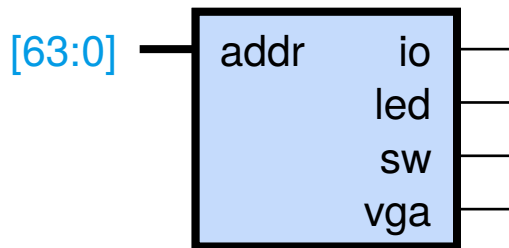
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```

85     jtag_reg #(.IR_LEN(IR_LEN), .DR_LEN(1), .IR_OPCODE(BYPASS_OP)) bypass_reg
86         (.tck(tck), .trst(trst), .tdi(tdi), .tdo(bypass_tdo), .state_tlr(state_tlr),
87         .state_capturedr(state_capturedr), .state_shiftdr(state_shiftdr),
88         .state_updatedr(1'b0), .ir_reg(ir_reg), .dr_dataOut(),
89         .dr_dataIn(1'b0), .dr_dataOutReady());
90
91     //Instruction Register
92     wire ir_tdo;
93     assign ir_tdo = ir_reg[0];
94     always @(posedge tck or negedge trst) begin
95         if(~trst) begin
96             ir_reg <= IDCODE_OP;
97         end else if(state_tlr) begin
98             ir_reg <= IDCODE_OP;
99         end else if(state_captureir) begin
100             //We need to load the BYPASS reg with seq ending in 01.
101             ir_reg <= {(IR_LEN-1){1'b0}},1'b1}; //e.g. b0001
102         end else if(state_shiftir) begin
103             ir_reg <= {tdi, ir_reg[IR_LEN-1:1]};
104         end
105     end
106
107     //IR selects the appropriate DR
108     reg tdo_pre;
109     always @(*) begin
110         tdo_pre = 0;
111         if(state_shiftdr) begin
112             case(ir_reg)
113                 IDCODE_OP:      tdo_pre = idcode_tdo;
114                 BYPASS_OP:      tdo_pre = bypass_tdo;
115                 USERDATA_OP:    tdo_pre = userData_tdo;
116                 USEROP_OP:      tdo_pre = userOp_tdo;
117                 default:         tdo_pre = bypass_tdo;
118             endcase
119         end else if(state_shiftir) begin
120             tdo_pre = ir_tdo;
121         end
122     end
123
124     //TDO updates on the negative edge according to the spec
125     always @(negedge tck)
126     begin
127         tdo <= tdo_pre;
128     end
129
130 endmodule

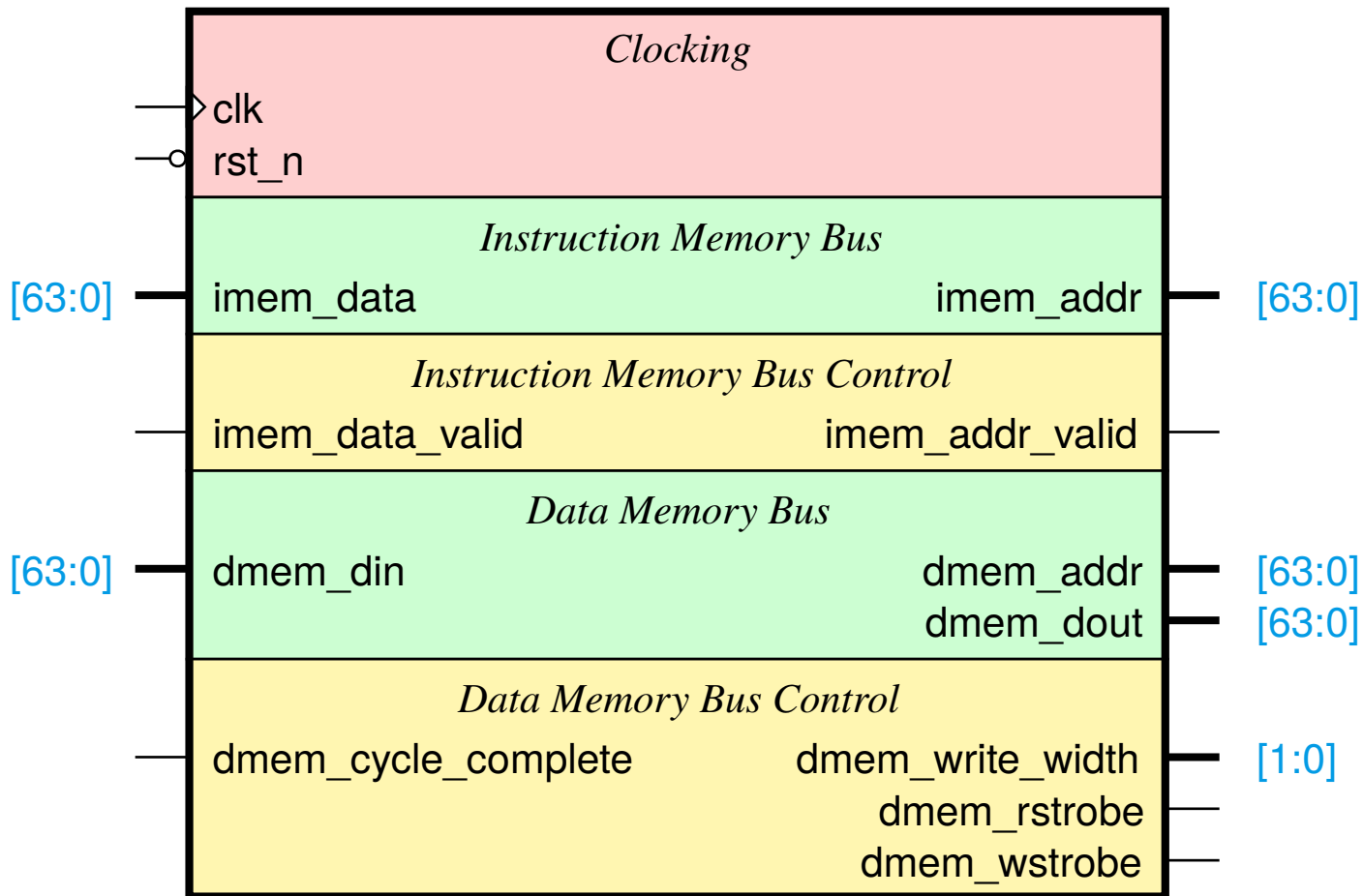
```

5.2.17 memory_map.v



```
1 //Raisin64 - Memory Map
2 module memory_map(
3     input [63:0] addr,
4     output io,
5     output led,
6     output sw,
7     output vga
8 );
9
10 //As physical addresses are sign-extended from the 47th bit,
11 //only bits 46:14 really matter
12
13 //Upper-half of the memory map is IO for now
14 assign io = addr[46];
15
16 assign led = (addr[46:14] == 33'h100000001);
17 assign sw  = (addr[46:14] == 33'h100000002);
18 assign vga = (addr[46:18] == 33'h100000001);
19
20 endmodule
```


5.2.18 pipeline.v



```

1  //Raisin64 - Pipeline
2
3  module pipeline(
4      //# {{clocks|Clocking}}
5      input clk,
6      input rst_n,
7
8      //# {{data|Instruction Memory Bus}}
9      output [63:0] imem_addr,
10     input [63:0] imem_data,
11
12     //# {{control|Instruction Memory Bus Control}}
13     input imem_data_valid,
14     output imem_addr_valid,
15
16     //# {{data|Data Memory Bus}}
17     output [63:0] dmem_addr,
18     output [63:0] dmem_dout,
19     input [63:0] dmem_din,
20
21     //# {{control|Data Memory Bus Control}}
22     input dmem_cycle_complete,

```

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```

23     output[1:0] dmem_write_width,
24     output dmem_rstrobe,
25     output dmem_wstrobe
26 );
27
28 wire sc_ready;
29 wire[63:0] jump_pc;
30 wire do_jump;
31 wire cancel_now;
32 assign cancel_now = do_jump;
33
34 /////////////// FETCH ///////////////
35 wire[63:0] fe_inst;
36 wire[63:0] fe_next_pc;
37
38 fetch fetch1(
39     .clk(clk),
40     .rst_n(rst_n),
41     .imem_addr(imem_addr),
42     .imem_data(imem_data),
43     .imem_data_valid(imem_data_valid),
44     .imem_addr_valid(imem_addr_valid),
45     .inst_data(fe_inst),
46     .next_jump_pc(fe_next_pc),
47     .jump_pc(jump_pc), .do_jump(do_jump),
48     .stall(~sc_ready)
49 );
50
51 reg fe_cancelled;
52 always @(posedge clk or negedge rst_n) begin
53     if(~rst_n) fe_cancelled <= 0;
54     else fe_cancelled <= cancel_now;
55 end
56
57 /////////////// DECODE ///////////////
58
59 wire de_type;
60 wire[2:0] de_unit;
61 wire[1:0] de_op;
62 wire[5:0] de_rd_rn;
63 wire[5:0] de_rd2_rn;
64 wire[5:0] de_rs1_rn;
65 wire[5:0] de_rs2_rn;
66 wire[63:0] de_imm_data;
67
68 wire[5:0] de_r1_rn;
69 wire[5:0] de_r2_rn;
70
71 decode decode1(
72     .clk(clk), .rst_n(rst_n),
73     .instIn(fe_inst),
74     .type(de_type),
75     .unit(de_unit),
76     .op(de_op),
77     .rs1_rn(de_rs1_rn), .rs2_rn(de_rs2_rn),
78     .rd_rn(de_rd_rn), .rd2_rn(de_rd2_rn),
79     .imm_data(de_imm_data),

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```

80     .r1_rn(de_r1_rn), .r2_rn(de_r2_rn),
81     .stall(~sc_ready), .cancel(cancel_now|fe_cancelled)
82 );
83
84 //Delay the Next PC to the schedule stage
85 reg[63:0] de_next_pc;
86 reg de_cancelled;
87
88 always @(posedge clk or negedge rst_n)
89 begin
90     if(~rst_n) begin
91         de_next_pc <= 64'h0;
92         de_cancelled <= 0;
93     end else begin
94         de_cancelled <= cancel_now|fe_cancelled;
95         if (sc_ready) begin
96             if(cancel_now|fe_cancelled) de_next_pc <= 64'h0;
97             else de_next_pc <= fe_next_pc;
98         end
99     end
100 end
101
102 //////////// REG FILE ////////////
103 //Concurrent with Schedule phase
104
105 wire[63:0] rf_writeback;
106 wire[63:0] rf_data1;
107 wire[63:0] rf_data2;
108 wire[5:0] rf_writeback_rn;
109
110 //Register file selected by the scheduler, registered in the execute stage
111 //and written to during commit.
112 regfile regfile1(
113     .clk(clk), .rst_n(rst_n), .w_data(rf_writeback), .r1_data(rf_data1),
114     .r2_data(rf_data2), .r1_rn(de_r1_rn), .r2_rn(de_r2_rn),
115     .w_rn(rf_writeback_rn), .w_en(|rf_writeback_rn)
116 );
117
118 //////////// SCHEDULE ////////////
119 //Concurrent with Register File
120
121 wire sc_alu1_en;
122 wire sc_alu2_en;
123 wire sc_advint_en;
124 wire sc_memunit_en;
125 wire sc_branch_en;
126
127 wire sc_alu1_busy;
128 wire sc_alu2_busy;
129 wire sc_advint_busy;
130 wire sc_memunit_busy;
131 wire sc_branch_busy;
132
133 wire[5:0] sc_rd_rn;
134 wire[5:0] sc_rd2_rn;
135
136 schedule schedule1(

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```

137     .clk(clk), .rst_n(rst_n),
138     .type(de_type), .unit(cancel_now|de_cancelled ? 3'h0 : de_unit),
139     .r1_in_rn(de_r1_rn), .r2_in_rn(de_r2_rn),
140     .rd_in_rn(cancel_now|de_cancelled ? 6'h0 : de_rd_rn),
141     .rd2_in_rn(cancel_now|de_cancelled ? 6'h0 : de_rd2_rn),
142     .sc_ready(sc_ready),
143     .rd_out_rn(sc_rd_rn), .rd2_out_rn(sc_rd2_rn),
144
145     .reg1_finished(rf_writeback_rn), .reg2_finished(6'h0),
146
147     .alu1_en(sc_alu1_en), .alu2_en(sc_alu2_en), .advint_en(sc_advint_en),
148     .memunit_en(sc_memunit_en), .branch_en(sc_branch_en),
149
150     .alu1_busy(sc_alu1_busy), .alu2_busy(sc_alu2_busy),
151     .advint_busy(sc_advint_busy), .memunit_busy(sc_memunit_busy),
152     .branch_busy(sc_branch_busy)
153 );
154
155 //Delay the relevant decode data used by execution through the schedule phase
156 reg sc_type;
157 reg[2:0] sc_unit;
158 reg[1:0] sc_op;
159 reg[63:0] sc_imm_data;
160 reg[63:0] sc_next_pc;
161
162 always @(posedge clk or negedge rst_n)
163 begin
164     if(~rst_n) begin
165         sc_type <= 0;
166         sc_unit <= 3'h0;
167         sc_op <= 2'h0;
168         sc_imm_data <= 64'h0;
169         sc_next_pc <= 64'h0;
170     end else begin
171         if(cancel_now|de_cancelled) sc_unit <= 3'h0;
172         else sc_unit <= de_unit;
173
174         sc_type <= de_type;
175         sc_op <= de_op;
176         sc_imm_data <= de_imm_data;
177         sc_next_pc <= de_next_pc;
178     end
179 end
180
181 ////////// EXECUTE //////////
182
183 wire[63:0] ex_alu1_result;
184 wire[63:0] ex_alu2_result;
185 wire[63:0] ex_advint_result;
186 wire[63:0] ex_advint_result2;
187 wire[63:0] ex_memunit_result;
188 wire[63:0] ex_branch_r63;
189
190 wire[5:0] ex_alu1_rd_rn;
191 wire[5:0] ex_alu2_rd_rn;
192 wire[5:0] ex_advint_rd_rn;
193 wire[5:0] ex_advint_rd2_rn;

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```

194     wire[5:0] ex_memunit_rd_rn;
195     wire ex_branch_r63_update;
196
197     wire ex_alu1_valid;
198     wire ex_alu2_valid;
199     wire ex_advint_valid;
200     wire ex_memunit_valid;
201
202     wire ex_alu1_stall;
203     wire ex_alu2_stall;
204     wire ex_advint_stall;
205     wire ex_memunit_stall;
206     wire ex_branch_stall;
207
208     ex_alu ex_alu1(
209         .clk(clk), .rst_n(rst_n), .in1(rf_data1), .in2(sc_type ? sc_imm_data : rf_
↳data2), .out(ex_alu1_result),
210         .ex_enable(sc_alu1_en), .ex_busy(sc_alu1_busy), .rd_in_rn(sc_rd_rn), .unit(sc_
↳unit),
211         .op(sc_op), .rd_out_rn(ex_alu1_rd_rn), .valid(ex_alu1_valid), .stall(ex_alu1_
↳stall)
212     );
213
214     ex_alu ex_alu2(
215         .clk(clk), .rst_n(rst_n), .in1(rf_data1), .in2(sc_type ? sc_imm_data : rf_
↳data2), .out(ex_alu2_result),
216         .ex_enable(sc_alu2_en), .ex_busy(sc_alu2_busy), .rd_in_rn(sc_rd_rn), .unit(sc_
↳unit),
217         .op(sc_op), .rd_out_rn(ex_alu2_rd_rn), .valid(ex_alu2_valid), .stall(ex_alu2_
↳stall)
218     );
219
220     ex_advint ex_advint(
221         .clk(clk), .rst_n(rst_n),
222         .in1(rf_data1), .in2(rf_data2),
223         .out(ex_advint_result), .out2(ex_advint_result2),
224         .ex_enable(sc_advint_en), .ex_busy(sc_advint_busy),
225         .rd_in_rn(sc_rd_rn), .rd2_in_rn(sc_rd2_rn),
226         .unit(sc_unit), .op(sc_op),
227         .rd_out_rn(ex_advint_rd_rn), .rd2_out_rn(ex_advint_rd2_rn),
228         .valid(ex_advint_valid), .stall(ex_advint_stall)
229     );
230
231     ex_memory ex_memory1(
232         .clk(clk), .rst_n(rst_n),
233         .dmem_din(dmem_din), .dmem_dout(dmem_dout), .dmem_addr(dmem_addr),
234         .dmem_cycle_complete(dmem_cycle_complete),
235         .dmem_width(dmem_write_width),
236         .dmem_rstrobe(dmem_rstrobe), .dmem_wstrobe(dmem_wstrobe),
237         .base(rf_data1), .data(rf_data2), .offset(sc_imm_data[31:0]),
238         .out(ex_memunit_result),
239         .ex_enable(sc_memunit_en), .ex_busy(sc_memunit_busy),
240         .rd_in_rn(sc_rd_rn), .unit(sc_unit), .op(sc_op),
241         .rd_out_rn(ex_memunit_rd_rn), .valid(ex_memunit_valid),
242         .stall(ex_memunit_stall)
243     );
244

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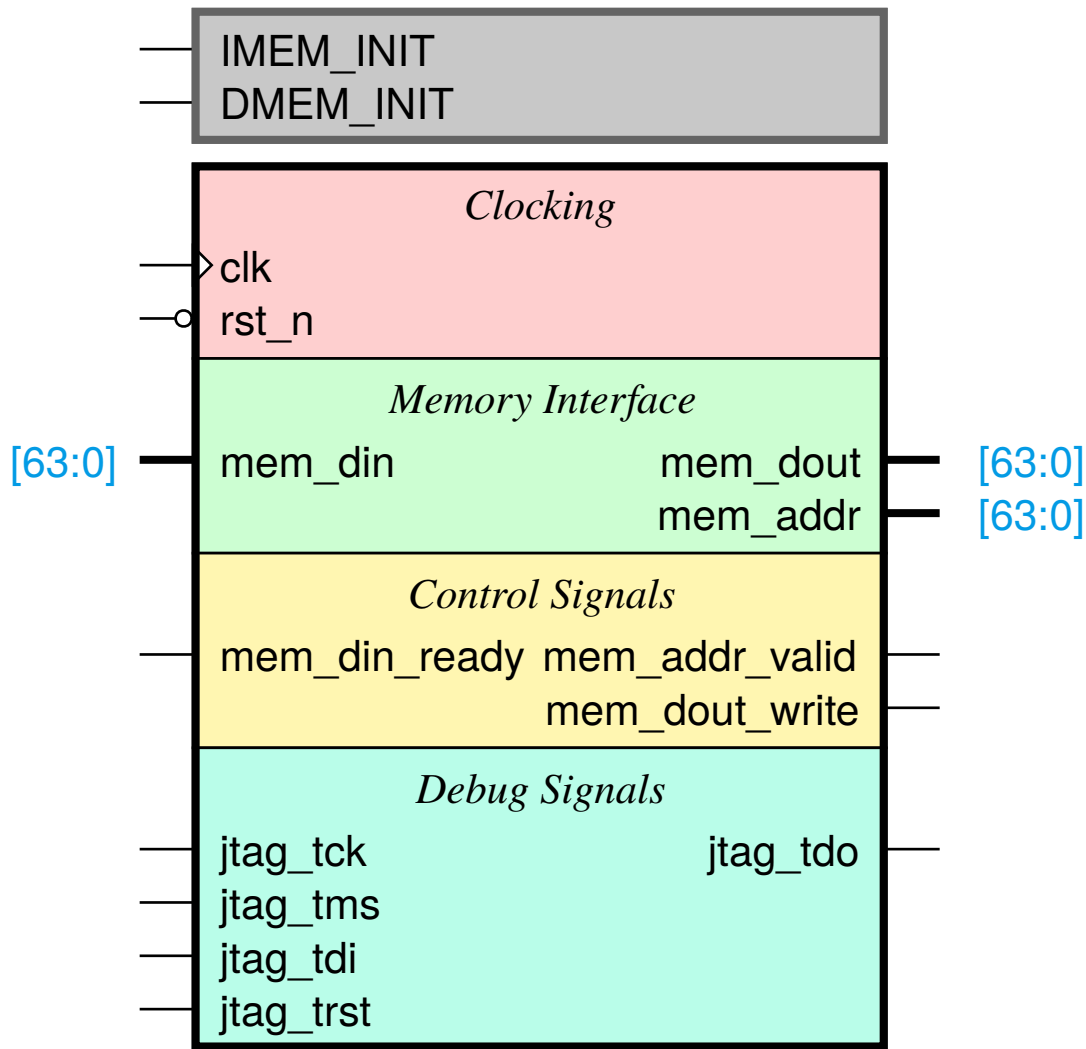
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245     ex_branch ex_branch1(
246         .clk(clk), .rst_n(rst_n),
247         .in1(rf_data1), .in2(rf_data2), .imm(sc_imm_data),
248         .next_pc(sc_next_pc), .jump_pc(jump_pc), .do_jump(do_jump),
249         .r63(ex_branch_r63), .r63_update(ex_branch_r63_update),
250         .ex_enable(sc_branch_en), .ex_busy(sc_branch_busy),
251         .stall(ex_branch_stall),
252         .op(sc_op), .type(sc_type)
253     );
254
255     /////////// COMMIT ///////////
256
257     commit commit1(
258         .clk(clk), .rst_n(rst_n),
259
260         .alul_result(ex_alul_result),
261         .alu2_result(ex_alu2_result),
262         .advint_result(ex_advint_result),
263         .advint_result2(ex_advint_result2),
264         .memunit_result(ex_memunit_result),
265         .branch_result(ex_branch_r63),
266
267         .alul_rn(ex_alul_rd_rn),
268         .alu2_rn(ex_alu2_rd_rn),
269         .advint_rn(ex_advint_rd_rn),
270         .advint_rn2(ex_advint_rd2_rn),
271         .memunit_rn(ex_memunit_rd_rn),
272
273         .alul_valid(ex_alul_valid),
274         .alu2_valid(ex_alu2_valid),
275         .advint_valid(ex_advint_valid),
276         .memunit_valid(ex_memunit_valid),
277         .branch_valid(ex_branch_r63_update),
278
279         .alul_stall(ex_alul_stall),
280         .alu2_stall(ex_alu2_stall),
281         .advint_stall(ex_advint_stall),
282         .memunit_stall(ex_memunit_stall),
283         .branch_stall(ex_branch_stall),
284
285         .write_data(rf_writeback), .write_rn(rf_writeback_rn)
286     );
287
288     endmodule

```

5.2.19 raisin64.v



```

1  /*
2   * Raisin64 CPU
3   */
4
5  module raisin64 (
6      // # {{clocks|Clocking}}
7      input  clk,
8      input  rst_n,
9
10     // # {{data|Memory Interface}}
11     input  [63:0] mem_din,
12     output [63:0] mem_dout,
13     output [63:0] mem_addr,
14
15     // # {{control|Control Signals}}
16     output mem_addr_valid,
17     output mem_dout_write,
18     input  mem_din_ready,

```

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```

19
20 // # {{debug|Debug Signals}}
21 input jtag_tck,
22 input jtag_tms,
23 input jtag_tdi,
24 input jtag_trst,
25 output jtag_tdo
26 );
27
28 parameter IMEM_INIT = "";
29 parameter DMEM_INIT = "";
30
31 // Debug Signals
32 wire dbg_resetrn_cpu, dbg_halt_cpu;
33 wire cpu_rst_n;
34 assign cpu_rst_n = rst_n & dbg_resetrn_cpu;
35
36 wire[63:0] dbg_imem_addr;
37 wire[63:0] dbg_imem_to_ram;
38 wire dbg_imem_ce;
39 wire dbg_imem_we;
40
41 wire[63:0] dbg_dmem_addr;
42 wire[63:0] dbg_dmem_to_ram;
43 wire dbg_dmem_ce;
44 wire dbg_dmem_we;
45
46
47 // Instruction RAM
48 wire[63:0] effective_imem_addr;
49 wire[63:0] effective_imem_data_to_cpu;
50
51 reg imem_data_ready;
52 wire imem_addr_valid;
53 wire[63:0] imem_addr;
54 wire[63:0] imem_data;
55
56 assign effective_imem_addr = dbg_halt_cpu ? dbg_imem_addr : imem_addr;
57 assign effective_imem_data_to_cpu = dbg_halt_cpu ? 64'h0 : imem_data;
58
59 always @(posedge clk or negedge rst_n) begin
60     if(~rst_n) imem_data_ready <= 0;
61     else imem_data_ready <= imem_addr_valid;
62 end
63
64 ram # (
65     .NUM_BYTES(2*1024),
66     .INIT_FILE(IMEM_INIT)
67 ) imem (
68     .clk(clk),
69     .we(dbg_imem_we), .cs(1'b1),
70     .write_width(2'h0),
71     .addr(effective_imem_addr),
72     .data_in(dbg_imem_to_ram),
73     .data_out(imem_data)
74 );
75

```

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```

76  ////////////////////////////////// Data RAM //////////////////////////////////
77
78  wire[63:0] effective_dmem_addr;
79  wire[63:0] effective_dmem_to_ram;
80
81  wire[63:0] dmem_addr;
82  wire[63:0] dmem_to_ram;
83  wire[63:0] dmem_to_cpu;
84  wire[63:0] dmem_from_ram;
85  wire[1:0] dmem_write_width;
86  reg dmem_cycle_complete;
87  wire dmem_rstrobe;
88  wire dmem_wstrobe;
89
90  wire io_space;
91
92  assign effective_dmem_addr      = dbg_halt_cpu ? dbg_dmem_addr : dmem_addr;
93  assign effective_dmem_to_ram    = dbg_halt_cpu ? dbg_dmem_to_ram : dmem_to_ram;
94
95  //TODO For now, the external memory bus is just for data memory. When the time
96  //comes for caches, this will change to the unified external memory bus.
97  assign dmem_to_cpu              = io_space ? mem_din : dmem_from_ram;
98  assign mem_dout                 = effective_dmem_to_ram;
99  assign mem_addr                 = effective_dmem_addr;
100  assign mem_addr_valid           = 1;
101  assign mem_dout_write           = dbg_halt_cpu ? dbg_dmem_we : dmem_wstrobe;
102
103  //Because the memory interface will change dramatically in the next revision,
104  ↪there
105  //is no reason to create special logic to handle misaligned accesses into data
106  ↪space
107  //in case an IO unit requires it (the ram modules handle this condition
108  ↪internally).
109  //Instead we simply state misaligned IO access it is unsupported (for now).
110  always @(*) begin
111      if((dmem_rstrobe|dmem_wstrobe) & io_space & |dmem_write_width & ~clk) begin
112          $display("Unaligned data IO access not supported in this revision");
113          $finish;
114      end
115  end
116
117  memory_map memory_map_internal(
118      .addr(mem_addr),
119      .io(io_space)
120  );
121
122  always @(posedge clk or negedge cpu_rst_n)
123  begin
124      if(~cpu_rst_n) dmem_cycle_complete <= 0;
125      else if(io_space & mem_din_ready) dmem_cycle_complete <= 1;
126      else if(dmem_rstrobe) dmem_cycle_complete <= 1;
127      else if(dmem_wstrobe) dmem_cycle_complete <= 1;
128      else dmem_cycle_complete <= 0;
129  end
130
131  ram #(
132      .NUM_BYTES(512),

```

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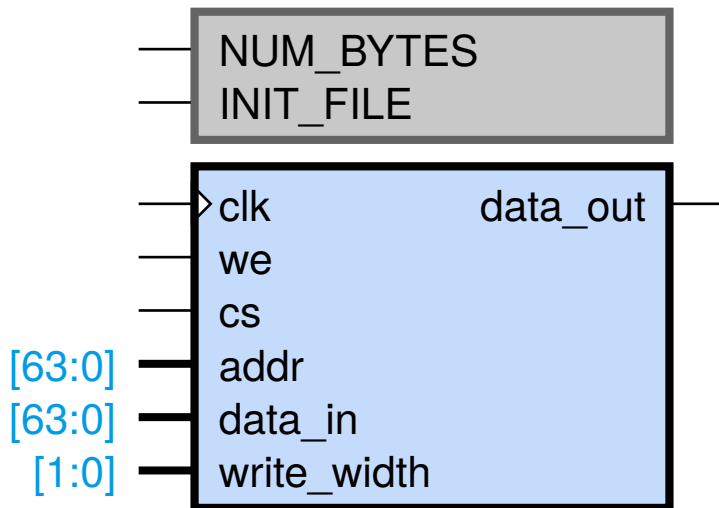
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```

130     .INIT_FILE(DMEM_INIT)
131   ) dmem (
132     .clk(clk),
133     .we(~io_space & (dmem_wstrobe|dbg_dmem_we)), .cs(~io_space & (dmem_
134     ↪wstrobe|dmem_rstrobe|dbg_dmem_ce)),
135     .write_width(dmem_write_width),
136     .addr(effective_dmem_addr),
137     .data_in(effective_dmem_to_ram),
138     .data_out(dmem_from_ram)
139   );
140
141   //////////// Raisin64 Execution Core ////////////
142   pipeline pipeline1(
143     .clk(clk),
144     .rst_n(cpu_rst_n),
145     .imem_addr(imem_addr),
146     .imem_data(effective_imem_data_to_cpu),
147     .imem_data_valid(imem_data_ready),
148     .imem_addr_valid(imem_addr_valid),
149     .dmem_addr(dmem_addr), .dmem_dout(dmem_to_ram),
150     .dmem_din(dmem_to_cpu),
151     .dmem_cycle_complete(dmem_cycle_complete & ~dmem_rstrobe & ~dmem_wstrobe),
152     .dmem_write_width(dmem_write_width),
153     .dmem_rstrobe(dmem_rstrobe),
154     .dmem_wstrobe(dmem_wstrobe)
155   );
156
157   //////////// JTAG Module ////////////
158   debug_control debug_if(
159     .jtag_tck(jtag_tck),
160     .jtag_tms(jtag_tms),
161     .jtag_tdo(jtag_tdo),
162     .jtag_tdi(jtag_tdi),
163     .jtag_trst(jtag_trst),
164     .cpu_clk(clk),
165     .sys_rstn(rst_n),
166     .cpu_imem_addr(dbg_imem_addr),
167     .cpu_debug_to_imem_data(dbg_imem_to_ram),
168     .cpu_imem_to_debug_data(imem_data),
169     .cpu_imem_we(dbg_imem_we),
170     .cpu_imem_ce(dbg_imem_ce),
171     .cpu_dmem_addr(dbg_dmem_addr),
172     .cpu_debug_to_dmem_data(dbg_dmem_to_ram),
173     .cpu_imem_to_debug_data_ready(dbg_imem_ce & ~dbg_imem_we),
174     .cpu_dmem_to_debug_data_ready(dbg_dmem_ce & ~dbg_dmem_we),
175     .cpu_dmem_to_debug_data(dmem_to_cpu),
176     .cpu_dmem_we(dbg_dmem_we),
177     .cpu_dmem_ce(dbg_dmem_ce),
178     .cpu_resetsn_cpu(dbg_resetsn_cpu),
179     .cpu_halt_cpu(dbg_halt_cpu)
180   );
181
182   endmodule
183

```

5.2.20 ram.v



```

1  //Test RAM
2
3  `include "io_def.vh"
4
5  module ram(input clk,
6             input we,
7             input cs,
8             input [63:0] addr,
9             input [63:0] data_in,
10            input [1:0] write_width, //0==64bit, 1==32bit, 2==16bit, 3==8bit
11            output reg [63:0] data_out);
12
13     parameter NUM_BYTES = 0;
14     parameter INIT_FILE = "";
15
16     reg [63:0] ram[0:(NUM_BYTES/8)-1]; //Nx64 RAM
17
18     reg [63:0] ramA_result, ramB_result;
19
20     reg [7:0] weA_b; //Which byte lines are write-enabled
21     reg [7:0] weB_b;
22
23     always @(*) begin
24         weA_b = 8'h00;
25         weB_b = 8'h00;
26         if (we) begin
27             case (write_width)
28                 `RAM_WIDTH64: {weA_b, weB_b} = 16'hFF00 >> addr[2:0];
29                 `RAM_WIDTH32: {weA_b, weB_b} = 16'hF000 >> addr[2:0];
30                 `RAM_WIDTH16: {weA_b, weB_b} = 16'hC000 >> addr[2:0];
31                 `RAM_WIDTH8: {weA_b, weB_b} = 16'h8000 >> addr[2:0];
32             endcase
33         end
34     end
35
36     wire [127:0] data_in_shift;

```

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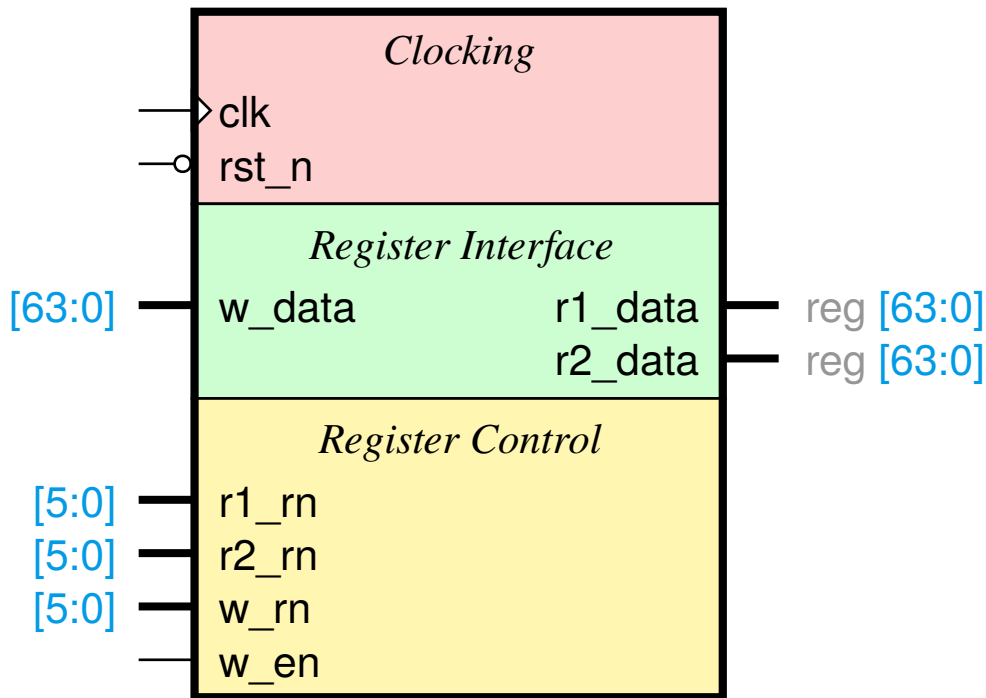
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```

37     assign data_in_shift = {data_in, 64'h0} >> addr[2:0]*8;
38
39     generate
40     genvar i;
41     for(i = 0; i < 8; i = i+1) begin
42         always @(posedge clk)
43             if(cs)
44                 if(weA_b[i]) begin
45                     ram[addr[63:3]][(i+1)*8-1:i*8] <= data_in_shift[64+(i+1)*8-
↪ 1:64+i*8];
46                 end
47             end
48
49     for(i = 0; i < 8; i = i+1) begin
50         always @(posedge clk)
51             if(cs)
52                 if(weB_b[i]) begin
53                     ram[addr[63:3]+1][(i+1)*8-1:i*8] <= data_in_shift[(i+1)*8-1:i*8];
54                 end
55             end
56     endgenerate
57
58     //Registered read (ready by next clock cycle)
59     always @(posedge clk) begin
60         if(cs) begin
61             ramA_result <= ram[addr[63:3]];
62             ramB_result <= ram[addr[63:3]+1];
63         end
64     end
65
66     reg[2:0] addr_lsb;
67     always @(posedge clk) begin
68         addr_lsb <= addr[2:0];
69     end
70
71     always @(*) begin
72         data_out = ({ramA_result,ramB_result} >> ((8-addr_lsb)*8)) & 64
↪ 'hFFFFFFFFFFFFFFFF;
73     end
74
75     //Populate our program memory with the user-provided hex file
76     initial begin
77         $readmemh(INIT_FILE, ram);
78     end
79
80
81 endmodule

```

5.2.21 regfile.v



```

1 //Raisin64 Register File
2 //Registered dual-ported register file two read, one write port
3
4 module regfile(
5     //# {{clocks|Clocking}}
6     input clk,
7     input rst_n,
8
9     //# {{data|Register Interface}}
10    input [63:0] w_data,
11    output reg [63:0] r1_data,
12    output reg [63:0] r2_data,
13
14    //# {{control|Register Control}}
15    input [5:0] r1_rn,
16    input [5:0] r2_rn,
17    input [5:0] w_rn,
18    input w_en
19
20    //# {{debug|Debug Signals}}
21 );
22
23 reg [63:0] file[1:63];
24 reg [63:0] r1_data_pre, r2_data_pre;
25 integer i;
26
27 initial for(i = 1; i<64; i = i+1) file[i] <= 64'h0;
28
29 always @(posedge clk) if(w_en && w_rn!=6'h0) file[w_rn] <= w_data;
30

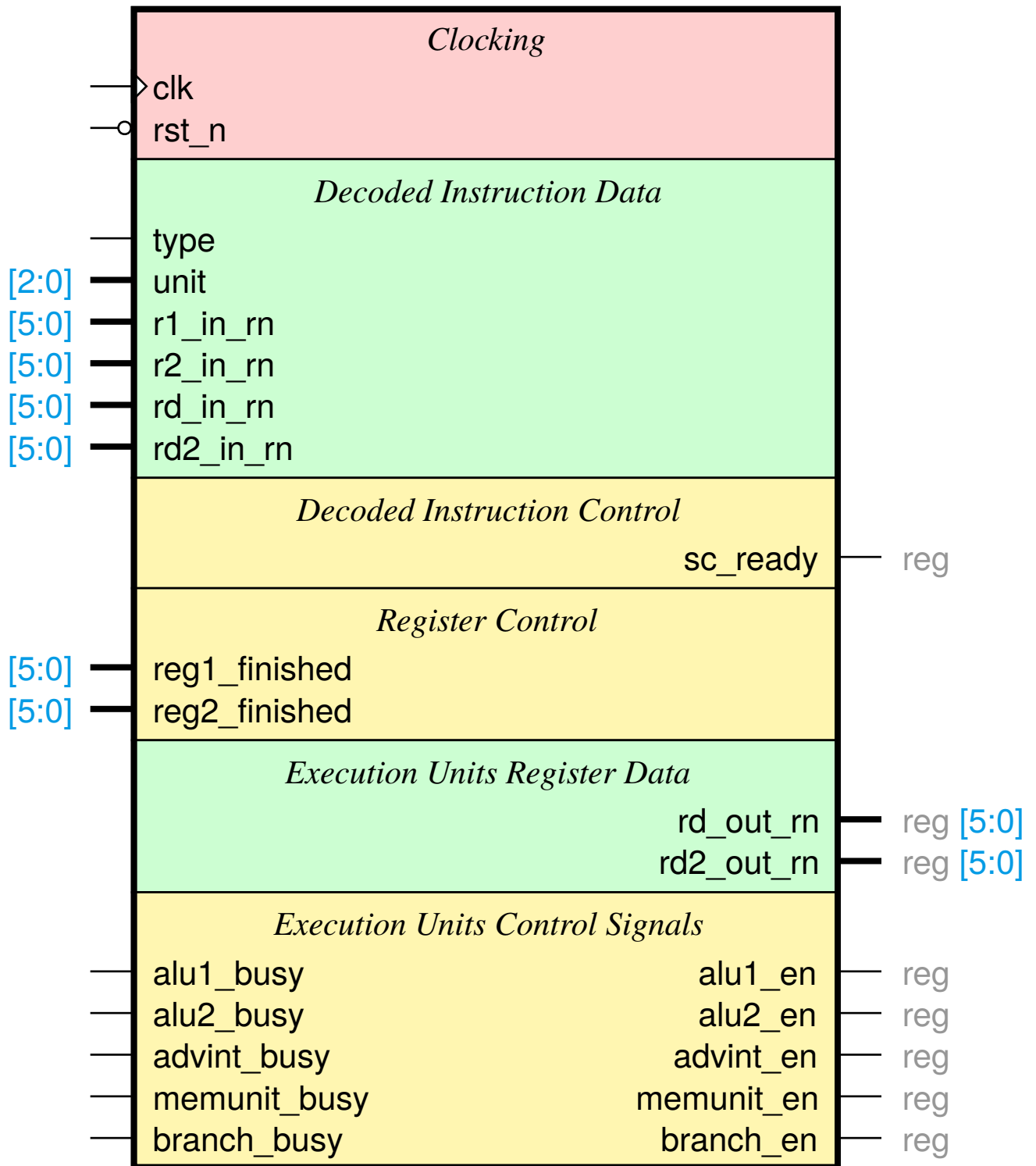
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```
31  always @(posedge clk or negedge rst_n)
32  begin
33      if(~rst_n) r1_data <= 64'h0;
34      else if(r1_rn==6'h0) r1_data <= 64'h0;
35      else r1_data <= (w_rn==r1_rn && w_en) ? w_data : file[r1_rn];
36  end
37
38  always @(posedge clk or negedge rst_n)
39  begin
40      if(~rst_n) r2_data <= 64'h0;
41      else if(r2_rn==6'h0) r2_data <= 64'h0;
42      else r2_data <= (w_rn==r2_rn && w_en) ? w_data : file[r2_rn];
43  end
44  endmodule
```

5.2.22 schedule.v



```

1 //Raisin64 Instruction Scheduler
2 //Schedules a ready instruction to a free execution unit capable of servicing it

```

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```

3
4 module schedule(
5     //# {{clocks|Clocking}}
6     input clk,
7     input rst_n,
8
9     //# {{data|Decoded Instruction Data}}
10    input type,
11    input [2:0] unit,
12    input [5:0] r1_in_rn,
13    input [5:0] r2_in_rn,
14    input [5:0] rd_in_rn,
15    input [5:0] rd2_in_rn,
16
17    //# {{control|Decoded Instruction Control}}
18    output reg sc_ready,
19
20    //# {{control|Register Control}}
21    input [5:0] reg1_finished,
22    input [5:0] reg2_finished,
23
24    //# {{data|Execution Units Register Data}}
25    output reg [5:0] rd_out_rn,
26    output reg [5:0] rd2_out_rn,
27
28    //# {{control|Execution Units Control Signals}}
29    output reg alu1_en,
30    output reg alu2_en,
31    output reg advint_en,
32    output reg memunit_en,
33    output reg branch_en,
34
35    input alu1_busy,
36    input alu2_busy,
37    input advint_busy,
38    input memunit_busy,
39    input branch_busy
40    );
41
42    reg [63:0] reg_busy;
43
44    wire alu_type, advint_type, memunit_type, branch_type;
45    assign alu_type = ~unit[2];
46    assign advint_type = ~type && unit==3'h4;
47    assign memunit_type = type && (unit==3'h4 | unit==3'h5 | unit==3'h6);
48    assign branch_type = unit==3'h7;
49
50    wire instIssued;
51    assign instIssued = alu1_en | alu2_en | advint_en | memunit_en | branch_en;
52
53    reg operand_unavailable;
54
55    always @(*)
56    begin
57        operand_unavailable = 0;
58
59        //The register was previously busy

```

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```

60     if(reg_busy[r1_in_rn] && r1_in_rn!=reg1_finished && r1_in_rn!=reg2_finished)
↳operand_unavailable = 1;
61     else if(reg_busy[r2_in_rn] && r2_in_rn!=reg2_finished && r2_in_rn!=reg1_
↳finished) operand_unavailable = 1;
62
63     //We just issued something to an execution unit
64     else if(instIssued) begin
65         //The incoming source register is non-zero
66         if(|r1_in_rn) begin
67             //And it matches the previous destination register number. We
68             //will stall here until it is picked up by reg_busy next cycle
69             if(rd_out_rn==r1_in_rn) operand_unavailable = 1;
70             else if(rd2_out_rn==r1_in_rn) operand_unavailable = 1;
71
72         end
73         if(|r2_in_rn) begin
74             if(rd_out_rn==r2_in_rn) operand_unavailable = 1;
75             else if(rd2_out_rn==r2_in_rn) operand_unavailable = 1;
76         end
77     end
78 end
79
80 always @(*)
81 begin
82     sc_ready = 0;
83     if(~operand_unavailable & ~branch_busy) begin //TODO Branch busy condition_
↳can probably be moved outside the module via muxing of the unit_en lines with the_
↳operation cancel signal
84         if(alu_type & (~alu1_busy | ~alu2_busy)) sc_ready = 1;
85         else if(advint_type & ~advint_busy) sc_ready = 1;
86         else if(memunit_type & ~memunit_busy) sc_ready = 1;
87         else if(branch_type) sc_ready = 1;
88     end
89 end
90
91 always @(posedge clk or negedge rst_n)
92 begin
93     if(~rst_n) begin
94         alu1_en <= 0;
95         alu2_en <= 0;
96         advint_en <= 0;
97         memunit_en <= 0;
98         branch_en <= 0;
99         rd_out_rn <= 6'h0;
100        rd2_out_rn <= 6'h0;
101        reg_busy <= 64'h0;
102
103    end else begin
104        //Only allow the scheduling of instructions if the source registers
105        //aren't the destination of in-progress instructions.
106        alu1_en <= 0;
107        alu2_en <= 0;
108        advint_en <= 0;
109        memunit_en <= 0;
110        branch_en <= 0;
111
112        reg_busy[reg1_finished] <= 0;

```

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```

113     reg_busy[reg2_finished] <= 0;
114
115     if(~operand_unavailable & ~branch_busy) begin
116         if(alu_type & ~alu1_busy) begin
117             alu1_en <= 1;
118             rd_out_rn <= rd_in_rn;
119             if(|rd_in_rn) reg_busy[rd_in_rn] <= 1;
120
121         end else if(alu_type & ~alu2_busy) begin
122             alu2_en <= 1;
123             rd_out_rn <= rd_in_rn;
124             if(|rd_in_rn) reg_busy[rd_in_rn] <= 1;
125
126         end else if(advint_type & ~advint_busy) begin
127             advint_en <= 1;
128             rd_out_rn <= rd_in_rn;
129             rd2_out_rn <= rd2_in_rn;
130             if(|rd_in_rn) reg_busy[rd_in_rn] <= 1;
131             if(|rd2_in_rn) reg_busy[rd2_in_rn] <= 1;
132
133         end else if(memunit_type & ~memunit_busy) begin
134             memunit_en <= 1;
135             rd_out_rn <= rd_in_rn;
136             if(|rd_in_rn && unit!=3'h6) reg_busy[rd_in_rn] <= 1;
137
138         end else if(branch_type) begin
139             branch_en <= 1;
140             rd_out_rn <= rd_in_rn;
141             //No need to mark R63 busy. If the branch is taken, other
142             //instructions in the pipeline are cancelled.
143         end
144     end
145 end
146 end
147
148 endmodule

```

FOOTNOTES