

ActiveCore

Laboratory work manual

Using Sigma MCU in FPGA designs

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1. TARGET SKILLS

- Implementation of Sigma MCU in hardware projects
- Building and implementation of embedded software for Sigma MCU
- Choosing optimal CPU configuration of Sigma MCU
- Acceleration of Sigma MCU applications using its coprocessor and expansion interfaces
- Using Xilinx FPGA and Vivado Design Suite for implementation of Sigma MCU

2. OVERVIEW

This laboratory work covers software (firmware) based implementation of functionality using embedded programmable processor core. Using programmable processors, through having lower efficiency compared to direct hardware implementation, offers multiple virtues: simplification of programming, faster compilation, software update capability, better availability of engineers, etc. In this Lab, basic open-source MCU with RISC-V central processor unit (CPU) core will be used. RISC-V is an open instruction set architecture being widely used both in academia and industry in recent years.

3. PREREQUISITES

1. Xilinx Vivado 2019.1 HLx Edition (free for target board, available at <https://www.xilinx.com/support/download.html>).
2. ActiveCore baseline distribution (available at <https://github.com/AntonovAlexander/activecore>)
3. Generated RISC-V CPU HDL sources
4. Working RISC-V GNU toolchain (available at <https://github.com/riscv/riscv-gnu-toolchain>)

NOTE: pre-built binaries for various hosts can be downloaded from <https://www.sifive.com/software>. Do not forget to update `PATH` variable after downloading. Consider using Cygwin (with `make` utility) or WSL for RISC-V software compilation in Windows hosts.

5. (for FPGA prototyping) Digilent Nexys A7 (Nexys 4 DDR) FPGA board (<https://digilent.com/shop/nexys-a7-fpga-trainer-board-recommended-for-ecce-curriculum/>)
6. (for FPGA prototyping) working Python 3 installation with `pyserial` package

4. TASK

1. Examine Sigma MCU baseline project
2. (if FPGA board available) Implement Sigma MCU in FPGA device and verify correctness of the baseline
3. Write and test software implementation of functionality for CPU according to your variant
4. Accelerate your software application using Sigma MCU coprocessor interface
5. Accelerate your software application using Sigma MCU expansion interface

5. GUIDANCE

Detailed guidance will be provided using the example of a program that searches for the maximum value in 16-element array and returns this value and its index in the array.

1. Examine Sigma MCU baseline project

Sigma MCU is a basic microcontroller unit soft core consisting of `sigma_tile` processing module, UDM and general-purpose input/output (GPIO) controller. GPIO controller is mapped on LEDs and switches on FPGA board.

Block diagram of Sigma MCU is located at:

https://github.com/AntonovAlexander/activecore/blob/master/designs/rtl/sigma/doc/sigma_struct.png

`Sigma_tile` module contains embedded CPU core with RISC-V ISA, tightly coupled on-chip RAM with single-cycle delay, interrupt controller, timer, Host InterFace (HIF), and eXpansion InterFace (XIF). Multiple `sigma_tile` modules can fit in a single FPGA device. HIF and XIF have the same bus protocol as UDM block. Address maps are identical for UDM and CPU. Working with UDM can be learned from the corresponding lab work:

https://github.com/AntonovAlexander/activecore/blob/master/designs/rtl/udm/doc/udm_lab_manual.pdf

Block diagram of `sigma_tile` module is located at:

https://github.com/AntonovAlexander/activecore/blob/master/designs/rtl/sigma_tile/doc/sigma_tile_struct.png

Address map of Sigma MCU is located at:

https://github.com/AntonovAlexander/activecore/blob/master/designs/rtl/sigma/doc/sigma_addr_map.md

Address map of `sigma_tile` module is located at:

https://github.com/AntonovAlexander/activecore/blob/master/designs/rtl/sigma_tile/doc/sigma_tile_addr_map.md

Pipeline structures of various RISC-V CPU configurations can be found here:

https://github.com/AntonovAlexander/activecore/blob/master/designs/rtl/sigma_tile/doc/aquaris_pipeline_structs

RISC-V CPU supports basic bare metal programming (RV32IM ISA). ActiveCore distribution provides six Sigma MCU projects with different CPU configurations (1-6 pipeline stages). Longer pipeline can operate on higher frequencies and have better performance, however, consuming more hardware resources and power.

The projects are located at: `activecore/designs/rtl/sigma/syn/syn_Xstage/NEXYS4_DDR`

Generate RISC-V CPU HDL sources or unpack the provided coregen archive in the following directory:

```
activecore/designs/rtl/sigma_tile/hw/riscv
```

E.g. `riscv_5stage.sv` file should be located at:

```
activecore/designs/rtl/sigma_tile/hw/riscv/coregen/riscv_5stage/sverilog
```

Open `NEXYS4_DDR.xpr` file using Xilinx Vivado.

NOTE: avoid spaces and non-English characters in project location path. Also, avoid very long project location path.

2. (if FPGA board available) Implement Sigma MCU in FPGA device and verify correctness of the baseline

Go to the following directories and build CPU software using make command:

- compliance tests: `activecore/designs/rtl/sigma/sw/riscv-compliance`
- demo applications: `activecore/designs/rtl/sigma/sw/apps`

Implement the design, generate the bitstream and upload it to FPGA device. LEDs should start blinking with variable speed, depending on value on switches.

Find out the name of COM port associated with the board (COM<number> on Windows hosts or tty<number> on Linux hosts). Go one directory up, open `hw_test_compliance.py` and `hw_test_apps.py` Python scripts and fill in the correct COM port name:

```
udm = udm("<correct COM port name>", 921600)
```

Run RISC-V compliance tests using `hw_test_compliance.py` Python script. The script will upload 52 test programs for CPU and verify correctness of their operation. The last line of console output should be:

```
Total tests PASSED: 52 , FAILED: 0
```

Run application tests using `hw_test_apps.py` Python script. The script will upload 9 test programs for CPU and verify correctness of their operation. The last line of console output should be:

```
Total tests PASSED: 9 , FAILED: 0
```

You can type `help(sigma)` and `help(sigma_tile)` in Python console for full API reference of Sigma MCU and `sigma_tile` module respectively.

3. Implement target functionality in pure software

1) Write C application for Sigma MCU

Sigma MCU distribution provides several demo applications that can be used as reference (see Table 1).

Demo application	Description
heartbeat_variable	A counter that is output to LED register. The period is continuously read from Switches register. Period is implemented as CPU busy waiting.
irq_counter	A counter that is output to LED register. Increment is triggered by interrupt 3 that is mapped on button on FPGA board.
dhrystone	Dhrystone synthetic benchmark
median	Three-element median filter operating on 400-element array of integers.
mul_sw	Software multiplication of two integers producing an integer.
qsort	Quick sort operating on 1024-element array of integers.
rsort	Radix sort operating on 1024-element array of integers.
crc32	CRC32 hash calculation
md5	MD5 hash calculation
timer_test	A counter that is output to LED register. Utilizes the timer to count the period. The period is read from Switches register on reset.
bootloader	Bootloader of programs in binary (ELF) format from the memory buffer

Table 1 Demo applications provided in Sigma MCU distribution

Write software application for CPU and check its correctness. You can use either local `gcc` installation or an online service (e.g. <https://cplayground.com/> or <https://ideone.com/>) for this task. Test result for our example is shown in Listing 1.

NOTE: PC and online programming environments don't provide the same peripherals as those included in Sigma MCU. Thus, consider testing only "algorithmic" part of your program in these environments.

```

1 #include <stdio.h>
2 #include <stdlib.h>
3
4 #define ARR_SIZE 16
5
6 typedef struct
7 {
8     unsigned int max_elem;
9     unsigned int max_index;
10 } maxval_data_t;
11
12 maxval_data_t FindMaxVal(unsigned int x[ARR_SIZE])
13 {
14     maxval_data_t ret_data;
15     ret_data.max_elem = 0;
16     ret_data.max_index = 0;
17
18     for (int i=0; i<ARR_SIZE; i++) {
19         if (x[i] > ret_data.max_elem) {
20             ret_data.max_elem = x[i];
21             ret_data.max_index = i;
22         }
23     }
24     return ret_data;
25 }
26
27 //-----
28 // Main
29
30 int main( int argc, char* argv[] )
31 {
32     maxval_data_t maxval_data;
33     unsigned int datain[16] = { 0x112233cc, 0x55aa55aa, 0x01010202, 0x44556677,
34                                0x00000003, 0x00000004, 0x00000005, 0x00000006,
35                                0x00000007, 0xdeadbeef, 0xfefe8800, 0x23344556,
36                                0x05050505, 0x07070707, 0x99999999, 0xbadc0ffe };
37
38     maxval_data = FindMaxVal(datain);
39     printf("max_index: %d\n", maxval_data.max_index);
40     printf("max_elem: 0x%x\n", maxval_data.max_elem);
41 }

```

```

Compiling...
g++ -o /cplayground/cplayground /cplayground/code.cpp -I/cplayground/include -L/cplayground
/lib -std=c++17 -O0 -Wall -no-pie -ln -pthread
Compiled in 133.578 ms
Executing...
max_index: 10
max_elem: 0xfefe8800
Execution finished (exit status 0)
Executed in 5.413 ms

```

Listing 1 Testing software implementation using cplayground.com

Go to `activecore/designs/rtl/sigma/sw/apps` directory and add new directory for your software. In our example, the new directory is called `findmaxval`.

Create new C source file in the new directory. In our example, the file is called `findmaxval.c`. Write your program in this file. Source code for the example program is shown in Listing 2:

```

#define IO_LED          (*(volatile unsigned int *) (0x80000000))
#define IO_SW           (*(volatile unsigned int *) (0x80000004))

#define ARR_SIZE 16

typedef struct
{
    unsigned int max_elem;
    unsigned int max_index;
} maxval_data_t;

maxval_data_t FindMaxVal(unsigned int x[ARR_SIZE])
{
    maxval_data_t ret_data;
    ret_data.max_elem = 0;
    ret_data.max_index = 0;

    for (int i=0; i<ARR_SIZE; i++) {
        if (x[i] > ret_data.max_elem) {
            ret_data.max_elem = x[i];
            ret_data.max_index = i;
        }
    }
    return ret_data;
}

//-----
// Main

int main( int argc, char* argv[] )
{

```

```

maxval_data_t maxval_data;
unsigned int datain[16] = { 0x112233cc, 0x55aa55aa, 0x01010202, 0x44556677,
0x00000003, 0x00000004, 0x00000005, 0x00000006, 0x00000007, 0xdeadbeef, 0xfefe8800,
0x23344556, 0x05050505, 0x07070707, 0x99999999, 0xbadc0ffe };
IO_LED = 0x55aa55aa;
maxval_data = FindMaxVal(datain);
IO_LED = maxval_data.max_index;
IO_LED = maxval_data.max_elem;
while (1) {}
}

```

Listing 2 C source code in findmaxval.c

NOTE: we have output 0x55aa55aa value to LEDs to mark the end of startup sequence and start of the target function FindMaxVal. In the end of the program, we output max_index and max_val values and send CPU to infinite loop.

NOTE: since Sigma MCU does not have standard output, we use LEDs to output resulting values.

Prepare executable image for CPU. Open Makefile in activecore/designs/rtl/sigma/sw/apps directory and add the reference to the new directory in bmarks variable (added line is highlighted in cyan). Source code for the updated bmarks assignment is shown in Listing 3:

```

bmarks = \
<available applications>
rsort \
findmaxval \
<commented lines>

```

Listing 3 Source code of the updated bmarks assignment in Makefile

Call make command from activecore/designs/rtl/sigma/sw/apps directory to build the program image.

2) Verify functional correctness in simulation

Open the testbench file activecore/designs/rtl/sigma/tb/riscv_tb.sv, select desired clock frequency (needed in Section 7), choose the CPU configuration, and make mem_data parameter of sigma instance reference to your ELF program image. For our example, code updates are shown in Listing 4.

```

//`define CLK_HALF_PERIOD 5000 // external 100 MHZ
//`define CLK_HALF_PERIOD 7143 // external 70 MHZ
//`define CLK_HALF_PERIOD 6250 // external 80 MHZ
//`define CLK_HALF_PERIOD 3571 // external 140 MHZ
`define CLK_HALF_PERIOD 3333 // external 150 MHZ
//`define CLK_HALF_PERIOD 3125 // external 160 MHZ

...

sigma
#(
    //CPU("riscv_1stage")
    //CPU("riscv_2stage")
    //CPU("riscv_3stage")
    //CPU("riscv_4stage")
    CPU("riscv_5stage")
    //CPU("riscv_6stage")

    , .UDM RTX_EXTERNAL_OVERRIDE("YES")
    , .DEBOUNCER_FACTOR_POW(2)
    , .delay_test_flag(0)

```

```

, .mem_init_type("elf")
, .mem_init_data("<PATH_TO_ACTIVECORE>/designs/rtl/sigma/sw/apps/findmaxval.riscv")
, .mem_size(8192)
) sigma
(
, .clk_i(CLK_100MHZ)
, .arst_i(RST)
, .irq_btn_i(irq_btn)
, .rx_i(rx)
//, .tx_o()
, .gpio_bi(SW)
, .gpio_bo(LED)
);

```

Listing 4 Updated module instantiation in `riscv_tb.sv` testbench

Once simulation starts, Tcl console should show notification of successful program image upload (see Figure 1).

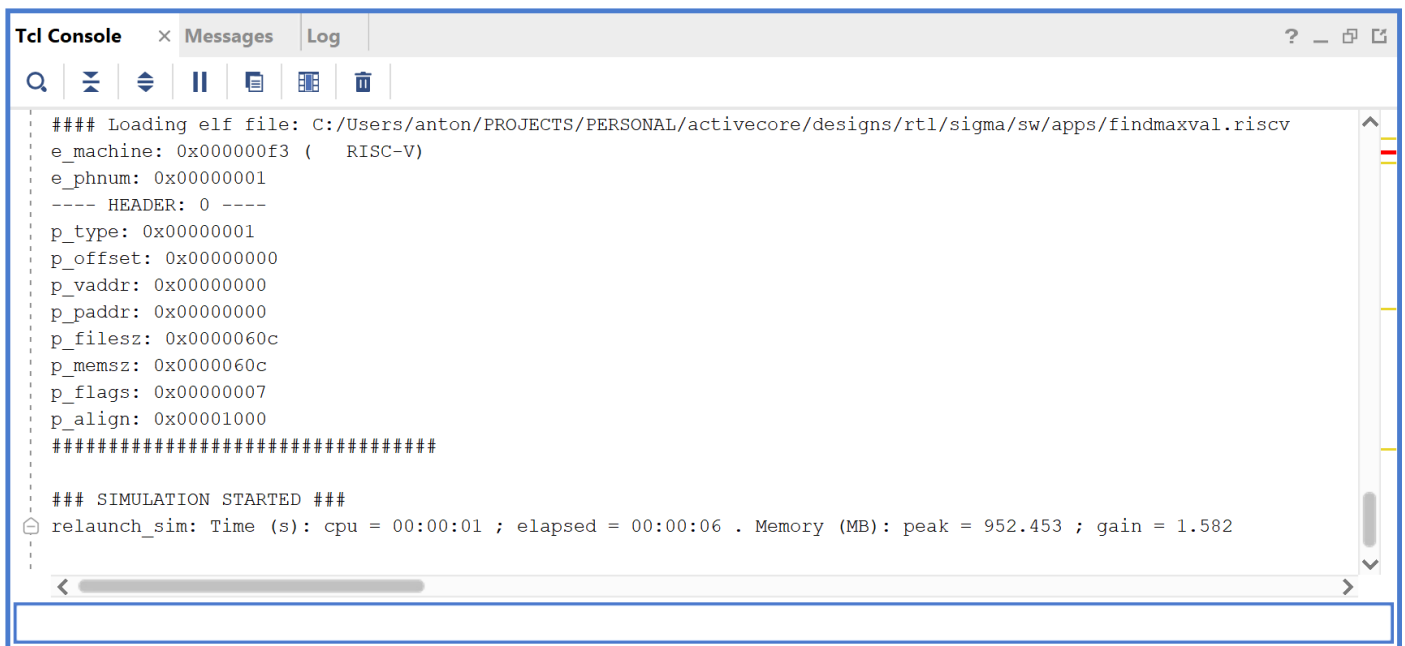


Figure 1 Notification of successful program image upload

Simulation waveform for 5-stage CPU configuration is shown in Figure 2.

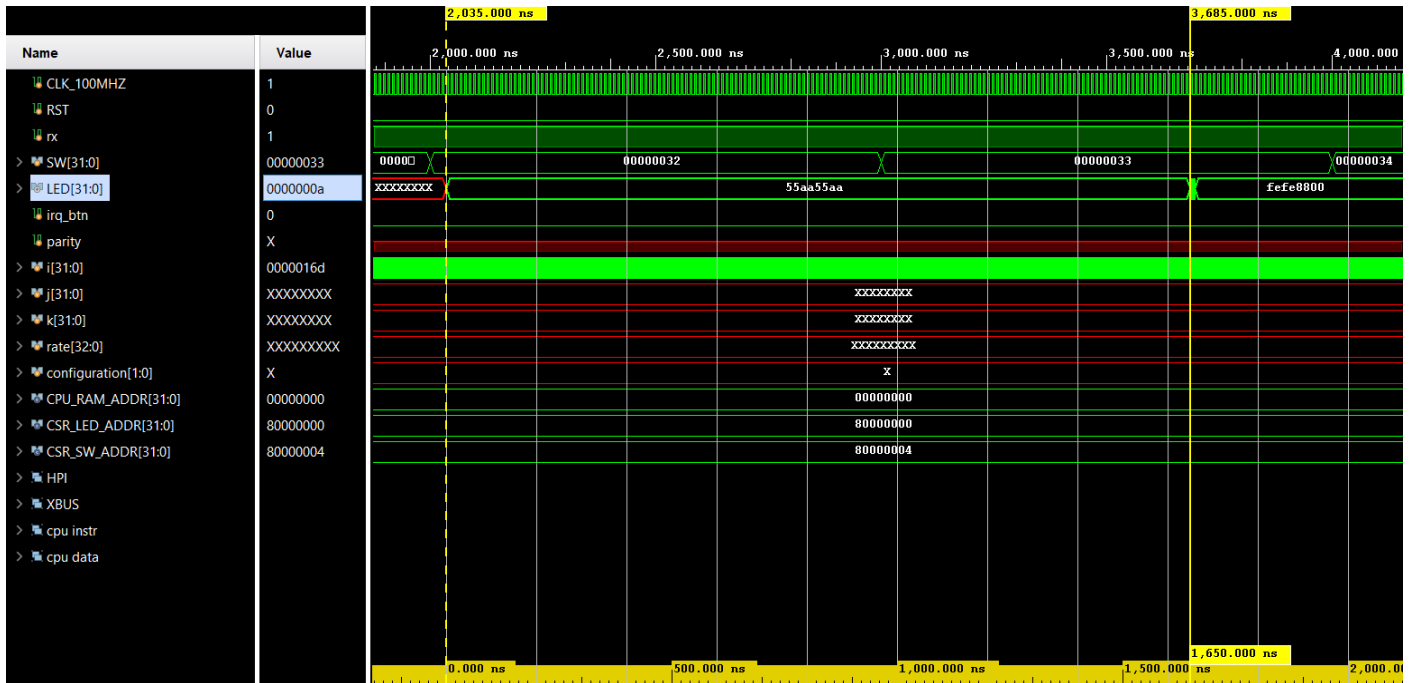


Figure 2 Simulation waveform of program working on CPU

The values on LEDs are correct, the program works as intended.

NOTE: if resulting values do not appear in simulation, try the following:

- Check the program is placed in sigma_tile RAM. Compare the content of RAM (RAM array is located at /riscv_tb/sigma/sigma_tile/ram/ram_dual/ram) to the program binary. Consider specifying absolute path in case the image is not loaded.
- Write intermediate values to LED register.
- Trace program execution.

The program can be traced in simulation using 1-stage CPU configuration. To switch CPU configurations for simulation, open corresponding Vivado project and change CPU parameter of sigma instance in riscv_tb.sv testbench. Display the following signals in CPU (located in /riscv_tb/sigma/sigma_tile/genblk1.riscv, see Figure 3):

- genpstage_EXEC_TRX_LOCAL.curinstr_addr – instruction address
- genpstage_EXEC_TRX_LOCAL.instr_code – instruction code
- genpsticky_glbl_regfile – general-purpose registers

NOTE: you can use the provided riscv_tb_behav.wcfg waveform configuration file to display the CPU state.

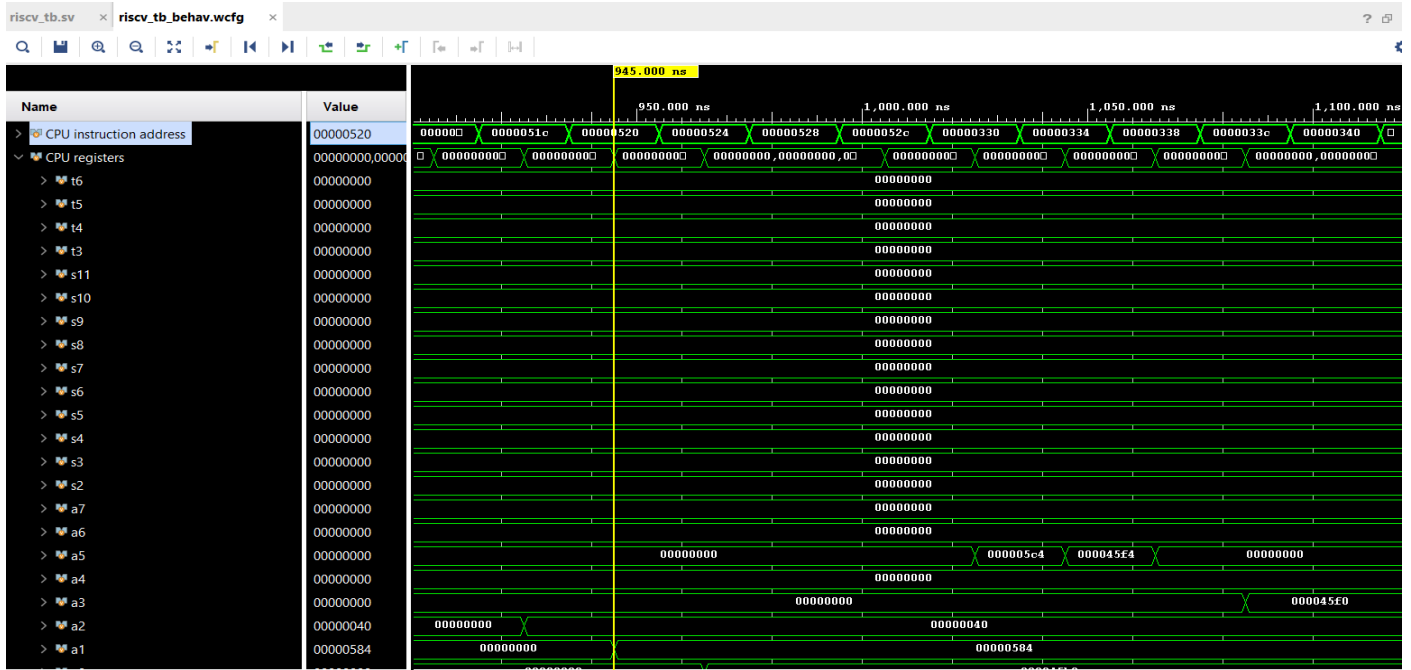


Figure 3 Tracing program execution using 1-stage CPU configuration

```

...
00000518 <main>:
518: fb010113      addi    sp,sp,-80
51c: 04000613      li      a2,64
520: 58400593      li      a1,1412
524: 00010513      mv      a0,sp
528: 04112623      sw      ra,76(sp)
...

```

Listing 5 Fragment of `findmaxval.riscv.dump` program dump file

Analyze dumped representation of program (`findmaxval.riscv.dump` in our case, see Listing 5) using RISC-V Assembly Programmer's Manual: github.com/riscv/riscv-asm-manual/blob/master/riscv-asm.md. E.g., in our example, instruction at address 0x520 (`li a1, 1412`) writes immediate value 1412 (0x584) to register a1. This operation is marked in Figure 3.

Identify and fix inconsistencies in program execution.

3) Implement the designs and collect metrics of the implementations

Characteristics of provided `sigma_tile` configurations are shown in Table 2:

CPU configuration	Frequency, MHz	LUTs	FFs
<code>riscv_1stage</code>	70	2144	1180
<code>riscv_2stage</code>	70	2263	1279
<code>riscv_3stage</code>	80	2293	1422
<code>riscv_4stage</code>	140	2284	1686
<code>riscv_5stage</code>	150	2385	1731
<code>riscv_6stage</code>	160	2314	1830

Table 2 Characteristics of provided `sigma_tile` implementations

- 4) (if FPGA board available) Upload your program to Sigma MCU and make sure it works correctly

To upload your program to Sigma MCU FPGA implementation, use `loadelf` function in Python environment. For example, copy `hw_test_apps.py` script and make the following corrections:

```
#sigma.run_app_tests()
sigma.tile.loadelf('<PATH_TO_ACTIVECORE>/designs/rtl/sigma/sw/apps/findmaxval.riscv')
```

In our example, the LEDs show 0x8800 (16 least significant bits of 0xfefe8800 value). The program works as intended.

- 5) Analyze performance for various CPU configurations

Now we can analyze performance values of functionality implementations based on various CPU configurations. Set the actual clock period for each CPU configuration according to Section 4. For our example, these values are shown in Table 3.

CPU configuration	Latency, ns
riscv_1stage	2943
riscv_2stage	1586
riscv_3stage	1938
riscv_4stage	1179
riscv_5stage	1100
riscv_6stage	1200

Table 3 Performance of implementations based on various CPU configurations

4. Accelerate your application in hardware using Sigma MCU expansion interface

XIF is a memory-mapped interface for connection of custom peripheral modules.

Since XIF protocol is identical to UDM bus protocol, UDM-compatible modules can be seamlessly integrated in Sigma MCU.

NOTE: Beware that XIF address space starts from 0x80000000.

Design and integrate custom accelerator in Sigma MCU according to UDM lab manual (modify `sigma.sv` module). Then, write software application that communicates with the designed accelerator.

5. Accelerate your application in hardware using Sigma MCU ISA extension interface

Sigma MCU provides coprocessor interface, where custom instructions belonging to `custom-0` opcode space (see RISC-V Unprivileged Spec, Vol. 1) are routed. This interface can be used to accelerate frequent and/or heavy computations.

- 1) Design custom coprocessor

By default, CPU coprocessor interface is connected to `coproc_custom0_wrapper` module. Modify this module to implement your coprocessor.

Two operands can be read and one operand written in a single instruction. Coprocessor requests are non-speculative (cannot be killed by the CPU), so this coprocessor can communicate with external modules and have its internal state.

NOTE: Beware that execution of custom instructions is synchronous to the main CPU pipeline (response delay will stall the CPU pipeline as well). Consider either accelerating short operations or implement asynchronous communication model (to make CPU and coprocessor operation overlap).

Coprocessor interface signals are summarized in Table 4.

Coprocessor interface signal	Description
stream_req_bus_genfifo_req_i	Request assertion
stream_req_bus_genfifo_ack_o	Request acknowledge
stream_req_bus_genfifo_rdata_bi.instr_code	Instruction code
stream_req_bus_genfifo_rdata_bi.src0_data	Rs0 read register data
stream_req_bus_genfifo_rdata_bi.src1_data	Rs1 read register data
stream_resp_bus_genfifo_req_o	Response assertion
stream_resp_bus_genfifo_ack_i	Response acknowledge
stream_resp_bus_genfifo_wdata_bo	Rd write register data

Table 4 Description of coprocessor interface signals

In our example, the coprocessor preserves the index and value of current maximum value. Within each request, the module reads two new values, updates the state, and returns the index of current maximum value. The coprocessor code is shown in Listing 6

```

`include "coproc_if.svh"

module coproc_custom0_wrapper (
    input logic unsigned [0:0] clk_i
    , input logic unsigned [0:0] rst_i
    , output logic unsigned [0:0] stream_resp_bus_genfifo_req_o
    , output resp_struct stream_resp_bus_genfifo_wdata bo
    , input logic unsigned [0:0] stream_resp_bus_genfifo_ack_i
    , input logic unsigned [0:0] stream_req_bus_genfifo_req_i
    , input req_struct stream_req_bus_genfifo_rdata_bi
    , output logic unsigned [0:0] stream_req_bus_genfifo_ack_o
);

assign stream_req_bus_genfifo_ack_o = stream_req_bus_genfifo_req_i;

logic unsigned [31:0] cur_index, max_index, max_val;
assign stream_resp_bus_genfifo_wdata_bo = max_index;

always @(posedge clk_i)
begin
    if (rst_i)
        begin
            stream_resp_bus_genfifo_req_o <= 1'b0;
            cur_index <= 0;
            max_index <= 0;
            max_val <= 0;
        end
    else
        begin
            stream_resp_bus_genfifo_req_o <= 1'b0;
            if (stream_req_bus_genfifo_req_i)
                begin
                    if (stream_req_bus_genfifo_rdata_bi.src0_data > max_val)
                        begin
                            max_index <= cur_index;
                            max_val <= stream_req_bus_genfifo_rdata_bi.src0_data;
                        end
                    if ((stream_req_bus_genfifo_rdata_bi.src1_data > max_val) &&
(stream_req_bus_genfifo_rdata_bi.src1_data
stream_req_bus_genfifo_rdata_bi.src0_data)) >
                        begin
                            max_index <= cur_index + 1;
                            max_val <= stream_req_bus_genfifo_rdata_bi.src1_data;
                        end
                end
        end
    end

```

```

        end
        stream_resp_bus_genfifo_req_o <= 1'b1;
        cur_index <= cur_index + 2;
    end
end
endmodule

```

Listing 6 Coprocessor design in coproc_custom0_wrapper module

2) Activate the designed coprocessor in software application

To request the coprocessor, the software should utilize instructions from custom-0 opcode space. Add the wrapper for the new instruction using inline assembly and call this wrapper to fire coprocessor requests. Updated software implementation utilizing the coprocessor is shown in Listing 7.

```

#define IO_LED          (*(volatile unsigned int *) (0x80000000))
#define IO_SW           (*(volatile unsigned int *) (0x80000004))

#define ARR_SIZE 16

typedef struct
{
    unsigned int max_elem;
    unsigned int max_index;
} maxval_data_t;

// wrapper for instruction activating custom coprocessor
inline unsigned int custom0_instr_wrapper (unsigned int a, unsigned int b)
{
    unsigned int result;
    asm volatile (".insn r 0x0b, 0x0, 0x0, %0, %1, %2"
        : "=r" (result)
        : "r" (a), "r" (b));
    return result;
}

maxval_data_t FindMaxVal(unsigned int x[ARR_SIZE])
{
    maxval_data_t ret_data;
    ret_data.max_elem = 0;
    ret_data.max_index = 0;

    for (int i=0; i<ARR_SIZE; i=i+2) {
        // custom coprocessor request
        ret_data.max_index = custom0_instr_wrapper(x[i], x[i+1]);
    }
    ret_data.max_elem = x[ret_data.max_index];

    return ret_data;
}

//-----
// Main

int main( int argc, char* argv[] )
{
    maxval_data_t maxval_data;

```

```

    unsigned int datain[16] = { 0x112233cc, 0x55aa55aa, 0x01010202, 0x44556677,
0x00000003, 0x00000004, 0x00000005, 0x00000006, 0x00000007, 0xdeadbeef, 0xfefe8800,
0x23344556, 0x05050505, 0x07070707, 0x99999999, 0xbadc0ffe };
    IO_LED = 0x55aa55aa;
    maxval_data = FindMaxVal(datain);
    IO_LED = maxval_data.max_index;
    IO_LED = maxval_data.max_elem;
    while (1) {}
}

```

Listing 7 Updated C source code in `findmaxval.c` utilizing coprocessor request instruction

After compilation, dump file should contain the instruction requesting the coprocessor. For our example, the dump is shown in Listing 8.

```

...
000002a4 <FindMaxVal>:
2a4: 00052023      sw      zero,0(a0)
2a8: 00058793      mv      a5,a1
2ac: 04058613      addi    a2,a1,64
2b0: 0007a703      lw      a4,0(a5)
2b4: 0047a683      lw      a3,4(a5)
2b8: 00d7070b      0xd7070b
2bc: 00e52023      sw      a4,0(a0)
2c0: 00878793      addi    a5,a5,8
2c4: fef616e3      bne     a2,a5,2b0 <FindMaxVal+0xc>
2c8: 00271713      slli    a4,a4,0x2
2cc: 00e58733      add     a4,a1,a4
...

```

Listing 8 Fragment of `findmaxval.riscv.dump` program dump file containing instruction requesting custom coprocessor

3) Test the updated hardware and software

Repeat the steps 2.2-2.5 to test the updated system in simulation and in hardware. Simulation waveform for our example is shown in Figure 4.



Figure 4 Waveform of CPU requesting custom coprocessor

Note that the new implementation takes 780 ns to complete, compared to 1,650 ns in pure software implementation. So, approximately 2x acceleration has been achieved.