Runtime Environment

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Introduction

You have already implement a minirv CPU

How to build a program to run on your CPU?

We have some programming tasks in this lecture

- But if your implementation of CPU is correct, only some software programming is needed

Some Preparations

minirv CPU

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- the RTL implementation of minirv CPU
- a reference model implemented in C/C++

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Some programs we are going to build may execute millions of instruciton to finish

- If you do not have the reference model, it will be extremely HARD to debug
  - It will be VERY HARD to find the wrong instruction

Confirm the Memory Model

From the RISC-V manual:

```
        1.4 Memory

        A RISC-V hart has a single byte-addressable address space of 2^{XLEN} bytes
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        memory accesses.
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  - CPU fetches a 4-bytes instruction from address `0x10`
  - CPU issues a `lw` to load a 4-bytes data from address `0x10`

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- For example, the following read results should be the same
  - CPU fetches a 4-bytes instruction from address `0x10`
  - CPU issues a `lw` to load a 4-bytes data from address `0x10`
- Software also sees only one memory, conforming to the ISA spec
  - Programs generate by modern toolchains satisfy this property

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- You have ROM for instruction and RAM for data in your design
  - But they are different memory units
- To really implement the memory model, we should add extra circuit to provide a unified memory interface

```
+-----+     inst. fetch    +------------+       +--------+
|     | <----------------> |   Memory   |       | Memory |
| CPU |                    |            | <---> |        |
|     | <----------------> | Controller |       |  Unit  |
+-----+  load/store inst.  +------------+       +--------+
```

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- Instead, by loading the same image file (the `.hex` file), we make ROM and RAM consistent

Recommandation for Implementation in RTL

- Implement memory as an array in C/C++
- Use DPI-C to let RTL code access the memory array in C/C++

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#define MEM_SIZE (128 * 1024 * 1024)
static char memory[MEM_SIZE];
extern "C" int mem_read(int raddr) {
  // Return the 4-byte data at address `raddr & ~0x3u`.
  ...
}
extern "C" void mem_write(int waddr, int wdata, char wmask) {
  // Write `wdata` according to `wmask` to the 4-byte data at address `waddr & ~0x3u`
  // Every bit in `wmask` represents the mask of 1-byte in `wdata`.
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We will finally change it to a real memory controller in SoC

Runtime Environment

The Running of a Hello Program

```c
// hello.c
#include <stdio.h>
int main() {
  printf("Hello, World!\n");
  return 0;
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gcc hello.c
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- Where is the actual code of `printf()`?
- How does the Hello program end?

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Intuition - The Hello program can not run only by itself

- There must be something helps the Hello program to run!
- That is runtime environment - a set of software helps other programs to run

Responsibility of the Runtime Environment

1. Before program execution - perform preparation
   - Load the program, set up the connection to libraries, set up arguments…
2. During program execution - provide the support of libraries
3. After program execution - clean up before the program really exits

Two Types of Runtime Environments

In the C standard document:

```
         5.1.2 Execution environments

         Two execution environments are defined: freestanding and hosted. In both
cases,
         program startup occurs when a designated C function is called by the
execution
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```

```
        5.1.2.1 Freestanding environment

        1. In a freestanding environment (in which C program execution may take place
        without any benefit of an operating system), the name and type of the
function
        called at program startup are implementation-defined.
```

- This is actually the runtime environment for a program to run on your CPU
  - Your CPU can not boot an OS now

Two Types of Runtime Environments(2)

```
5.1.2.2 Hosted environments
5.1.2.2.1 Program startup

1. The function called at program startup is named main...
```

- In a hosted environment, there is a hosted OS
  - This is the runtime environment used when you learn C Programming Language
  - Linux provides a hosted environment to program

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```
        2. If they are declared, the parameters to the main function shall obey the
following
        constraints:
        ...
        — If the value of argc is greater than zero, the string pointed to by argv[0]
          represents the program name; ...
          If the value of argc is greater than one, the strings pointed to by argv[1]
          through argv[argc-1] represent the program parameters.
```

- The convention of the program parameters

Freestanding Environment

Freestanding Environment for `1+2+...+10`

1. Before program execution
   - Program loading
     - Use GUI to choose the image file in Logisim
     - Initialize with a global array, or read from file in sEMU
   - No support for argument passing

2. During program execution
   - No support for library functions

3. After program execution
   - Use an infinity loop to indicate the end of the program
     - Implemented by `bner0`

Enhancement of Runtime Environment

- The summation program does not need a complicated runtime environment to run
  - In other words, to run more complicated programs, the runtime environment should provide more functionalities

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TASK 1 - displaying an integer in sEMU (the reference model)

- sISA - add a new instruction `out rs`
- sEMU - when executing `out rs`, display `R[rs]` to the terminal
- program - use this instruction

Enhancement of Runtime Environment(2)

TASK 2 - input `n` as an argument from command line, then compute `1+2+...+n`

- Let runtime environment places `n` somewhere before the program runs
- Program reads `n` from the same place
- This is a kind of convention between the runtime environment and the program

- sEMU - place the argument input by user to register `r0`
- program - get the last term of the summation from `r0`, and compute the summation

Summary - the Enhanced Runtime Environment

1. Before program execution
   - Program loading - initialize with a global array, or read from file in sEMU
   - Argument passing - use register `r0` to pass an integer to the program

2. During program execution
   - Can display an integer with `out` instruction

3. After program execution
   - Use an infinity loop to indicate the end of the program
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Abstract Machine - a Freestanding Environment for Building Computer System

Challenges during Building Computer System

1. Several platforms are slightly different to support program
   - Logisim, instruction set simulator, RTL simulation for CPU, RTL simulation with SoC, real chip, …
     - The way to load a program
     - The way to display a digit/character
     - The way to terminate a program
     - …
   - For the program, how to code once, run everywhere?

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     - …
   - For the program, how to code once, run everywhere?

2. CPU (or computer system) is developed step by step
   - Pure computation, I/O, exception & interrupt, virtual memory, …
   - How to let runtime environment and program enhance gradually along with CPU?

Two Important Principles in Computer System

1. Abstraction - add a new layer to hide the underlying differences

- Abstract the differences as APIs
  - They are implemented by the runtime environment
- Program calls these APIs, without knowing the implementation

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2. Modularity - group these APIs by the phases of development, and select them on demand
   - TRM(TuRing Machine) - pure computation, which is mandatory
   - IOE(I/O Extension)
   - CTE(ConText Extension)
   - VME(Virtual Memory Extension)
   - MPE(Multi-Processor Extension)

Abstract Machine - a New Runtime Env.

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- Following the principles, we propose Abstract Machine (AM)
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- The power of abstraction
  - For program - write/port once, run everywhere
  - For platform - support AM, run everything
  - For Debugging - can benefit from the decoupling
    - First debug the program on Linux native
    - Then debug your CPU with the program

```
                                         +-------+------+-----+------------------+---
--+
                                         | Mario | Demo |Shell|        ...       |
... |
        +----------+-------+-------------+------ +------+-----+------------------+---
--+
        | CoreMark | LLaMa | Typing Game | FCEUX | RTOS | xv6 | Self-designed OS |
... |
        +----------+-------+-------------+-------+------+-----+------------------+---
--+
```

Use AM to Build Programs for Your CPU

Build a minirv Program

1. Install tools

```
sudo apt install g++-riscv64-linux-gnu git
```

2. Clone the repo

```
git clone https://github.com/NJU-ProjectN/abstract-machine
git clone https://github.com/NJU-ProjectN/am-kernels
```

3. Set environment variable

```
cd abstract-machine
echo "export AM_HOME=`pwd`" >> ~/.bashrc  # change this if your shell is not bash
source ~/.bashrc  # or close the terminal and open a new terminal
```

4. Check the environment variable

```
echo $AM_HOME   # should display the path you just set in the previous step
```

5. Build a program

```
cd am-kernels/tests/cpu-tests
make ARCH=minirv-npc ALL=dummy  # npc stands for New Processor Core
```

You may encounter a compile error, fix it according the next page…

Build a minirv Program(2)

```
make ARCH=minirv-npc ALL=dummy
```

Try to fix the compile error as following:

```
/usr/riscv64-linux-gnu/include/bits/wordsize.h:28:3: error: #error "rv32i-based targets are not supported"
```

```diff
--- /usr/riscv64-linux-gnu/include/bits/wordsize.h
+++ /usr/riscv64-linux-gnu/include/bits/wordsize.h
@@ -25,5 +25,5 @@
 #if __riscv_xlen == 64
 # define __WORDSIZE_TIME64_COMPAT32 1
 #else
-# error "rv32i-based targets are not supported"
+# define __WORDSIZE_TIME64_COMPAT32 0
 #endif
```

```
/usr/riscv64-linux-gnu/include/gnu/stubs.h:8:11: fatal error: gnu/stubs-ilp32.h: No such file or directory
```

```diff
--- /usr/riscv64-linux-gnu/include/gnu/stubs.h
+++ /usr/riscv64-linux-gnu/include/gnu/stubs.h
@@ -7,3 +7,3 @@
 #if __WORDSIZE == 32 && defined __riscv_float_abi_soft
-# include <gnu/stubs-ilp32.h>
+//# include <gnu/stubs-ilp32.h>
 #endif
```

Run the Program

```
make ARCH=minirv-npc ALL=dummy
ls build/  # should contain the following files
    dummy-minirv-npc.bin # the binary to load into the memory array in the simulation
    dummy-minirv-npc.elf # ELF program, which contains some structural information
    dummy-minirv-npc.txt # disassembly result
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```

TASK 3 - run `dummy` in your CPU

- For convention, memory should be at the address space above `0x80000000`
  - Address space below `0x80000000` is usually for devices
- Change the reset value of PC to `0x80000000`
- `dummy` should get stucked inside an infinite loop with `a0 = 0`

Run the Program(2)

TASK 4 - add `ebreak` in `halt()` to finish simulation automatically

- Insert `ebreak` in `halt()` by inline assembly:

```
--- abstract-machine/am/src/riscv/npc/trm.c
+++ abstract-machine/am/src/riscv/npc/trm.c
@@ -17,3 +17,4 @@
 void halt(int code) {
+  asm volatile("mv a0, %0; ebreak" : :"r"(code));
   while (1);
 }
```

- Add `ebreak` to your CPU
- Modify the simulator to check `a0` when CPU executes `ebreak`
  - if `a0 == 0`, let the simulation exit with `0`
  - if `a0 != 0`, let the simulation exit with a non-zero value

Run the Program(3)

TASK 5 - implement the `run` rule in Makefile `abstract-machine/scripts/platform/npc.mk`

- So `make ARCH=minirv-npc ALL=dummy run` will compile and run the program on your CPU
  - This can help you to run lots of tests automatically
  - In the following days, you will run lots of tests again and again
- Hint: use `$(IMAGE).bin` in Makefile to refer to the path of binary file which is generated

TRM - A Basic Part of Runtime Environment for Pure Computation

TRM - A Simple Freestanding Runtime Environment

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  - But it is OK, since it is implementation-defined
- A way to exit - `halt()`
- A way to display a character - `putch()`
  - Every meaningful program should output something

Read the Friendly Source Code

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- `am-kernels` - some programs developed over AM

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   - `abstract-machine/scripts/linker.ld`

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5. `objcopy` copies code and data in the executable file into a binary image
6. Load the binary image into the memory of your CPU and run!

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2. `_start` will do the following:
   - first set the stack pointer
   - then call `_trm_init()`, which is defined in `abstract-machine/am/src/riscv/npc/trm.c`

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   - which is defined in `abstract-machine/am/src/riscv/npc/start.S`
2. `_start` will do the following:
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5. `halt()` will finally terminate the program

OPTIONAL: How to control `gcc` to only generate 8 instructions?

See `abstract-machine/tools/minirv/`

In general:

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  - In other words, we implement other instructions using the 8 target instructions

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   - `inst-replace.h` contains code to replace other instructions by the 8 target instructions
     - In other words, we implement other instructions using the 8 target instructions
3. Let `gcc` compile the `.S` file into a `.o` file
   - The `.o` file should contain only 8 instructions

Run More Programs to Test Your CPU

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TASK 6 - run `riscv-tests` to test your CPU

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cd riscv-tests-am
make ARCH=minirv-npc run TEST_ISA=i # run all testcases for rv32i
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TASK 7 - run `cpu-tests` to test your CPU

```
cd am-kernels/tests/cpu-tests
make ARCH=minirv-npc run          # run all testcases
make ARCH=minirv-npc run ALL=fib  # only run one testcase
```

NOTE: `string` and `hello-str` should fail

- They depend on klib, which we will provide later
- Just ignore them now

END