

# Runtime Environment

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# Introduction

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You have already implemented 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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You should have

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

# minirv CPU

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- a reference model implemented in C/C++

Some programs we are going to build may execute millions of instruction 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

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From the RISC-V manual:

## 1.4 Memory

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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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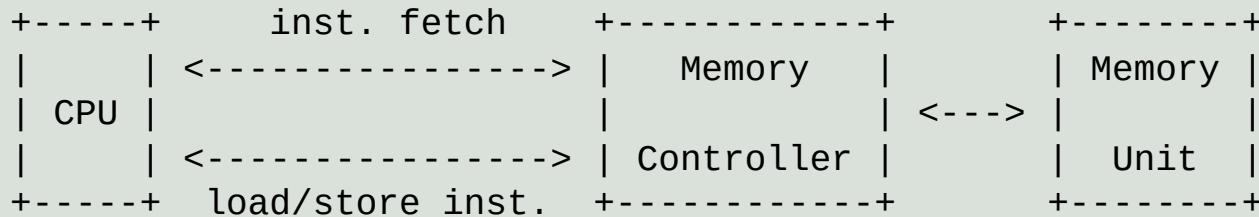
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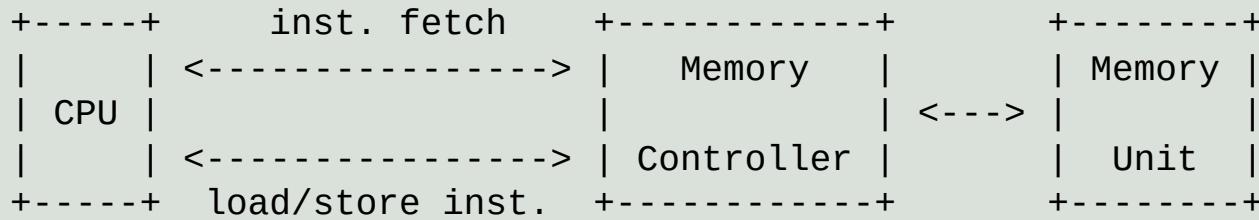


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- Instead, by loading the same image file (the **.hex** file), we make ROM and RAM consistent

# 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++

```
#define MEM_SIZE (128 * 1024 * 1024)
static char memory[MEM_SIZE];
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    // 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

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```
// 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

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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

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In the C standard document:

## 5.1.2 Execution environments

Two execution environments are defined: freestanding and hosted. In both cases,

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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)

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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 $1+2+\dots+10$

---

## 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 `bne r0`

# Enhancement of Runtime Environment

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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)

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**TASK 2** - input  $n$  as an argument from command line, then compute  $1+2+\dots+n$

- 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

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## 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
  - Implemented by `bne r0`

# 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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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

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

- Abstract the differences as APIs
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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)

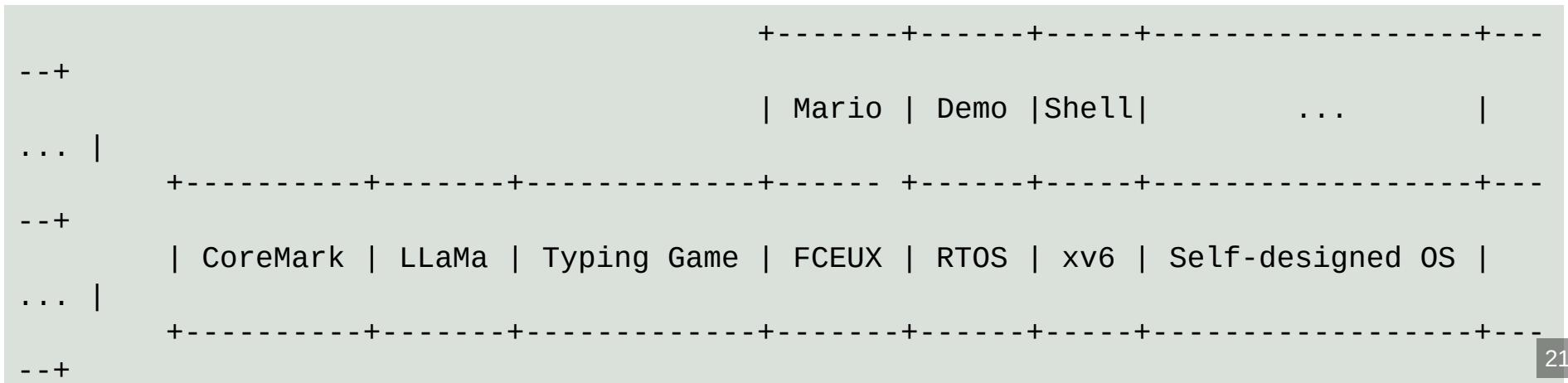
# Abstract Machine - a New Runtime Env.

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- Following the principles, we propose **Abstract Machine (AM)**
  - A new freestanding runtime environment suitable for building computer system

# Abstract Machine - a New Runtime Env.

- Following the principles, we propose **Abstract Machine (AM)**
    - A new freestanding runtime environment suitable for building computer system
  - 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



# 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"
```

```
--- /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
```

```
--- /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

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```
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
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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

# How to Build a Program

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

# How does the Program start and end?

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- which is defined in `abstract-machine/am/src/riscv/npc/start.S`

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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`

# How does the Program start and end?

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  - which is defined in `abstract-machine/am/src/riscv/npc/start.S`
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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:

1. Let `gcc` compile a `.c` file to a `.S` file

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In general:

1. Let `gcc` compile a `.c` file to a `.S` file
  2. Insert one line of `#include "inst-replace.h"` at the beginning of the `.S` file
- `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

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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

# Run More Programs

First change the memory size to 128MB

- It should be enough for the following programs

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

```
git clone https://github.com/NJU-ProjectN/riscv-tests-am
cd riscv-tests-am
make ARCH=minirv-npc run TEST_ISA=i # run all testcases for rv32i
make ARCH=minirv-npc run ALL=addi    # only run one testcase
```

# Run More Programs

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make ARCH=minirv-npc run ALL=addi # only run one testcase
```

## 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

