Computer Architecture 2025fall Project 1

> *By Prof. Jie Zhang*
>
> **Due:** 11:59:59 pm, October 8, 2025

Nowadays, `gem5` has been the most popular simulation framework used by computer architecture research community. This project will cover the tutorial of building up a computer system framework by using `gem5` simulator. We will study how different CPU types and main memory systems can impact the whole performance of computer system. Please note that `gem5` simulation usually takes a long time. So you need to start the project as early as possible.

For your convenience, we have tried to minimize the hassles of setting up `gem5` , but still, it is somewhat tricky. Whenever you face the trouble or problem on this project, please refer to `gem5` documentation or contact TAs by WeChat or e-mail. All the following information have been verified on Ubuntu 20.04.1 with Linux Kernel 5.15.0 and Ubuntu 22.04.2 LTS with the Linux Kernel 5.19.0.

Setup: Install Toolchain and Compile `gem5`

Install environment

As a complicated software, `gem5` requires several prerequisites to run properly. However, manually preparing the correct environment is very challenging. For your convenience, we provide a Docker image with correctly installed prerequisites. To use the image, you first need to install Docker. On Windows system, you can easily install it by installing Docker Desktop; on Linux system, you can install Docker following the documentation. You can use the following command to check your installation:

```
docker --version

# You'll see contents like the following:
Docker version 24.0.2, build cb74dfc
```

> **Docker install tips**
>
> On Windows system, pay particular attention to verifying whether **WSL2** is already installed on your computer or whether **Hyper-V** functionality is enabled. Failure to do so may result in various unexpected issues during the installation process. We recommend using WSL2 to support Docker. You can verify if WSL2 is installed with the following command:
>
> ```
> wsl --version
> ```

Once you've installed Docker, you can pull our image with the following command:

```
docker pull chaselab/archlab
```

> **Note**

If you can't connect to Docker Hub, you can also download the image archive from our PKU Disk and load it with the following command:

```
docker load -i archlab-image.tar
```

All the resources used in labs will be visible in the PKU Disk.

After pull (load) the image, you can find it by running the following command:

```
docker images

# you'll see contents like the following:
REPOSITORY          TAG             IMAGE ID        CREATED          SIZE
chaselab/archlab    latest          c028b12a3ac4    1 second ago     1.8GB
```

Note

If you prefer to install the prerequisites for `gem5` manually, you can follow the commands listed below.

```
sudo apt-get update; sudo apt-get upgrade
# For Ubuntu 20.04
sudo apt install build-essential git m4 scons zlib1g zlib1g-dev
libprotobuf-dev protobuf-compiler libprotoc-dev libgoogle-perftools-
dev python3-dev python-is-python3 libboost-all-dev pkg-config

# For Ubuntu 18.04
sudo apt install build-essential git m4 scons zlib1g zlib1g-dev
libprotobuf-dev protobuf-compiler libprotoc-dev libgoogle-perftools-
dev python3-dev python libboost-all-dev pkg-config
```

After preparing the environment, you should clone the codes of `gem5`. We have provided a skeleton code which you can clone from its repo, or download the code package from PKU Disk and then extract the codes to a directory.

Code clone tips

> On Windows system, please run the following command before cloning the code repository:
>
> ```
> git config --global core.autocrlf false
> ```
>
> This will prevent compilation issues caused by differences in line ending definitions between Windows and Linux.

Once you have the codes, you are able to compile `gem5`. If you are using Docker (if not you can skip this part), you need to firstly create a container to setup the environment. Also, you need to mount the code onto the container when you start it, so that you can read and modify the code files inside the container. The command is as follows:

```
docker run -it --name <container name> -v <local path>:<container path>
chaselab/archlab /bin/bash
```

- The `-it` option means to attach stdin, stdout and stderr to current terminal, so you can operate the container interactively.
- The `--name <container name>` option specifies the name of the new container. It may be useful when you try to run other commands on the container, but it is rather optional, because you can always specify a container by its individual ID. You can see the IDs and names of all existing containers with this command:

  ```
  docker ps -a

  # you'll see contents like the following:
  CONTAINER ID   IMAGE                 COMMAND       CREATED
  STATUS                       PORTS   NAMES
  43518d84eb29   chaselab/archlab      "/bin/bash"   14 seconds ago
  Exited (0) 14 seconds ago            lab1
  ```

- The `-v <local path>:<container path>` allows you to mount a local directory to a directory in the container. Here, you need to specify the `local path` as the path to your `gem5` code, for example, `C:\Users\myname\gem5`. The `container path` can be simple, for example, `/gem5`. When you enter the container, you can see all the codes under container path. Please note that this option **only accepts absolute paths**, otherwise the contents in the directory will not be correctly mounted.

- The first argument after the options is the image name, here is `chaselab/archlab`.
- The second argument is the command you want to run upon container start. Here we use `/bin/bash` to start an interactive terminal.

Thus, filling up all the options and arguments makes the command look like this:

```
docker run -it --name lab1 -v C:\Users\myname\gem5:/gem5 chaselab/archlab
/bin/bash
```

Server account

If you still cannot compile or cannot setup WSL and Docker Desktop, feel free to contact TA for a server account.

Docker command tips

After starting the container, you can run any commands in it. However, you need to know more docker commands when meeting other situations:

- If you've closed the container by running `exit` and want to run the lab again, you do not need to create another container with `docker run`. Instead, you can use the following command to restart your container and attach stdin, stdout and stderr to your terminal:

  ```
  docker start -ia <container ID/name>
  ```

  If you are using a Windows system, you can also launch the corresponding container directly from the graphical interface of the Docker Desktop software.
- If you start the simulation and want to close the terminal while keeping `gem5` running, you can type `ctrl+p+q` to stop the interactive evironment and return to your own terminal. Then, when you want to return to the container, you can use the following commands:

```
docker attach <container ID/name> # return to the original
container terminal
docker exec -it <container ID/name> <command> # start a new
container terminal
```

- If you want to make accessing Docker feel similar to accessing a remote server, you can use the *Dev Containers* extension for VS Code (refer to Appendix). This allows you to directly access the running container through VS Code, and use VS Code to edit code and execute command-line commands.

Compile gem5

Once the container has started, or if you have manually prepared the environment, you can proceed to compile `gem5`. Please note that `gem5` must be built on a Unix platform (e.g., Linux and MacOS). `gem5` uses SCons to manage its compilation. In this lab, we'll compile for ARM ISA:

```
cd gem5
scons build/ARM/gem5.opt -j $(nproc) # use all your cores to compile
```

Compile tips

If you run `scons` to compile and are warned with `Cannot find 'pre-commit'` (messages like the following), you can ignore the message (press enter and then press y). This is only required for contributing to `gem5` and will not prevent the compilation.

```
You're missing the pre-commit/commit-msg hooks. These hook help to
ensure your
code follows gem5's style rules on git commit and your commit messages
follow
our commit message requirements. This script will now install these
hooks in
your .git/hooks/ directory.
Press enter to continue, or ctrl-c to abort:
 Cannot find 'pre-commit'. Please ensure all Python requirements are
installed. This can be done via 'pip install -r requirements.txt'.
It is strongly recommended you install the pre-commit hooks before
working with gem5. Do you want to continue compilation (y/n)?
```

Building `gem5` may take you *more than 30 minutes* on your PC. If it completes successfully, you will see the following results:

```
 [     CXX] ARM/base/date.cc -> .o
 [    LINK]  -> ARM/gem5.opt
scons: done building targets.
```

You now have a binary in the directory `build/ARM` called `gem5.opt` .

Deliverables

Please include a **screenshot that shows your `gem5` can compile correctly** in your report.

Part 1: Create and Run a Simple Configuration Script

`gem5` simulator is built from a collection of Python objects, `SimObject`. In this part, you need to set up a simple configuration script to describe the `SimObject` to be instantiated, their parameters, and their relationships. Following the instructions in this part, you are able to model a simple computer system, including a simple CPU core, a single DDR4 memory channel, and a system-wide memory bus connecting CPU core and memory channel.

Let's get started by creating a new configuration file:

```
mkdir configs/proj1
touch configs/proj1/simple.py
```

This configuration file is a normal Python file. Therefore, you can use any legal grammar or available libraries in Python.

The first thing we should write in the script is to import the class definitions from the `m5` modules and all `SimObject` as follows:

```
import m5
from m5.objects import *
```

> **Info**
>
> `gem5` is an open-source project based on another project `m5`, which is still involved in `gem5` from many aspects.

In `gem5`, to simplify the description of large systems, the overall simulation specification is organized as a tree. Each node in the tree is a `SimObject` instance. The program must create a special object root of class `Root` to identify the root of the tree hierarchy. When parsing the configuration program, the tree hierarchy is walked recursively to identify the objects from the root to its descendants. We will create the first object which is the `Root` and specify its parameters in the "m5 main process":

```python
if __name__ == '__m5_main__':
    root = Root()
    root.full_system = False
    root.system = System()
```

`gem5` provides two simulation modes: system call emulation (SE) mode and full system (FS) mode. In FS mode, Gem5 can simulate a complete system with devices and an operating system, while in SE mode, only essential system services are provided by simulator to execute workloads. In our projects, we will use SE mode for faster simulation (`root.full_system = False`). The above codes also instantiate class `System` . It is the parent of all the other objects in the simulated system, and contains a lot of functional information, such as the physical memory ranges, the root clock domain, the root voltage domain, etc.

Note

Here is an alternative method to pass the parameters as named arguments:

```python
root = Root(full_system = False, system = System())
```

All the definitions of the used Python objects can be found under `gem5/src/.../*.py` . For example, `Root` can be found in `gem5/src/sim/Root.py` . You can check the usages of objects and choose your favorite way.

Now that a reference to the system for the simulation has been created, let's build a simple but complete system. The first thing is to set the clock on the system. We first need to create the clock domain, which is an instance of class `SrcCLockDomain` . Clock domain contains multiple parameters such as clock (clock frequency), voltage domain (voltage), etc. Each parameter has its default value defined in the python class. We can also manually set the values in the configuration script as follows:

```python
def init_system(system):
    system.clk_domain = SrcClockDomain(clock='4GHz',
voltage_domain=VoltageDomain())
```

Once the clock domain is set up, we can move to create the memory and the memory controller. We need to configure the memory simulation mode and memory range. Since we make configurations for normal simulation, we are going to select *timing mode* for the memory simulation, which can be applied in most conditions. In other simulation conditions such as restoring memory system from a checkpoint, you may select *atomic mode*.

Then, we will also set up a single memory range of size 2GB and assign it to the system. We should also get instances of memory controller (`MemCtrl`) and memory device from various memory device classes such as DDR4 DRAM (`DDR4_2400_8x8`), HMC (`HMC_2500_x32`), etc. All available memory devices classes are listed in `src/mem/DRAMInterface.py` . Last, we assign the memory device with the memory range.

```
system.mem_mode = 'timing'
system.mem_ranges = [AddrRange ('2GB')]
system.mem_ctrl = MemCtrl()
system.mem_ctrl.dram = DDR4_2400_8x8()
system.mem_ctrl.dram.range = root.system.mem_ranges[0]
```

So far, we have almost completed memory setup. Now, we can create a CPU. `gem5` provides various types of CPU such as `SimpleCPU` (simplified CPU timing model), `MinorCPU` (in-order CPU), `O3CPU` (out-of-order CPU), etc. As an example, we choose simple timing-based CPU in Gem5, `TimingSimpleCPU` . This CPU model executes each instruction in a single clock cycle, except for memory requests, which flow through the memory. You can instantiate the object in the system:

```
system.cpu = TimingSimpleCPU()
```

Next, we need to create a system bus to connect between the CPU and memory controller. The command to instantiate memory bus is as follows:

```
system.membus = SystemXBar()
```

Now that we have created the system bus, the next step is to describe the interconnect logic which actually connect the CPU to the memory. For CPU, we need to connect the ICache and DCache ports to the system bus (currently we do not include any cache in the CPU). For memory, we need to connect memory controller port to the system bus. In addition, we need to create an interrupt controller on the CPU and connect a system port to the memory bus. This port is a functional-only port to allow the system to read/write memory:

```
system.cpu.icache_port = system.membus.cpu_side_ports
system.cpu.dcache_port = system.membus.cpu_side_ports
system.mem_ctrl.port = system.membus.mem_side_ports
system.cpu.createInterruptController()
system.system_port = system.membus.cpu_side_ports
# system.cpu.interrupts[0].pio = system.membus.mem_side_ports
# system.cpu.interrupts[0].int_requestor = system.membus.cpu_side_ports
# system.cpu.interrupts[0].int_responder = system.membus.mem_side_ports
```

Info

For your information, X86 ISA also requires connecting PIO and interrupt ports to the memory bus. Here we use ARM ISA and ignore these requirements, but we leave the code in comments.

Note

In code above, we manually connect all the necessary ports of CPU to show the details of system wiring up. In fact, `gem5` source codes have provided a wrapped helper function to perform this procedure. You can use it as follows:

```
system.cpu.connectBus(system.membus)
system.mem_ctrl.port = system.membus.mem_side_ports
system.cpu.createInterruptController()
system.system_port = system.membus.cpu_side_ports
```

So far, we have finished the configuration of simulated system. Next, we will set up the program to be executed. `gem5` allows you to specify any application built for ARM ISA and that's been **statically** compiled. In this script, we will execute a simple "Hello World" program. You can compile the code with `make` in `tests/labexe`, or download the pre-built binaries from PKU Disk.

Important note

In our released codes, we've included five simple but representative algorithm programs in `gem5/tests/labexe`. The Docker image also includes the cross-compile toolchain. To compile these programs, simply run following commands:

```
cd tests/labexe
make
```

Then the executable files can be found under `tests/labexe`.

If you want to compile your own programs, just use `arm-linux-gnueabihf-gcc` and `arm-linux-gnueabihf-g++` as the compiler. Remember to add `-static` option so that `gem5` can correctly load the executables.

If you are not using Docker and want to compile ARM executables, you should install the cross-compile toolchain:

```
sudo apt install gcc-arm-linux-gnueabihf
```

If you prefer not to build the excutables by yourself or the building process takes a lot of time, you can just download the pre-built binaries from PKU Disk.

To inform `gem5` to execute our program, we first need to set system workload to the executable. Then we create a process and set the process command to the workload we want to run. This is a list structure with the executable in the first field and the arguments passed to the executable in the rest of the list. Then we configure the CPU to execute the process and finally create the functional execution contexts in the CPU:

```python
import os
def init_process(root):
    exe_path = 'tests/labexe/hello'
    root.system.workload = SEWorkload.init_compatible(exe_path)
    process = Process()
    process.executable = exe_path
    process.cwd = os.getcwd()
    process.cmd = [exe_path]
    root.system.cpu.workload = process
    root.system.cpu.createThreads()
```

Finally, we need to instantiate the object hierarchy by calling `instantiate()` function. Once the object hierarchy has been instantiated, the actual simulation can begin. The `simulate()` function invokes the C++ event loop. By default, this function will simulate forever, or until some other factor causes the simulation loop to exit (such as the CPU has been shutdown).

If a positive integer argument is passed to the simulate function, it will simulate at most that number of additional ticks, but may exit sooner if another cause arises first. In any case, the `simulate()` function will return an event object that represents the reason for exiting. The object can be queried via its `getCause()` method for a string explaining that reason. Let's return to m5 main process, initialize the system and process, then start the simulation:

```
if __name__ == '__m5_main__':
    root = Root()
    root.full_system = False
    root.system = System()
    # new codes:
    init_system(root.system)
    init_process(root)
    m5.instantiate()
    exit_event = m5.simulate()
    print(f'{exit_event.getCause()} ({exit_event.getCode()}) @ {m5.curTick()}')
```

Now, we have created a simple but complete simulation script, we are ready to run `gem5`:

```
build/ARM/gem5.opt configs/proj1/simple.py
```

If everything goes fine, you'll see contents like follows:

```
...
Hello, World!
exiting with last active thread context (0) @ 14307750
```

Deliverables

Please include a **screenshot of the output on stdout of your configuration script** in your ***report***.

Part 2: Understand `gem5` Statistics and Output

After `gem5` simulation completes, by default there are three files generated in directory `m5out` :

- `config.ini` : contains a list of `SimObject` and the values of their parameters for simulation.
- `config.json` : same with `config.ini` , but in json format.
- `stats.txt` : detailed statistics generated from `gem5` simulation. Specifically, it contains general information about the execution, which is shown as follows:

```
---------- Begin Simulation Statistics ----------
simSeconds                                   5.148973        # Number of seconds simulated
(Second)
simTicks                                5148973163000        # Number of ticks simulated
(Tick)
...
```

It contains three columns: left lists the statistics names, middle column lists the values, and the right column shows the explanation. In this project, simSeconds and simInsts are important. You can calculate your simulated computer system performance (instructions per second) by `simInsts / simSeconds` . You also can find out system.cpu.numCycles and calculate IPC (instruction per cycle) by `simInsts / system.cpu.numCycles` . Each `SimObject` in the simulated system will print its own statistics. You can use any finding approach (e.g., `grep`) to check specific statistics, like the statistics of `system.cpu` .

Tip

You can change the output directory of `gem5` using command options like these (the options need to be **before** the script argument):

```
build/ARM/gem5.opt -d another-dir configs/proj1/simple.py
build/ARM/gem5.opt --outdir=another-dir configs/proj1/simple.py
```

> This is important for this and other projects, because `gem5` will override previous output in the same directory, which may delete your experiment results and waste your time. **Make sure to backup important results before running `gem5` again!**

Part 3: Add Options in the Configuration Script

In this project, you are required to explore different CPU and memory configurations for different workloads. However, it is cumbersome to edit your configuration script every time you want to test the system with different parameters. To smoothly solve this issue, you can add command-line parameters to your configuration scripts. Since the configuration script is a Python script, it can use Python libraries that support argument parsing (e.g., `argparse`). Adding options to configuration script requires several steps. After importing `argparse` , you need to specify the arguments in m5 main process:

```python
import argparse
if __name__ == "__m5_main__":
    parser = argparse.ArgumentParser()
    parser.add_argument(
        "commands_to_run",
        nargs="*",
        help="Command(s) to run",
    )
    parser.add_argument(
        "--cpu",
        type=str,
        choices=list(cpu_types.keys()),
        default="simple",
        help="CPU model to use",
    )
    parser.add_argument(
        "--mem",
        type=str,
        choices=list(mem_types.keys()),
        default="DDR4",
        help="type of memory to use",
    )
    parser.add_argument(
        "--clock",
        type=str,
        default="4GHz"
    )
    args = parser.parse_args()
    ...
```

Info

`argparse` is a very useful Python library that provides a set of methods to help build user-friendly CLI. In codes above we add a *positional argument* `commands_to_run` and three *options* with prefix `--`. `gem5` support you to use `-h,--help` options to check the usage of a configuration script:

```
build/ARM/gem5.opt configs/proj1/simple.py --help

# you'll see contents like the following:
...
usage: simple.py [-h] [--cpu CPU] [--mem MEM] [--clock CLOCK]
[commands_to_run [commands_to_run ...]]
...
```

For detailed usage of `argparse`, please refer to the official documentation.

You may notice that we have specified the `choices` in `--cpu` and `--mem`, which is a Python `list` that can specify the available choices. We've also defined `cpu_types` and `mem_types` and used their `keys()` as the choices. This is a convenient way to simplify the arugments used in commands. We can transform the argument short strings to detailed `SimObject` names with them. `gem5` provides various alternative CPU and memory models alongside `TimingSimpleCPU` and `DDR4` memory, such as `O3CPU` (out-of-order), `MinorCPU` (in-order), `DDR5` memory. We can use these models as choices. Example defines are as follows:

```
cpu_types = {
    "simple": TimingSimpleCPU,
    "minor": MinorCPU,
    "o3": O3CPU,
}
mem_types = {
    "DDR3": DDR3_1600_8x8,
    "DDR4": DDR4_2400_8x8,
    "DDR5": DDR5_8400_4x8,
}
```

Next, we need to pass the CPU type option and memory type option to the system. We can modify the `init_system()` function by following codes:

```
# DELETE: def init_system(system):
def init_system(system, args):
    ...
    # DELETE: system.mem_ctrl.dram = DDR4_2400_8x8()
    system.mem_ctrl.dram = mem_types[args.mem]()
    # DELETE: system.cpu = TimingSimpleCPU()
    system.cpu = cpu_types[args.cpu]()
    ...
```

We've also set the clock speed (`--clock`) option in codes above, and we can also pass it to the system:

```
# DELETE: system.clk_domain = SrcClockDomain(clock='4GHz',
voltage_domain=VoltageDomain())
system.clk_domain = SrcClockDomain(clock=args.clock,
voltage_domain=VoltageDomain())
```

Finally, we can pass the first positional argument `command_to_run` to the process, which allows us to specify executables other than simply `hello` :

```
# DELETE: def init_process(root):
def init_process(root, args):
    # DELETE: exe_path = 'tests/labexe/hello'
    exe_path = args.commands_to_run[0]
    root.system.workload = SEWorkload.init_compatible(exe_path)
    process = Process()
    process.executable = exe_path
    precess.cwd = os.getcwd()
    # DELETE: process.cmd = [exe_path]
    process.cmd = args.commands_to_run
    root.system.cpu.workload = process
    root.system.cpu.createThreads()
```

Now, we have completed the modification to our configuration script, we can run the script like follows:

```
build/ARM/gem5.opt configs/proj1/simple.py tests/labexe/gemm --cpu minor --mem
DDR5 --clock 2GHz
```

Tip

- Except the `hello`, other executables are quite complex, and will take hours for `gem5` to finish simulation. You can early-stop the simulation with all statistics printed by specifying the `max_insts_any_thread` in CPU, which will shutdown the CPU when that many instructions are already executed (you can also set an option for this parameter):

```
system.cpu.max_insts_any_thread = 1e+9
```

- Find the proper `max_insts_any_thread` number for your PC that allows a fast simulation, but still generate reasonable statistics (warmup phases in executables may show quite different performance statistics compared to real execution phases). A **recommended number is** `5e+8` for this project.

Deliverables

Please include the following in your ***report***:

- Use these system settings (`cpu=simple` , `clock=2GHz` , `mem=DDR3`) to run simulation. Please use the **complex** executables provided in `tests/labexe` (i.e., `shell_sort` , `gemm` , `spfa` and `binary_search`). Please **calculate and show (in tables or figures) the IPC** for these executables.
- Repeat the experiments, but change the CPU type (with `mem=DDR3` and `clock=2GHz` unchanged) to achieve better performance for different executables. Also calculate and show the IPC for each executable and CPU type.
- Repeat the experiments, but change the mem type (with a **fixed** CPU type and `clock=2GHz` unchanged) to achieve better performance for different executables. Also calculate and show the IPC for each executable and CPU type.

Important note

Running complex executables with `gem5` takes you a lot of time. This part requires you to run multiple settings, so it takes much longer time. Since `gem5` is basically a single-thread process, you can run different settings **in parallel** to accelerate your experiments.

Also, please remind to **set a unique output directory** (refer to part 2) for each parallel run, otherwise these runs may override with each other!

You can also use a shell script to automate this parallel running. Things may be like the following:

```bash
#!/bin/bash

# examples
cpus=("c1" "c2")
mems=("m1" "m2")
exes=("shell_sort" "gemm" "spfa" "binary_search")

for c in ${cpus[@]}; do
for m in ${mems[@]}; do
for e in ${exes[@]}; do
    # set output dir, name it however you like
    build/ARM/gem5.opt -d $e$c$m \
    configs/proj1/simple.py tests/labexe/$e \
    --cpu $c --mem $m &
    # add `&` after the command to let it run in background
done
done
done
```

Then use `ctrl+p+q` to quit container terminal while keeping the background threads runing.

Submission

Submission

- Please submit the deliverables for each part in order and clearly defined in a report form (e.g., PDF or Word). Please give a brief description of the results in your report. You **DO NOT** need to submit your configuration script **in this project**.
- Please submit your report as an attachment at course.pku.edu.cn. The title of the attachment should be Student-ID_Name_Proj1 (e.g., 123456789_WangXiaoming_Proj1).
- You can also send your report to 2501112042@stu.pku.edu.cn. The titles of your email AND attachment should both be Student-ID_Name_Proj1.
- **DO NOT PLAGIARIZE**. We will select 10 students randomly and ask them to answer our questions related to their results.

Late policy

- You will be given **3 slip days** (shared by all projects), which can be used to extend project deadlines, e.g., 1 project extended by 3 days or 3 projects each extended by 1 day.
- Projects are due at 23:59:59, no exceptions; 20% off per day late, 1 second late = 1 hour late = 1 day late.

Deliverables

Please include the following in your ***report***:

1. **Startup:** a screenshot that shows you `gem5` can compile correctly.
2. **Part 1:** a screenshot of the output on stdout of your configuration script.
3. **Part 3:**
    - Use these system settings (`cpu=simple` , `clock=2GHz` , `mem=DDR3`) to run simulation. Please use the **complex** executables provided in

`tests/labexe`. Please **calculate and show (in tables or figures) the IPC** for these executables.
  - Repeat the experiments, but change the CPU type (with `mem=DDR3` and `clock=2GHz` unchanged) to achieve better performance for different executables. Also calculate and show the IPC for each executable and CPU type.
  - Repeat the experiments, but change the mem type (with and **fixed** CPU type and `clock=2GHz` unchanged) to achieve better performance for different executables. Also calculate and show the IPC for each executable and CPU type.

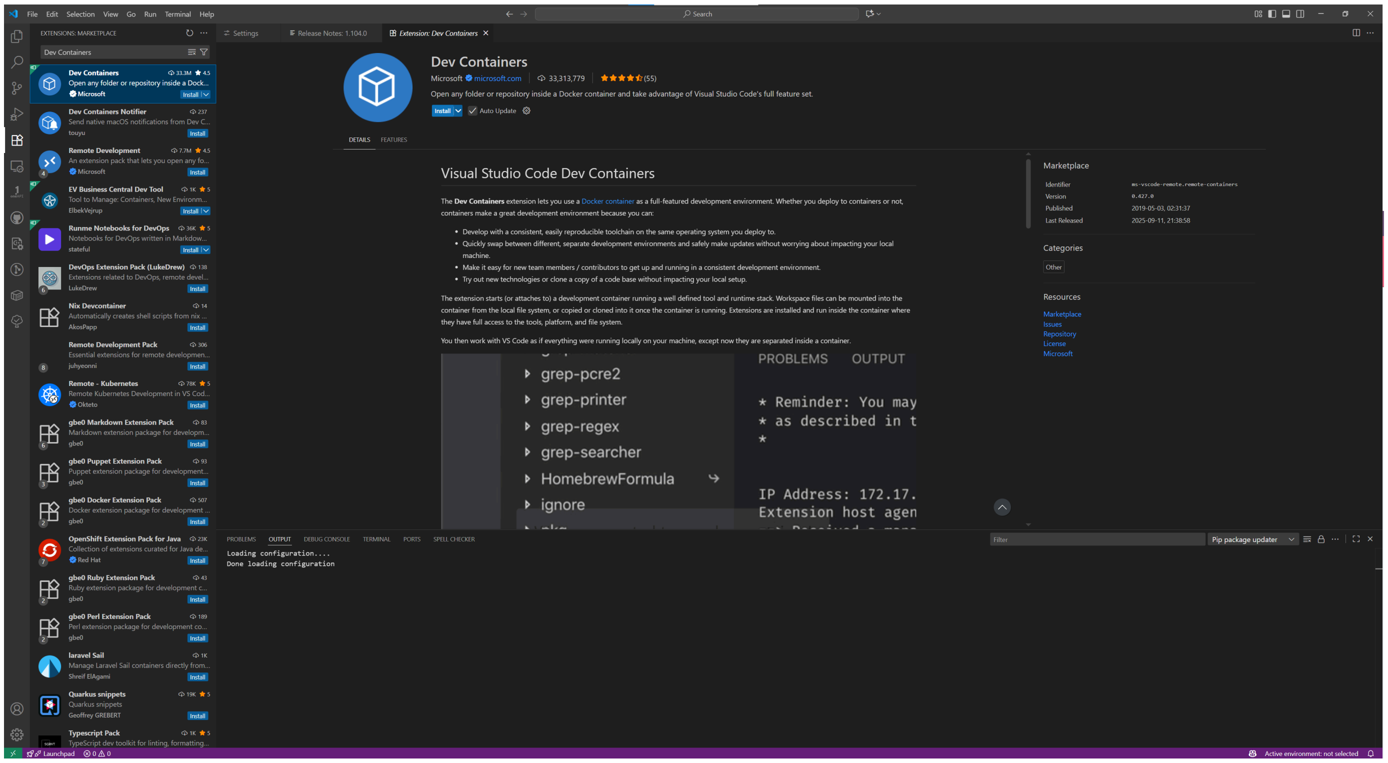
You **DO NOT** need to submit your configuration script **in this project**.

Appendix: VSCode and Docker Working Together on Windows

First, you need to install Docker and Visual Studio Code and ensure they are functioning properly.

Install the Dev Containers plugin

- Open Visual Studio Code
- click the Extensions icon in the left sidebar
- Search for “Dev Containers” in the search bar at the top of the Extensions list that appears
- select the desired extension from the search results and click the Install button on the opened page



Dev Containers 33.3M 4.5
Open any folder or repository inside a Dock...
Microsoft

Dev Containers Notifier 237
Send native macOS notifications from Dev C...
touyu

Remote Development 7.7M 4.5
An extension pack that lets you open any fo...
Microsoft

EV Business Central Dev Tool 1K 5
Tool to Manage: Containers, New Environm...
ElbekVejrup

Runme Notebooks for DevOps 36K 5
Notebooks for DevOps written in Markdow...
stateful

DevOps Extension Pack (LukeDrew) 138
Extensions related to DevOps, remote devel...
LukeDrew

Nix Devcontainer 14
Automatically creates shell scripts from nix ...
AkosPapp

Remote Development Pack 306
Essential extensions for remote developmen...
juhyeonni

Remote - Kubernetes 78K 5
Remote Kubernetes Development in VS Cod...
Okteto

gbe0 Markdown Extension Pack 83
Markdown extension package for developm...
gbe0

gbe0 Puppet Extension Pack 93
Puppet extension package for development...
gbe0

gbe0 Docker Extension Pack 507
Docker extension package for development ...
gbe0

OpenShift Extension Pack for Java 23K
Collection of extensions curated for Java de...
Red Hat

gbe0 Ruby Extension Pack 43
Ruby extension package for development c...
gbe0

gbe0 Perl Extension Pack 189
Perl extension package for development co...
gbe0

laravel Sail 1K
Manage Laravel Sail containers directly from...
Shreif ElAgami

Quarkus snippets 19K 5
Quarkus snippets
Geoffrey GREBERT

Typescript Pack 1K 5
TypeScript dev toolkit for linting, formatting...

Dev Containers
Microsoft microsoft.com | 33,313,779 | (55)
Open any folder or repository inside a Docker container and take advantage of Visual Studio Code's full feature set.

Visual Studio Code Dev Containers

The **Dev Containers** extension lets you use a Docker container as a full-featured development environment. Whether you deploy to containers or not, containers make a great development environment because you can:

- Develop with a consistent, easily reproducible toolchain on the same operating system you deploy to.
- Quickly swap between different, separate development environments and safely make updates without worrying about impacting your local machine.
- Make it easy for new team members / contributors to get up and running in a consistent development environment.
- Try out new technologies or clone a copy of a code base without impacting your local setup.

The extension starts (or attaches to) a development container running a well defined tool and runtime stack. Workspace files can be mounted into the container from the local file system, or copied or cloned into it once the container is running. Extensions are installed and run inside the container where they have full access to the tools, platform, and file system.

You then work with VS Code as if everything were running locally on your machine, except now they are separated inside a container.

Marketplace

Identifier	ms-vscode-remote.remote-containers
Version	0.427.0
Published	2019-05-03, 02:31:37
Last Released	2025-09-11, 21:38:58

Categories

Other

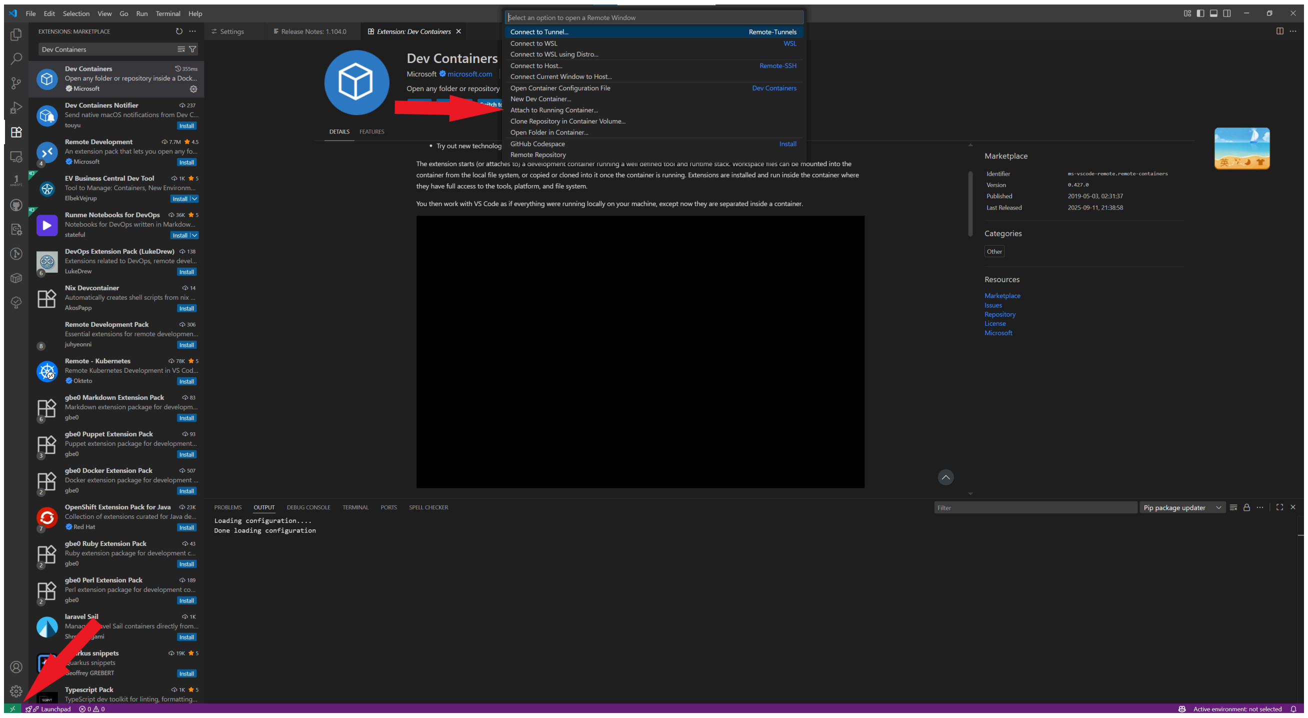
Resources

Marketplace
Issues
Repository
License
Microsoft

```
Loading configuration....
Done loading configuration
```

Connecting to a container using VS Code

- Launch the container using the method described earlier (refer to setup)
- Launch VS Code, then click the green “Open a Remote Window” button in the bottom-left corner


Select an option to open a Remote Window
Connect to Tunnel... Remote-Tunnels
Connect to WSL WSL
Connect to WSL using Distro...
Connect to Host... Remote-SSH
Connect Current Window to Host...
Open Container Configuration File Dev Containers
New Dev Container...
Attach to Running Container...
Clone Repository in Container Volume...
Open Folder in Container...
GitHub Codespace Install
Remote Repository
Dev Containers
PROBLEMS
OUTPUT
DEBUG CONSOLE
TERMINAL
PORTS
SPELL CHECKER

The extension starts (or attaches to) a development container running a well defined tool and runtime stack. Workspace files can be mounted into the container from the local file system, or copied or cloned into it once the container is running. Extensions are installed and run inside the container where they have full access to the tools, platform, and file system.

You then work with VS Code as if everything were running locally on your machine, except now they are separated inside a container.

```
Loading configuration....
Done loading configuration
```

- Then it will display a list of currently running containers at the top. Select the container you want to enter and click on it

Appendix: Log in to the server account provided to you using Visual Studio Code

Create configuration command

If you have applied to the teaching assistant for a server account, we will typically return two commands similar to those shown below, along with their corresponding passwords.

```
ssh -p <port1> jzlab@<IP>
ssh -p <port2> root@127.0.0.1
```

Based on these two commands, we need to assemble a new string in the following format:

```
Host <your favourite name>
    Hostname 127.0.0.1
    User root
    Port <port2>
    ProxyJump jzlab@<IP>:<port1>
```

For example, if the command you receive is

```
ssh -p 11451 jzlab@114.514.114.514
ssh -p 14514 root@127.0.0.1
```

Then you can obtain the string

```
Host helloworld
    Hostname 127.0.0.1
    User root
    Port 14514
    ProxyJump jzlab@114.514.114.514:11451
```

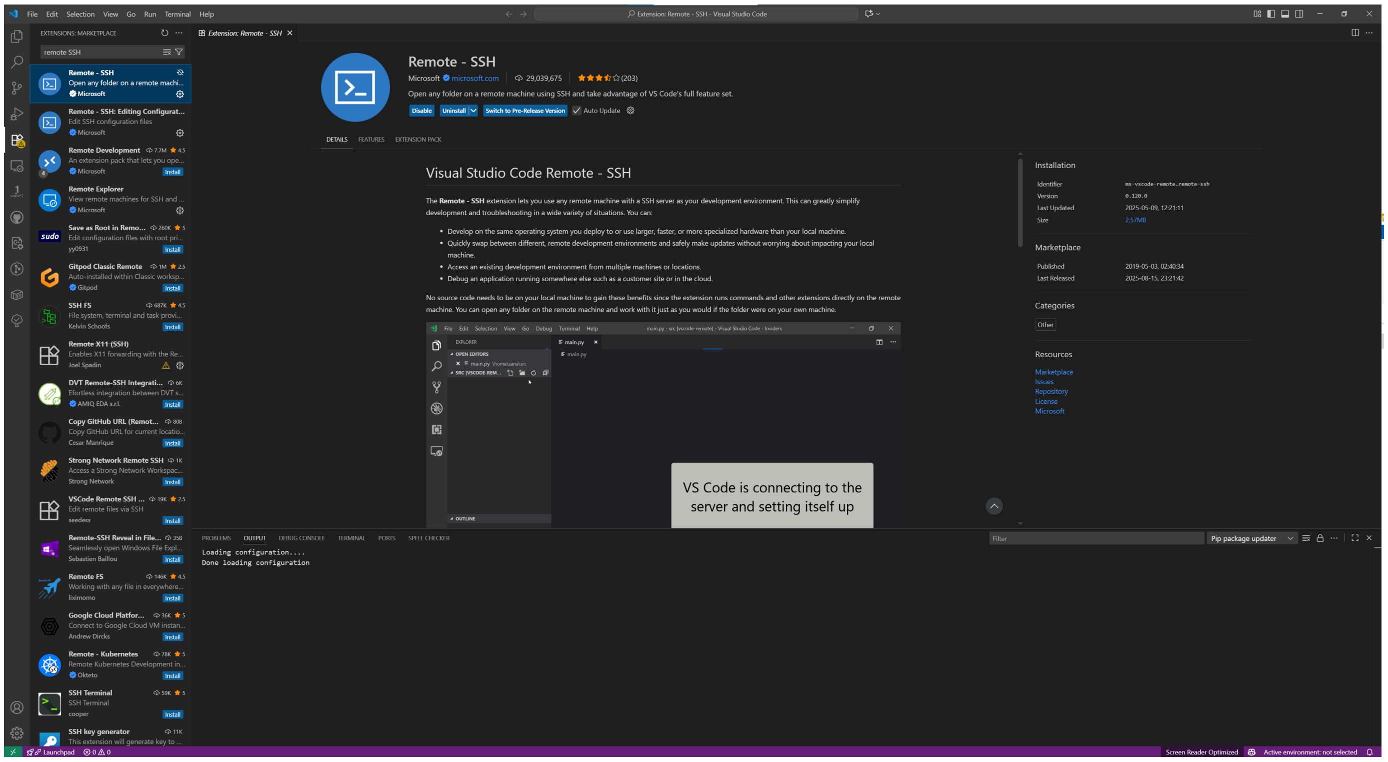
Install Visual Studio Code

Visit the official Visual Studio Code website, where you will find the download button readily available. Please ensure you download the appropriate version for your operating system.

Then open the installation package you have downloaded and follow the step-by-step instructions to complete the installation.

Install the remote-ssh plugin

Once you've downloaded Visual Studio Code, you'll need to install the SSH-related extensions. First, open your Visual Studio Code. Then locate the extensions icon in the left-hand sidebar. Upon clicking the icon, an expanded list and a search box appeared. Enter **“remote-SSH”** in the search box to locate the corresponding plugin.Finally, select the corresponding result and click “Install”.



Remote - SSH

Microsoft microsoft.com | 29,039,675 | (203)

Open any folder on a remote machine using SSH and take advantage of VS Code's full feature set.

Visual Studio Code Remote - SSH

The **Remote - SSH** extension lets you use any remote machine with a SSH server as your development environment. This can greatly simplify development and troubleshooting in a wide variety of situations. You can:

- Develop on the same operating system you deploy to or use larger, faster, or more specialized hardware than your local machine.
- Quickly swap between different, remote development environments and safely make updates without worrying about impacting your local machine.
- Access an existing development environment from multiple machines or locations.
- Debug an application running somewhere else such as a customer site or in the cloud.

No source code needs to be on your local machine to gain these benefits since the extension runs commands and other extensions directly on the remote machine. You can open any folder on the remote machine and work with it just as you would if the folder were on your own machine.

VS Code is connecting to the server and setting itself up

Installation

Identifier	ms-vscode-remote.remote-ssh
Version	0.120.0
Last Updated	2025-05-09, 12:21:11
Size	2.57MB

Marketplace

Published	2019-05-03, 02:40:34
Last Released	2025-08-15, 23:21:42

Categories

Other

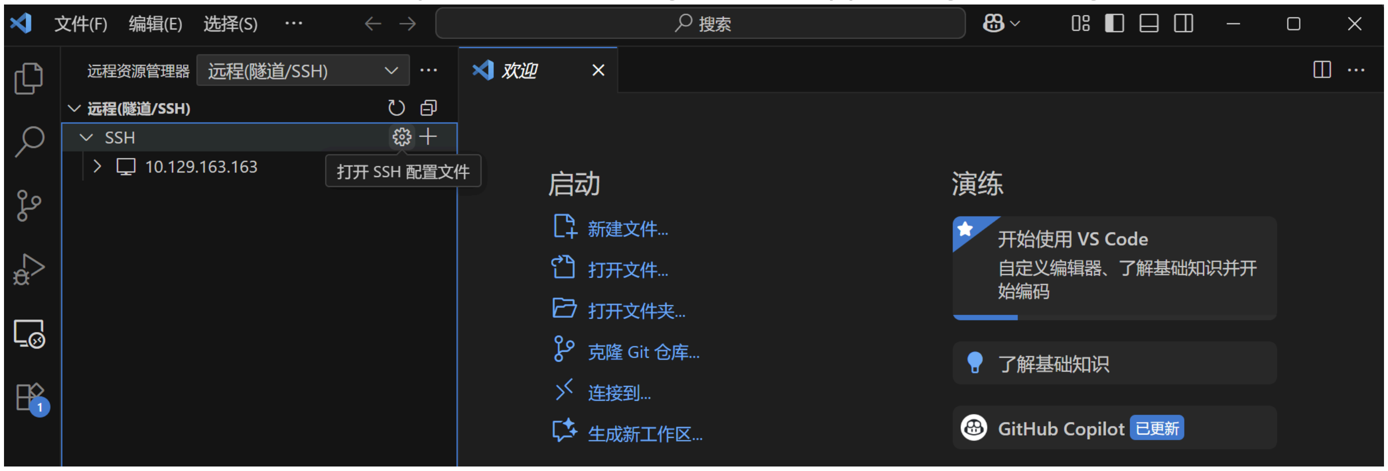
Resources

Marketplace
Issues
Repository
License
Microsoft

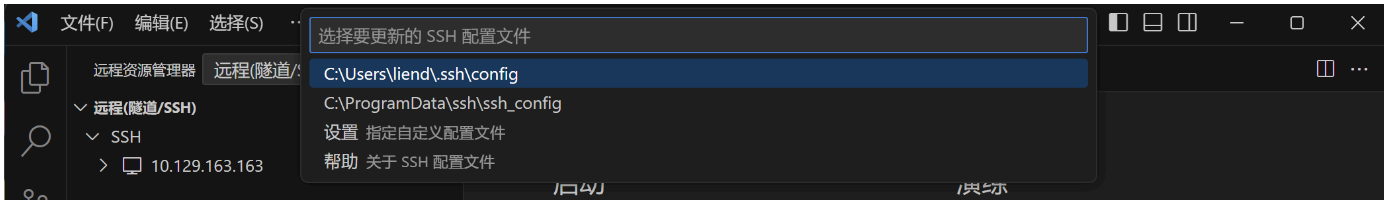
```
Loading configuration....
Done loading configuration
```

Add configuration command

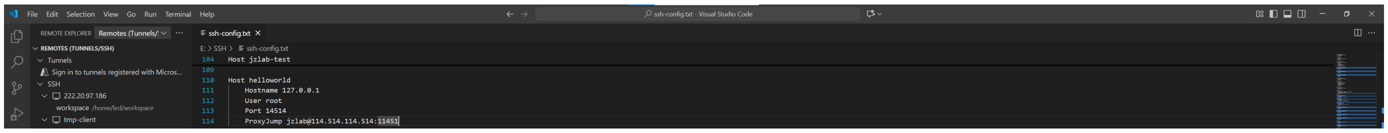
Upon installing the Remote-SSH extension, a new icon resembling a monitor symbol appears in the left-hand pane of VS Code, labelled Remote Explorer. Clicking this icon displays all SSH connections previously accessed through VS Code. When you hover your mouse over the SSH folder, you will notice a gear icon appearing to the right of SSH.



Clicking this gear icon will prompt you to select a configuration file. Simply choose the default option, and you will then open the SSH configuration file.



Next, paste the newly acquired configuration command onto the last newly created line, maintaining its formatting.



```
Host jzlab-test

Host helloworld
    Hostname 127.0.0.1
    User root
    Port 14514
    ProxyJump jzlab@114.514.114.514:11451
```

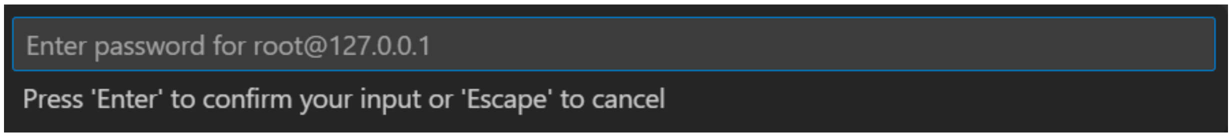
Finally, remember to save!

Start your journey

When you wish to connect to your server account, open Visual Studio Code and click the green or blue square in the bottom-left corner, which represents the creation of a new remote connection. A list will then appear at the top; select “Connect to Host”. You will then notice “helloworld” (or your select name) appearing in this list. Click on it to initiate the SSH connection. Please note you will need to enter your password twice: once for `ssh -p <port1> jzlab@<IP>` and once for `ssh -p <port2> root@127.0.0.1`. If all proceeds smoothly, you will enter the VSCode workspace and can now try this lab.

password input tip

If you're unsure which password the VSCode prompt is asking for, delete all characters you've entered into the password field. You'll notice a prompt appears in the field.


Enter password for root@127.0.0.1

Press 'Enter' to confirm your input or 'Escape' to cancel

Appendix: Common Questions

Here are some common questions that we collected on Part 1, especially for installing environment and compiling `gem5` :

Pull image issue

If you failed to pull the Docker image with `docker pull` , it is probably because the Docker Hub is blocked currently. Try to use VPN or download the image from our PKU Disk.

Warning about `pre-commit`

If you run `scons` to compile and are warned with `Cannot find 'pre-commit'` (messages like the following), you can ignore the message. This is only required for contributing to `gem5` and will not prevent the compilation.

```
You're missing the pre-commit/commit-msg hooks. These hook help to ensure your
code follows gem5's style rules on git commit and your commit messages follow
our commit message requirements. This script will now install these hooks in
your .git/hooks/ directory.
Press enter to continue, or ctrl-c to abort:
 Cannot find 'pre-commit'. Please ensure all Python requirements are
installed. This can be done via 'pip install -r requirements.txt'.
It is strongly recommended you install the pre-commit hooks before working with
gem5. Do you want to continue compilation (y/n)?
```

Format issue (`\r`) with `git` and Windows

If you use Docker Desktop on a Windows system, you may meet a file format issue during compilation, especially when you clone the codes under Windows using `git` . `git` will automatically replace `\n` (LF) with `\r\n` (CRLF) for you. SCons may report the occurance of `\r` (or `^M`) and throw an error. Here's three possible solutions:

- Disable the auto replacement by `git config --global core.autocrlf false`, and clone (re-clone) the codes.
- Use `dos2unix` under your container (you need to firstly install it using `apt`) to transform `\r\n` to `\n`. The command referring to this blog can be

  ```
  find . -type f -print0 | xargs -0 dos2unix
  ```

- Clone the codes inside container. Be careful, **you will lose your codes when you remove the container** if you choose this solution.

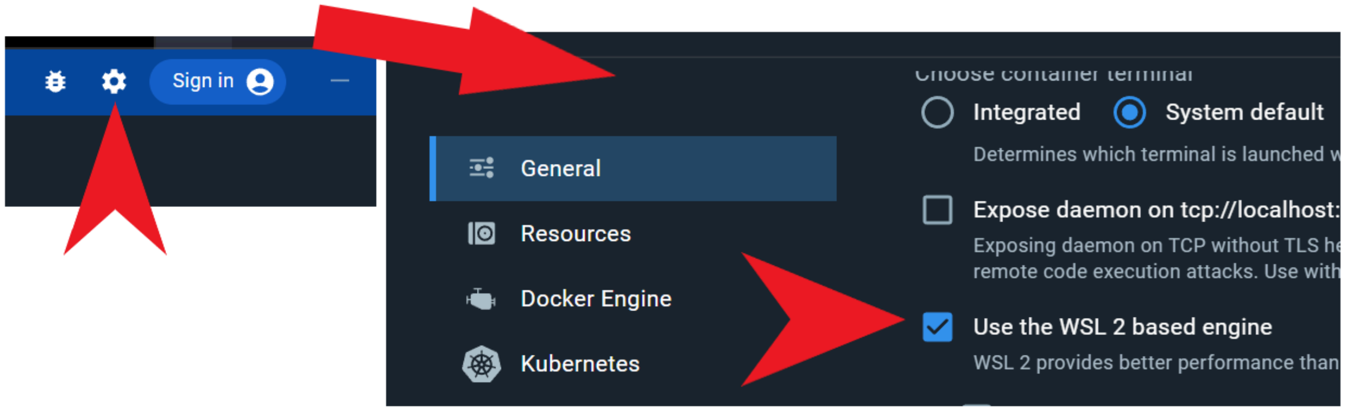
Run out of memory (SCons killed) issue

If you fail to compile and SCons reports message like the following, you are probably running out of memory:

```
collect2: fatal error: ld terminated with signal 9 [Killed]
# ... or
g++: fatal error: Killed signal terminated program cc1plus
```

As reference values, with 8 compile jobs (`-j 8`), the compilation and the link process (`[LINK]  -> build/ARM/gem5.opt`) may both take up to ***12GB*** memory. If your PC's physical memory is equal to or less than 16GB, you may probably meet this issue.

If you face this trouble, you can manually enlarge the swap space used by Docker container. On Windows, you need to firstly change the backend to WSL2 (installation method can be found in official doc). The setting process is like the following:



Choose container terminal

Integrated [✓ System default]

Determines which terminal is launched w

☐ Expose daemon on tcp://localhost:

Exposing daemon on TCP without TLS he
remote code execution attacks. Use with

✓ Use the WSL 2 based engine

WSL 2 provides better performance than

Next, stop Docker Desktop, and stop WSL by `wsl --shutdown` . Then, create a file named `.wslconfig` under `C:\Users\Yourname` , and write the following configs:

```
[wsl2]
memory=4GB
swap=32GB
autoMemoryReclaim=gradual
```

You can adjust the `memory` and `swap` values based on your PC's physical memory and disk space limits. WSL2 uses up to 50% of your physical memory by default. According to the memory usage values described above, the `swap` is recommended to be larger than ***20GB***. Set `autoMemoryReclaim=gradual` to save your physical memory when you are not running WSL or containers.

Lastly, start WSL, Docker Desktop and your container again. You can also start a new container by restricting its memory and swap limits:

```
docker run -it --memory 4G --memory-swap 20G -v ...
```

Remember to use the same `<container path>` in `-v` , otherwise compilation may fail. Or you can delete `build/` and re-compile completely.

Use docker on server

If you still cannot compile or cannot setup WSL and Docker Desktop, feel free to contact TA for a server account. However, please note:

- You still need to **use docker image**, since the environment on the server is not checked.
- You **DO NOT need to pull** the image again. Just use ssh to log in your container and clone code and all operations requiring storage space within the `/workspace` directory.
- We recommend using **Visual Studio Code** to log into the container assigned to you. As the login process involves SSH jump server principles, we advise you to consult relevant tutorials.
- **DO NOT MALICIOUSLY ENTER OTHER STUDENTS' CONTAINERS OR MODIFY THEIR CODES!**