中国科学技术大学

# 实验报告

## 计算机系统详解

## Cache Lab

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# 目录

# 一、 简介

## 1. 实验目的

- 理解高速缓存 (Cache) 的工作原理, 掌握常见的映射方式和替换策略.
- 学会针对 Cache 对程序代码进行优化.

## 2. 实验要求

- Part A:
  编写一个 Cache 模拟器 `csim` , 支持任意参数的组相连映射 (Set associative), 采用最近最少使用 (Least recently used) 替换策略, 功能应当与给定的参考程序 `csim-ref` 一致.

- Part B:
  优化一个矩阵转置函数, 尽可能减少 Cache misses, 提高 Cache 命中率. 考虑 32×32, 64×64 和 61 × 67 三种情形. 要求遵守给定的编程规则.

## 3. 实验环境

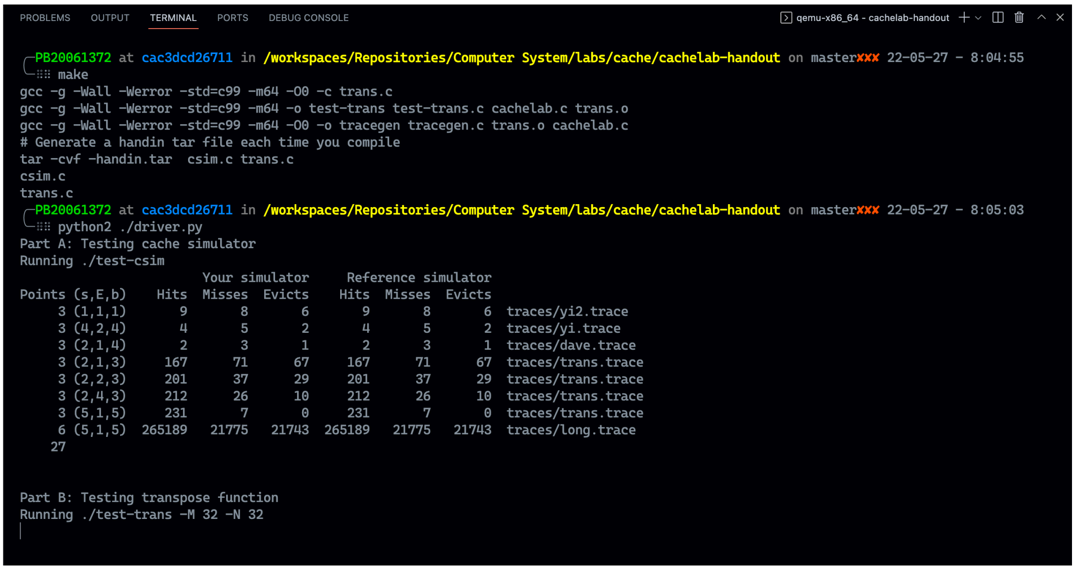
本实验 Part A 在以下环境完成:

| | |
|---|---|
| Machine | MacBook Pro 13” |
| SoC | Apple M1, 基于 ARM, 含 8 核 CPU、8 核 GPU 及 16GB RAM |
| OS | macOS Monterey 12.4 |
| IDE | Visual Studio Code 1.68.1 |
| Docker | Docker 20.10.13 |
| Image | Ubuntu 22.04, amd64 |
| Packages | GCC 11.2.0, Make 4.3, Python 2.7.18, Valgrind 3.18.1 |

容器配置参见附录 A `Dockerfile`.

## 二、 实验成果

由于时间不足与设备问题[1], Part B 尚未完成. Part A 的测试结果如图 1 所示.



```
╭─PB20061372 at cac3dcd26711 in /workspaces/Repositories/Computer System/labs/cache/cachelab-handout on master✘✘✘ 22-05-27 - 8:04:55
╰─⠿ make
gcc -g -Wall -Werror -std=c99 -m64 -O0 -c trans.c
gcc -g -Wall -Werror -std=c99 -m64 -o test-trans test-trans.c cachelab.c trans.o
gcc -g -Wall -Werror -std=c99 -m64 -O0 -o tracegen tracegen.c trans.o cachelab.c
# Generate a handin tar file each time you compile
tar -cvf -handin.tar  csim.c trans.c
csim.c
trans.c
╭─PB20061372 at cac3dcd26711 in /workspaces/Repositories/Computer System/labs/cache/cachelab-handout on master✘✘✘ 22-05-27 - 8:05:03
╰─⠿ python2 ./driver.py
Part A: Testing cache simulator
Running ./test-csim
                        Your simulator     Reference simulator
Points (s,E,b)    Hits  Misses  Evicts    Hits  Misses  Evicts
     3 (1,1,1)       9       8       6       9       8       6  traces/yi2.trace
     3 (4,2,4)       4       5       2       4       5       2  traces/yi.trace
     3 (2,1,4)       2       3       1       2       3       1  traces/dave.trace
     3 (2,1,3)     167      71      67     167      71      67  traces/trans.trace
     3 (2,2,3)     201      37      29     201      37      29  traces/trans.trace
     3 (2,4,3)     212      26      10     212      26      10  traces/trans.trace
     3 (5,1,5)     231       7       0     231       7       0  traces/trans.trace
     6 (5,1,5)  265189   21775   21743  265189   21775   21743  traces/long.trace
    27


Part B: Testing transpose function
Running ./test-trans -M 32 -N 32
```

**图 1:** 在终端中运行 `driver.py`, 验证 Part A 的正确性

完整源文件, 参见附录 A `csim.c`.

## 三、 实验过程

### 1. Part A: 工作原理

采用组相连映射方案, Cache 结构如图 2 所示.

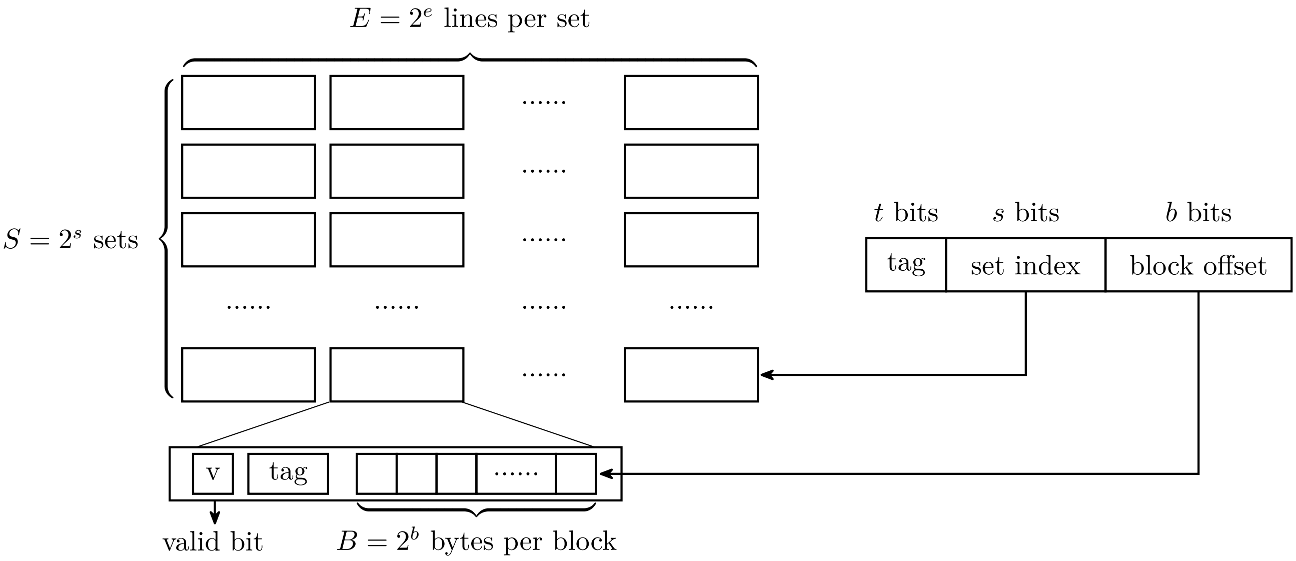


**图 2:** Cache 的组成结构

Cache 空间被分为 $2^s$ 个组 (set)，每个组含有 $E$ 个行 (line), 称作 $E$ 路组相连. cache line 由一个有效位 (valid bit)，标签 (tag) 以及 $2^b$ 个字的数据块 (block) 组成.

[1] 在 ARM 机器上使用 QMEU 仿真 amd64 架构, 无法正常运行 `valgrind`, `gdb` 等跟踪调试工具.

在 Cache 的硬件实现中，CPU 每次访问内存，内存地址被划分为 tag, set index, block offset 三部分. 在 set index 对应的组中，逐个比较有效 cache line 的 tag 与地址中的 tag，若匹配则 Cache 命中，根据 block offset 访问数据；若未命中，按照某种策略替换 cache line 内容.

通常采用 LRU 替换策略. 为每个 cache line 增设一个计数值，当一个 cache line 被访问时，其计数值归零，其余的有效 cache line 计数值加一. 每次 Cache 未命中而 Cache 已满时，优先替换计数值最大的 cache line.

## 2. Part A: 程序流程

根据 Cache 工作原理以及实验材料的提示，设计得程序流程大致如图 3 所示.

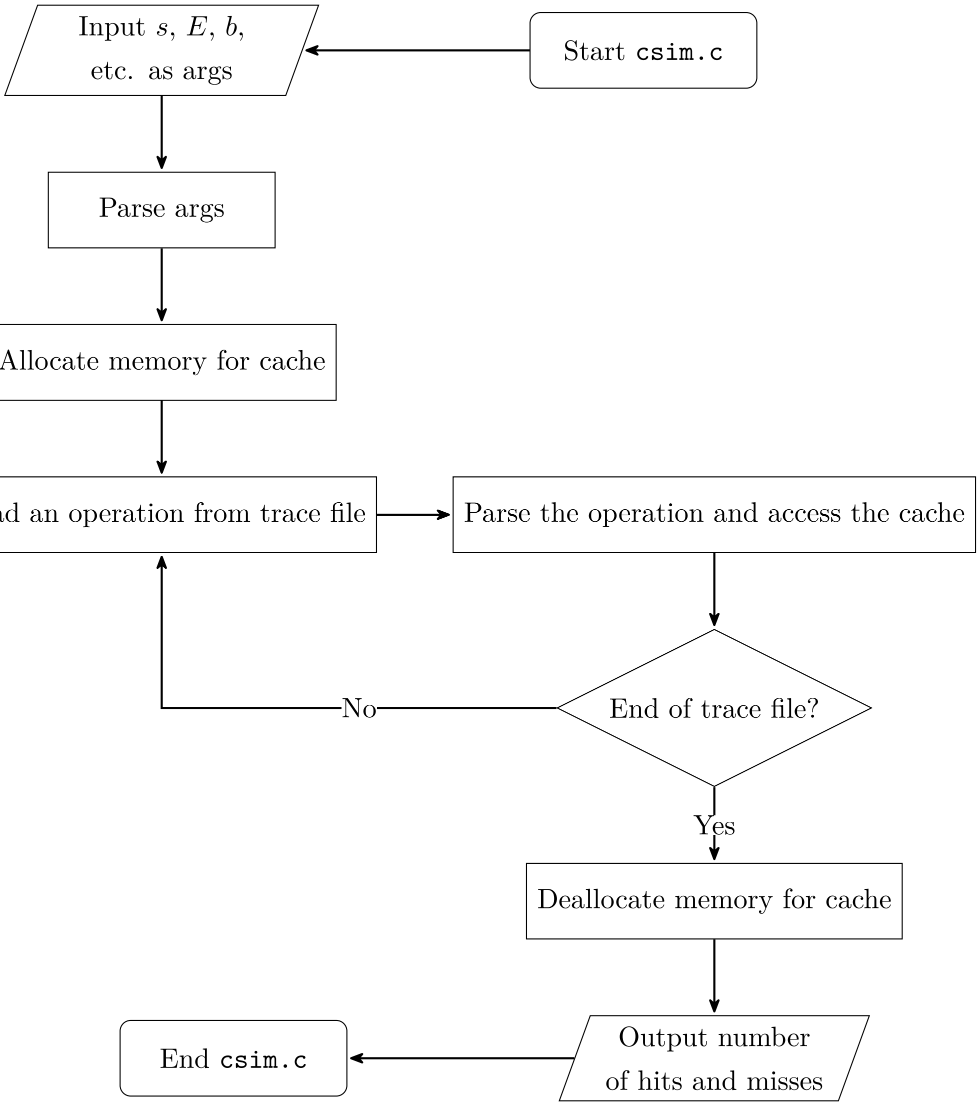

Start csim.c
Input $s$, $E$, $b$, etc. as args
Parse args
Allocate memory for cache
Read an operation from trace file
Parse the operation and access the cache
End of trace file?
No
Yes
Deallocate memory for cache
Output number of hits and misses
End csim.c

**图 3:** Cache 模拟程序的流程图

主函数的代码如下：

```
int main(int argc, char *argv[]) {
  parseArgs(argc, argv);
  initCache();
  FILE *trace_fp = fopen(trace_file, "r");

  char line[32];
  while (fgets(line, 32, trace_fp)) {
    /* Ignore instruction cache accesses */
    if (line[0] == 'I')
      continue;

    /* Parse operation */
    char op;
    unsigned int addr;
    int size;
    sscanf(line, " %c %x,%d", &op, &addr, &size);

    accessCache(op, addr, size);
  }

  fclose(trace_fp);
  deinitCache();
  printSummary(num_hits, num_misses, num_evictions);
  return 0;
}
```

## 3. Part A: 处理命令行参数

首先考虑如何处理命令行参数. 根据参考程序 csim-ref 的功能, 并遵循 test_trans.c 的编程风格, 不妨用如下 usage 函数打印帮助信息:

```
 *argv[]) {
  printf("Usage: %s [-hv] -s <num> -E <num> -b <num> -t <file>", argv[0]);
  printf("Options:\n");
  printf("  -h         Print this help message.\n");
  printf("  -v         Optional verbose flag.");
  printf("  -s <num>   Number of set index bits.\n");
  printf("  -E <num>   Number of lines per set.\n");
  printf("  -b <num>   Number of block offset bits.\n");
  printf("  -t <file>  Trace file.\n");
  printf("\n");
  printf("Examples:\n");
  printf("  linux>  %s -s 4 -E 1 -b 4 -t traces/yi.trace\n", argv[0]);
  printf("  linux>  %s -v -s 8 -E 2 -b 4 -t traces/yi.trace\n", argv[0]);
}
```

程序支持 -h, -v 两个可选项, 分别用于显示帮助信息和设置是否打印详细信息. -s, -E, -b 为必需参数, 已在Part A: 工作原理中解释. -t 也为必需参数, 用于指定跟踪文件.

设置如下全局变量用于存储上述参数:

```c
/* Globals set on the command line */
static int s = 0; // Number of set index bits
static int E = 0; // Number of lines per set
static int b = 0; // Number of block offset bits
static int verbose_mode = 0;
static char *trace_file = NULL;
```

根据提示, 可用 getopt 库函数解析命令行参数. 遵循 test_trans.c 的编程风格, 编写如下 parseArgs 函数:

```c
void parseArgs(int argc, char *argv[]) {
  char c;

  while ((c = getopt(argc, argv, "hvs:E:b:t:")) != -1) {
    switch (c) {
    case 's':
      s = atoi(optarg);
      break;
    case 'E':
      E = atoi(optarg);
      break;
    case 'b':
      b = atoi(optarg);
      break;
    case 't':
      trace_file = optarg;
      break;
    case 'v':
      verbose_mode = 1;
      break;
    case 'h':
      usage(argv);
      exit(0);
    default:
      usage(argv);
      exit(1);
    }
  }
}
```

## 4. Part A: 分配内存空间

视命令行参数不同, Cache 大小也不同, 需要动态分配内存. 首先, 给出用于存储 Cache 的结构体:

```c
/* Struct for cache lines */
typedef struct cache_line {
  int count; // Number of times this line has been accessed
  int valid;
  unsigned int tag;
} cache_line_t, *cache_set_t, **cache_t;
static cache_t cache;
```

本实验仅要求模拟 Cache 的命中与否, 无需对数据进行操作, 因此 `cache_line` 结构体不含数据块. 此外, 为了实现 LRU 替换策略, 增设了一个计数值 `count`.

每个 set 视为 cache line 数组, Cache 视为 set 数组. 不难编写 `initCache` 和 `deinitCache` 函数, 分别用于创建与销毁 Cache.

```c
void initCache() {
  int S = 1 << s; // Number of sets
  cache = malloc(sizeof(cache_set_t) * S);
  for (int i = 0; i < S; i++)
    cache[i] = calloc(E, sizeof(cache_line_t));
}

void deinitCache() {
  int S = 1 << s; // Number of sets
  for (int i = 0; i < S; i++)
    free(cache[i]);
  free(cache);
}
```

## 5. Part A: 模拟 Cache 访问

Cache 的访问和更新, 由以下 `accessCache` 函数实现:

```c
void accessCache(char op, unsigned int addr, int size) {

  /* Calculate tag in address */
  unsigned int tag = addr >> (s + b);
  /* Get cache set by index */
  cache_set_t set = cache[addr >> b & ((1 << s) - 1)];

  /* 'M' operation always results in an extra hit */
  if (op == 'M')
    num_hits++;

  if (verbose_mode)
    printf("%c %x,%d ", op, addr, size);

  /* Check if there is a hit */
  int empty = -1, lru = 0;
  for (int i = 0; i < E; i++) {
    if (!set[i].valid)
      empty = i; // Search for an empty line
    else if (set[i].tag == tag) {
      if (verbose_mode)
        printf(op == 'M' ? "hit hit\n" : "hit\n");
      num_hits++;
      set[i].count = 0; // Update time count using LRU policy
      return;
    } else if (++set[i].count >= set[lru].count)
      lru = i; // Search for the LRU line
  }

  /* If there is no empty line, evict the LRU line */
  cache_line_t *line;
  if (empty >= 0) {
    if (verbose_mode)
      printf(op == 'M' ? "miss hit\n" : "miss\n");
    line = &set[empty];
  } else {
    if (verbose_mode)
      printf(op == 'M' ? "miss eviction hit\n" : "miss eviction\n");
    line = &set[lru];
    num_evictions++;
  }
  line->valid = 1;
  line->tag = tag;
  line->count = 0;
  num_misses++;
}
```

根据图 2, 不难得到由地址获取 tag 与 set index 的位操作表达式:

```
tag = addr >> (s + b)
set_index = addr >> b & ((1 << s) - 1)
```

随后循环匹配 tag, 与此同时查找空行与最近最少使用的行. 使用三个全局变量 (`num_hits` 等) 记录统计数据, 适时更新. 对于跟踪文件中的数据调整操作 (以 ‘`M`’ 开头), 本质为先读后写, 应当额外考虑.

至此, 实现了 Cache 模拟器, 测试结果参见图 1.

## 6. Part B: 第一次尝试

To be continued...

## 7. Part B: 针对 $32 \times 32$ 情形优化

To be continued...

## 8. Part B: 针对 $64 \times 64$ 情形优化

To be continued...

## 9. Part B: 针对 $61 \times 67$ 情形优化

To be continued...

# 四、 总结

完成 Cache Lab, 主要有以下收获:

- 深入理解了内存访问的时空局部性, Cache 的原理和意义;
- 掌握了 Cache 的组成结构, 与主存的映射方式;
- 掌握了组相连映射的思想, 能够定量分析映射过程;
- 掌握了 LRU 替换策略的思想, 能够自行通过软件实现;
- 体会了 Cache 对程序性能的影响, 明白了代码优化的重要性;
- 学会了矩阵转置算法中, 针对 Cache 进行优化的几种途径;
- 学会了使用 `getopt` 库函数解析命令行参数;

本实验的所有材料已上传至 GitHub:

`https://github.com/HasiNed/Computer-System`

# 附录 A　代码清单

## 1. csim.c

```c
#include "cachelab.h"
#include <getopt.h>
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

/* Globals set on the command line */
static int s = 0; // Number of set index bits
static int E = 0; // Number of lines per set
static int b = 0; // Number of block offset bits
static int verbose_mode = 0;
static char *trace_file = NULL;

/* Struct for cache lines */
typedef struct cache_line {
  int count; // Number of times this line has been accessed
  int valid;
  unsigned int tag;
} cache_line_t, *cache_set_t, **cache_t;
static cache_t cache;

/* Globals for cache statistics */
static int num_hits = 0;
static int num_misses = 0;
static int num_evictions = 0;

/*
 * usage - Print usage info
 */
void usage(char *argv[]) {
  printf("Usage: %s [-hv] -s <num> -E <num> -b <num> -t <file>", argv[0]);
  printf("Options:\n");
  printf("  -h         Print this help message.\n");
  printf("  -v         Optional verbose flag.");
  printf("  -s <num>   Number of set index bits.\n");
  printf("  -E <num>   Number of lines per set.\n");
  printf("  -b <num>   Number of block offset bits.\n");
  printf("  -t <file>  Trace file.\n");
  printf("\n");
  printf("Examples:\n");
  printf("  linux>  %s -s 4 -E 1 -b 4 -t traces/yi.trace\n", argv[0]);
  printf("  linux>  %s -v -s 8 -E 2 -b 4 -t traces/yi.trace\n", argv[0]);
}

/*
 * parseArgs - Parse the command line arguments
 */
void parseArgs(int argc, char *argv[]) {
  char c;

  while ((c = getopt(argc, argv, "hvs:E:b:t:")) != -1) {
    switch (c) {
    case 's':
      s = atoi(optarg);
      break;
    case 'E':
      E = atoi(optarg);
      break;
    case 'b':
      b = atoi(optarg);
      break;
    case 't':
      trace_file = optarg;
      break;
    case 'v':
      verbose_mode = 1;
      break;
    case 'h':
      usage(argv);
      exit(0);
    default:
      usage(argv);
      exit(1);
    }
  }
}

/*
 * initCache - Initialize the cache with s, E and b
 */
void initCache() {
  int S = 1 << s; // Number of sets
  cache = malloc(sizeof(cache_set_t) * S);
  for (int i = 0; i < S; i++)
    cache[i] = calloc(E, sizeof(cache_line_t));
}

/*
 * deinitCache - Deinitialize the cache
 */
void deinitCache() {
  int S = 1 << s; // Number of sets
  for (int i = 0; i < S; i++)
    free(cache[i]);
  free(cache);
}
```

```c

/*
 * accessCache - Simulate to access cache
 */
void accessCache(char op, unsigned int addr, int size) {

  /* Calculate tag in address */
  unsigned int tag = addr >> (s + b);
  /* Get cache set by index */
  cache_set_t set = cache[addr >> b & ((1 << s) - 1)];

  /* 'M' operation always results in an extra hit */
  if (op == 'M')
    num_hits++;

  if (verbose_mode)
    printf("%c %x,%d ", op, addr, size);

  /* Check if there is a hit */
  int empty = -1, lru = 0;
  for (int i = 0; i < E; i++) {
    if (!set[i].valid)
      empty = i; // Search for an empty line
    else if (set[i].tag == tag) {
      if (verbose_mode)
        printf(op == 'M' ? "hit hit\n" : "hit\n");
      num_hits++;
      set[i].count = 0; // Update time count using LRU policy
      return;
    } else if (++set[i].count >= set[lru].count)
      lru = i; // Search for the LRU line
  }

  /* If there is no empty line, evict the LRU line */
  cache_line_t *line;
  if (empty >= 0) {
    if (verbose_mode)
      printf(op == 'M' ? "miss hit\n" : "miss\n");
    line = &set[empty];
  } else {
    if (verbose_mode)
      printf(op == 'M' ? "miss eviction hit\n" : "miss eviction\n");
    line = &set[lru];
    num_evictions++;
  }
  line->valid = 1;
  line->tag = tag;
  line->count = 0;
  num_misses++;
}
```

```c

/*
 * main - Main routine
 */
int main(int argc, char *argv[]) {
  parseArgs(argc, argv);
  initCache();
  FILE *trace_fp = fopen(trace_file, "r");

  char line[32];
  while (fgets(line, 32, trace_fp)) {
    /* Ignore instruction cache accesses */
    if (line[0] == 'I')
      continue;

    /* Parse operation */
    char op;
    unsigned int addr;
    int size;
    sscanf(line, " %c %x,%d", &op, &addr, &size);

    accessCache(op, addr, size);
  }

  fclose(trace_fp);
  deinitCache();
  printSummary(num_hits, num_misses, num_evictions);
  return 0;
}
```

## 2. Dockerfile

```dockerfile
# Emulate x86 architecture
FROM --platform=linux/x86_64 ubuntu:latest

# Switch apt source to mirror
RUN sed -i "s/archive.ubuntu.com/mirrors.ustc.edu.cn/g" /etc/apt/sources.list
RUN sed -i "s/security.ubuntu.com/mirrors.ustc.edu.cn/g" /etc/apt/sources.list

# Install packages
RUN apt-get update \
    && DEBIAN_FRONTEND=noninteractive apt-get install -y build-essential sudo git locales zsh vim perl curl gdb valgrind python2\
    && apt-get clean -y

# Generate locale
RUN locale-gen --no-purge en_US.UTF-8

```

```
# Create a user to show my student ID
ARG USERNAME="PB20061372"
RUN useradd $USERNAME -m \
    && echo "$USERNAME ALL=(ALL) NOPASSWD: ALL" > /etc/sudoers.d/$USERNAME \
    && chmod 0440 /etc/sudoers.d/$USERNAME
USER $USERNAME

# Install oh-my-zsh and set theme to fino-time (my favorite)
RUN sh -c "$(curl -fsSL https://raw.githubusercontent.com/ohmyzsh/ohmyzsh/master/tools/install.sh)" ""
RUN sed -i "s/robbyrussell/fino-time/g" ~/.zshrc
```