2020年秋季学期数据库课程设计

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Github地址

https://github.com/12138xs/2020-Fall-DBMS-Project

目录

实验环境

- 硬件型号：Intel(R) Core(TM) i5-8250U CPU @ 1.60Ghz
- 平台版本：Ubuntu 20.04.1 LTS

实验工具

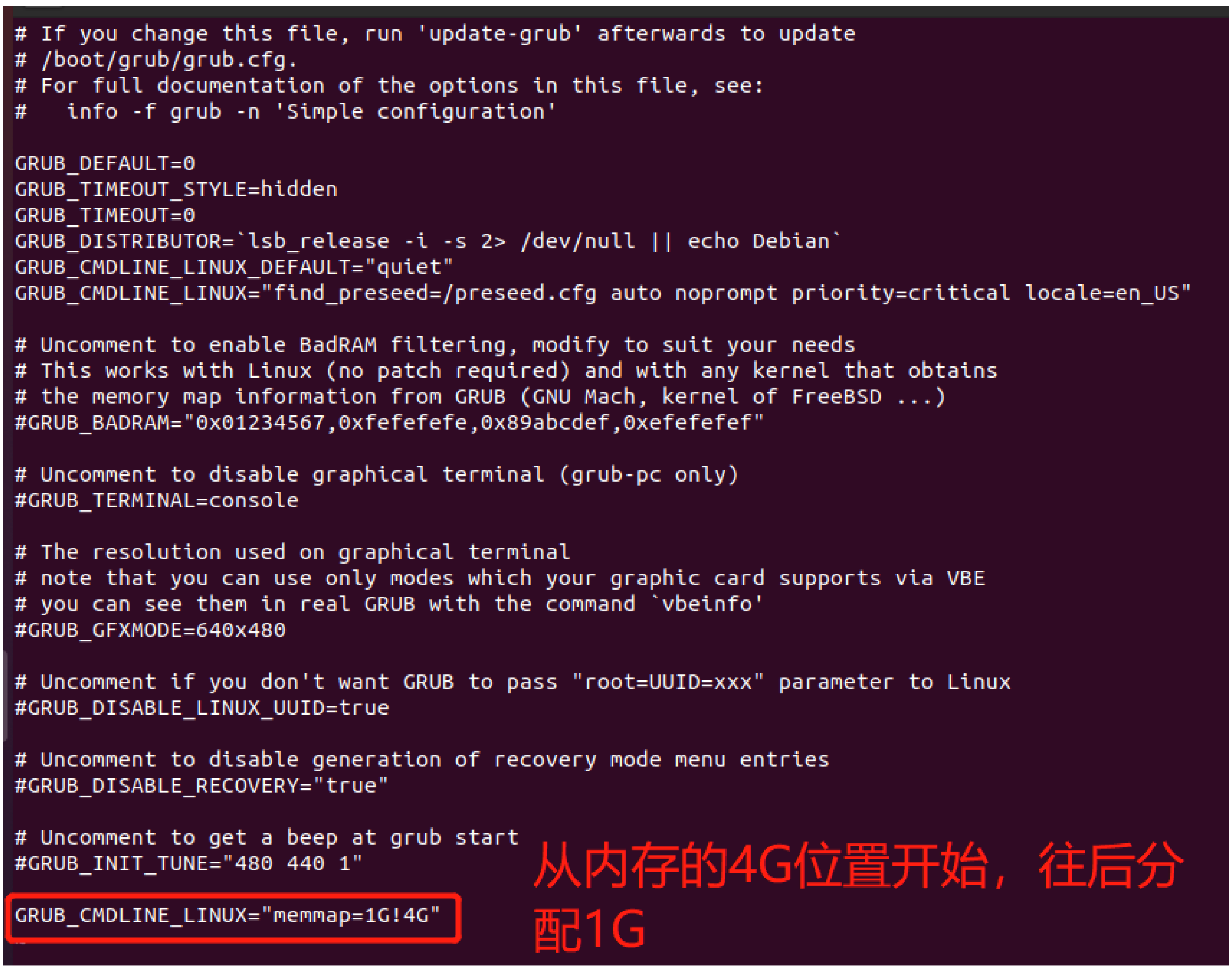
- gcc version 9.3.0
- GNU Make 4.2.1
- cmake version 3.16.3
- VS code

实验任务

一、利用普通内存模拟NVM环境并测试

根据Intel公司提供的How to Emulate Persistent Memory Using Dynamic Random-access Memory教程，在linux系统内核的英特尔处理器上使用DRAM设置持久性内存仿真，由于**Ubuntu 20.04.1**是比较新的Linux发行版，因此可以直接从**GRUB Configuration**这一步开始配置具体步骤如下所示。

1. 在 `/etc/default/grub` 文件中配置环境，添加片段 `GRUB_CMDLINE_LINUX="memmap=nn[KMG]!ss[KMG]"` 。下图为配置的文件示例。

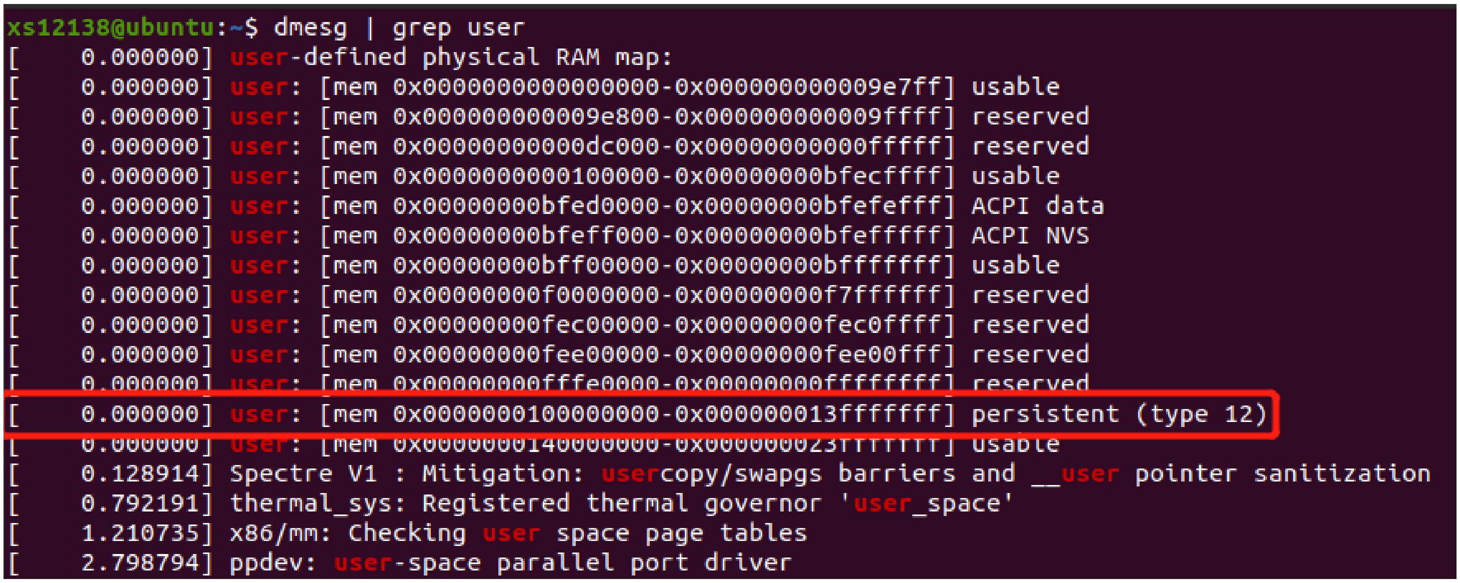


```
# If you change this file, run 'update-grub' afterwards to update
# /boot/grub/grub.cfg.
# For full documentation of the options in this file, see:
#   info -f grub -n 'Simple configuration'

GRUB_DEFAULT=0
GRUB_TIMEOUT_STYLE=hidden
GRUB_TIMEOUT=0
GRUB_DISTRIBUTOR=`lsb_release -i -s 2> /dev/null || echo Debian`
GRUB_CMDLINE_LINUX_DEFAULT="quiet"
GRUB_CMDLINE_LINUX="find_preseed=/preseed.cfg auto noprompt priority=critical locale=en_US"

# Uncomment to enable BadRAM filtering, modify to suit your needs
# This works with Linux (no patch required) and with any kernel that obtains
# the memory map information from GRUB (GNU Mach, kernel of FreeBSD ...)
#GRUB_BADRAM="0x01234567,0xfefefefe,0x89abcdef,0xefefefef"

# Uncomment to disable graphical terminal (grub-pc only)
#GRUB_TERMINAL=console

# The resolution used on graphical terminal
# note that you can use only modes which your graphic card supports via VBE
# you can see them in real GRUB with the command `vbeinfo'
#GRUB_GFXMODE=640x480

# Uncomment if you don't want GRUB to pass "root=UUID=xxx" parameter to Linux
#GRUB_DISABLE_LINUX_UUID=true

# Uncomment to disable generation of recovery mode menu entries
#GRUB_DISABLE_RECOVERY="true"

# Uncomment to get a beep at grub start
#GRUB_INIT_TUNE="480 440 1"

GRUB_CMDLINE_LINUX="memmap=1G!4G"
```


2. 配置成功之后，需要更新配置和设置配置(以root身份运行)，使用到以下两个命令。

```
update-grub
grub-mkconfig -o /boot/grub/grub.cfg
```

运行 `dmesg | grep user` 检测配置结果，结果如下图所示。



3. 建立直接访问的文件系统，使用以下三个命令。

```
mkdir /mnt/pmemdir
mkfs.ext4 /dev/pmem3
mount -o dax /dev/pmem3 /mnt/pmemdir
sudo fdisk -l /dev/pmem0
```

配置过程截图如下所示。

```
xs12138@ubuntu:~$ lsblk
NAME    MAJ:MIN RM   SIZE RO TYPE MOUNTPOINT
loop0     7:0    0  55.4M  1 loop /snap/core18/1932
loop1     7:1    0 255.6M  1 loop /snap/gnome-3-34-1804/36
loop2     7:2    0  55.4M  1 loop /snap/core18/1944
loop3     7:3    0 217.9M  1 loop /snap/gnome-3-34-1804/60
loop4     7:4    0  62.1M  1 loop /snap/gtk-common-themes/1506
loop5     7:5    0  49.8M  1 loop /snap/snap-store/467
loop6     7:6    0    51M  1 loop /snap/snap-store/518
loop7     7:7    0  64.8M  1 loop /snap/gtk-common-themes/1514
loop8     7:8    0  31.1M  1 loop /snap/snapd/10492
loop9     7:9    0    31M  1 loop /snap/snapd/9721
sda       8:0    0    20G  0 disk
├─sda1    8:1    0   512M  0 part /boot/efi
├─sda2    8:2    0     1K  0 part
└─sda5    8:5    0  19.5G  0 part /
sr0      11:0    1  1024M  0 rom
pmem0   259:0    0     1G  0 disk
xs12138@ubuntu:~$ sudo mkdir /mnt/pmemdir
[sudo] password for xs12138:
xs12138@ubuntu:~$ mkfs.ext4 /dev/pmem0
mke2fs 1.45.5 (07-Jan-2020)
Could not open /dev/pmem0: Permission denied
xs12138@ubuntu:~$ sudo mkfs.ext4 /dev/pmem0
mke2fs 1.45.5 (07-Jan-2020)
Creating filesystem with 262144 4k blocks and 65536 inodes
Filesystem UUID: e6da9b64-30ab-4ba3-a6ce-9aa97e4f2c8d
Superblock backups stored on blocks:
        32768, 98304, 163840, 229376

Allocating group tables: done
Writing inode tables: done
Creating journal (8192 blocks): done
Writing superblocks and filesystem accounting information: done

xs12138@ubuntu:~$ sudo mount -o dax /dev/pmem0 /mnt/pmemdir
```

```
xs12138@ubuntu:~$ sudo fdisk -l /dev/pmem0
Disk /dev/pmem0: 1 GiB, 1073741824 bytes, 2097152 sectors
Units: sectors of 1 * 512 = 512 bytes
Sector size (logical/physical): 512 bytes / 4096 bytes
I/O size (minimum/optimal): 4096 bytes / 4096 bytes
```

二、PMDK库的介绍与安装

PMDK(**Persistent Memory Development Kit**)是Intel公司为了方便设计非易失性内存的应用而开发的函数库和工具包。本次实验主要使用**PMDK**中 `libpmem` 库中的三个函数。

```
pmem_map()      //将目标文件通过内存映射的方式打开并返回文件的虚拟地址
pmem_persist()  //显示持久化相应的数据，修改数据库的数据项之后都需要调用该函数
pmem_unmap()    //用于关闭通过pmem_map()打开的文件
```

安装方法主要参考PMDK的GitHub，具体安装过程如下所示。

1. 安装依赖软件

```
sudo apt-get install autoconf
sudo apt-get install pkg-config
sudo apt-get install libndctl-dev   //默认安装版本为v61
sudo apt-get install libdaxctl-dev  //默认安装版本为v61
sudo apt-get install pandoc
sudo apt-get install libfabric
```

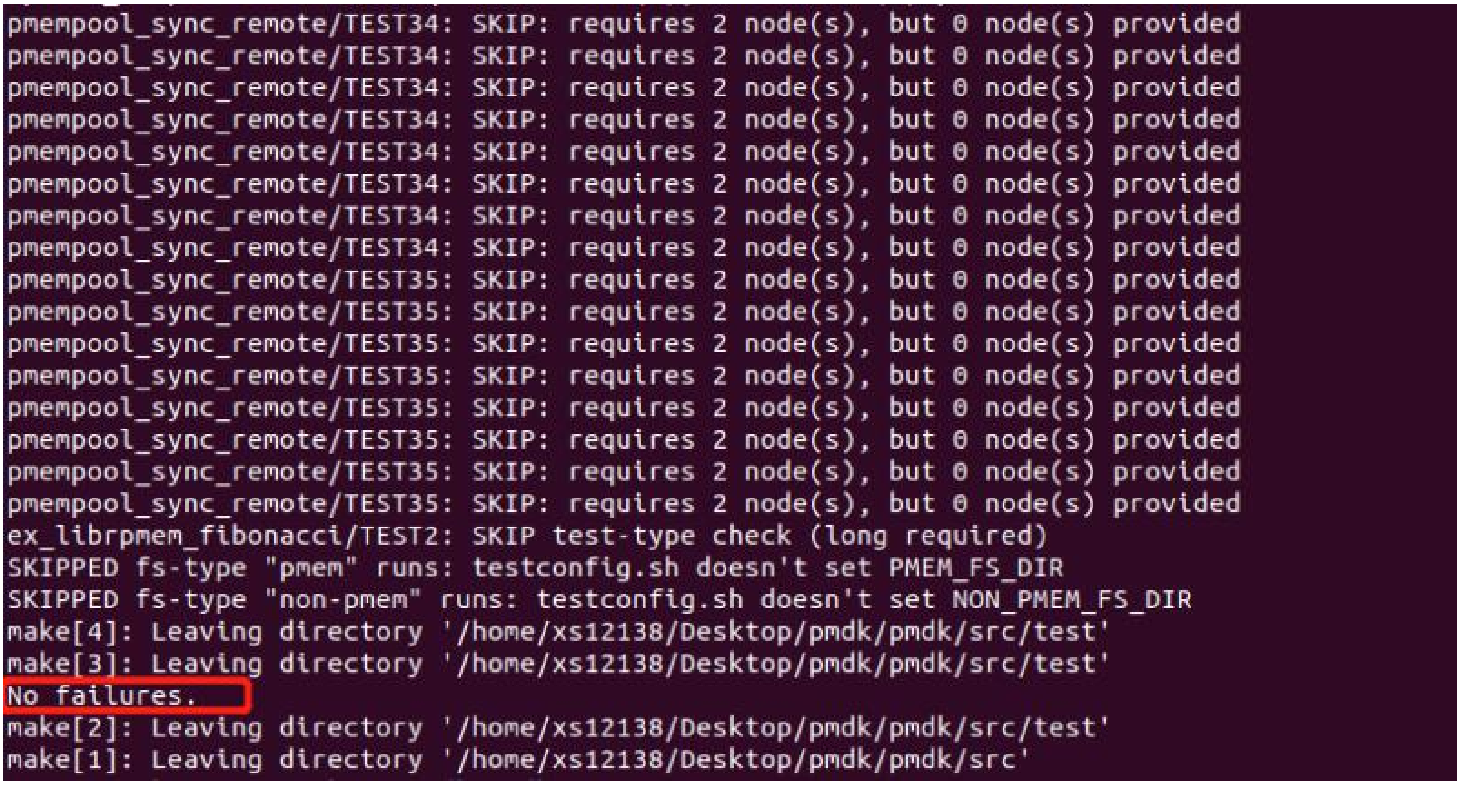
2. libndctl-dev和libdaxctl-dev的版本需要大于v63，因此还需要对两个进行升级

```
sudo apt-get update
sudo apt-get upgrade libndctl-dev
sudo apt-get upgrade libdaxctl-dev
```

3. 执行make test和make check(以 root 身份运行)

```
cd ./pmdk
make test
make check
```

`make check` 执行过程中会出现输出很多PASS，如果出现错误，请检查依赖软件是否安装成功，是否版本正确。



```
pmempool_sync_remote/TEST34: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST34: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST34: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST34: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST34: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST34: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST34: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST34: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST35: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST35: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST35: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST35: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST35: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST35: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST35: SKIP: requires 2 node(s), but 0 node(s) provided
pmempool_sync_remote/TEST35: SKIP: requires 2 node(s), but 0 node(s) provided
ex_librpmem_fibonacci/TEST2: SKIP test-type check (long required)
SKIPPED fs-type "pmem" runs: testconfig.sh doesn't set PMEM_FS_DIR
SKIPPED fs-type "non-pmem" runs: testconfig.sh doesn't set NON_PMEM_FS_DIR
make[4]: Leaving directory '/home/xs12138/Desktop/pmdk/pmdk/src/test'
make[3]: Leaving directory '/home/xs12138/Desktop/pmdk/pmdk/src/test'
No failures.
make[2]: Leaving directory '/home/xs12138/Desktop/pmdk/pmdk/src/test'
make[1]: Leaving directory '/home/xs12138/Desktop/pmdk/pmdk/src'
```

1. 编译源代码(以 root 身份进行)

```
make
```

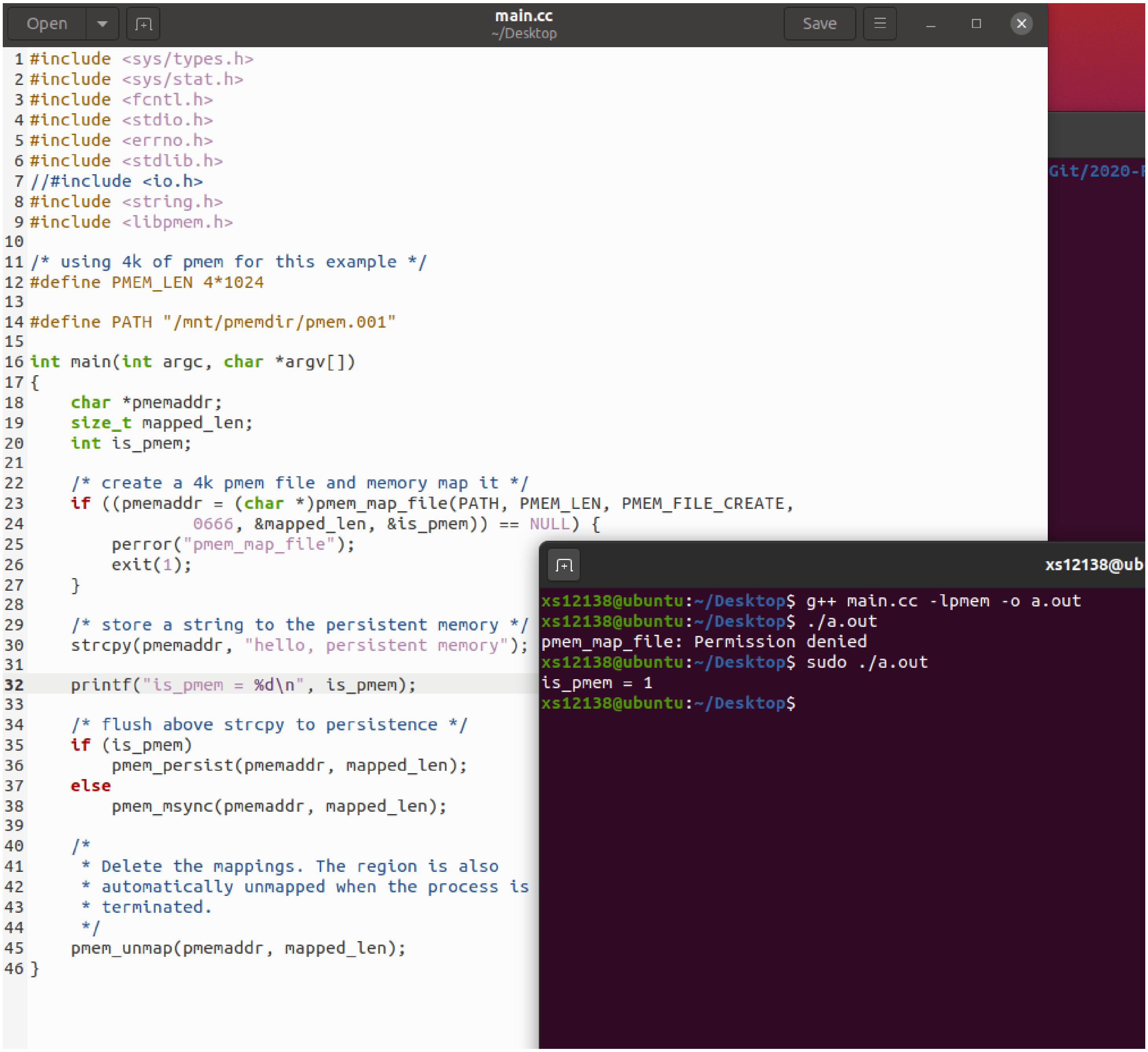
5. 安装pmdk库(以 root 身份运行)

```
make install
```

6. 通过以下代码判断是否安装成功

```c
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>
#include <stdio.h>
#include <errono.h>
#include <stdlib.h>
#include <string.h>
#include <libpmem.h>

#define PMEM_LEN 4*1024
#define PATH "mnt/pmemdir/pmem.001"

int main(int argc, char* argv[])
{
    char* pmemaddr;
    size_t mapped_len;
    int is_pmem;

    /* create a 4k pmem file and memory map it */
    if ((pmemaddr = pmem_map_file(PATH, PMEM_LEN, PMEM_FILE_CREATE,
                        0666, &mapped_len, &is_pmem)) == NULL) {
            perror("pmem_map_file");
            exit(1);
        }

    /* store a string to the persistent memory */
    strcpy(pmemaddr, "hello, persistent memory");
    printf("is_pmem = %d\n", is_pmem);

    /* flush above strcpy to persistence */
    if (is_pmem)
        pmem_persist(pmemaddr, mapped_len);
    else
        pmem_msync(pmemaddr, mapped_len);

    /*
    * Delete the mappings. The region is also
    * automatically unmapped when the process is
    * terminated.
    */
    pmem_unmap(pmemaddr, mapped_len);
}
```

运行截图如下所示，可以看到变量 `is_pmem` 为1，表明 PMDK 库安装成功并且成功运行在非易失性内存上。



三、线性哈希的具体实现

本次课程设计主要实现线性哈希的插入(insert)、查询(search)、删除(remove)、更新(update)功能。

1. 文件路径及运行方式

在 `main.cc` 文件中有一个 `FILE_PATH` 的变量，其中路径 `/mnt/pmemdir` 是前面设置的搭载了 DAX 文件系统的 NVM 环境文件夹，其中创建的文件可用于实现非易失内存应用的设计。

```
/*
* pmem file path
* NVM
* The folder with the file system ext4-dax mounted
*/
#define FILE_PATH "/mnt/pmemdir/pml_hash_file"
```

可以使用两种方法编译执行代码，第一种方式，使用 Cmake 自动化编译运行：

```
mkdir build
cd build
cp ../benchmark
cmake ..
make
sudo ./pmlhash
```

另一种方式是直接在代码文件路径下编译执行：

```
g++ main.cc pmlhash.cc -o pmlhash -lpmem
sudo ./pmlhash
```

2. 数据结构

```
# define TABLE_INIT 4  // adjustable
<p class="mume-header " id="define-table_init-4-adjustable"></p>

# define TABLE_SIZE 32 // adjustable
<p class="mume-header " id="define-table_size-32-adjustable"></p>

# define HASH_SIZE  1024 // adjustable
<p class="mume-header " id="define-hash_size-1024-adjustable"></p>

# define FILE_SIZE 1024 * 1024 * 16  // 16 MB adjustable
<p class="mume-header " id="define-file_size-1024-1024-16-16-mb-adjustable"></p>

# define BITSET_SIZE 1024 * 8        // 8 KB adjustable
<p class="mume-header " id="define-bitset_size-1024-8-8-kb-adjustable"></p>


typedef struct metadata {
    size_t size;            // the size of whole hash table array
    size_t level;           // level of hash
    uint64_t next;          // the index of the next split hash table
    uint64_t overflow_num;  // amount of overflow hash tables
} metadata;

// data entry of hash table
typedef struct entry {
    uint64_t key;
    uint64_t value;
} entry;

// hash table
typedef struct pm_table {
    entry kv_arr[TABLE_SIZE];   // data entry array of hash table
    uint64_t fill_num;          // amount of occupied slots in kv_arr
    uint64_t next_offset;       // the file address of overflow hash table
} pm_table;

// persistent memory linear hash
class PMLHash {
private:
    void* start_addr;      // the start address of mapped file
    void* overflow_addr;   // the start address of overflow table array
    metadata* meta;        // virtual address of metadata
    pm_table* table_arr;   // virtual address of hash table array

    void split();
    uint64_t hashFunc(const uint64_t &key, const size_t &hash_size);
    pm_table* newOverflowTable(uint64_t &offset);       // find an available overflow table

public:
    PMLHash() = delete;
    PMLHash(const char* file_path);
```

```
    ~PMLHash();

    int insert(const uint64_t &key, const uint64_t &value);
    int search(const uint64_t &key, uint64_t &value);
    int remove(const uint64_t &key);
    int update(const uint64_t &key, const uint64_t &value);

    void display_table();       // dispaly the whole table, for test
};
```

- `TABLE_INIT` 是指线性哈希初始时桶的数量。
- `TABLE_SIZE` 是指每个桶可以容纳项的最大数量。
- `HASH_SIZE` 是指线性哈希容纳桶的最大数量。
- `FILE_SIZE` 申请空间的总大小。
- `BITSET_SIZE` 实现桶回收的 bitmap 空间大小。
- `metadata` 用来存储线性哈希相关的基础数据，包括哈希表的大小(size)、当前的循环级(level)、本次循环中下一个应当要分裂的桶的编号(next)、溢出桶的数量(overflow_num)。
- `entry` 是指桶中的每一项，包括了键值和数据值。
- `pm_table` 是指线性哈希中的桶，包括了 entry 数组(kv_arr)、当前桶中项的数量(fill_num)、假如该桶有溢出桶，则 next_offset 为溢出桶序号，如果没有则为-1。
- `start_addr` 是线性哈希的起始地址。
- `overflow_addr` 是线性哈希中溢出桶的起始地址。
- `table_arr` 是用来存储线性哈希桶的其实地址

3. 构造函数与析构函数的代码实现

```
PMLHash::PMLHash(const char* file_path) {
    size_t mapped_len;
    int is_pmem;

    // get address
    if((start_addr = pmem_map_file(file_path, FILE_SIZE, PMEM_FILE_CREATE,
                0666, &mapped_len, &is_pmem)) == NULL) {
        perror("pmem_map_file");
        exit(1);
    }

    overflow_addr = (void *)((uint64_t)start_addr + (uint64_t)FILE_SIZE/2);
    meta = (metadata*)start_addr;
    table_arr = (pm_table*)((uint64_t)meta + sizeof(metadata));
    is_used = (bool *)((uint64_t)overflow_addr - BITSET_SIZE);
    overflow_table_num = (FILE_SIZE/2)/(sizeof(pm_table));

    // initial data
    meta->size = TABLE_INIT;
    meta->level = 0;
    meta->next = 0;
    meta->overflow_num = 0;
    for(int i = 0; i < HASH_SIZE; i++){
        table_arr[i].fill_num = 0;
        table_arr[i].next_offset = -1;
        for(int j = 0; j < TABLE_SIZE; j++)
            table_arr[i].kv_arr[j].key = table_arr[i].kv_arr[j].value = -1;
    }
    memset(is_used, 0, BITSET_SIZE);
}
```

构造函数中有三个地方值得注意

- 调用pmem_map_file()函数，该函数返回一个虚拟地址，可以实现在非易失性内存上运行。

```
    if((start_addr = pmem_map_file(file_path, FILE_SIZE, PMEM_FILE_CREATE,
                0666, &mapped_len, &is_pmem)) == NULL) {
        perror("pmem_map_file");
        exit(1);
    }
    overflow_addr = (void *)((uint64_t)start_addr + (uint64_t)FILE_SIZE/2);
```

overflow_addr变量指向申请空间的中间位置，将申请的空间划分为两部分。

- 变量is_used用来存储溢出桶是否为空，可以间接实现溢出桶空间回收

```
    is_used = (bool*)((uint64_t)overflow_addr - (uint64_t)
```

- 从start_addr开始之后的FILE_SIZE大小的空间中，其数据分布如下图所示

```
| Metadata | Hash Table Array | is_used | Overflow Hash Tables |
+----------------- 8 MB ----------------+------- 8 MB ---------+
```

4. insert函数的实现

首先根据键值计算哈希值，之后根据哈希值定位对应的桶。定位桶时有以下三种可能性。

- 哈希值对应的桶正好未满，可以直接插入新添加的键值和数据
- 哈希值对应的桶已经满了，且其具有未填满的溢出桶，则可以插入到溢出桶中。根据线性哈希规则，此次插入会分裂 `meta->next` 对应的桶。
- 哈希值对应的桶和溢出桶都已经填满，则需要申请新的哈希桶，如果溢出空间已经满了，则输出**no enough overflow table for insert**。

insert函数的具体实现如下所示。

```
int PMLHash::insert(const uint64_t &key, const uint64_t &value) {
    uint64_t h_key = hashFunc(key, meta->size);
    pm_table* table = (pm_table *)((uint64_t)start_addr + sizeof(metadata) + h_key * sizeof(pm_t

    int split_flag = 0, i;     //check if the table is full
    while(table->fill_num == TABLE_SIZE){
        split_flag = 1;
        if(table->next_offset != -1){
            table = (pm_table *)((uint64_t)overflow_addr + table->next_offset);
        }else{
            for(i = 0; i < overflow_table_num; i++){
                if(is_used[i] != 1){
                    table->next_offset = (uint64_t)(i*sizeof(pm_table));
                    table = newOverflowTable(table->next_offset);
                    is_used[i] = 1;
                    break;
                }
            }
            if(i == overflow_table_num){
                printf("no enough overflow table for insert\n");
                return -1;
            }
        }
    }
    table->kv_arr[table->fill_num].key = key;
    table->kv_arr[table->fill_num].value = value;
    table->fill_num++;
    //if the table is full, split
    if(split_flag == 1)
        split();
    pmem_persist(start_addr,FILE_SIZE);
    return 0;
}
```

由于 `insert` 函数改变了线性哈希存储的内容，因此需要调用 `pmem_persist` 函数来显式持久化相应的数据。以下是insert函数的测试代码和测试结果截图。

```
int main()
{
    PML_Hash hash(FILE_PATH);
    for(uint64_t i = 1;i <= (HASH_SIZE+1)*TABLE_SIZE;i++){
        hash.insert(i,i)
    }
    hash.display_table();
    return 0;
}
```

```
xs12138@ubuntu:/mnt/hgfs/Git/2020-Fall-DBMS-Project$ sudo ./a.out
# Table   0$  (  8,  8) ( 16, 16) ( 24, 24) ( 32, 32) ( 40, 40) ( 48, 48) ( 56, 56) ( 64, 64)
  overflow $  ( 72, 72)
# Table   1$  (  1,  1) (  9,  9) ( 17, 17) ( 25, 25) ( 33, 33) ( 41, 41) ( 49, 49) ( 57, 57)
  overflow $  ( 65, 65)
# Table   2$  (  2,  2) ( 10, 10) ( 18, 18) ( 26, 26) ( 34, 34) ( 42, 42) ( 50, 50) ( 58, 58)
  overflow $  ( 66, 66)
# Table   3$  (  3,  3) ( 11, 11) ( 19, 19) ( 27, 27) ( 35, 35) ( 43, 43) ( 51, 51) ( 59, 59)
  overflow $  ( 67, 67)
# Table   4$  (  4,  4) ( 12, 12) ( 20, 20) ( 28, 28) ( 36, 36) ( 44, 44) ( 52, 52) ( 60, 60)
  overflow $  ( 68, 68)
# Table   5$  (  5,  5) ( 13, 13) ( 21, 21) ( 29, 29) ( 37, 37) ( 45, 45) ( 53, 53) ( 61, 61)
  overflow $  ( 69, 69)
# Table   6$  (  6,  6) ( 14, 14) ( 22, 22) ( 30, 30) ( 38, 38) ( 46, 46) ( 54, 54) ( 62, 62)
  overflow $  ( 70, 70)
# Table   7$  (  7,  7) ( 15, 15) ( 23, 23) ( 31, 31) ( 39, 39) ( 47, 47) ( 55, 55) ( 63, 63)
  overflow $  ( 71, 71)
```

5. search函数的实现

search函数接受一个键值(key)和一个引用变量value，如果线性哈希中可以找到对应的key值，则返回0，并给value赋值；如果没有找到对应的key值，则返回-1，不给value赋值。该函数的具体实现如下所示。

```cpp
int PMLHash::search(const uint64_t &key, uint64_t &value) {
    uint64_t h_key = hashFunc(key, meta->size);
    pm_table* table = (pm_table *)((uint64_t)start_addr + sizeof(metadata) + h_key * sizeof(pm_t

    while(true){
        for(int i = 0; i < table->fill_num; i++){
            if(table->kv_arr[i].key == key){
                value = table->kv_arr[i].value;
                return 0;
            }
        }
        if(table->next_offset == -1)    break;
        table = (pm_table*)((uint64_t)overflow_addr + table->next_offset);
    }
    return -1;
}
```

以下是search函数的测试代码和测试结果截图。

```
int main()
{
    PML_Hash hash(FILE_PATH);
    for(uint64_t i = 1;i <= (HASH_SIZE+1)*TABLE_SIZE;i++){
        hash.insert(i,i)
    }
    hash.display_table();
    int ret = 0;
    for(uint64_t i = 1,j = 0;i <= (HASH_SIZE+5)*TABLE_SIZE;j++,i+=j){
        uint64_t val;
        ret = hash.search(i,val);
        if(!ret)
            cout << "key: " << i << ", value: " << val << endl;
        else
            cout << "no such key: " << i << endl;
    }
    return 0;
}
```

```
xs12138@ubuntu:/mnt/hgfs/Git/2020-Fall-DBMS-Project$ sudo ./a.out
# Table    0$  (  8,  8)  ( 16, 16)  ( 24, 24)  ( 32, 32)  ( 40, 40)  ( 48, 48)  ( 56, 56)  ( 64, 64)
  overflow $  ( 72, 72)
# Table    1$  (  1,  1)  (  9,  9)  ( 17, 17)  ( 25, 25)  ( 33, 33)  ( 41, 41)  ( 49, 49)  ( 57, 57)
  overflow $  ( 65, 65)
# Table    2$  (  2,  2)  ( 10, 10)  ( 18, 18)  ( 26, 26)  ( 34, 34)  ( 42, 42)  ( 50, 50)  ( 58, 58)
  overflow $  ( 66, 66)
# Table    3$  (  3,  3)  ( 11, 11)  ( 19, 19)  ( 27, 27)  ( 35, 35)  ( 43, 43)  ( 51, 51)  ( 59, 59)
  overflow $  ( 67, 67)
# Table    4$  (  4,  4)  ( 12, 12)  ( 20, 20)  ( 28, 28)  ( 36, 36)  ( 44, 44)  ( 52, 52)  ( 60, 60)
  overflow $  ( 68, 68)
# Table    5$  (  5,  5)  ( 13, 13)  ( 21, 21)  ( 29, 29)  ( 37, 37)  ( 45, 45)  ( 53, 53)  ( 61, 61)
  overflow $  ( 69, 69)
# Table    6$  (  6,  6)  ( 14, 14)  ( 22, 22)  ( 30, 30)  ( 38, 38)  ( 46, 46)  ( 54, 54)  ( 62, 62)
  overflow $  ( 70, 70)
# Table    7$  (  7,  7)  ( 15, 15)  ( 23, 23)  ( 31, 31)  ( 39, 39)  ( 47, 47)  ( 55, 55)  ( 63, 63)
  overflow $  ( 71, 71)

key: 1, value: 1
key: 2, value: 2
key: 4, value: 4
key: 7, value: 7
key: 11, value: 11
key: 16, value: 16
key: 22, value: 22
key: 29, value: 29
key: 37, value: 37
key: 46, value: 46
key: 56, value: 56
key: 67, value: 67
no such key: 79
no such key: 92
```

6. remove函数的实现

remove函数是比较关键的一个函数，在删除掉项之后，往往需要判断桶是否为空，如果为空，则需要进行同回收操作。remove函数的具体实现如下图所示。

```
int PMLHash::remove(const uint64_t &key) {
    uint64_t h_key = hashFunc(key, meta->size);
    pm_table* table = (pm_table*)((uint64_t)start_addr + sizeof(metadata) + h_key * sizeof(pm_ta
    pm_table* last = table;

    while(true){
        for(int i = 0; i < table->fill_num; i++){
            if(table->kv_arr[i].key == key){
                for(int j = i; j < table->fill_num-1; j++){
                    table->kv_arr[j].key = table->kv_arr[j+1].key;
                    table->kv_arr[j].value = table->kv_arr[j+1].value;
                }
                while(table->next_offset != -1){
                    last = table;
                    table = (pm_table*)((uint64_t)overflow_addr + table->next_offset);
                    last->kv_arr[TABLE_SIZE-1].key = table->kv_arr[0].key;
                    last->kv_arr[TABLE_SIZE-1].value = table->kv_arr[0].value;
                    for(int j = 0; j < table->fill_num-1; j++){
                        table->kv_arr[j].key = table->kv_arr[j+1].key;
                        table->kv_arr[j].value = table->kv_arr[j+1].value;
                    }
                }
                table->fill_num--;
                //remove the empty table
                if(table->fill_num == 0 && last != table){
                    last->next_offset = -1;
                    meta->overflow_num--;
                    int temp = ((uint64_t)table - (uint64_t)overflow_addr)/sizeof(pm_table);
                    is_used[temp] = 0;
                }
                pmem_persist(start_addr,FILE_SIZE);
                return 0;
            }
        }
        if(table->next_offset == -1)    break;
        last = table;
        table = (pm_table*)((uint64_t)overflow_addr + table->next_offset);
    }
    printf("couldn't find the key, failed to remove\n");
    return -1;
}
```

remove函数中有三个地方需要注意

- 当查找到key对应的项之后，需要先将桶内项之后的数据向前移动一格，通过下列片段实现。

```
for(int j = i; j < table->fill_num-1; j++){
    table->kv_arr[j].key = table->kv_arr[j+1].key;
    table->kv_arr[j].value = table->kv_arr[j+1].value;
}
```

- 需要考虑如下情况，如果删除桶中一项之后并且该桶具有溢出桶，应当将溢出桶内的一项移动到非溢出桶中，通过以下代码片段实现。

```
while(table->next_offset != -1){
    last = table;
    table = (pm_table*)((uint64_t)overflow_addr + table->next_offset);
    last->kv_arr[TABLE_SIZE-1].key = table->kv_arr[0].key;
    last->kv_arr[TABLE_SIZE-1].value = table->kv_arr[0].value;
    for(int j = 0; j < table->fill_num-1; j++){
        table->kv_arr[j].key = table->kv_arr[j+1].key;
        table->kv_arr[j].value = table->kv_arr[j+1].value;
    }
}
table->fill_num--;
```

- 如果溢出桶为空则要进行删除操作。在线性哈希中，桶与桶的连接是以链表的形式组织的。该函数删除空溢出桶的方法和删除链表中其中一项一样，主要依靠下述代码片段完成。

```
if(table->fill_num == 0 && last != table){
    last->next_offset = -1;
    meta->overflow_num--;
    int temp = ((uint64_t)table - (uint64_t)overflow_addr)/sizeof(pm_table);
    is_used[temp] = 0;
}
```

以下是remove函数的测试代码和测试结果截图。

```
int main()
{
    PML_Hash hash(FILE_PATH);
    for(uint64_t i = 1;i <= (HASH_SIZE+1)*TABLE_SIZE;i++){
        hash.insert(i,i)
    }
    hash.display_table();

    cout << "remove key: ";
    for(uint64_t i = 1,j = 0;i <= HASH_SIZE*TABLE_SIZE;j++,i+=j){
        cout << i << ' ';
        hash.remove(i);
    }
    cout << endl;
    hash.display_table();
    return 0;
}
```

```
xs12138@ubuntu:/mnt/hgfs/Git/2020-Fall-DBMS-Project$ sudo ./a.out
# Table   0$  (  8,  8)  ( 16, 16)  ( 24, 24)  ( 32, 32)  ( 40, 40)  ( 48, 48)  ( 56, 56)  ( 64, 64)
  overflow $  ( 72, 72)
# Table   1$  (  1,  1)  (  9,  9)  ( 17, 17)  ( 25, 25)  ( 33, 33)  ( 41, 41)  ( 49, 49)  ( 57, 57)
  overflow $  ( 65, 65)
# Table   2$  (  2,  2)  ( 10, 10)  ( 18, 18)  ( 26, 26)  ( 34, 34)  ( 42, 42)  ( 50, 50)  ( 58, 58)
  overflow $  ( 66, 66)
# Table   3$  (  3,  3)  ( 11, 11)  ( 19, 19)  ( 27, 27)  ( 35, 35)  ( 43, 43)  ( 51, 51)  ( 59, 59)
  overflow $  ( 67, 67)
# Table   4$  (  4,  4)  ( 12, 12)  ( 20, 20)  ( 28, 28)  ( 36, 36)  ( 44, 44)  ( 52, 52)  ( 60, 60)
  overflow $  ( 68, 68)
# Table   5$  (  5,  5)  ( 13, 13)  ( 21, 21)  ( 29, 29)  ( 37, 37)  ( 45, 45)  ( 53, 53)  ( 61, 61)
  overflow $  ( 69, 69)
# Table   6$  (  6,  6)  ( 14, 14)  ( 22, 22)  ( 30, 30)  ( 38, 38)  ( 46, 46)  ( 54, 54)  ( 62, 62)
  overflow $  ( 70, 70)
# Table   7$  (  7,  7)  ( 15, 15)  ( 23, 23)  ( 31, 31)  ( 39, 39)  ( 47, 47)  ( 55, 55)  ( 63, 63)
  overflow $  ( 71, 71)

remove key: 1 2 4 7 11 16 22 29 37 46 56
# Table   0$  (  8,  8)  ( 24, 24)  ( 32, 32)  ( 40, 40)  ( 48, 48)  ( 64, 64)  ( 72, 72)
# Table   1$  (  9,  9)  ( 17, 17)  ( 25, 25)  ( 33, 33)  ( 41, 41)  ( 49, 49)  ( 57, 57)  ( 65, 65)
# Table   2$  ( 10, 10)  ( 18, 18)  ( 26, 26)  ( 34, 34)  ( 42, 42)  ( 50, 50)  ( 58, 58)  ( 66, 66)
# Table   3$  (  3,  3)  ( 19, 19)  ( 27, 27)  ( 35, 35)  ( 43, 43)  ( 51, 51)  ( 59, 59)  ( 67, 67)
# Table   4$  ( 12, 12)  ( 20, 20)  ( 28, 28)  ( 36, 36)  ( 44, 44)  ( 52, 52)  ( 60, 60)  ( 68, 68)
# Table   5$  (  5,  5)  ( 13, 13)  ( 21, 21)  ( 45, 45)  ( 53, 53)  ( 61, 61)  ( 69, 69)
# Table   6$  (  6,  6)  ( 14, 14)  ( 30, 30)  ( 38, 38)  ( 54, 54)  ( 62, 62)  ( 70, 70)
# Table   7$  ( 15, 15)  ( 23, 23)  ( 31, 31)  ( 39, 39)  ( 47, 47)  ( 55, 55)  ( 63, 63)  ( 71, 71)
```

7. update函数的实现

update函数首先根据key值定位相应的桶，如果在线性哈希的桶数组中找不到对应的key值，则返回-1，表明未查找到对应的键值，同时输出**couldn't find the key, failed to update**；如果可以定位到对应的key值，则更新对应的数据，并返回0。该函数的具体实现如下所示。

```
int PMLHash::update(const uint64_t &key, const uint64_t &value) {
    uint64_t h_key = hashFunc(key, meta->size);
    pm_table* table = (pm_table*)((uint64_t)start_addr + sizeof(metadata) + h_key * sizeof(pm_ta

    //while this table may be not the final table
    while(true){
        for(int i = 0; i < table->fill_num; i++){
            if(table->kv_arr[i].key == key){
                table->kv_arr[i].value = value;
                pmem_persist(start_addr,FILE_SIZE);
                return 0;
            }
        }
        //if no more overflow table
        if(table->next_offset == -1)    break;
        table = (pm_table*)((uint64_t)overflow_addr + table->next_offset);
    }
    printf("couldn't find the key, failed to update\n");
    return -1;
}
```

以下是update函数的测试代码和测试结果截图。

```
int main()
{
    PML_Hash hash(FILE_PATH);
    for(uint64_t i = 1;i <= (HASH_SIZE+1)*TABLE_SIZE;i++){
        hash.insert(i,i)
    }
    hash.display_table();

    cout << "remove key: ";
    for(uint64_t i = 1,j = 0;i <= HASH_SIZE*TABLE_SIZE;j++,i+=j){
        cout << i << ' ';
        hash.update(i);
    }
    cout << endl;
    hash.display_table();
    return 0;
}
```

```
xs12138@ubuntu:/mnt/hgfs/Git/2020-Fall-DBMS-Project$ sudo ./a.out
# Table   0$  (  8,  8)  ( 16, 16)  ( 24, 24)  ( 32, 32)  ( 40, 40)  ( 48, 48)  ( 56, 56)  ( 64, 64)
  overflow $  ( 72, 72)
# Table   1$  (  1,  1)  (  9,  9)  ( 17, 17)  ( 25, 25)  ( 33, 33)  ( 41, 41)  ( 49, 49)  ( 57, 57)
  overflow $  ( 65, 65)
# Table   2$  (  2,  2)  ( 10, 10)  ( 18, 18)  ( 26, 26)  ( 34, 34)  ( 42, 42)  ( 50, 50)  ( 58, 58)
  overflow $  ( 66, 66)
# Table   3$  (  3,  3)  ( 11, 11)  ( 19, 19)  ( 27, 27)  ( 35, 35)  ( 43, 43)  ( 51, 51)  ( 59, 59)
  overflow $  ( 67, 67)
# Table   4$  (  4,  4)  ( 12, 12)  ( 20, 20)  ( 28, 28)  ( 36, 36)  ( 44, 44)  ( 52, 52)  ( 60, 60)
  overflow $  ( 68, 68)
# Table   5$  (  5,  5)  ( 13, 13)  ( 21, 21)  ( 29, 29)  ( 37, 37)  ( 45, 45)  ( 53, 53)  ( 61, 61)
  overflow $  ( 69, 69)
# Table   6$  (  6,  6)  ( 14, 14)  ( 22, 22)  ( 30, 30)  ( 38, 38)  ( 46, 46)  ( 54, 54)  ( 62, 62)
  overflow $  ( 70, 70)
# Table   7$  (  7,  7)  ( 15, 15)  ( 23, 23)  ( 31, 31)  ( 39, 39)  ( 47, 47)  ( 55, 55)  ( 63, 63)
  overflow $  ( 71, 71)

remove key: 1 2 4 7 11 16 22 29 37 46 56 67 79 92
# Table   0$  (  8,  8)  ( 16,1600)  ( 24, 24)  ( 32, 32)  ( 40, 40)  ( 48, 48)  ( 56,5600)  ( 64, 64)
  overflow $  ( 72, 72)
# Table   1$  (  1,100)  (  9,  9)  ( 17, 17)  ( 25, 25)  ( 33, 33)  ( 41, 41)  ( 49, 49)  ( 57, 57)
  overflow $  ( 65, 65)
# Table   2$  (  2,200)  ( 10, 10)  ( 18, 18)  ( 26, 26)  ( 34, 34)  ( 42, 42)  ( 50, 50)  ( 58, 58)
  overflow $  ( 66, 66)
# Table   3$  (  3,  3)  ( 11,1100)  ( 19, 19)  ( 27, 27)  ( 35, 35)  ( 43, 43)  ( 51, 51)  ( 59, 59)
  overflow $  ( 67,6700)
# Table   4$  (  4,400)  ( 12, 12)  ( 20, 20)  ( 28, 28)  ( 36, 36)  ( 44, 44)  ( 52, 52)  ( 60, 60)
  overflow $  ( 68, 68)
# Table   5$  (  5,  5)  ( 13, 13)  ( 21, 21)  ( 29,2900)  ( 37,3700)  ( 45, 45)  ( 53, 53)  ( 61, 61)
  overflow $  ( 69, 69)
# Table   6$  (  6,  6)  ( 14, 14)  ( 22,2200)  ( 30, 30)  ( 38, 38)  ( 46,4600)  ( 54, 54)  ( 62, 62)
  overflow $  ( 70, 70)
# Table   7$  (  7,700)  ( 15, 15)  ( 23, 23)  ( 31, 31)  ( 39, 39)  ( 47, 47)  ( 55, 55)  ( 63, 63)
  overflow $  ( 71, 71)
```

四、利用benchmark测试及测试结果

测试采用的是YCSB测试，一种键值benchmark，给定的数据集每行操作由操作类型和数据组成，由于项目使用8字节键值，所以在读取数据的时候直接将前8字节的数据复制进去即可，键和值内容相同。运行流程分load和run，load用于初始化数据库，run为真正运行阶段，其中包括了insert操作和read操作。

测试结果如下所示，第一个结果是在每次修改数据后都调用 `pmem_persist()` 函数，第二个结果是仅在析构函数中调用 `pmem_persist` 函数。每次修改数据都调用 `pmem_persist()` 函数：

```
#  Test 0
<p class="mume-header " id="test-0"></p>

* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 58.808853
 OPS = 1700
* Run file
 Total 10000 opertions. Insert 10000 times. Read 0 times
 cost time = 6.088393
 OPS = 1642

#  Test 1
<p class="mume-header " id="test-1"></p>

* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 55.323030
 OPS = 1807
* Run file
 Total 10000 opertions. Insert 7516 times. Read 2484 times
 cost time = 4.490477
 OPS = 2226

#  Test 2
<p class="mume-header " id="test-2"></p>

* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 55.799033
 OPS = 1792
* Run file
 Total 10000 opertions. Insert 5102 times. Read 4898 times
 cost time = 3.057599
 OPS = 3270

#  Test 3
<p class="mume-header " id="test-3"></p>

* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 56.924400
 OPS = 1756
* Run file
 Total 10000 opertions. Insert 2488 times. Read 7512 times
 cost time = 1.513926
 OPS = 6605

#  Test 4
<p class="mume-header " id="test-4"></p>
```

```
* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 56.705464
 OPS = 1763
* Run file
 Total 10000 opertions. Insert 0 times. Read 10000 times
 cost time = 0.004503
 OPS = 2220741
```

仅在析构函数中调用 `pmem_persist()` 函数：

```
#  Test 0
<p class="mume-header " id="test-0-1"></p>

* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 0.066591
 OPS = 1501704
* Run file
 Total 10000 opertions. Insert 10000 times. Read 0 times
 cost time = 0.008679
 OPS = 1152206

#  Test 1
<p class="mume-header " id="test-1-1"></p>

* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 0.058176
 OPS = 1718921
* Run file
 Total 10000 opertions. Insert 7516 times. Read 2484 times
 cost time = 0.010933
 OPS = 914662

#  Test 2
<p class="mume-header " id="test-2-1"></p>

* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 0.059953
 OPS = 1667973
* Run file
 Total 10000 opertions. Insert 5102 times. Read 4898 times
 cost time = 0.011856
 OPS = 843454

#  Test 3
<p class="mume-header " id="test-3-1"></p>

* Load file
 Total 100000 opertions. Insert 100000 times. Read 0 times
 cost time = 0.058279
 OPS = 1715883
* Run file
 Total 10000 opertions. Insert 2488 times. Read 7512 times
 cost time = 0.012970
 OPS = 771010

#  Test 4
<p class="mume-header " id="test-4-1"></p>
```

```
* Load file
  Total 100000 opertions. Insert 100000 times. Read 0 times
  cost time = 0.059744
  OPS = 1673808
* Run file
  Total 10000 opertions. Insert 0 times. Read 10000 times
  cost time = 0.014067
  OPS = 710883
```

以下表格记录所有测试类型的时延和OPS，其中第一列 Type 指示是否在每次 insert 操作后调用 `pmem_persist` 函数来持久化数据；第二列 File Type 指示文件的类型是 Load 或 Run。

Type	File Type	Test	0	1	2	3	4
With	Load	delay	58.808853	55.323030	55.799033	56.924400	56.705464
With	Load	OPS	1700	1807	1792	1756	1763
With	Run	delay	6.088393	4.490477	3.057599	1.513926	0.004503
With	Run	OPS	1642	2226	3270	6605	2220741
Without	Load	delay	0.066591	0.058176	0.059953	0.058279	0.059744
Without	Load	OPS	1501704	1718921	1667973	1715883	1673808
Without	Run	delay	0.008679	0.010933	0.011856	0.012970	0.014067
Without	Run	OPS	1152206	914662	843454	771010	710883

五、溢出桶空间回收的实现

本次实验有两个加分项，分别是**溢出桶空间回收**和**多线程实现**。在本次课程设计中，我们**实现了溢出桶空间回收**。虽然并未成功实现多线程设计，但是我们小组仍然对多线程设计进行了思考和尝试，会在本报告的最后部分呈现。接下来简述溢出桶空间回收实现。

溢出桶空间回收是指如果溢出桶大小为空，则删除溢出桶。在创建线性哈希时，我们增加了 `is_used` 变量用来指示溢出桶是否被使用， `is_used` 是一个bool类型的指针，指向可非易失性内存中的一个位置，位置分布可参考此处。简单来说，通过设置溢出桶对应的 `is_used` 就可以实现溢出桶的回收。

在insert操作中，由于插入新的项可能会导致桶溢出，因此有可能会使用到溢出桶，从而需要通过 `is_used` 变量寻找未被使用的溢出桶，并且将溢出桶的is_used位设置为**1**。

```
if(new_table->fill_num == TABLE_SIZE){
    for(i = 0; i < overflow_table_num; i++){
        if(is_used[i] != 1){
            new_table->next_offset = (uint64_t)(i*sizeof(pm_table));
            new_table = newOverflowTable(new_table->next_offset);
            is_used[i] = 1;
            break;
        }
    }
}
```

在remove操作中，如果检测到溢出桶为空，则需要删除溢出桶，即将对应的is_used位设置为**0**。

```
//remove the empty table
if(table->fill_num == 0 && last != table){
    last->next_offset = -1;
    meta->overflow_num--;
    int temp = ((uint64_t)table - (uint64_t)overflow_addr)/sizeof(pm_table);
    is_used[temp] = 0;
}
```

六、关于多线程的思考

1. 使用线程池

- 由于该线性哈希仅有简单的增删查减操作，考虑可以使用操作系统课程中学习的线程池技术来实现并行化。
- 如果只是简单地进行并行化，由于命令都在文件中，同时读取文件内容容易导致线程不安全；也可以手动对文件进行划分，让每个线程读取不同的文件并进行操作。
- 而线程池维护了多个线程，只需要主线程一直读入文件，之后每次读入一条语句后添加到任务队列中，让任务线程去获取任务并执行。如此一来可以大幅减少创建线程所需的开销，并提高线程的可管理性。
- 初始化线程池创建的线程数应该在哈希桶数量以内，因为对哈希桶插入键值时需要加锁，若当所有桶哈希值对应的桶都在进行插入操作时，所有其余线程必须等待。

2. 使用读写锁

- 可以通过使用读写锁来加快上锁效率。在读取数据的时候加读锁，使得可以同时支持多个读操作；在插入数据时加写锁，使得所有读或写操作都不能进入。
- 但是如何加读写锁是一个难题，若是简单的锁，可以考虑对所有可能哈希值申请互斥量数组，之后对每个哈希值进行锁操作，在调用哈希函数得到哈希值后进行加锁，每次只能让一个线程处理一个哈希值的所有桶。

3. ...