操作系统(D)

项目 8

李子龙 518070910095

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设计虚拟内存管理器

1. 起步

首先将测试用的地址写入 trial.txt，以测试 `addext` 内存地址分析模块的正确性。

Listing 1: src/trial.txt

```
1
256
32768
32769
128
65534
33153
```

```
logcreative@ubuntu: /mnt/hgfs/VMShared/linux/OS/Project/Projec...
logcreative@ubuntu:/mnt/hgfs/VMShared/linux/OS/Project/Project8/src$ ./vmm trial.txt
Input:      1    Page number:   1        Offset:   1
Input:    256    Page number:   0        Offset:   0
Input:  32768    Page number:   0        Offset:   0
Input:      0    Page number:   0        Offset:   0
Input:  32769    Page number:   1        Offset:   1
Input:      0    Page number:   0        Offset:   0
Input:    128    Page number: 128        Offset: 128
Input:  65534    Page number: 254        Offset: 254
Input:      0    Page number:   0        Offset:   0
Input:  33153    Page number: 129        Offset: 129
logcreative@ubuntu:/mnt/hgfs/VMShared/linux/OS/Project/Project8/src$
```

定义地址结构和地址提取器如下：

Listing 2: src/addext.h

```c
#include <stdlib.h>

typedef struct address
{
    int number;
    int offset;
} add;
```

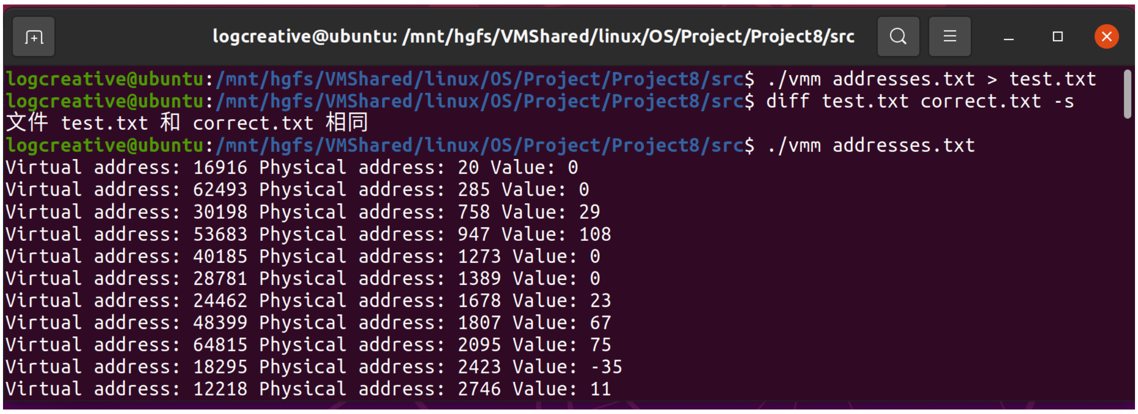
```c
add addext(int _rline);
int getAdd(add _addin);
```

Listing 3: src/addext.c

```c
#include "addext.h"

add addext(int _rline) {
    add add_;
    _rline = _rline & 0x0000FFFF;
    add_.number = (_rline & 0x0000FF00) >> 8;
    add_.offset = _rline & 0x000000FF;
    return add_;
}

int getAdd(add _addin) {
    return (_addin.number << 8) + _addin.offset;
}
```

2. 处理页面错误

接着，先不考虑 TLB，只使用页表。将输出结果与正确参考比较，结论是正确：



首先对输入流分析，在 main 函数里的情形如下：

```c
    while(fgets(addline, MAXLINE, addfile)!=NULL){
        int rline = atoi(addline);
        add viradd = addext(rline);
        add phyadd = getPhyAdd(viradd);
        fprintf(stdout, "Virtual address: %d Physical address: %d Value: %d\n",
            getAdd(viradd), getAdd(phyadd), getValue(phyadd));
    }
```

获取值是直接从内存中获得对应位置的值：

```c
int getValue(add _phyadd) {
    return mem[_phyadd.number][_phyadd.offset];
}
```

其中 mem 是用 char 存储的：

Listing 4: src/memory.h

```
#ifndef MEMORY
#define MEMORY 1

#include <stdio.h>
#include "lru.h"
#include "addext.h"

#define MEMSIZE 128
#define FRAMESIZE 256

char mem[MEMSIZE][FRAMESIZE];

// a negative number means there is a fault.
int read_frame(int page_number);
int get_value(add _phyadd);

#endif
```

当前只使用页表是不需要考虑 TLB 的获取物理地址的函数如下：

```
add getPhyAdd(add _inadd) {
    add phyadd;

    if (!page_table[_inadd.number][1])
        handle_pagefault(_inadd.number);

    phyadd.number = page_table[_inadd.number][0];
    phyadd.offset = _inadd.offset;
    return phyadd;
}
```

一旦有页面错误就会触发对应的函数，将内容存放到内存中去：

```
void handle_pagefault(int page_number) {
    int frame_number = read_frame(page_number);
    page_table[page_number][0] = frame_number;
    page_table[page_number][1] = 1;
}
```

由于现在的内存充足，帧码直接用静态变量 `frame_number` 递增存储。

```
int read_frame(int page_number) {
    static int frame_number = 0;

    FILE* backstore;
    if ((backstore = fopen("BACKING_STORE.bin", "rb")) == NULL) {
        fprintf(stderr, "Empty file storage!\n");
        return -1;
    }

    int frame_number_ = frame_number++;
    long pos = page_number * FRAMESIZE;
    fseek(backstore, pos, SEEK_SET);
    fread(mem[frame_number_], sizeof(char), FRAMESIZE, backstore);
    fclose(backstore);
```

```
    return frame_number_;
}
```

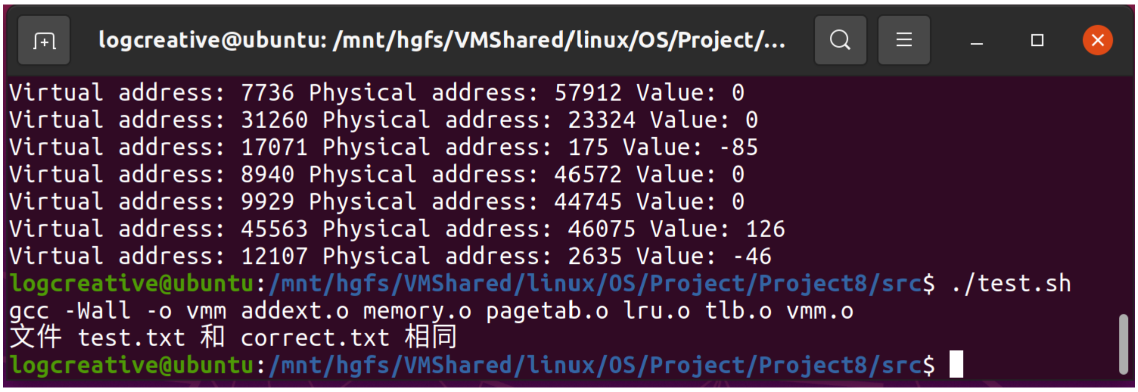
这里使用了二进制文件读取的方式复制到内存中去。

3. 使用 TLB

使用 `test.sh` 脚本进行相同的测试后，结果仍然是一致的。

Listing 5: src/test.sh

```
make
./vmm addresses.txt > test.txt
diff test.txt correct.txt -s
```



首先，输入流分析被重定向到 TLB 对应的接口。

```
add getPhyAdd(add _inadd) {
    add phyadd;

    phyadd.number = tlb_search(_inadd.number);
    phyadd.offset = _inadd.offset;

    return phyadd;
}
```

TLB 由 16 个内存块组成。

Listing 6: src/tlb.h

```
#ifndef TLB_GUARD
#define TLB_GUARD 1

#include "pagetab.h"
#include "lru.h"

#define TLBSIZE 16

// TLB[i][2] - isOccupied:
//      0 - empty
//      1 - occupied
int TLB[TLBSIZE][3];
```

```c
int tlb_search(int page_number);

double get_pagefault_rate();
double get_tlbhit_rate();

#endif // !TLB_GUARD
```

而最主要的 tlb_search 函数首先会尝试 TLB 命中，接着如果是 TLB 未命中，就看需不需要触发页面缺失，然后看是否由空余 TLB 空间用于存储到 TLB 中。如果 TLB 满，就会使用 LRU 算法进行 TLB 置换。

Listing 7: src/tlb.c

```c
#include "tlb.h"

int all_number = 0;
int page_fault_number = 0;
int tlb_hit_number = 0;

int tlb_search(int page_number) {
    static struct used_node* tlb_head = NULL;
    static struct used_node* tlb_tail = NULL;

    ++all_number;

    int result = -1;
    for (int i = 0; i < TLBSIZE; ++i) {
        if (TLB[i][2]          // is occupied
            && TLB[i][0] == page_number) {
            result = i;
            break;
        }
    }
    if (result >= 0) {         // TLB hit
        search_pop(&tlb_head, &tlb_tail, page_number);
        push(&tlb_head, &tlb_tail, page_number);
        ++tlb_hit_number;
        return TLB[result][1];
    }
    else {                     // TLB miss

        if (!page_table[page_number][1]) { // page fault
            if (handle_pagefault(page_number)) { // page replacement
                int frame_number_r = page_table[page_number][0];
                for (int i = 0; i < TLBSIZE; ++i)
                    if (TLB[i][2]
                        && TLB[i][1] == frame_number_r)
                        TLB[i][2] = 0;
            }
            ++page_fault_number;
        }

        int frame_number = page_table[page_number][0];

        int hole = -1;
```

```c
        for (int i = 0; i < TLBSIZE; ++i)
            if (!TLB[i][2]) { // is empty
                hole = i;
                break;
            }

        if (hole >= 0) {
            TLB[hole][0] = page_number;
            TLB[hole][1] = frame_number;
            TLB[hole][2] = 1;
            push(&tlb_head, &tlb_tail, page_number);
        } else {              // full TLB
            // LRU Algorithm
            int least_used = bottom_pop(&tlb_head, &tlb_tail);
            int least_used_index = 0;
            for (; TLB[least_used_index][0] != least_used; ++least_used_index);
            TLB[least_used_index][0] = page_number;
            TLB[least_used_index][1] = frame_number;
            push(&tlb_head, &tlb_tail, page_number);
        }

        return frame_number;
    }
}

double get_pagefault_rate() { return (double)page_fault_number / all_number; }
double get_tlbhit_rate() { return (double)tlb_hit_number / all_number; }
```

对于 TLB 使用状态使用了双向链表式栈存储，记录头 tlb_head 和尾 tlb_tail。对应的 LRU 操作具有如下定义：

Listing 8: src/lru.h

```c
#ifndef LRU
#define LRU 1

#include <stdlib.h>

struct used_node {
    int page_number;
    struct used_node* prev;
    struct used_node* next;
};

void search_pop(struct used_node** head, struct used_node** tail, int page_number);

void push(struct used_node** head, struct used_node** tail, int page_number);

int bottom_pop(struct used_node** head, struct used_node** tail);

#endif
```

- search_pop 将会寻找对应的栈节点，并移除。

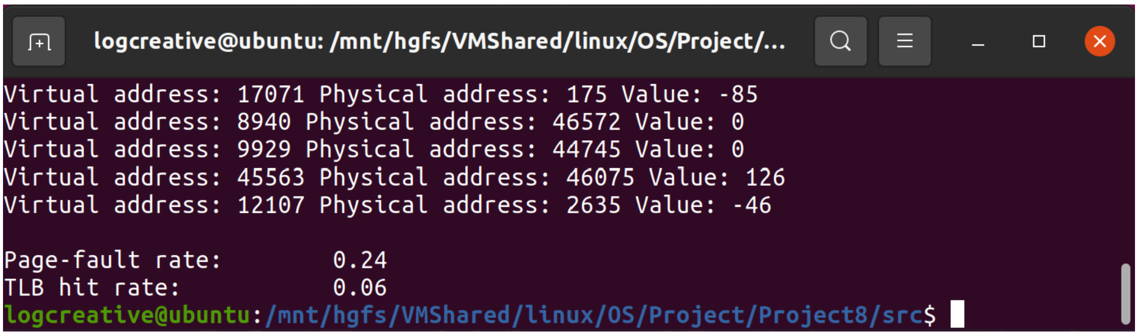
- push 入栈操作。
- bottom_pop 栈底出栈。

Listing 9: src/lru.c

```
#include "lru.h"

void search_pop(struct used_node** head, struct used_node** tail, int page_number) {
    struct used_node* tmp = *head;
    while (tmp && tmp->page_number != page_number)
        tmp = tmp->next;
    if (!tmp) return;     // If nothing is found, then do nothing.
    if (*head == *tail) {
        *head = *tail = NULL;
        return;
    }
    if (tmp == *head) {
        tmp->next->prev = tmp->prev;
        *head = tmp->next;
    }
    else if (tmp == *tail) {
        tmp->prev->next = tmp->next;
        *tail = tmp->prev;
    }
    else {
        tmp->next->prev = tmp->prev;
        tmp->prev->next = tmp->next;
    }
    free(tmp);
}

void push(struct used_node** head, struct used_node** tail, int page_number) {
    struct used_node* new_node = (struct used_node*)malloc(sizeof(struct used_node));
    new_node->page_number = page_number;
    new_node->prev = NULL;
    new_node->next = NULL;

    if (!*head) {
        *head = *tail = new_node;
        return;
    }

    new_node->next = *head;
    (*head)->prev = new_node;
    *head = new_node;
}

int bottom_pop(struct used_node** head, struct used_node** tail) {
    if (!*tail) return -1;

    int bottom = (*tail)->page_number;
    if (*head == *tail) {
        *head = *tail = NULL;
        return bottom;
    }
```

```
    *tail = (*tail)->prev;
    free((*tail)->next);
    (*tail)->next = NULL;
    return bottom;
}
```

4. 添加统计信息

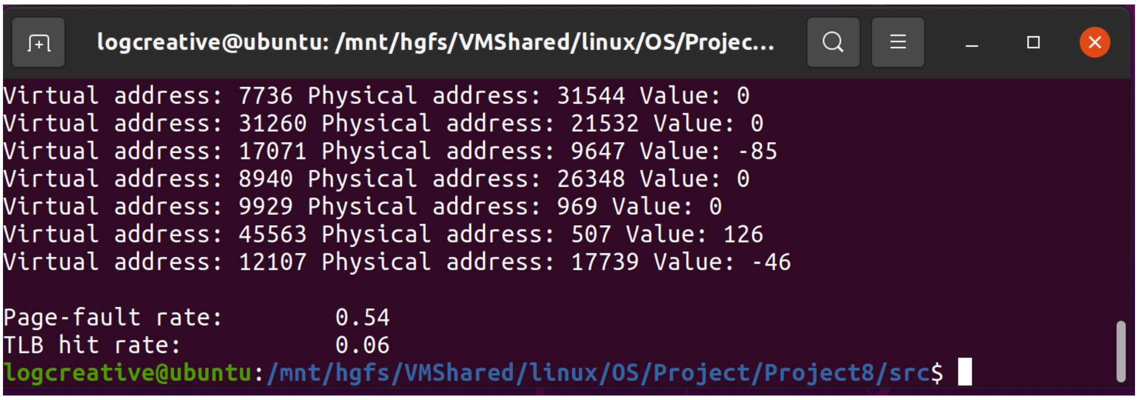


添加统计接口，方可在主函数中获得统计信息。添加 -s 参数可以显示统计信息。

```
    if(argc==3 && strcmp(argv[2],"-s")==0)
        fprintf(stdout, "\nPage-fault rate:\t%.2f\nTLB hit rate:\t\t%.2f\n", get_pagefault_rate(),
            get_tlbhit_rate());
```

5. 页面置换

将内存帧数设定为 128 后，结果如下：



当下的内存关于读取帧的定义发生了改变，采用 LRU 算法进行页面置换。

Listing 10: src/memory.h

```
#ifndef MEMORY
#define MEMORY 1

#include <stdio.h>
#include "lru.h"
#include "addext.h"

#define MEMSIZE 128
#define FRAMESIZE 256

char mem[MEMSIZE][FRAMESIZE];
```

```c
// a negative number means there is a fault.
int read_frame(int page_number);
int get_value(add _phyadd);

#endif
```

Listing 11: `src/memory.c`

```c
#include "memory.h"

static struct used_node* mem_head = NULL;
static struct used_node* mem_tail = NULL;

int read_frame(int page_number) {
    static int frame_number = 0;

    FILE* backstore;
    if ((backstore = fopen("BACKING_STORE.bin", "rb")) == NULL) {
        fprintf(stderr, "Empty file storage!\n");
        return -1;
    }

    int fault = frame_number >= MEMSIZE;

    int frame_number_ = fault ? MEMSIZE : frame_number++;

    if (fault) // Page Replacement
        frame_number_ = bottom_pop(&mem_head, &mem_tail);

    long pos = page_number * FRAMESIZE;
    fseek(backstore, pos, SEEK_SET);
    fread(mem[frame_number_], sizeof(char), FRAMESIZE, backstore);
    fclose(backstore);

    return fault ? -frame_number_-1 : frame_number_;
}

int get_value(add _phyadd) {
    int frame_number = _phyadd.number;
    search_pop(&mem_head, &mem_tail, frame_number);
    push(&mem_head, &mem_tail, frame_number);
    return mem[frame_number][_phyadd.offset];
}
```

对于发生了页面置换后的帧 N，将会返回

$$-N-1$$

标识替换。

获取内存值时，将会对访问后的帧对应的内存访问栈进行更新。注意，当页面置换已经弹出该帧时，`search_pop` 将会什么都不做。

Listing 12: src/pagetab.h

```c
#ifndef PAGETAB
#define PAGETAB 1

#include "memory.h"

#define PAGETABLESIZE 256

// [FN][0] Frame Number
// [FN][1] Valid Byte:
//      1 - valid
//      0 - invalid

int page_table[PAGETABLESIZE][2];

// return 1 if there is a page replacement
int handle_pagefault(int page_number);

#endif
```

Listing 13: src/pagetab.c

```c
#include "pagetab.h"

int handle_pagefault(int page_number) {
    int frame_number = read_frame(page_number);
    int fault = frame_number < 0;
    frame_number = fault ? -frame_number - 1 : frame_number;

    if (fault) {
        // in-valid the original page_number
        int original_page_number = 0;
        for (; original_page_number < PAGETABLESIZE &&
            !(page_table[original_page_number][1] &&
                page_table[original_page_number][0]==frame_number);
            ++original_page_number);
        page_table[original_page_number][1] = 0;
    }

    page_table[page_number][0] = frame_number;
    page_table[page_number][1] = 1;
    return fault;
}
```

对应的置换信息将会传递页表中，采用下面的方式复原

$$-(-N-1)-1=N$$

并从当前的页表中寻找对应的替换帧置为无效。

```c
        if (!page_table[page_number][1]) { // page fault
            if (handle_pagefault(page_number)) { // page replacement
                int frame_number_r = page_table[page_number][0];
                for (int i = 0; i < TLBSIZE; ++i)
```

```
                if (TLB[i][2]
                    && TLB[i][1] == frame_number_r)
                    TLB[i][2] = 0;
            }
            ++page_fault_number;
        }
```

替换信息将会按照 0-1 返回到 TLB 中，将会寻找当前 TLB 中是否有对应帧的存储信息，如果有将会被置为无效，变成可以被 `hole` 捕捉的 TLB 位置。找不到就什么都不做。

A Makefile

Listing 14: src/Makefile

```
CC=gcc
CFLAGS=-Wall

all: addext.o memory.o pagetab.o lru.o tlb.o vmm.o
	$(CC) $(CFLAGS) -o vmm addext.o memory.o pagetab.o lru.o tlb.o vmm.o

addext.o: addext.c
	$(CC) $(CFLAGS) -c addext.c

vmm.o: vmm.c
	$(CC) $(CFLAGS) -c vmm.c

memory.o: memory.c
	$(CC) $(CFLAGS) -c memory.c

pagetab.o: pagetab.c
	$(CC) $(CFLAGS) -c pagetab.c

lru.o: lru.c
	$(CC) $(CFLAGS) -c lru.c

tlb.o: tlb.c
	$(CC) $(CFLAGS) -c tlb.c

clean:
	rm -rf *.o
	rm -rf vmm
```