COMP 3300 OPERATING SYSTEMS FUNDAMENTALS Course Project
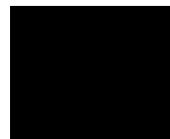
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Group Members and Student ID

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Introduction

This project is about a project on Memory management. Our team wrote a C program that translates logical addresses to physical addresses for virtual address space of $2^{16} = 65536$ bytes. Memory management is the functionality of an operating system, which handles or manages primary memory, moves processes back and forth between main memory, and disk during execution. Memory management keeps track of each memory location, regardless of its state; whether it is allocated some process, or it is free. It does the following:

- Checks how much memory is to be allocated for each process, and it decides which process will get memory is to be allocated at what time
- Tracks whenever some memory gets freed or unallocated and correspondingly it updates the memory status.

Our program will read a file containing 32-bit integer representing logical address using a TLB page table that will translate all physical corresponding physical address and output the value of the byte stored at the physical address. The technique used in this program is paging, a memory management technique in which process address space is broken into blocks of the same size called pages (that is always in size of power of 2) in which the size of the process is measured in the number of pages. Similarly, address translation is called logical address that is represented by page number and the offset. The frame address is called physical address and represented by aa frame number and the offset. The two most important formulas needed for address translation the logical address = page number + page offset and physical address = frame number + page offset. The goal behind this project is to stimulate the steps involved in translating logical to address.

Our Approach

Our program has global definitions for the following specifics:
- Page size in bytes
- Page entries
- Page number in bits
- Frame size in bytes
- Frame entries in the physical memory
- Memory size in bytes
- The Max TLB entries

Initially, the page number is extracted from the logical address and the TLB is consulted. An inverted page table or a frame table is used to keep track of all its logical pages and its physical pages. It contains one entry for each real page of memory (frame). Each entry consists of the virtual address of the page stored in that real memory location, with information about the process that owns that page. Therefore, only one-page table is in the system, having only one entry. It decreases memory needed to store each page table but increases the time needed to search the table when a page reference occurs. We use a hash table to limit the search to one or at most a few page-table entries.

The TLB can accelerate the access. In the case of a TLB-hit, the frame number is obtained from the TLB. In the case of a TLB-miss, the page table must be consulted. In the latter case, either the frame number is obtained from the page table or a page fault occurs.
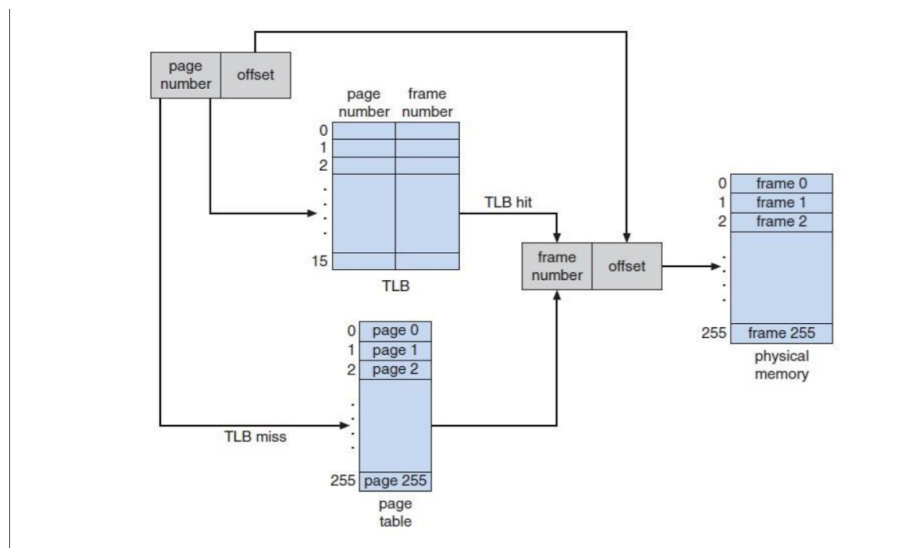
The program implements demand paging to load pages on-demand from a lazy swapper or the backing-store. A lazy swapper never swaps a page into memory unless the page will be needed. The backing store is represented by the file BACKING_STORE.bin, a binary file size of 65,536 bytes. When a page fault occurs, you will read in a 256-byte page from the file BACKING_STORE and store it in an available page frame in physical memory. If a page is needed, it references it. If it is an invalid reference, t aborts. If it is "not-in-memory", it brings it to memory. For example, if a logical address with page number 15 resulted in a page fault, your program would read in page 15 from BACKING_STORE (remember that pages begin at 0 and are 256 bytes in size) and store it in a page frame in physical memory.

Once this frame is stored (and the page table and TLB are updated), subsequent accesses to page 15 will be resolved by either the TLB or the page table. To implement this, we treated the BACKING_STORE.bin as a random-access file so that the program can randomly find certain positions

of the file for reading. We used standard C library functions such as fopen(), fread(), and fclose() to perform I/O between the information processing system and the BACKING_STORE.bin.
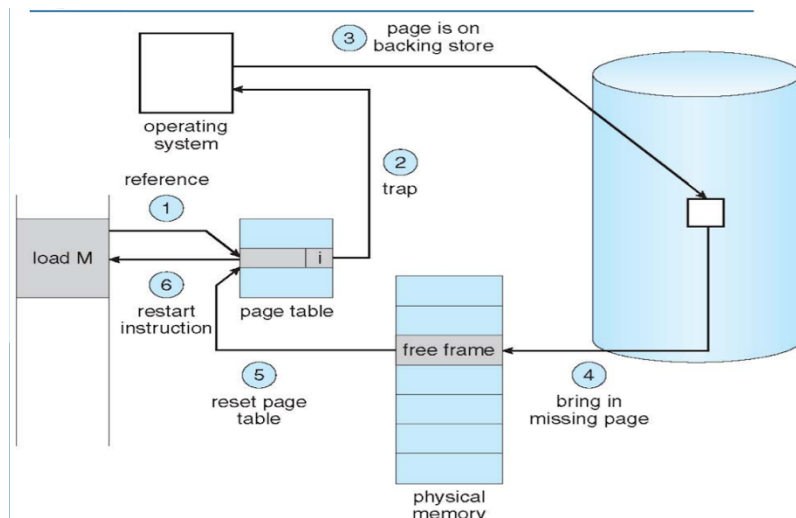
Since the size of the physical memory is smaller than the size of the virtual address space, we had to take into consideration the page replacements during a page fault. Since there are only 128-page frames rather than 256, we had to keep track of free page frames as well as implementing a page-replacement policy using FIFO.

Page replacement is when paging-in pages of a process are there but there aren't any free frames. It completes the separation between the logical memory and physical memory. For example, a user process of 20 pages can be executed in 3 frames simply by using demand-paging and using a page-replacement algorithm to find a free frame or unused frame when necessary. We used the FIFO (first in first out) page replacement algorithm, where each page brought into memory is also inserted into a first-in first-out queue. The idea is that the page to be replaced is the oldest page or the one at the head of the queue.

Translation Lookaside Table (TLB):

Each process creates a page table in memory. This Page Table Entry (PTE) references where the page is located in main memory. PTEs contain information such as frame number, valid/invalid bit, dirty bit, protection bit, and more. The real memory address in main memory can be generated using the frame number.

PTEs now need to be stored efficiently for runtime. Highspeed cache is allocated for PTEs called the Translation Lookaside Buffer (TLB). This TLB contains recently used PTEs.

When given a virtual address, the TLB is referenced. If the PTE exists within the TLB, this is known as a TLB hit. When a TLB hit occurs, the frame number is supplied which generates the real memory address. If the PTE does not exist within the TLB, this is known as a TLB miss. When a TLB miss occurs, the page number is used to search the process page table. The TLB then checks if the page exists in main memory, if not, a page fault is issues and the new page entry is added to the TLB.

Explanation of Code

The headers files and Constant definitions used for this project:

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

#define TLB_SIZE 16
#define PAGES 256
#define PAGE_MASK 255
#define PAGE_SIZE 256
#define OFFSET_BITS 8
#define OFFSET_MASK 255

#define MEMORY_SIZE PAGES * PAGE_SIZE

// Max number of characters per line from the input file to read
#define BUFFER_SIZE 10

struct tlb_entry_address {
    unsigned char logical_address;
    unsigned char physical_address;
};

// TLB is kept track of as a circular array, with the oldest element
// being overwritten once the TLB is full.
struct tlb_entry_address tlb[TLB_SIZE];
// number of inserts into TLB that have been completed. Use as
// tlbindex % TLB_SIZE for the index of the next TLB line to use.
int tlbindex = 0;

// this is the physical_address page number for logical_address page.
// e. Value is -1 if that logical_address page isn't yet in the table.
int pagetable[PAGES];

signed char main_memory[MEMORY_SIZE];
```

```c
const char *output_file = "output.txt";

// Pointer to memory mapped backing file
signed char *backing;

// function prototype to search the page tables for TLB, add TLB to
page, and find the max tlb

int search_tlb(unsigned char logical_page);

void add_to_tlb(unsigned char logical_address, unsigned char
physical_address);

int max_tlb(int x, int y);


int main(int argc, const char *argv[])
{
    FILE *output_fp=fopen(output_file, "w"); // writes the result to
the file

    if (argc != 3) {
        fprintf(stderr, "Usage ./a.out BACKINGSTORE.bin
addressess.txt\n");
        exit(1);
    }

    const char *backing_filename = argv[1];

    //open and return a file descripter for the bin file
    int backing_fd = open(backing_filename, O_RDONLY);
    backing = mmap(0, MEMORY_SIZE, PROT_READ, MAP_PRIVATE, backing_fd,
0);

    const char *input_filename = argv[2];
    FILE *input_fp = fopen(input_filename, "r");

    // Fill page table entries with -1 (null) for the initially empty
table.
    int i;
    for (i = 0; i < PAGES; i++)
        { pagetable[i] = -1; }

    // Character buffer for reading lines of input file.
    char buffer[BUFFER_SIZE];

    int total_addresses = 0, tlb_hits = 0, page_faults = 0;
```

```c
    // Number of the next unallocated physical_address page in main
memory
    unsigned char free_page = 0;
    while (fgets(buffer, BUFFER_SIZE, input_fp) != NULL)
        {total_addresses++;
         int logical_address = atoi(buffer);
         int offset = logical_address & OFFSET_MASK;
         int logical_page = (logical_address >> OFFSET_BITS) &
PAGE_MASK; // to get the 16-bit size
         int physical_page = search_tlb(logical_page);
         // TLB hit
         if (physical_page != -1)
         {
             tlb_hits++;
             // TLB miss
         } else
         {
             physical_page = pagetable[logical_page];

             // Page fault, calculating
             if (physical_page == -1)
             {
                 page_faults++;
                 physical_page = free_page;
                 free_page++;
                 // read in a 256-byte page from the file BACKING_STORE
and store it in an available page frame in physical memory
                 memcpy(main_memory + physical_page * PAGE_SIZE,
backing + logical_page * PAGE_SIZE, PAGE_SIZE);
                 pagetable[logical_page] = physical_page;
             }
             add_to_tlb(logical_page, physical_page);
         }

         //The signed byte value stored at the translated physical
address
         int physical_address = (physical_page << OFFSET_BITS) |
offset; // get the 16 bit size of the physical address
         signed char value = main_memory[physical_page * PAGE_SIZE +
offset];

         // Writes the logical and physical address and the value to
the output file
         fprintf(output_fp,"Virtual Address: %d  physical address:  %d
Value:  %d\n", logical_address, physical_address, value);
         // Writes the logical and physical address and the value to
the screen
         printf("Virtual address: %d physical_address address: %d Value:
%d\n", logical_address, physical_address, value);
    }
```

```c
    printf("Number of Translated Addresses = %d\n", total_addresses);
    fprintf(output_fp, "Number of Translated Addresses = %d\n",
total_addresses);
    printf("Page Faults = %d\n", page_faults);
    fprintf(output_fp, "Page Faults = %d\n", page_faults);
    printf("Page Fault Rate = %.3f\n", page_faults / (1. *
total_addresses));
    fprintf(output_fp, "Page Fault Rate = %.3f\n", page_faults / (1. *
total_addresses));
    printf("TLB Hits = %d\n", tlb_hits);
    fprintf(output_fp, "TLB Hits = %d\n", tlb_hits);
    printf("TLB Hit Rate = %.3f\n", tlb_hits / (1. *
total_addresses));
    fprintf(output_fp, "TLB Hit Rate = %.3f\n", (tlb_hits / (1. *
total_addresses)));
    return 0;
}


int max_tlb(int x, int y)
{
    if (x > y)
    { return x;
    }
    else
    {
        return y;
    }
}

// Returns the physical_address address from TLB or -1 if the address
is not present in the table
int search_tlb(unsigned char logical_page)
{
    int i;
    for (i = max_tlb((tlbindex - TLB_SIZE), 0); i < tlbindex; i++)
        { struct tlb_entry_address *entry_address = &tlb[i%TLB_SIZE];
            if (entry_address->logical_address == logical_page)
            {
                return entry_address->physical_address;
            }
        }
    return -1;
}

// Page Replacement: Adds the specified mapping to the TLB, replacing
the oldest mapping using a FIFO replacement technique
void add_to_tlb(unsigned char logical_address, unsigned char
physical_address)
```

```
{
    struct tlb_entry_address *entry_address = &tlb[tlbindex %
TLB_SIZE];
    tlbindex++;
    entry_address->logical_address = logical_address;
    entry_address->physical_address = physical_address;
}
```

Sample Runs – Screenshots and Explanation

How to Run the Program:

Files needed: -
1. memory_manager.c
2. BACKING_STORE.bin
3. addresss.txt
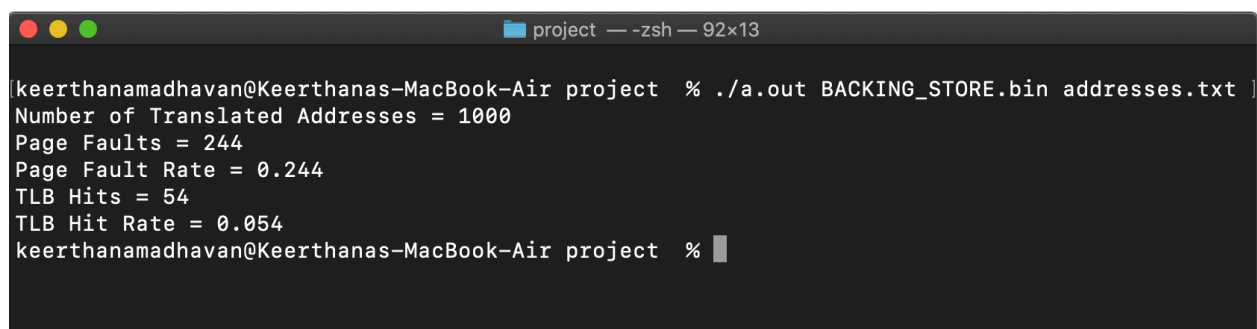
Files Generated: -
1. output.txt (that contains the virtual address, physical address, values)

Compile the programs as follows

      gcc memory_manager.c

      ./a.out BACING_STORE.bin address.txt

After Compilation the result follows: -

```
[keerthanamadhavan@Keerthanas-MacBook-Air project  % ./a.out BACKING_STORE.bin addresses.txt ]
Number of Translated Addresses = 1000
Page Faults = 244
Page Fault Rate = 0.244
TLB Hits = 54
TLB Hit Rate = 0.054
keerthanamadhavan@Keerthanas-MacBook-Air project  %
```

Comments on Output

Page Faults:
      A page fault occurs when a program attempts to access a block of memory that is not stores in the physical memory. The fault notifies the operating system that it must locate the data in virtual memory,

then transfer it from the storage device. In general, a page fault generates an exception, which notifies the operating system that it must retrieve the pages from virtual memory in order for the program to continue. Once the address is moved into physical memory, the program continues as normal since the process takes place in the background and usually goes unnoticed by the user. In this program while translating 1000 virtual addresses, we have 244 page fault because process tried to access invalid page.

Page Fault Rate:

The Page-fault rate is the percentage of address references that resulted in page faults. In this case, since the number of page faults is 244. The page-fault rate is (244/1000) = 0.244.

TLB Hits:

A Translation lookaside Buffer (TLB) is a memory cache that stores recent translation of virtual memory to physical addresses for faster retrieval. In the program, the TLB Hits value is 54, that means 54 virtual addresses are translated and the values referenced are added to the TLB table.

TLB Hit Rate:

The TLB hit rate is the percentage of address references that we resolved in the TLB. In this case, since the number of TLB Hits is 54. The TLB hit rate is (54/1000) = 0.054.

Script File

```
Virtual Address: 16916  physical address:  20  Value:  0
Virtual Address: 62493  physical address:  285  Value:  0
Virtual Address: 30198  physical address:  758  Value:  29
Virtual Address: 53683  physical address:  947  Value:  108
Virtual Address: 40185  physical address:  1273  Value:  0
Virtual Address: 28781  physical address:  1389  Value:  0
Virtual Address: 24462  physical address:  1678  Value:  23
Virtual Address: 48399  physical address:  1807  Value:  67
Virtual Address: 64815  physical address:  2095  Value:  75
Virtual Address: 18295  physical address:  2423  Value:  -35
Virtual Address: 12218  physical address:  2746  Value:  11
Virtual Address: 22760  physical address:  3048  Value:  0
Virtual Address: 57982  physical address:  3198  Value:  56
Virtual Address: 27966  physical address:  3390  Value:  27
Virtual Address: 54894  physical address:  3694  Value:  53
Virtual Address: 38929  physical address:  3857  Value:  0
Virtual Address: 32865  physical address:  4193  Value:  0
Virtual Address: 64243  physical address:  4595  Value:  -68
Virtual Address: 2315  physical address:  4619  Value:  66
Virtual Address: 64454  physical address:  5062  Value:  62
Virtual Address: 55041  physical address:  5121  Value:  0
Virtual Address: 18633  physical address:  5577  Value:  0
Virtual Address: 14557  physical address:  5853  Value:  0
Virtual Address: 61006  physical address:  5966  Value:  59
Virtual Address: 62615  physical address:  407  Value:  37
Virtual Address: 7591  physical address:  6311  Value:  105
Virtual Address: 64747  physical address:  6635  Value:  58
Virtual Address: 6727  physical address:  6727  Value:  -111
Virtual Address: 32315  physical address:  6971  Value:  -114
```

Virtual Address: 60645 physical address: 7397 Value: 0
Virtual Address: 6308 physical address: 7588 Value: 0
Virtual Address: 45688 physical address: 7800 Value: 0
Virtual Address: 969 physical address: 8137 Value: 0
Virtual Address: 40891 physical address: 8379 Value: -18
Virtual Address: 49294 physical address: 8590 Value: 48
Virtual Address: 41118 physical address: 8862 Value: 40
Virtual Address: 21395 physical address: 9107 Value: -28
Virtual Address: 6091 physical address: 9419 Value: -14
Virtual Address: 32541 physical address: 9501 Value: 0
Virtual Address: 17665 physical address: 9729 Value: 0
Virtual Address: 3784 physical address: 10184 Value: 0
Virtual Address: 28718 physical address: 1326 Value: 28
Virtual Address: 59240 physical address: 10344 Value: 0
Virtual Address: 40178 physical address: 1266 Value: 39
Virtual Address: 60086 physical address: 10678 Value: 58
Virtual Address: 42252 physical address: 10764 Value: 0
Virtual Address: 44770 physical address: 11234 Value: 43
Virtual Address: 22514 physical address: 11506 Value: 21
Virtual Address: 3067 physical address: 11771 Value: -2
Virtual Address: 15757 physical address: 11917 Value: 0
Virtual Address: 31649 physical address: 12193 Value: 0
Virtual Address: 10842 physical address: 12378 Value: 10
Virtual Address: 43765 physical address: 12789 Value: 0
Virtual Address: 33405 physical address: 12925 Value: 0
Virtual Address: 44954 physical address: 13210 Value: 43
Virtual Address: 56657 physical address: 13393 Value: 0
Virtual Address: 5003 physical address: 13707 Value: -30
Virtual Address: 50227 physical address: 13875 Value: 12
Virtual Address: 19358 physical address: 14238 Value: 18
Virtual Address: 36529 physical address: 14513 Value: 0
Virtual Address: 10392 physical address: 14744 Value: 0
Virtual Address: 58882 physical address: 14850 Value: 57
Virtual Address: 5129 physical address: 15113 Value: 0
Virtual Address: 58554 physical address: 15546 Value: 57
Virtual Address: 58584 physical address: 15576 Value: 0
Virtual Address: 27444 physical address: 15668 Value: 0
Virtual Address: 58982 physical address: 14950 Value: 57
Virtual Address: 51476 physical address: 15892 Value: 0
Virtual Address: 6796 physical address: 6796 Value: 0
Virtual Address: 21311 physical address: 9023 Value: -49
Virtual Address: 30705 physical address: 16369 Value: 0
Virtual Address: 28964 physical address: 16420 Value: 0
Virtual Address: 41003 physical address: 8747 Value: 10
Virtual Address: 20259 physical address: 16675 Value: -56
Virtual Address: 57857 physical address: 3073 Value: 0
Virtual Address: 63258 physical address: 16922 Value: 61
Virtual Address: 36374 physical address: 14358 Value: 35
Virtual Address: 692 physical address: 17332 Value: 0
Virtual Address: 43121 physical address: 17521 Value: 0
Virtual Address: 48128 physical address: 17664 Value: 0

Virtual Address: 34561 physical address: 17921 Value: 0
Virtual Address: 49213 physical address: 8509 Value: 0
Virtual Address: 36922 physical address: 18234 Value: 36
Virtual Address: 59162 physical address: 10266 Value: 57
Virtual Address: 50552 physical address: 18552 Value: 0
Virtual Address: 17866 physical address: 9930 Value: 17
Virtual Address: 18145 physical address: 18913 Value: 0
Virtual Address: 3884 physical address: 18988 Value: 0
Virtual Address: 54388 physical address: 19316 Value: 0
Virtual Address: 42932 physical address: 19636 Value: 0
Virtual Address: 46919 physical address: 19783 Value: -47
Virtual Address: 58892 physical address: 14860 Value: 0
Virtual Address: 8620 physical address: 20140 Value: 0
Virtual Address: 38336 physical address: 20416 Value: 0
Virtual Address: 64357 physical address: 4965 Value: 0
Virtual Address: 23387 physical address: 20571 Value: -42
Virtual Address: 42632 physical address: 20872 Value: 0
Virtual Address: 15913 physical address: 21033 Value: 0
Virtual Address: 15679 physical address: 11839 Value: 79
Virtual Address: 22501 physical address: 11493 Value: 0
Virtual Address: 37540 physical address: 21412 Value: 0
Virtual Address: 5527 physical address: 21655 Value: 101
Virtual Address: 63921 physical address: 21937 Value: 0
Virtual Address: 62716 physical address: 508 Value: 0
Virtual Address: 32874 physical address: 4202 Value: 32
Virtual Address: 64390 physical address: 4998 Value: 62
Virtual Address: 63101 physical address: 22141 Value: 0
Virtual Address: 61802 physical address: 22378 Value: 60
Virtual Address: 19648 physical address: 22720 Value: 0
Virtual Address: 29031 physical address: 16487 Value: 89
Virtual Address: 44981 physical address: 13237 Value: 0
Virtual Address: 28092 physical address: 3516 Value: 0
Virtual Address: 9448 physical address: 23016 Value: 0
Virtual Address: 44744 physical address: 11208 Value: 0
Virtual Address: 61496 physical address: 23096 Value: 0
Virtual Address: 31453 physical address: 23517 Value: 0
Virtual Address: 60746 physical address: 23626 Value: 59
Virtual Address: 12199 physical address: 2727 Value: -23
Virtual Address: 62255 physical address: 23855 Value: -53
Virtual Address: 21793 physical address: 24097 Value: 0
Virtual Address: 26544 physical address: 24496 Value: 0
Virtual Address: 14964 physical address: 24692 Value: 0
Virtual Address: 41462 physical address: 25078 Value: 40
Virtual Address: 56089 physical address: 25113 Value: 0
Virtual Address: 52038 physical address: 25414 Value: 50
Virtual Address: 47982 physical address: 25710 Value: 46
Virtual Address: 59484 physical address: 25948 Value: 0
Virtual Address: 50924 physical address: 26348 Value: 0
Virtual Address: 6942 physical address: 26398 Value: 6
Virtual Address: 34998 physical address: 26806 Value: 34
Virtual Address: 27069 physical address: 27069 Value: 0

Virtual Address: 51926 physical address: 27350 Value: 50
Virtual Address: 60645 physical address: 7397 Value: 0
Virtual Address: 43181 physical address: 17581 Value: 0
Virtual Address: 10559 physical address: 27455 Value: 79
Virtual Address: 4664 physical address: 27704 Value: 0
Virtual Address: 28578 physical address: 28066 Value: 27
Virtual Address: 59516 physical address: 25980 Value: 0
Virtual Address: 38912 physical address: 3840 Value: 0
Virtual Address: 63562 physical address: 28234 Value: 62
Virtual Address: 64846 physical address: 2126 Value: 63
Virtual Address: 62938 physical address: 28634 Value: 61
Virtual Address: 27194 physical address: 28730 Value: 26
Virtual Address: 28804 physical address: 1412 Value: 0
Virtual Address: 61703 physical address: 22279 Value: 65
Virtual Address: 10998 physical address: 12534 Value: 10
Virtual Address: 6596 physical address: 29124 Value: 0
Virtual Address: 37721 physical address: 29273 Value: 0
Virtual Address: 43430 physical address: 29606 Value: 42
Virtual Address: 22692 physical address: 2980 Value: 0
Virtual Address: 62971 physical address: 28667 Value: 126
Virtual Address: 47125 physical address: 29717 Value: 0
Virtual Address: 52521 physical address: 29993 Value: 0
Virtual Address: 34646 physical address: 18006 Value: 33
Virtual Address: 32889 physical address: 4217 Value: 0
Virtual Address: 13055 physical address: 30463 Value: -65
Virtual Address: 65416 physical address: 30600 Value: 0
Virtual Address: 62869 physical address: 28565 Value: 0
Virtual Address: 57314 physical address: 30946 Value: 55
Virtual Address: 12659 physical address: 31091 Value: 92
Virtual Address: 14052 physical address: 31460 Value: 0
Virtual Address: 32956 physical address: 4284 Value: 0
Virtual Address: 49273 physical address: 8569 Value: 0
Virtual Address: 50352 physical address: 14000 Value: 0
Virtual Address: 49737 physical address: 31561 Value: 0
Virtual Address: 15555 physical address: 31939 Value: 48
Virtual Address: 47475 physical address: 32115 Value: 92
Virtual Address: 15328 physical address: 32480 Value: 0
Virtual Address: 34621 physical address: 17981 Value: 0
Virtual Address: 51365 physical address: 32677 Value: 0
Virtual Address: 32820 physical address: 4148 Value: 0
Virtual Address: 48855 physical address: 32983 Value: -75
Virtual Address: 12224 physical address: 2752 Value: 0
Virtual Address: 2035 physical address: 33267 Value: -4
Virtual Address: 60539 physical address: 7291 Value: 30
Virtual Address: 14595 physical address: 33283 Value: 64
Virtual Address: 13853 physical address: 31261 Value: 0
Virtual Address: 24143 physical address: 33615 Value: -109
Virtual Address: 15216 physical address: 32368 Value: 0
Virtual Address: 8113 physical address: 33969 Value: 0
Virtual Address: 22640 physical address: 2928 Value: 0
Virtual Address: 32978 physical address: 4306 Value: 32

Virtual Address: 39151 physical address: 4079 Value: 59
Virtual Address: 19520 physical address: 22592 Value: 0
Virtual Address: 58141 physical address: 34077 Value: 0
Virtual Address: 63959 physical address: 21975 Value: 117
Virtual Address: 53040 physical address: 34352 Value: 0
Virtual Address: 55842 physical address: 34594 Value: 54
Virtual Address: 585 physical address: 17225 Value: 0
Virtual Address: 51229 physical address: 32541 Value: 0
Virtual Address: 64181 physical address: 4533 Value: 0
Virtual Address: 54879 physical address: 3679 Value: -105
Virtual Address: 28210 physical address: 34866 Value: 27
Virtual Address: 10268 physical address: 14620 Value: 0
Virtual Address: 15395 physical address: 31779 Value: 8
Virtual Address: 12884 physical address: 30292 Value: 0
Virtual Address: 2149 physical address: 35173 Value: 0
Virtual Address: 53483 physical address: 35563 Value: 58
Virtual Address: 59606 physical address: 26070 Value: 58
Virtual Address: 14981 physical address: 24709 Value: 0
Virtual Address: 36672 physical address: 35648 Value: 0
Virtual Address: 23197 physical address: 35997 Value: 0
Virtual Address: 36518 physical address: 14502 Value: 35
Virtual Address: 13361 physical address: 36145 Value: 0
Virtual Address: 19810 physical address: 36450 Value: 19
Virtual Address: 25955 physical address: 36707 Value: 88
Virtual Address: 62678 physical address: 470 Value: 61
Virtual Address: 26021 physical address: 36773 Value: 0
Virtual Address: 29409 physical address: 37089 Value: 0
Virtual Address: 38111 physical address: 37343 Value: 55
Virtual Address: 58573 physical address: 15565 Value: 0
Virtual Address: 56840 physical address: 37384 Value: 0
Virtual Address: 41306 physical address: 24922 Value: 40
Virtual Address: 54426 physical address: 19354 Value: 53
Virtual Address: 3617 physical address: 10017 Value: 0
Virtual Address: 50652 physical address: 18652 Value: 0
Virtual Address: 41452 physical address: 25068 Value: 0
Virtual Address: 20241 physical address: 16657 Value: 0
Virtual Address: 31723 physical address: 12267 Value: -6
Virtual Address: 53747 physical address: 1011 Value: 124
Virtual Address: 28550 physical address: 28038 Value: 27
Virtual Address: 23402 physical address: 20586 Value: 22
Virtual Address: 21205 physical address: 37845 Value: 0
Virtual Address: 56181 physical address: 25205 Value: 0
Virtual Address: 57470 physical address: 38014 Value: 56
Virtual Address: 39933 physical address: 38397 Value: 0
Virtual Address: 34964 physical address: 26772 Value: 0
Virtual Address: 24781 physical address: 38605 Value: 0
Virtual Address: 41747 physical address: 38675 Value: -60
Virtual Address: 62564 physical address: 356 Value: 0
Virtual Address: 58461 physical address: 15453 Value: 0
Virtual Address: 20858 physical address: 39034 Value: 20
Virtual Address: 49301 physical address: 8597 Value: 0

Virtual Address: 40572 physical address: 39292 Value: 0
Virtual Address: 23840 physical address: 39456 Value: 0
Virtual Address: 35278 physical address: 39886 Value: 34
Virtual Address: 62905 physical address: 28601 Value: 0
Virtual Address: 56650 physical address: 13386 Value: 55
Virtual Address: 11149 physical address: 40077 Value: 0
Virtual Address: 38920 physical address: 3848 Value: 0
Virtual Address: 23430 physical address: 20614 Value: 22
Virtual Address: 57592 physical address: 38136 Value: 0
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Virtual Address: 21514 physical address: 52234 Value: 21
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Virtual Address: 45583 physical address: 7695 Value: -125
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Virtual Address: 38697 physical address: 46889 Value: 0
Virtual Address: 59188 physical address: 10292 Value: 0
Virtual Address: 24593 physical address: 38417 Value: 0
Virtual Address: 57641 physical address: 61225 Value: 0
Virtual Address: 36524 physical address: 14508 Value: 0
Virtual Address: 56980 physical address: 37524 Value: 0
Virtual Address: 36810 physical address: 35786 Value: 35
Virtual Address: 6096 physical address: 9424 Value: 0
Virtual Address: 11070 physical address: 39998 Value: 10
Virtual Address: 60124 physical address: 10716 Value: 0
Virtual Address: 37576 physical address: 21448 Value: 0
Virtual Address: 15096 physical address: 24824 Value: 0
Virtual Address: 45247 physical address: 49087 Value: 47
Virtual Address: 32783 physical address: 4111 Value: 3
Virtual Address: 58390 physical address: 15382 Value: 57

Virtual Address: 60873 physical address: 23753 Value: 0
Virtual Address: 23719 physical address: 54951 Value: 41
Virtual Address: 24385 physical address: 1601 Value: 0
Virtual Address: 22307 physical address: 11299 Value: -56
Virtual Address: 17375 physical address: 61663 Value: -9
Virtual Address: 15990 physical address: 21110 Value: 15
Virtual Address: 20526 physical address: 56878 Value: 20
Virtual Address: 25904 physical address: 36656 Value: 0
Virtual Address: 42224 physical address: 46320 Value: 0
Virtual Address: 9311 physical address: 22879 Value: 23
Virtual Address: 7862 physical address: 58038 Value: 7
Virtual Address: 3835 physical address: 10235 Value: -66
Virtual Address: 30535 physical address: 16199 Value: -47
Virtual Address: 65179 physical address: 48539 Value: -90
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Virtual Address: 63579 physical address: 28251 Value: 22
Virtual Address: 4946 physical address: 13650 Value: 4
Virtual Address: 9037 physical address: 48205 Value: 0
Virtual Address: 61033 physical address: 5993 Value: 0
Virtual Address: 55543 physical address: 58359 Value: 61
Virtual Address: 50361 physical address: 14009 Value: 0
Virtual Address: 6480 physical address: 29008 Value: 0
Virtual Address: 14042 physical address: 31450 Value: 13
Virtual Address: 21531 physical address: 52251 Value: 6
Virtual Address: 39195 physical address: 55579 Value: 70
Virtual Address: 37511 physical address: 21383 Value: -95
Virtual Address: 23696 physical address: 54928 Value: 0
Virtual Address: 27440 physical address: 15664 Value: 0
Virtual Address: 28201 physical address: 34857 Value: 0
Virtual Address: 23072 physical address: 35872 Value: 0
Virtual Address: 7814 physical address: 57990 Value: 7
Virtual Address: 6552 physical address: 29080 Value: 0
Virtual Address: 43637 physical address: 12661 Value: 0
Virtual Address: 35113 physical address: 39721 Value: 0
Virtual Address: 34890 physical address: 26698 Value: 34
Virtual Address: 61297 physical address: 42353 Value: 0
Virtual Address: 45633 physical address: 7745 Value: 0
Virtual Address: 61431 physical address: 42487 Value: -3
Virtual Address: 46032 physical address: 51152 Value: 0
Virtual Address: 18774 physical address: 61782 Value: 18
Virtual Address: 62991 physical address: 22031 Value: -125
Virtual Address: 28059 physical address: 3483 Value: 102
Virtual Address: 35229 physical address: 39837 Value: 0
Virtual Address: 51230 physical address: 32542 Value: 50
Virtual Address: 14405 physical address: 5701 Value: 0
Virtual Address: 52242 physical address: 46610 Value: 51
Virtual Address: 43153 physical address: 17553 Value: 0
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Virtual Address: 54066 physical address: 51762 Value: 52

Virtual Address: 10054 physical address: 60230 Value: 9
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Virtual Address: 11525 physical address: 41477 Value: 0
Virtual Address: 17684 physical address: 9748 Value: 0
Virtual Address: 41681 physical address: 41937 Value: 0
Virtual Address: 27883 physical address: 44267 Value: 58
Virtual Address: 56909 physical address: 37453 Value: 0
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Virtual Address: 38734 physical address: 46926 Value: 37
Virtual Address: 28972 physical address: 16428 Value: 0
Virtual Address: 59684 physical address: 47396 Value: 0
Virtual Address: 11384 physical address: 54392 Value: 0
Virtual Address: 21018 physical address: 37658 Value: 20
Virtual Address: 2192 physical address: 35216 Value: 0
Virtual Address: 18384 physical address: 2512 Value: 0
Virtual Address: 13464 physical address: 36248 Value: 0
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Virtual Address: 62958 physical address: 28654 Value: 61
Virtual Address: 30611 physical address: 16275 Value: -28
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Virtual Address: 18904 physical address: 61912 Value: 0
Virtual Address: 26773 physical address: 42645 Value: 0
Virtual Address: 55491 physical address: 58307 Value: 48
Virtual Address: 21899 physical address: 24203 Value: 98
Virtual Address: 64413 physical address: 5021 Value: 0
Virtual Address: 47134 physical address: 29726 Value: 46
Virtual Address: 23172 physical address: 35972 Value: 0
Virtual Address: 7262 physical address: 43102 Value: 7
Virtual Address: 12705 physical address: 31137 Value: 0
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Virtual Address: 58815 physical address: 55231 Value: 111
Virtual Address: 34916 physical address: 26724 Value: 0
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Virtual Address: 58008 physical address: 3224 Value: 0
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Virtual Address: 381 physical address: 57213 Value: 0
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Virtual Address: 48769 physical address: 32897 Value: 0
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Virtual Address: 38025 physical address: 37257 Value: 0
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Virtual Address: 39530 physical address: 43370 Value: 38
Virtual Address: 59003 physical address: 14971 Value: -98
Virtual Address: 6029 physical address: 9357 Value: 0
Virtual Address: 20920 physical address: 39096 Value: 0
Virtual Address: 8077 physical address: 33933 Value: 0
Virtual Address: 42633 physical address: 20873 Value: 0

Virtual Address: 17443 physical address: 40995 Value: 8
Virtual Address: 53570 physical address: 834 Value: 52
Virtual Address: 22833 physical address: 52785 Value: 0
Virtual Address: 3782 physical address: 10182 Value: 3
Virtual Address: 47758 physical address: 56462 Value: 46
Virtual Address: 22136 physical address: 56696 Value: 0
Virtual Address: 22427 physical address: 11419 Value: -26
Virtual Address: 23867 physical address: 39483 Value: 78
Virtual Address: 59968 physical address: 10560 Value: 0
Virtual Address: 62166 physical address: 62422 Value: 60
Virtual Address: 6972 physical address: 26428 Value: 0
Virtual Address: 63684 physical address: 28356 Value: 0
Virtual Address: 46388 physical address: 50228 Value: 0
Virtual Address: 41942 physical address: 38870 Value: 40
Virtual Address: 36524 physical address: 14508 Value: 0
Virtual Address: 9323 physical address: 22891 Value: 26
Virtual Address: 31114 physical address: 62090 Value: 30
Virtual Address: 22345 physical address: 11337 Value: 0
Virtual Address: 46463 physical address: 50303 Value: 95
Virtual Address: 54671 physical address: 48783 Value: 99
Virtual Address: 9214 physical address: 48382 Value: 8
Virtual Address: 7257 physical address: 43097 Value: 0
Virtual Address: 33150 physical address: 53630 Value: 32
Virtual Address: 41565 physical address: 41821 Value: 0
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Virtual Address: 3595 physical address: 9995 Value: -126
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Virtual Address: 34660 physical address: 18020 Value: 0
Virtual Address: 51961 physical address: 27385 Value: 0
Virtual Address: 58634 physical address: 55050 Value: 57
Virtual Address: 57990 physical address: 3206 Value: 56
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Virtual Address: 64098 physical address: 4450 Value: 62
Virtual Address: 606 physical address: 17246 Value: 0
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Virtual Address: 32228 physical address: 49892 Value: 0
Virtual Address: 63437 physical address: 17101 Value: 0
Virtual Address: 29085 physical address: 16541 Value: 0
Virtual Address: 65080 physical address: 48440 Value: 0
Virtual Address: 38753 physical address: 46945 Value: 0
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Virtual Address: 42090 physical address: 46186 Value: 41
Virtual Address: 46388 physical address: 50228 Value: 0
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Virtual Address: 36636 physical address: 35612 Value: 0
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Virtual Address: 19833 physical address: 36473 Value: 0
Virtual Address: 36464 physical address: 14448 Value: 0
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Virtual Address: 12712 physical address: 31144 Value: 0
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Virtual Address: 15578 physical address: 31962 Value: 15
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Virtual Address: 60498 physical address: 7250 Value: 59
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Virtual Address: 43973 physical address: 57541 Value: 0
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Virtual Address: 57751 physical address: 61335 Value: 101
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Virtual Address: 42816 physical address: 19520 Value: 0
Virtual Address: 58219 physical address: 34155 Value: -38
Virtual Address: 37606 physical address: 21478 Value: 36
Virtual Address: 18426 physical address: 2554 Value: 17
Virtual Address: 21238 physical address: 37878 Value: 20
Virtual Address: 11983 physical address: 59855 Value: -77
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Virtual Address: 11036 physical address: 39964 Value: 0
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Virtual Address: 49847 physical address: 31671 Value: -83
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Virtual Address: 48065 physical address: 25793 Value: 0
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Virtual Address: 7736 physical address: 57912 Value: 0
Virtual Address: 31260 physical address: 23324 Value: 0
Virtual Address: 17071 physical address: 175 Value: -85
Virtual Address: 8940 physical address: 46572 Value: 0
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Virtual Address: 12107 physical address: 2635 Value: -46
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Page Faults = 244
Page Fault Rate = 0.244
TLB Hits = 54
TLB Hit Rate = 0.054