CS210 Computer Systems, Fall-2023
ps5 A

Instructions

You may work in teams of two for this assignment
For this problem set you will need to clone the assignment respository in the UNIX environment provided. The problems have you explore and evaluate the two provided binaries.

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Background

You are given two binaries: `mm1` and `mm2`. These two binaries carry out the same calculation on a $n \times n$ matrix of values. The programs are identical except that the core routine that does the work, `mm`, is implemented differently between the two binaries. To run the programs, the binaries take a single command line parameter. This parameter is the path of a matrix file, where a matrix file is an $n \times n \times 8$ byte binary file of values. Each element of the matrix is an 8 byte signed integer.

Setup

Both programs do a series of setup steps to "memory map" the specified file and calculate what the dimension of the matrix is (what is the value of n for the file). Recalling from Lecture 15,"Processes and Virtual Memory", operating systems can allow a process to create a virtual memory mapping that allows the data of a file to appear in the process's address space.

`https://jappavoo.github.io/UndertheCovers/lecturenotes/assembly/L15.html#virtual-memory-trick-2-memory-mapping-files`

This is precisely what the setup does. It memory maps a file that contains the values of a matrix so that its contents appear at a location in the virtual address space. This allows the rest of the program to access the matrix values via this virtual memory address.

The `mm` routine

Once the setup is done the values of the specified matrix file will be accessible at a particular address, and the program will execute the `mm` routine. The address of the matrix data will be in `rdi` and the dimension of the matrix will be in `rsi`. The `mm` routine calculates a single 8 byte integer value that it returns in the `rax` register when it is done.

Part of your task will be figuring out what the `mm` routine is calculating and how the binaries differ with respect to their `mm` routine.

Result

Once the `mm` routine returns, the calling code writes the value returned to standard output. So to save the output you can use redirection. To interpret the binary output as a decimal number in ascii you can use `od -t d8`

Matrix Data Files

We have created matrix files of various dimensions that you can use to explore the binaries. Each file has a url that you can use to get a copy. To get a copy into your UNIX environment you can use the `wget` command. Eg. for the `16x16.matrix` file you would use the command:

```
wget https://www.cs.bu.edu/courses/cs210/files/16x16.matrix
```

16x16.matrix : https://www.cs.bu.edu/courses/cs210/files/16x16.matrix A 16 by 16 matrix of random 8 byte integer values

32x32.matrix :: https://www.cs.bu.edu/courses/cs210/files/32x32.matrix A 32 by 32 matrix of random 8 byte integer values

64x64.matrix :: https://www.cs.bu.edu/courses/cs210/files/64x64.matrix A 64 by 64 matrix of random 8 byte integer values

128x128.matrix : https://www.cs.bu.edu/courses/cs210/files/128x128.matrix A 128 by 128 matrix of random 8 byte integer values

256x256.matrix : https://www.cs.bu.edu/courses/cs210/files/256x256.matrix A 256 by 256 matrix of random 8 byte integer values

512x512.matrix : https://www.cs.bu.edu/courses/cs210/files/512x512.matrix A 512 by 512 matrix of random 8 byte integer values

1024x1024.matrix : https://www.cs.bu.edu/courses/cs210/files/1024x1024.matrix A 1024 by 1024 matrix of random 8 byte integer values

2048x2048.matrix : https://www.cs.bu.edu/courses/cs210/files/2048x2048.matrix A 2048 by 2048 matrix of random 8 byte integer values

4096x4096.matrix : https://www.cs.bu.edu/courses/cs210/files/4096x4096.matrix A 4096 by 4096 matrix of random 8 byte integer values

8192x8192.matrix : https://www.cs.bu.edu/courses/cs210/files/8192x8192.matrix A 8192 by 8192 matrix of random 8 byte integer values

Remember, the sizes of these files in bytes are 8 times the number of elements. This means the largest file is 512 Megabytes big, so it might take a few minutes to get a copy of the larger files.

Running the binaries

To run the binaries you will need to issue an appropriate command line, where the command is the path of the binary and the argument is the path of a matrix file. For example, let's assume you have gotten a copy the matrix file `16x16.matrix` in your current working directory, then you can run `mm1` with it as follows:
```
./mm1 16x16.matrix
```
Of course you will want to redirect the output to a file.

The following is an example session of running both binaries on the `16x16.matrix` file.

```
$ pwd
/home/jovyan/ps5b
$ ls
16x16.matrix  mm1  mm2
```

```
$ ./mm1 16x16.matrix > out1
$ ./mm2 16x16.matrix > out2
$ ls
16x16.matrix  mm1  mm2  out1  out2
$ od -Ad -t d8 out1
0000000                  115
0000008
$ od -Ad -t d8 out2
0000000                  115
0000008
$
```

The Hunt

Given that we don't have source code, you will need to put your 210 puzzling skills to use. As always, `gdb` is your friend. Remember gdb can work with any executable binary. Even if you don't have the source code, you can still:

- set breakpoints
- single step instructions
- print values of registers
- examine memory
- disassemble opcodes in memory

In gdb, to start a process running with a command line argument you specify the argument to the 'run' command. Additionally to disassemble instructions you can use the examine command with the 'i' format.

Eg.

```
$ gdb mm1
...
Reading symbols from mm1...
(No debugging symbols found in mm1)
(gdb) set disassembly-flavor intel
(gdb) b _start
Breakpoint 1 at 0x401034
(gdb) run 16x16.matrix
Starting program: /home/jovyan/mm/mm1

Breakpoint 1, 0x0000000000401034 in _start ()
(gdb) x/20i _start
=> 0x401034 <_start>:   pop    rdi
```

```
   0x401035 <_start+1>: cmp    rdi,0x2
   0x401039 <_start+5>: jne    0x401151 <usageError>
   0x40103f <_start+11>:        pop    rdi
   0x401040 <_start+12>:        pop    rdi
   0x401041 <_start+13>:        call   0x4010b5 <mapFile>
   0x401046 <_start+18>:        mov    rsi,QWORD PTR ds:0x403068
   0x40104e <_start+26>:        shr    rsi,0x3
   0x401052 <_start+30>:        mov    QWORD PTR ds:0x403070,rsi
   0x40105a <_start+38>:        fild   QWORD PTR ds:0x403070
   0x401061 <_start+45>:        fsqrt
   0x401063 <_start+47>:        fistp  QWORD PTR ds:0x403070
   0x40106a <_start+54>:        mov    rsi,QWORD PTR ds:0x403070
   0x401072 <_start+62>:        mov    rdi,QWORD PTR ds:0x403060
   0x40107a <_start+70>:        call   0x401000 <mm>
   0x40107f <_start+75>:        mov    QWORD PTR ds:0x403078,rax
   0x401087 <_start+83>:        mov    rax,0x1
   0x40108e <_start+90>:        mov    rdi,0x1
   0x401095 <_start+97>:        mov    rsi,0x403078
   0x40109c <_start+104>:       mov    rdx,0x8
(gdb) x/10i mm
   0x401000 <mm>:       lea    rcx,[rsi*8+0x0]
   0x401008 <mm+8>:     xor    rdx,rdx
   0x40100b <mm+11>:    xor    r8,r8
   0x40100e <fori>:     cmp    rdx,rsi
   0x401011 <fori+3>:   jge    0x401030 <done>
   0x401013 <fori+5>:   xor    rax,rax
   0x401016 <forj>:     cmp    QWORD PTR [rdi+rax*8],0x0
   0x40101b <forj+5>:   js     0x401020 <neg>
   0x40101d <forj+7>:   inc    r8
   0x401020 <neg>:      inc    rax
(gdb)
```

Happy hunting!

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The Questions

The Setup

1. (1 point) Which section of the program's memory layout does _start in the setup code find the string of the matrix file path ?

   ____

2. (1 point) How many "function" calls are made prior to calling the `mm` routine? (Eg. the number of times the code executes the `call` instruction prior to calling the `mm` routine.)

   ____

3. (2 points) How many system calls are invoked in total if no errors were raised? (Note: both programs are identical with respect to the setup code. Additionally, make sure to also consider the code after the `mm` routine. You might want to set multiple breakpoints).

   ____

4. (3 points) What are the unique Linux system calls used **prior** to calling `mm`? (Your answer should identify the system call numbers and the Linux english system call routine name).

   ____

———————————————Notes———————————————

Note1: You can find a table of the system calls here : `https://filippo.io/linux-syscall-table/` and here `https://hackeradam.com/x86-64-linux-syscalls/`.

Note2: You don't need to fully understand what each system call does. You simply need to figure out what system calls are being made by the setup code. This is to give you an idea for how a "real" program uses system calls to create a memory mapping of a file.

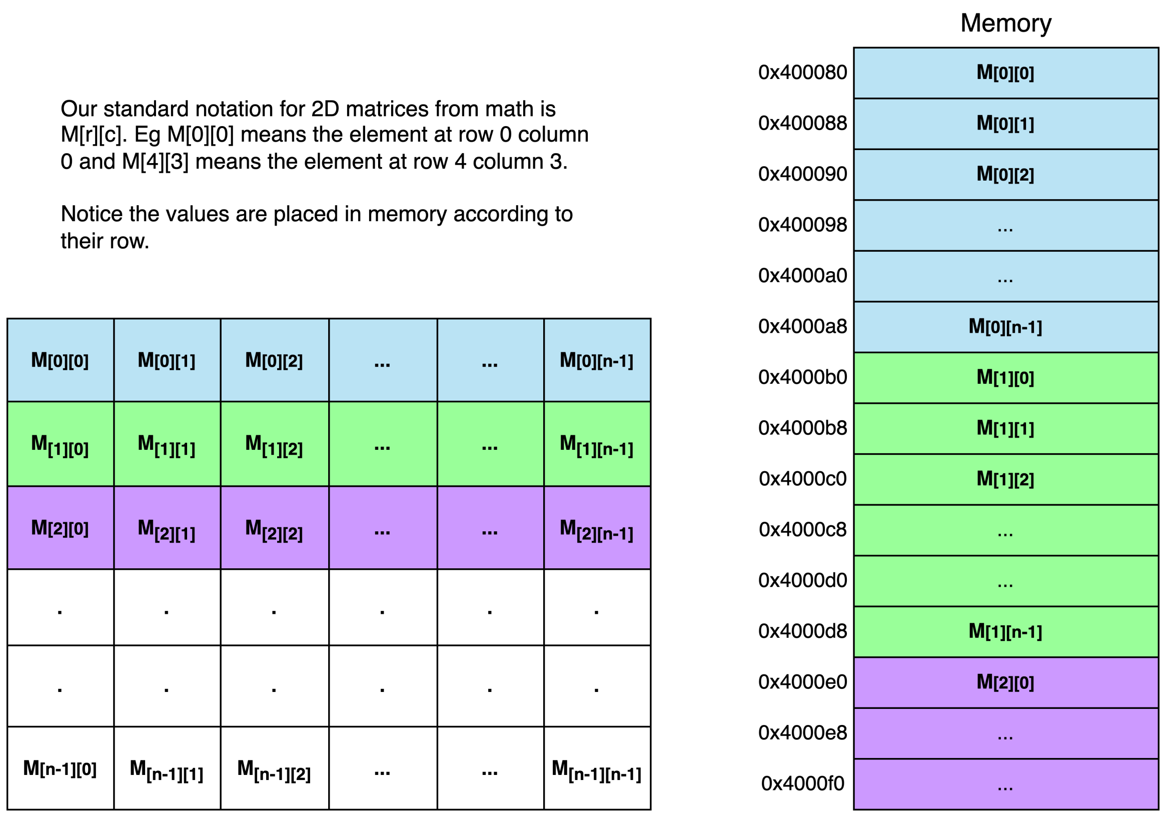
Note3: FYI: In the setup code you will find the following sequence of instructions:

```
    shr     rsi,0x3
    mov     QWORD PTR ds:0x403070, rsi
    fild    QWORD PTR ds:0x403070
    fsqrt
    fistp   QWORD PTR ds:0x403070
```

This code calculates the dimension of the matrix in elements. It starts with the size of the file in bytes in `rsi`. Using a shift right instruction, `shr`, it shifts the size in bytes by three bits to the right. This is the same as dividing by eight. At this point we have the size of the matrix in 8-byte elements in `rsi`. The remaining instructions calculate the square root of this value to determine the dimension of the matrix. Specifically, they use support that the INTEL processors have for doing more complex math using what are called floating point instructions and registers.

The Calculation

The standard way for representing a two dimensional array/matrix in memory is called row major ordering. In this ordering we place the elements of the first row of the array in memory first. We then place the second row of elements and so on. The following diagram illustrates row-major ordering.



Our standard notation for 2D matrices from math is M[r][c]. Eg M[0][0] means the element at row 0 column 0 and M[4][3] means the element at row 4 column 3.

Notice the values are placed in memory according to their row.

Our programs and data files assume row major ordering of the matrixes.

LEA

The code for the `mm` routine uses the INTEL `lea` instruction. LEA stands for Load Effective Address. This instruction can be used to do simple address calculations and load a register with the resulting address.

Here is the use of LEA that you will find in the `mm1` version of the `mm` routine

```
 lea    rcx,[rsi*8+0x0]
```

The effect of this instruction is to load `rcx` with the value of `rsi * 8`. Eg. if `rsi` has the value 2 then this instruction will set `rcx` with the value of `rsi * 2 = 2 * 8 = 16`.

For the `mm2` version of `mm` has and additional use of lea

```
 lea     r9,[rdi+rax*8]
```

In this case `r9` will be loaded with the result of the following calculation: `rdi + (rax * 8)` where we would substitute the current values in the `rdi` and `rax` registers. Eg. if `rdi = 12` and `rax = 3` the `r9` would be set to the result of `rdi + (rax * 8) = 12 + (3 * 8) = 36`.

5. (10 points) Using the `mm1` binary, figure out what the 'mm' routine is doing. This verison is composed of 17 instructions (Eg. `x/17i mm` will disassemble them in gdb, don't forget to `set disassembly-flavor intel`). Do not simply state the intructions that are being executed. Rather, provide pseudocode (`https://en.wikipedia.org/wiki/Pseudocode/`) that describes what the `mm` routine is doing. Then provide a short english summary of what the result represents. Do NOT include registers or assembly instructions in your pseudocode. Eg. The `mm` routine calculates the sum of all the elements of the matrix. Here is an example of pseudocode:

```
n : number of students
scores : is an n element array. Each element is the score for the ith student.

passes : count of the number of students that passed
failures: count of the number of students that failed

initialize passes to zero
initialize failures to zero

for (i=0; student < n; i++):
    if scores[i] a passing grade
        passes++
    else:
        failures++
```

Your answer should be provided in the space below.

6. (10 points) Using the `mm2` binary figure out how its verison of the `mm` routine works. This version is composed of 18 instructions. Again, provide pseudocode for the routine's operation and state how it differs from the `mm1` version.

   Your answer should be provided in the space below.

Measure the performance

Bash provides a builtin command called `time`. While it is not always the most accurate way of measuring the time it takes for a program to execute, it will be good enough for our purposes. If you are interested in the details see `man time`.

If you place the `time` command at the start of a command line, bash will give you a rough measure of how long your command line takes to execute. Eg.

```
$ ls
16x16.matrix  mm1  mm2  ps5a.pdf  README.md
$ time ./mm1 16x16.matrix > out1

real 0m0.001s
user 0m0.001s
sys 0m0.000s
$ time ./mm2 16x16.matrix > out2

real 0m0.001s
user 0m0.000s
sys 0m0.001s
$
```

Time reports three values. In our case the only one we will care about is the value called 'user'. This value attempts to measure how much time was spent executing our binary.

7. (10 points) Run each binary 10 times for each matrix file and create a line plot of the results, where the plot has one line for each program's results. The x-axis should be the matrix size of the matrix in bytes and the y-axis the user time in seconds. Remember the size of a matrix in bytes is the dimension squared times 8. This size should match the file size for the matrix. Eg. The size in bytes of the `16x16.matrix` is $16 \times 16 \times 8 = 2048$ bytes.

   For each program you will have 10 time measurements for each matrix size. On a single graph you should plot two lines, one for each program, where each line is composed of the results for the particular program. The points on the line should be the mean value of the 10 runs for a particular matrix size. You should also check these runs to understand how much the min and max times of the 10 runs vary.

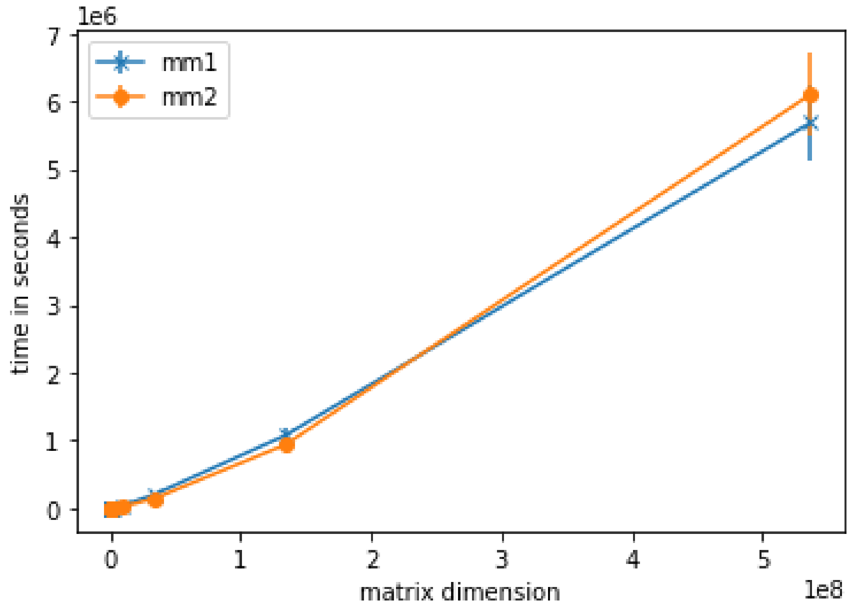
Notes

Note1: We recommend writing a script to automate gathering your data to save you time. We looped over each program (mm1 and mm2) as p and over each matrix size as s, then ran this loop to generate 10 times for every combination:

```
for ((i=0; i<10; i++)); do
    time ./$p ${s}x${s}.matrix > $p.$s.out
done 2>&1 | grep user | cut -c 8-11 > $p.$s.times
```

Note2: You can use any software you like to create the graph from the data you gather. Hand-drawn graphs will not be accepted. We included error bars in our graphs but these are optional.

The following is an example of how the graph should look with respect to formatting. **The data on the following graph is dummy data - do not expect your plots to look the same**



Please place a copy of your graph here.

8. (5 points) Provide a brief paragraph, below, that summarizes what the plot is telling you. Also, in words, how much do the max and min vary between runs. This should be no more than three to four sentences in length.

What's going on?

Use the following commands to gather a report on how the programs behave with respect to their memory accesses and the caches.

```
$ valgrind --tool=cachegrind ./mm1 8192x8192.matrix > mm1.8192.out

$ valgrind --tool=cachegrind ./mm2 8192x8192.matrix > mm2.8192.out
```

These commands will produce quite a bit of output. This tool runs the given program and analyzes its memory access behaviour. Do a little research on the terms you see in the report. Identify what seems to be different between the two programs.

9. (5 points) Write one short paragraph, in the space provided below, describing what you learned and why there might be a difference in performance. Please follow the notes on how to find the reason they are different.

Notes

Note1: "Valgrind" is a powerful tool that allows us to learn about how a program accesses memory. In particular we are using a sub-tool called "cachegrind" (`https://valgrind.org/docs/manual/cg-manual.html`). Cachegrind uses data it gathers about the memory accesses (what addresses and number of bytes the program loads and stores to) along with knowledge it has about the system's caches to provide us with insight on how a program behaves with respect to caching.

Note2: Remember what we observed in the in-class"role" play we did in Lecture 16 (`https://jappavoo.github.io/UndertheCovers/lecturenotes/assembly/L16.html`. Remember what we said regarding "cache hits" and "cache misses".

Note3: You may find the following useful (please note these are not academic articles and may have flaws):

- `https://www.extremetech.com/extreme/188776-how-l1-and-l2-cpu-caches-work-and-why-theyre-an-essential-part-of-modern-chips`
- `https://www.makeuseof.com/tag/what-is-cpu-cache/`
- `https://en.wikipedia.org/wiki/CPU_cache`