# CSCI 2021: Virtual Memory

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*Last Updated:*
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# Logistics

## Reading

B&O Ch 9 on Virtual Memory

## Lab / HW 13 on VirtMem

Both lead lecture a bit, TAs will introduce the `mmap()` function which is very useful for certain types of I/O

## Goals

- Logical and Physical Memory
- Virtual Memory System

## P4

- Delayed due to tuning performance problem, just about ready
- 3 Problems
  1. Optimize a Matrix Squaring Function
  2. Navigate a binary ELF file via `mmap()`
  3. ~~Complete a simple implementation of `malloc()`~~
- Due 01-May (Last day of classes)

# Announcements

None

# Exercise: Memories of Memory

**4 Logical Memory Regions**

1. ???
2. ???
3. ???
4. ???

What are they and how do C programs interact with them?

**Physical Memory Devices**

1. ???
2. ???
3. ???

...

Name some of these and describe their properties (e.g. size / speed / use)

Is there any correspondence between the Logical Regions and Physical Devices?

# **Answers**: Memories of Memory

## 4 Logical Memory Regions

1. Stack: function locals, sizes known at compile time
2. Heap: `malloc()` / `free()`, sizes determined at run time (e.g. load from file)
3. Globals: vars outside any function
4. Text: Assembly instructions in binary form (object code)

*Order above reflects typical appearance memory (stack at high address, text at lowest address)*

## Physical Memory Devices

1. Registers: specified in assembly instructions, SRAM, fastest memory possible, hundreds of bytes
2. Cache: SRAM, layered into L1, L2, L3, progressively larger and slower, on CPU so still fast, hundreds of KB to a few MB
3. Main Memory: DRAM, separate chips from CPU, dozens of GB
4. SSD (Solid State Drive): Hundreds of GB to a few TB, permanent storage via "electron packing", limited write lifetime
5. HDD (Hard Disk Drive): Hundreds of GB to a few TB, permanent storage via magnetic medium, unlimited write lifetime, very slow compared to others
6. Tape Drive: Easily dozens to hundreds of TB, permanent storage via magnetic medium, unlimited write lifetime but impractical to write repeatedly, used mainly for backups

Is there any correspondence between the Logical Regions and Physical Devices? *In a word: No.*

# Exercise: Potential Conflicts in Memory

- Running multiple programs gets interesting particularly if they both reference the *same memory location*, e.g. address 8192

```
PROGRAM 1                    PROGRAM 2
...                          ...
## load global from #8192    ## add to global at #8192
movq 8192, %rax              addl %esi, 8192
...                          ...
```

- What conflict exists between these programs?
- What are possible solutions to this conflict?

# **Answers**: Potential Conflicts in Memory

- Both programs use address #8192, behavior depends on order that instructions are interleaved between them

```
ORDER A: Program 1 loads first           ORDER B: Program 2 adds first
---------------------------------        -----------------------------------
PROGRAM 1          PROGRAM 2             PROGRAM 1          PROGRAM 2
movq 8192, %rax    ...                   ...                addl %esi, 8192
...                addl %esi, 8192       movq 8192, %rax    ...
```

- **Solution 1:** Never let Programs 1 and 2 run together (bleck!)
- **Solution 2:** Translate every memory address/access in every program while it runs

As wild as it sounds, most modern systems use memory address translation schemes called **Virtual Memory** (Solution 2) due to its many powerful features

# Paged Memory

- Physical devices divide memory into chunks called **pages**
- Common page size supported by many OS's (Linux) and hardware is 4KB = 4096 bytes, can be larger with OS config
- CPU models use some # of bits for **Virtual Addresses**

```
> cat /proc/cpuinfo
vendor_id       : GenuineIntel
cpu family      : 6
model           : 79
model name      : Intel(R) Xeon(R) CPU E5-1620 v4 @ 3.50GHz
...
address sizes : 46 bits physical, 48 bits virtual
                                  ^^^^^^^^
```

- Example of address with page number and offset labelled

```
   xxxxPagenumbrOff    : 48 bits used
 0x00007ffa0997a428    : 64 bit address
   |   |         |
   |   |         +-> Offset 0x428 within page, 12 bits
   |   +-> Page number 0x7ffa0997a, 36 bits
   +-> Constant bits, not used by processor
```

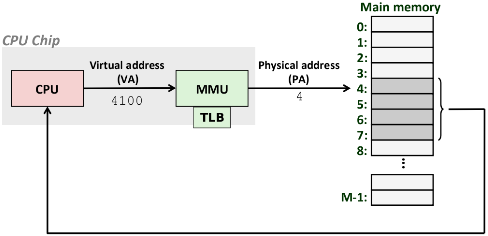
# Translation happens at the Page Level

- Within a page, addresses are sequential
- Between pages, may be non-sequential

```
Page Table:
|------------------+------+-----------------------|
| Virtual Page Num | Size | Physical Page Num     |
|------------------+------+-----------------------|
| 00007ffa0997a000 | 4K   | RAM: 0000564955aa1000 |
| 00007ffa0997b000 | 4K   | RAM: 0000321e46937000 |
| ...              |      | ...                   |
|------------------+------+-----------------------|

Address Space From Page Table:
|------------------+-------------+------------------|
| Virtual Address  | Page Offset | Physical Address |
|------------------+-------------+------------------|
| 00007ffa0997a000 |           0 | 0000564955aa1000 |
| 00007ffa0997a001 |           1 | 0000564955aa1001 |
| 00007ffa0997a002 |           2 | 0000564955aa1002 |
| ...              |             | ...              |
| 00007ffa0997afff |        4095 | 0000564955aa1fff |
|------------------+-------------+------------------|
| 00007ffa0997b000 |           0 | 0000321e46937000 |
| 00007ffa0997b001 |           1 | 0000321e46937001 |
| ...              |             | ...              |
|------------------+-------------+------------------|
```

# Addresses Translation Hardware

- Translation must be **FAST** so usually involves hardware
- **MMU (Memory Manager Unit)** is a hardware element specifically designed for address translation
- Usually contains a special cache, **TLB (Translation Lookaside Buffer)**, which stores recently translated addresses

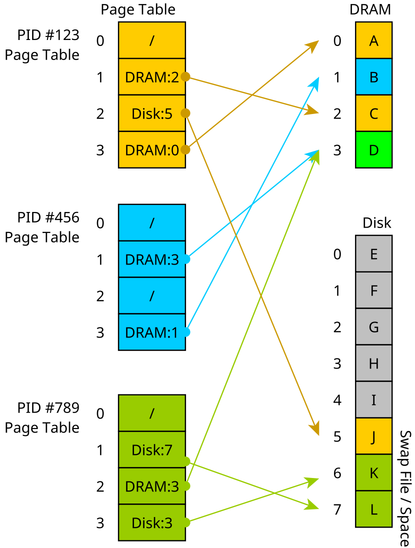



- OS Kernel interacts with MMU
- Provides location of the **Page Table**, data structure relating Virtual/Physical Addresses
- **Page Fault** : MMU couldn't map Virtual to Physical page, runs a Kernel routine to handle the fault

# Exercise: Translating Virtual Addresses

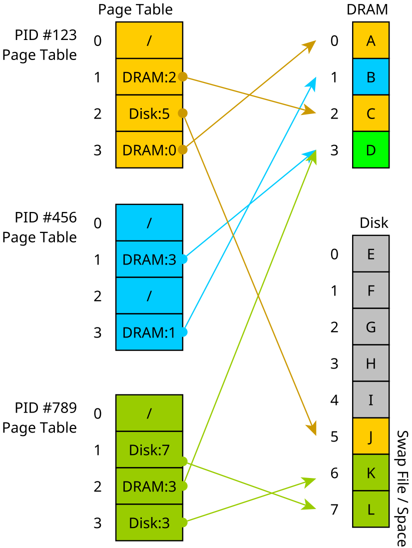
Nearby diagram illustrates relation of Virtual Pages to Physical Pages

1. How many page tables are there?
2. Where can a page table entry refer to?
3. Count the number of Virtual pages, compare to the number of physical pages - which his larger?
4. What happens if PID #123 accesses its Virtual Page #2
5. What happens if PID #456 accesses its Virtual Page #2



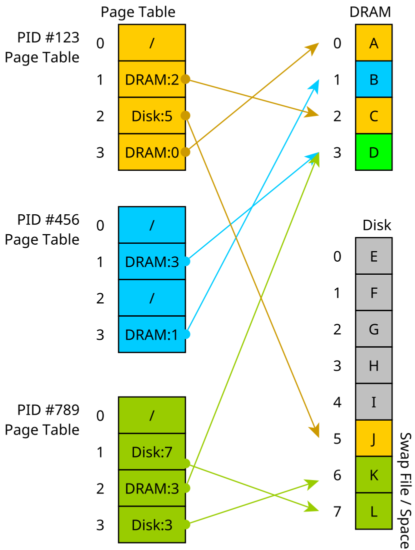
# Translating Virtual Addresses 1/2

- On using a Virtual Memory address, MMU will search TLB for physical DRAM address,
- If found in TLB, Hit, use physical DRAM address
- If not found, MMU will search Page Table, if found and in DRAM, cache in TLB
- Else Miss = **Page fault**, OS decides..
    1. Page is swapped to Disk, move to DRAM, potentially evicting another page
    2. Page not in page table = Segmentation Fault



# Translating Virtual Addresses 2/2

- Each process has its own page table, OS maintains mapping of Virtual to Physical addresses
- Processes "compete" for RAM
- OS gives each process impression it owns all of RAM
- OS may not have enough memory to back up all or even 1 process
- Disk used to supplement ram as **Swap Space**
- **Thrashing** may occur when too many processes want too much RAM, "constantly swapping"



# Trade-offs of Address Translation

## Wins of Virtual Memory

1. Avoids memory Conflicts where separate programs each use the same memory address
2. Programs can be compiled to assume they will have all memory to themselves
3. OS can make decisions about DRAM use and set policies for security and efficiency (next slide)

## Losses of Virtual Memory

1. Address translation is not constant O(1), has an impact on performance of real algorithms*
2. Requires special hardware to make translation fast enough: MMU/TLB
3. Not needed if only a single program is running on a machine

Wins outweigh Losses in most systems so Virtual Memory is used widely, a *great idea* in CS

*See On a Model of Virtual Address Translation (2015)

# The Many Other Advantages of Virtual Memory

1. Swap Space: System can project larger total memory than available DRAM by using Disk Space, DRAM is a "cache" for larger disk space, Swap program memory between DRAM+Disk as it is used
2. Security: Translation allows OS to check memory addresses for validity, segfault on out-of bounds access
3. Debugging: Valgrind checks addresses for validity
4. Sharing Data: Processes can share data with one another; request OS to map virtual addresses to same physical addresses
5. **Sharing Libraries**: Can share same program text between programs by mapping address space to same shared library
6. **Convenient I/O**: Map internal OS data structures for files to virtual addresses to make working with files free of read()/write()

# Virtual Memory and `mmap()`

- Normally programs interact indirectly with Virtual Memory system
  - Stack/Heap/Globals/Text are mapped automatically to regions in Virtual Memory System
  - Maps are adjusted as Stack/Heap Grow/Shrink
- `mmap()` / `munmap()` directly manipulate page tables
  - `mmap()` creates new entries in page table
  - `munmap()` deletes entries in the page table
  - Can map arbitrary or specific addresses into memory
- `mmap()` is used to initially set up Stack / Heap / Globals / Text when a program is loaded by the program loader
- While a program is running can also use `mmap()` to interact with virtual memory
- A convenient way to do File I/O via **Memory Mapped Files**

# Exercise: Printing Contents of file

Examine the two programs below which print the contents of a file

- Identify differences between them
- Which has a higher memory requirement?

```c
// print_file.c
int main(int argc, char *argv[]){
  FILE *fin = fopen(argv[1], "r");
  char inbuf[256];
  while(1){
    int nread =
      fread(inbuf, sizeof(char),
            256, fin);
    if(nread == 0){
      break;
    }
    for(int i=0; i<nread; i++){
      printf("%c",inbuf[i]);
    }
  }

  fclose(fin);
  return 0;
}
```

```c
// mmap_print_file.c
int main(int argc, char *argv[]){
  int fd = open(argv[1], O_RDONLY);

  struct stat stat_buf;
  fstat(fd, &stat_buf);
  int size = stat_buf.st_size;

  char *file_chars =
    mmap(NULL, size,
         PROT_READ, MAP_SHARED,
         fd, 0);

  for(int i=0; i<size; i++){
    printf("%c",file_chars[i]);
  }
  printf("\n");

  munmap(file_chars, size);
  close(fd);
  return 0;
}
```

## **Answers**: Printing Contents of file

1. Write a simple program to print all characters in a file. What are key features of this program?
   - Open file
   - Read up to 256 characters into memory using `fread()/fscanf()`
   - Print those characters with `printf()`
   - Read more characters and print
   - Stop when end of file is reached
   - Close file
2. Examine `mmap_print_file.c`: does it contain all of these key features? Which ones are missing?
   - Missing the `fread()/fscanf()` portion
   - Uses `mmap()` to get **direct access** to the bytes of the file
   - Treat bytes as an array of characters and print them directly

# mmap(): Mapping Addresses is Amazing

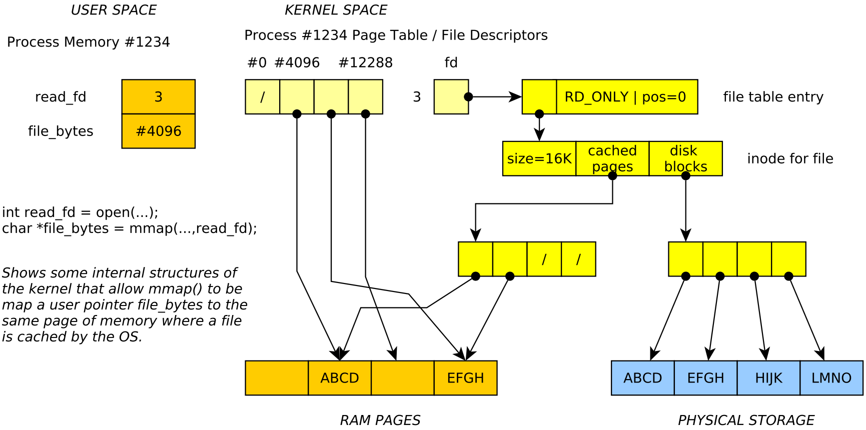
- `ptr = mmap(NULL, size,...,fd,0)` arranges backing entity of `fd` to be mapped to be mapped to `ptr`
- `fd` often a file opened with `open()` system call

```c
int fd = open("gettysburg.txt", O_RDONLY);
// open file to get file descriptor

char *file_chars = mmap(NULL, size, PROT_READ, MAP_SHARED,
                        fd, 0);
// call mmap to get a direct pointer to the bytes in file associated
// with fd; NULL indicates don't care what address is returned;
// specify file size, read only, allow sharing, offset 0

printf("%c",file_chars[0]);                // print 0th file char
printf("%c",file_chars[5]);                // print 5th file char
```

# OS usually Caches Files in RAM

- For efficiency, part of files are stored in RAM by the OS
- OS manages internal data structures to track which parts of a file are in RAM, whether they need to be written to disk
- `mmap()` alters a process Page Table to translate addresses to the cached file page
- OS tracks whether page is changed, either by file write or `mmap()` manipulation
- Automatically writes back to disk when needed
- Changes by one process to cached file page will be seen by other processes
- **See diagram on next slide**

# Diagram of Kernel Structures for `mmap()`




```
int read_fd = open(...);
char *file_bytes = mmap(...,read_fd);
```

*Shows some internal structures of the kernel that allow mmap() to be map a user pointer file_bytes to the same page of memory where a file is cached by the OS.*

# Changing Files

- mmap() exposes several capabilities from the OS

```c
char *file_chars =
  mmap(NULL, size,
       PROT_READ | PROT_WRITE, // map allowing read + write
       MAP_SHARED,             // share changes with original file
       fd, 0);                 // file to map + offset from start
```

- Assign new value to memory, OS writes changes into the file
- **Example**: mmap_tr.c to transform one character to another

# Mapping things that aren't characters

`mmap()` just gives a pointer: can assert type of what it points at

- Example `int *`: treat file as array of binary ints
- Notice changing array will write to file

```c
// mmap_increment.c: demonstrate working with mmap()'d binary data

int fd = open("binary_nums.dat", O_RDWR);
// open file descriptor, like a FILE *

int *file_ints = mmap(NULL, size, PROT_READ | PROT_WRITE, MAP_SHARED, fd, 0);
// get pointer to file bytes through mmap,
// treat as array of binary ints

int len = size / sizeof(int);
// how many ints in file

for(int i=0; i<len; i++){
  printf("%d\n",file_ints[i]);  // print all ints
}

for(int i=0; i<len; i++){
  file_ints[i] += 1;  // increment each file int, writes back to disk
}
```

# `mmap()` Compared to Traditional `fread()`/`fwrite()` I/O

## Advantages of `mmap()`

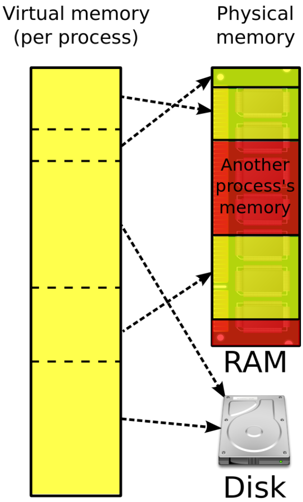
- Avoid following cycle
  - `fread()`/`fscanf()` file contents into memory
  - Analyze/Change data
  - `fwrite()`/`fscanf()` write memory back into file
- Saves memory and time
- Many Linux mechanisms backed by `mmap()` like processes sharing memory

## Drawbacks of `mmap()`

- Always maps **pages** of memory: multiple of 4096b (4K)
- For small maps, lots of wasted space
- Cannot change size of files with `mmap()`: must used `fwrite()` to extend or other calls to shrink
- No bounds checking, just like everything else in C

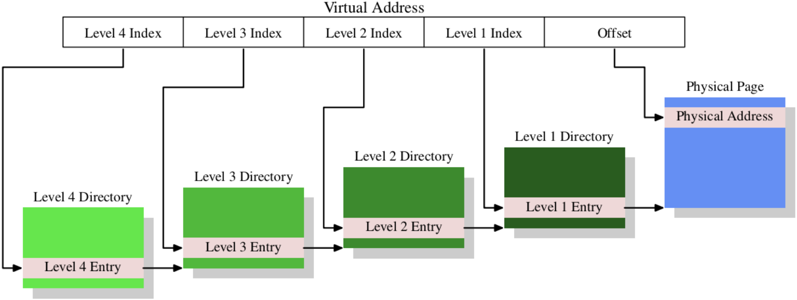
# Page Table Size

- Page tables map a virtual page to physical location
- Page tables maintained by operating system in Kernel Memory
- A **direct page** table has one entry per virtual page
- Each page is $4K = 2^{12}$ bytes, so 12 bits for offset of address into a page
- Virtual Address Space is $2^{48}$ bytes
- So, $2^{36}$ virtual pages mapped in the page table...
  - 68,719,476,736 pages
  - At 8 bytes per page entry...
  - 1 Terabyte for a page table




*How big does the page table mapping virtual to physical pages need to be?*

# Page "Tables" are Multi-Level Sparse Trees

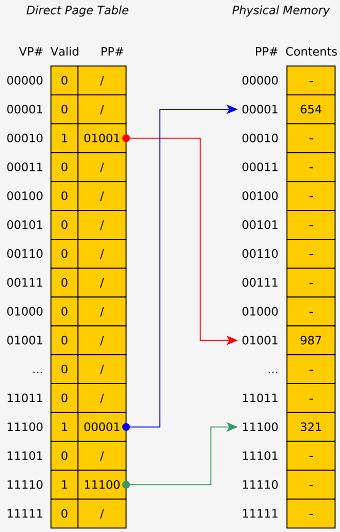



"What Every Programmer Should Know About Memory" by Ulrich Drepper, Red Hat, Inc.

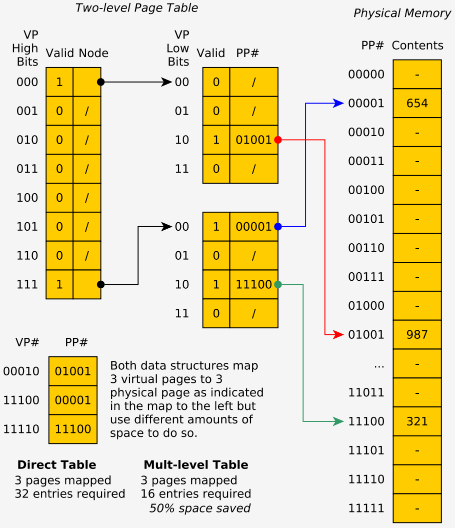
- Fix this absurdity with **multi-level page tables**: a sparse tree
- Virtual address divided into sections which indicate which PTE to access at different table levels
- 3-4 level page table is common in modern architectures
- Programs typically use only small amounts of virtual memory: most entries in different levels are `NULL` (not mapped) leading to much smaller page tables than a direct (array) map

# Direct Page Table vs Sparse Tree Page Table

## Direct Page Table: Array-Like, 5-bit addresses




## Two-level Page Table: Sparse Tree, 5-bit addresses




| VP# | PP# |
|---|---|
| 00010 | 01001 |
| 11100 | 00001 |
| 11110 | 11100 |

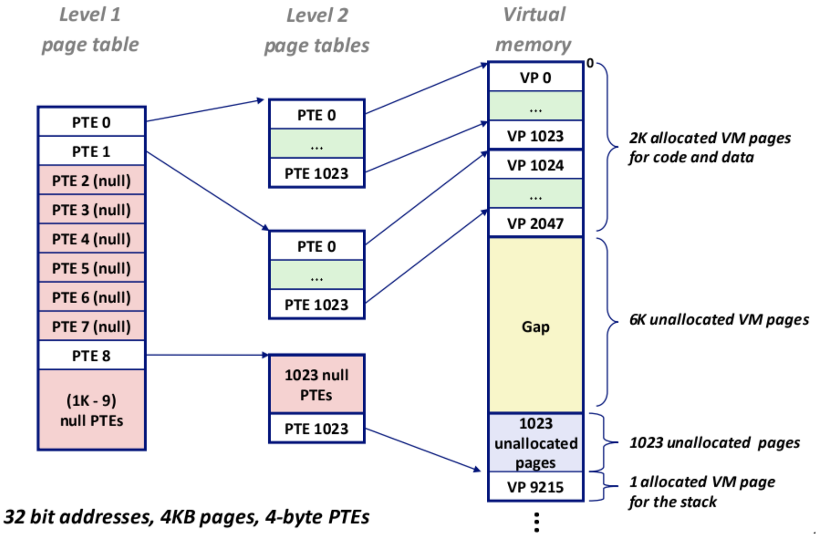
Both data structures map 3 virtual pages to 3 physical page as indicated in the map to the left but use different amounts of space to do so.

**Direct Table**
3 pages mapped
32 entries required

**Mult-level Table**
3 pages mapped
16 entries required
*50% space saved*

# Textbook Example: Two-level Page Table

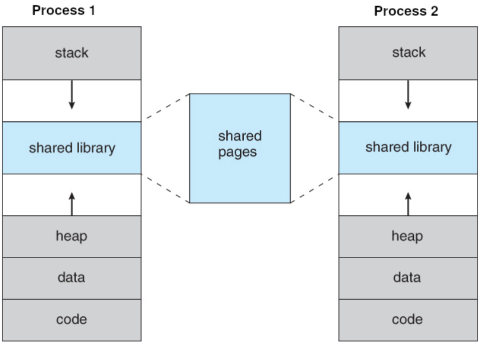
Space savings gained via `NULL` portions of the page table/tree




Source: Bryant/O'Hallaron, CSAPP 3rd Ed

# Virtual Memory Enables Shared Libraries: `*.so` Files

- Many programs need to use `malloc()`, `printf()`, `fopen()`, `etc.`
- Rather than each program having its own copy, modern systems use **Shared Objects** and **Shared Libraries**




Source: John T. Bell Operating Systems Course Notes

- Example: `libc.so` is the C Library which contains Code/Text for `malloc()`, `printf()`, `fopen()`, `etc.`, 1-2MB of code
- One copy of `libc.so` exists in DRAM
- Many programs “share it” via Page Table mappings in Virtual Memory, reduces overall memory required

# pmap: show virtual address space of running process

```
> ./memory_parts
0x5575555a71e9 : main()
0x5575555aa0c0 : global_arr
0x557555b482a0 : heap_arr
0x600000000000 : mmap'd block1
0x600000001000 : mmap'd block2
0x7f2244dc4000 : mmap'd file
0x7ffff0133b70 : stack_arr
my pid is 496605
press any key to continue
```

- Determine **process id** of running program
- pmap reports its virtual address space
- Reports features of each mapped page range such as size, permissions, possibly logical area

```
> pmap 496605
496605:   ./memory_parts
00005575555a6000    4K r---- memory_parts
00005575555a7000    4K r-x-- memory_parts TEXT
00005575555a8000    4K r---- memory_parts
00005575555a9000    4K r---- memory_parts
00005575555aa000    4K rw--- memory_parts GLOBALS
00005575555ab000    4K rw---   [ anon ]
0000557555b48000  132K rw---   [ anon ]   HEAP
0000600000000000    8K rw---   [ anon ]
00007f2244bca000    8K rw---   [ anon ]
00007f2244bcc000  152K r---- libc-2.32.so
00007f2244bf2000 1332K r-x-- libc-2.32.so
00007f2244d3f000  304K r---- libc-2.32.so
00007f2244d8e000   12K rw--- libc-2.32.so
00007f2244d91000   24K rw---   [ anon ]
00007f2244dc4000    4K r---- gettysburg.txt
00007f2244dc5000    8K r---- ld-2.32.so
00007f2244dc7000  132K r-x-- ld-2.32.so
00007f2244de8000   36K r---- ld-2.32.so
00007f2244df2000    8K rw--- ld-2.32.so
00007ffff0114000  132K rw---   [ stack ]   STACK
00007ffff014d000   12K r----   [ anon ]
 total            2352K
```

# Memory Protection

- Output of `pmap` indicates another feature of virtual memory: **protection**
- OS marks pages of memory with Read/Write/Execute/Share permissions like files
- Attempt to violate these and get segmentation violations (segfault)
- Ex: Executable page (instructions) usually marked as `r-x`: no write permission.
- Ensures program don't accidentally write over their instructions and change them
- Ex: By default, pages are not shared (no `'s'` permission) but can make it so with the right calls

# Physical Locations of Pages

- UMN Kernel Object Student group members put together a `vpmap` program to print virtual to physical page locations on Linux
- Requires Administrator rights to use as physical locations are OS business
- https://github.com/UMN-Kernel-Object/virtmem

# vpmap Sample Output

```
###############################################################################
## vpmap shows Virtual Page Number (vpn) followed by Page Frame Number (pfn)
$> sudo ./vpmap 64814
[sudo] password for sudo:
Process 64814
55d11d5c7000-55d11d5c8000 r--p 00000000 fe:01 5119082       /virtmem/memory_parts
| vpn: 55d11d5c7  present  pfn: 2a9314  dirty: 1  exclu: 1  wprot: 0  isfile: 1

55d11d5c8000-55d11d5c9000 r-xp 00001000 fe:01 5119082       /virtmem/memory_parts
| vpn: 55d11d5c8  present  pfn: 1fddc6  dirty: 1  exclu: 1  wprot: 0  isfile: 1
...

55d11e7f0000-55d11e811000 rw-p 00000000 00:00 0             [heap]
| vpn: 55d11e7f0  present  pfn: 440dc0  dirty: 1  exclu: 1  wprot: 0  isfile: 0
| vpn: 55d11e7f1
| vpn: 55d11e7f2
| vpn: 55d11e7f3  ## unmapped pages (promised but not delivered)
...

7fc074a41000-7fc074a63000 r--p 00000000 fe:01 19139877      /usr/lib/libc.so.6
| vpn: 7fc074a41  present  pfn: 22b275  dirty: 1  exclu: 0  wprot: 0  isfile: 1
| vpn: 7fc074a42  present  pfn: 3b677d  dirty: 1  exclu: 0  wprot: 0  isfile: 1
...

7fc074a63000-7fc074bbd000 r-xp 00022000 fe:01 19139877      /usr/lib/libc.so.6
| vpn: 7fc074a63  present  pfn: 3ac617  dirty: 1  exclu: 0  wprot: 0  isfile: 1
...
| vpn: 7fc074a6b  present  pfn: 3ac61f  dirty: 1  exclu: 0  wprot: 0  isfile: 1
| vpn: 7fc074a6c  present  pfn: 22b200  dirty: 1  exclu: 0  wprot: 0  isfile: 1
| vpn: 7fc074a6d  present  pfn: 22b201  dirty: 1  exclu: 0  wprot: 0  isfile: 1

7ffd46c53000-7ffd46c74000 rw-p 00000000 00:00 0             [stack]
...               ## Highest addresses in stack in use but no physical pages
| vpn: 7ffd46c6f  ## yet assigned to lower pages
| vpn: 7ffd46c70
| vpn: 7ffd46c71  present  pfn: 403934  dirty: 1  exclu: 1  wprot: 0  isfile: 0
| vpn: 7ffd46c72  present  pfn: 21b607  dirty: 1  exclu: 1  wprot: 0  isfile: 0
| vpn: 7ffd46c73  present  pfn: 18ef8e  dirty: 1  exclu: 1  wprot: 0  isfile: 0
...
```

# Exercise: Quick Review

1. While running a program, memory address #1024 always refers to a physical location in DRAM (True/False: why?)
2. Two programs which both use the address #1024 cannot be simultaneously run (True/False: why?)
3. What do MMU and TLB stand for and what do they do?
4. What is a memory page? How big is it usually?
5. What is a Page Table and what is it good for?

# **Answers:** Quick Review

1. While running a program, memory address #1024 always refers to a physical location in DRAM (True/False: why?)
   - False: #1024 is usually a **virtual address** which is translated by the OS/Hardware to a physical location which *may* be in DRAM but may instead be paged out to disk
2. Two programs which both use the address #1024 cannot be simultaneously run (True/False: why?)
   - False: The OS/Hardware will likely translate these identical virtual addresses to **different physical locations** so that the programs doe not clobber each other's data
3. What do MMU and TLB stand for and what do they do?
   - Memory Management Unit: a piece of hardware involved in translating Virtual Addresses to Physical Addresses/Locations
   - Translation Lookaside Buffer: a special cache used by the MMU to make address translation **fast**
4. What is a memory page? How big is it usually?
   - A discrete hunk of memory usually 4Kb (4096 bytes) big
5. What is a Page Table and what is it good for?
   - A table maintained by the operating system that is used to map Virtual Addresses to Physical addresses for each page

# Additional Review Questions

- What OS data structure facilitates the Virtual Memory system? What kind of data structure is it?
- What does `pmap` do?
- What does the `mmap()` system call do that enables easier I/O? How does this look in a C program?
- Describe at least 3 benefits a Virtual Memory system provides to a computing system