CSCI 2021: Virtual Memory

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Logistics

Reading Bryant/O'Hallaron

- Ch 9: Virtual Memory
- Ch 7: Linking (next)

Goals

- Address Spaces, Translation, Paged Memory
- `mmap()`, Sharing Pages

P5: Questions?

- Problem 1: (50pts) Binary ELF File Parsing
- Problem 2: OPTIONAL MAKEUP CREDIT (50pts) Malloc Implementation

Date	Event
12/07 Mon	Virtual Mem 1/2
12/09 Wed	Virtual Mem 2/2
	Lab 14 VirtMem
12/11 Fri	ELF Files/Linking 1/2
12/14 Mon	Obj Code/Linking 2/2
12/16 Wed	Last Lecture, Review
	Lab 15 Review
	P5 Due
12/19 Sat	Sec 001 (1:25pm)
	Final Exam at 8:00am
12/21 Mon	Sec 010 (3:35pm)
	Final Exam 10:30am

NOTE: **Check your section number** before reporting a Final Exam conflict. In CSCI 2041 at 1:25pm? You are in CSCI 2021 010 at 3:35pm

The View of Memory Addresses so Far

- Every **process** (running program) has some memory, divided into roughly 4 areas (which are...?)
- Reference different data/variables through their addresses
- If only a single program could run at time, no trouble: load program into memory and go
- Running multiple programs gets interesting particularly if they both reference the *same memory location*, e.g. address 1024

```
PROGRAM 1                      PROGRAM 2
...                            ...
## load global from #1024      ## add to global at #1024
movq 1024, %rax                addl %esi, 1024
...                            ...
```

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

Answers: The View of Memory Addresses so Far

- 4 areas of memory are roughly: (1) Stack (2) Heap (3) Globals (4) Text/Instructions
- Both programs use physical address #1024, behavior depends on order that instructions are interleaved between them

```
ORDER A: Program 1 loads first
---------------------------------
PROGRAM 1          PROGRAM 2
movq 1024, %rax    ...
...                addl %esi, 1024
```

```
ORDER B: Program 2 adds first
-----------------------------------
PROGRAM 1          PROGRAM 2
...                addl %esi, 1024
movq 1024, %rax    ...
```

- **Solution 1:** Never let Programs 1 and 2 run together (bleck!)
- **Solution 2:** Translate every memory address in every program on **loading** it, run with physical addresses
  - Tough/impossible as not all addresses are known at compile/load time...
- **Solution 3:** Translate every memory address/access in every program while it runs (!!!)

Paged Memory

- Physical memory is divided into hunks called **pages**
- Common page size supported by many OS's (Linux) and hardware is 4KB $=$ 4096 bytes
- Memory is usually byte addressable so need offset into page
- 12 bits for offset into page
- $A - 12$ bits for **page number** where A is the address size in bits
- Usually A is NOT 64-bits

```
> 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
```

- Leaves one with something like $48 - 12 = 36$ bits for page #s
- Means a **page table** may have up to 2^{36} entries (!)

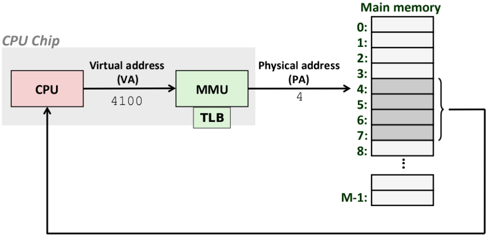
Translation happens at the Page Level

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

```
Page Table:
|-----------------+------+----------------------|
| Virtual Page    | Size | Physical Page        |
|-----------------+------+----------------------|
| 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

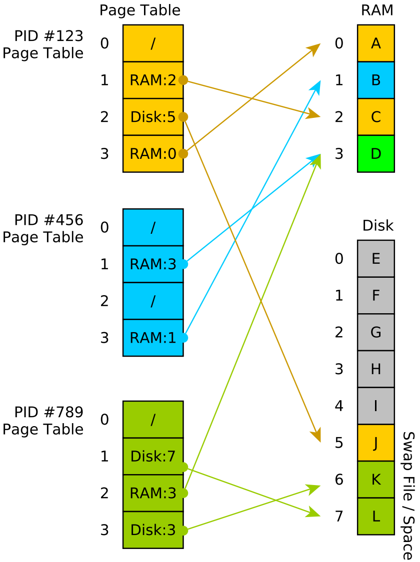
- Translation must be **FAST** so usually involves hardware
- **MMU (Memory Manager Unit)** is a hardware element specifically designed for address translation
- Usually contains a special cache, **TLB (Translation Lookaside Buffer)**, which stores recently translated addresses



- 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

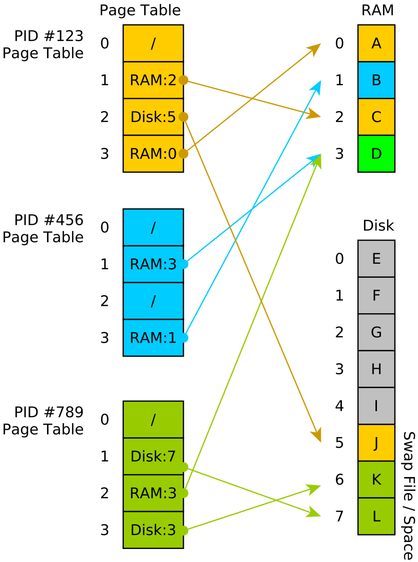
Translating Virtual Addresses 1/2

- 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 searches 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

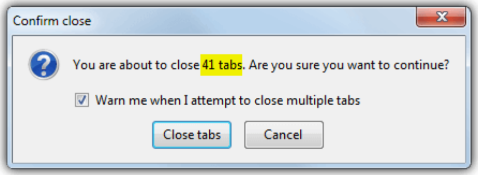
- Each process has its own page table, OS maintains mapping of Virtual to Physical addresses
- Processes "compete" for RAM
- OS gives each process impression it owns all of RAM
- OS may not have enough memory to back up all or even 1 process
- Disk used to supplement ram as **Swap Space**
- **Thrashing**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



Virtual Memory Caches Physical Memory

- Virtual Memory allows illusion of 2^{48} bytes (hundreds of TBs) of memory when physical memory might only be 2^{30} to 2^{36} (few to hundreds of GBs)
- Disk space is used for space beyond main memory
- Pages that are frequently used stay in DRAM (swapped in)
- Pages that haven't been used for a while end up on disk (**swapped out**)

- DRAM (physical memory) is then thought of as a cache for Virtual Memory which can be as big as disk space allows



Like when I was writing my composition paper but then got distracted and opened 41 Youtube tabs and when I wanted to write again it took like 5 minutes for Word to load back up because it was swapped out.

Trade-offs of Address Translation

Wins of Virtual Memory

1. Avoids processes each referencing the same address, conflicting
2. Allows each Process (running program) to believe it has entire memory to itself
3. Gives OS tons of flexibility and control over memory layout
   - Present a continuous Virtual chunk which is spread out in Physical memory
   - Use Disk Space as memory
   - Check for out of bounds memory references

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 often outweigh Losses so Virtual Memory is used in *most* modern computing systems, a "great idea" in CS

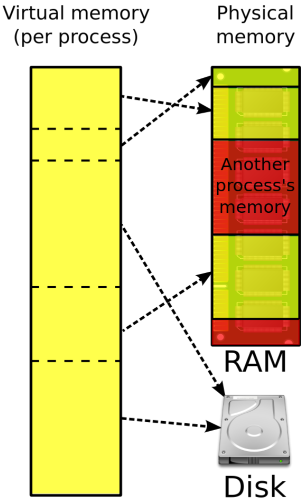
*See On a Model of Virtual Address Translation (2015)

The Many Other Advantages of Virtual Memory

- Caching: Seen that VirtMem can treat main memory as a cache for larger memory
- Security: Translation allows OS to check memory addresses for validity
- Debugging: Similar to above, Valgrind checks addresses for validity
- Sharing Data: Processes can share data with one another by requesting OS to map virtual addresses to same physical addresses
- Sharing Libraries: Can share same program text between programs by mapping address space to same shared library
- Convenient I/O: Map internal OS data structures for files to virtual addresses to make working with files free of read()/write()

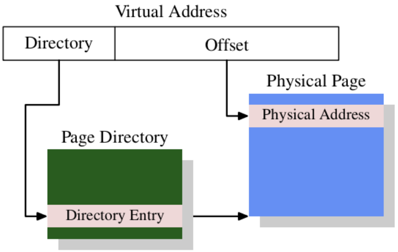
Page Table Size

- Page tables map a virtual page to physical location
- Page tables Maintained by **Operating System** in Kernel Memory for every running Process
- 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
- **How many** pages of virtual memory are there?
  - How many bits specify a virtual page number?
  - How big is the page table? Is this a problem?



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

Answers: Page Table Size



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

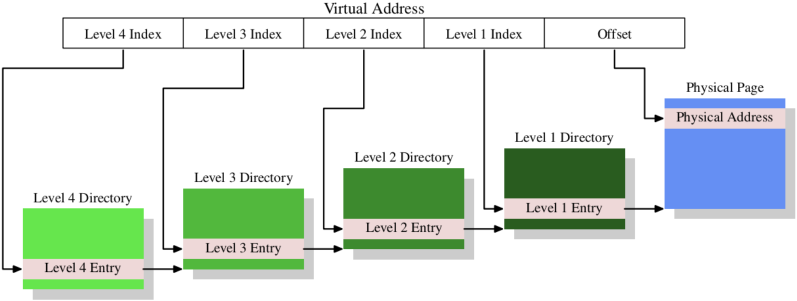
```
  48 bits for virtual address
- 12 bits for offset
--------------------
  36 bits for virtual page number
```

So, 2^{36} virtual pages...

- Every page table entry needs at least 8 bytes for a physical address
- Plus maybe 8 bytes for other stuff (on disk, permissions)
- 16 bytes per PTE $= 2^4$ bytes $\times$ 2^{36} PTEs $= ..$
- 2^{40} bytes $=$ 1 Terabyte of space for the Page Table (!!!)

Clearly a system with 4-32 GB (Gigabytes) of main memory can't use a Direct Mapped page table

Page Tables Usually Have Multiple Levels

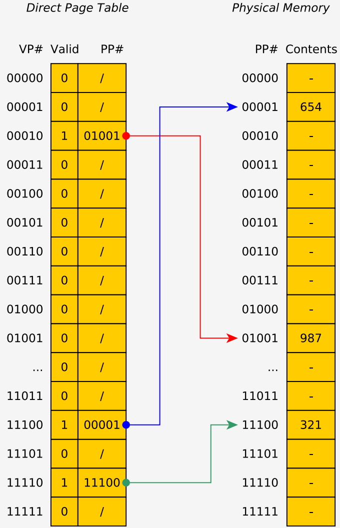


"What Every Programmer Should Know About Memory" by Ulrich Drepper, Red Hat, Inc.

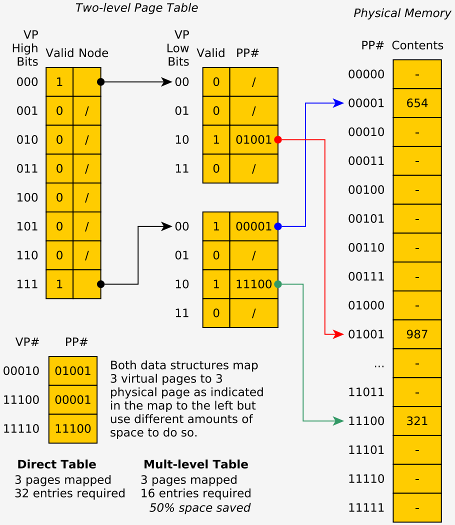
- Fix this absurdity with **multi-level page tables**: a sparse tree
- Virtual address divided into sections which indicate which PTE to access at different table levels
- 3-4 level page table is common in modern architectures
- Programs typically use only small amounts of virtual memory: most entries 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



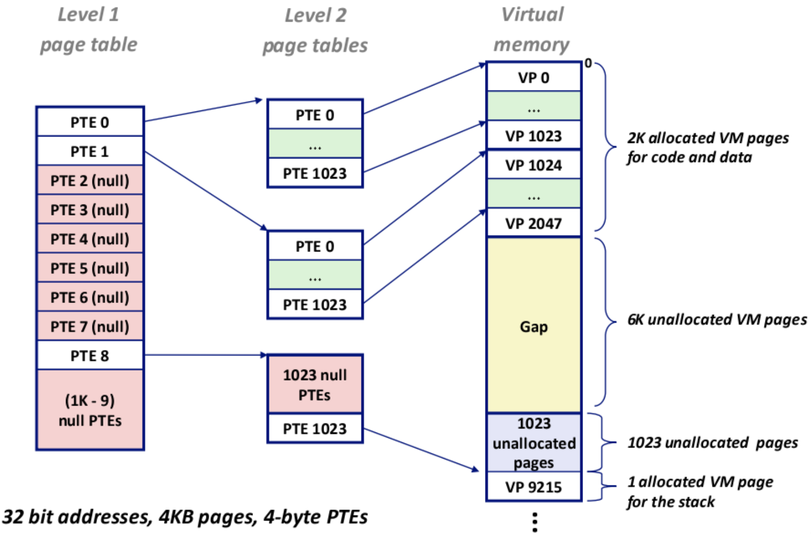
Both data structures map 3 virtual pages to 3 physical page as indicated in the map to the left but use different amounts of space to do so.

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

Exercise: Printing Contents of file

1. Examine `print_file.c`: reads contents of a file and prints it to the screen. Identify the key parts of this program and its **memory requirements.**
2. Examine `mmap_print_file.c`: does it contain all of these key features? Which ones are missing?

Exercise: Printing Contents of file

```c
// print_file.c
int main(int argc, char *argv[]){
  FILE *fin = fopen(argv[1], "r");
  char inchar;
  while(1){
    int result =
      fscanf(fin, "%c", &inchar);
    if(result == EOF){
      break;
    }
    printf("%c", inchar);
  }

  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 1 or more 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

```
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
```

`mmap()` allows file reads/writes without `read()`/`write()`

- Memory mapped files are not just for reading
- With appropriate options, writing is also possible

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

- 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

```
// 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()`

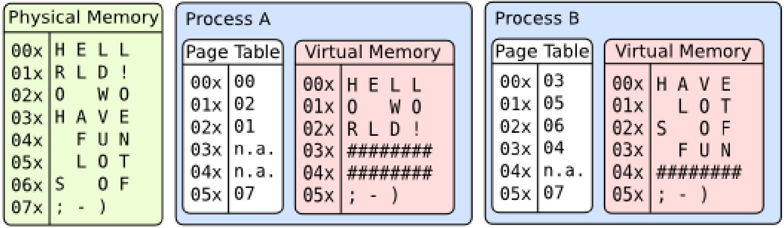
- Avoid following cycle
  - `fread()/fscanf()` file contents into memory
  - Analyze/Change data
  - `fwrite()/fscanf()` write memory back into file
- Saves memory and time
- Many Linux mechanisms backed by `mmap()` like processes sharing memory

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

One Page Table Per Process

- OS maintains a page table for each running program (1 page table per **process**)
- Each process believes its address space ranges from `0x00` to `0xBIG` (0 to 2^{48}), its virtual address space
- Virtual addresses are mapped to physical locations in DRAM or on Disk via page tables

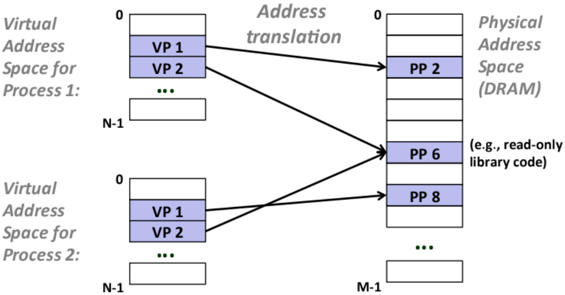


Source: OSDev.org

Two processes with their own page tables. Notice how contiguous virtual addresses are mapped to non-contiguous spots in physical memory. Notice also the ***sharing*** *of a page.*

Pages and Mapping

- Memory is segmented into hunks called **pages**, 4Kb is common (use `page-size.c` to see your system's page size)
- OS maintains tables of which pages of memory exist in RAM, which are on disk
- OS maintains tables per process that translate process virtual addresses to physical pages
- **Shared Memory** can be arranged by mapping virtual addresses for two processes to the same memory page



Shared Memory Calls

- Using OS system calls, can usually create shared memory
- Unix POSIX standard specifies following setup:

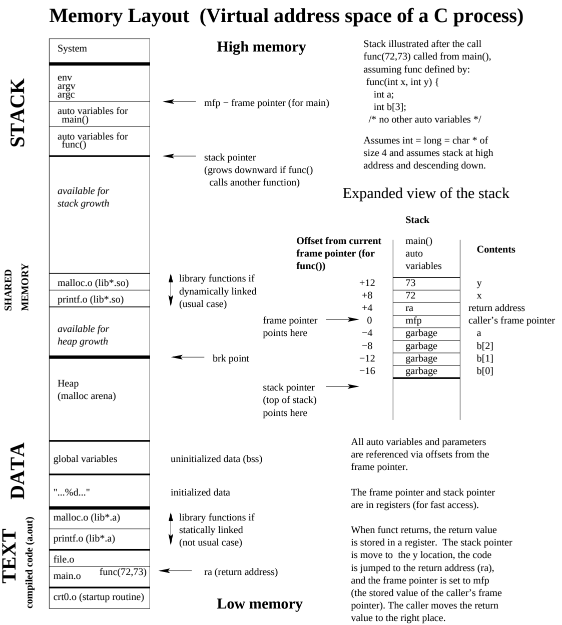
```
char *shared_name = "/something_shared";
int shared_fd =
    shm_open(shared_name, O_CREAT | O_RDWR, S_IRUSR | S_IWUSR);
// retrieve a file descriptor for shared memory

ftruncate(shared_fd, SHM_SIZE);
// set the size of the shared memory area

char *shared_bytes =
    mmap(NULL, SHM_SIZE, PROT_READ | PROT_WRITE,
         MAP_SHARED, shared_fd, 0);
// map into process address space
```

- Multiple processes can all "see" the same unit of memory
- Discussed in intro OS classes (CSCI 4061)
- This is an old style but still useful
- Modern incarnations use `mmap()` which we'll get momentarily

Exercise: Process Memory Image and Libraries

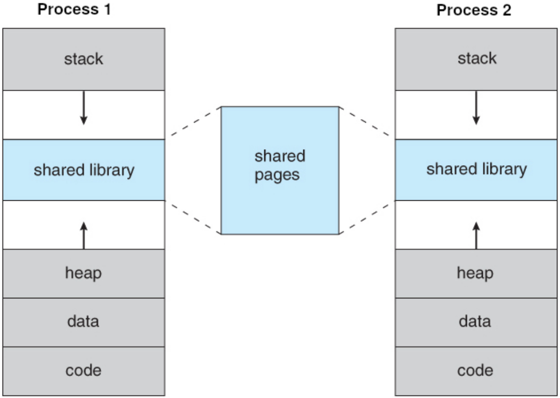
- How many programs on the system need to use `malloc()` and `printf()`?
- Where is the code for `malloc()` or `printf()` in the process memory?

Right: A detailed picture of the virtual memory image, by Wolf Holzman



Shared Libraries: `*.so` Files

- Code for libraries can be shared
- `libc.so`: shared library with `malloc()`, `printf()` etc in it
- OS puts into one page, maps all linked procs to it



Source: John T. Bell Operating Systems Course Notes

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
- More details of pmap output in this article from Andreas Fester
- His diagram is awesome

```
> 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

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

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