CSCI 4061: Virtual Memory

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Last Updated:
Wed Mar 3 03:58:55 PM CST 2021

Logistics

Reading

- Stevens/Rago Ch 3, 4, 5, 6 on File System
- Stevens/Rago: Ch 14.8 on `mmap()`
- Virtual Memory Reference: Bryant/O'Hallaron, Computer Systems. Ch 9 (CSCI 2021)

Goals

- ☒ Finish up File Ops
- ☐ Virtual Memory System
- ☐ Memory Mapped Files

Reminders

~~HW05 / Feedback Survey~~
~~Due Tonight~~

Assignments

- Lab06: `stat()` / `lstat()`
- HW06: Directory traversals

P2 is Coming

The View of Memory Addresses so Far

- Consider 2 running programs about to execute the following instructions

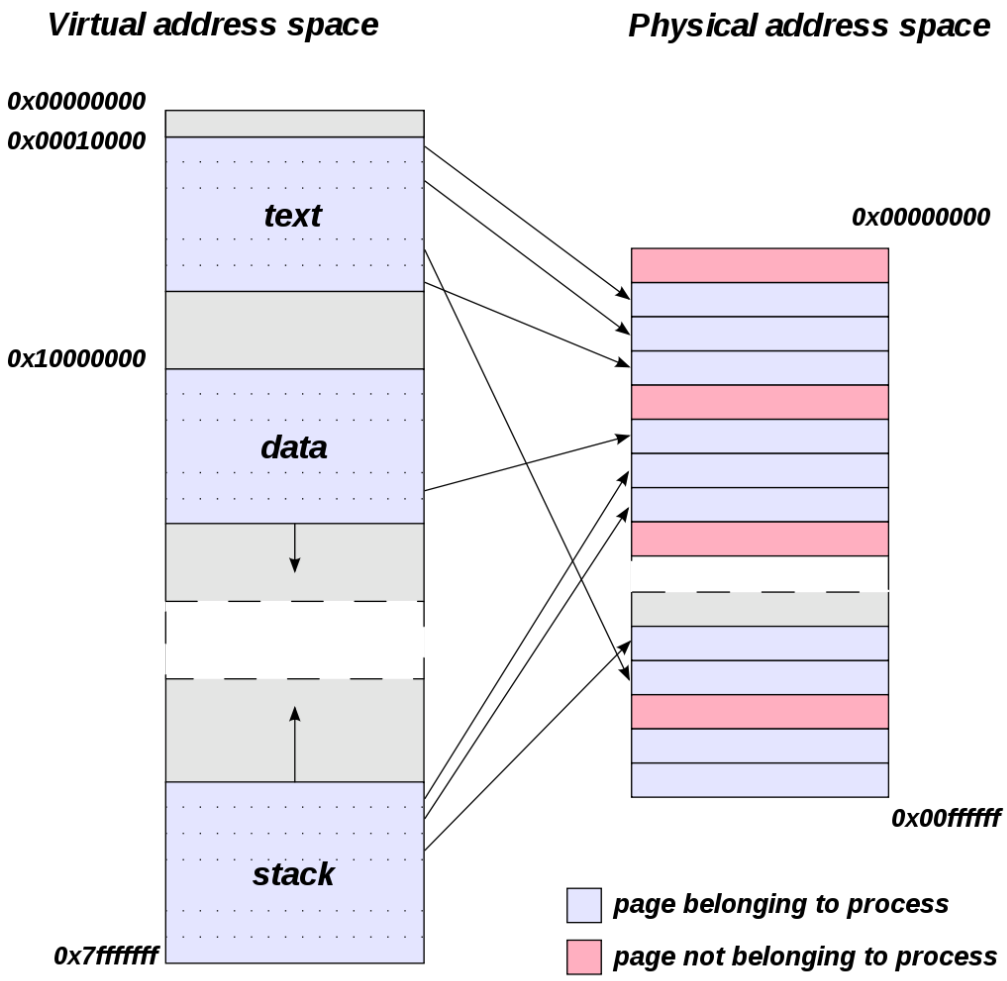
```
## Address 1024 holds  long x=75;
PROGRAM 1                        PROGRAM 2
## load global from 1024         ## add to global at #1024
movq 1024, %rax                  addl %esi, 1024
...                              ... # ^ esi = 5
```

- Both Programs accessing physical address 1024 leads to a concurrency problem
  - PROGRAM 1 first: loads 75
  - PROGRAM 2 first: adds on 5, Program 1 loads 85
- OS is usually tasked with preventing such problems
- Various Hardware/Software techniques have been used over the history of computing but the most popular and important at the moment is

  Virtual Memory: Neither of Program 1/2 directly access Physical Address #1024

Addresses are a Lie

- Operating system uses tables and hardware to translate every memory address reference **on the fly**
- Processes know **virtual addresses** which are translated via the memory subsystem to physical addresses in RAM and on disk
- Hunks of addresses are translated together as **pages**



Source: Wikipdia "Page Table"

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 for Process #1234:

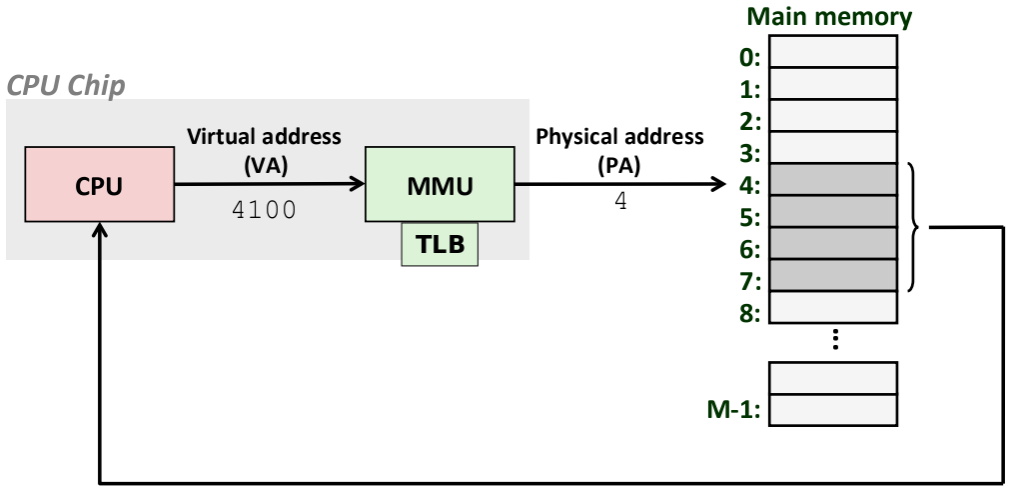
Virtual Page	Size	Physical Page
00007ffa0997a000	4K	RAM: 0000564955aa1000
00007ffa0997b000	4K	RAM: 0000321e46937000
...		...

Address Space From Page Table for Process #1234:

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

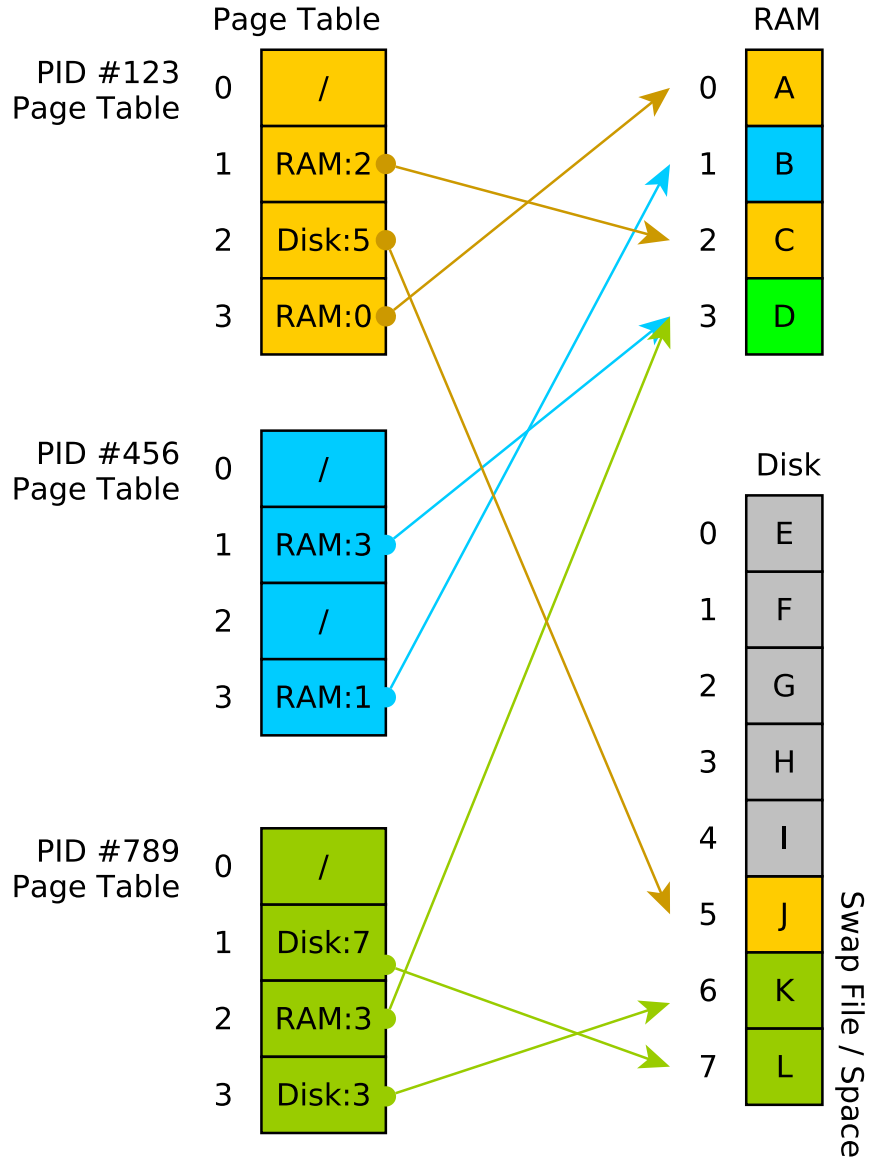
- Translation must be **FAST** so usually involves hardware
- **MMU (Memory Manager Unit)** is a hardware element specifically designed for address translation
- Usually contains a special cache, **TLB (Translation Lookaside Buffer)**, which stores recently translated addresses



- 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

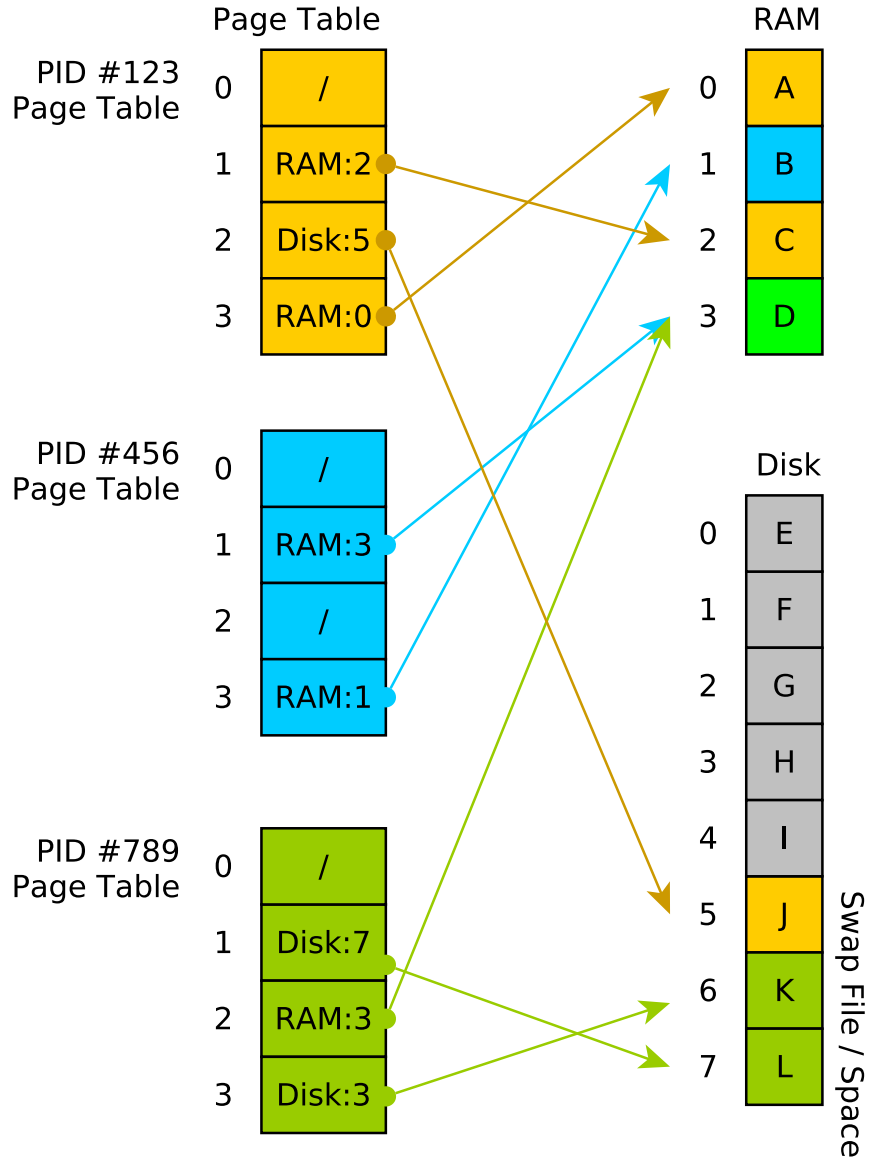
Translating Virtual Addresses 1/2

- On using a Virtual Memory address, hardware attempts to resolve in MMU via TLB cache of pages
- If valid (hit), address is already in DRAM, translates to physical DRAM address
- Miss = **Page fault**, OS decides..
  1. Page is swapped out, move disk data to DRAM, potentially evicting another page
  2. Not mapped = Segmentation Fault



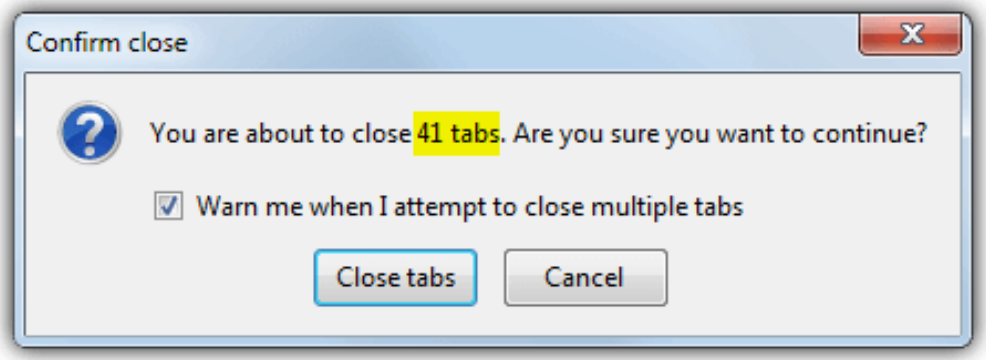
Translating Virtual Addresses 2/2

- 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.

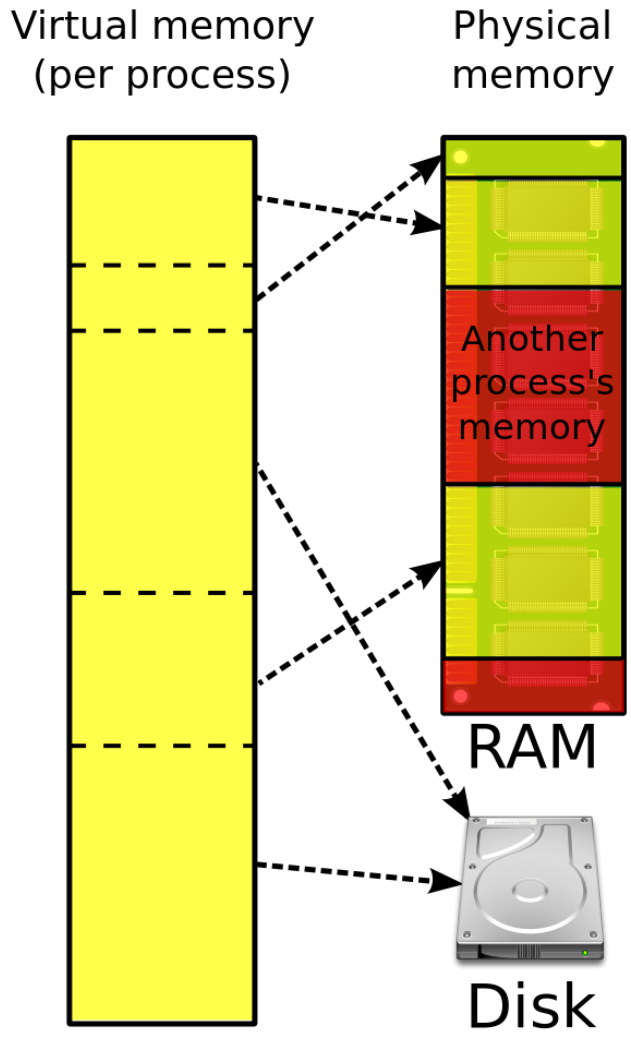
The Many Other Advantages of Virtual Memory

- 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()

But first...

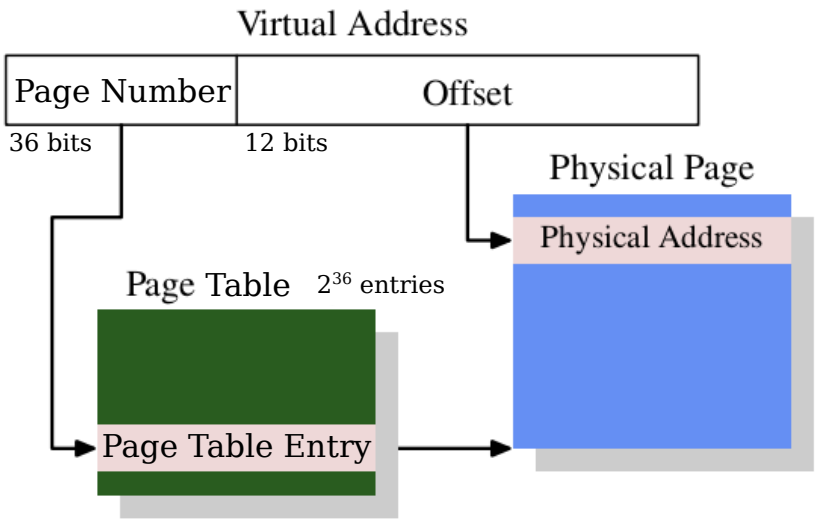
Exercise: Page Table Size

- Page tables map a virtual page to physical location
- 1 Page Table per Process, **Maintained by OS 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}
- **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.

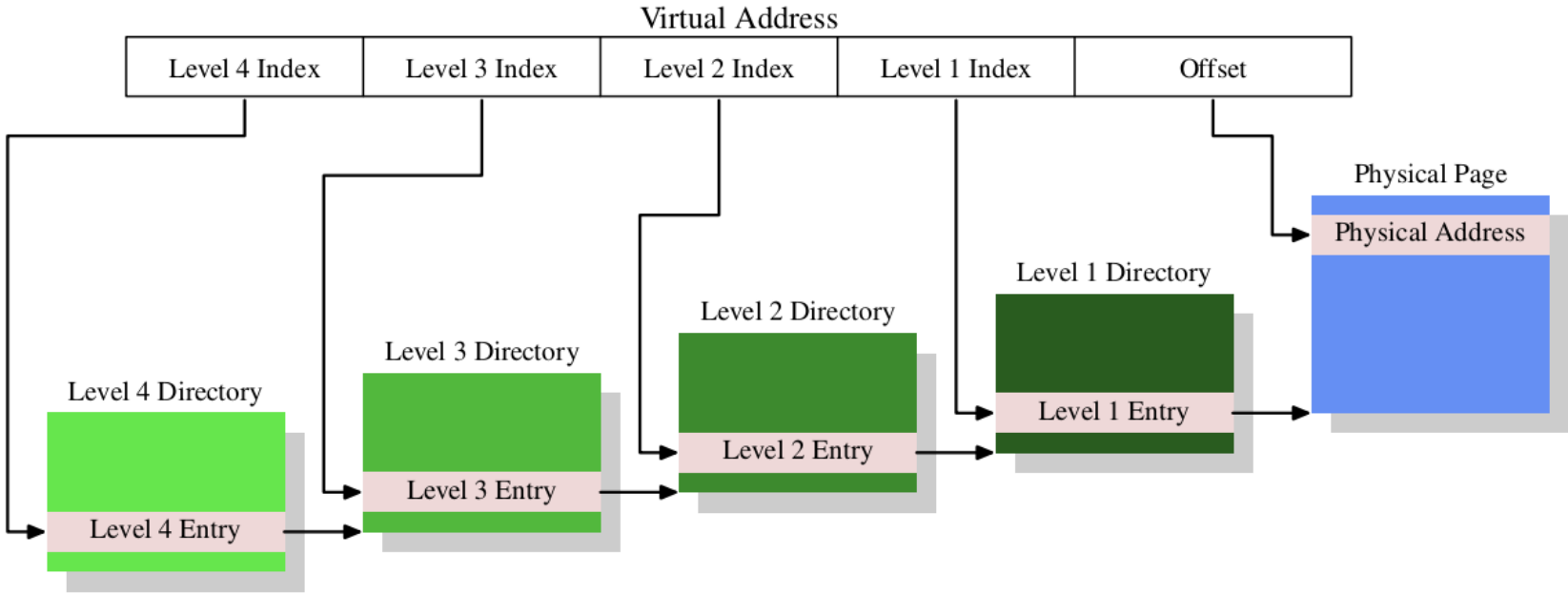
```
  48 bits for virtual address
- 12 bits for offset
--------------------
  36 bits for virtual page number
```

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 $=$
- $2^{40} = 1$ Terabyte of space for the Page Table (!!!)

You've been lying again, haven't you professor...

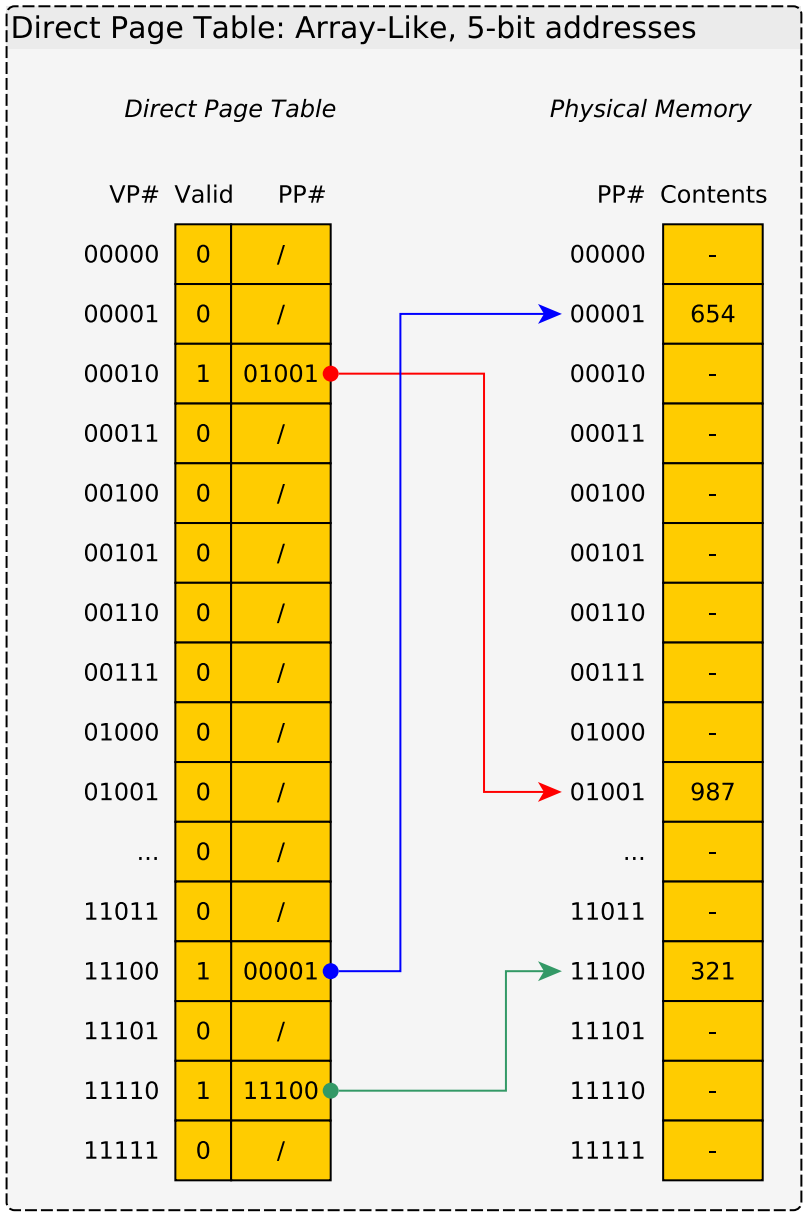
Page Tables Usually Have Multiple Levels

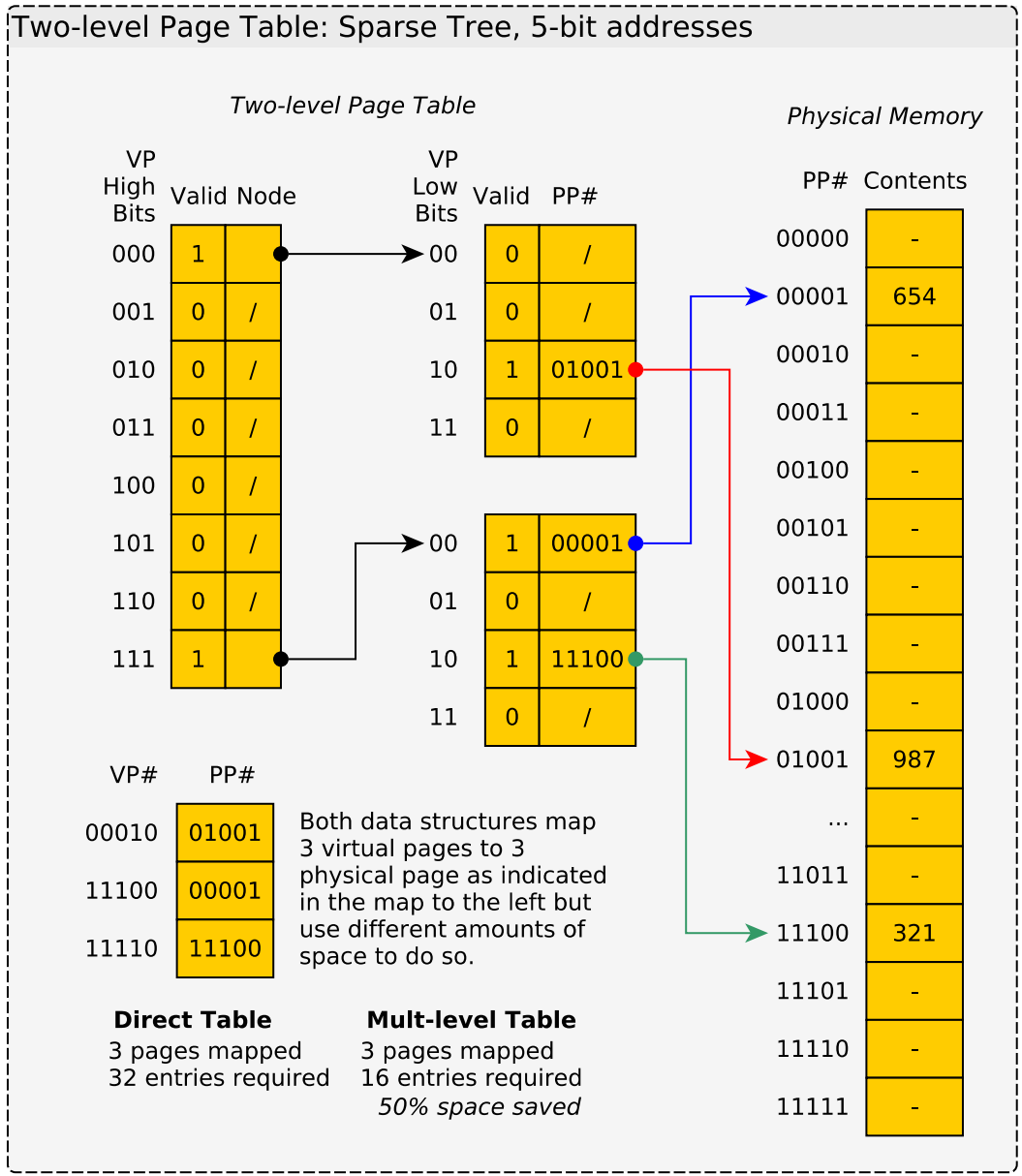


"What Every Programmer Should Know About Memory" by Ulrich Drepper, Red Hat, Inc.

- 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
- Many entries in different levels are `NULL` (not mapped) most of the 2^{36} virtual pages are not mapped to a physical page (see next diagram)

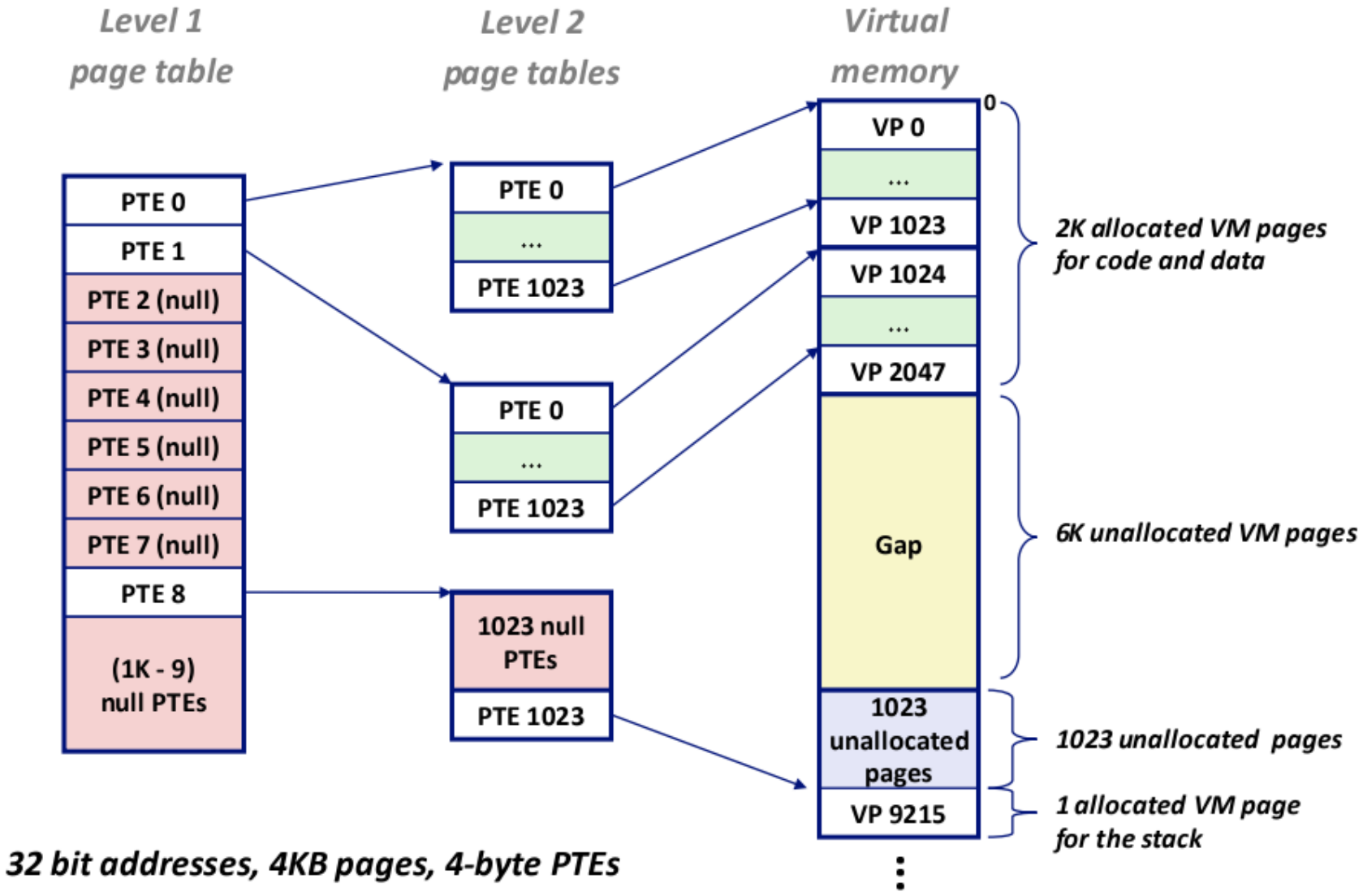
Direct Page Table vs Sparse Tree Page Table





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. Write a simple program to print all characters in a file **using `read()` / `write()`** system calls. What are key features of this program?
2. Examine `mmap_print_file.c`: does it contain all of these key features? Which ones are missing?

Answers: Printing Contents of file

1. Write a simple program to print all characters in a file. What are key features of this program? **From `my_cat.c`:**
   - Open file
   - Read characters **into memory** `buf` using `read()`
   - Write characters to screen with `write()`
   - Repeat this until 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 `read()/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 Ammazing

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

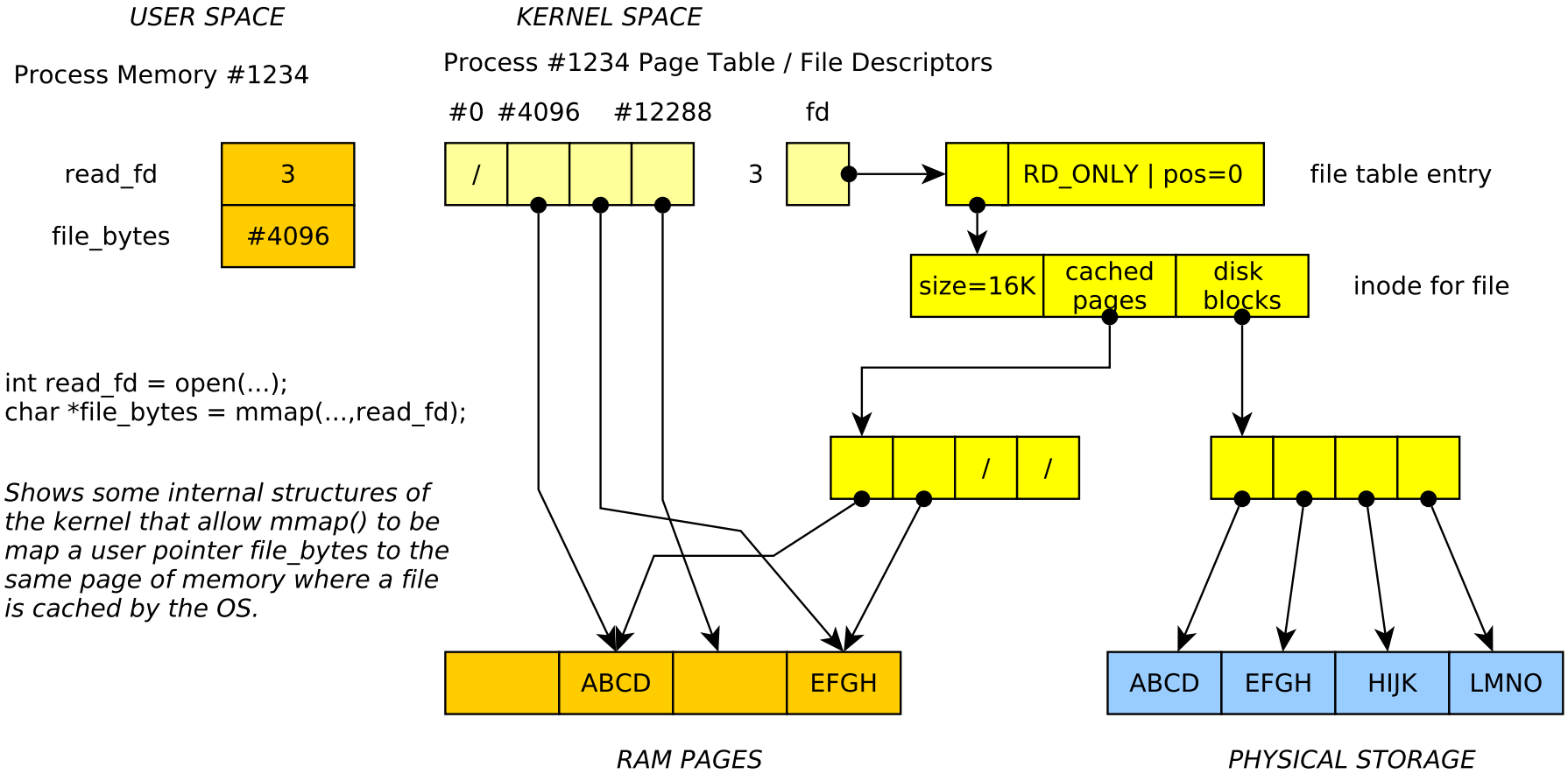
- Example `int *`: treat file as array of binary ints
- Notice changing array will write to file

```
// mmap_increment.c

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
}
```

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()`



Exercise: mmap_tr.c

Speculate on how to use mmap() to write the following program.

```
> gcc -o mmap_tr mmap_tr.c
> mmap_tr gettysburg.txt f p
Transforming 'f' to 'p' in gettysburg.txt
Transformation complete

> mmap_tr gettysburg.txt F P
Transforming 'F' to 'P' in gettysburg.txt
Transformation complete

> head gettysburg.txt
Pour score and seven years ago our pathers brought porth on this continent, a
new nation, conceived in Liberty, and dedicated to the proposition that all men
are created equal.

Now we are engaged in a great civil war, testing whether that nation, or any
nation so conceived and so dedicated, can long endure. We are met on a great
battle-pield op that war. We have come to dedicate a portion op that pield, as
pinal resting place por those who here gave their lives that that nation might
live. It is altogether pitting and proper that we should do this.

>
```

Answers in mmap_tr.c

`mmap()` Compared to Traditional `read()`/`write()` I/O

Advantages of `mmap()`

- Avoid following cycle
  - `read()`/`fread()`/`fscanf()` file contents into memory
  - Analyze/Change data
  - `write()`/`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
- Memory Map is fixed size while `write()` and `ftruncate()` can change the size of a file (though can `mremap()` once a file changes in size)
- No bounds checking, just like everything else in C

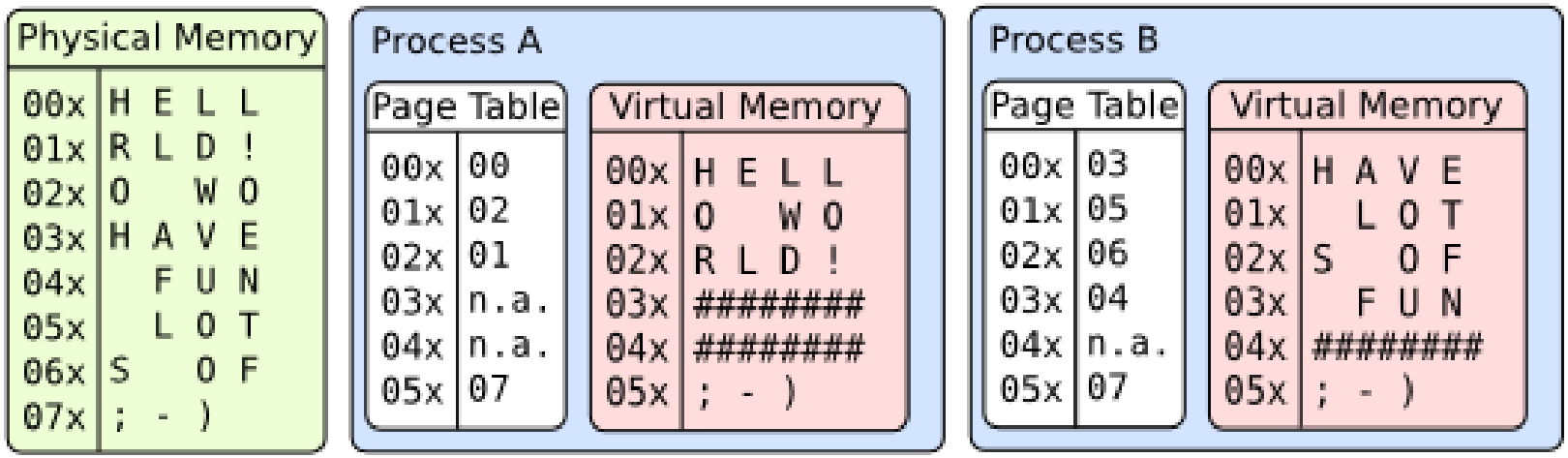
Malloc Uses `mmap()`

- `mmap()` system call manipulates the process Page Table
- `malloc()` is a request for memory from the "Heap" but for large requests, may invoke `mmap()` to map in space directly
- **Demo**: `strace` to trace system calls on the `max_memory.c`

```
...
# "small" malloc() - no system calls
write(1, "       65536 bytes: Success\n", 28) = 28

# "small" malloc() - no system calls
write(1, "      131072 bytes: Success\n", 28) = 28

# "big" malloc() - use mmap()
mmap(NULL, 266240, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0)
    = 0x7f52f2ed5000
write(1, "      262144 bytes: Success\n", 28) = 28
munmap(0x7f52f2ed5000, 266240)          = 0

# "big" malloc() - use mmap()
mmap(NULL, 528384, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0)
    = 0x7f52f2e95000
write(1, "      524288 bytes: Success\n", 28) = 28
munmap(0x7f52f2e95000, 528384)          = 0
...
```

One Page Table Per Process

- OS maintains a page table for each running 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.*

Shared Memory Calls: Modern Posix

- Using OS system calls, can usually create shared memory
- Modern POSIX systems favor `mmap()/fork()` for this
- Will cover more **interprocess communication (IPC)** later

```
char *shared_name = "/something_shared";
int SHM_SIZE = 1024
// global params for shared memory segment

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

int child_pid = fork();
// child/parent share array shared_bytes
```

Shared Memory Calls: Historical System V

- Using OS system calls, can usually create shared memory
- Unix System V (five) IPC includes the following

```
key_t key  = ftok("crap", 'R');
// make the SysV IPC key

int shmid  = shmget(key, 1024, 0644 | IPC_CREAT);
// connect to (and possibly create) the segment:

char *data = shmat(shmid, (void *)0, 0);
// attach to the segment to get a pointer to it:
```

- Multiple processes can all "see" the same unit of memory
- This is an old style but still useful
- Will cover more **interprocess communication (IPC)** later
- Modern incarnations favor `mmap()` followed by `fork()`

Exercise: What can be shared safely?

Traditional Unix Processes didn't share anything in **user memory** with each other to preserve security: processes are isolated.

1. Why is this wasteful of Memory?
2. What items in user memory could be shared safely?
3. What is shared between processes **outside of user space?**

Answers: What can be shared safely?

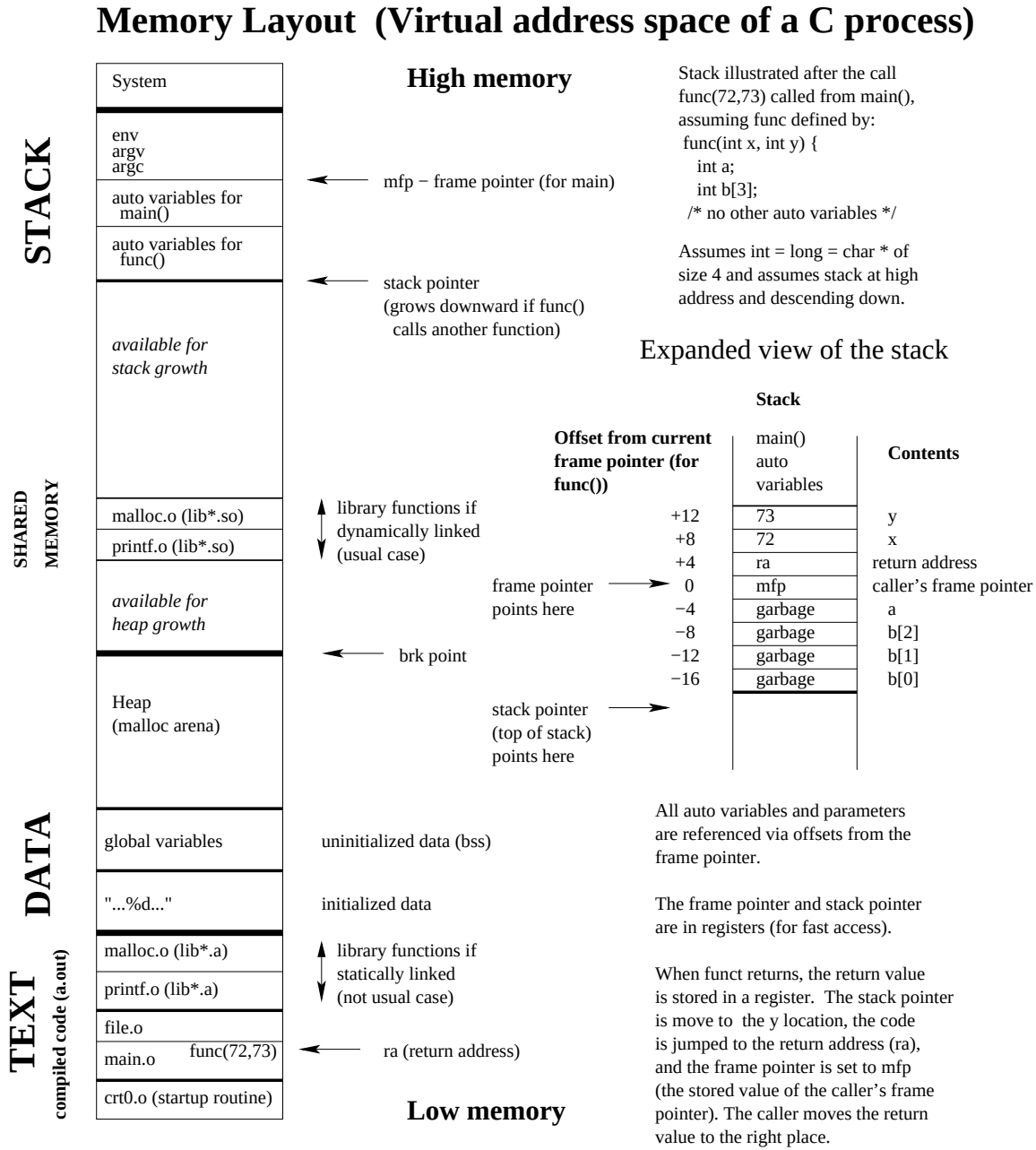
Traditional Unix Processes didn't share anything in **user memory** with each other to preserve security: processes are isolated.

1. Why is this wasteful of Memory?
   Every program has its own identical copies of `printf()`, `malloc()`, *etc. Lots of copies of the same stuff sitting in MANY processes.*
2. What items in user memory could be shared safely?
   The Text (Code) and other Read-only data for libraries can be shared: every program executes them, no program changes them.
3. What is shared between processes **outside of user space?**
   Kernel data is shared by all processes; some parent/child processes directly share file table entries, all access same kernel structures

Process Memory Image and Libraries

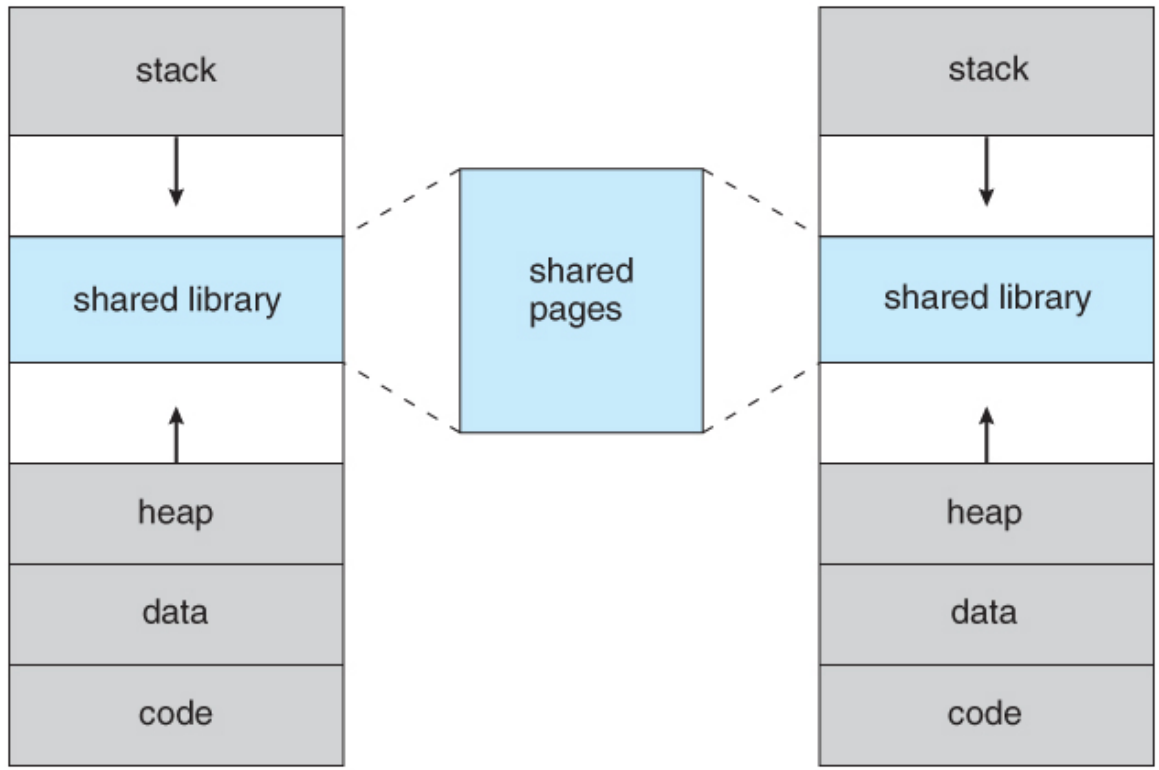
Most programs on the system need to use `malloc()` and `printf()`: **shared library** versions of these reduce memory footprint w/o being dangerous

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
0x5579a4cbe0c0 : global_arr
0x7fff96aff6f0 : local_arr
0x5579a53aa260 : malloc_arr
0x7f441f8bb000 : mmap'd file
my pid is 7986
press any key to continue
```

- While a program is running, determine its **process id**
- Call pmap to see how its virtual address space maps
- For more details of pmap output, refer to this diagram from a now defunct article by Andreas Fester

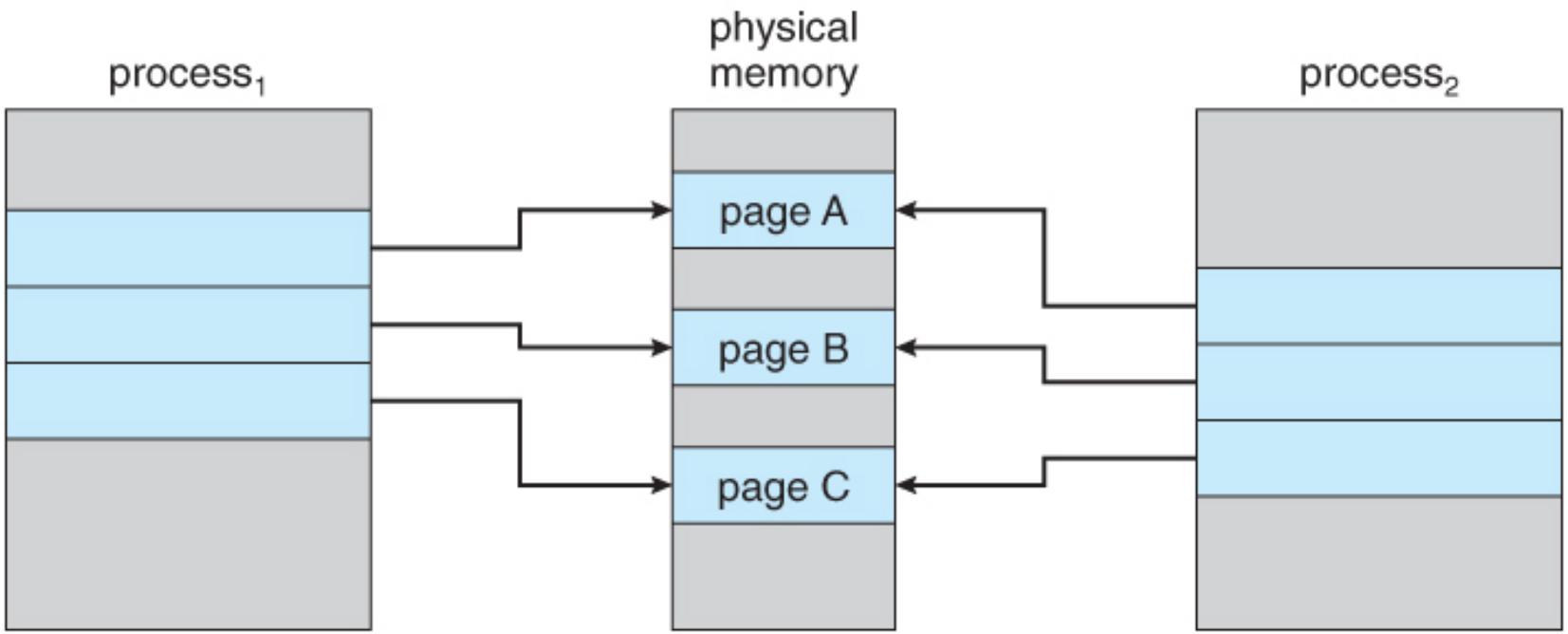
```
> pmap 7986
7986:   ./memory_parts
00005579a4abd000      4K r-x-- memory-parts
00005579a4cbd000      4K r---- memory-parts
00005579a4cbe000      4K rw--- memory-parts
00005579a4cbf000      4K rw---   [ anon ]
00005579a53aa000    132K rw---   [ heap ]
00007f441f2e1000   1720K r-x-- libc-2.26.so
00007f441f48f000   2044K ----- libc-2.26.so
00007f441f68e000     16K r---- libc-2.26.so
00007f441f692000      8K rw--- libc-2.26.so
00007f441f694000     16K rw---   [ anon ]
00007f441f698000    148K r-x-- ld-2.26.so
00007f441f88f000      8K rw---   [ anon ]
00007f441f8bb000      4K r--s- gettysburg.txt
00007f441f8bc000      4K r---- ld-2.26.so
00007f441f8bd000      4K rw--- ld-2.26.so
00007f441f8be000      4K rw---   [ anon ]
00007fff96ae1000    132K rw---   [ stack ]
00007fff96b48000     12K r----   [ anon ]
00007fff96b4b000      8K r-x--   [ anon ]
 total             4276K
```

Memory Protection

- Output of `pmap` indicates another feature of virtual memory: protection
- OS marks pages of memory with Read/Write/Execute/Share permissions
- 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

Fork and Shared Pages

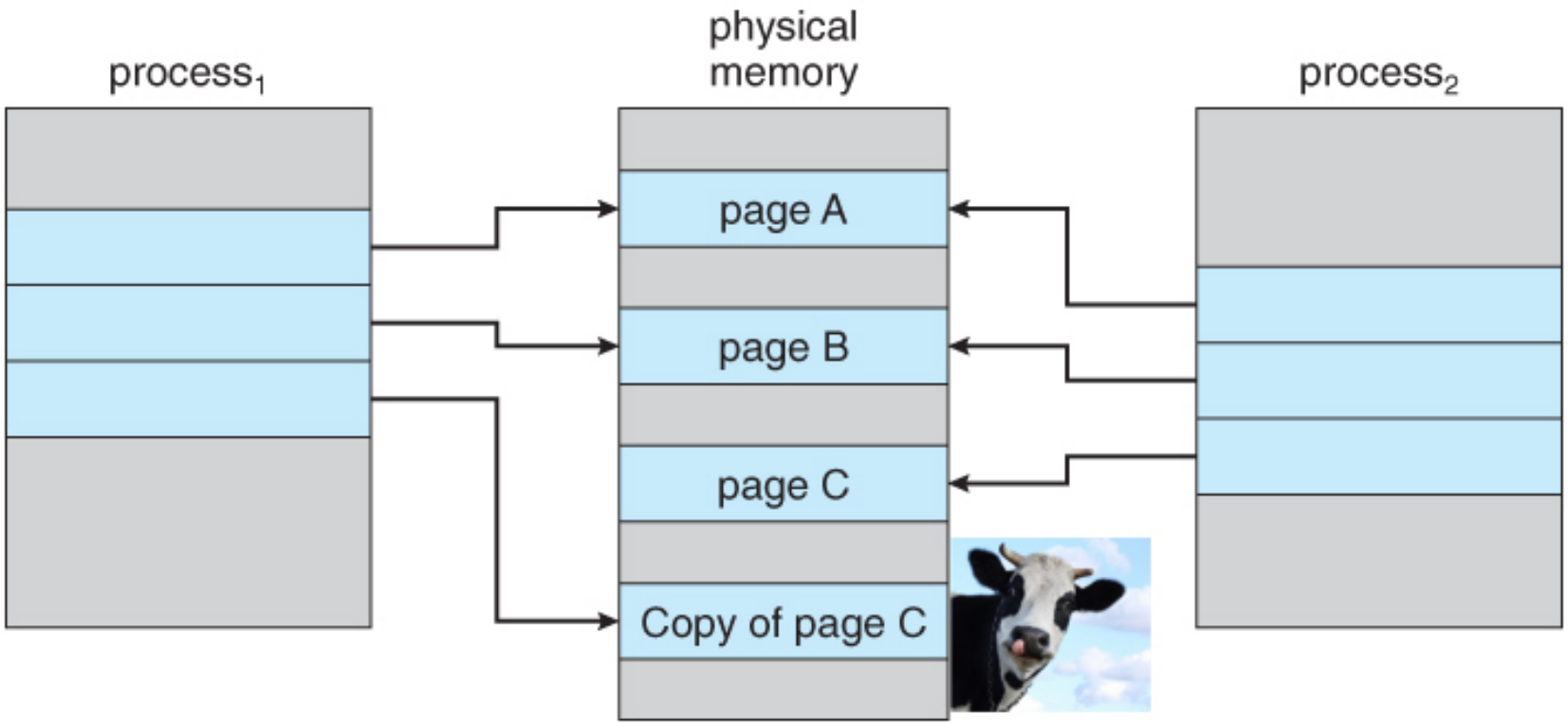
- `fork()`'ing a process creates a nearly identical copy of a process
- Might need to copy all memory form parent to child pages
- Can save a lot of time if memory pages of child process are **shared with parent** - no copying needed (initially)
- What's the major danger here?



Source: John T. Bell Operating Systems Course Notes

Fork, Shared Pages, Copy on Write (COW Pages)

- If neither process writes to the page, sharing doesn't matter
- If either process writes, OS will make a copy and remap addresses to copy so it is exclusive
- Fast if hardware Memory Management Unit and OS know what they are doing (Linux + Parallel Python/R + Big Data)



Source: John T. Bell Operating Systems Course Notes

Summary

A computer using a Virtual Memory system sees the OS and hardware cooperate to translate every program address from a virtual address to a physical RAM address.

- **Consequence 1**: All programs see a linear address space but each has its own #1024 which does not conflict
- **Consequence 2**: The OS must maintain Page Table data structures that map each process's virtual addresses to physical locations
- **Consequence 3**: Computers with small amounts of RAM can "fake" larger amounts by using disk space; RAM serves as a cache for this larger virtual memory
- **Consequence 4**: Every address deference is translated so the OS can catch out of bounds references or direct the dereference to special RAM areas like memory mapped files
- **Consequence 5**: Memory can shared and manipulated for efficiency such as `fork()` using Copy on Write

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 on onto 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