CSC2/452 Computer Organization
Using Virtual Memory

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URCS

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Outline

Outline

Administrivia

- Assignment #3 is due Nov 13, 2022 at 7PM
- Homework #6 is due this Wednesday
- Assignment #4 will be out Monday, Nov 14
- Mid-term grades are out
  - HW+A1+A2+Midterm is 49% of grade
  - 51% still due!

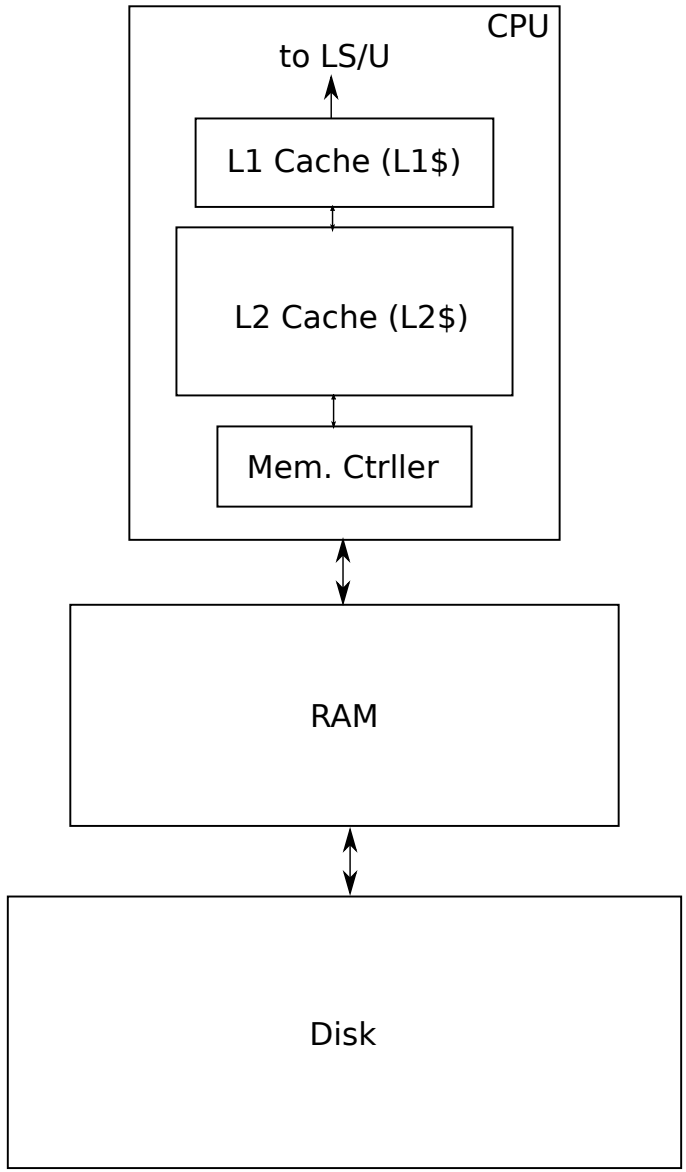
Outline

Virtual Memory

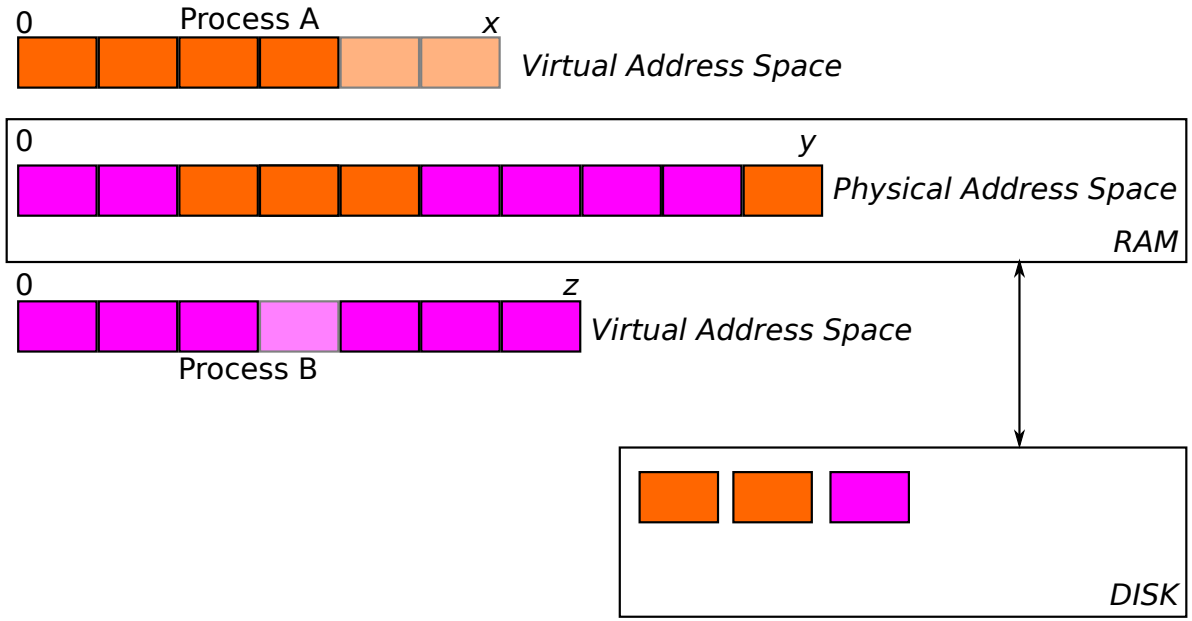
- Virtual address space
- Physical address space
- All loads/stores use virtual addresses
- MMU translates virtual addresses to physical addresses
  - Uses page tables
  - On 64-bit x86, 4 levels of page tables
- Page tables allow pages to not be present in memory!
  - Loads/stores to such pages trigger page faults
  - OS can handle these page faults

Outline

The Revised Memory Hierarchy

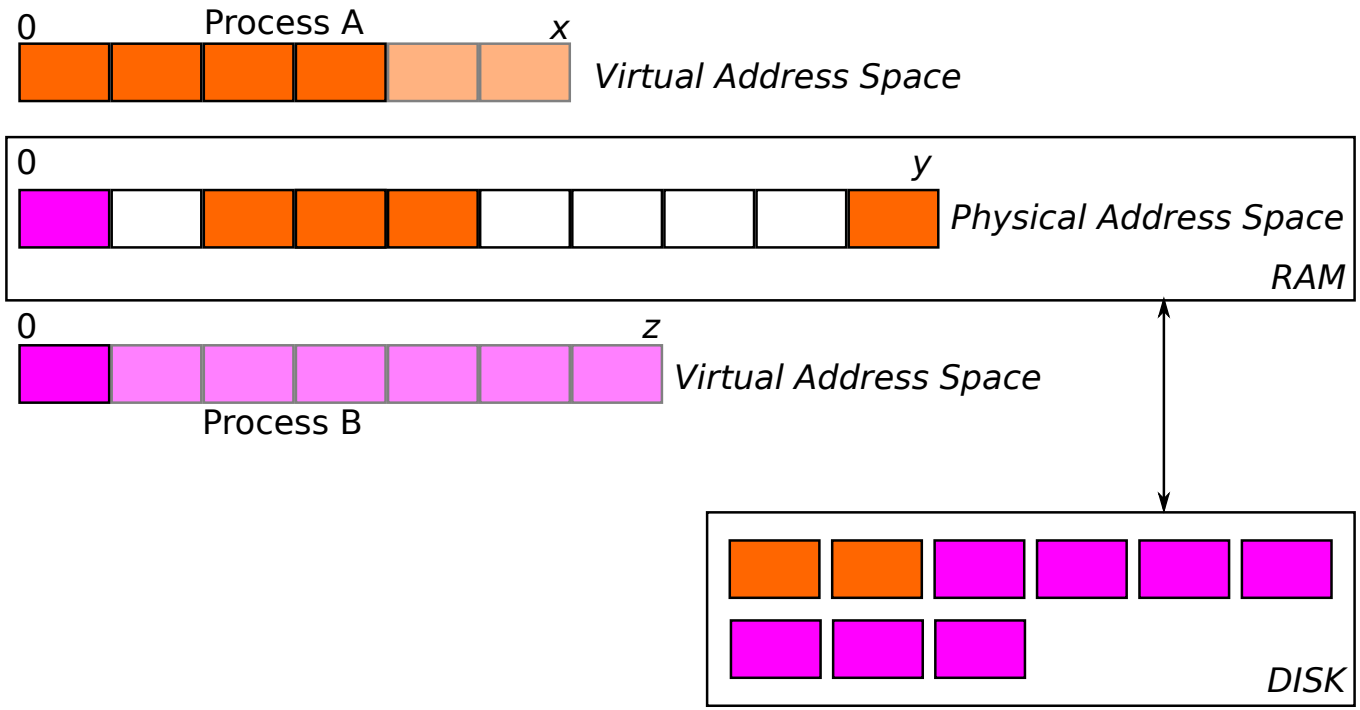


Programs and Virtual Memory



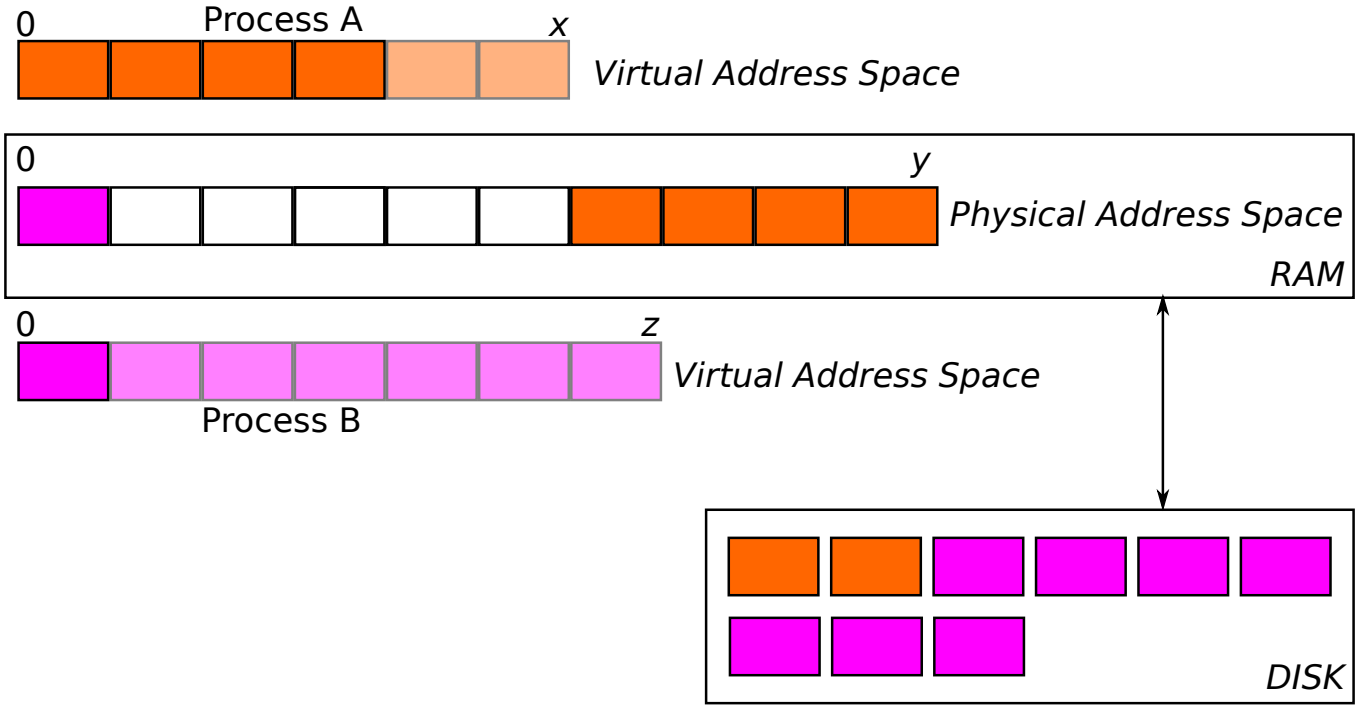
- Each block corresponds to a page
  - Process A has 6 pages, Process B has 7 pages
- Physical memory can accommodate 10 pages
- Disk can accommodate as many pages as it has space
  - Depends on OS
- Shaded blocks indicate pages swapped out

Loading Process B



- Assume Process B is being loaded for the first time
  - Or maybe it was completely swapped out
- Only one page has been loaded
- From the perspective of the memory hierarchy, all data is initially on disk

Defragmenting Virtual Memory



- This slide demonstrates that you can change virtual to physical mappings
  - Here, for physical pages belonging to process A have been moved
- "Defragmentation" allows larger, physically contiguous chunks to be assigned to the same process
  - Can improve performance and allocator behaviour

Loading Process B

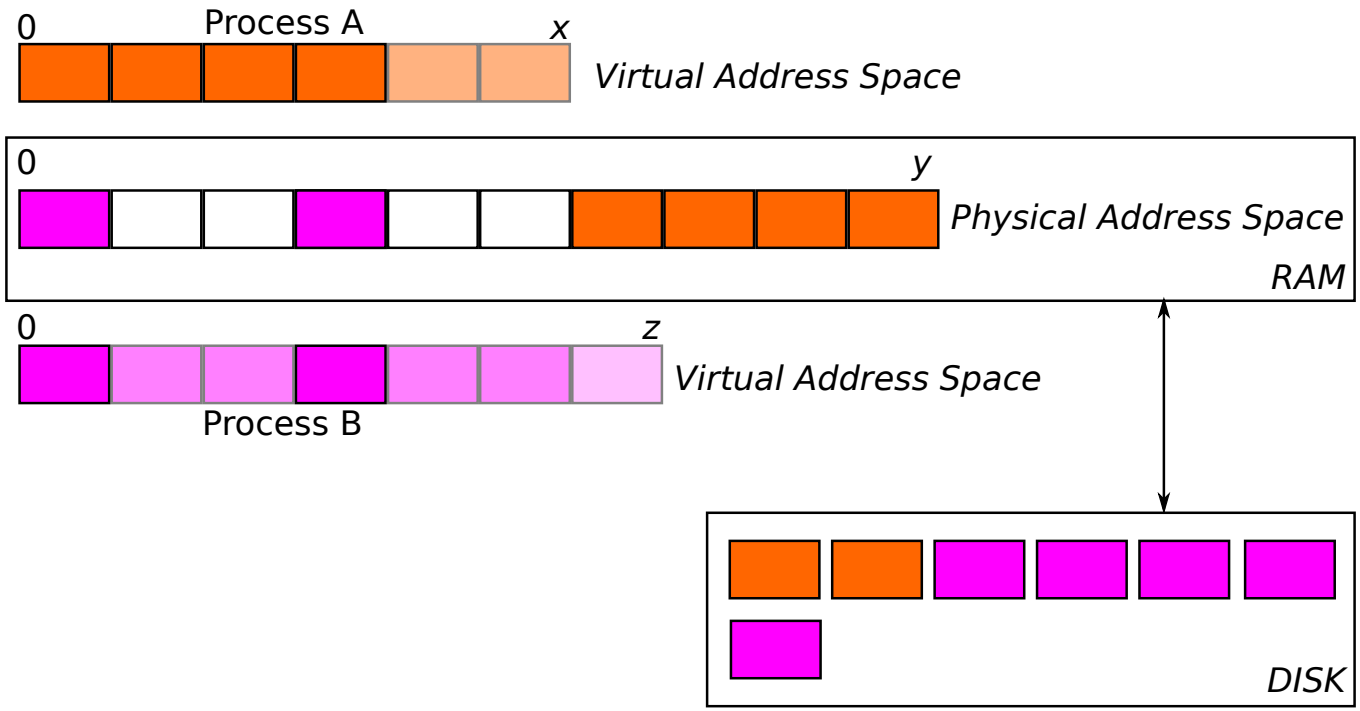
Should we load all pages from disk to memory at once?

- Will Process B access all the pages?
  - Do you use all the functionality of most programs in a single run?

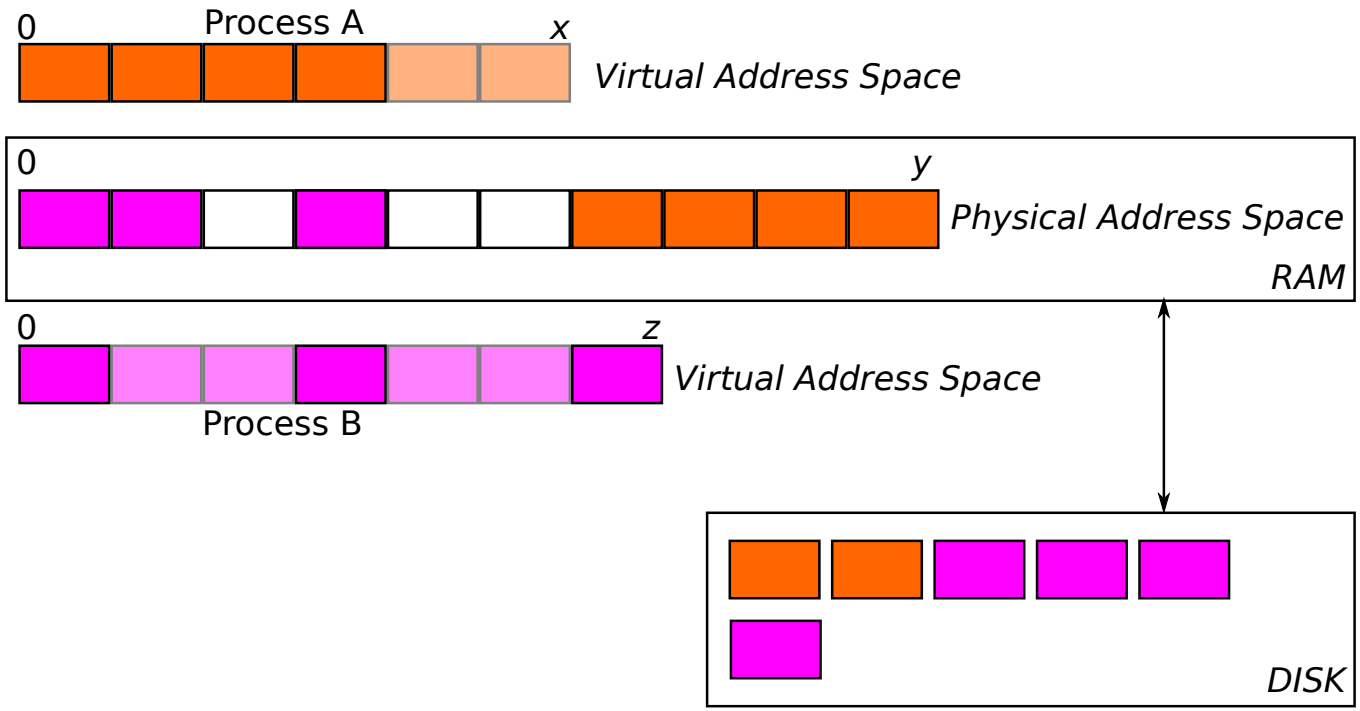
Demand Paging

- OS simply marks pages as belonging to process B
  - but marks them all as not present
- When Process B accesses a page for the first time, it triggers a fault
  - OS then loads the page from disk

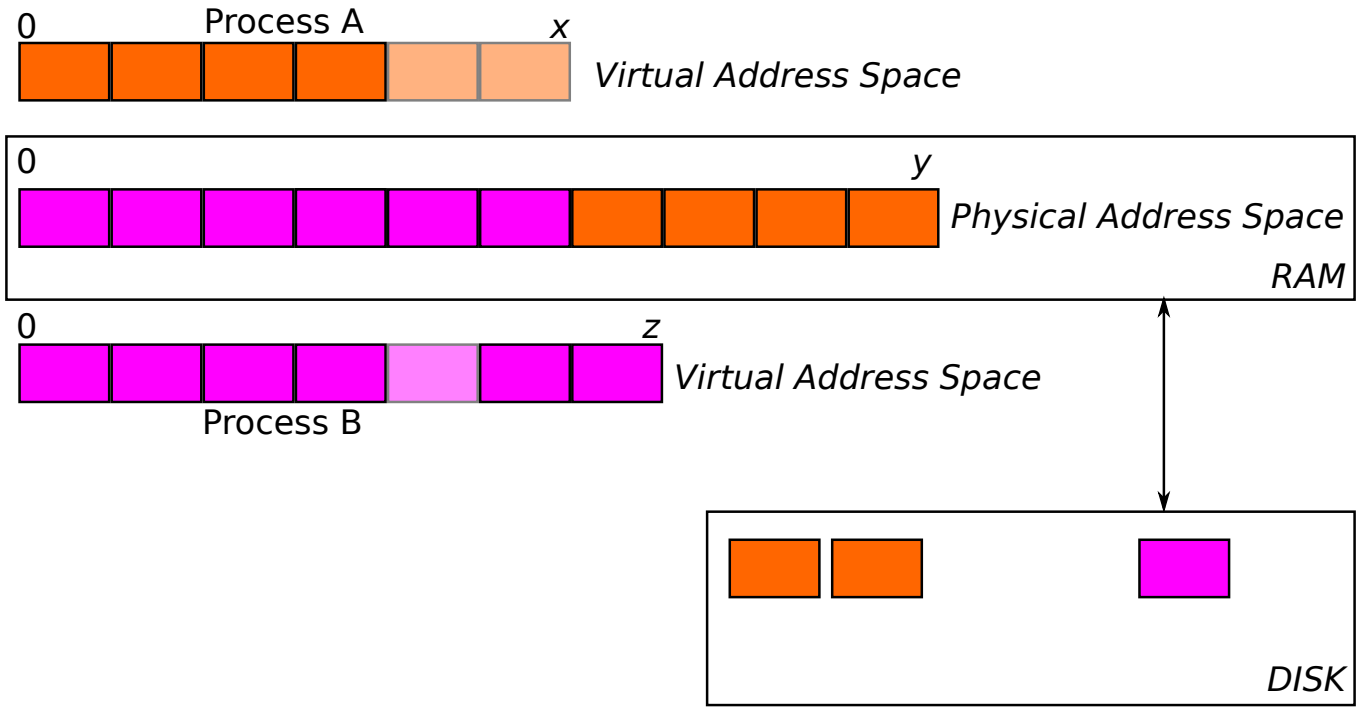
Paging Process B in (2 pages)



Paging Process B in (3 pages)

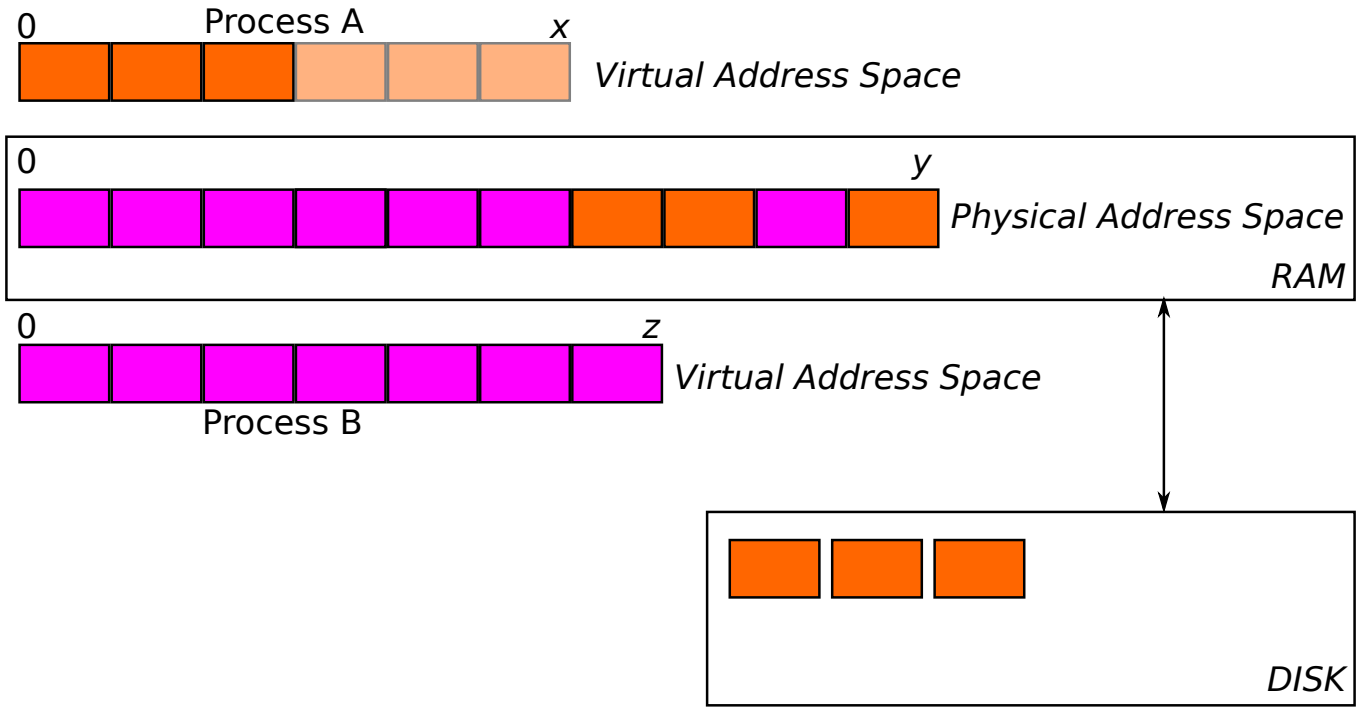


Paging Process B in (6 pages)



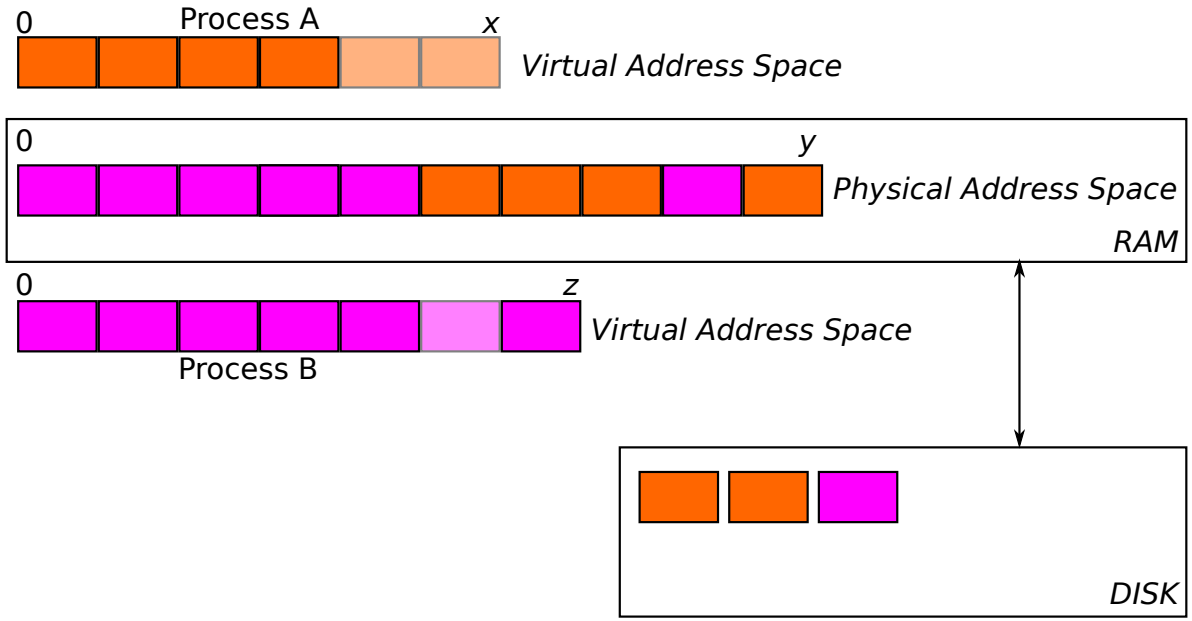
- In this case, B *is* accessing all pages
- No more free physical pages
  - Which page should we kick out?

Which page to throw out?



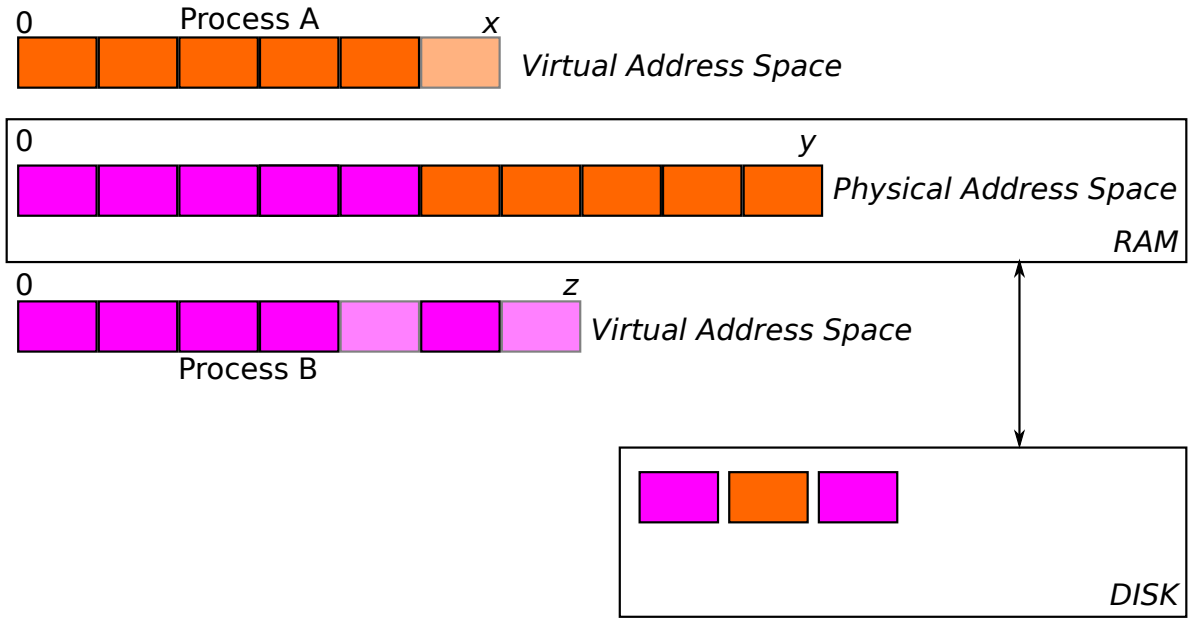
- Same problem as cache replacement
- Similar solutions
  - LRU is often used

Context switch back to Process A



- Process A is now active and brought the recently kicked out page back in
  - Bad luck on replacement!
- We throw out a page from Process B

Context switch again



- Process B is now active and brought its recently kicked out page back in
  - More bad luck on replacement!
- We throw out a page from Process A
- Ad infinitum?

(Disk/VM) Thrashing

- When physical memory is full and
- OS spends more time swapping pages in and out than actually running programs
  - Replacement policy is not picking the right pages
- Happens because of oversubscription
  - More virtual pages than physical RAM can accommodate

Outline

Traditional File I/O

```
f = fopen(argv[1], "r");
if(f) {
  while(!feof(f)) {
    c = fgetc(f);
    if(c == EOF) break;

    if(c >= 'A' && c <= 'Z') {
      counter[c - 'A']++;
    }
  }
}
```

- Open file using `fopen`
- Read data using `fgetc` (or `fread`, `fscanf`, etc.)

Memory Mapped I/O for Files

- Recall that disk is part of the virtual memory system
- Files are on disk
- Can we use the virtual memory subsystem to read/write files?

Functionality needed

- Ask OS (i.e. virtual memory subsystem) to read a file into a bunch of pages
- Use pointers to read/write the data in the pages directly
- Save changed data back to disk

The mmap function

```
int fd = fileno(f);
struct stat st;
char *data;

if(fstat(fd, &st) == 0) {
  data = mmap(NULL, st.st_size, PROT_READ, MAP_SHARED, fd, 0);
  if(data) {
    int i;
    for(i = 0; i < st.st_size; i++) {
      if(*data >= 'A' && *data <= 'Z') {
        counter[*data - 'A']++;
      }
      data++;
    }
  }
```

- The mmap function allows you to do map files into memory
  - Also supports other functionality such as allocation
- Use fopen as usual, but convert FILE to a file descriptor understood by OS (fileno)
  - Or use open to get a file descriptor in the first place
- Use fstat to obtain the size of the file
- Call mmap to map data from the file into memory

Examining mmap

```
data = mmap(NULL, st.st_size, PROT_READ, MAP_SHARED, fd, 0);
```

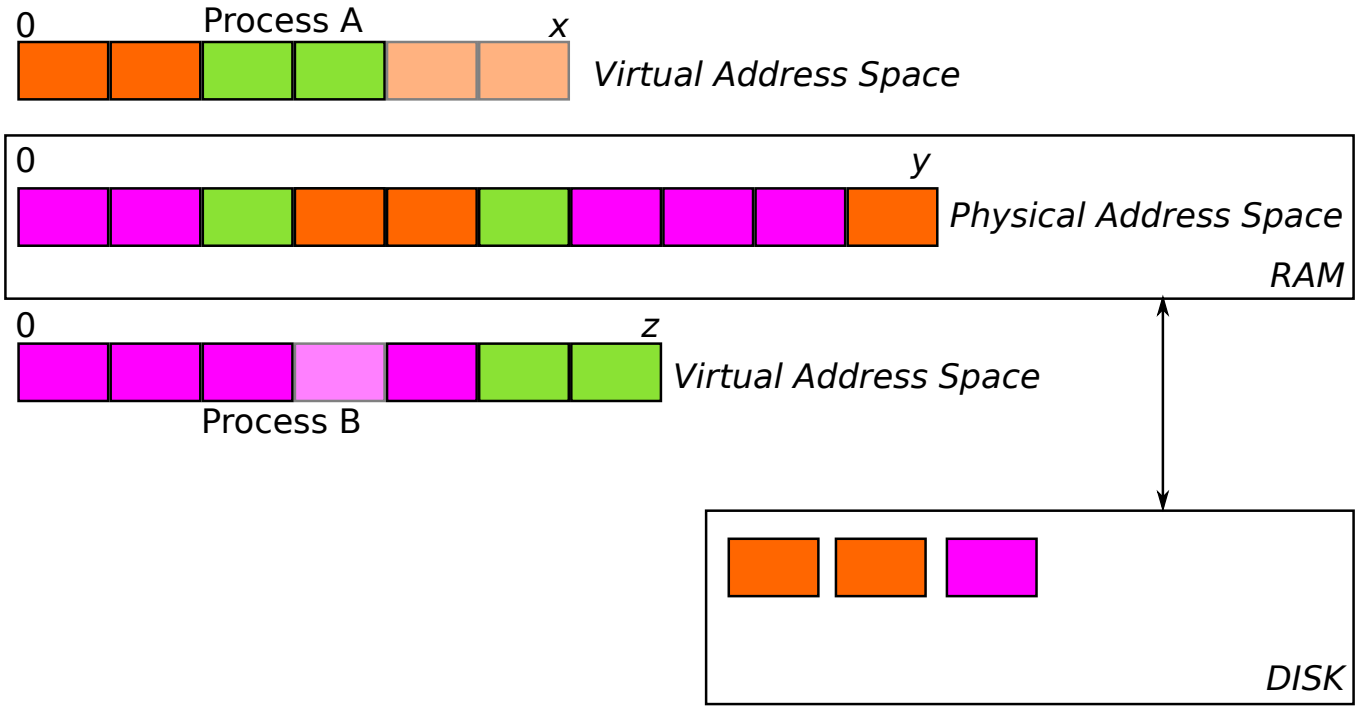
- First argument (NULL), which virtual address to map file to
  - NULL specifies any address is okay
- Second argument (st.st_size) is size of file
  - This will be rounded up to page size
- Third argument (PROT_READ) opens the data in read-only mode
  - Attempting to write will cause a page fault
- Fourth argument (MAP_SHARED) makes all writes visible immediately to other processes who have opened this file using mmap
  - In this case, writes by other processes will be visible to this program
- Fifth argument (fd) gives the file descriptor
- Sixth argument (0) gives the offset from which the data must be loaded
  - 0 is the first byte of the file

Private copies vs shared copies

```
data = mmap(NULL, st.st_size, PROT_READ | PROT_WRITE,
            MAP_PRIVATE, fd, 0);
```

- A `MAP_PRIVATE` flag maps a file privately
- Changes are not visible to other processes
  - And are also not written through to the file being mapped

How shared `mmap` works



- Green blocks are shared pages
  - Same file `mmap`'ed by two different processes
- Same physical pages
- Different virtual addresses per process
  - But could be the same

Unmapping files

```
munmap(data, st.st_size);
```

- `munmap` removes the page mapping
  - Here, all pages in addresses from `data` to `data + st.st_size`
  - Future accesses to the page will cause segfaults
  - All changes are written to disk
- You can remove individual page from the mapping
  - Just change the pointer and the size
- All mapped regions are automatically unmapped when the process ends

Writing to pages

- When you `munmap`, all changed pages must be flushed to disk
  - OS can also periodically flush changes to disk
- This makes writes to `mmap`'ed files visible to processes using traditional file-based I/O
  - Note, writes are always immediately visible to other processes using `mmap`ed I/O
- Two issues:
  - How does the OS track changed pages?
  - Can we control flushing to disk?

Dirty pages

- A page with changed data is called a “dirty” page
- This page must be written to disk eventually
- How can the OS track dirty pages efficiently?

Mechanism

- Assume a file is mapped with `PROT_WRITE`
- When data is first mapped, its protection is set to read only
  - Regardless of `PROT_WRITE`
- On first write, page fault occurs
- OS detects the page fault, and marks page as dirty
  - Is there a bit in the PTE it could use?
  - Also enables write permission for page
  - Future writes will not cause segfaults
  - Note on x86 – the dirty bit is set by hardware, but cleared by software
- Ultimately, pages that are marked dirty need to be flushed to disk
  - Dirty bit is reset and write permission removed
- What about unchanged pages?

Flushing data to disk

```
msync(data, st.st_size, MS_SYNC);
```

- `msync` forces the OS to write changed data back to disk
  - Note only changed pages are written
- The flag `MS_SYNC` causes it to wait until all data is actually on disk

Prefetching

```
madvise(data, st.st_size, MADV_SEQUENTIAL);
```

- Provides hints to the OS on the order in which you will read/write data
- This affects OS-level prefetching of pages
- It also affects page replacement policy
- For example, `MADV_SEQUENTIAL` will:
  - prefetch pages in sequential order
  - throw away pages (since there will be no reuse)

Anonymous Pages

```
data = mmap(NULL, 1048576, PROT_READ | PROT_WRITE,
            MAP_PRIVATE | MAP_ANONYMOUS, -1, 0);
```

- `MAP_ANONYMOUS` allocates pages
  - Like `malloc`
  - Actually used by `malloc` under the hood
- Here, we're allocating 1MB of memory *not* backed by a file
- Note, for anonymous mappings:
  - `fd` should be -1
  - offset should be 0

Fixed Address Pages

```
data = mmap(0x7ffff0001000, 1048576, PROT_READ | PROT_WRITE,
            MAP_PRIVATE | MAP_ANONYMOUS, -1, 0);
```

- You can provide a fixed address to mmap (both anonymous and non-anonymous)
- This allows you to control which addresses you use
  - If this call succeeds, data will contain `0x7ffff0001000`
- Can fail

Outline

Change page protections

```
data = mmap(..., PROT_READ | PROT_WRITE, ...);
 ...
mprotect(data, st.st_size, PROT_READ)
```

- `mprotect` allows you to change permissions for pages after you've loaded them.
  - Here, all pages in address range `data` to `data + st.st_size`
- You can:
  - remove all permissions (`PROT_NONE`)
  - change some pages to executable (`PROT_EXEC`)

Locking pages

What if you want to prevent pages from being swapped out?

- Maybe you want good performance?
- Maybe the page contains secret data that you don't want written to disk?

The `mlock`/`munlock` functions

```
mlock(data, 4096);
```

- If successful, `mlock` prevents the pages in the address range `data` to `data + 4096`.
  - Why could this fail?

References and Acknowledgements

- The GNU libc Manual
  - Portions of Chapter 3 (3.1: Process Memory Concepts)
  - Portions of Chapter 13 (13.8: Memory-mapped I/O)
  - See References on the course website for the manual
- Chapter 9 of the textbook