Week 5.2

Virtual memory

School of Information Technology and Electrical Engineering
The University of Queensland

Coming up

- Lectures - Today
  - Memory Management
    - Virtual Memory
- Tuesday
    - debugging and Ass2
- Friday week
  - User-space memory management.
    - Memory bugs

Recall from Week One

- Operating Systems provide *abstractions* to
  - make computer hardware easier to use
    - for user, programmer, system administrator…
  - manage hardware resources
- Example abstractions

Abstraction	Resource
Virtual Memory	**Memory**
Processes	CPU time+
Sockets, etc	Network
File systems	Disk space

Objectives of Memory Management

- In a system with multiple running processes, program can not know code/data addresses before execution
  - Need to support **relocation**
- Program logical addresses might not be the same as physical memory addresses
  - Need to support address **translation**
- Processes should not (in general) be permitted to access memory allocated to other processes
  - Need to support **protection**

Objectives of Memory Management (cont.)

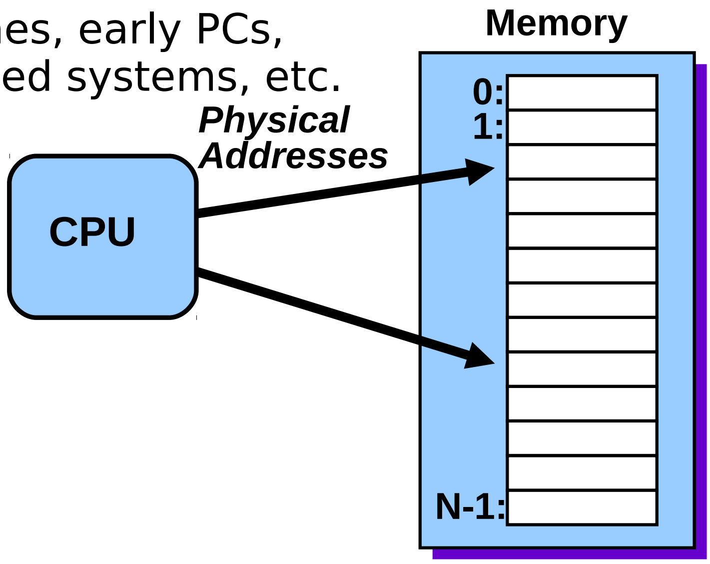
- Sometimes, multiple processes should be able to access the same memory
  - Need to support memory **sharing**
- Processes can dynamically change the amount of memory they need to access
  - Need to support **allocation**
- Processes may need more memory than a machine physically has
  - Need to support **paging (aka swapping)**
    - data is moved between primary storage (memory) and secondary storage (disk)

Virtual Memory

- **Virtual memory** is an abstraction that helps in the management of memory
  - Processes see a *virtual memory* that is different from the physical memory
    - e.g.
      - different size (smaller or larger)
      - different addresses
  - Can be used to support the objectives listed on prior slides

A System with Physical Memory Only

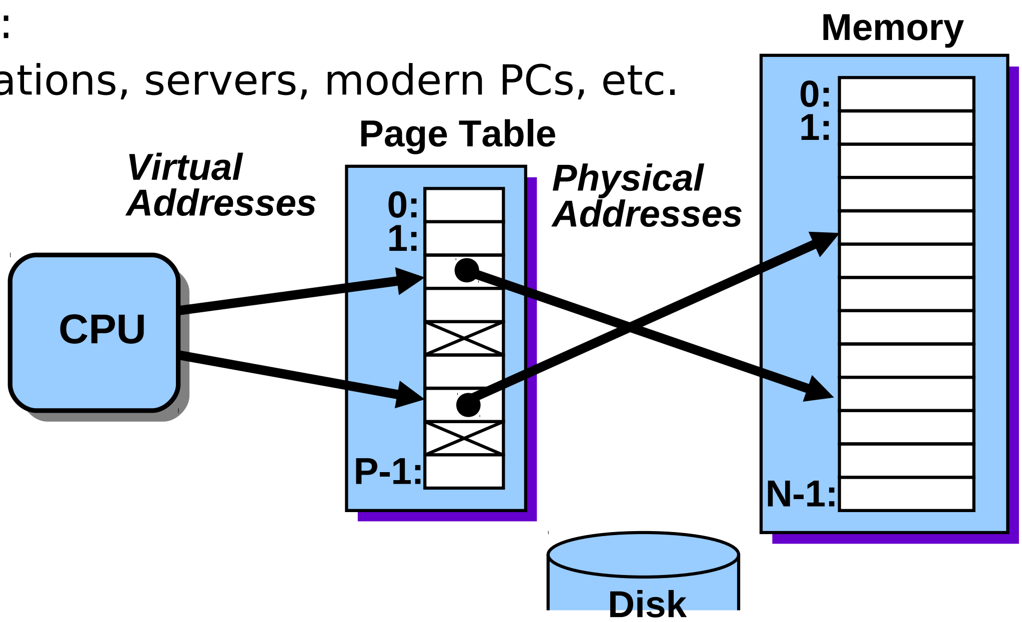
- Examples:
  - most Cray machines, early PCs, nearly all embedded systems, etc.



- Addresses generated by the CPU correspond directly to bytes in physical memory

A System with Virtual Memory

- Examples:
  - workstations, servers, modern PCs, etc.



- Address Translation: Hardware converts virtual addresses to physical addresses via OS-managed lookup table (**page table**)

Paging

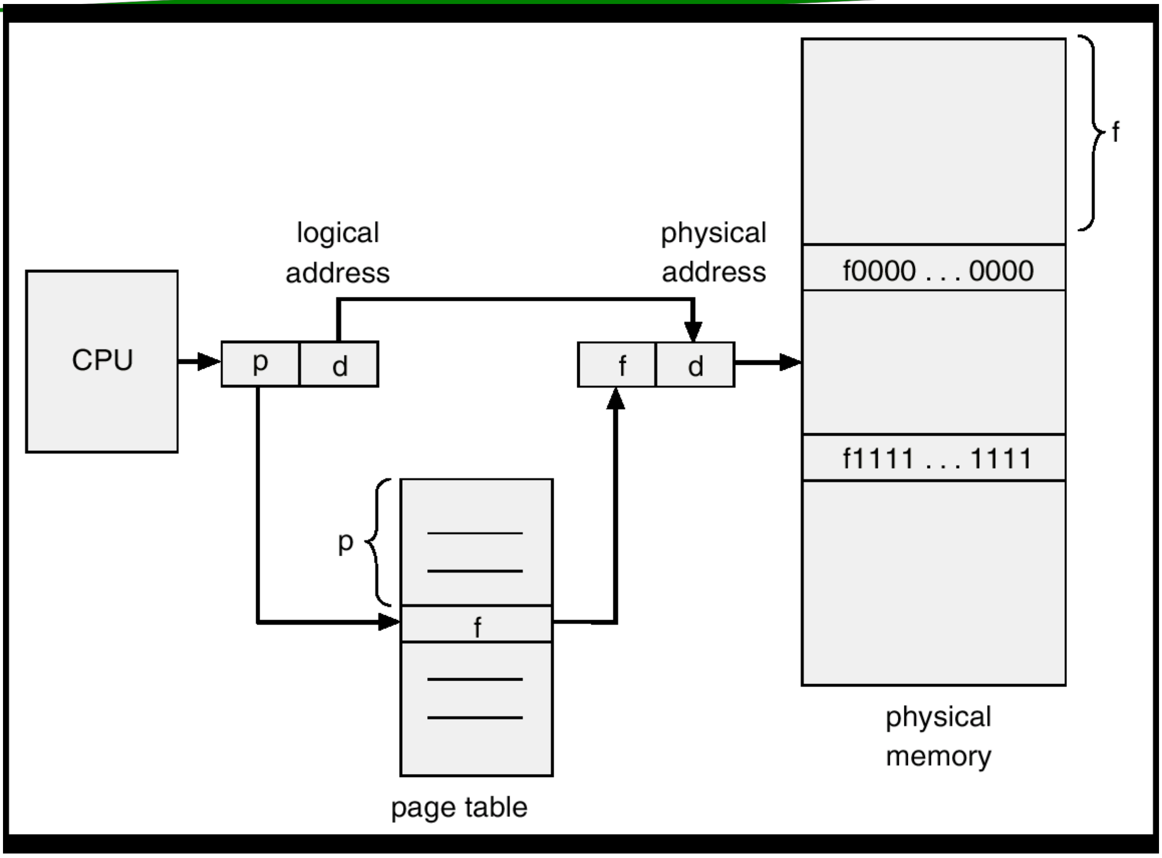
- One of several methods of implementing virtual memory
- Divide physical memory into fixed-sized blocks called **page frames**
  - size is power of 2, usually between 512 bytes and 8192 bytes
- Divide logical memory into blocks of same size called **pages**
- Keep track of all free page frames
- To run a program of size n pages, need to find n free frames and load program
- Set up a page table to translate logical to physical addresses

Address Translation Scheme

- Address generated by CPU is divided into:
  - **Page number** (p) – used as an index into a page table which contains base address of each page in physical memory
  - **Page offset** (d) – combined with base address to define the physical memory address that is sent to the memory unit

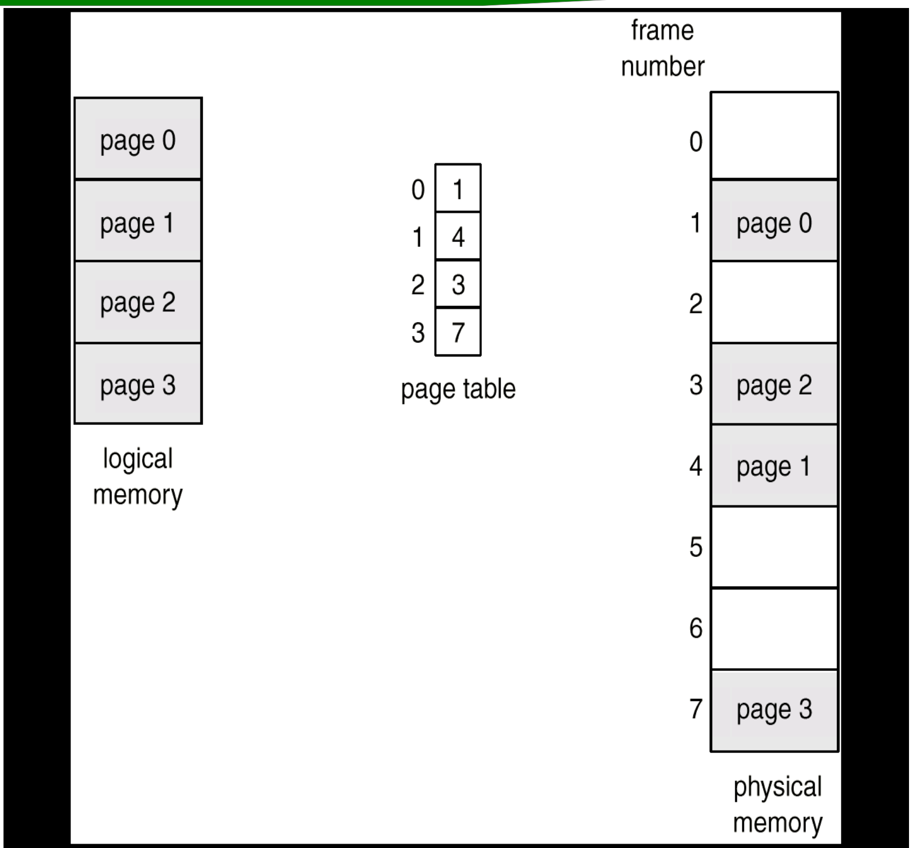
Address: | p | d |

Address Translation Architecture



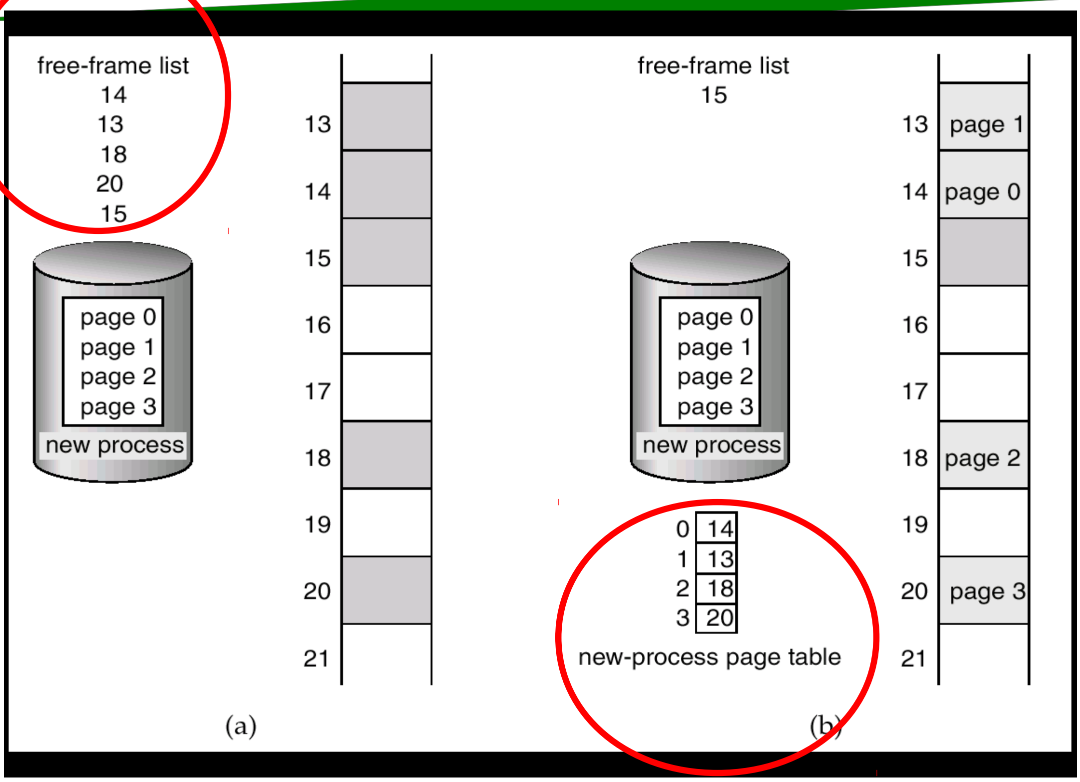
CSSE 2310 7231

Paging Example



BREAK

Free Frames



Before allocation

After allocation

Implementation of Page Table

- Page table is kept in main memory
- In this scheme every data/instruction access requires two memory accesses
  - One for the page table and one for the data/instruction
- The two memory access problem can be solved by the use of a special fast-lookup hardware cache called associative memory or **translation look-aside buffers** (**TLBs**)

CSSE 2310 7231

Aside: Associative Memory

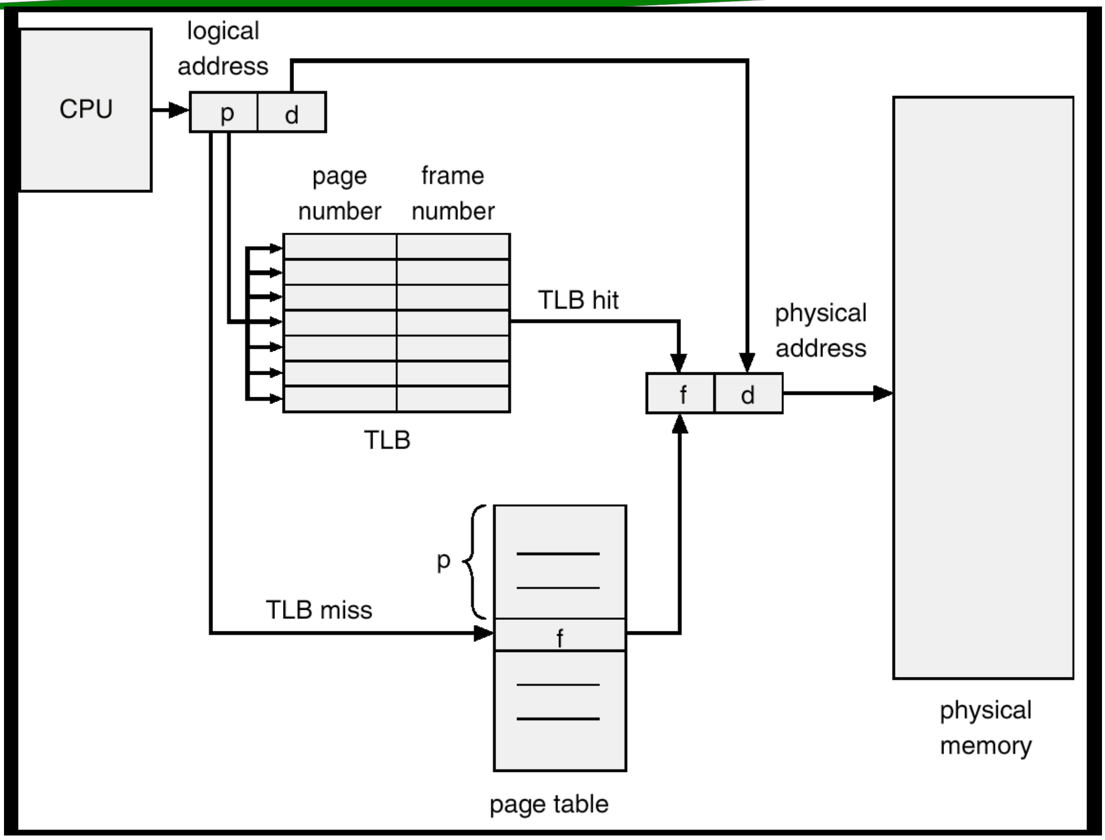
- Associative memory allows parallel search

Page #	Frame #

Address translation (A´, A´´)

- If A´ is in associative register, get frame # out.
- Otherwise get frame # from page table in memory

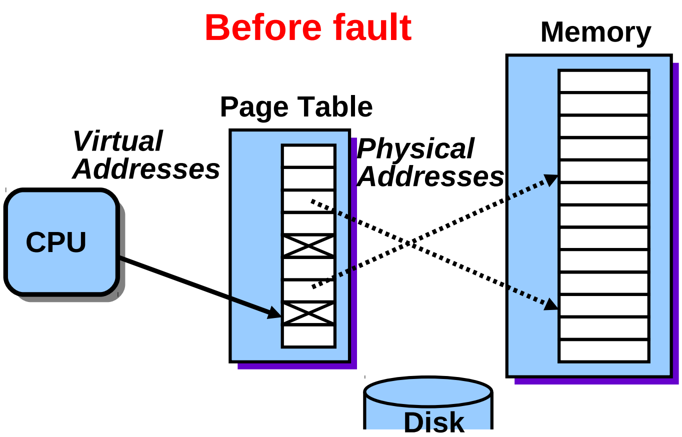
Paging Hardware With TLB

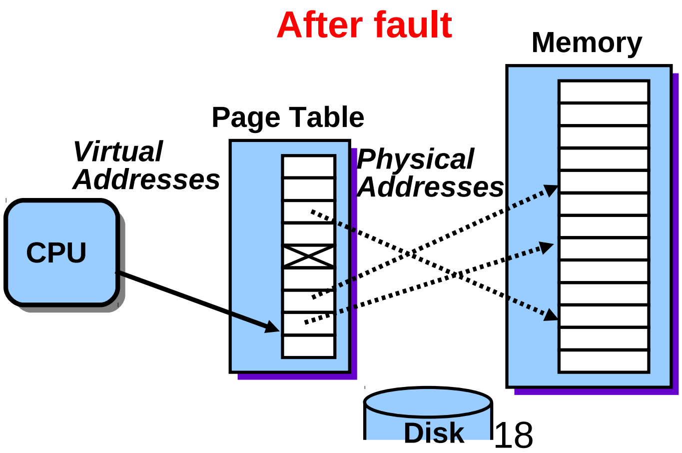


CSSE 2310 7231

Page Faults

- What if an object is on disk rather than in memory?
  - Page table entry indicates virtual address not in memory
  - OS exception handler invoked to move data from disk into memory
    - current process suspended, others can resume
    - OS has full control over placement, etc.





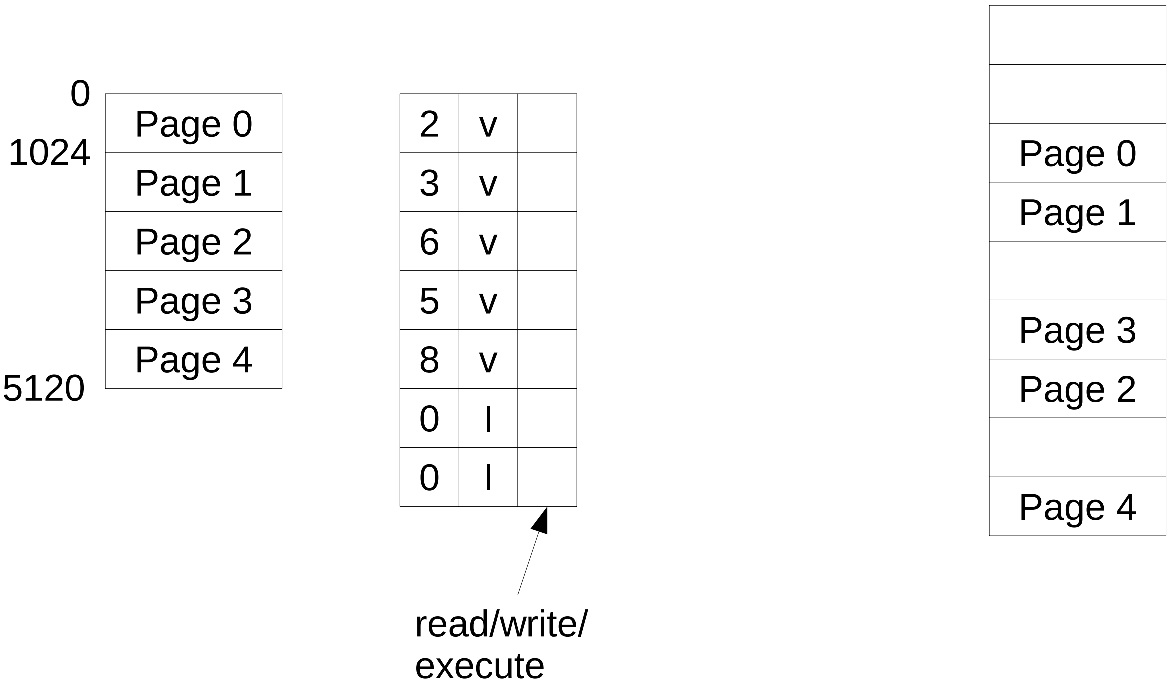
Page Replacement Algorithms

- On a page fault, which page should be removed to make space for incoming page?
  - **Optimal** approach – choose page not needed until furthest in future
    - Impossible to predict the future!
- Many algorithms possible
  - **NRU** - Not recently used
  - **FIFO** - First-in, First-out
  - **LRU** - Least Recently Used
  - **NFU** - Not Frequently Used
  - **Clock**
  - **Working Set**
  - **Working Set Clock**
- Not a topic for this course

Memory Protection

- Memory protection implemented by associating protection bit with each frame
- Valid-invalid bit attached to each entry in the page table:
  - "valid" indicates that the associated page is in the process' logical address space, and is thus a legal page
  - "invalid" indicates that the page is not in the process' logical address space

Memory protection (ctd)

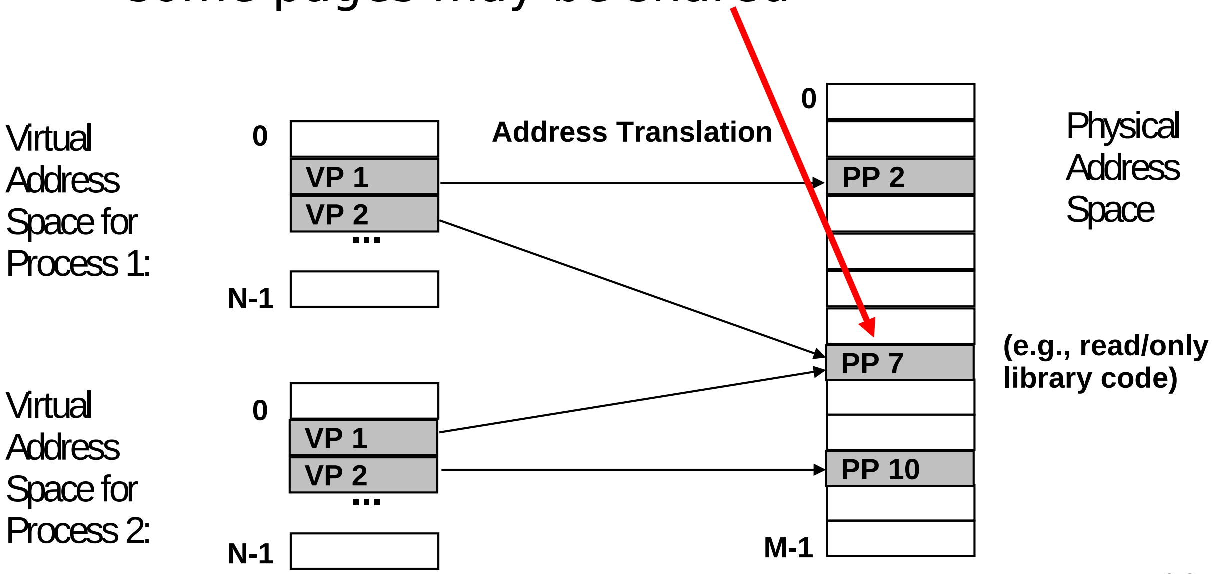


Segmentation Faults

- Segmentation Fault arises when
  - Accessing invalid memory page
  - Trying to write to a read-only page

Separate Virtual Address Spaces

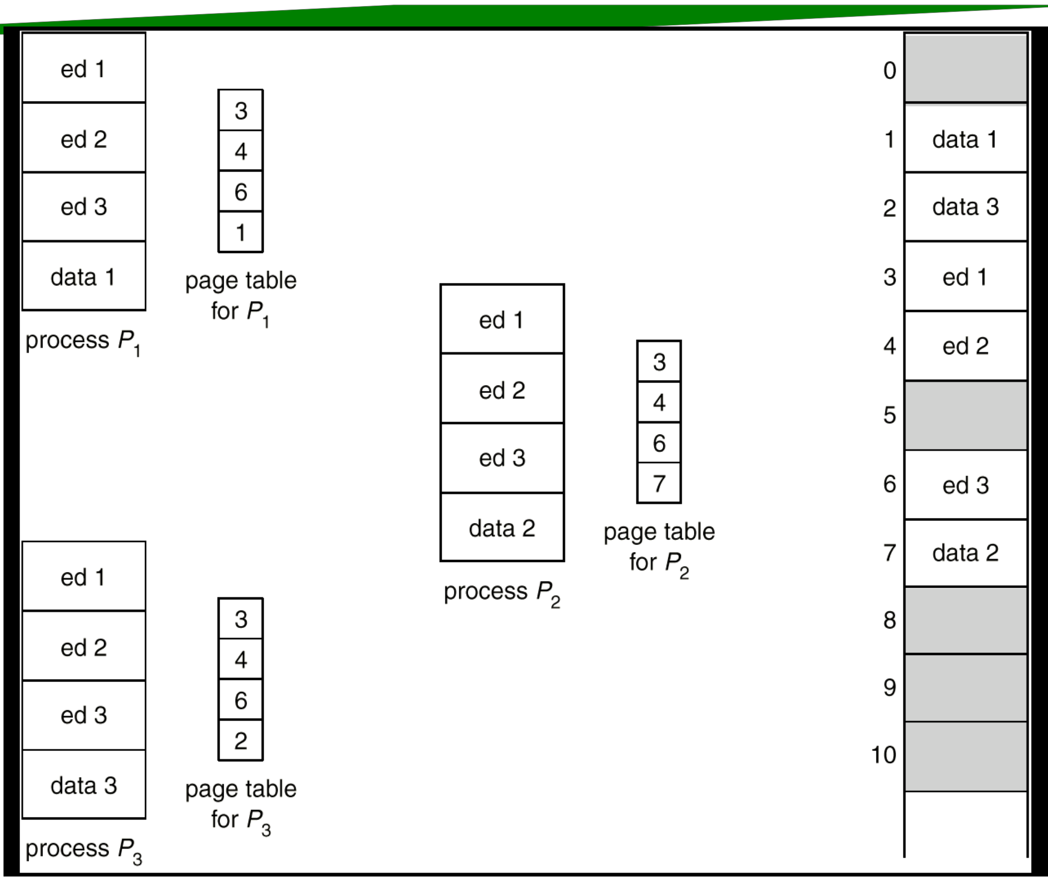
- Each process has its own virtual address space
  - separate page tables
  - some pages may be shared



Shared Pages

- Shared code
  - One copy of read-only code shared among processes (i.e., text editors, compilers, window systems)
  - Shared code must appear in same location in the virtual address space of all processes.
- Private code and data
  - Each process keeps a separate copy of the code and data
  - The pages for the private code and data can appear anywhere in the virtual address space
- Data can be shared also
  - Pages can be at different locations in the virtual address spaces of each process

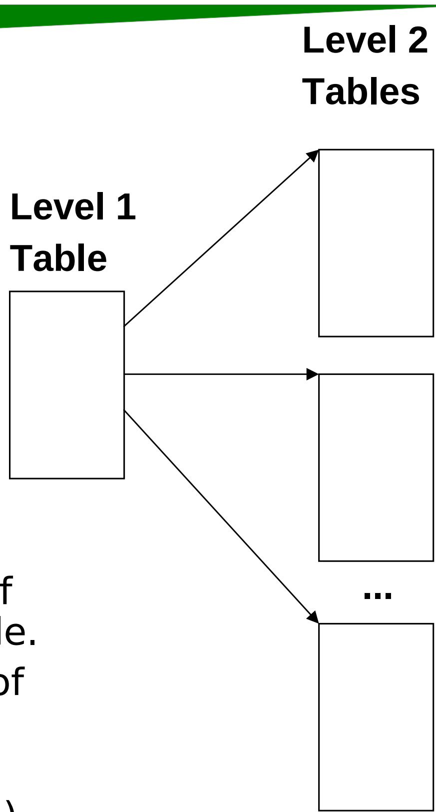
Shared Pages Example



CSSE 2310 7231

Multi-Level Page Tables

- Example:
  - 4kB (2^{12} bytes) page size
  - 32-bit address space
  - 4-byte page table entry
- Problem:
  - Would need a 4 MB page table!
    - 2^{20} *4 bytes
- Common solution
  - multi-level page tables
  - e.g. 2-level table (Intel processors)
    - Level 1 table: 1024 entries, each of which points to a Level 2 page table.
    - Level 2 table: 1024 entries, each of which points to a page
- Note – page tables at each level typically occupy one full page (4kB in this example)



Example

- Given multi-level page table structure as described on previous slide, how much memory is needed for the page table(s) for a process using 512MB of memory?
- What about for a process using 1MB of memory?

- Remember
  - 512MB = 2^9MB = $2^9 \times 2^{10} \times 2^{10}$ bytes
  - 1MB = 2^{20}bytes

Exercise

- Consider a system with 36-bit physical memory addresses and 32-bit virtual memory addresses. Pages are of size 8kB (2^{13} bytes) and page table entries are 4 bytes each.
- If the system uses single level page tables, how much memory is used by the page table for a process?
- If the system uses two-level page tables, how much memory is used by the page tables for a process using 1GB (2^{30} bytes)?

You have 2 minutes

Exercise

- Consider a system with 36-bit physical memory addresses and 32-bit virtual memory addresses. Pages are of size 8kB (2^{13} bytes) and page table entries are 4 bytes each.
- ...

You have 2 minutes

Other Issues

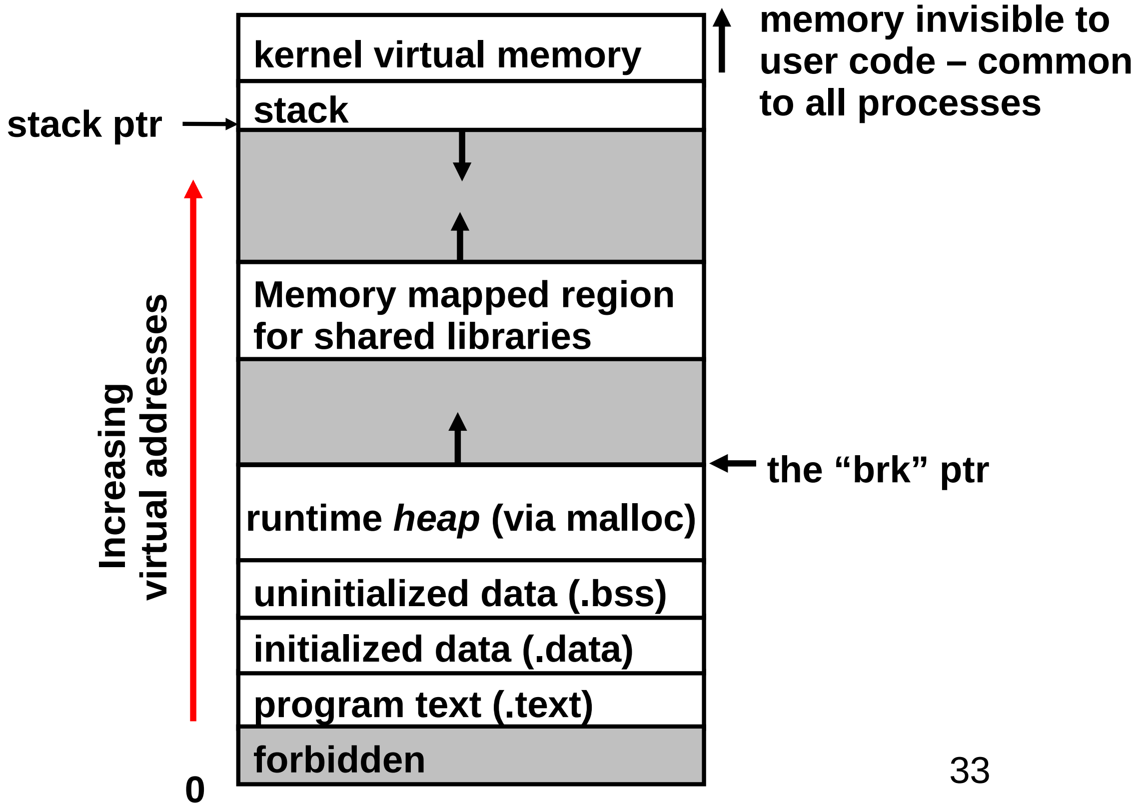
- Hashed page tables
- Inverted page tables
- Segmentation
- Ideal size of pages

- Not topics for this course

User-space Memory management

Typical Process Memory Usage

Process memory image (UNIX / Linux)



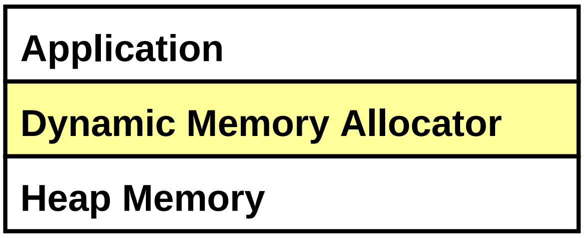
User-space vs Kernel

- The operating system controls the address ranges (pages) a process can use. It does not decide how that space is used.
- Management of those pages is the responsibility of the process.
  - Usually via standard libraries.

User-space vs Kernel

- The operating system controls the address ranges (pages) a process can use. It does not decide how that space is used.
- Management of those pages is the responsibility of the process.
  - Usually via standard libraries.

Dynamic Memory Allocation



- Explicit vs. Implicit Memory Allocator
  - **Explicit**: application allocates and frees space
    - E.g., `malloc` and `free` in C
  - **Implicit**: application allocates, but does not free space
    - E.g. **garbage collection** in functional languages, scripting languages, and modern object oriented languages: Lisp, Java, Perl, Mathematica, …
- Allocation
  - In both cases the memory allocator provides an abstraction of memory as a set of blocks
  - Doles out free memory blocks to application

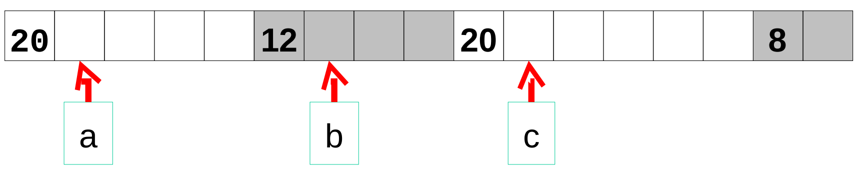
Where Does `malloc()` get its Memory?

- System calls
  - `brk()`
  - `sbrk()`
- See manual pages on moss
- See also end (section 3c)

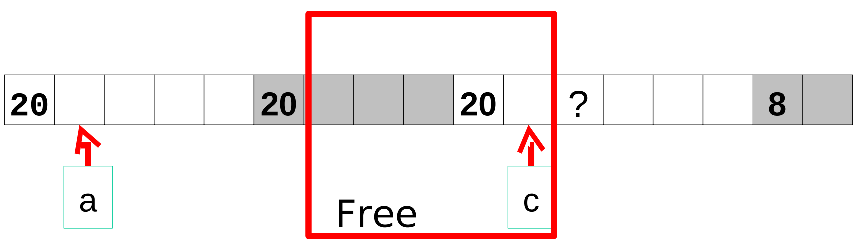
- `free()` doesn't necessarily return memory to the operating system – may just keep track of it for future use by the application

Trashing the heap

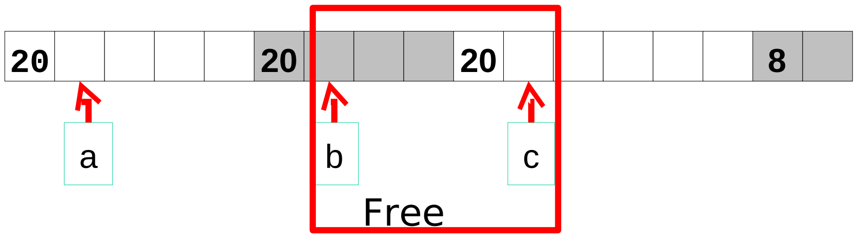
- Allocators may record audit information near the allocated memory. (For example the size of the allocation)



- Now consider a[4]=20; free(b);



Trashing the heap



- Now c[0] is in free space (as is the size of c).
- If this space is allocated to something else, free(c) could get very interesting.

Memory-Related Bugs

- Dereferencing bad pointers
- Reading uninitialized memory
- Overwriting memory
- Referencing nonexistent variables
- Freeing blocks multiple times
- Referencing freed blocks
- Failing to free blocks

Dereferencing Bad Pointers

- The classic scanf bug

```
scanf("%d", val);
```


Reading Uninitialized Memory

- Assuming that heap data is initialized to zero

```
/* return y = Ax */
int *matvec(int **A, int *x) {
    int *y = malloc(N*sizeof(int));
    int i, j;

    for (i=0; i<N; i++) {
        for (j=0; j<N; j++) {
            y[i] += A[i][j]*x[j];
        }
    }
    return y;
}
```

Overwriting Memory

- Allocating the (possibly) wrong sized object

```
int **p;

p = malloc(N*sizeof(int));

for (i=0; i<N; i++) {
    p[i] = malloc(M*sizeof(int));
}
```


Overwriting Memory

- Off-by-one error

```
int **p;

p = malloc(N*sizeof(int));

for (i=0; i<=N; i++) {
    p[i] = malloc(M*sizeof(int));
}
```

Overwriting Memory

- Not checking max string size

```
char s[8];

get(s); // enter 1234567890
```

- Basis for classic buffer overflow attacks.

Overwriting Memory

- Referencing a pointer instead of the object it points to

```
void swap(int* a, int* b) {
    int c=a;
    a=b;
    c=c;
}
```

Overwriting Memory

- Misunderstanding pointer arithmetic

```
int* search(int* p, int val) {
    while (*p && *p!=val) {
        p+=sizeof(int);
    }
    return p;
}
```


Referencing Nonexistent Variables

- Forgetting that local variables disappear when a function returns

```
int *foo () {
    int val;
    return &val;
}
```

Freeing Blocks Multiple Times

- Nasty!

```
x = malloc(N*sizeof(int));
<manipulate x>
free(x);

y = malloc(M*sizeof(int));
<manipulate y>
free(x);
```


Referencing Freed Blocks

- Evil!

```
x = malloc(N*sizeof(int));
<manipulate x>
free(x);
...
y = malloc(M*sizeof(int));
for (i=0; i<M; i++) {
    y[i] = x[i]++;
}
```

CSSE 2310 7231

Failing to Free Blocks (Memory Leaks)

- Slow, long-term killer!

```
foo() {
    int *x = malloc(N*sizeof(int));
    ...
    return;
}
```


CSSE 2310 7231

Failing to Free Blocks (Memory Leaks)

- Freeing only part of a data structure

```
struct list {
    int val;
    struct list* next;
};

void foo() {
    struct list* head=
           malloc(sizeof(struct list));
    head->val=0;
    head->next=0;
    <create and use the rest of the list>
    …
    free(head);
}
```

Dealing With Memory Bugs

- Conventional debugger (`gdb`)
  - Good for finding bad pointer dereferences
  - Hard to detect the other memory bugs
- Debugging `malloc` (CSRI UToronto `malloc`)
  - Wrapper around conventional `malloc`
  - Detects memory bugs at `malloc` and `free` boundaries
    - Memory overwrites that corrupt heap structures
    - Some instances of freeing blocks multiple times
    - Memory leaks
  - Cannot detect all memory bugs
    - Overwrites into the middle of allocated blocks
    - Freeing block twice that has been reallocated in the interim
    - Referencing freed blocks

Dealing With Memory Bugs (cont.)

- Check while executing:
  - valgrind (linux)
  - bcheck (agave)
- Garbage collection (Boehm-Weiser Conservative GC)
  - Let the system free blocks instead of the programmer

Memory Matters!

- Memory is not unbounded
  - It must be allocated and managed
    - malloc(), free() etc
  - Many applications are memory dominated
    - Especially those based on complex, graph algorithms
- Memory referencing bugs especially pernicious
  - Effects are distant in both time and space
- Memory performance is not uniform
  - Cache and virtual memory effects can greatly affect program performance
  - Adapting program to characteristics of memory system can lead to major speed improvements