CSCI [4 | 6]730
Operating Systems

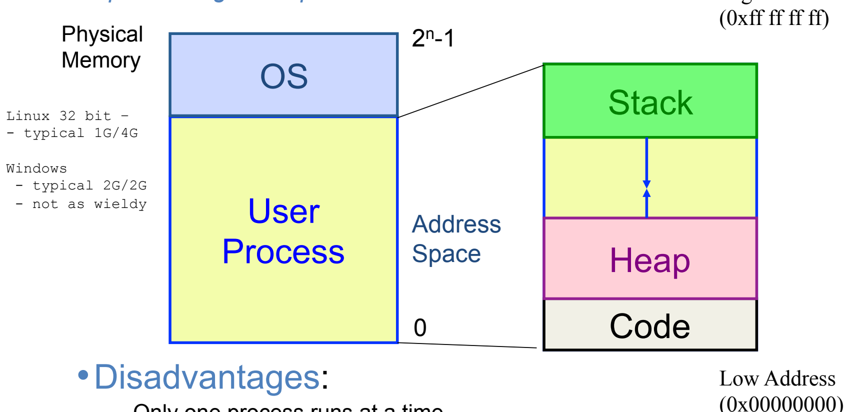
Main Memory

Memory Questions?

- What is main memory?
- How does *multiple* processes share memory space?
  - Key is how do they refer to the memory addresses.
    - Utilizing memory access for everyone! Dynamically!
- What is *static* and *dynamic* allocation?
- What is *segmentation*?

Review: Motivation for Multiprogramming

Uni-*processing: One process runs at a time*



- **Disadvantages**:
  - Only one process runs at a time
  - Process can destroy OS (need to avoid)

http://duartes.org/gustavo/blog/post/anatomy-of-a-program-in-memory/

Multiprogramming Goals

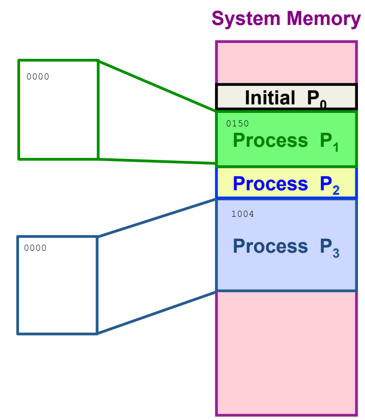
- Sharing
  - Several processes co-exist in main memory
  - Cooperating processes can share portions of address space (
- Transparency
  - Processes are not aware that memory is shared
  - Works regardless of number and/or location of processes
- Protection
  - Cannot corrupt OS or other processes
  - Privacy: Cannot read data of other processes
- Efficiency
  - Do not waste CPU or memory resources
  - Keep fragmentation low (later)

Memory Addresses

- Address space
  - What we got so far:
    - **Physical addresses**
    - How can we make access to these transparent?
- Need to provide support for **multiple** processes loaded into memory (and make memory accessible).
  - Option 1: Static Reallocation (IBM S/360)

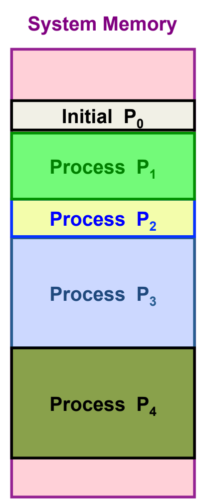
Static Relocation (after loading)

- Goal: Allow transparent sharing - Each address space may be placed *anywhere* in memory
  - OS finds free space for new process
  - Modify (rewrite) addresses (similar to linker) when loading the process (addresses modified only once).
  - Fixed addresses.
- Advantages:
  - Allows multiple processes to run
  - Requires **no hardware** support



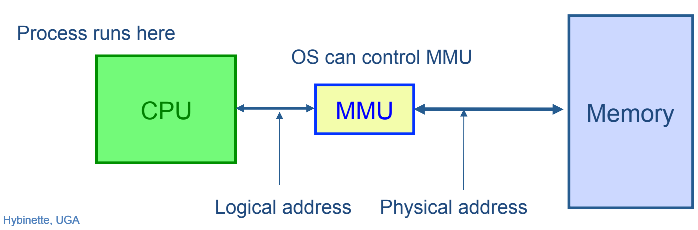
Static Reallocation

- Disadvantages:
  - No protection
    - Process can destroy OS or other processes
    - No privacy
  - Address space must be allocated contiguously
    - Allocate space for worst-case stack and heap
    - Processes may not grow (in size).
  - Cannot move process after they are placed or loaded (static addresses)
  - Fragmentation (later)



Dynamic Relocation (hardware support)

- Goal: *Protect* processes from one another
- Requires hardware support
  - Memory Management Unit (MMU)
- MMU dynamically changes process address *at every* memory reference (compute address on-the-fly)
  - Process generates logical or virtual addresses
  - Memory hardware uses physical or real addresses

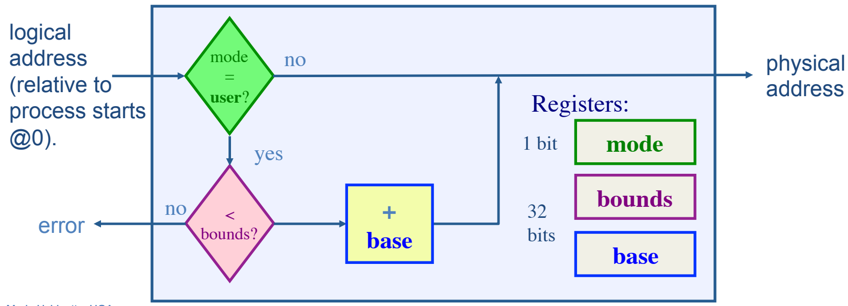


Hardware Support for Dynamic Relocation

- Two operating modes
  - Privileged (protected, kernel) mode: OS runs
    - When enter OS (trap, system calls, interrupts, exceptions)
    - Allows certain instructions to be executed
      - Can manipulate contents of MMU
    - Allows OS to access all of physical memory
  - User mode: User processes run
    - Perform translation of logical address to physical address
- MMU contains base and bounds registers
  - base: start location for address space (physical address)
  - bounds: size limit of address space (memory span)

Implementation of Dynamic Relocation

- Translation on every memory access of user process
  - MMU compares logical address to bounds register
    - if logical address is greater, then generate error
  - MMU adds base register to logical address to form physical address



Example of Dynamic Relocation

- What are the physical addresses for the following 16-bit logical addresses (HEX: highest F:1111)?
- Process 1: base: `0x4320`, bounds: `0x2220 (in HEX)`
  - `0x0000:`
  - `0x1110:`
  - `0x3000:`
- Process 2: base: `0x8540`, bounds: `0x3330`
  - `0x0000:`
  - `0x1110:`
  - `0x3000:`
- Operating System
  - `0x0000:`
  - `0x5FFF:`

Example of Dynamic Relocation

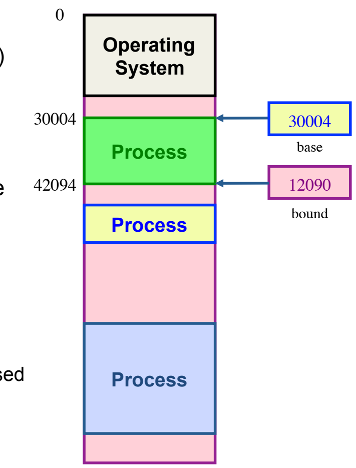
- What are the physical addresses for the following 16-bit logical addresses (HEX: highest F: 0x1111)?
- Process 1: base: `0x4320`, bounds: `0x2220 (in HEX)`
  - `0x0000:    0x4320`
  - `0x1110:    0x5430`
  - `0x3000:    segmentation fault`
- Process 2: base: `0x8540`, bounds: `0x3330`
  - `0x0000:    0x8540`
  - `0x1110:    0x9650`
  - `0x3000:    0xB540`
- Operating System
  - `0x0000:    0x0000`
  - `0x5FFF:    0x5FFF`

Managing Processes with *Base* and *Bounds*

- Context-switch
  - Add base and bounds registers to (process control block) PCB
  - Steps:
    1. Change to privileged mode
    2. Save base and bounds registers of old process
    3. Load base and bounds registers of new process
    4. Change to user mode and jump to new process
- What if don’t change base and bounds registers when switch?
- Protection requirement
  - User process cannot change base and bounds registers
  - User process cannot change to privileged mode

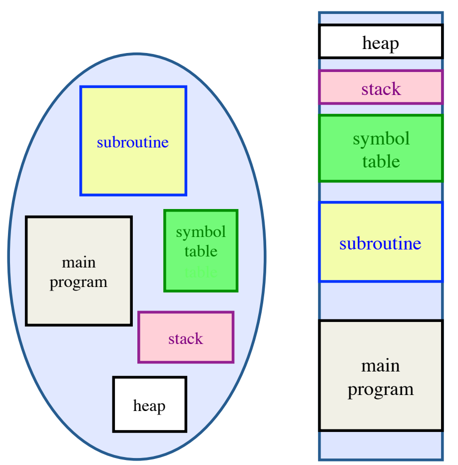
Base and Bounds Discussion

- Advantages
  - Provides protection (both read and write) across address spaces
  - Supports dynamic relocation
    - Can move address spaces
    - Why might you want to do this?
  - Simple, inexpensive: Few registers, little logic in MMU
  - Fast: Add and compare can be done in parallel
- Disadvantages
  - Each process must be allocated contiguously in physical memory
    - Must allocate memory that may not be used by process in advance
  - No partial sharing: Cannot share limited parts of address space
- Examples: MINIX, IBM 360, UNIVAC



Segmentation

- Divide address space into logical segments
  - Each segment corresponds to logical entity in address space
    - code,
    - stack,
    - heap
- Each segment can independently:
  - be placed separately in physical memory
  - grow and shrink
  - be protected (separate read/write/execute protection bits)
- Example: MULTICS, UNIX ancestor.



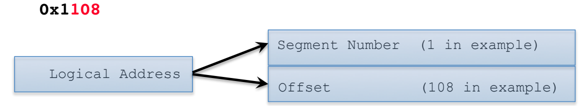
Logical Address Space

Physical Address Space

Segmented Addressing

- How does process designate a particular segment?
  - Use part of logical address
    - Top bits of logical address select segment
    - Low bits of logical address select offset within segment

```
Example: 4 bits - nibble
    0x1108
```




```
Need Base Address
Need Bounds
```

Segmentation Implementation

- MMU accesses a Segment Table (per process)
  - Each segment has own base and bounds, (+ protection bits)
  - Example : 0x1108

Segment	Base	Bounds	R W
0 (stack)	0x4000	0x06ff	1 0
1 (heap)	0x0000	0x04ff	1 1
2 (code)	0x3000	0x0fff	1 1
3	0x1000	0x0fff	0 0

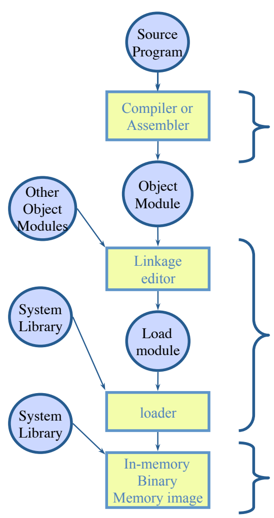
- **Translate logical addresses ⇒ physical addresses:**
  - `0x0240`: 0^{th} segment 240 internal address within segment ⇒ what address?
  - `0x1108`:
  - `0x265c`:
  - `0x3002`:

Discussion of Segmentation

- Advantages
  - Enables sparse allocation of address space
    - Stack and heap can grow independently
    - Heap: If no data on free list, dynamic memory allocator requests more from OS (e.g., UNIX: malloc calls sbrk())
    - Stack: OS recognizes reference outside legal segment, **extends** stack implicitly
  - Different protection for different segments
    - Read-only status for code
  - Enables sharing of selected segments
  - Supports dynamic relocation of each segment
- Disadvantages
  - Each segment must be allocated contiguously
    - May not have sufficient physical memory for large segments

When to *Bind* Physical & Logical Addresses

- Compile time: If memory location known a priori, absolute code can be generated; must recompile code if starting location changes
- Load time: Must generate relocatable code if memory location is not known at compile time
- Run Time: Binding delayed until run time if the process can be moved during its execution from one memory segment to another.
  - ** Need hardware support for address maps (e.g., base and limit registers)



Motivation for Dynamic Memory

- Why do processes need dynamic allocation of memory?
  - Do not know amount of memory needed at compile time
  - Must be pessimistic when allocate memory statically
    - Allocate enough for worst possible case
    - Storage is used inefficiently
- Recursive procedures
  - Do not know how many times procedure will be nested
- Complex data structures: lists and trees
  - ```
    struct my_t
      *p = (struct my_t *)malloc(sizeof(struct my_t));
    ```
- Two types of dynamic allocation
  - Stack
  - Heap
    ```

Stack Organization

- Definition: Memory is freed in opposite order from allocation

```
alloc(A);
alloc(B);
alloc(C);
free(C);
alloc(D);
free(D);
free(B);
free(A);
```

- Implementation: Pointer separates allocated and freed space
  - Allocate: Increment pointer
  - Free: Decrement pointer

Stack Discussion (Review)

OS uses stack for procedure call frames (local variables)

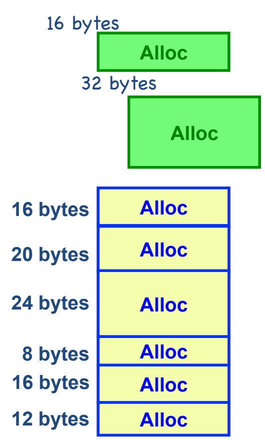
```
main()
{
  int A = 0;
  maria(A);
  printf("A: %d\n", A);
}
```

```
void maria( int Z )
{
  int A = 2;
  Z = 5; // input parameter
  printf("A: %d Z: %d\n", A, Z);
}
```

- Advantages
  - » **Keeps all free space contiguous (and keep order of calls)**
  - » **Simple to implement**
  - » **Efficient at run time**
- Disadvantages
  - » **Not appropriate for all data structures**

Heap Organization

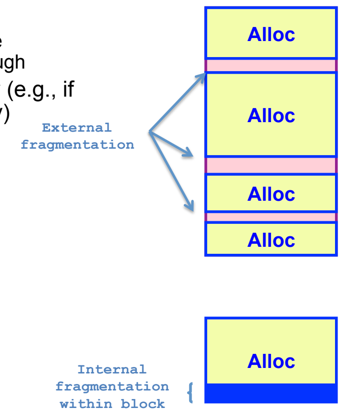
- Definition: Allocate from any random location
  - Memory consists of allocated areas and free areas (holes)
  - Order of allocation and free is unpredictable
- Advantage
  - Works for all data structures
- Disadvantages
  - Allocation can be slow
  - End up with small chunks of free space
    - Fragmentation



- Heap: Design Question:
  - Selection of which memory block to use.
  - Keeping Track of Free List, what do do with a block that has just been freed.
  - What to do with left over space (if any) in a block.
  - Avoid fragmentation

Fragmentation

- Definition: Free memory that is too small to be usefully allocated
  - External: Visible to allocator
    - Free memory exist but not single contiguous free block is big enough
  - Internal: Visible to requester only (e.g., if must allocate at some granularity)
- Goal:
- Minimize fragmentation
  - Few holes, each hole is large
  - Free space is contiguous
- Stack
  - All free space is contiguous
  - No fragmentation

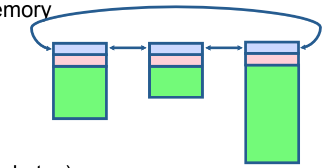


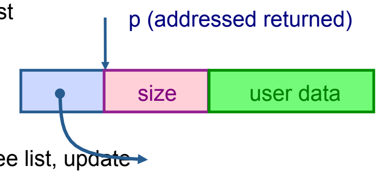
`Lets look at free block data structure first.`

Heap Implementation: Free List

Data Structure Setup

- Data structure: free list
  - A circular linked list of free blocks, tracks memory not in use
  - Header in each block
    - size of block
    - ptr to next block in list
- `void *Allocate( x bytes )`
  - Choose block large enough for request (>= x bytes)
  - Keep remainder of free block on free list
  - Update list pointers and size variable
  - Return pointer to allocated memory
- `Free( ptr )`
  - Add block back to free list
  - Merge (coalesce) adjacent blocks in free list, update ptrs and size variables





Heap Allocation Policies

Which Block?

- Best fit
  - Search entire list for each allocation
  - Choose free block that most closely matches size of request
  - Optimization: Stop searching if see exact (close) match
- First fit
  - Version 1:
    - Allocate first block that is large enough
  - Version 2:
    - Rotating first fit (or "Next fit"):
      - Variant of first fit, remember place in list
      - Start with next free block each time
- Worst fit
  - Allocate largest block to request (most left-over space)

Heap Allocation Examples

Scenario: Two free blocks of size 20 and 15 bytes

- Allocation stream: 10, 20
  - Best
  - First
  - Worst
- Allocation stream: 8, 12, 12
  - Best
  - First
  - Worst

Comparison of Allocation Strategies

- No optimal algorithm
  - Fragmentation highly dependent on workload
- Best fit
  - Tends to leave some (large holes) and some small holes
    - Can't use small holes easily
- First fit
  - Tends to leave "average" sized holes
  - Advantage: Faster than best fit
  - Next fit used often in practice
- Uses a 'Modified' Buddy allocation Scheme (Linux)
  - Minimizes external fragmentation
  - Disadvantage: *Internal* fragmentation when not 2^n request

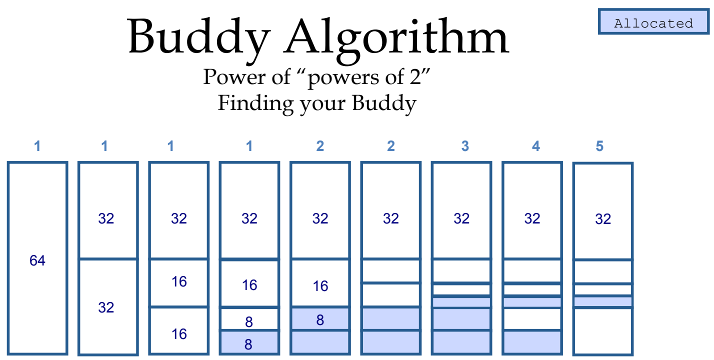
A Simple Buddy Allocation

Boundary at Powers of 2

- Fast, simple allocation for blocks of 2^n bytes [Knuth68] (Markowitz 1963) – keeps memory alignment, blocks addressing begins at powers of 2 by allocating / coalescing buddy's
- `void *Allocate ( k bytes )`
  - Raise allocation request to nearest (next highest) $s = 2^n$
    - 63K allocates a 64K block
    - 65K allocates a 128K block
    - 31K allocates a 32K block
  - Search free list for appropriate size (near s)
    - Recursively divide larger free blocks until find block of size s
    - "Buddy" block remains free
- `Free( ptr )`
  - Mark blocks as as free
  - **Recursively coalesce block with buddy**, if buddy is free
    - May coalesce lazily (later, in background) to avoid overhead

Buddy Algorithm

Power of "powers of 2"
Finding your Buddy



Toy Example: Assume there is initially 64K bytes of memory and the first request is for 5K bytes -> all requests: [5K, 8K, 4K, Free 8K]

1. Round up request to nearest s=2^n K ⇒ so we need a s= 8K bytes and search for a block of that size
   - Divide 64K block chunk into half (again, again and again) until desired block size and return to caller (shaded area)
2. Suppose second request is for 8K then return remaining free chunk to be used
3. Third request is for 4K -- split block again and again and return to caller
4. Fourth and last allocated 8K chunk is released and returned
5. Finally the other is released and coalesced

https://en.wikipedia.org/wiki/Buddy_memory_allocation

Buddy Implementation

Who is my buddy?

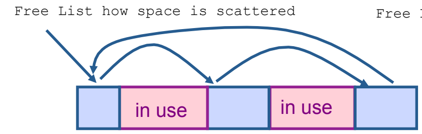
- IF holes in free list is of **power of 2** in size then very easy to implement:
  - A buddy's hole is the **exclusive OR (✪)** if the hole size and starting address of hole.
- Example:
  - Buddy's block of hole size 4 when we start at addresses:
    - 0, 4, 8, 12, 16, 20,

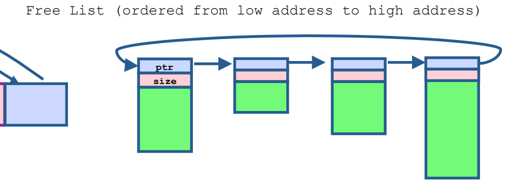
		My &	Size	Buddy &	
0	0 ✪ 4	0000000	0000100	**0000100**	4
4	4 ✪ 4	0000100	0000100	**0000000**	0
8	8 ✪ 4	0001000	0000100	**0001100**	12
12	12 ✪ 4	0001100	0000100	**0001000**	8
16	16 ✪ 4	0010000	0000100	**0011000**	20
20	20 ✪ 4	0010100	0000100	**0010000**	16

Buddy algorithm

- Finds a ‘Best’ Fit in the power of 2.
- Little external fragmentation (compared to previous)
- Efficient
  - Binary tree – to keep track of used blocks (or unused)
  - Exclusive OR to find buddy.
- Still some Internal fragmentation

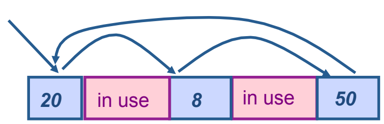
In Practice:
`malloc()/free()` Implementation





- **`Malloc/free`: Program calls these as needed program may also request space without using this allocator.**
  - **So space may not be contiguous in memory**
  - **Free list : keeps track of free blocks (circular list)**
  - **Allocate: First fit- first block big enough use, split block if too large.**
  - **Free: Possibly coalesce with (free) adjacent blocks (buddy)**
- **Disadvantage:**
  - » **Fragmentation of memory due to first-fit (next-fit) strategy**
  - » **Linear time to scan list during `malloc` and `free`**

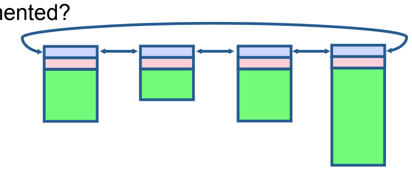
Possible Improvements



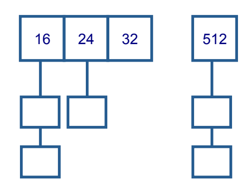
- Placement: Reducing fragmentation
  - Deciding which free chuck to use
  - Use best fit or *good* fit
    - Example: malloc(8) returns 8 byte block instead of 20 byte block (for first fit, good not best has some threshold)
- Splitting: only split when saving is “big enough”: malloc(14) allocate the entire block.
- Coalescing: defer coalescing
- Performance:
  - Use Double - linked list to be able to search quicker.

Memory Allocation in Practice
Binning

- How are `malloc(), free()` implemented?
- Data structure: Free lists
  - Header for each element of free list
    - pointer to next free block
    - size of block
    - magic number
      - consistency checking



- Two free lists
  - One organized by size (binning)
    - Separate list for each popular, small size (e.g., 1 KB) -- range of sizes -- fewer bins
    - Allocation is fast, no external fragmentation
  - Second is sorted by address
    - Use next fit to search appropriately
    - Free blocks shuffled between two lists



Linux: Dynamic Memory
Buddy Allocator + "Cache of Slabs"

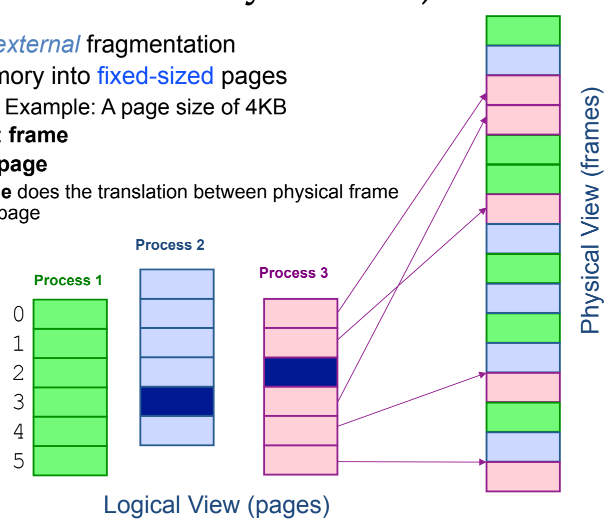
- Linux uses buddy system with the additional of having a cache of Slabs of pointers to free memory of a fixed size (typically for objects smaller than a page). Common sizes – inode, task_struct.
- Slab Allocator:
  - Fixed Size slab allocator: Cache contains objects of same size
    - Different "Common" sizes: 1, 2, 4, 8.
  - General Purpose blocks of size 2^n
    - Buddy Algorithm

Slab Allocator

- Advantages
  - Reduce internal fragmentation: many objects in one page.
  - Fast
- Disadvantages
  - Memory overhead for bookkeeping
  - Internal fragmentation for general-purpose slab allocator

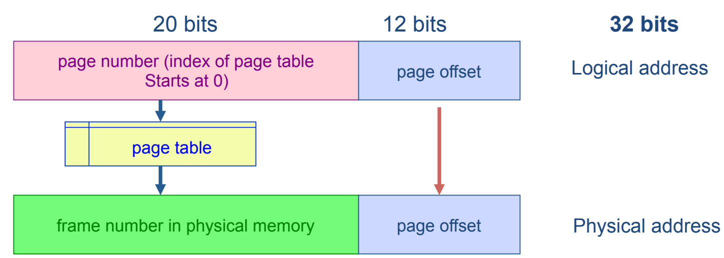
Paging (fixed memory blocks)

- Goal: Eliminate *external* fragmentation
- Idea: Divide memory into fixed-sized pages
  - Page Size: 2^n, Example: A page size of 4KB
  - Physical page: **frame**
  - Logical page: **page**
    - A **page table** does the translation between physical frame and logical page

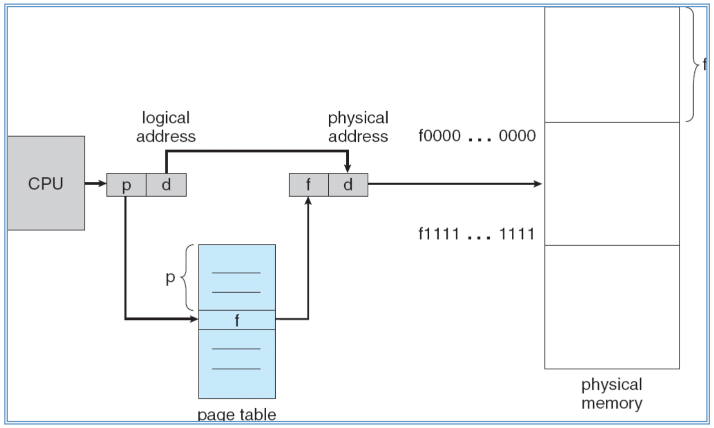


Translation of Page Addresses

- How to translate logical address to physical address:
  - High-order bits of address designate page number
  - Low-order bits of address designate offset within page



Paging Hardware



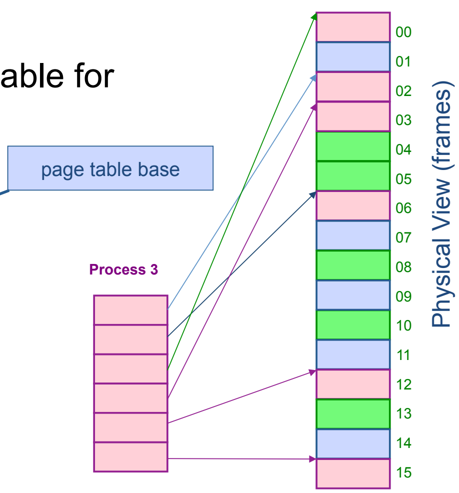
Page Table Implementation

- One page table per process
  - Page table entry (PTE) for each virtual page number (vpn)
    - frame number or physical page number (ppn)
    - **R/W protection bits**
- Simple vpn ⇒ ppn mapping:
  - No bounds checking, no addition
  - Simply table lookup and bit substitution
- **How many entries in table?**
- Track page table base in **PCB**, change on context-switch

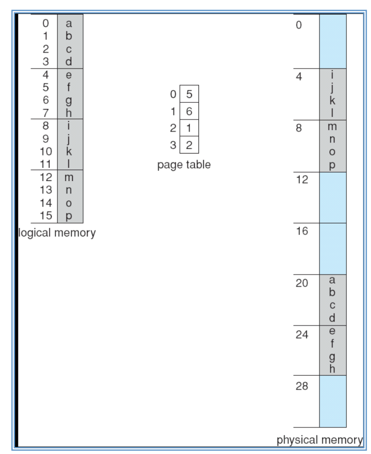
Page Table Example

- Contents of page table for process 3.

frame	R W
2	1 1
6	1 1
0	1 1
3	0 0
12	1 1
15	1 1



Page Table: Example 2 Logical Memory & Page Table



32-byte (8 pages) addressable memory and 4-byte pages

Advantages of Paging

- No **external fragmentation**
  - Any page can be placed in any frame in physical memory
  - Fast to allocate and free
    - Alloc: No searching for suitable free space
    - Free: No need to coalesce with adjacent free space
    - Just use bitmap to show free/allocated page frames
- Simple to swap-out portions of memory to disk
  - Page size matches disk block size
  - Can run process when some pages are on disk
  - Add "present" bit to page table entry (PTE)
- Enables sharing of portions of address space
  - To share a page, have PTE point to same frame

Disadvantages of Paging

- Internal fragmentation: Page size may not match size needed by process
  - Wasted memory grows with larger pages
  - large vs small page size
- Additional memory reference to look up in page table --> Very inefficient
  - Page table must be stored in memory
  - MMU stores only base address of page table
- Storage for page tables may be substantial
  - Simple page table: Requires PTE for all pages in address space
    - Entry needed even if page not allocated
  - Problematic with dynamic stack and heap within address space

Combine Paging and Segmentation

- Goal: More efficient support for sparse address spaces
- Idea:
  - Divide address space into segments (code, heap, stack)
    - Segments can be variable length
  - Divide each segment into fixed-sized pages
- Logical address divided into three portions: System 370

seg # (4 bits)	page number (18 bits)	page offset (12 bits)

- **Implementation**
  - » **Each segment has a page table**
  - » **Each segment track base (physical address) and bounds of page table (number of PTEs)**

Example of Paging and Segmentation

Example of Paging and Segmentation

seg	base	bounds	R W
0	1400	5	1 0
1	6300	400	0 0
2	4300	1100	1 1
3	1100	5	1 1

	...
1100	0x01f
	0x011
	0x003
	0x02a
	0x013
	...
1400	0x00c
	0x007
	0x004
	0x00b
	0x006
	...

Advantages of Paging and Segmentation

- Advantages of Segments
  - Supports sparse address spaces
    - Decreases size of page tables
    - If segment not used, not need for page table
- Advantages of Pages
  - No external fragmentation
  - Segments can grow without any reshuffling
  - Can run process when some pages are swapped to disk
- Advantages of Both
  - Increases flexibility of sharing
    - Share either single page or entire segment

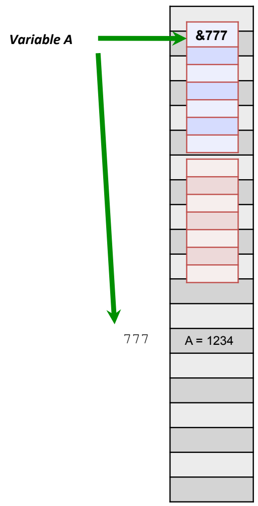
Disadvantages of Paging and Segmentation

- Overhead of accessing memory
  - Page tables reside in main memory
  - Overhead reference for every real memory reference
- Large page tables
  - Must allocate page tables contiguously
  - More problematic with more address bits
  - Page table size
    - Assume 2 bits for segment, 18 bits for page number, 12 bits for offset

Disadvantages of *Paging* and Segmentation

Details

- Overhead of accessing memory
  - Page tables reside in main memory
  - Overhead reference for every real memory reference
- Large page tables
  - Must allocate page tables contiguously
  - More problematic with more address bits
  - Page table size (32 bit address):
    - Logical address space: 2^{32}
    - Assume page size is 4 KB, 4,096 -> 2^{12}
    - Page table has $2^{32}/2^{12}$ entries = 2^{20}
      - 1,048,576 Entries ! Each entry is 4 bytes
        - » 4MB for EACH page table

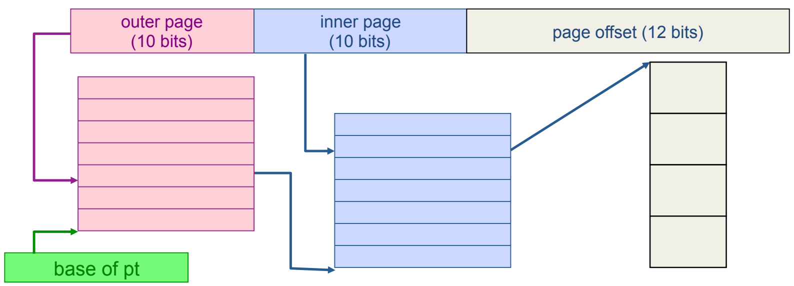


- 4 MB page tables Now page tables are becoming large.
  - Contagious in memory?
    - Divide the page tables into smaller pieces
    - Idea is to page the page table hierarchically
      - Assume 2 levels for a start.

Hierarchical Paging: Page the Page Tables

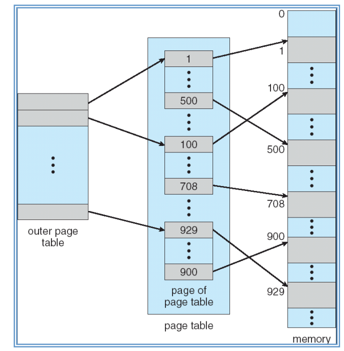
- Problem: Large logical address space 2^{32} - 2^{64}
- Goal: Allow page tables to be allocated non-contiguously
- Approach: Page the page tables (4K page size 4,096 is 2^{12})
  - Creates multiple levels of page tables
  - Only allocate page tables for pages in use (allows)

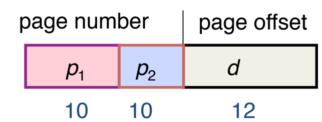
32-bit address:



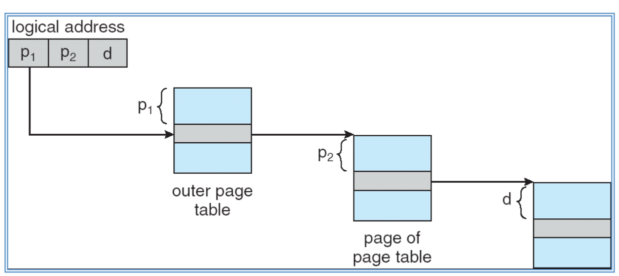
Example: Two Level Page Table

- **A logical address (on 32-bit machine with 4K page size) is divided into:**
  - » **a page number consisting of 20 bits**
  - » **a page offset consisting of 12 bits**
- **Since the page table is paged, the page number is further divided into:**
  - » **a 10-bit page number**
  - » **a 10-bit page offset**
- **Thus, a logical address is as follows:**
  - » **where p_1 is an index into the outer page table, and p_2 is the displacement within the page of the outer page table**





Address-Translation Scheme



Page the Page Tables (thinking)

- How should logical address be structured?
  - How many bits for each paging level? [10,10,12]?
- Calculate such that the page table fits within a page (frame) (A Page Table Entry = PTE)
  - Goal: PTE size * number PTE = page size
  - Assume PTE size = 4 bytes (32 bits); page size = 4 KB

    2^2 * number PTE = 2^12

    --> number PTE = 2^10

    →# bits for selecting inner page = 10 (see earlier slides)

→Apply recursively throughout logical address

Other Observation

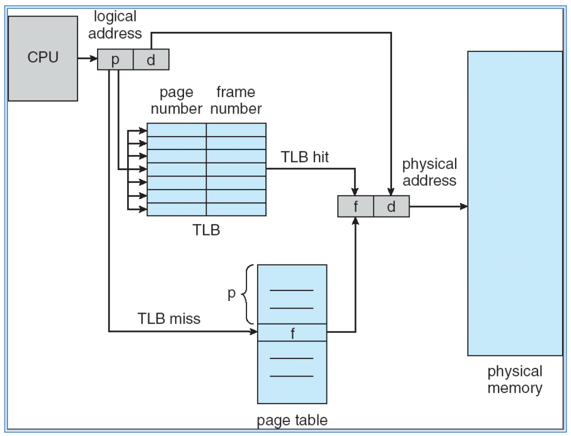
- Accessing a memory location requires two accesses in main memory.
  - One to access the page table (which is in main memory)
    - A contiguous lookup table.
  - Another one that access the memory location.
    - Anywhere in memory
- Problem: Expensive! Can we do better?

Use a Cache: Translation Look-Aside Buffer (TLB)

- Goal: Avoid page table lookups in main memory (i.e., a total of two memory accesses)
- Idea: Hardware cache of recent page translations
  - Typical size: 64 - 2K entries
  - Index by segment + vpn --> ppn
- Why does this work?
  - process references few unique pages in time interval
  - spatial, temporal locality
- On each memory reference, check TLB for translation
  - If present (hit): use ppn and append page offset
  - Else (miss): Use segment and page tables to get ppn
    - Update TLB for next access (replace some entry)
- How does page size impact TLB performance? (food for thought).

Paging Hardware With TLB

if it is a miss have to access main memory **twice**



Effective Access Time

- Associative Lookup (TLB) = ε time unit (small fraction of the time to go to main memory)
  - Assume memory cycle time is 1 microsecond
  - Hit ratio – percentage of times that a page number is found in the *associative registers*; ratio related to number of associative registers
  - Hit ratio = α (alpha)
  - Effective Access Time (EAT)

$$EAT = (1 + \varepsilon)\,\alpha + (2 + \varepsilon)(1 - \alpha)$$

$$= 2 + \varepsilon - \alpha$$

What Page Size?
Page Size Trade-offs

- Internal Fragmentation
  - Smaller the page size the less the internal fragmentation
- Number of pages
  - The smaller the pages the greater the **number** of pages
  - Larger Page tables
- Page size and page faults
  - Larger page size implies (less or more) page faults.