TCSS 422: OPERATING SYSTEMS

Free Space Management, Introduction to Paging, Translation Lookaside Buffer

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OBJECTIVES

- Ungraded Quiz 3– Synchronized Array
- Homework 2 Questions
- Homework 3 Questions

- Ch. 17
  - Free Space Management
- Ch. 18
  - Introduction to Paging
- Ch. 19
  - Translation Lookaside Buffer (TLB)

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FEEDBACK FROM 2/21

- Is this how my output will be tested (by running 'cat /proc/proc_report' command)? I'm able to get the output printed to the proc file.

```
PROCESS REPORTER
Unrunnable:0
Runnable:4
Stopped:174
Process ID=1 Name=systemd number_of_children=29 first_child_pid=234 first_child_name: systemd-journal
Process ID=2 Name=kthreadd number_of_children=67 first_child_pid=4 first_child_name: kworker/0:0H
Process ID=4 Name=kworker/0:0H *No Children
Process ID=6 Name=ksoftirqd/0 *No Children
Process ID=7 Name=rcu_sched *No Children
Process ID=8 Name=rcu_bh *No Children
Process ID=9 Name=migration/0 *No Children
Process ID=10 Name=lru-add-drain *No Children
Process ID=11 Name=watchdog/0 *No Children
Process ID=12 Name=cpuhp/0 *No Children
Process ID=13 Name=cpuhp/1 *No Children
Process ID=14 Name=watchdog/1 *No Children
Process ID=15 Name=migration/1 *No Children
Process ID=16 Name=ksoftirqd/1 *No Children
Process ID=18 Name=kworker/1:0H *No Children
Process ID=19 Name=kdevtmpfs *No Children
Process ID=20 Name=netns *No Children
Process ID=21 Name=khungtaskd *No Children
Process ID=22 Name=oom_reaper *No Children
```

- YES

FEEDBACK - 2

- 2. Do I also need to print output to kernel log messages? (when I type 'dmesg') or only print the proc file?

- NO, this is optional... The kernel log output is only used to grade the program if the procfile is not implemented.

- 3. I notice process ID skips numbers, is that okay? See 'Process ID = ' below.

```
Process ID=896 Name=VBoxService *No Children
Process ID=921 Name=Xorg *No Children
Process ID=925 Name=dhclient *No Children
Process ID=938 Name=dnsmasq *No Children
Process ID=1089 Name=lightdm number_of_children=1 first_child_pid=1098 first_child_name: upstart
Process ID=1094 Name=systemd number_of_children=1 first_child_pid=1095 first_child_name: (sd-pam)
```

- YES, the process that formerly had the PID has likely terminated.

FEEDBACK - 3

- I am confused about trying to get this assignment going. I understand the importance of process tree traversal being separate from output being placed in proc file, however I don't know how to go about completely separating these two.
- I am thinking I need to make a method that traverses the process tree, and I store that information in some sort of data structure?
- **This is a good approach. Store the information in a data structure so it can be accessed later. Note that malloc is called kmalloc for kernel module programming.**
- Or make a temporary output file?
- **This is a less optimal solution.**

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FEEDBACK - 4

- The assignment description says: "Report generation and process list computation cannot occur in the /proc output routines. "
- I am confused as to what this report generation is supposed to look like it it's not the /proc output.
- **Points are deducted if report generation is done in the proc file output routine. (e.g. the event handler that is called when someone tries to read /proc/proc_report.)**
- **Page 2 of Assignment 2 shows example output of the proc file.**

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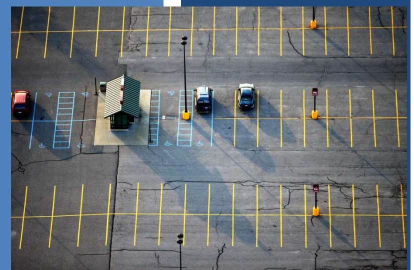

CHAPTER 17: FREE SPACE MANAGEMENT

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FREE SPACE MANAGEMENT

- Management of memory using
- Only fixed-sized units
  - Easy: keep a list
  - Memory request → return first free entry
    - Simple search
- With variable sized units
  - More challenging
  - Results from variable sized malloc requests
  - Leads to fragmentation

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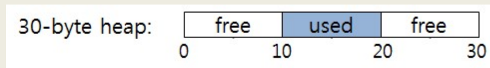
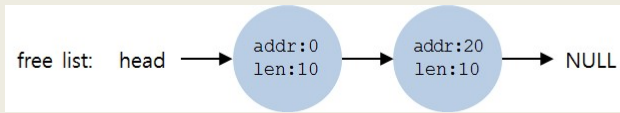
FRAGMENTATION

- Consider a 30-byte heap



- Request for 15-bytes



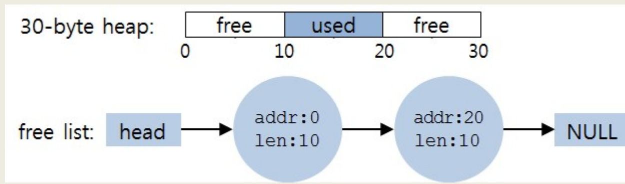
- Free space: 20 bytes
- No available contiguous chunk → return NULL

FRAGMENTATION - 2

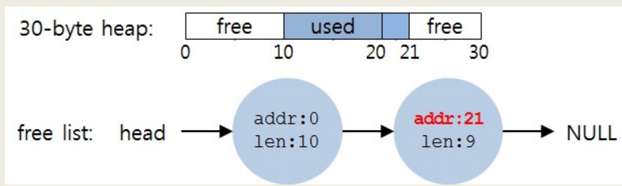
- External: *OS can compact*
  - Example: Client asks for 100 bytes: malloc(100)
  - OS: No 100 byte contiguous chunk is available: returns NULL
  - Memory is externally fragmented - - Compaction can fix!
- Internal: *lost space – OS can't compact*
  - OS returns memory units that are too large
  - Example: Client asks for 100 bytes: malloc(100)
  - OS: Returns 125 byte chunk
  - Fragmentation is *in* the allocated chunk
  - Memory is lost, and unaccounted for – can't compact

ALLOCATION STRATEGY: SPLITTING

- Request for 1 byte of memory: malloc(1)

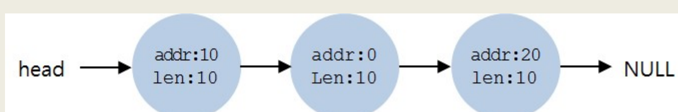


- OS locates a free chunk to satisfy request
- Splits chunk into two, returns first chunk

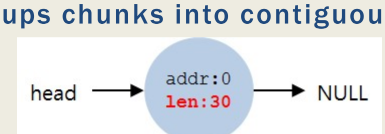


ALLOCATION STRATEGY: COALESCING

- Consider 30-byte heap
- Free() frees all 10 bytes segments *(list of 3-free 10-byte chunks)*



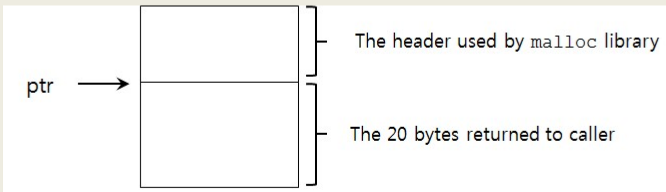
- Request arrives: malloc(30)
- ***SPLIT DOES NOT WORK*** - no contiguous 30-byte chunk exists!
- Coalescing regroups chunks into contiguous chunk



- Allocation can now proceed
- Coalescing is defragmentation of the free space list

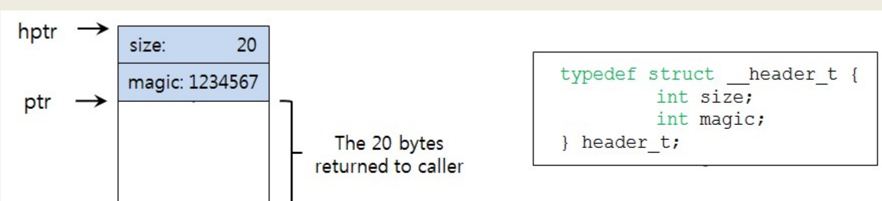
MEMORY HEADERS

- free(void *ptr): Does not require a size parameter
- *How does the OS know how much memory to free?*
- Header block
  - Small descriptive block of memory at start of chunk



An Allocated Region Plus Header

MEMORY HEADERS - 2



Specific Contents Of The Header

A Simple Header

- Contains size
- Pointers: for faster memory access
- Magic number: integrity checking

MEMORY HEADERS - 3

- Size of memory chunk is:
- Header size + user malloc size
- N bytes + sizeof(header)

- Easy to determine address of header

```
void free(void *ptr) {
        header_t *hptr = (void *)ptr - sizeof(header_t);
}
```


THE FREE LIST

- Simple free list struct

```
typedef struct __node_t {
        int size;
        struct __node_t *next;
} nodet_t;
```

- Use mmap to create free list
- 4kb heap, 4 byte header, one contiguous free chunk

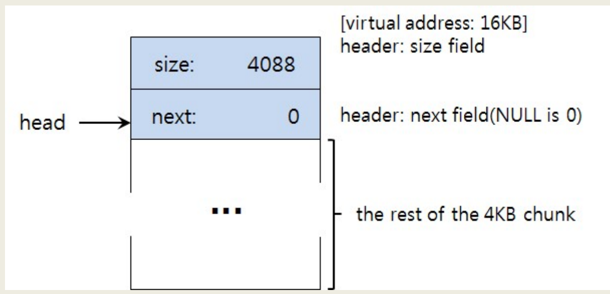
```
// mmap() returns a pointer to a chunk of free space
node_t *head = mmap(NULL, 4096, PROT_READ|PROT_WRITE,
                        MAP_ANON|MAP_PRIVATE, -1, 0);
head->size = 4096 - sizeof(node_t);
head->next = NULL;
```

FREE LIST - 2

- Create and initialize free-list "heap"

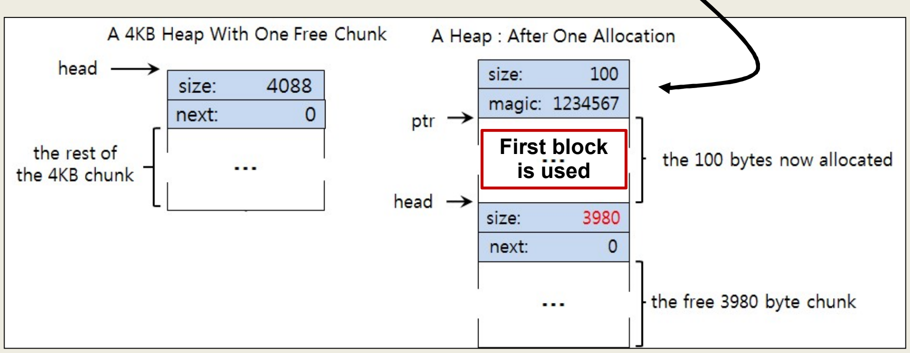
```
// mmap() returns a pointer to a chunk of free space
node_t *head = mmap(NULL, 4096, PROT_READ|PROT_WRITE,
                    MAP_ANON|MAP_PRIVATE, -1, 0);
head->size = 4096 - sizeof(node_t);
head->next = NULL;
```

- Heap layout:



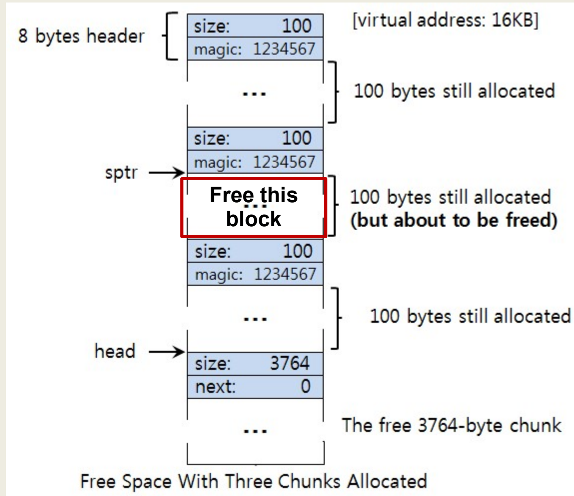
FREE LIST: MALLOC() CALL

- Consider a request for a 100 bytes: malloc(100)
- Header block requires 8 bytes
  - 4 bytes for size, 4 bytes for magic number
- Split the heap – <u>header goes with each block</u>



FREE LIST: FREE() CALL

- Addresses of chunks
- Start=16384
  + 108 (end of 1st chunk)
  + 108 (end of 2nd chunk)
  + 108 (end of 3rd chunk)
  = 16708



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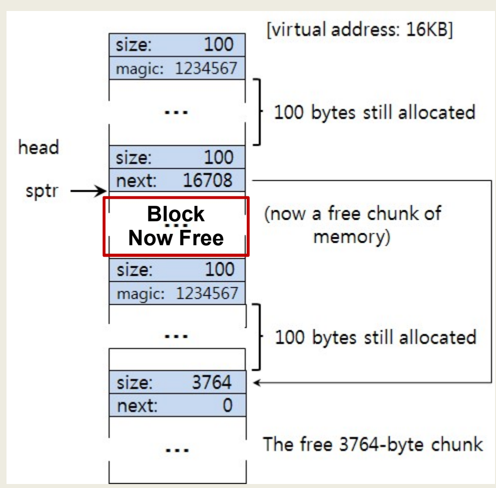
FREE LIST: FREE() CHUNK #2

- Free(sptr)
- Our 3 chunks start at 16 KB (@ 16,384 bytes)
- Free chunk #2 - sptr
- Sptr = 16500
  - addr – sizeof(node_t)
- Actual start of chunk #2
  - 16492



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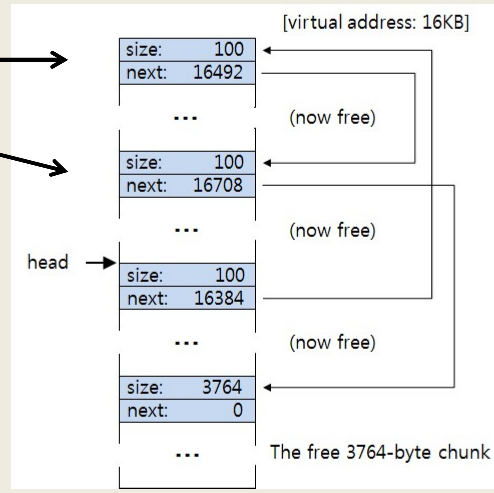
FREE LIST- FREE ALL CHUNKS

- Now free remaining chunks:
- Free(16392)
- Free(16608)
- Walk back 8 bytes for actual start of chunk
- External fragmentation
- Free chunk pointers out of order
- Coalescing of next pointers is needed



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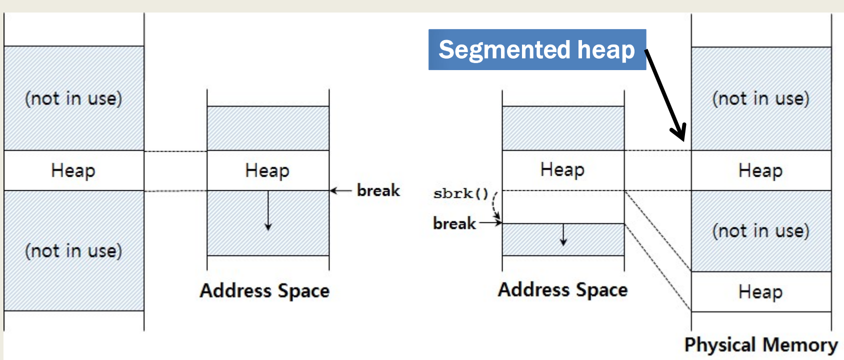
GROWING THE HEAP

- Start with small sized heap
- Request more memory when full
- sbrk(), brk()



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MEMORY ALLOCATION STRATEGIES

- Best fit
  - Traverse free list
  - Identify all candidate free chunks
  - Note which is smallest (has best fit)
  - When splitting, "leftover" pieces are small (and potentially less useful -- fragmented)

- Worst fit
  - Traverse free list
  - Identify largest free chunk
  - Split largest free chunk, leaving a still large free chunk

EXAMPLES

- Allocation request for 15 bytes

- Result of Best Fit

- Result of Worst Fit

MEMORY ALLOCATION STRATEGIES - 2

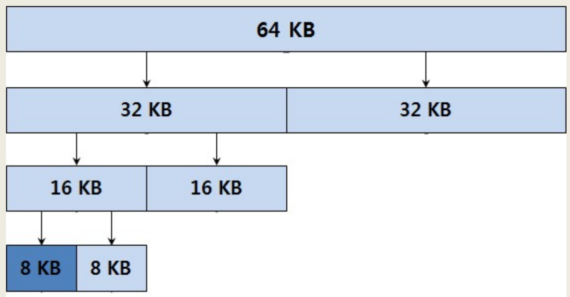
- First fit
  - Start search at beginning of free list
  - Find first chunk large enough for request
  - Split chunk, returning a “fit” chunk, saving the remainder
  - Avoids full free list traversal of best and worst fit
- Next fit
  - Similar to first fit, but start search at last search location
  - Maintain a pointer that “cycles” through the list
  - Helps balance chunk distribution vs. first fit
  - Find first chunk, that is large enough for the request, and split
  - Avoids full free list traversal

SEGREGATED LISTS

- For popular sized requests
  e.g. for kernel objects such as locks, inodes, etc.
- Manage as segregated free lists
- Provide object caches: stores pre-initialized objects
- How much memory should be dedicated for specialized requests (object caches)?
- If a given cache is low in memory, can request “*slabs*” of memory from the general allocator for caches.
- General allocator will reclaim slabs when not used

BUDDY ALLOCATION

- Binary buddy allocation
  - Divides free space by two to find a block that is big enough to accommodate the request; the next split is too small…
- Consider a 7KB request



64KB free space for 7KB request

BUDDY ALLOCATION - 2

- Buddy allocation: suffers from internal fragmentation
- Allocated fragments, typically too large
- Coalescing is simple
  - Two adjacent blocks are promoted up

CHAPTER 18: INTRODUCTION TO PAGING

PAGING

- Split up address space of process into ***fixed sized pieces*** called **pages**
- Alternative to ***variable sized pieces*** (Segmentation) which suffers from significant fragmentation
- Physical memory is split up into an array of fixed-size slots called **page frames**.
- Each process has a **page table** which translates virtual addresses to physical addresses

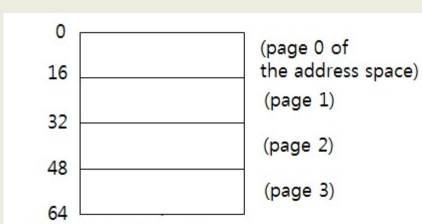
ADVANTAGES OF PAGING

- Flexibility
  - Abstracts the process address space into pages
  - No need to track direction of HEAP / STACK growth
    - *Just add more pages...*
  - No need to store unused space
    - *As with segments...*
- Simplicity
  - Pages and page frames are the same size
  - Easy to allocate and keep a free list of pages

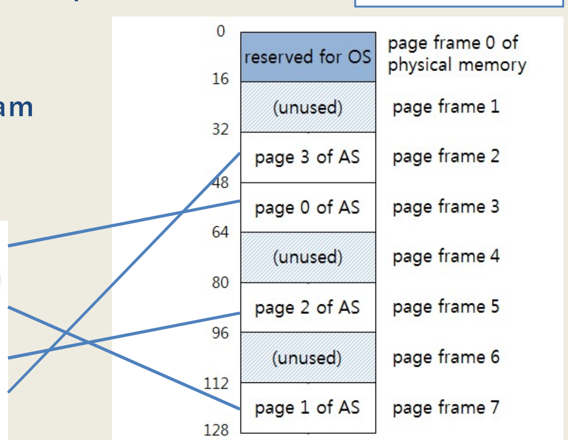
PAGING: EXAMPLE

Page Table:
VP0 → PF3
VP1 → PF7
VP2 → PF5
VP3 → PF2

- Consider a 128 byte address space with 16-byte pages
- Consider a 64-byte program address space



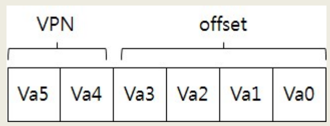
A Simple 64-byte Address Space



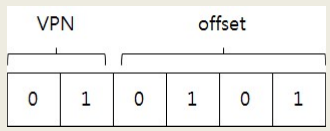
64-Byte Address Space Placed In Physical Memory

PAGING: ADDRESS TRANSLATION

- PAGE: Has two address components
  - VPN: Virtual Page Number
  - Offset: Offset within a Page



- Example:
  Page Size: 16-bytes, Address Space: 64-bytes



Here there are just four pages…

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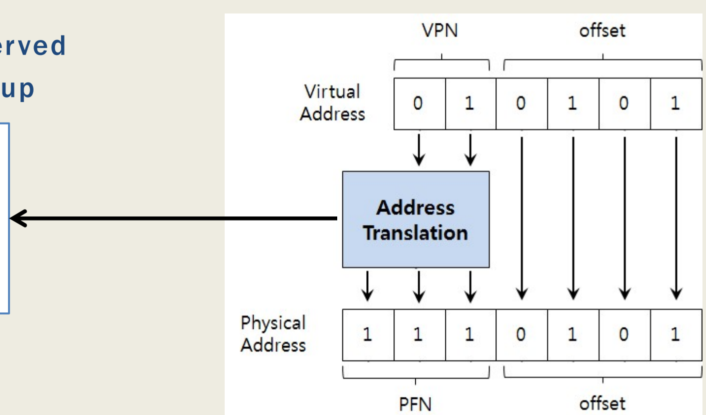
EXAMPLE: PAGING ADDRESS TRANSLATION

- Consider a 64-byte program address space (4 pages)
- Stored in 128-byte physical memory (8 frames)

- Offset is preserved
- VPN is looked up

Page Table:
VP0 → PF3
VP1 → PF7
VP2 → PF5
VP3 → PF2



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PAGING DESIGN QUESTIONS

- Where are page tables stored?
- What are the typical contents of the page table?
- How big are page tables?
- Does paging make the system too slow?

WHERE ARE PAGE TABLES STORED?

- Example:
  - Consider a 32-bit process address space (up to 4GB)
  - With 4 KB pages
  - 20 bits for VPN (2^{20} pages)
  - 12 bits for the page offset (2^{12} unique bytes in a page)
- Page tables for each process are stored in RAM
  - Support potential storage of 2^{20} translations = 1,048,576 pages per process
  - Each page has a page table entry size of 4 bytes

PAGE TABLE EXAMPLE

- With 2^{20} slots in our page table for a single process
- Each slot dereferences a VPN
- Provides physical frame number
- Each slot requires 4 bytes (32 bits)
  - 20 for the PFN on a 4GB system with 4KB pages
  - 12 for the offset which is preserved
  - (note we have no status bits, so this is unrealistically small)
- How much memory to store page table for 1 process?
  - 4,194,304 bytes (or 4MB) to index one process

VPN_0
VPN_1
VPN_2
…
…
$VPN_{1048576}$

NOW FOR AN ENTIRE OS

- If 4 MB is required to store one process
- Consider how much memory is required for an entire OS?
  - With for example 100 processes…
- Page table memory requirement is now 4MB x 100 = 400MB
- If computer has 4GB memory (maximum for 32-bits), the page table consumes 10% of memory

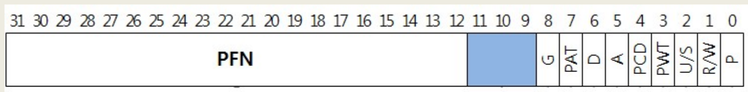
400 MB / 4000 GB

- Is this efficient?

WHAT'S ACTUALLY IN THE PAGE TABLE

- Page table is data structure used to map virtual page numbers (VPN) to the physical address (Physical Frame Number PFN)
  - Linear page table → simple array

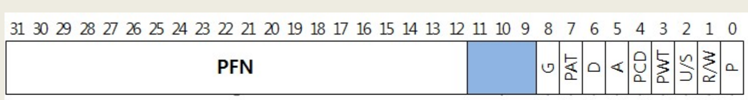
- Page-table entry
  - 32 bits for capturing state



An x86 Page Table Entry(PTE)

PAGE TABLE ENTRY

- P: present
- R/W: read/write bit
- U/S: supervisor
- A: accessed bit
- D: dirty bit
- PFN: the page frame number



An x86 Page Table Entry(PTE)

PAGE TABLE ENTRY - 2

- Common flags:
- **Valid Bit:** Indicating whether the particular translation is valid.
- **Protection Bit:** Indicating whether the page could be read from, written to, or executed from
- **Present Bit:** Indicating whether this page is in physical memory or on disk(swapped out)
- **Dirty Bit:** Indicating whether the page has been modified since it was brought into memory
- **Reference Bit(Accessed Bit):** Indicating that a page has been accessed

HOW BIG ARE PAGE TABLES?

- Page tables are too big to store on the CPU
- Page tables are stored using physical memory
- Paging supports efficiently storing a sparsely populated address space
  - Reduced memory requirement
    Compared to base and bounds, and segments

DOES PAGING MAKE THE SYSTEM TOO SLOW?

- Translation
- **Issue #1:** Starting location of the page table is needed
  - HW Support: Page-table base register
    - stores active process
    - Facilitates translation

Stored in RAM →

Page Table:
VP0 → PF3
VP1 → PF7
VP2 → PF5
VP3 → PF2

- **Issue #2:** Each memory address translation for paging requires an extra memory reference
  - HW Support: TLBs (Chapter 19)

PAGING MEMORY ACCESS

```
// Extract the VPN from the virtual address
VPN = (VirtualAddress & VPN_MASK) >> SHIFT

// Form the address of the page-table entry (PTE)
PTEAddr = PTBR + (VPN * sizeof(PTE))

// Fetch the PTE
PTE = AccessMemory(PTEAddr)

// Check if process can access the page
if (PTE.Valid == False)
        RaiseException(SEGMENTATION_FAULT)
else if (CanAccess(PTE.ProtectBits) == False)
        RaiseException(PROTECTION_FAULT)
else
        // Access is OK: form physical address and fetch it
        offset = VirtualAddress & OFFSET_MASK
        PhysAddr = (PTE.PFN << PFN_SHIFT) | offset
        Register = AccessMemory(PhysAddr)
```

COUNTING MEMORY ACCESSES

- Example: Use this Array initialization Code

```
int array[1000];
...
for (i = 0; i < 1000; i++)
        array[i] = 0;
```

- Assembly equivalent:

```
0x1024 movl $0x0,(%edi,%eax,4)
0x1028 incl %eax
0x102c cmpl $0x03e8,%eax
0x1030 jne 0x1024
```

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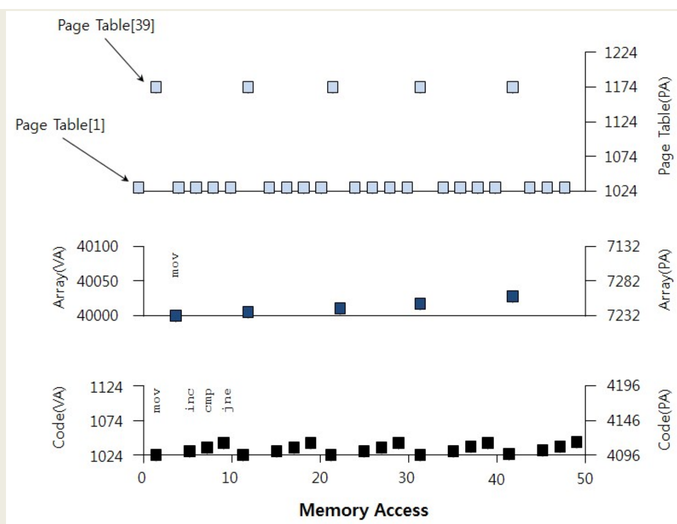
VISUALIZING MEMORY ACCESSES:
FOR THE FIRST 5 LOOP ITERATIONS

- Locations:
  - Page table
  - Array
  - Code
- 50 accesses for 5 loop iterations



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QUESTIONS