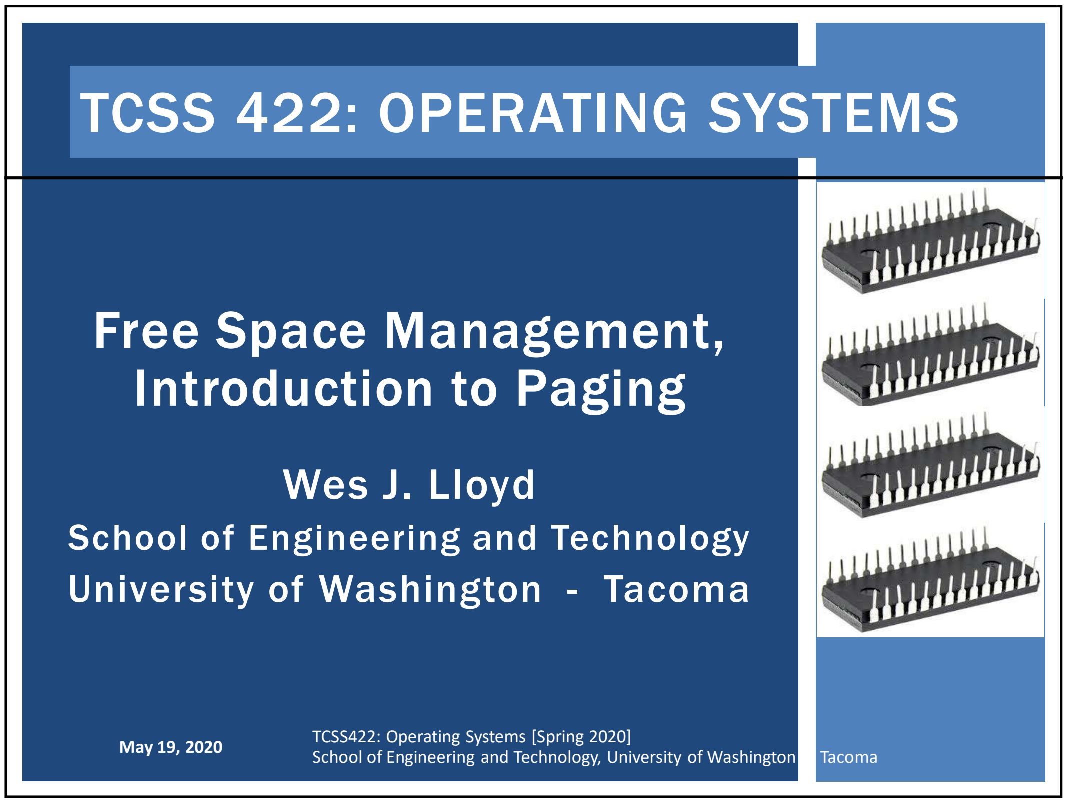

TCSS 422: OPERATING SYSTEMS

Free Space Management, Introduction to Paging

Wes J. Lloyd
School of Engineering and Technology
University of Washington - Tacoma

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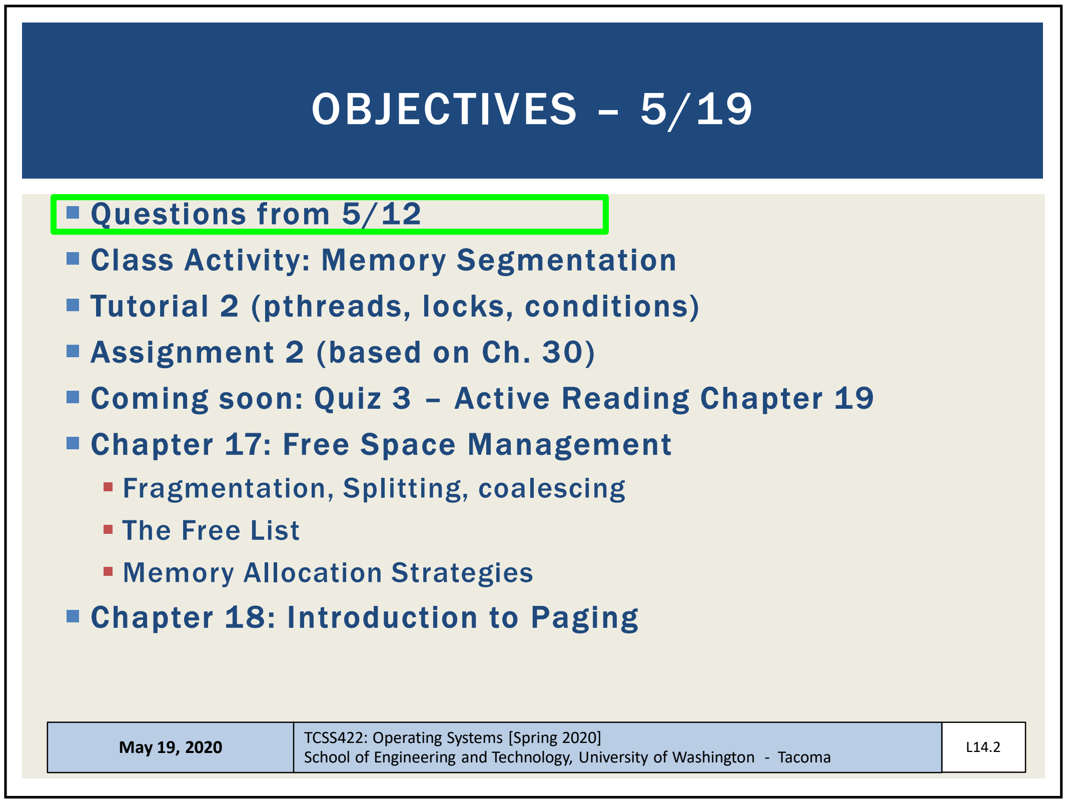

OBJECTIVES – 5/19

- Questions from 5/12
- Class Activity: Memory Segmentation
- Tutorial 2 (pthreads, locks, conditions)
- Assignment 2 (based on Ch. 30)
- Coming soon: Quiz 3 – Active Reading Chapter 19
- Chapter 17: Free Space Management
  - Fragmentation, Splitting, coalescing
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  - Memory Allocation Strategies
- Chapter 18: Introduction to Paging

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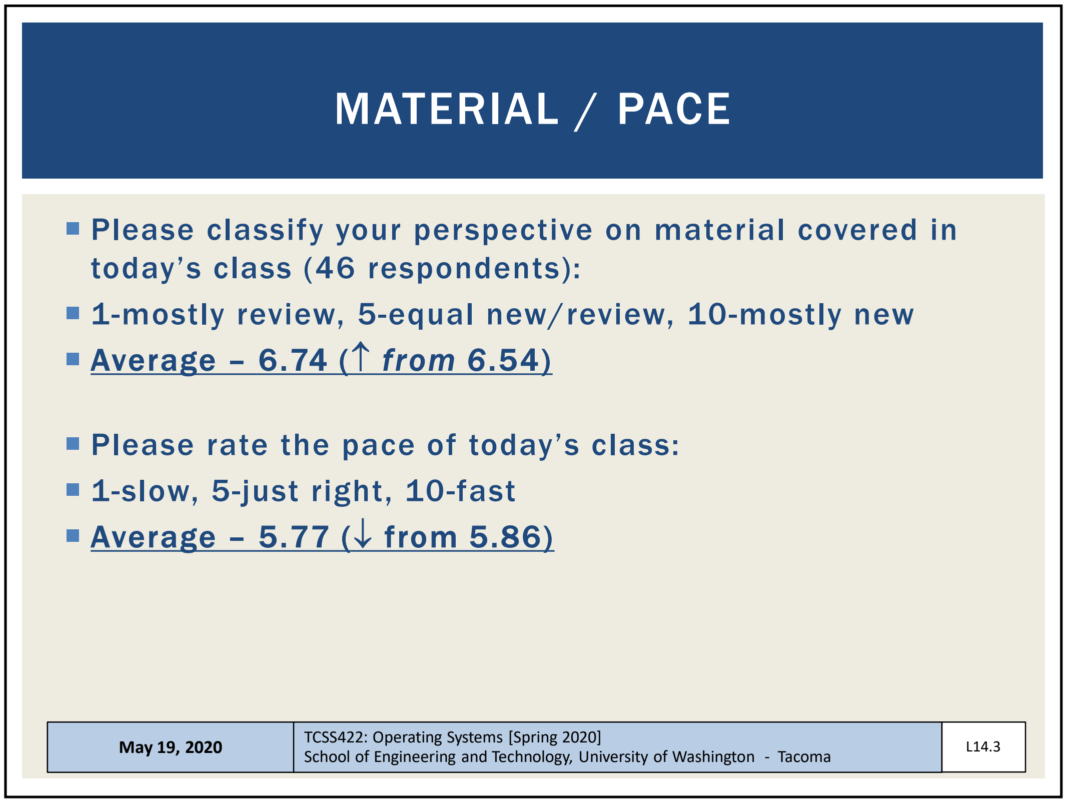

MATERIAL / PACE

- Please classify your perspective on material covered in today's class (46 respondents):
- 1-mostly review, 5-equal new/review, 10-mostly new
- Average – 6.74 (↑ *from* 6.54)

- Please rate the pace of today's class:
- 1-slow, 5-just right, 10-fast
- Average – 5.77 (↓ from 5.86)

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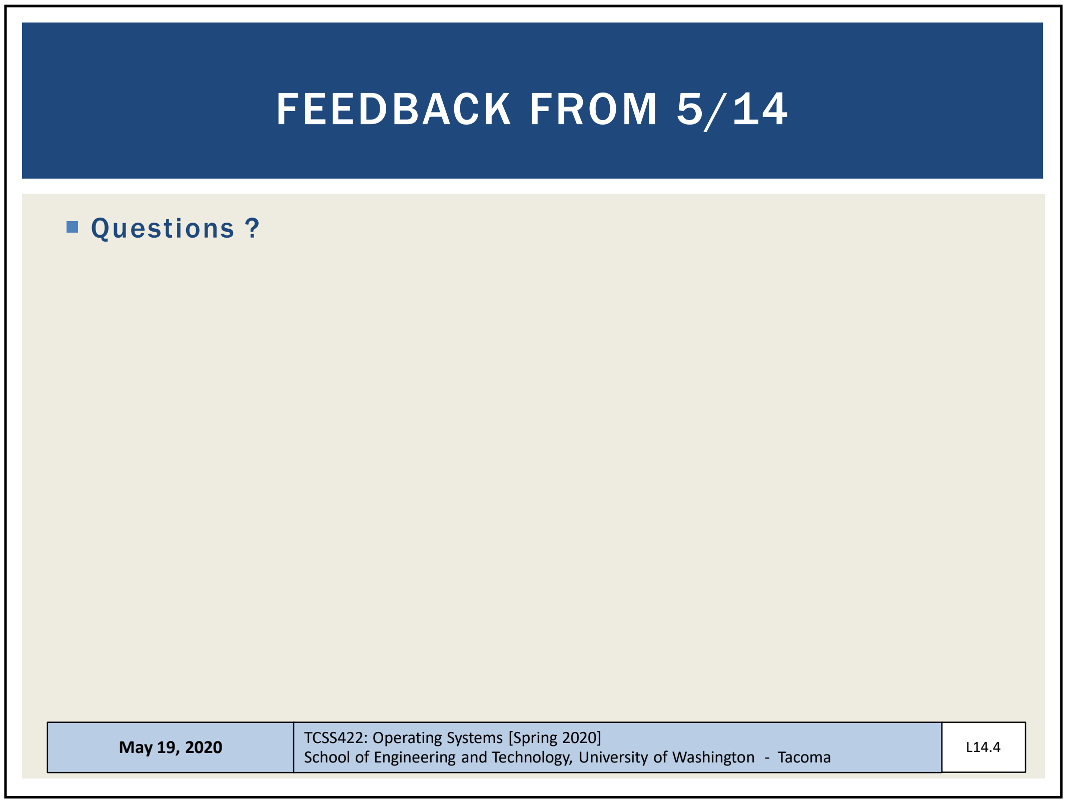

FEEDBACK FROM 5/14

- Questions ?

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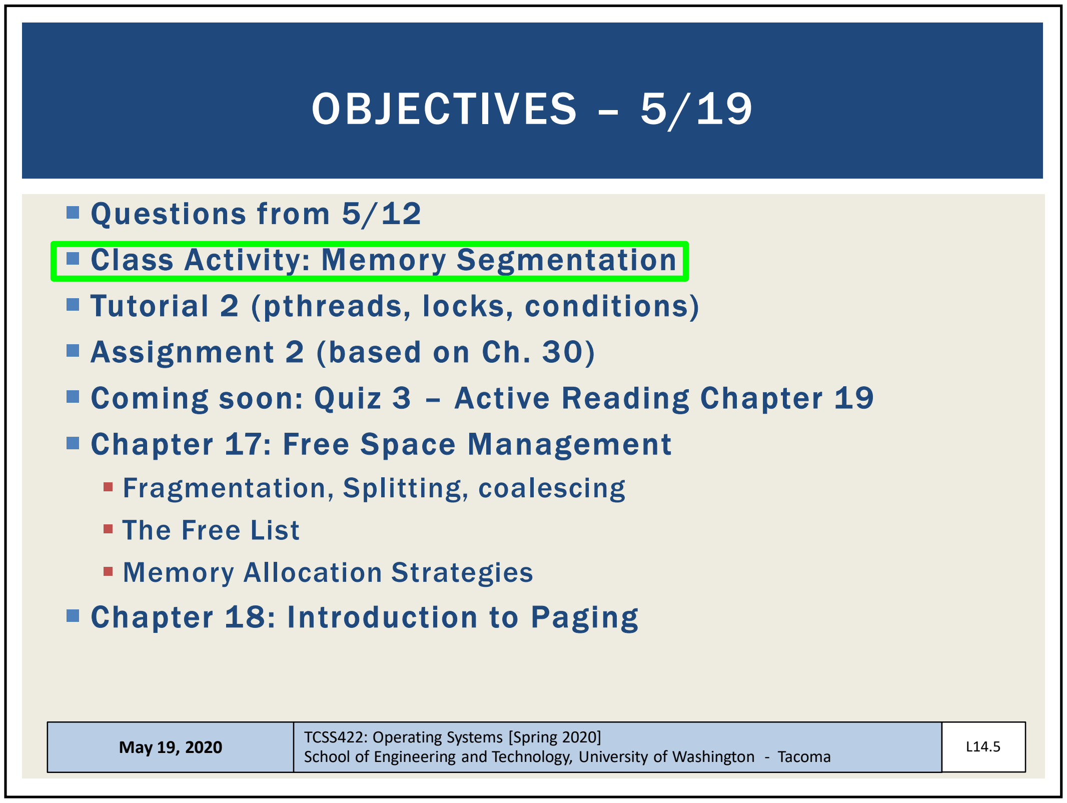

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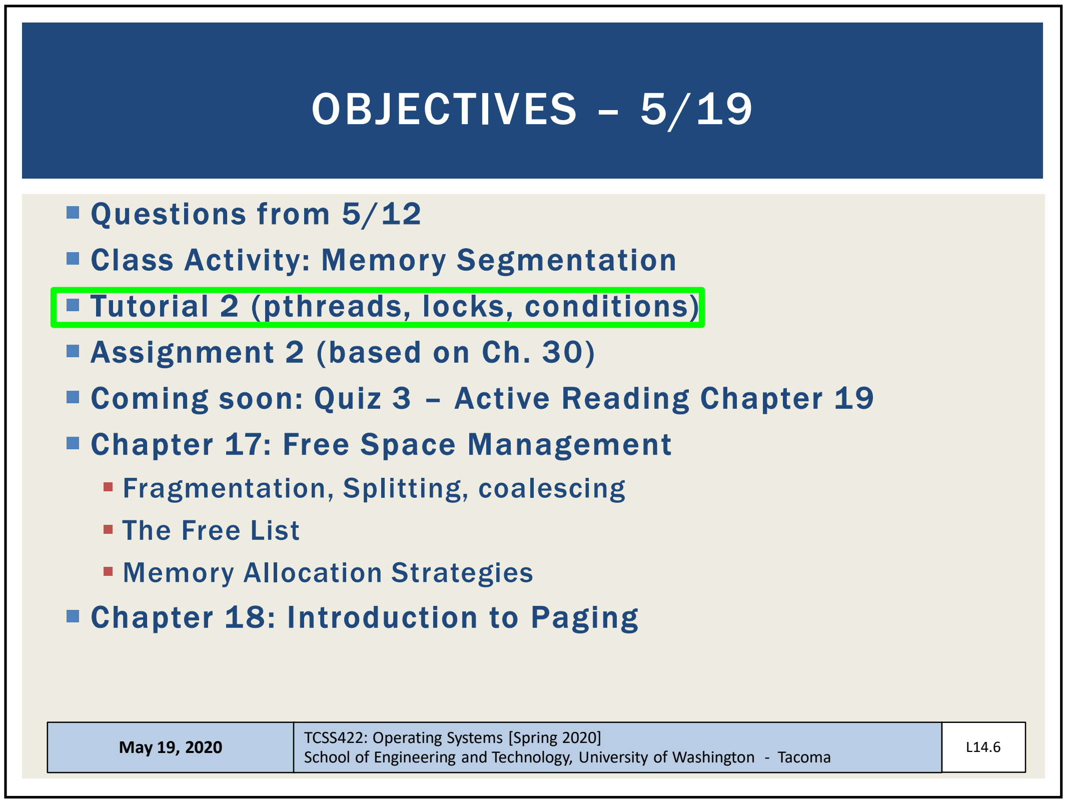

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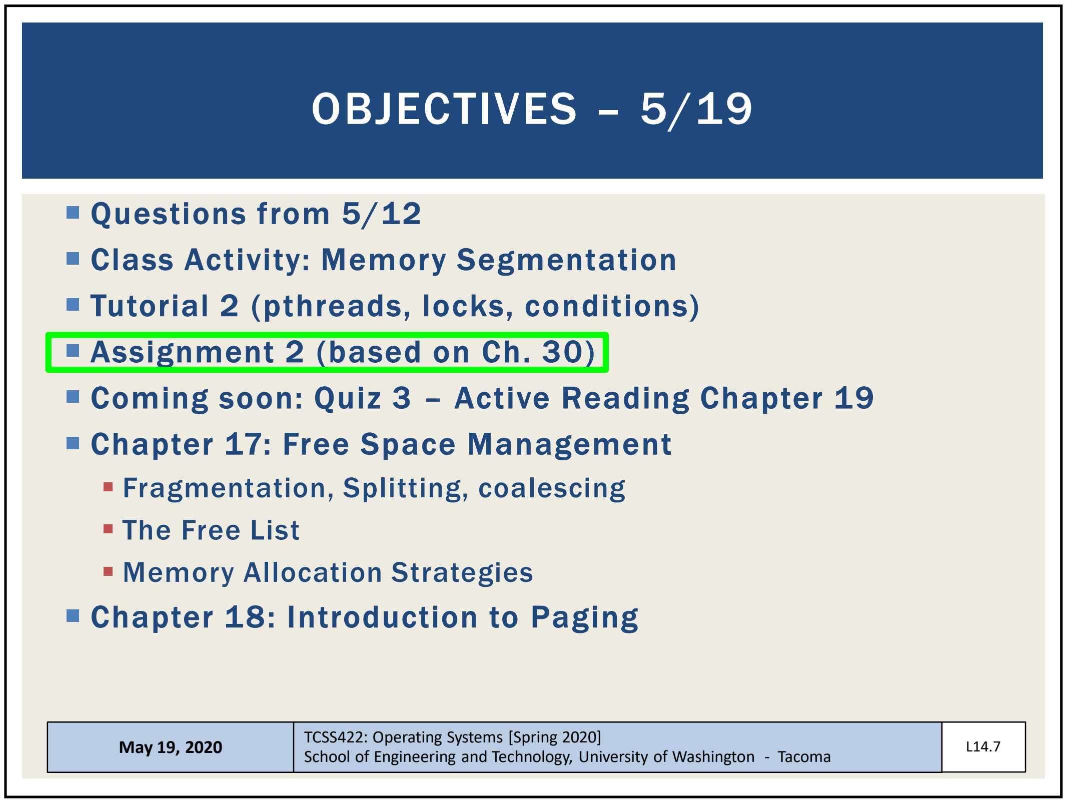

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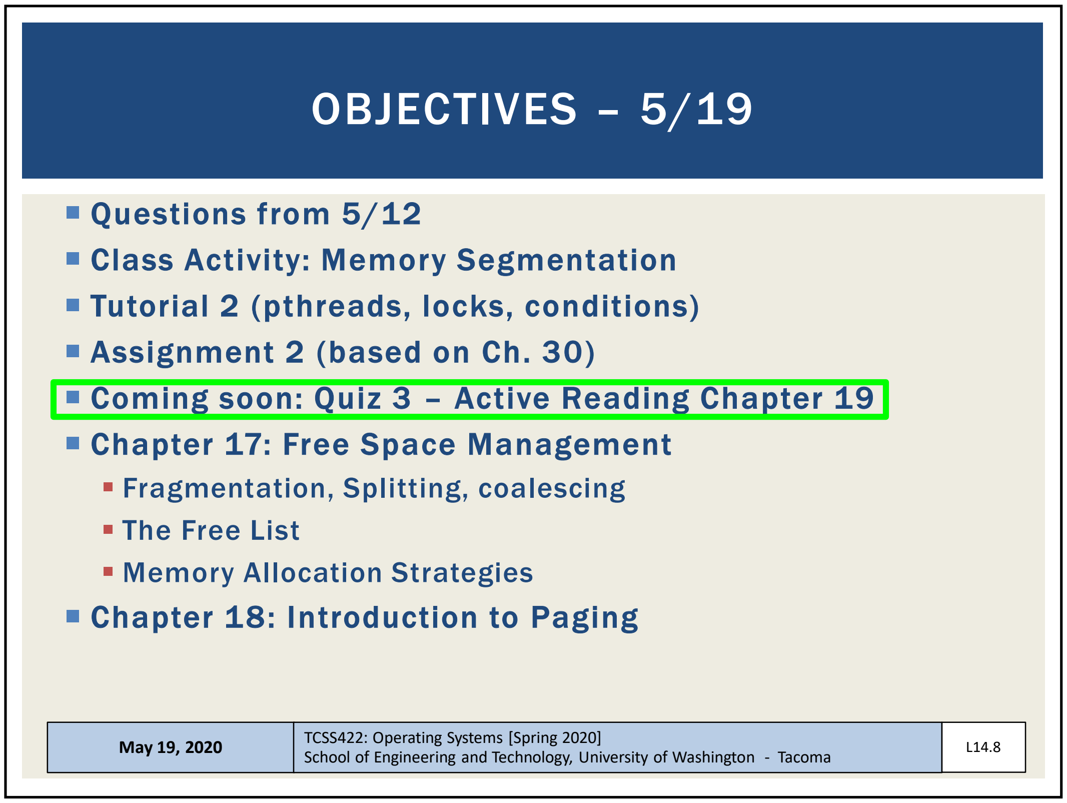

OBJECTIVES – 5/19

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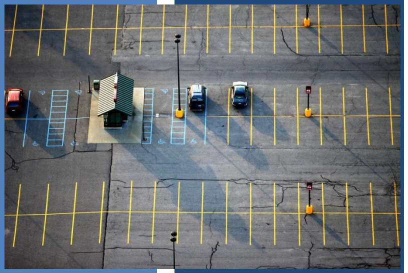
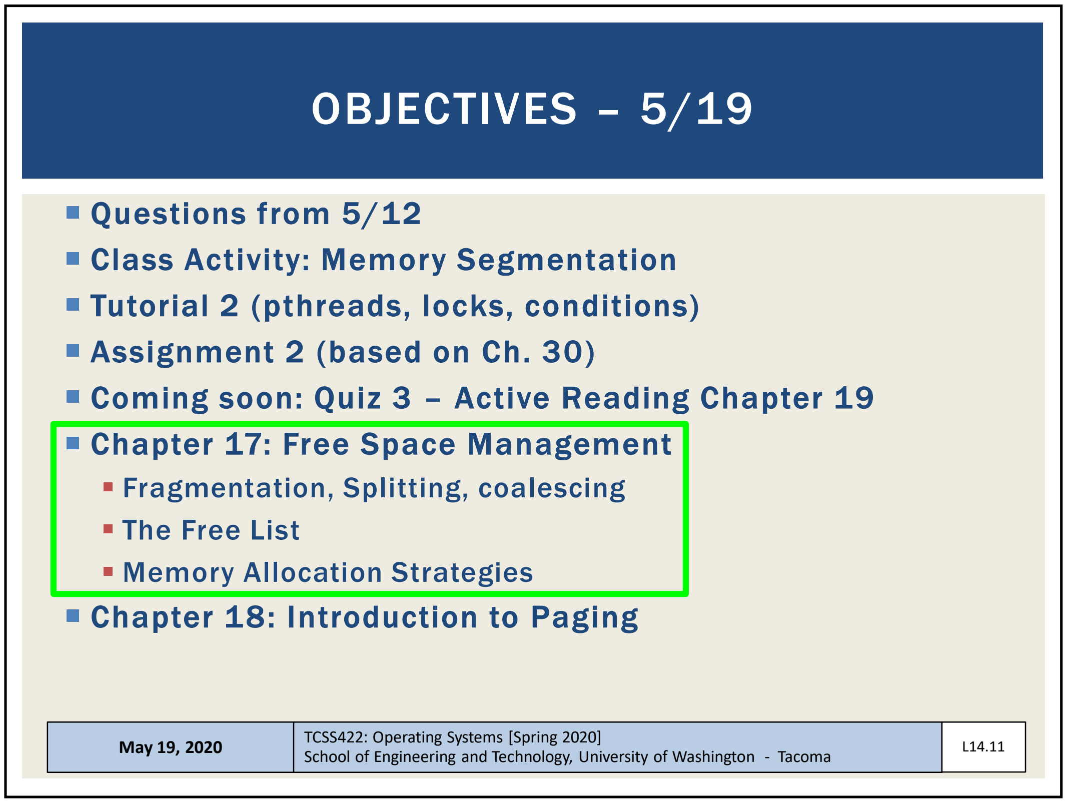
TCSS 422 WILL RETURN AT ~2:40PM



CHAPTER 17: FREE SPACE MANAGEMENT



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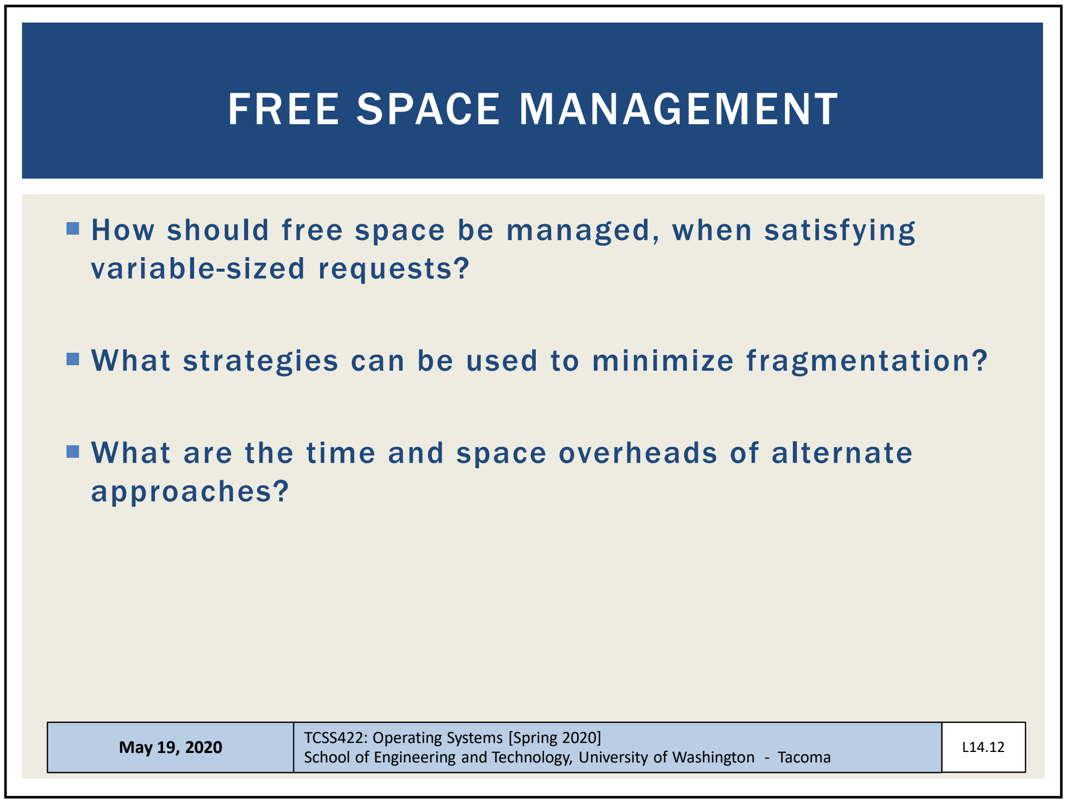
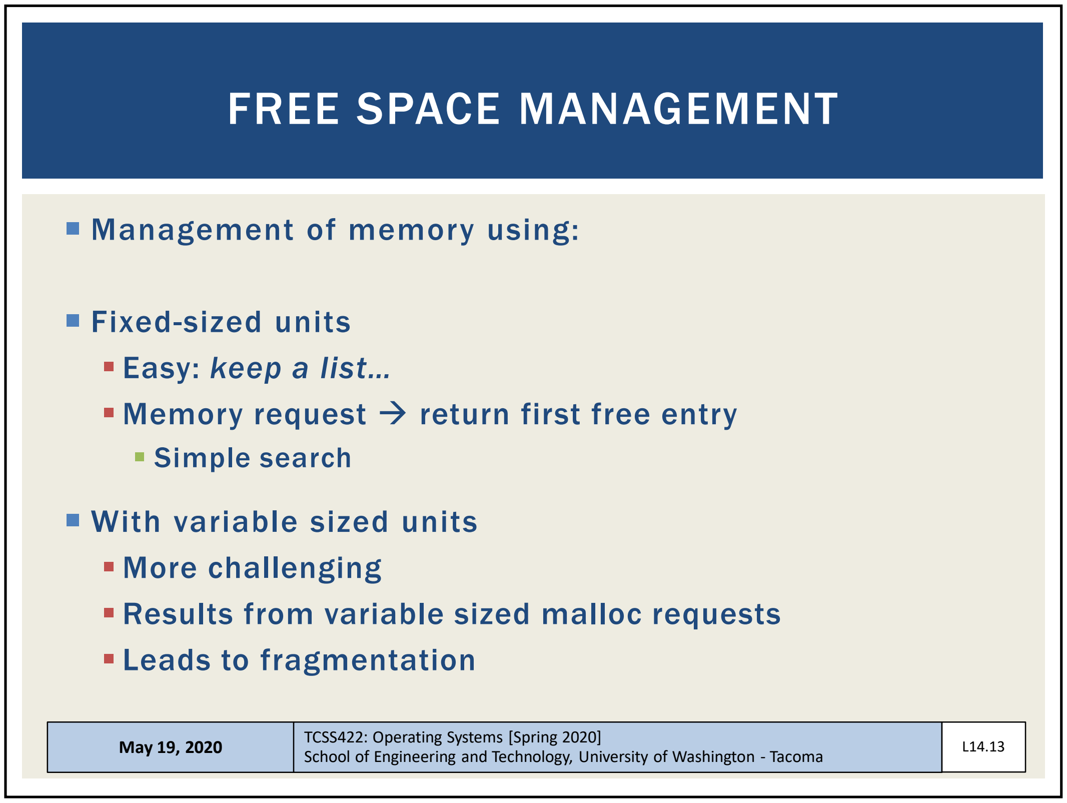


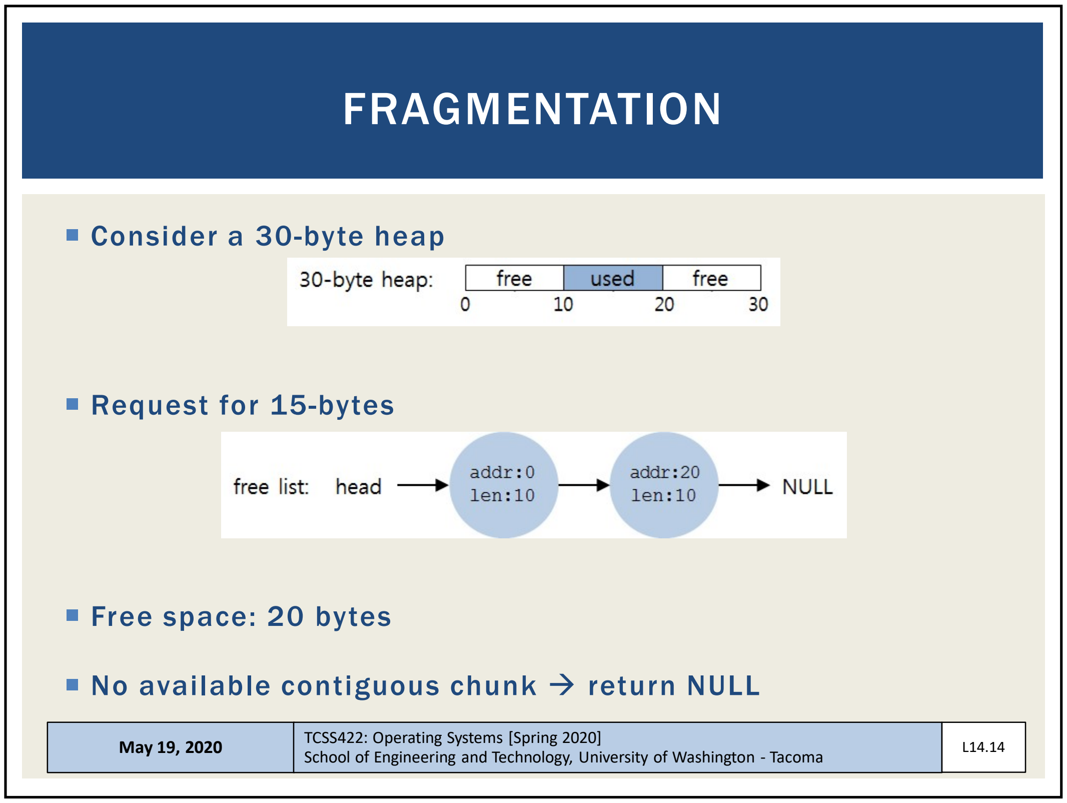
FREE SPACE MANAGEMENT

- How should free space be managed, when satisfying variable-sized requests?
- What strategies can be used to minimize fragmentation?
- What are the time and space overheads of alternate approaches?



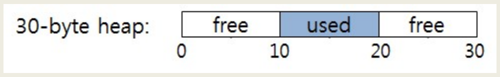
FREE SPACE MANAGEMENT

- Management of memory using:
- 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

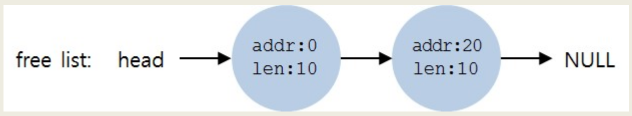


FRAGMENTATION

- Consider a 30-byte heap



- Request for 15-bytes



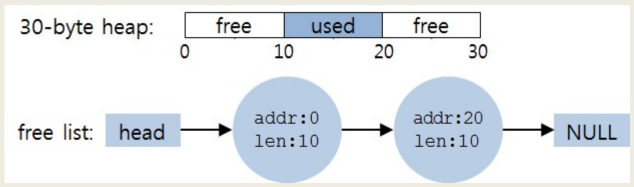
- Free space: 20 bytes
- No available contiguous chunk → return NULL

FRAGMENTATION - 2

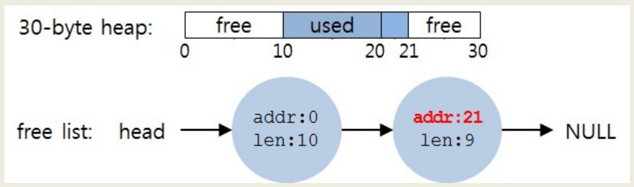
- **External:** *OS can compact*
  - Example: Client asks for 100 bytes: malloc(100)
  - OS: No 100 byte contiguous chunk is available: returns NULL
  - Memory is externally fragmented - - Compaction can fix!
- **Internal:** *lost space – OS can't compact*
  - OS returns memory units that are too large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

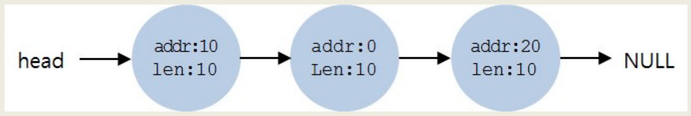


- OS locates a free chunk to satisfy request
- Splits chunk into two, returns first chunk

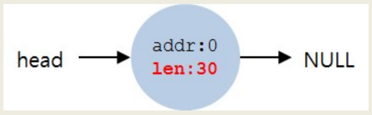


ALLOCATION STRATEGY: COALESCING

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



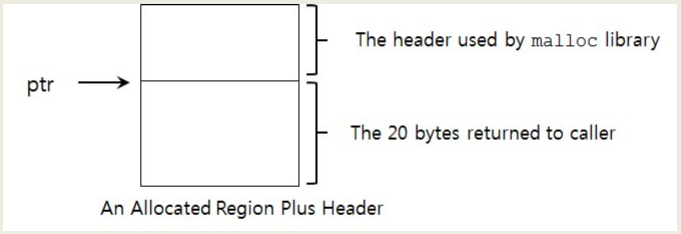
- Request arrives: malloc(30)
- ***SPLIT DOES NOT WORK*** - no contiguous 30-byte chunk exists!
- Coalescing regroups chunks into contiguous chunk



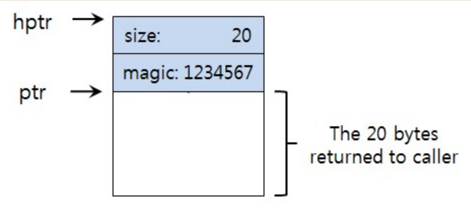
- Allocation can now proceed
- Coalescing is defragmentation of the free space list

MEMORY HEADERS

- Memory API:
  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


ptr
The header used by malloc library
The 20 bytes returned to caller
An Allocated Region Plus Header

MEMORY HEADERS - 2



Specific Contents Of The Header

```
typedef struct __header_t {
        int size;
        int magic;
} header_t;
```

A Simple Header

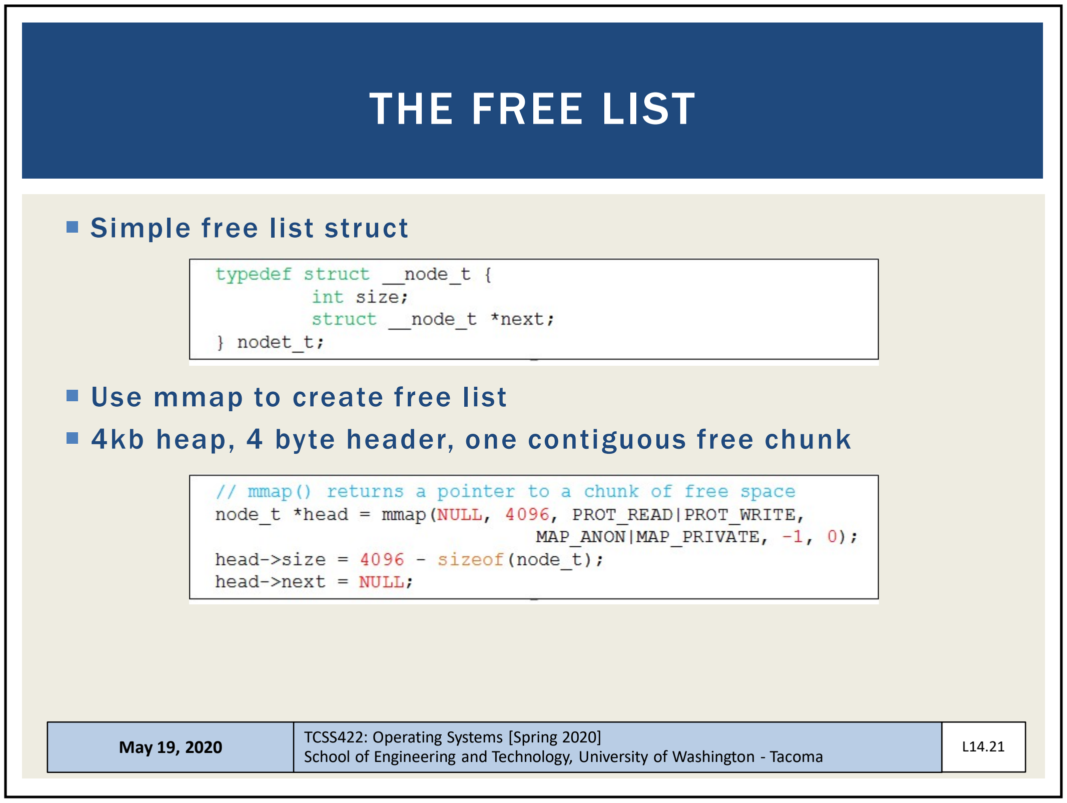
- Contains size
- Pointers: for faster memory access
- Magic number: integrity checking

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;
```

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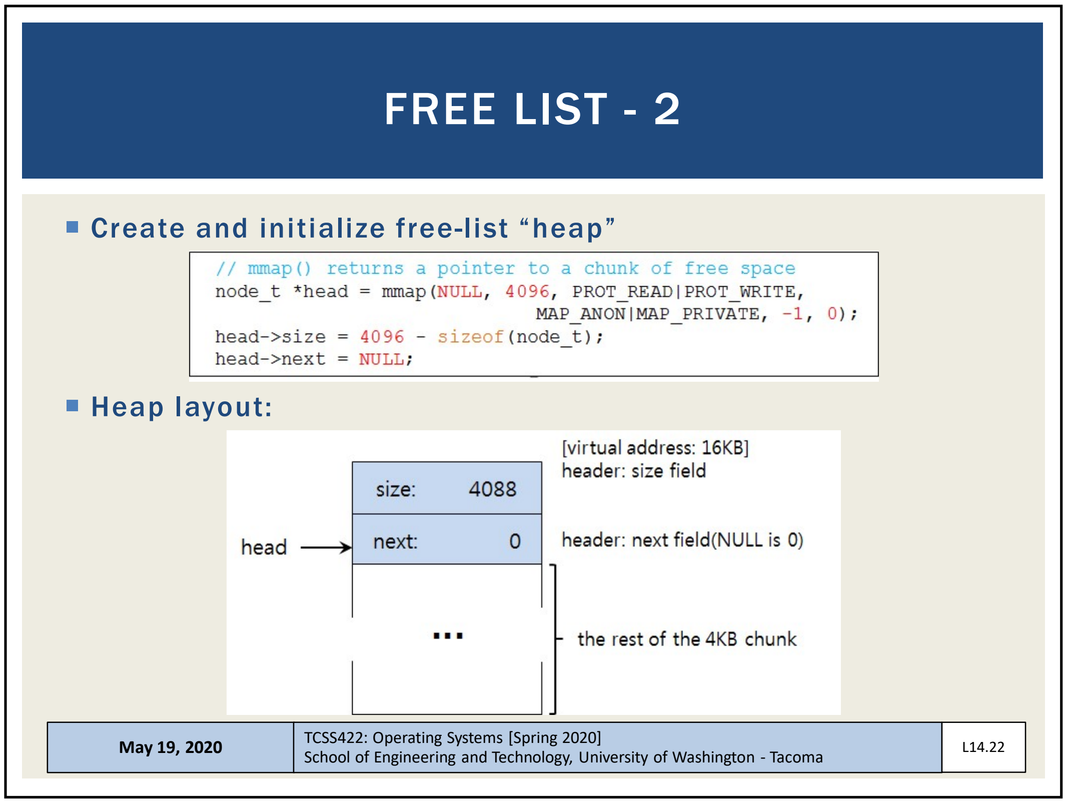
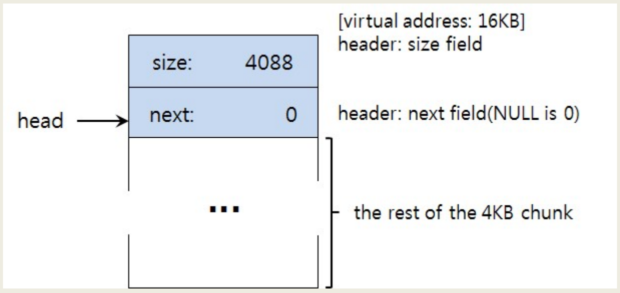


FREE LIST - 2

- 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:



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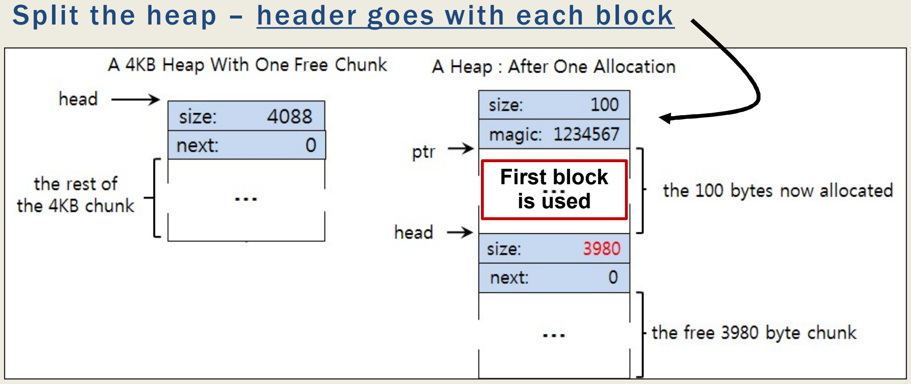
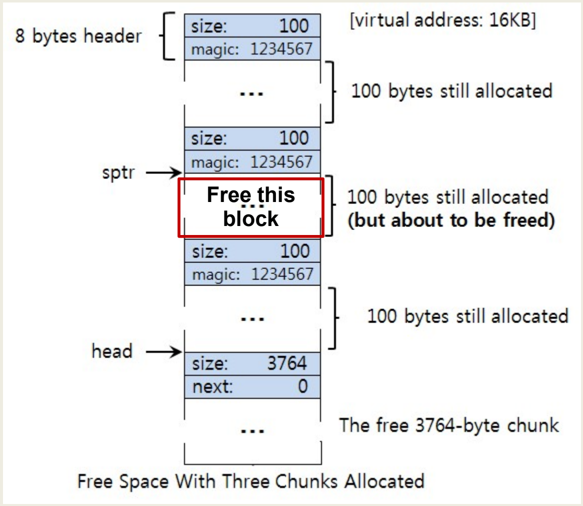
FREE LIST: MALLOC() CALL

- 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 – header goes with each block



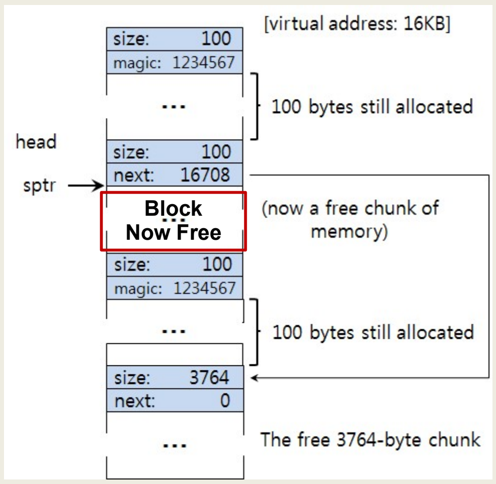
FREE LIST: FREE() CALL

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



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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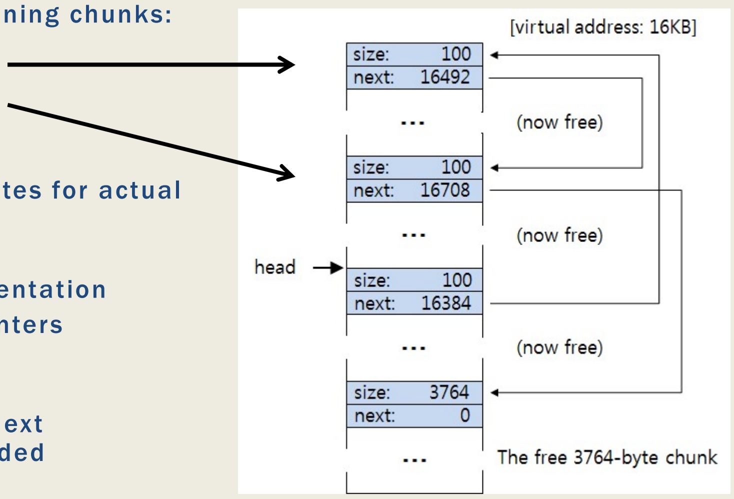
FREE LIST- FREE ALL CHUNKS

- 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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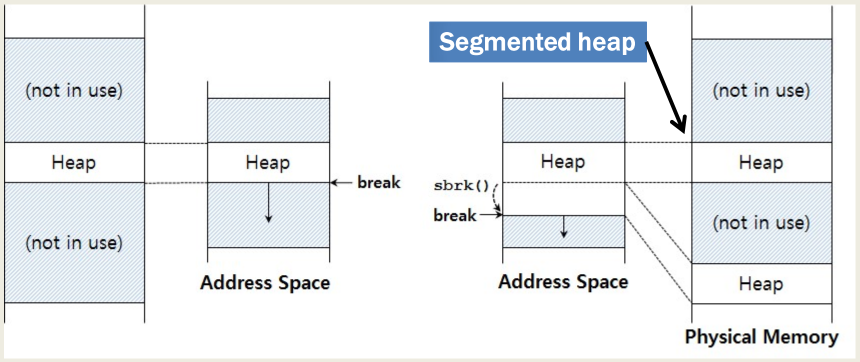
GROWING THE HEAP

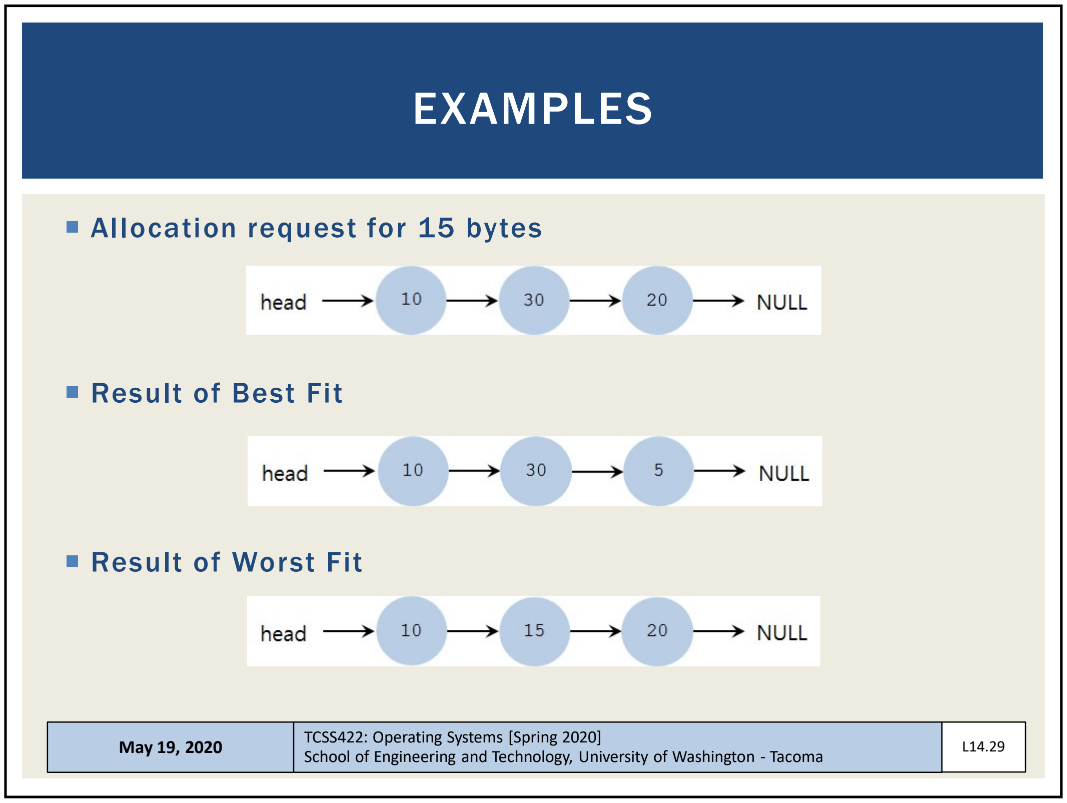
- Start with small sized heap
- Request more memory when full
- sbrk(), brk()



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

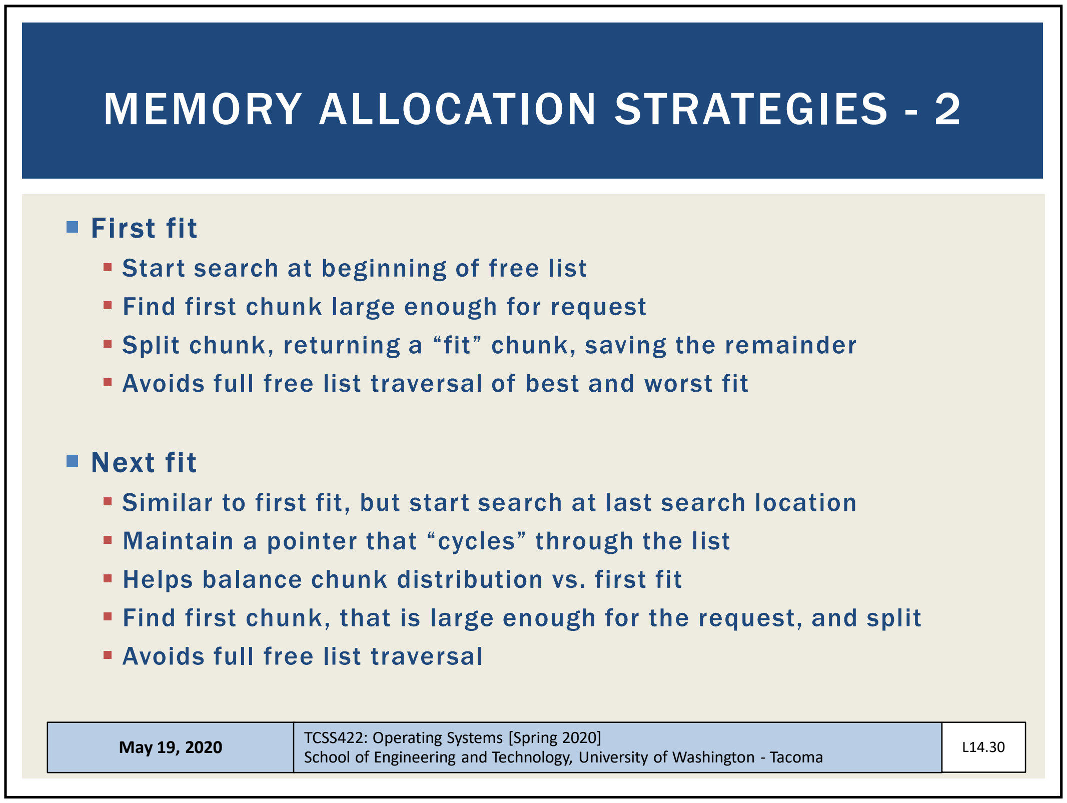
$$\begin{tikzcd} \text{head} \arrow[r] & 10 \arrow[r] & 30 \arrow[r] & 20 \arrow[r] & \text{NULL} \end{tikzcd}$$

- Result of Best Fit

$$\begin{tikzcd} \text{head} \arrow[r] & 10 \arrow[r] & 30 \arrow[r] & 5 \arrow[r] & \text{NULL} \end{tikzcd}$$

- Result of Worst Fit

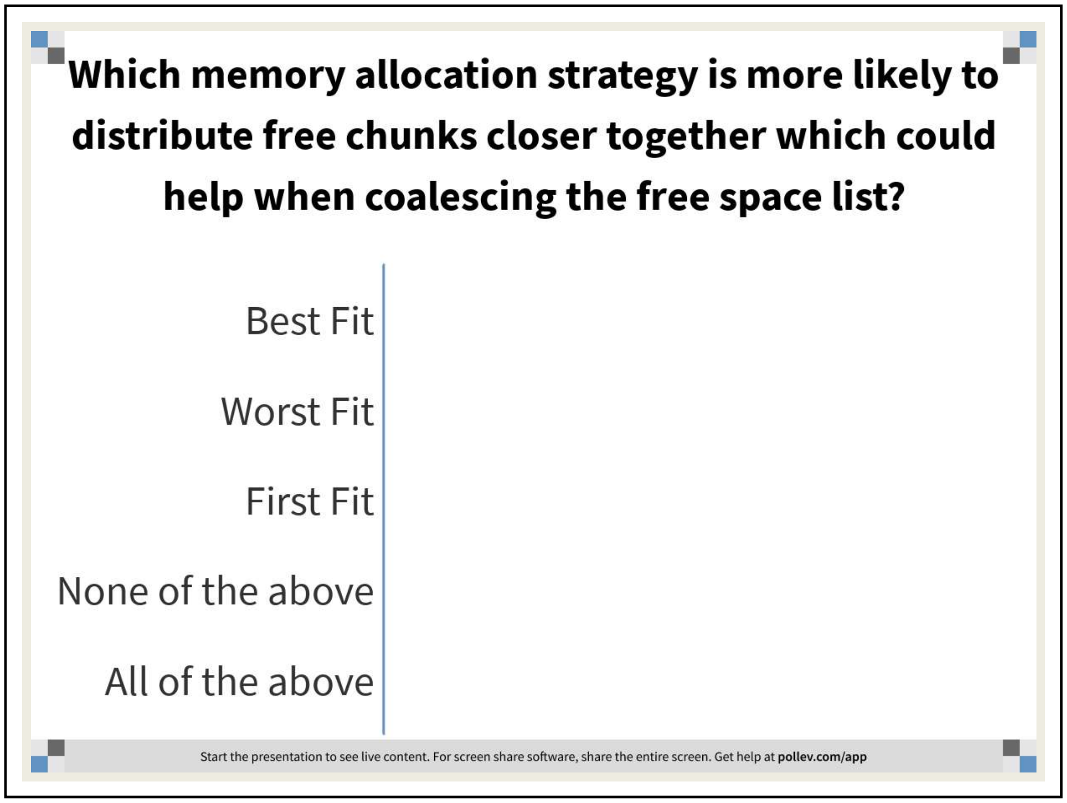
$$\begin{tikzcd} \text{head} \arrow[r] & 10 \arrow[r] & 15 \arrow[r] & 20 \arrow[r] & \text{NULL} \end{tikzcd}$$



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



Which memory allocation strategy is more likely to distribute free chunks closer together which could help when coalescing the free space list?

- Best Fit
- Worst Fit
- First Fit
- None of the above
- All of the above

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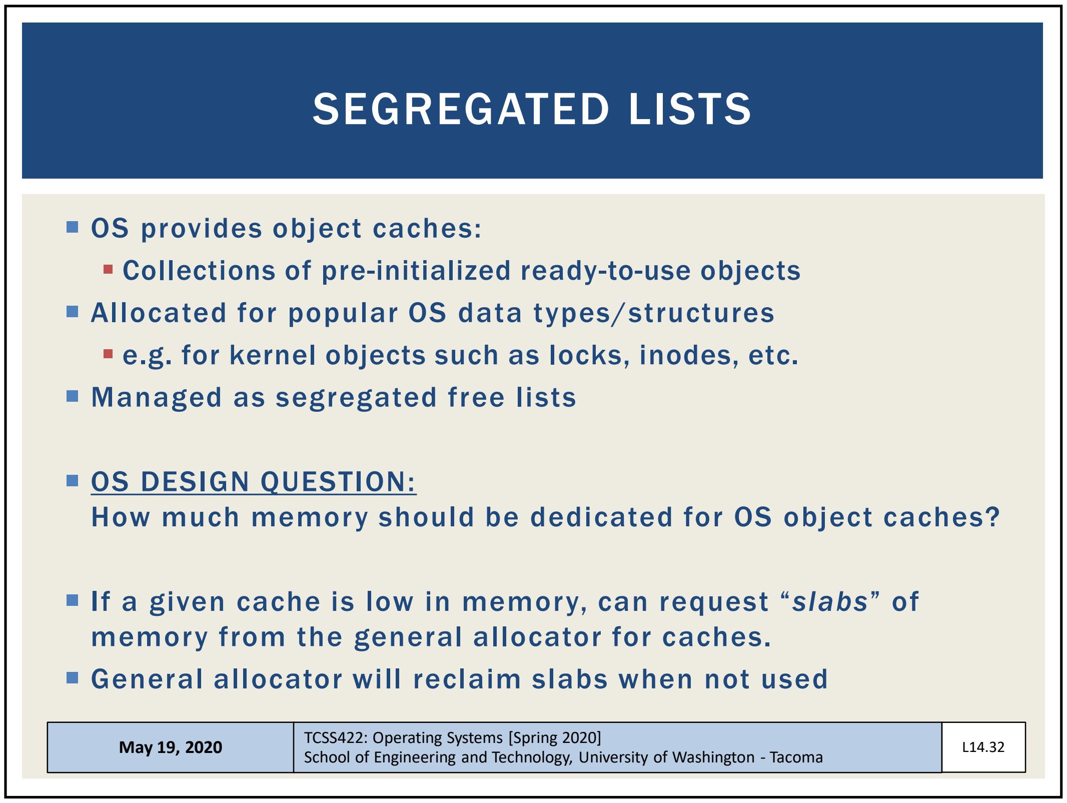

SEGREGATED LISTS

- OS provides object caches:
  - Collections of pre-initialized ready-to-use objects
- Allocated for popular OS data types/structures
  - e.g. for kernel objects such as locks, inodes, etc.
- Managed as segregated free lists

- OS DESIGN QUESTION:
  How much memory should be dedicated for OS 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

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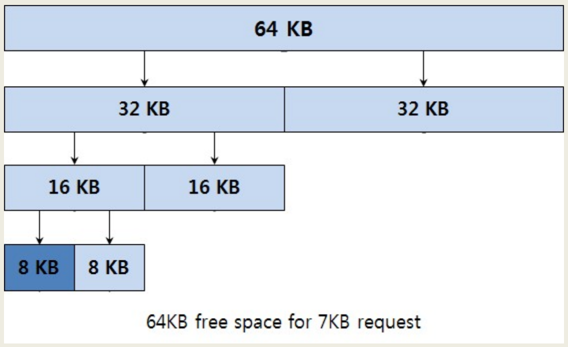
BUDDY ALLOCATION

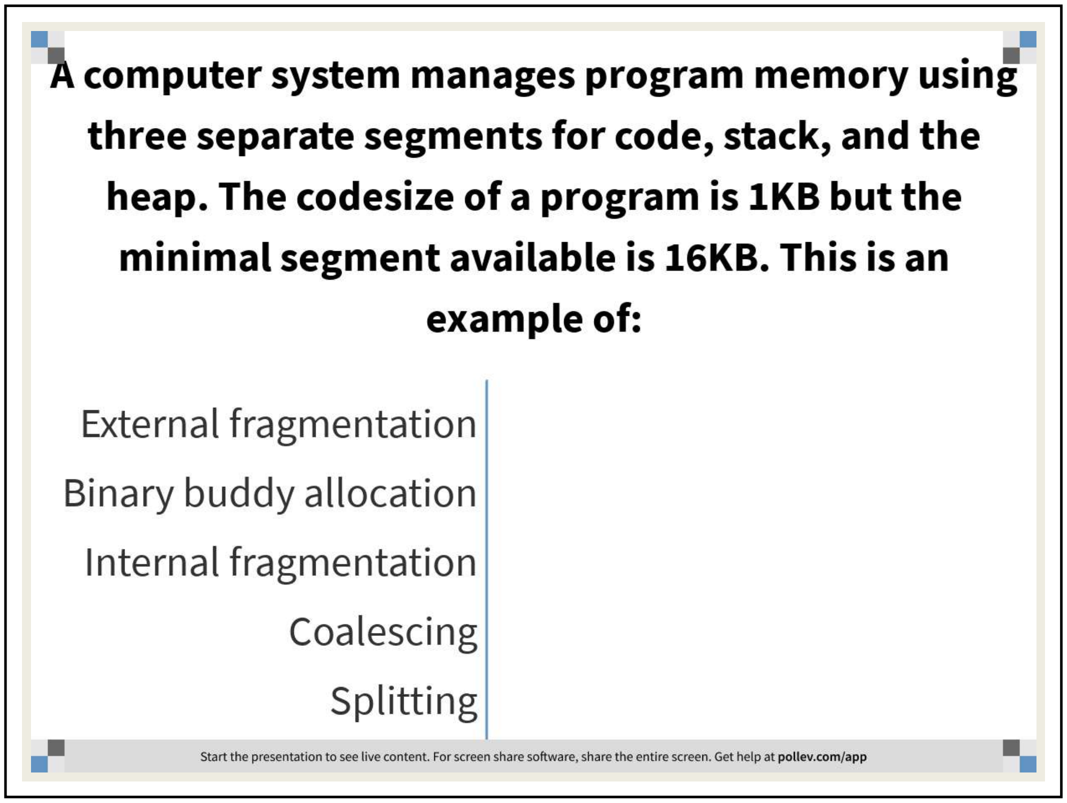
- Binary buddy allocation
  - Divides free space by two to find a block that is big enough to accommodate the request; the next split is too small…
- Consider a 7KB request



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



A computer system manages program memory using three separate segments for code, stack, and the heap. The codesize of a program is 1KB but the minimal segment available is 16KB. This is an example of:

External fragmentation
Binary buddy allocation
Internal fragmentation
Coalescing
Splitting

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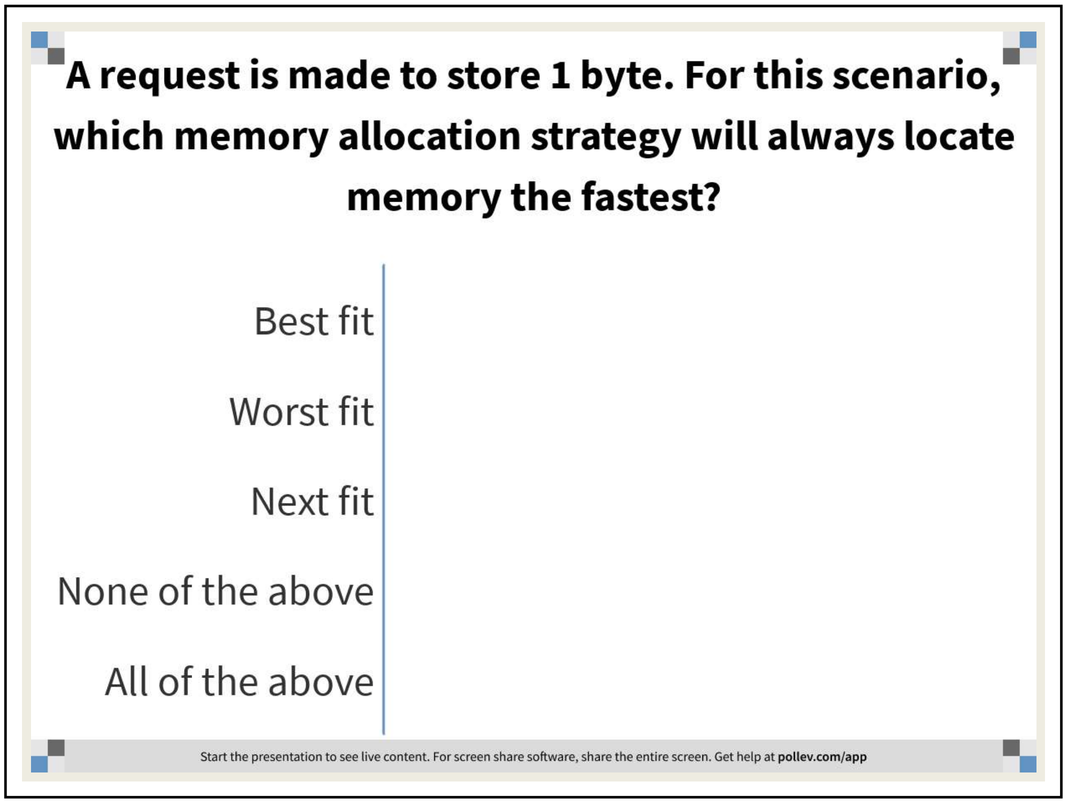

A request is made to store 1 byte. For this scenario, which memory allocation strategy will always locate memory the fastest?

Best fit
Worst fit
Next fit
None of the above
All of the above

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CHAPTER 18: INTRODUCTION TO PAGING

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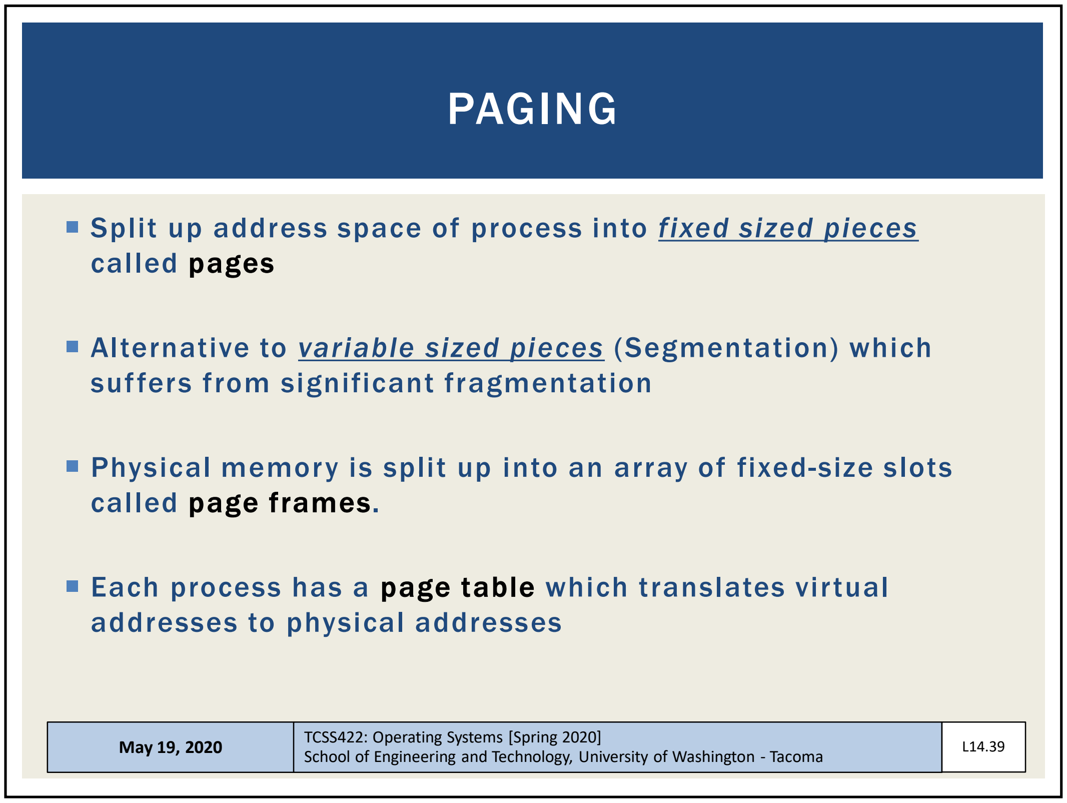
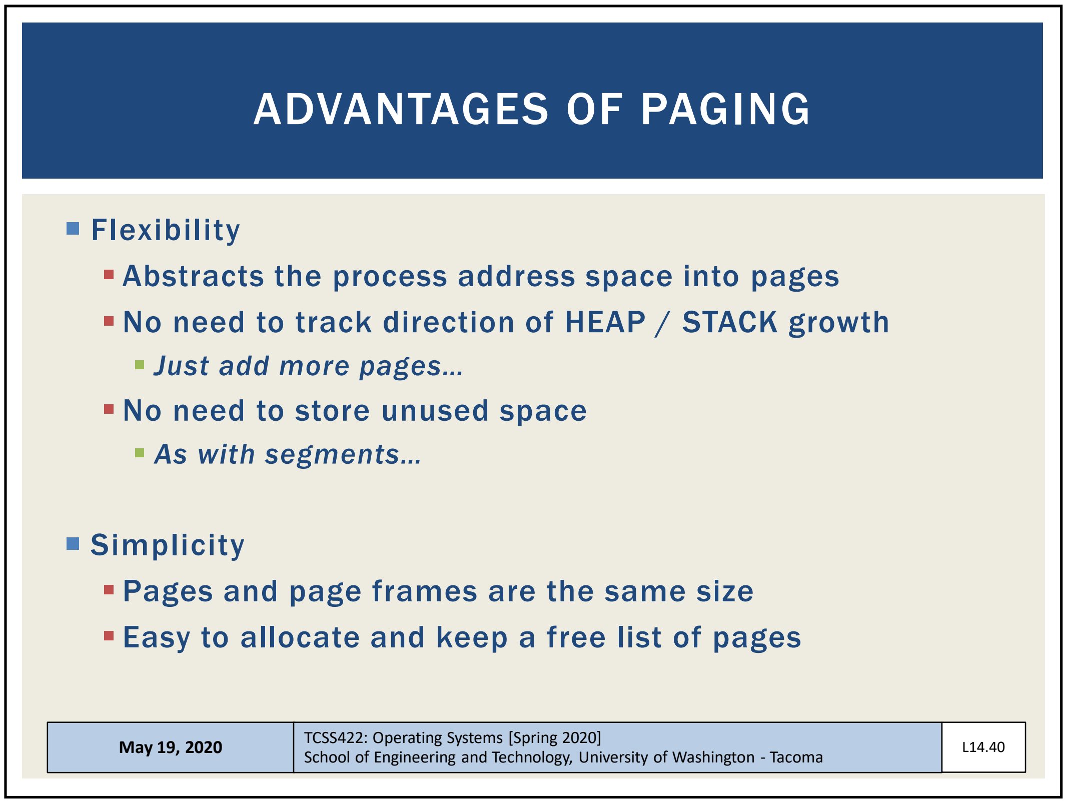


PAGING

- 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



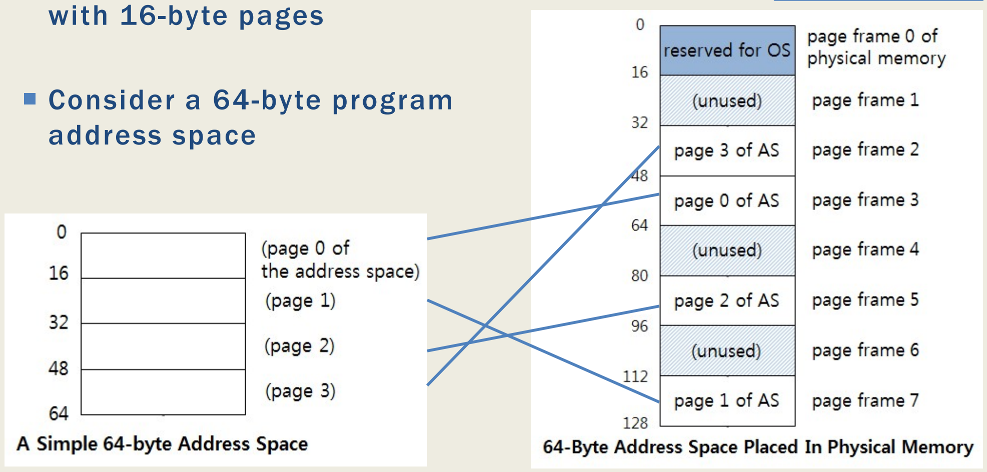
ADVANTAGES OF PAGING

- 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

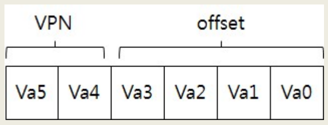


A Simple 64-byte Address Space

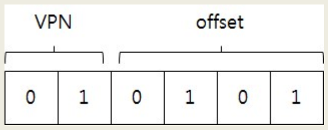
64-Byte Address Space Placed In Physical Memory

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



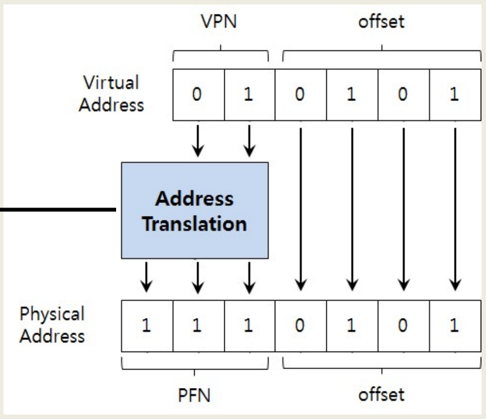
Here there are just four pages...

EXAMPLE: PAGING ADDRESS TRANSLATION

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

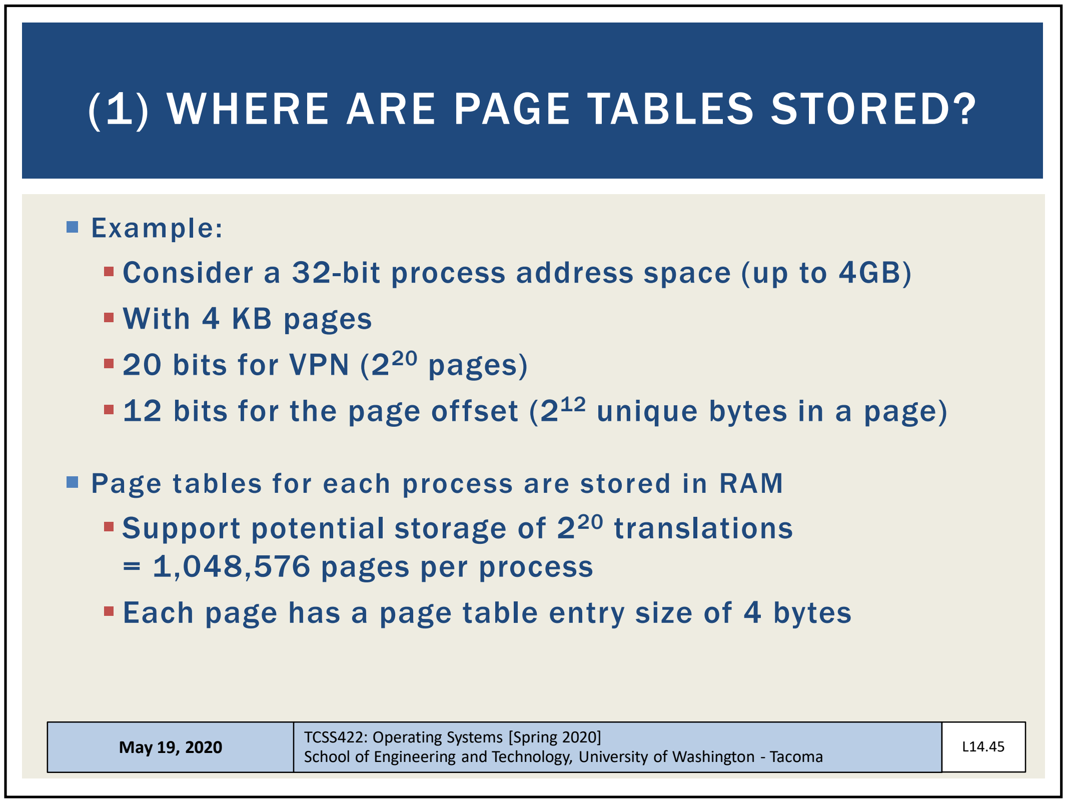
- Offset is preserved
- VPN is looked up

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



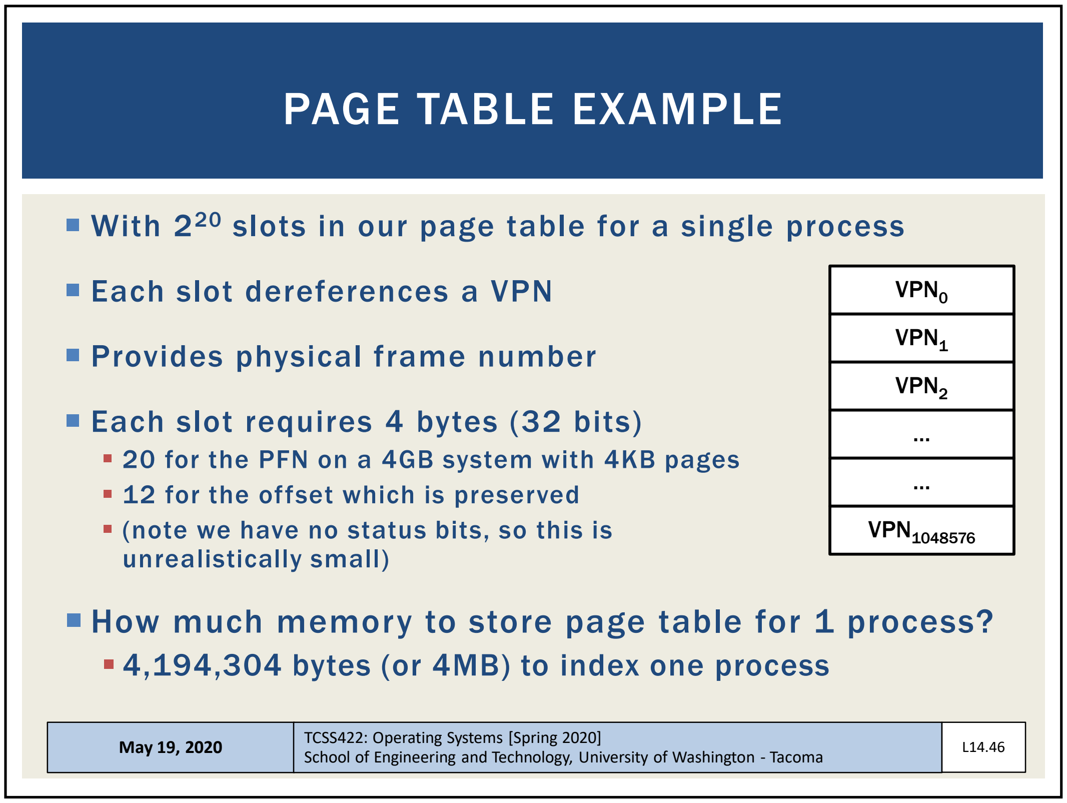
PAGING DESIGN QUESTIONS

- (1) Where are page tables stored?
- (2) What are the typical contents of the page table?
- (3) How big are page tables?
- (4) Does paging make the system too slow?



(1) 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)

VPN_0
VPN_1
VPN_2
…
…
$VPN_{1048576}$

- How much memory to store page table for 1 process?
  - 4,194,304 bytes (or 4MB) to index one process

NOW FOR AN ENTIRE OS

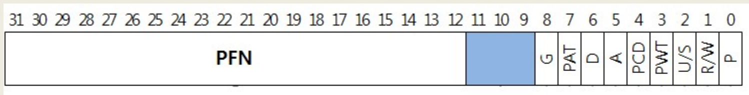
- If 4 MB is required to store one process
- Consider how much memory is required for an entire OS?
  - With for example 100 processes…
- Page table memory requirement is now 4MB x 100 = 400MB
- If computer has 4GB memory (maximum for 32-bits), the page table consumes 10% of memory

400 MB / 4000 GB

- Is this efficient?

(2) WHAT'S ACTUALLY IN THE PAGE TABLE

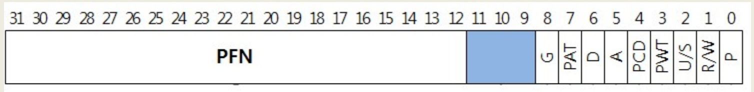
- Page table is data structure used to map virtual page numbers (VPN) to the physical address (Physical Frame Number PFN)
  - Linear page table → simple array
- Page-table entry
  - 32 bits for capturing state



An x86 Page Table Entry(PTE)

PAGE TABLE ENTRY

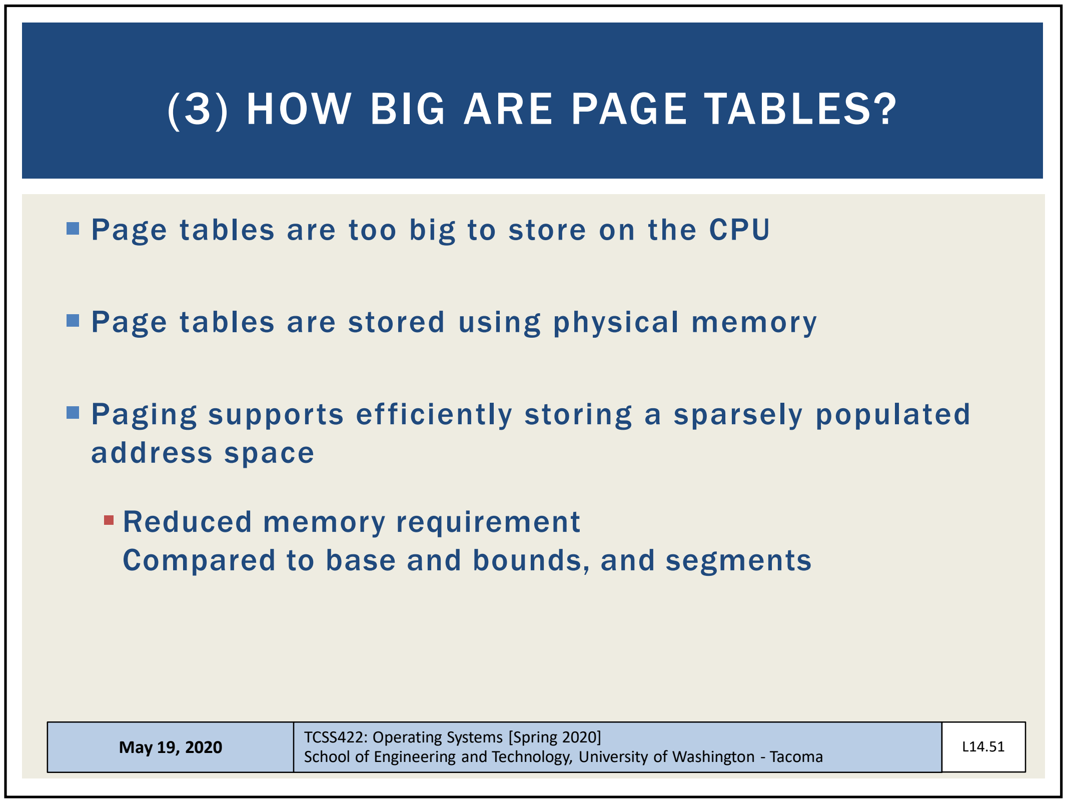
- P: present
- R/W: read/write bit
- U/S: supervisor
- A: accessed bit
- D: dirty bit
- PFN: the page frame number



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



(3) 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

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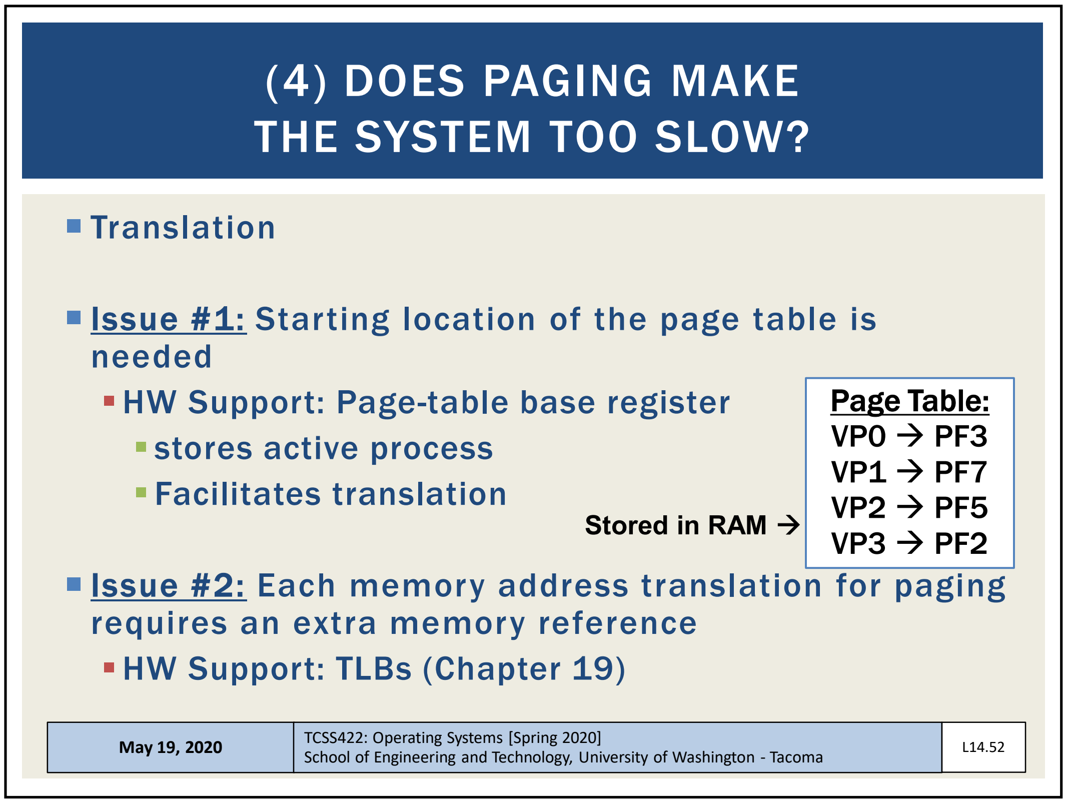

(4) DOES PAGING MAKE THE SYSTEM TOO SLOW?

- 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)

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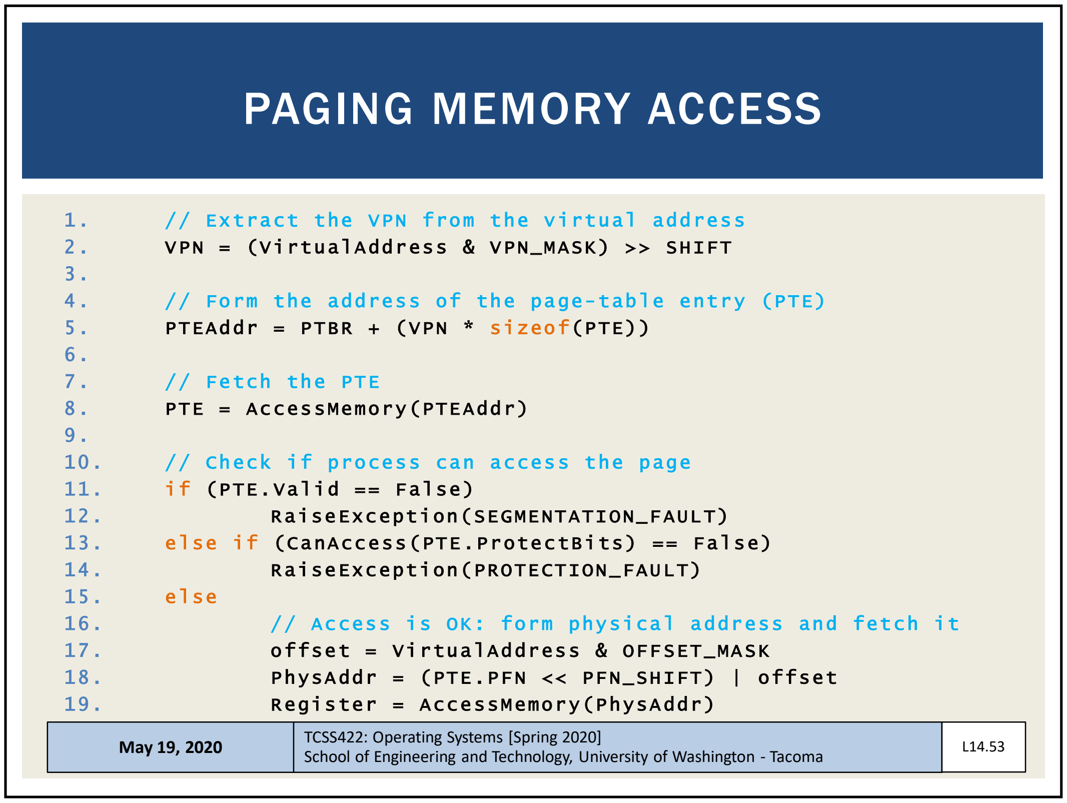


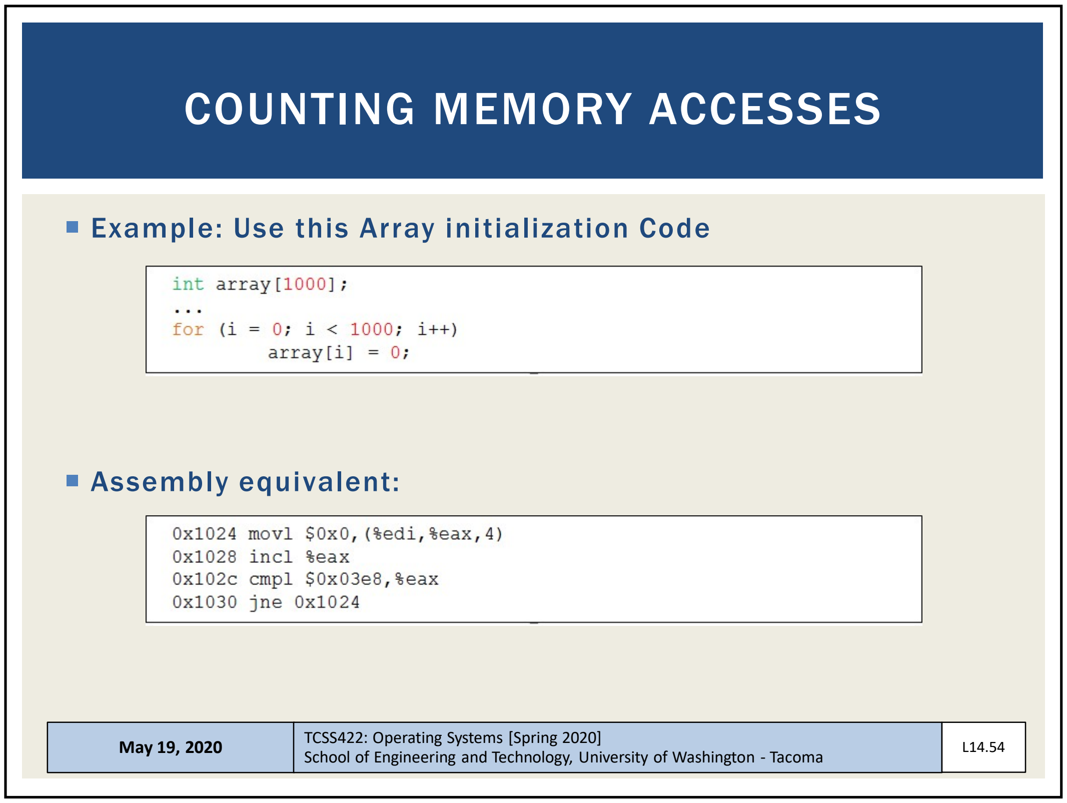
PAGING MEMORY ACCESS

```
// 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

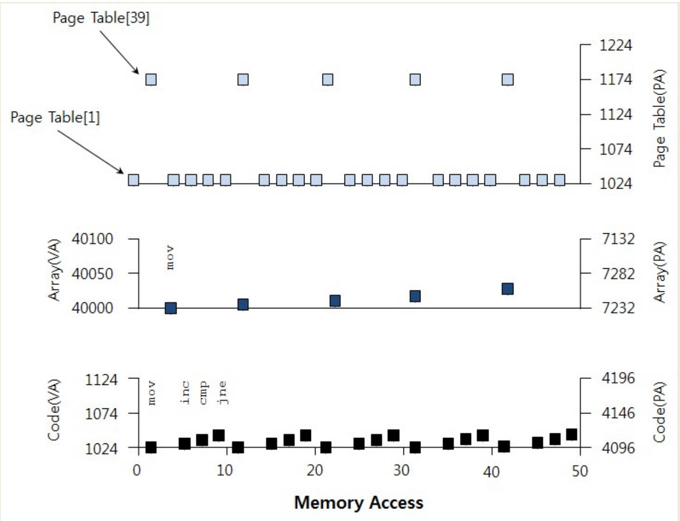
```
int array[1000];
...
for (i = 0; i < 1000; i++)
        array[i] = 0;
```

- Assembly equivalent:

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

VISUALIZING MEMORY ACCESSES: FOR THE FIRST 5 LOOP ITERATIONS

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



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PAGING SYSTEM EXAMPLE

- Consider a 4GB Computer:
- With a 4096-byte page size (4KB)
- How many pages would fit in physical memory?
- Now consider a page table:
- For the page table entry, how many bits are required for the VPN?
- If we assume the use of 4-byte (32 bit) page table entries, how many bits are available for status bits?
- How much space does this page table require? Page Table Entries x Number of pages
- How many page tables (for user processes) would fill the entire 4GB of memory?

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QUESTIONS

WILL RETURN IN A FEW MINUTES