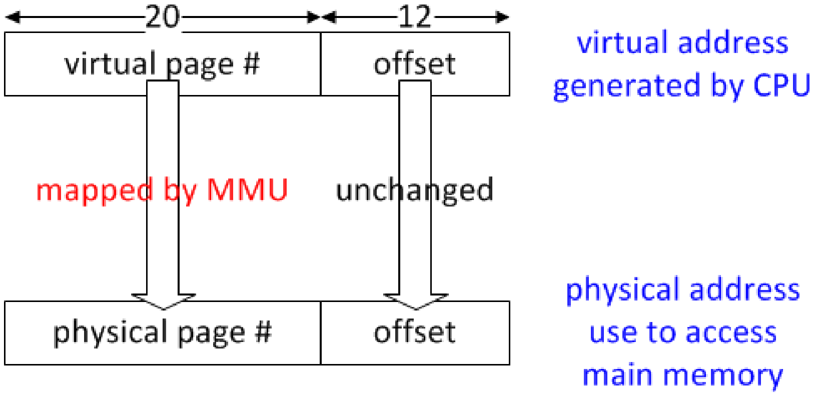
Memory Management Units

- memory management unit (MMU) simply converts a *virtual* address generated by a CPU into a *physical* address which is applied to the memory system


20
12
virtual page #
offset
virtual address generated by CPU
mapped by MMU
unchanged
physical page #
offset
physical address use to access main memory

- address space divided into fixed sized pages [eg. 4Kbytes]

- low order address bits [offset within a page] not effected by MMU operation

- virtual page # converted into a physical page #

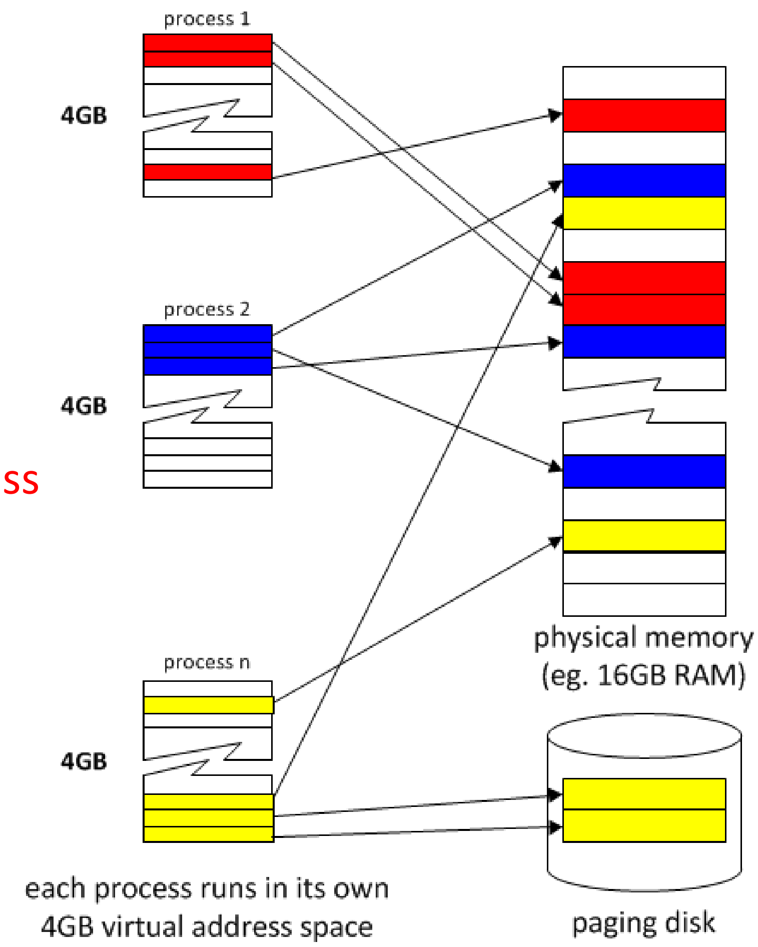
Memory Management Units…

- MMUs integrated on-chip with the CPU
- each CPU core will typically have separate MMUs for instruction and data accesses
- examples as per IA32
  - 2^{32} byte [4GByte] address space divided into… 2^{20} [1,048,576] × 2^{12} [4K] byte pages
- virtual and physical address spaces need NOT be the same size
- which would you prefer?
  - virtual > physical

    OR…
  - physical > virtual

Mapping Virtual Address Spaces onto Physical Memory [IA32]

- each process runs in own 4GB virtual address space
- pages in each virtual address space mapped by MMU onto real physical pages in memory
- pages allocated and mapped on demand by Operating System (OS)
- virtual pages [in a process] may be
  - not allocated/mapped [probably because process hasn't accessed virtual page yet]
  - allocated in physical memory
  - allocated on paging disk
- typical Windows 7 process memory usage
  - Word 43MB, IE 15MB, Firefox 27MB, …
- small fraction of 4GB virtual address space



each process runs in its own 4GB virtual address space

Mapping Virtual Address Spaces onto Physical Memory

- Atlas Computer 1962 [Manchester University] first to support virtual memory
  - 48bit CPU, 24bit virtual and physical address spaces, 96KB RAM, 576KB drum [disk]
- OS normally attempts to keep the *"working set"* of a process in physical memory to minimise the page-fault rate [thrashing]
- every page used in a process' virtual address space requires an equivalent page either in physical memory or on the paging disk
- 4GB [total] of physical memory and paging disk space needed for a program which uses/accesses all 4GB of its virtual address space [e.g. large array]
- can view physical memory as acting as a cache to the paging disk!

Memory Management Units

Memory Cruncher

- consider the following program outline

```
#define GB (1024*1024*1024)

char *p = malloc(4*GB);                    // just moves internal OS pointer

for (size_t i = 0; i < 4*GB; i += PAGESIZE, p += PAGESIZE)
    *p = 0;                                // access causes physical memory to be allocated
```

- a more complete version of Memory Cruncher.cpp is on the CS3021/3421 website
  - designed to run as a Win32 [32 bit] or x64 [64 bit] process
  - size_t is the size of an address [Win32 32 bits, x64 64 bits]
  - Windows PAGESIZE is 4K

Memory Management Units

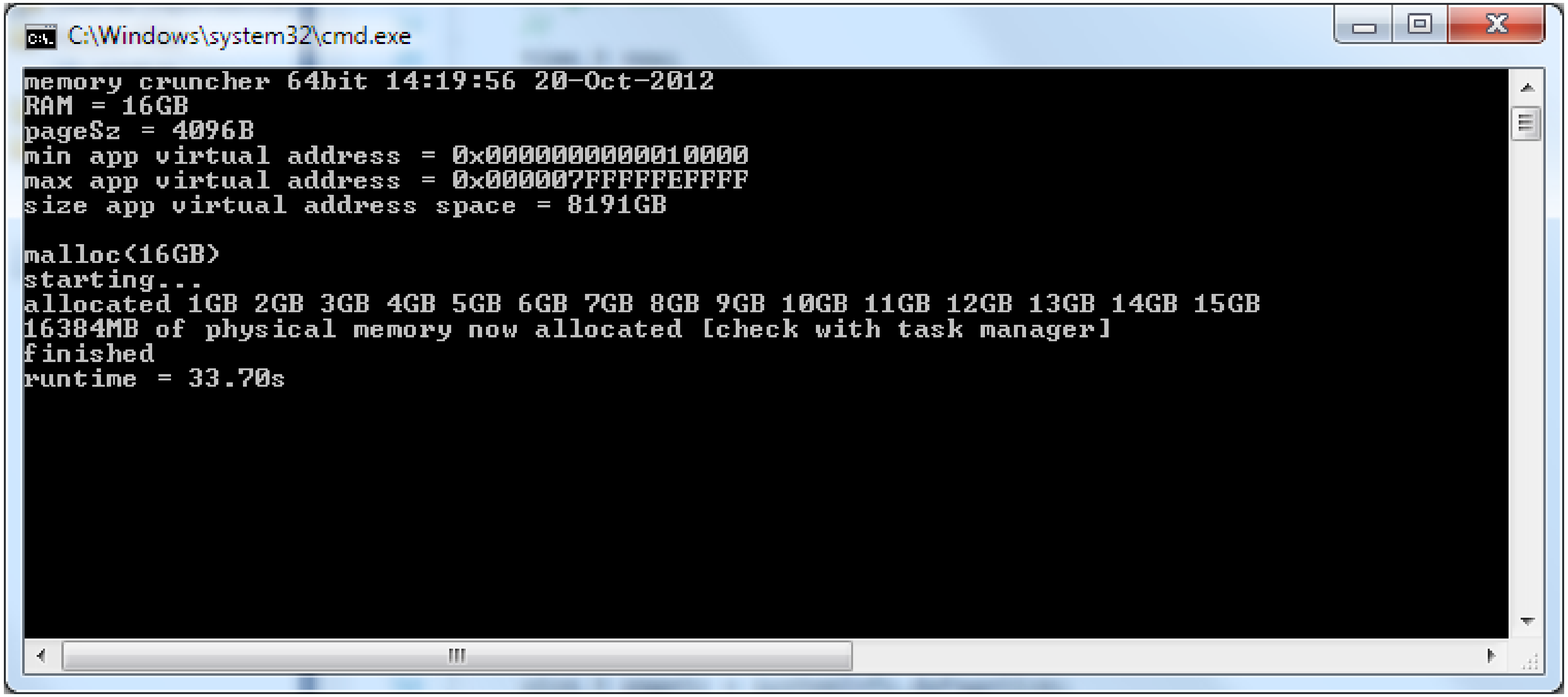
Memory Cruncher…

- what is the largest contiguous memory block that can be allocated?
- Windows 7 Win32
  - 4GB virtual address space, bottom 2GB for user and top 2GB for OS
  - can malloc() a 1535MB contiguous memory block
  - right click on project name [Properties][Linker][System][EnableLargeAddresses]

    can now malloc() a 2047MB contiguous memory block
- Windows 7 x64
  - program reports it can allocate a contiguous memory block of 8191GB or 8TB [2^{43}]
  - *mallocing* a block much greater than size of physical memory [16GB] results in PC becoming extremely unresponsive [had to reboot by turning off power]
  - RUN with caution

Memory Management Units

Memory Cruncher…

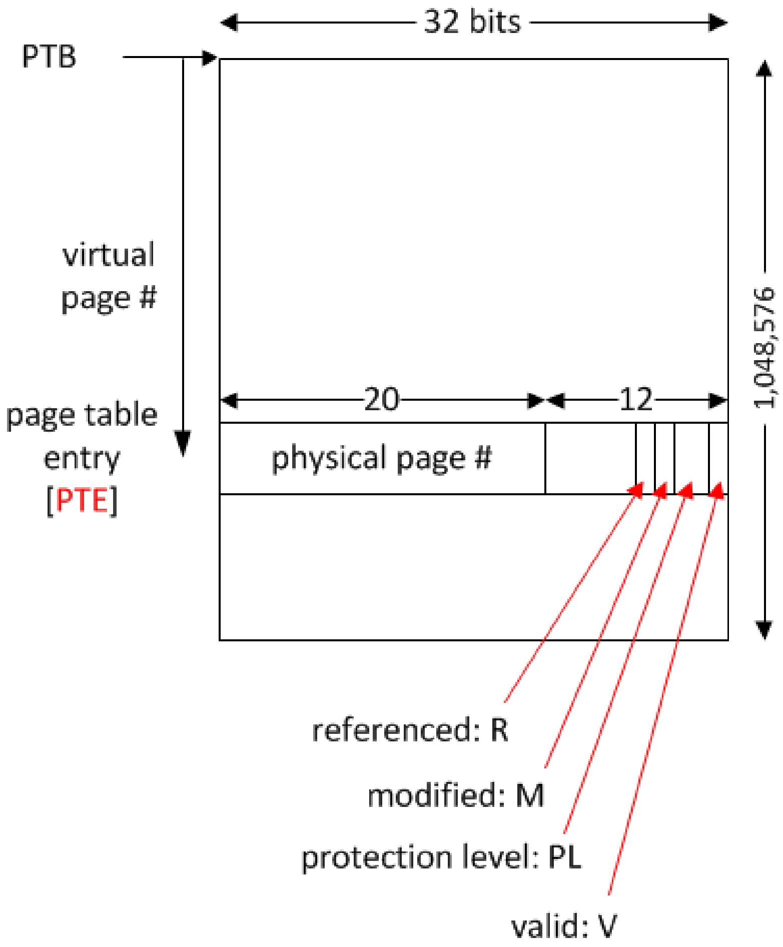


```
memory cruncher 64bit 14:19:56 20-Oct-2012
RAM = 16GB
pageSz = 4096B
min app virtual address = 0x0000000000010000
max app virtual address = 0x000007FFFFFEFFFF
size app virtual address space = 8191GB

malloc(16GB)
starting...
allocated 1GB 2GB 3GB 4GB 5GB 6GB 7GB 8GB 9GB 10GB 11GB 12GB 13GB 14GB 15GB
16384MB of physical memory now allocated [check with task manager]
finished
runtime = 33.70s
```

Generic MMU Operation [IA32, x64, MIPS, …]

- virtual page # converted to a physical page # by table look-up
- virtual page # used as an index into a page table stored in physical memory.
- page table per process [and sometimes one for OS]
- page table base register PTB [CR3 in IA32] contains the physical address of the page table of the currently running process
- 4MB physical memory [1,048,576 x 4] needed for page table of every process
- **IMPRACTICAL**

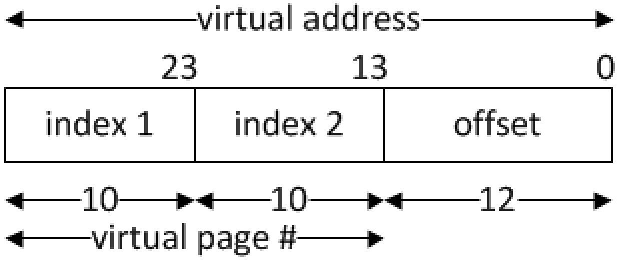


N-level Page Table

- in order to reduce the size of the page table structure that needs to be allocated to a process, a n-level look-up table is used

- a n-level page table means that the *"larger"* the process [in terms of its use of its virtual address space], the more memory is needed for its page tables

- consider a 2-level scheme

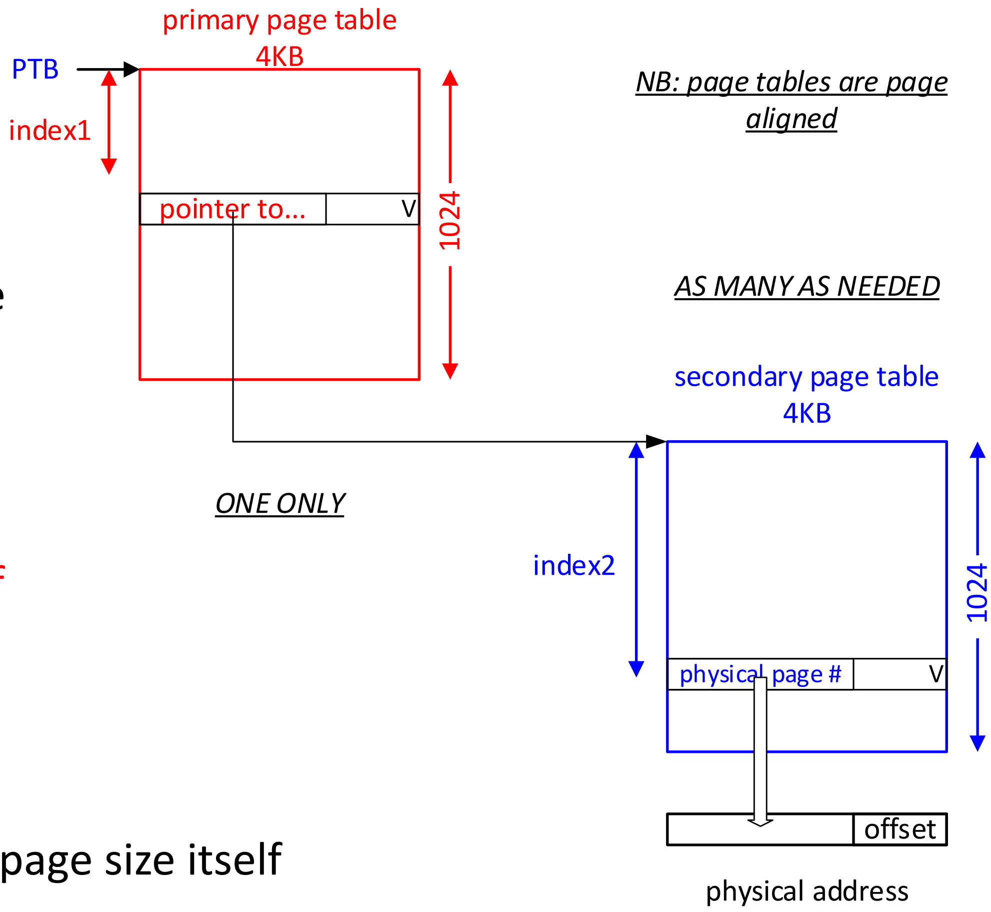


- *index1* is used to index into a primary page table, *index2* into a secondary page table and so on…

Memory Management Units

N-Level Page Table…

- PTB points to primary page table
- a valid primary page table entry points to a secondary page table
- each process has one primary page table + multiple secondary page tables
- secondary page tables created on demand [depends on how much of its virtual address space the process uses]



- NB: size of page tables is 4KB - the page size itself

MEMORY MANAGEMENT UNITS

Generic MMU Operation…

- when MMU accesses a page table entry it checks the **V**alid bit
- if V ==0 and accessing a primary page table entry
  - then NO physical memory allocated for corresponding secondary page table
- if V == 0 and accessing a secondary page table entry
  - then NO physical memory allocated for referenced page [i.e. virtual address NOT mapped to physical memory]
- in both cases a "page fault" occurs, the instruction is aborted and the MMU interrupts the CPU

MEMORY MANAGEMENT UNITS

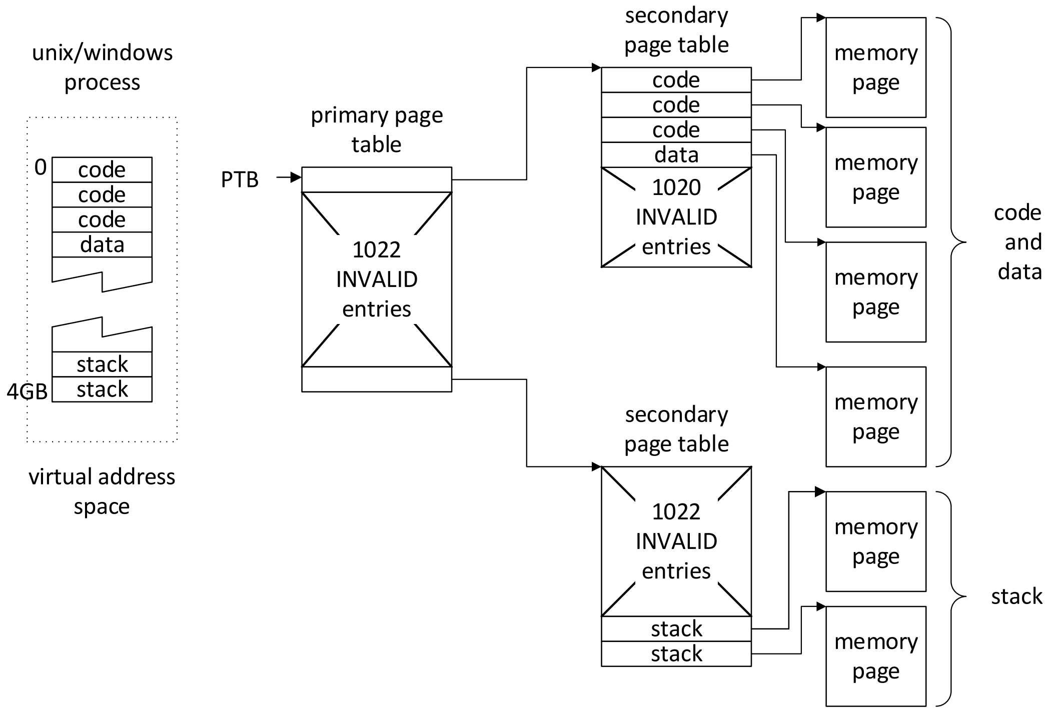
Page fault handling

- OS must resolve page fault by performing one or more of the following actions:
  - allocating a page of physical memory for use as a secondary page table [from an OS maintained list of free memory pages]
  - allocating a page of physical memory for the referenced page
  - updating the associated page table entry/entries
  - reading code or initialised data from disk to initialise the page contents [context switches to another process while waiting]
  - signalling an access violation [e.g. writing to a read-only code page]
  - restarting [or continuing] the faulting instruction

Memory Management Units

Process Page Table Structure

- example process needs 3 code pages [12K], 1 data page [4K] and 2 stack pages [8K]
- code and data pages start at virtual address 0 with the stack at top of virtual address space
- require 2 secondary page tables to map code and stack areas [as at opposite ends of the virtual address space]

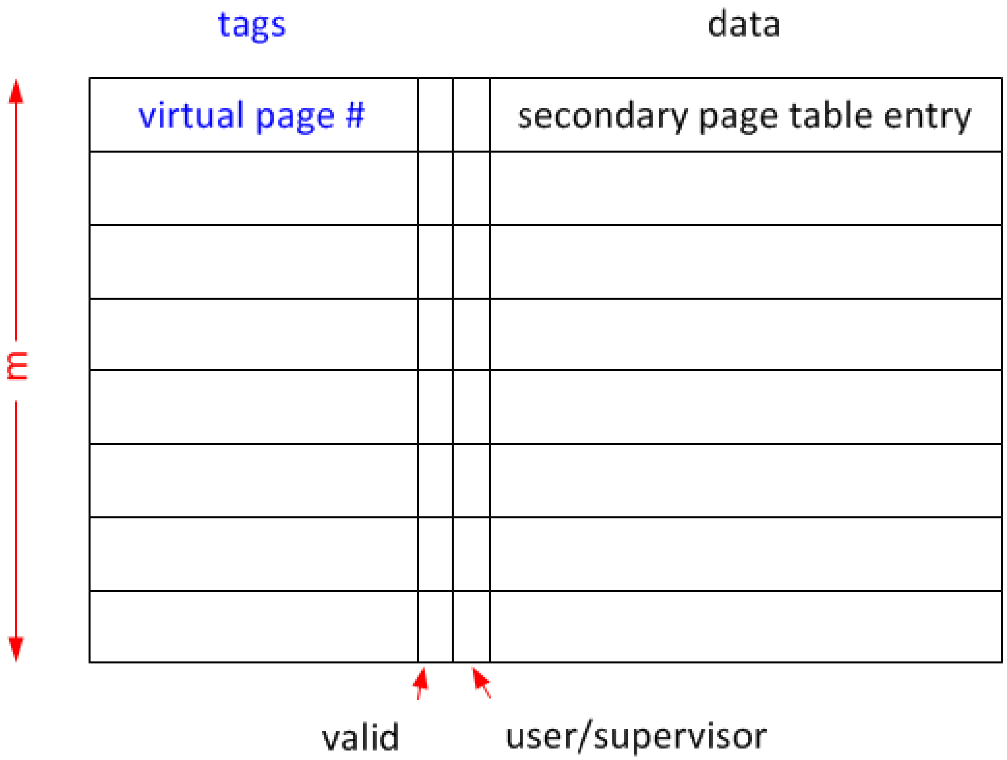


- a secondary page table can map 1024×4K pages = 4MB
- need ONLY 2 secondary page tables providing program doesn't use more than 4MB of code/data and 4MB of stack space

Translation Look Aside Buffer [TLB]

- without an internal TLB, each virtual to physical address translation requires 1 memory access for each level of page table [2 accesses for a 2 level scheme]

- MMU contains an m-entry on-chip translation cache [TLB] which provides direct mappings for the m most recently accessed virtual pages



Translation Look Aside Buffer [TLB]…

- when a virtual address is sent to the TLB, the virtual page # is compared with ALL m tag entries in the TLB in parallel [a fully associative cache]
- if a match is found [TLB hit], the corresponding cached secondary page table entry is output by the TLB/MMU to provide the physical address
  - the address translation is completed *"instantaneously"*
- if a match is NOT found [TLB miss], page tables walked by CPU/MMU
  - IA32/x64 page tables walked by a hardware state machine hardwired into CPU/MMU
- the *"least recently used"* [LRU] TLB entry is replaced with new mapping
- how can the hardware find the LRU entry *SIMPLY and QUICKLY*?

Memory Management Units

RISC TLB Miss Handling

- Remember that the page tables are just data structures held in main memory and can be walked by a CPU using ordinary instructions
- this approach is taken by many RISCs, a TLB miss generates an interrupt and the CPU walks the page table using ordinary instructions [TLB miss ≡ page fault]
- in such cases the organisation of page table structure is more flexible since it can be set by software and is NOT hard-wired into CPU/MMU [e.g. could implement a hash table]
- need a CPU instruction to replace the LRU TLB entry
- TLBs are normally small
- a typical 64 entry fully associative TLB has a hit rate > 90%
- a CPU would typically have a MMU for instruction accesses and a MMU for data accesses [needed for parallel accesses to the instruction and data caches]

TLB Coherency OS implications

- what happens on a process switch?
- TLB looked up by virtual address
- **ALL** processes use the same virtual addresses…

  *e.g. process 0 virtual address 0x1000 is **NOT** mapped to the same physical memory location as process N virtual address 0x1000 unless the page really is shared*

- **ALL** TLB entries referring to the old process must be invalidated on a context switch otherwise the new process will access the memory pages of the old process
- normally the OS [if it runs in its own virtual address space] and one user process can share the entries in the TLB
- user/supervisor bit appended to TLB tag [see diagram slide 14]

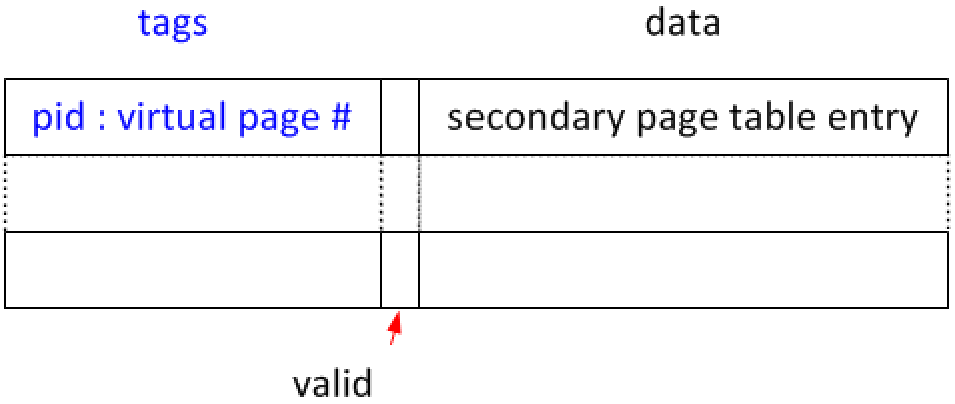
TLB Coherency OS implications…

- whenever the page table base register [e.g. PTB0 for OS or PTB1 for user process] is changed ALL corresponding TLB entries are invalidated
  - PTB1 changed every time there is a context switch between processes
  - PTB0 unlikely to change
- if a page table entry is changed in main memory [when handling a page fault], the OS must make sure that this change is reflected in the TLB
  - must be able to invalidate old PTEs in the TLB
  - CPU has an instruction to do this [e.g. IA32 "*INVAL va*" will invalidate PTE entry corresponding to virtual address *va* if present in TLB]
- also need to keep TLBs in a multicore CPU coherent

Memory Management Units

Multiple Processes sharing TLB

- possible for processes to share TLB if a process ID is appended to the virtual page # as part of the TLB tag



- extension of user/supervisor bit as part of tag

- need to handle PID reuse as number of bits used for PID limited [e.g. 8 bits]

Referenced and Modified Bits

- CPU/MMU automatically updates the PTE Referenced and Modified bits [IA32/x64 Accessed and Dirty bits] in the PTEs

- PTE changes "*written through*" to corresponding PTE in physical memory
  - CPU/MMU automatically executes these bus cycles

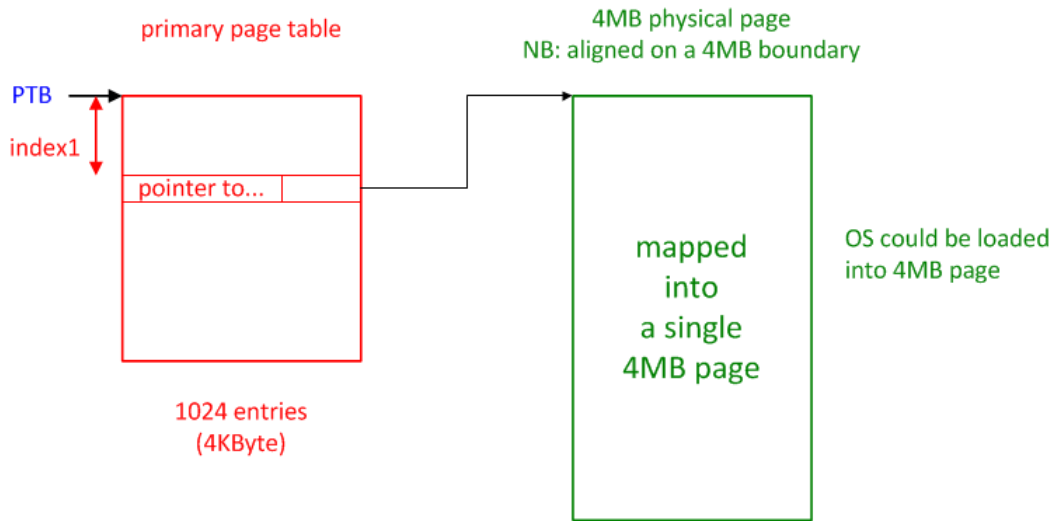
- CPU/MMU never clears the reference and modified bits
  - up to the OS [eg. a background process regularly clearing the referenced bits?]

- OS can use the Referenced and Modified bits to determine
  - which pages are good candidates for being paged out [ones that have not been referenced for a while]
  - whether pages have to be written to the paging disk [may be unchanged since last write]

Support for Different Page Sizes

- often useful if MMU supports a number of different page sizes
- one reason is that a TLB typically contains very few entries [32 or 64]
- *large pages* allows a single TLB entry map a *large* virtual page onto similar sized area of contiguous physical memory
  - OS could be loaded into a contiguous area of physical memory which could then be mapped using a single TLB entry
  - similarly for a memory mapped graphics buffer
- IA32 solution
  - first level PTE points to a 4MB page of physical memory [not a 2nd level page table]
  - bit set in primary PTE to indicate that it points to a *large* page [not a 2nd level page table]

IA32 Support for Large Pages



- corresponding TLB entry maps 4MB virtual page to a 4MB page of physical memory
- 4MB page aligned on a 4MB boundary in virtual and physical address spaces
- TLB operation needs to be modified to accommodate these *large 4MB* TLB entries

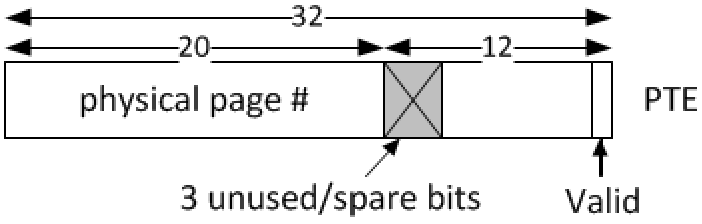
Memory Management Units

Breakpoints Registers

- the MMU typically supports a number of *breakpoint address registers* and *breakpoint control registers*
- the MMU can generate an interrupt if the breakpoint address [virtual or physical] is read or written [watchpoint] or executed [breakpoint]
- debugger normal sets breakpoints and watchpoints using virtual addresses
- used to implement real-time debugger breakpoints and watchpoints
- hardware support needed to set breakpoints in ROM and for watchpoints
- MMU breakpoint registers are part of the process state
    - save/restored as part of the context switch
    - hence more than one processes can be debugged *at the same time*
- used by Linux ptrace system call

Integrating MMU and Operating System

- page table entries normally have a number of bits set aside for use by the OS implementer [i.e. not altered by hardware]
- IA32 PTEs have 3 such bits



- use spare bits to store OS specific PTE types
- consider the OS specific PTE types used in a hypothetical Unix implementation [closely modelled on GENIX for the NS32000 microprocessor which was the first demand paged microprocessor Unix implementation]
- uses 2 spare bits in PTE to define four PTE types when V == 0 and four when V == 1

Memory Management Units

Types when V == 1 [VALID]

- MEM - maps virtual address to a physical address
- LOCK - same as MEM except page is locked into physical memory
  - *vlock(va)* system call [superuser ONLY]
  - software, not hardware, locking
  - really a hint to OS
- SPY - maps virtual address [*va*] to a specific physical address [*pa*]
  - can be used to map hardware device registers into a user process' virtual address space
  - *vspy(va, pa)* system call [superuser ONLY]
  - allows user level device drivers to be implemented

MEMORY MANAGEMENT UNITS

Types when V == 0 [INVALID]

- NULL - page NOT yet mapped to physical memory

- DISK - page not mapped to physical memory, but when mapped the page must be initialised using data stored on disk

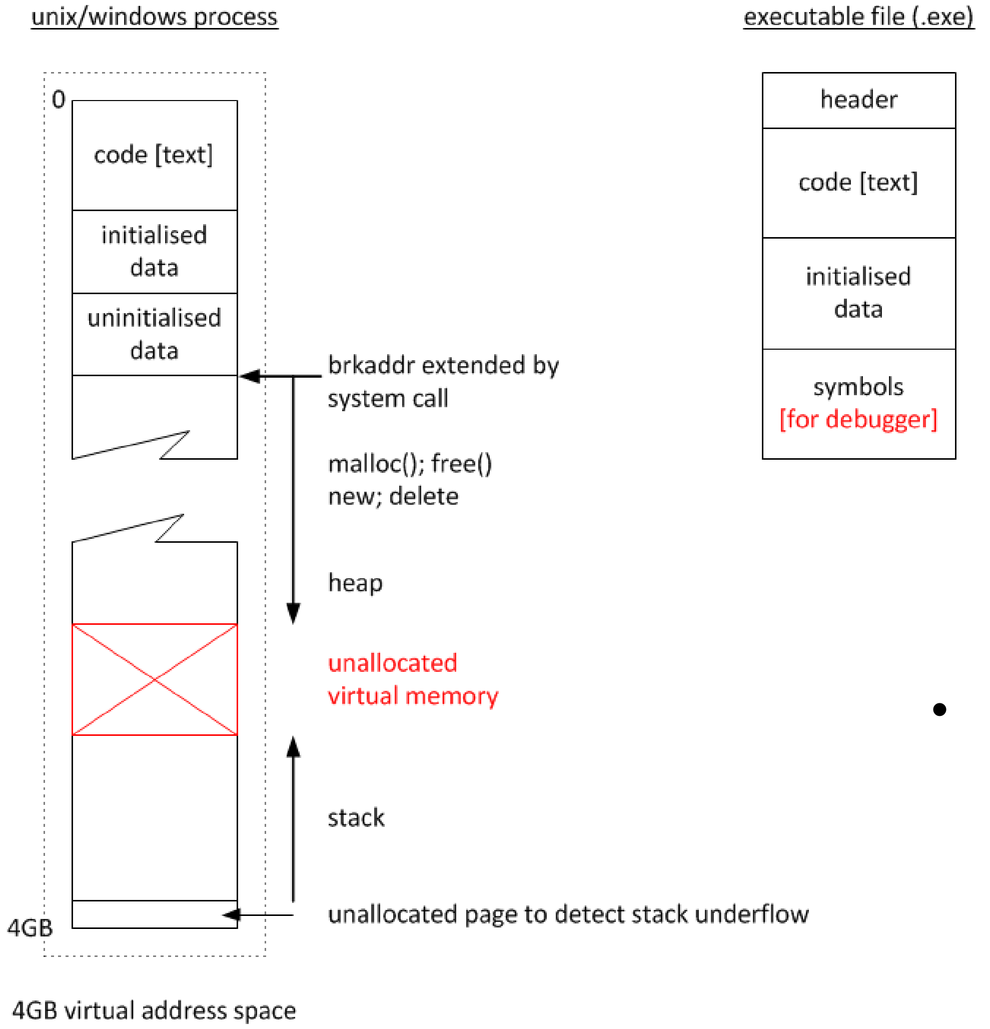
  - when V == 0, the PTE *physical page #* field contains a disk block number where the data is located on disk
  - assuming a 20 bit *physical page #* field, a 4K page size and a 4K disk block size it is possible to accommodate a 2^{20} x 2^{12} = 4GB disk [limiting with current disk sizes]

- IOP - indicates that the disk I/O is in progress

- SPT shared PTE [explained in next section of notes]

  - allows code to be shared between processes
  - contains a pointer to a PTE in another page table

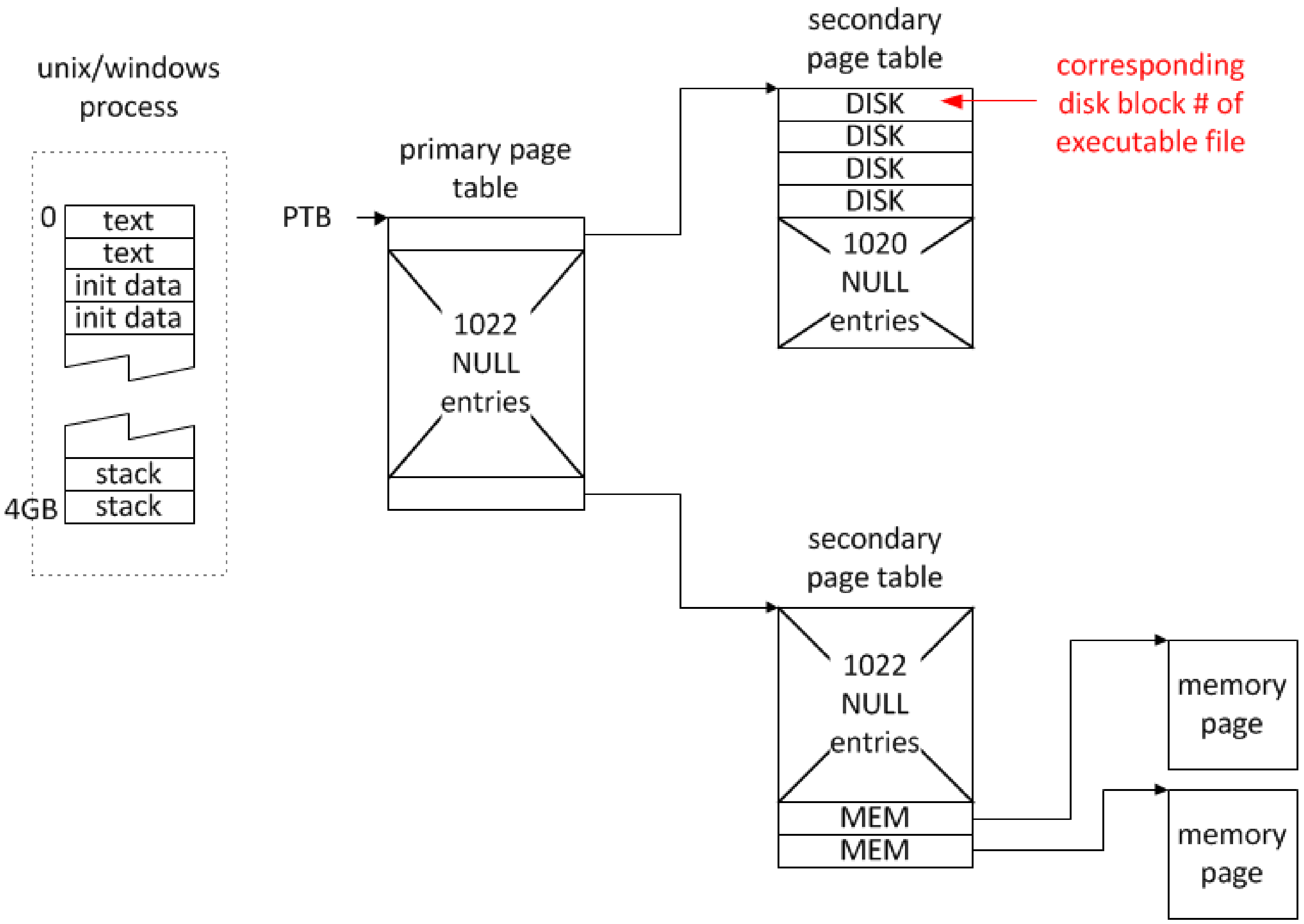
Initial Mapping of Unix/Windows Process



- need to create a virtual address space + page table for process

Memory Management Units

Initial Mapping of Unix/Windows Process…



Initial Mapping of Unix/Windows Process…

- text and initialised data PTEs initialised to type DISK
    - disk block number allows data to be quickly located on disk
- enough real stack pages allocated [type MEM] to hold the arguments and environmental data passed to the process
- ALL remaining PTEs initialised to type NULL
- process allocated ONLY 5 pages of physical memory initially
    - primary page table
    - 2 secondary page tables
    - 2 stack pages
- further pages allocated to process on demand

Initial Execution of Unix/Windows Process

- after the initial page table is created the process starts execution [start address in .exe header]
- will instantly generate a page fault as the first instruction is still on disk
- page faults will continue to occur as the process executes and each PTE type fault will be handled as follows:

PTE type	action
DISK	allocate a page of physical memory [OS maintains a free list] and fill with data read from disk [context switch while waiting for disk] code pages normally read ONLY, initialised data pages typically read/write code and initialised data paged in "on demand" DISK → IOP → MEM

Memory Management Units

Initial Execution of Unix/Windows Process…

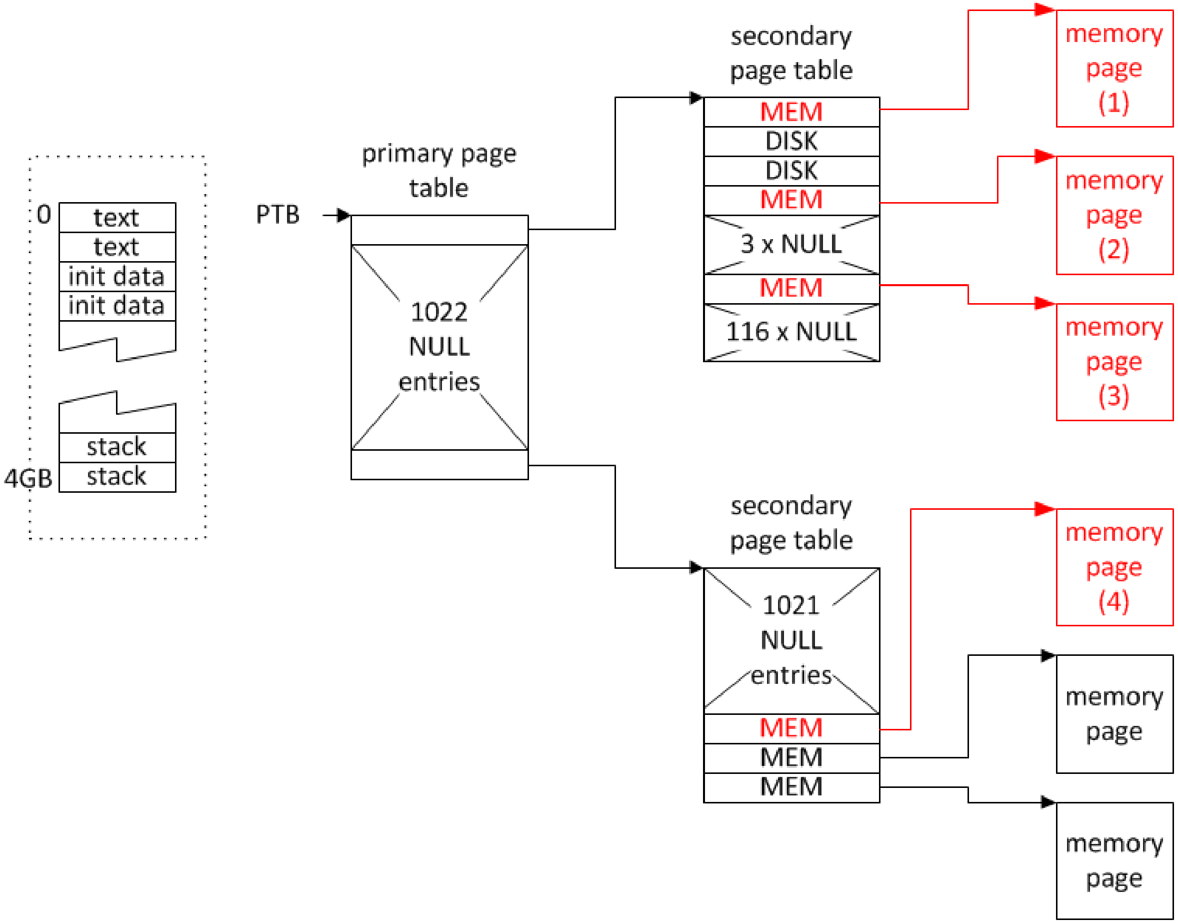
PTE type	action
NULL	physical memory has not yet been allocated the virtual fault address is checked to see if it's sensible / in range if page fault virtual address not in uninitialised data, heap or stack then it is considered to be an illegal memory access and a memory access violation is signalled otherwise a page of [zeroed] physical memory is allocated by OS NULL → MEM
MEM	protection level fault [e.g. writing to text via a NULL pointer]
IOP	wait for I/O to complete [see DISK type fault]
SPY	*protection level fault?*
LOCK	*protection level fault?*

if OS gets confused and cannot resolve page fault it calls panic() which reboots OS

Page Table Snapshot after Process has Started to Execute

Diagram show the following pages added to the initial process page table

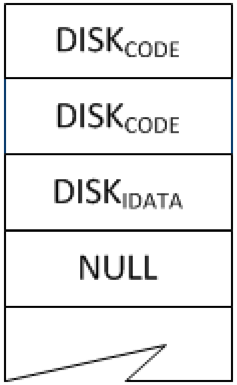
- 1 code page (1)
- 1 initialised data page (2)
- 1 uninitialised data page (3)
- 1 stack page (4)



MEMORY MANAGEMENT UNITS

Text/Code Sharing

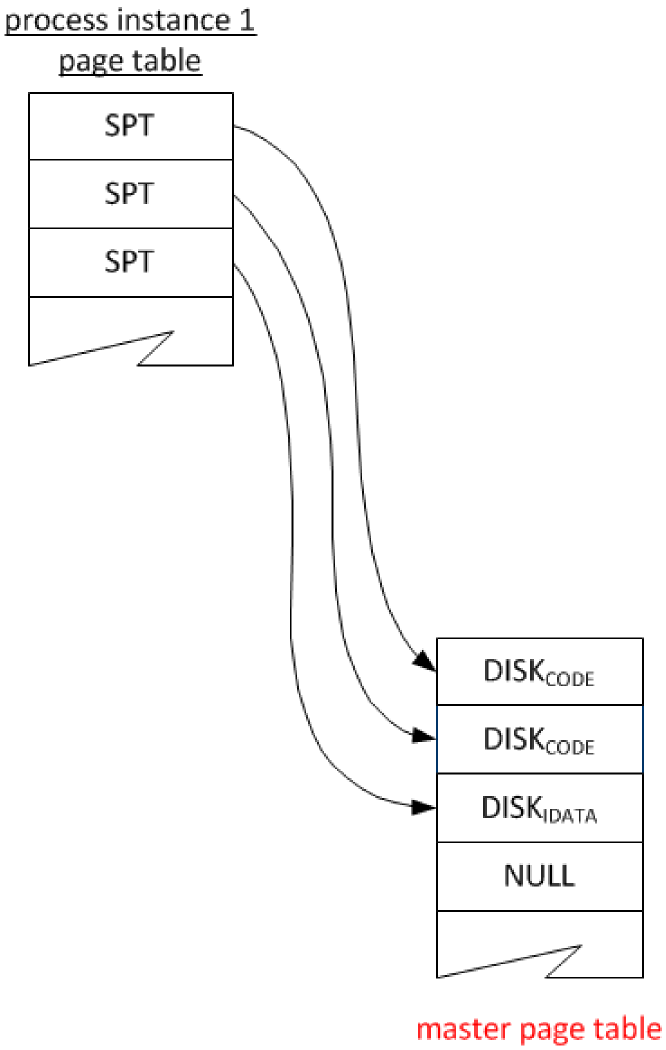
- if the same process is executing more then once, ONLY a single shared copy of the code need be in memory
- NB: each process still needs its own pages for its data, heap and stack
- NB: initialised data can be shared if read-only
- when a process is executed for the first time, a master page table is created
- the PTEs corresponding to the code and initialised data are initialised to type DISK
- remaining PTEs set to type NULL


$\text{DISK}_{\text{CODE}}$
$\text{DISK}_{\text{CODE}}$
$\text{DISK}_{\text{IDATA}}$
NULL

master page table

Text/Code Sharing..

- a process page table is created by initialising its code and initialised data PTEs to type SPT
- the SPT PTEs point to their corresponding entries in the master page table
- physical pages for its initial stack are attached to the process page table
- remaining PTEs set to type NULL

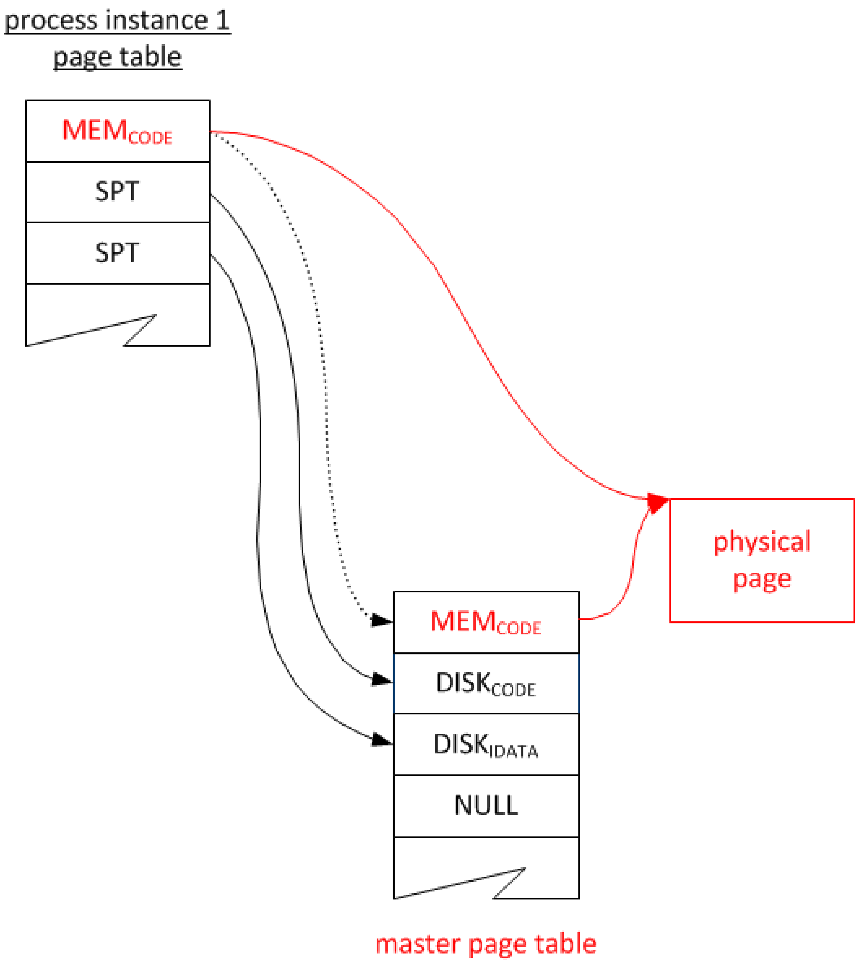


Text/Code Sharing..

- on a SPT page fault, the OS follows the SPT entry to the corresponding PTE in the master page table

- action performed depends on master page table PTE type

- $\text{DISK}_{\text{CODE}}$
  - allocate page of physical memory
  - fill with data read from disk
  - update PTEs in master and process page tables to point to allocated page [MEM_{CODE}]


process instance 1 page table
MEM_{CODE}
SPT
SPT
physical page
MEM_{CODE}
$\text{DISK}_{\text{CODE}}$
$\text{DISK}_{\text{IDATA}}$
NULL
master page table

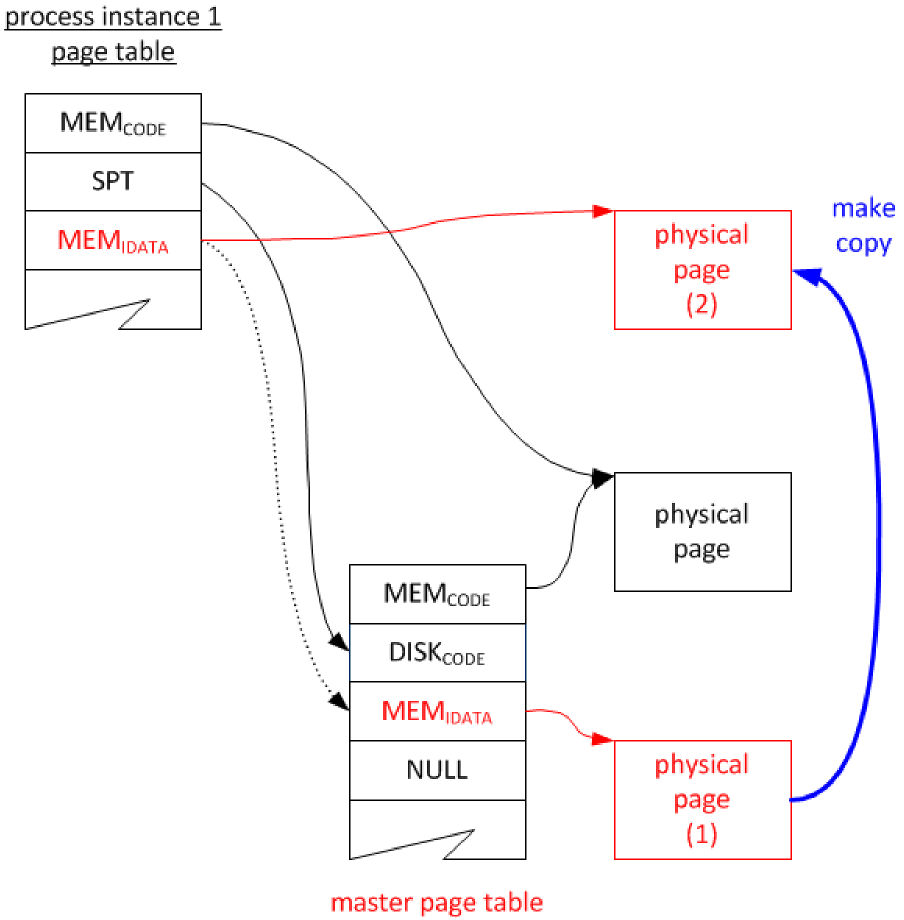
Memory Management Units

Text/Code Sharing..

- DISK$_{\text{IDATA}}$
  - allocate page of physical memory (1)
  - fill with data read from disk
  - attach to master page table [MEM]
  - now have a read-only *master copy* of the initialised data page

  - allocate page of physical memory (2)
  - copy data from master copy
  - attach to process page table [MEM]
  - process now has its own copy of the initialised data page which it is free to over write

  - could implement *copy-on-write* instead of *copy-on-access*



Memory Management Units

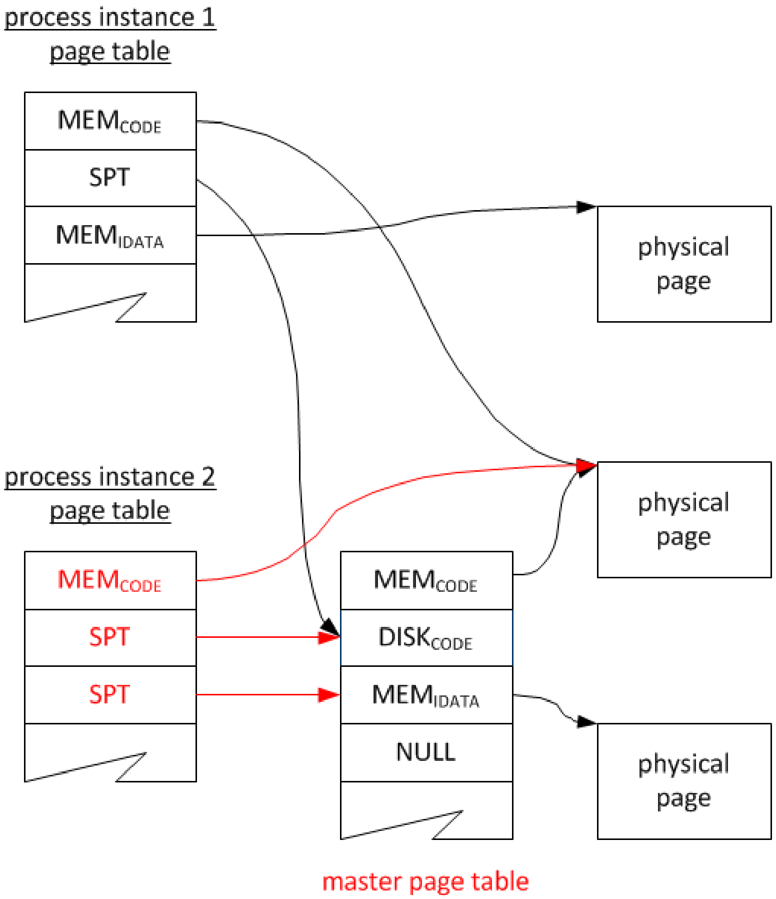
Text/Code Sharing..

- diagram shows how another process instance is created from the master page table

- the MEM$_{code}$ entries are copied thus sharing the code

- the remaining PTEs for the code and initialised data are set to the SPT type and point to corresponding entry in the master page table

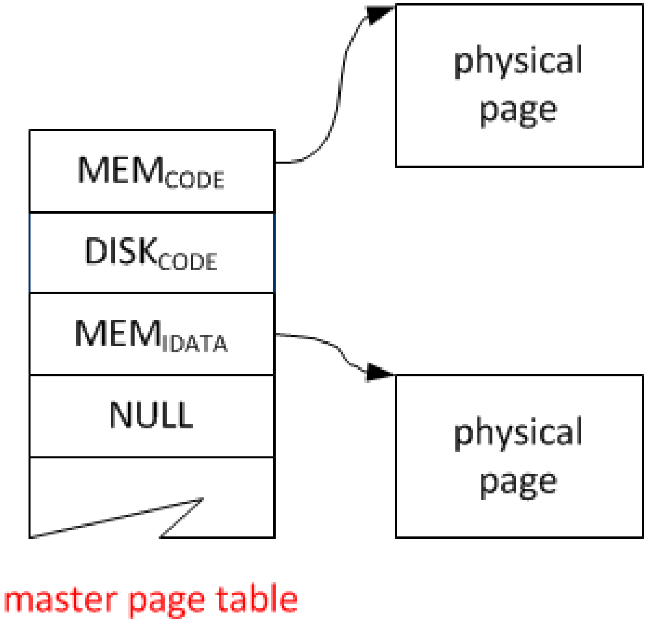
- the remaining PTEs are initialised as per the non-shared case since each instance needs its own its uninitialised data, heap and stack



Memory Management Units

Text/Code Sharing..

- if all processes terminate, the OS will try to keep the master table and its attached pages in memory
- if another instance of the process is then created, it can quickly attach to the code pages already in memory
- it can also make its own copies of the initialised data pages, as needed, from the master copies attached to the master page table
- this is why a process run, for a second time, often starts up more quickly



Memory Management Units

IA-32e address spaces > 2^{32} bytes [x64]

- pragmatic implementation [not currently realistic to implement 2^{64} virtual and physical address spaces – just think of the cost of 2^{64} bytes RAM]

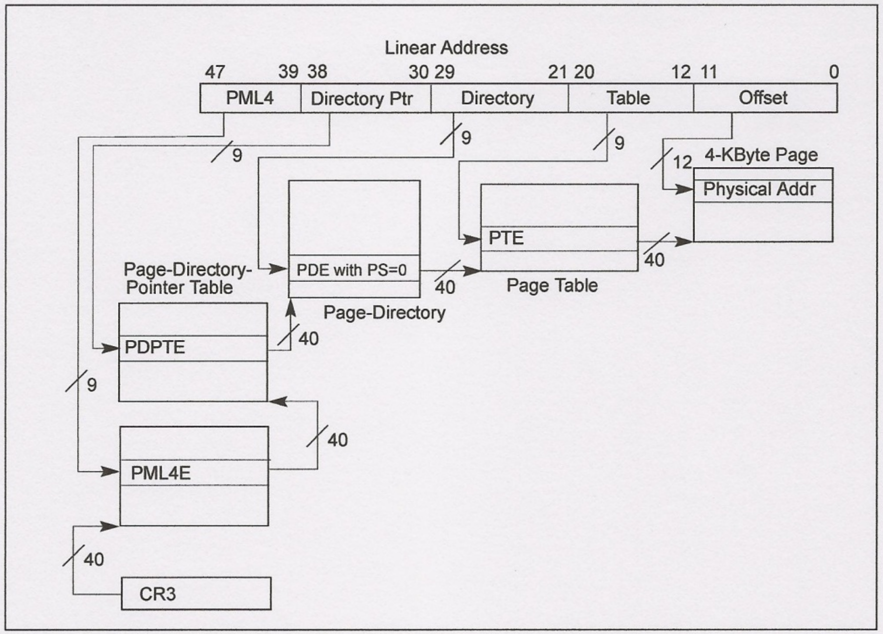


Figure 4-8. Linear-Address Translation to a 4-KByte Page using IA-32e Paging

Memory Management Units

IA-32e address spaces > 2^{32} bytes…

- 2^{48} byte virtual [linear in Intel terminology] and 2^{52} byte physical address spaces
- 4 level page table structure 9-9-9-9-12 [Intel naming: PML4, Directory Ptr, Directory, Table]
- page table sizes 2^9 * 8 as each PTE is 64 bits [4K]
- PTE comprises 52 bit physical address + 12 house keeping bits [64 bits]
- how many bits of the 52 bit physical address actually used depends on CPU model [2^{40} = 1TB, 2^{42} = 4TB, 2^{50} = 1PB and 2^{52} = 4PB]

MEMORY MANAGEMENT UNITS

Summary

- you are now able to:
  - explain the concept and benefits of virtual memory
  - explain the operation of an n-level page table
  - construct the contents of an n-level page table
  - explain the operation of a TLB
  - calculate the TLB hit rate
  - explain how a MMU and an OS together support on-demand paging
  - explain how code and initialised data can be shared between processes