Memory Management Units

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

- address space divided into fixed sized pages [e.g. 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... $2^{20} [1,048,576] \times 2^{12} [4K]$ 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 that 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
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 Cruncher

• consider the following program outline

```c
#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 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 Cruncher...
Generic MMU Operation \([\text{IA32, x64, MIPS, ...}]\)

- 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 \([\text{and sometimes one for OS}]\)

- page table base register PTB \([\text{CR3 in IA32}]\) contains the physical address of the page table of the currently running process

- 4MB physical memory \([1,048,576 \times 4]\) 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

\[\text{virtual address} \quad 23 \quad 13 \quad 0\]

\[
\begin{array}{|c|c|c|}
\hline
\text{index 1} & \text{index 2} & \text{offset} \\
\hline
\end{array}
\]

\[\text{virtual page #} \quad 10 \quad 10 \quad 12\]

• \textit{index1} is used to index into a primary page table, \textit{index2} into a secondary page table and so on...
N-Level Page Table...

- PTB points to primary page table of currently running process

- a valid primary page table (PTE) 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
Generic MMU Operation...

- when MMU accesses a PTE it checks the Valid bit

- if accessing a primary PTE and V == 0 (i.e. PTE is invalid)
  - then NO physical memory allocated for corresponding secondary page table

- If accessing a secondary PTE and V == 0
  - 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
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 [eg. writing to a read-only code page]
  - restarting [or continuing] the faulting instruction
Process Page Table Structure

- example small 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 $1024 \times 4K$ 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 the new mapping

- how can the hardware find the LRU entry SIMPLY and QUICKLY?
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 is the approach taken by many RISCs, a TLB miss generates an interrupt and the CPU walks the page table using ordinary instructions \([\text{TLB miss} \equiv \text{page fault}]\)

- 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 \([\text{eg. could implement a hash table}]\)

- 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 \([\text{needed for parallel accesses to the instruction and data caches}]\)
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 is really 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 [eg. PTB0 for OS or PTB1 for the 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 by executing an instruction
  
  ▪ CPUs have an instruction to do this [eg. IA32 "INVLPG va" will invalidate PTE entry corresponding to the processes' virtual address va if present in TLB]

• also need to keep TLB entries in a multicore CPU coherent
Multiple Processes sharing TLB

- possible for processes to share TLB if a process ID (PID) 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 may be 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
  - IA32/x64 CPU/MMU automatically executes these bus cycles

• IA32/x64 CPU/MMU never clears the reference and modified bits
  - up to the OS [eg. a background process that regularly clears the referenced bits]

• OS can use the Referenced and Modified bits to determine
  - which pages are good candidates for being paged out [eg. ones that have not been referenced recently]
  - if pages have to be written to the paging disk [eg. no need to save if a read only code page in executable file or may be unchanged since last saved]
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 2\textsuperscript{nd} level page table]
  ▪ bit set in primary PTE to indicate that it points to a large page [not a 2\textsuperscript{nd} 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
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
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
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 $2^{20} \times 2^{12} = 4$GB 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
Initial Mapping of Unix/Windows Process...

unix/windows process

0
- text
- text
- init data
- init data

4GB
- stack
- stack

PTB

primary page table

1022 NULL entries

secondary page table

DISK
DISK
DISK
DISK
1020 NULL entries

secondary page table

1022 NULL entries

memory page

memory page

corresponding disk block # of executable file
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 page containing 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:

<table>
<thead>
<tr>
<th>PTE type</th>
<th>action</th>
</tr>
</thead>
<tbody>
<tr>
<td>DISK</td>
<td>allocate a page of physical memory [OS maintains a free list] and fill with data read from disk [context switch while waiting for disk]</td>
</tr>
<tr>
<td></td>
<td>code pages normally read ONLY, initialised data pages typically read/write</td>
</tr>
</tbody>
</table>
|          | code and initialised data paged in "on demand"

DISK → IOP → MEM
Initial Execution of Unix/Windows Process...

<table>
<thead>
<tr>
<th>PTE type</th>
<th>action</th>
</tr>
</thead>
</table>
| 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] if OS gets confused and cannot resolve page fault it calls panic() which reboots OS  |
| IOP      | wait for I/O to complete [see DISK type fault] |
| SPY      | protection level fault? |
| LOCK     | protection level fault? |
Page Table Snapshot after Process has Started to Execute

Diagram shows page table after the following pages have been accessed by the process:

- 1 code page (1)
- 1 initialised data page (2)
- 1 uninitialised data page (3)
- 1 stack page (4)
Text/Code Sharing

- if the same process is executing more than 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

- consider the following technique for sharing pages

- 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/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

**DISK\_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]
Text/Code Sharing..

- **DISK\_DATA**
  - 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*
Text/Code Sharing..

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

• the \text{MEM}_{\text{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
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 when a process runs for a second time, it often starts up more quickly
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]
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 [\(2^{40} = 1\text{TB}, 2^{42} = 4\text{TB}, 2^{50} = 1\text{PB} \text{ and } 2^{52} = 4\text{PB}\)]
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