How does OS handle a page fault?

- Interrupt causes system to be entered
- System saves state of running process, then vectors to page fault handler routine
  - find or create (through eviction) a page frame into which to load the needed page (1)
    - if I/O is required, run some other process while it’s going on
    - find the needed page on disk and bring it into the page frame (2)
      - run some other process while the I/O is going on
      - fix up the page table entry
        - mark it as “valid,” set “referenced” and “modified” bits to false, set protection bits appropriately, point to correct page frame
        - put the process on the ready queue

- (2) Find the needed page on disk and bring it into the page frame
  - processor makes process ID and faulting virtual address available to page fault handler
  - process ID gets you to the base of the page table
  - VPN portion of VA gets you to the PTE
  - data structure analogous to page table (an array with an entry for each page in the address space) contains disk address of page
  - at this point, it’s just a simple matter of I/O
    - must be positive that the target page frame remains available!
    - or what?

- (1) Find or create (through eviction) a page frame into which to load the needed page
  - run page replacement algorithm
    - free page frame
    - assigned but unmodified (“clean”) page frame
    - assigned and modified (“dirty”) page frame
    - assigned but “clean”
    - find PTE (may be a different process!)
      - mark as invalid (disk address must be available for subsequent reload)
    - assigned and “dirty”
      - find PTE (may be a different process!)
      - mark as invalid
      - write it out

“Issues”

- Memory reference overhead of address translation
  - 2 references per address lookup (page table, then memory)
  - solution: use a hardware cache to absorb page table lookups
    - translation lookaside buffer (TLB)
- Memory required to hold page tables can be huge
  - need one PTE per page in the virtual address space
  - 32 bit AS with 4KB pages = 2^32 PTEs = 1,048,576 PTEs
  - 4 bytes/PT = 4MB per page table
    - OS’s typically have separate page tables per process
    - 25 processes = 100MB of page tables
  - 48 bit AS, same assumptions, 64GB per page table!
    - solution: page the page tables!
    - (ow, my brain hurts ...)
**Paging the page tables 1**

- Simplest notion:
  - put user page tables in a pageable segment of the system’s address space
  - wire down the system’s page table(s) in physical memory
  - allow the system segment containing the user page tables to be paged
    - a reference to a non-resident portion of a user page table is a page fault in the system address space
    - the system’s page table is wired down
      - “no smoke and mirrors”
  - As a practical matter, this simple notion doesn’t cut the mustard today
    - although it is exactly what VAX/VMS did!
  - But it’s a useful model for what’s actually done

**Paging the page tables 2**

- How can we reduce the physical memory requirements of page tables?
  - observation: only need to map the portion of the address space that is actually being used (often a tiny fraction of the total address space)
    - a process may not use its full 32/48/64-bit address space
    - a process may have unused “holes” in its address space
    - a process may not reference some parts of its address space for extended periods
  - all problems in CS can be solved with a level of indirection!
    - two-level (three-level, four-level) page tables

**Two-level page tables**

- With two-level PT’s, virtual addresses have 3 parts:
  - master page number, secondary page number, offset
  - master PT maps master PN to secondary PT
  - secondary PT maps secondary PN to page frame number
  - offset and PFN yield physical address

**Generalizing**

- Early architectures used 1-level page tables
- VAX, P-II used 2-level page tables
- SPARC uses 3-level page tables
- 68030 uses 4-level page tables
- Key thing is that the outer level must be wired down (pinned in physical memory) in order to break the recursion – no smoke and mirrors
Alternatives

- Hashed page table (great for sparse address spaces)
  - VPN is used as a hash
  - collisions are resolved because the elements in the linked list at the hash index include the VPN as well as the PFN
- Inverted page table (really reduces space!)
  - one entry per page frame
  - includes process id, VPN
  - hell to search! (but IBM PC/RT actually did this!)

Making it all efficient

- Original page table scheme doubled the cost of memory lookups
  - one lookup into page table, a second to fetch the data
- Two-level page tables triple the cost!
  - two lookups into page table, a third to fetch the data
- How can we make this more efficient?
  - goal: make fetching from a virtual address about as efficient as fetching from a physical address
  - solution: use a hardware cache inside the CPU
    - cache the virtual-to-physical translations in the hardware
    - called a translation lookaside buffer (TLB)
    - TLB is managed by the memory management unit (MMU)

Making it all efficient (2)

- TLBs
  - Translation lookaside buffer
    - translates virtual page #s into PTEs (page frame numbers) (not physical addr)
    - can be done in single machine cycle
  - TLB is implemented in hardware
    - is a fully associative cache (all entries searched in parallel)
    - cache tags are virtual page numbers
    - cache values are PTEs (page frame numbers)
    - with PTE + offset, MMU can directly calculate the PA
  - TLBs exploit locality
    - processes only use a handful of pages at a time
    - 16-48 entries in TLB is typical (64-192KB)
    - can hold the “hot set” or “working set” of a process
    - hit rates in the TLB are therefore really important

Managing TLBs

- Address translations are mostly handled by the TLB
  - >99% of translations, but there are TLB misses occasionally
  - in case of a miss, translation is placed into the TLB
- Hardware (memory management unit (MMU))
  - knows where page tables are in memory
  - OS maintains them, HW access them directly
  - tables have to be in HW-defined format
  - this is how x86 works
- Software loaded TLB (OS)
  - TLB miss faults to OS, OS finds right PTE and loads TLB
  - must be fast (but, 20-200 cycles typically)
  - CPU ISA has instructions for TLB manipulation
  - OS gets to pick the page table format

Managing TLBs (2)

- OS must ensure TLB and page tables are consistent
  - when OS changes protection bits in a PTE, it needs to invalidate the PTE if it is in the TLB
- What happens on a process context switch?
  - remember, each process typically has its own page tables
  - need to invalidate all the entries in TLB! (flush TLB)
    - this is a big part of why process context switches are costly
  - can you think of a hardware fix to this?
- When the TLB misses, and a new PTE is loaded, a cached PTE must be evicted
  - choosing a victim PTE is called the “TLB replacement policy”
  - implemented in hardware, usually simple (e.g., LRU)

Cool Paging Tricks

- Exploit level of indirection between VA and PA
  - shared memory
    - regions of two separate processes’ address spaces map to the same physical frames
      - read/write: access to share data
      - execute: shared libraries
    - will have separate PTEs per process, so can give different processes different access privileges
    - must the shared region map to the same VA in each process?
      - copy-on-write (COW), e.g., on fork()  
        - instead of copying all pages, created shared mappings of parent pages in child address space
          - make shared mappings read-only in child space
          - when child does a write, a protection fault occurs, OS takes over and can then copy the page and resume client
• Memory-mapped files
  – instead of using open, read, write, close
    • "map" a file into a region of the virtual address space
    – e.g., into region with base 'X'
    • accessing virtual address 'X+N' refers to offset 'N' in file
  – initially, all pages in mapped region marked as invalid
  – OS reads a page from file whenever invalid page accessed
  – OS writes a page to file when evicted from physical memory
  • only necessary if page is dirty

Summary
• We know how address translation works in the "vanilla" case (single-level page table, no fault, no TLB)
  – hardware splits the virtual address into the virtual page number and the offset; uses the VPN to index the page table; concatenates the offset to the page frame number (which is in the PTE) to obtain the physical address
• We know how the OS handles a page fault
  – find or create (through eviction) a page frame into which to load the needed page
  – find the needed page on disk and bring it into the page frame
  – fix up the page table entry
  – put the process on the ready queue

• We’re aware of two “gotchas” that complicate things in practice
  – the memory reference overhead of address translation
  • the need to reference the page table doubles the memory traffic
  • solution: use a hardware cache (TLB = translation lookaside buffer) to absorb page table lookups
  – the memory required to hold page tables can be huge
  • solution: use multi-level page tables; can page the lower levels, or at least omit them if the address space is sparse
    – this makes the TLB even more important, because without it, a single user-level memory reference can cause two or three or four page table memory references ... and we can’t even afford one!

TLB details
• Implemented in hardware
  – fully associative cache (all entries searched in parallel)
  – cache tags are virtual page numbers
  – cache values are page table entries (page frame numbers)
  – with PTE + offset, MMU can directly calculate the physical address
  – Can be small because of locality
  • 16-48 entries can yield a 99% hit ratio
  – Searched before the hardware walks the page table(s)
    • Hit: address translation does not require an extra memory reference (or two or three or four) – "free"
    • Miss: the hardware walks the page table(s) to translate the address; this translation is put into the TLB, evicting some other translation; typically managed LRU by the hardware

• On context switch
  • TLB must be purged/flushed (using a special hardware instruction) unless entries are tagged with a process ID
    – otherwise, the new process will use the old process’s TLB entries and reference its page frames!

• Cool tricks
  – shared memory
  – copy-on-write
  – memory-mapped files