EECS 3221.3
Operating System Fundamentals

No.9

Memory Management (2)

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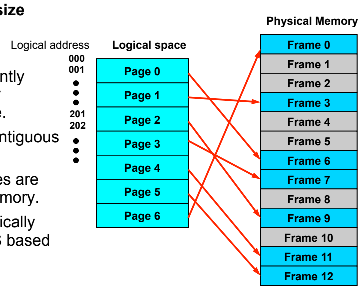
Memory Management Approaches

- Contiguous Memory Allocation
- Paging
- Segmentation
- Segmentation with paging

Contiguous Memory Allocation suffers serious external fragmentation

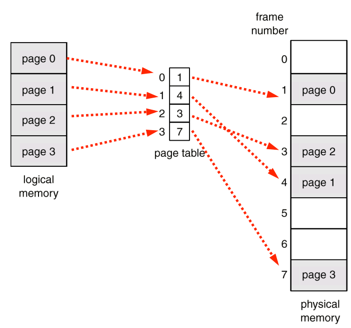
Paging(1)

- Logical space is contiguous and consists of pages
- Physical space is broken into frames
- Page size = Frame size



- Each page is independently mapped to (or physically supported by) one frame.
- User program sees a contiguous logical space.
- But the supporting frames are scattered in physical memory.
- The mapping is automatically done by hardware or OS based on a **page table**.

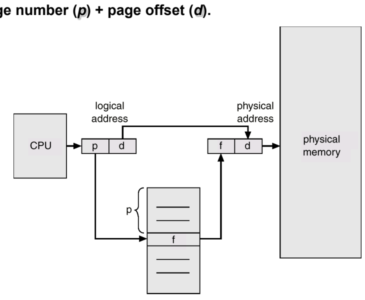
Paging Example(1)



Address Translation Architecture

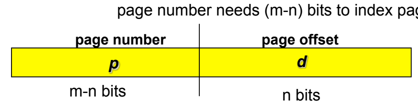
- Convert logical address into page # and offset :
  Logical address (X) = page number (*p*) + page offset (*d*).
- Assume page size k:
  p = X/k (quotient).
  d = X%k (remainder).

- *p* is used to index page table to find frame number or base physical address of this page.
- *d* is the offset in the mapped frame.
- The physical address Y:
  Y = *f* *k + d
  (*f* is frame number).



Translation of logical address (for binary address)

- Page size (frame size) is typical a power of 2. (4k – 16M).
- Logical address is a concatenated bit stream of page number and page offset.
- **An example:** 1) logical space is 2**m: logical address is m bits.
  2) page size is 2**n: page offset is n bits.
  3) a logical space needs at most 2**(m-n) pages: page table contains at most 2**(m-n) elements
  page number needs (m-n) bits to index page table

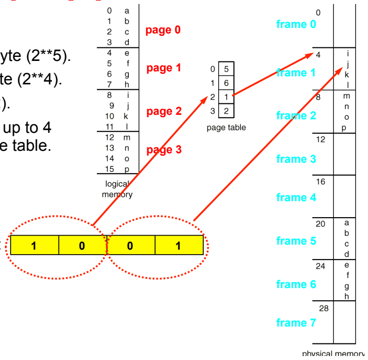


Given a binary logical address, the last n bits is page offset and the first m-n bits is page number.

Paging Example (2)

- Physical memory: 32-byte (2**5).
- Logical memory: 16-byte (2**4).
- Page size: 4-byte (2**2).
- Logical memory needs up to 4 pages: 4 entries in page table.
- m=4, n=2.

Logical address 9 :



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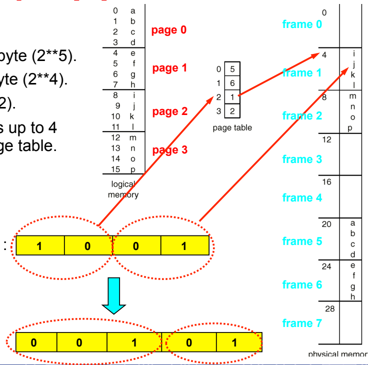
Physical address 5 :



Paging Hardware

- OS maintains a page table for every process.
- All page tables are kept in physical memory.
- The currently active page table is page table of the currently running process.
- For small active page-table (<256 entries): using registers
- For large page-table: using two indexing registers
  - *page-table base register (*PTBR) points to the active page table.
  - *page-table length register* (PTLR) indicates size of the active page table.
  - In this scheme every data/instruction access requires two memory accesses. One for the page table and one for the data/instruction.

Paging Hardware: TLB

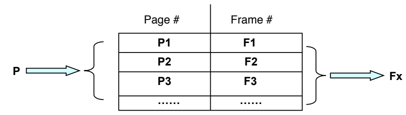
- **Caching**: using of a special fast-lookup hardware cache called *associative registers* or ***translation look-aside buffers (TLBs)***
  - Associative registers (expensive) – parallel search
  - speedup translation from page # → frame # :

    Assume page number is P:

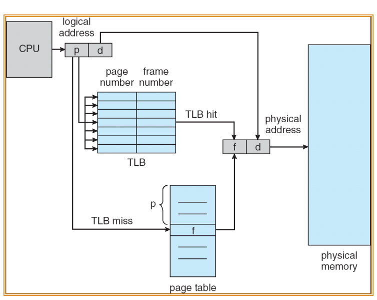
    -- If P is in associative register, get frame # out. (hit)

    -- Otherwise get frame # from page table in memory (miss)

    Save to TLB for next reference, replace an old one if full



Paging Hardware with TLB: MMU in Paging



Need to flush TLB's in context switch

Effective Access Time of paging after TLB

- Assume memory cycle time is **a** time unit.
- One TLB Lookup = **b** time unit.
- Hit ratio – percentage of times that a page number is found in the associative registers; ration related to number of associative registers.
- Hit ratio = λ**.**
- Effective Access Time (EAT):

$$EAT = (\mathbf{a} + \mathbf{b})\,\lambda + (2\mathbf{a} + \mathbf{b})(1 - \lambda) = (2 - \lambda)\mathbf{a} + \mathbf{b}$$

Example: a = 100 nanoseconds, **b** = 20 nanosecond.

If λ = 0.80, EAT = 140 nanoseconds (40% slower).
If λ = 0.98, EAT = 122 nanoseconds (22% slower).

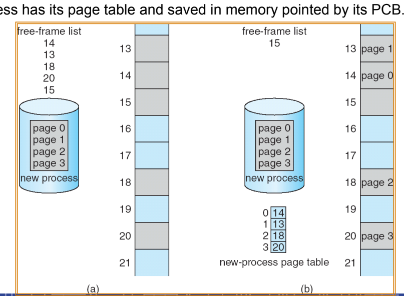
Paging (2)

- No external fragmentation in paging.
- Internal fragmentation: process size does not happen to fall on page boundaries.
  - Average one-half page per process.
- How to choose page size:
  - Smaller page size:
    - less internal fragmentation.
    - large page table (more overhead).
  - Typical 4K—8KB
- If each page table entry is 4 bytes long, it can point to one of 2**32 frames
  - Maximal physical address: frame size * (2**32)

  (from this we can deduce the bit number in physical address)

Paging (3): Memory Allocation

- OS keeps track of all free frames.
- To run a program of size n pages, OS needs to find *n* free frames and load program.
- OS sets up a page table to translate logical to physical addresses.
- Each process has its page table and saved in memory pointed by its PCB.

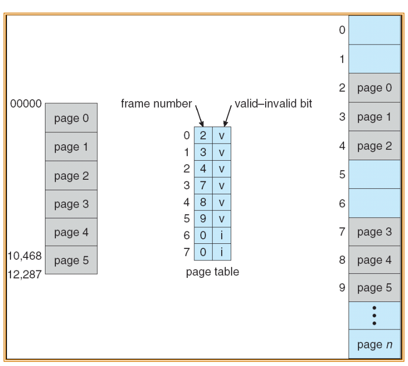


OS data structure for Paging

- OS maintain a page table for each process in memory, pointed by the PCB of the process.
  - Used to translate logical address in a process' address space into physical address.
  - Example: one process make an I/O system call and provide an address as parameter (logical address in user space). OS must use its page-table to produce the correct physical address.
- OS maintains a global **frame table:**
  - One entry for each physical frame in memory.
  - To indicate the frame is free or allocated, if allocated, to which page of which process.
- In context switch, the saved page-table is loaded by the CPU dispatcher to MMU for every memory reference and flush TLB. (This increases context switch time)

Memory Protection in paging

- How is memory protected from different processes?
  - In paging, other process memory space is protected automatically.
- Memory protection can be implemented by associating protection bits with each frame in page table
  - One bit for read-only or read-write
  - One bit for execute-only
  - One *Valid-invalid* bit
    - "valid" indicates that the associated page is in the process' logical address space, and is thus a legal page.
    - "invalid" indicates that the page is not in the process' logical address space.
    - Use page-table length register (PTLR): to indicate the size of page table
    - *Valid-invalid* bit is mainly used for virtual memory
- In every memory reference, the protection bits are checked. Any invalid access will cause a trap into OS.



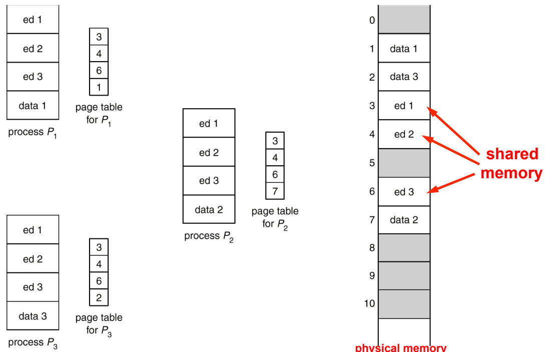
Example:

--14-bit address
-- page size 2KB
-- valid space
0-16383 (2**14)

Sharing Memory in Paging

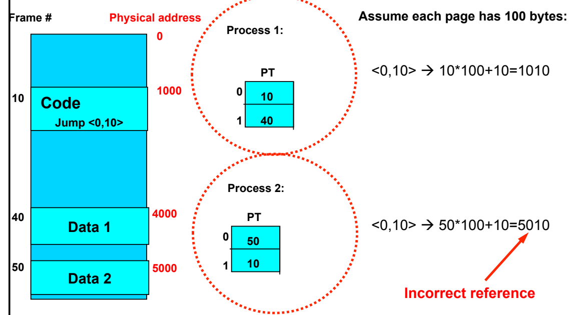
- Different pages of several processes can be mapped to the same frame to let them share memory.
- Shared-memory for inter-process communication.
- Private code and data:
  - Each process keeps a separate copy of the code and data.
  - The pages for the private code and data can appear anywhere in the logical address space.
- Shared code:
  - One copy of read-only (reentrant) code shared among processes (i.e., text editors, compilers, window systems).
  - Shared code must appear in same location in the logical address space of all processes (i.e. same locations in the page tables).

Shared Pages Example



Shared Pages

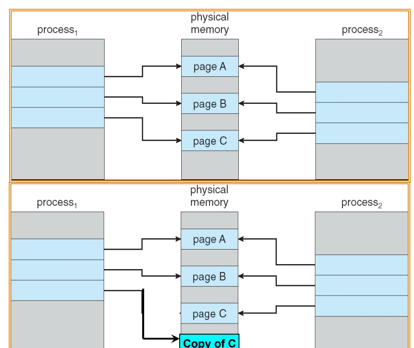
- How to share pages with code which has a direct address reference?



Copy-on-Write

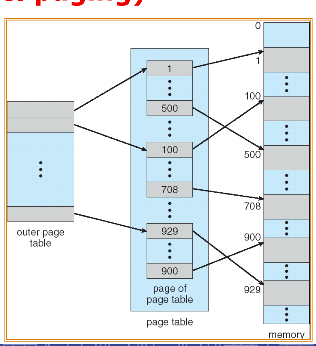
- For quick process creation: *fork()*
- Traditionally, fork() copies parent's address space for the child.
- *Copy-on-Write*: without copying, the parent and child process initially share the same pages, and these pages are marked as copy-on-write.
  - If either process needs to write to a shared page, a copy of the shared page is created and stop sharing this page.
- Advantages of copy-on-write:
  - Quick process creation (no copying, just modify page table for page sharing)
  - Eventually, only modified pages are copied. All non-modified pages are still shared by the parent and child processes.
    - Better memory utilization

Copy-on-Write



Hierarchical Paging (multilevel paging)

- In modern computer, we require a large logical-address space, which results in some huge page table.
- No contiguous memory space for the large page table.
- Hierarchical paging: using paging technique to divide the large page table into smaller pieces

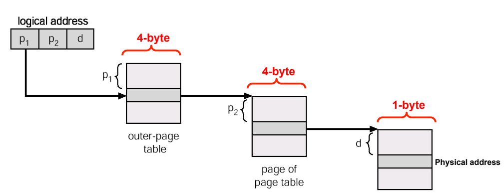


Address-Translation in two-level paging

- Logical address 32-bit, page size 4K, maximal physical address 2**32 frames
- A logical address is divided into 20 bits page number and 12 bits page offset.
- Since page-table is paged, the logical address is as follows:

page number		page offset
p_i	p_2	d
10	10	12

where p_i is an index into the outer page table, and p_2 is the displacement within the page of the outer page table.



Multilevel Paging and Performance

- 64-bit logical address may require 6-level paging.
- Since each level is stored as a separate table in memory, converting a logical address to a physical one may take seven memory accesses.
- TLB-based caching permits performance to remain reasonable.
- Cache hit rate of 98 percent yields:

$$\text{effective access time} = 0.98 \times 120 + 0.02 \times 720$$
$$= 132 \text{ nanoseconds.}$$

which is only 32 percent slowdown in memory access time.

- But the overhead is too high to maintain many page-tables
- In 64-bit Linux, it uses 4-level paging to page 48-bit address.