CSE 3221.3
Operating System Fundamentals

No. 10

Virtual Memory

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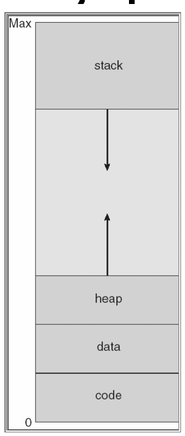
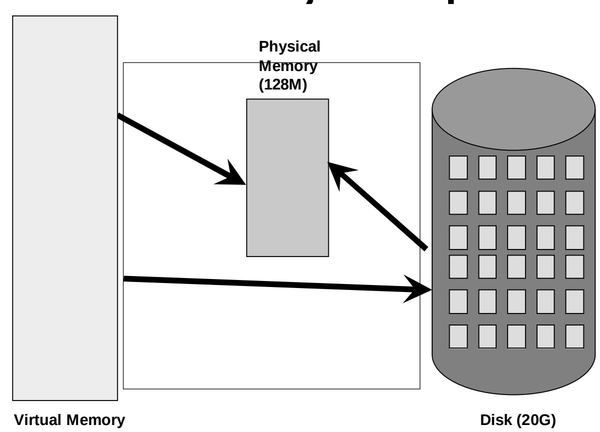
Background

- Memory-management methods requires the entire process to be in memory before the process can execute.
- Better not to load the whole process in memory for execution:
  - Programs often have code to handle unusual error conditions.
  - Arrays, lists, and tables are often allocated more memory than they actually need.
  - Certain options and features of a program may be used rarely.
  - Even all codes are needed, they may not all be needed at the same time.
- Our goal: partially load the program
  - No longer be constrained by the amount of physical memory
  - Each program takes less memory → CPU utilization and throughput up
  - Less I/O to load program → run faster
- Overlay and dynamic loading can ease the restriction, but require extra work by the programmer.

Logical Memory Space (review)



Virtual Memory: concepts



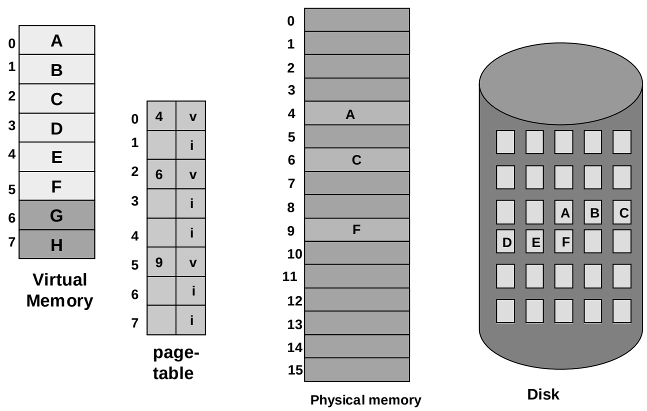
Virtual Memory

- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation
    - Hard since segments have variable size

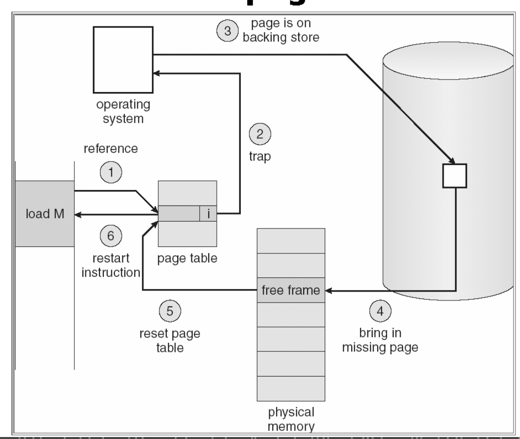
Demand Paging(1)

- Demand paging:
  - A paging system with page swapper
  - A lazy swapper: never swap a page into memory unless the page will be used.
- In demand paging:
  - When a process is executed,
  - The pager guess which pages are needed. (optional)
  - The pager brings only these necessary pages into memory. (optional)
  - When referring a page not in a memory, the pager bring it in as needed and possibly replace an old page when no more free space.
- Hardware support: to distinguish those pages in memory and those pages in disk
  - Use valid-invalid bit

An example: Demand Paging



Handle a page fault



Handle a Page Fault

The interrupt service routine to handle page fault in virtual memory:

- Check an internal table to see if the reference was a valid or invalid memory access.
- If invalid, terminate the process; If valid, this page is on disk. Need page it into memory.
- Find a free frame from the free-frame list. (if no free frame, need replace an old page)
- Schedule a disk operation to read the desired page into the newly allocated frame.
- When the disk read is complete, modify the internal table and page table to set the bit as valid to indicate this page is now in memory.
- Restart the instruction that was interrupted. The process can now access the page as though it had always been in memory

Handle a Page Fault (more details)

- Trap to the OS
- Save the user registers and process state
- Determine the interrupt was a page fault
- Determine the location of the page on the disk
- Find a free frame from the free-frame list
  - If no free frame, page replacement
- Issue a read from the disk to the free frame:
  - Wait in a queue for the disk until serviced
  - Wait for the disk seek and latency time
  - Begin the transfer of the page to the free frame
- While waiting, allocate the CPU to other process (optional)
- Interrupt from the disk (I/O completed)
- Save the registers and process state for other running process(optional)
- Determine the interrupt was from the disk

Handle a Page Fault (more details) (cont'd)

- …
- Correct the page table and other tables to show the desired page is now in memory.
- Wake up the original waiting process.
- Wait for the CPU to be allocated to this process again.
- Restore the user registers and process state and new page table.
- Resume the interrupted instruction.

Pure Demand Paging

- Never bring a page into memory until it is referred.
- Start executing a process with no pages in memory
- OS set instruction pointer to the first instruction
- Once run, it causes a page fault to load the first page
- Faulting as necessary until every page is in memory

Some Architecture Concerns in demand paging

- Straightforward in most cases:

ADD A,B,C ⟶

1. Fetch and decode ADD
2. Fetch A
3. Fetch B
4. Add A and B
5. Store the sum to C

- But some instructions which may modify something are not easy to handle:
  - IBM 360/370: MVC (move 256 bytes)
  - PDP-11: auto-decrement or auto-increment addressing mode

    mov (R2)++, --(R3)

Performance of Demand Paging

- To service a page fault is very time-consuming:
  - Service the page-fault interrupt
  - Read in the page
  - Restart the process
- Effective access time for a demand-paged system:

Effective access time = (1-p) * ma + p * page fault time

- One example: memory access 100 nanosecond

  page fault 25 millisecond

Effective access time = 100 + 24,999,900 * p

If **p**=1/1000, **EAT** = 25 microsecond (slow down a factor of 250)
If requiring only 10% slow down, **p**<4/10000000 (one out of 2.5 million)

- How to achieve low page fault rate??

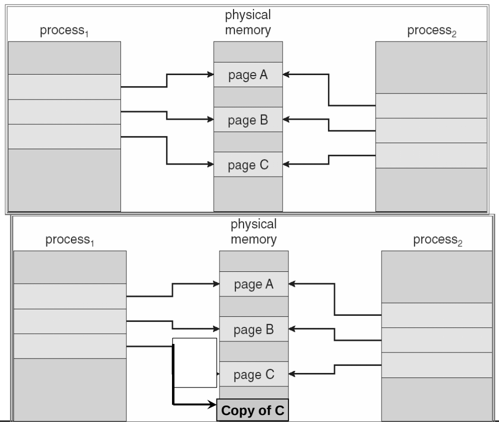
Handling Swap Space on Disk

- For fast speed:
  - Use swap space, not file system
  - Swap space: in larger blocks, no file lookup and indirect allocation.
  - Copying an entire file image into swap space at process startup and then perform demand paging from the swap space.
  - First load pages by file system, then write to swap space.

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



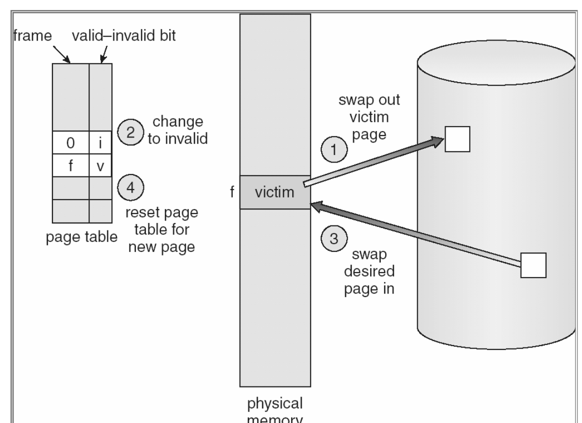
Page Replacement(1)

- In demand paging, when increasing multiprogramming level, it is possible to run out of all free frames.
- How about if a page fault occurs when no free frames are available
  - Stop the process
  - Swap out a process to free some frames
  - Page replacement
    - Replacing in page level

Page Replacement(2)

- If no frame is free, find one that is not currently being used and free it.
  - Write the page into swap space and change page-table to indicate that this page is no longer in memory.
  - Use the freed frame to hold the page for which the process faulted.
- Use a page-replacement algorithm to select a victim frame
- In this case, two disk accesses are required (one write one read).
- Use a ***modify bit*** to reduce overhead:
  - Each frame has a modify bit associated in hardware.
  - Any write in page will set the bit by hardware
  - In page replacement, if the bit is not set, no need to write back to disk
- For read-only pages, always no need to write back
- With page replacement, we can run a large program in a small memory.
- Page-replacement algorithm: how to select the frame to be replaced
- Frame-allocation algorithm: how many frames to allocate to each process

Page Replacement



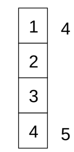
Page-Replacement Algorithm

- To achieve the lowest page-fault rate
- Common schemes:
  - Optimal page replacement
  - FIFO page replacement
  - LRU page replacement
  - LRU approximation page replacement
    - Additional-reference-bits algorithm
    - Second-chance page-replacement algorithm
  - Counting-based page replacement
  - Page-buffering algorithm
- Evaluated with a reference string:
  - e.g., 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

Optimal Page-Replacement

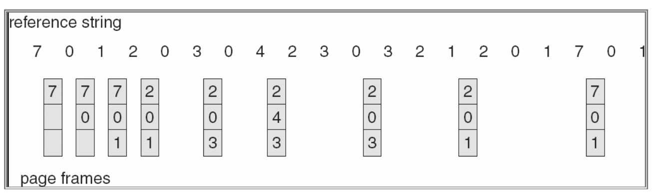
- An optimal page-replacement has the lowest page-fault rate among all possible replacement algorithms.
- OPT: replace the page that will not be used for the longest period of time.
- Guarantee the lowest page-fault rate
- Not feasible since future knowledge is required.
- Used for performance comparison of algorithms.

Reference String: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
4-frame example:



6 page faults

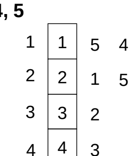
Optimal Page Replacement



FIFO(first-in-first-out) Page-Replacement

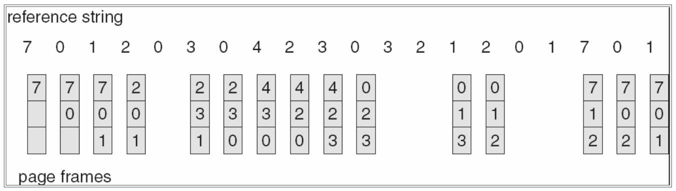
- Always replace the oldest page in memory
- Implement FIFO queue to hold all pages in memory. Replace the page at the head. When a page is brought into memory, it is inserted at the tail of the queue.
- Simple and easy to implement.
- Performance is not always good.
  - The replaced page may be a heavily used one
    → increasing page-fault rate

Reference String: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
4-frame example:



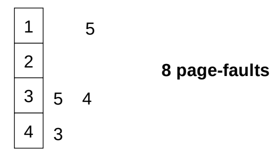
10 page faults

FIFO Page Replacement

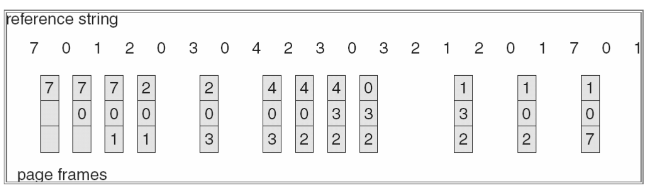


Least-recently-used (LRU) Page Replacement (1)

- Replace the page that has not been used for the longest period of time
- LRU has to associate with each page the time of last use.
- LRU chooses the oldest page based on the time stamp for replacement.
- The performance of LRU is considered to be good.
- Example: 4-frame
  - <u>Reference String</u>: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



LRU Page Replacement



LRU Page Replacement (2)

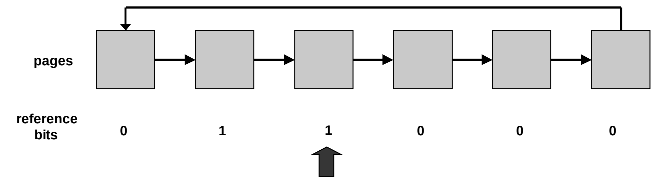
- LRU implementations
  - <u>Counters</u>:
    - CPU maintains a memory reference counter
    - Add time-of-use in each entry in page-table
    - Search the oldest page based on time-of-use
  - <u>Stack</u>:
    - Keep a stack of all page numbers.
    - When one page is referenced, it is moved to the stack top.
    - The stack tail is always the LRU page.
- LRU implementation with hardware is very expensive.
- Few computers provide sufficient hardware for true LRU

LRU Approximation Replacement(1)

- ***Reference bit***:
  - Initially cleared by OS
  - set by the hardware whenever the page is referenced.
- ***Additional-reference-bits algorithm***:
  - We gain additional ordering information by recording the reference bits at regular intervals.
  - Keep an 8-bit byte for each page in memory
  - A timer interrupts at regular intervals (every 100 milliseconds)
  - Shift all bits right 1 bit and discard the low-order bit
  - OS copies the reference bit into the high-order bit and clear reference bit
  - Interpret the 8-bit byte as unsigned integer, the page with the lowest number is the LRU page.

LRU Approximation Replacement(2): Second-Chance Algorithm (clock)

- Based on FIFO policy, but check the reference bit of the selected page.
- If reference bit is 0, the page is replaced.
- If reference bit is set to 1, the page is given the second chance
  - The reference bit is cleared.
  - Its arrival time is reset to the current time.
- Second-chance (clock) algorithm can be implemented as a circular queue:



Other Replacement Algorithms

- Counting-based page replacement
  - Keep a counter of the number of references made to each page
  - The *least frequently used (LFU)* page-replacement: replace the page with the smallest count
  - The *most frequently used (MFU)* page-replacement algorithm (the page with small count was just brought in and has yet to be used)
- Page-Buffering Algorithm:
  - Keep a pool of free frames
  - Select a victim frame, but the desired page is read into one free frame in the pool without waiting for write-out. The victim is written out later on and is added to free pool.
  - Remember which page was in each frame of free pool. When a page is needed, check if it is in the free pool.

Frame Allocation

- In single-user system, user process compete free frames with OS
- In multi-programming system, how to allocate the fixed amount of free memory among various processes??
- Minimum number of frames: a minimum number of frames must be allocated to the process (depending on instruction-set architecture)
- Allocation algorithms:
  - Equal allocation: free frames are equally allocated to all processes
  - Proportional allocation: allocate available frames to each process according to its size, its priority, or a combination.
- Global versus local allocation in replacement
  - *Global allocation*: allow a process to select a replacement frame from the set of all frames. (can take frames from others)
  - *Local allocation*: require a process to select from only its own set of allocated frames.

Example: proportional frame allocation

s_i = size of process p_i

$S = \sum s_i$

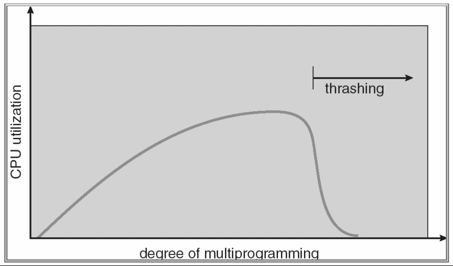
m = total number of frames

a_i = allocation for $p_i = \frac{s_i}{S} \times m$

$$m = 64$$
$$s_i = 10$$
$$s_2 = 127$$
$$a_1 = \frac{10}{137} \times 64 \approx 5$$
$$a_2 = \frac{127}{137} \times 64 \approx 59$$

Thrashing

- **Thrashing: a process is spending a significant time in paging.**
- **Thrashing results in severe performance problem. The process is spending more time in paging than executing.**
- **Cause of thrashing:**
  - **The process is not allocated enough frames to hold all the pages currently in active use.**



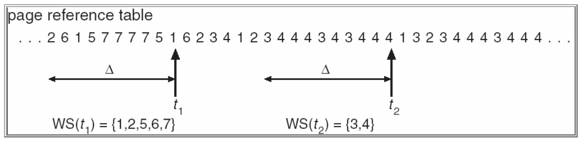
Locality Model of Programs

- **A locality is a set of pages that are currently in an active use.**
- **A process moves from locality to locality.**
- **A program is generally composed of several different localities.**
- **The localities are defined by the program structure and its data structures.**
- **Locality model is the basic principle for caching as well as demand paging**
  - We only need a small number of frames to hold all pages in the current locality in order to avoid further page faults.

Working-set Model

- **The model define a working-set window, say Δ page references, e.g., 10,000 page references.**
- **The set of all referenced pages in the most recent Δ page references is the working set.**
- **How to choose the window ?**
  - **if Δ too small will not encompass entire locality.**
  - **if Δ too large will encompass several localities.**
  - **if Δ = ∞ ⇒ will encompass entire program.**
- **If WSS_i = working-set size of process P_i**
  - **➔ $D = \sum WSS_i \equiv$ total demand frames**
- **if $D > m$ (m: total available frames) ⇒ Thrashing**
- **Policy:**
  - **CPU monitors working sets of all processes and allocate enough frames for the current working set.**
  - **if D > m, then suspend one of the processes.**

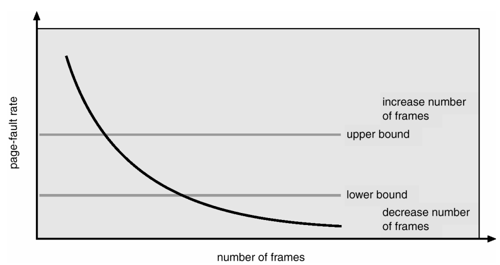
Working-Set Model



Keeping Track of the Working Set

- **Approximate with interval timer + a reference bit**
- **Example: Δ = 10,000 references**
  - **Timer interrupts after every 5000 references.**
  - **Keep in memory 2 bits for each page.**
  - **Whenever a timer interrupts copy and sets the values of all reference bits to 0.**
  - **If one of the bits in memory = 1 ⇒ page in working set.**
- **The cost to service these frequent interrupts is high.**

Page-Fault Frequency



- **Establish "acceptable" page-fault rate.**
  - **If actual rate too low, process loses frame.**
  - **If actual rate too high, process gains frame.**

Other Considerations in demand-paging

- **Pre-paging:**
  - **To prevent high page-fault rate at the beginning.**
  - **Try to bring more pages at once.**
- **Page size: in powers of 2 (2**12 – 2*22)**
  - **Small page size → large page-table**
  - **Small page size → less internal fragmentation**
  - **Small page size → more I/O overhead in paging**
  - **Small page size → more page-faults**
  - **Small page size → less I/O amount (better resolution)**
    less total allocated memory
  - **A historical trend is toward larger page sizes.**

Other Considerations in demand-paging (cont'd)

- **Program structure: a careful selection of data structure and programming structure**
  - **To increase locality and hence lower the page-fault rate.**
  - **To reduce total number of memory access**
  - **To reduce total number of pages touched.**
- **Also compiler and loader can improve.**
- **Example: Array** `A[1024][1024]` **of integer**
  - **Each row is stored in one page**
  - **Program 1**

    ```
    for j = 1 to 1024 do
       for i = 1 to 1024 do
             A[i][j] = 0;
    ```

    1024 x 1024 page faults
  - **Program 2**

    ```
    for i = 1 to 1024 do
       for j = 1 to 1024 do
             A[i][j] = 0;
    ```

    1024 page faults