0117401: Operating System
计算机原理与设计

Chapter 9: Virtual Memory(虚存)

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温馨提示：

为了您和他人的工作学习，
请在课堂上关机或静音。

不要在课堂上接打电话。

提纲

Outline

Background

- Instructions must be loaded into memory before execution.
- Solutions in chapter 8:

$$\text{Program} \xrightarrow{\text{entire}} \text{Physical memory}$$

- Sometimes, jobs may be too big or too many.
  How to expand the main memory?
  - Physically? COST TOO HIGH!
  - Logically? √

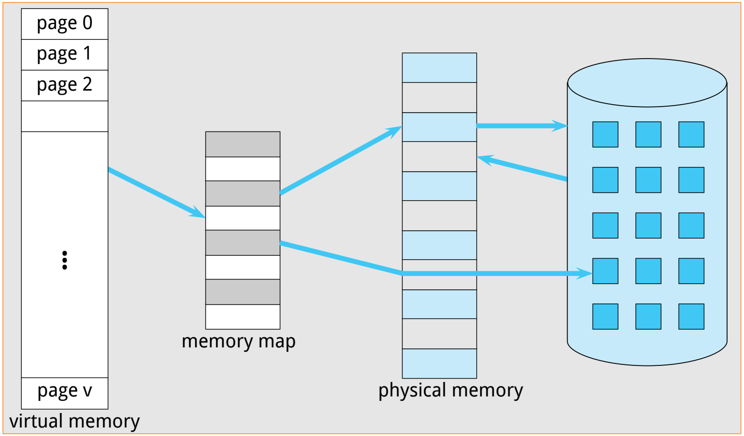
Background

- Virtual memory: Why and How?
  - Some code may get no, or only little, opportunity of execution, for example, code for error handlers
  - Some data may get no opportunity of access
  - Locality of reference (程序的局部性原理), 1968, Denning
    - Temporal locality (时间局部性)
    - Spatial locality (空间局部性)
  - Idea: partly loading (部分装入)、demand loading (按需装入)、replacement (置换)

Background

- Virtual Memory (虚拟存储器)
  是指具有请求调度功能和置换功能，能从逻辑上对内存容量加以扩充的一种存储器系统
  - Logical size:
    从系统角度看：内存容量 + 外存容量
    从进程角度看：地址总线宽度范围内；内存容量 + 外存容量
  - Speed: close to main memory
  - Cost per bit: close to secondary storage (disks)
- Virtual memory : separation of user logical memory from physical memory.
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation

Background



Example: virtual memory that is larger than physical memory

Background

- Virtual memory can be implemented via:
  1. Demand paging
     - Paging technology +
       pager (请求调页) and page replacement
     - Pager VS. swapper
       the unit of swapping in/out is not the entire process but page.
  2. Demand segmentation

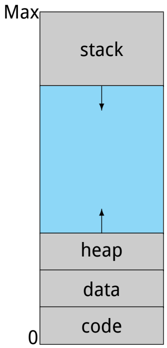
虚拟存储器的特征

1. 多次性：最重要的特征
   - 一个作业被分成多次装入内存运行
2. 对换性
   - 允许在进程运行的过程中，（部分）换入换出
3. 虚拟性
   - 逻辑上的扩充

- 虚拟性是以多次性和对换性为基础的。
- 多次性和对换性是建立在离散分配的基础上的

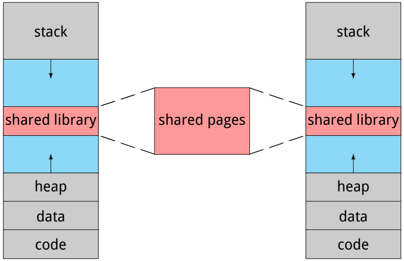
Virtual-address Space (虚拟地址空间)

- The virtual address space of a process refers to the logical (or virtual) view of how a process is stored in memory.
  - Typically: 0~xxx & exists in contiguous memory
- In fact, the physical memory are organized (partitioned) in page frames & the page frames assigned to a process may not be contiguous⇒MMU



Some benefits

1. Shared library using virtual memory



2. Shared memory
3. Speeding up process creation

Outline

2 Demand Paging (按需调页)

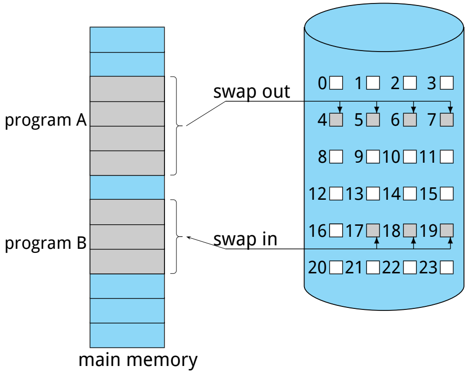
- Basic Concepts (Hardware support)
- Performance of Demand Paging

Demand Paging (按需调页)

- Do not load the entire program in physical memory at program execution time.
  NO NEED!
- Bring a page into memory only when it is needed
  1. Less I/O needed
  2. Less memory needed
  3. Faster response
  4. More users
- A page is needed $\Leftarrow$ Reference to it
  - Invalid reference $\Rightarrow$Abort
  - Not-in-memory $\Rightarrow$Bring to memory

Demand Paging (按需调页)

- Swapper VS. Pager
  - A swapper manipulates the entire processes
  - Lazy swapper
    Never swaps a page into memory unless the page will be needed
    - Swapper that deals with individual pages is a pager



Example: Transfer of a paged memory to contiguous disk space

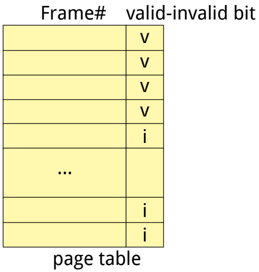
Outline

Hardware support

1. The modified page table mechanism
2. Page fault
3. Address translation
4. Secondary memory (as swap space)

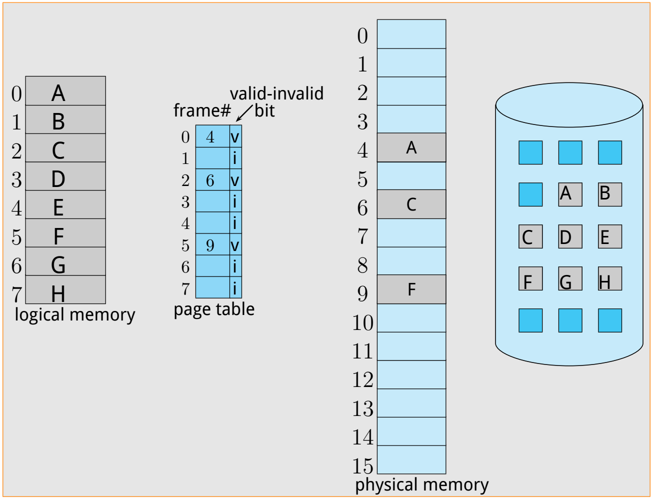
1) The modified page table mechanism

1. Valid-Invalid Bit (PRESENT bit)
   - With each page table entry a valid-invalid bit is associated
     - v $\Rightarrow$ in-memory, i $\Rightarrow$ not-in-memory
   - Initially valid-invalid bit is set to i on all entries
   - During address translation, if valid-invalid bit in page table entry is i $\Rightarrow$ page fault
2. Reference bits (for pager out)
3. Modify bit (or dirty bit)
4. Secondary storage info (for pager in)



1) The modified page table mechanism

- Page table when some pages are not in main memory

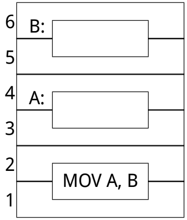


2) Page Fault (缺页故障)

- First reference to a page will trap to OS:

  page fault(缺页故障/异常/中断)

- Page fault trap (缺页异常)
  - Exact exception (trap), 精确异常
    Restart the process in exactly the same place and state.
    Re-execute the instruction which triggered the trap
- Execution of one instruction may cause multiply page faults



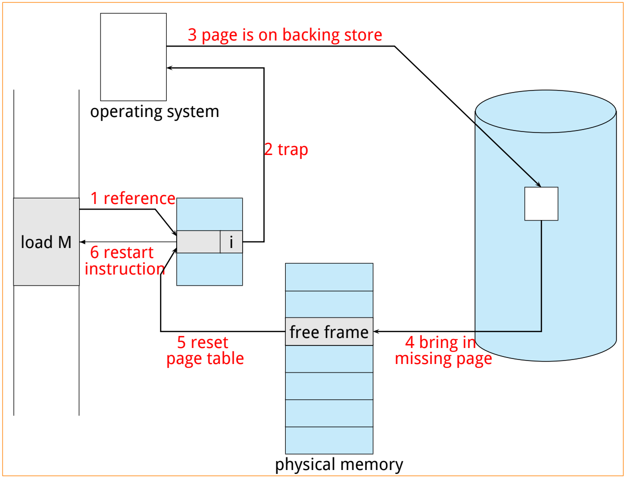
Example: One instruction and 6 page faults

- Page fault may occur at every memory reference
- One instruction may cause multiply page faults while fetching instruction or r/w operators

2) Page Fault (缺页故障)

- Page Fault Handling:
  1. OS looks at an internal table to decide:
     - Invalid reference $\Rightarrow$ abort
     - Just not in memory $\Rightarrow$
  2. Get empty frame
  3. Swap page into frame
     - Pager out & pager in
  4. Modify the internal tables & Set validation bit = v
  5. Restart the instruction that caused the page fault

2) Page Fault (缺页故障)



Steps in handling a page fault

3) address translation

- Address translation hardware + page fault handling

Resume the execution

- Context save (保存现场)
  Before OS handling the page fault, the state of the process must be saved
  - Example: record its register values, PC
- Context restore (恢复现场)
  The saved state allows the process to be resumed from the line where it was interrupted.
- NOTE: distinguish the following 2 situation
  - Illegal reference$\Rightarrow$The process is terminated
  - Page fault$\Rightarrow$ Load in or pager in

Outline

2 Demand Paging (按需调页)
- Basic Concepts (Hardware support)
- Performance of Demand Paging

Performance of Demand Paging

- Let p $=$ Page Fault Rate $(0 \leq p \leq 1.0)$
  - If p $= 0$, no page faults
  - If p $= 1$.0, every reference is a fault
- Effective Access Time (EAT)

$$\begin{aligned} \text{EAT} &= (1 - \text{p}) \times \text{memory access} \\ &\quad + \text{p} \times \text{page fault time} \end{aligned}$$

$$\begin{aligned} \text{page fault time} &= \text{page fault overhead} \\ &\quad + \text{swap page out} \\ &\quad + \text{swap page in} \\ &\quad + \text{restart overhead} \end{aligned}$$

Performance of Demand Paging

- Example
  - Memory access time $= 200$ns
  - Average page-fault service time $= 8$ms

$$\begin{aligned} \text{EAT} &= (1-\text{p}) \times 200 + \text{p} \times 8\text{ms} \\ &= (1-\text{p}) \times 200 + \text{p} \times 8,000,000 \\ &= 200 + \text{p} \times 7,999,800 \end{aligned}$$

1. If one access out of 1,000 causes a page fault, then

$$\begin{aligned} \text{p} &= 0.001 \\ \text{EAT} &= 8,199.8\text{ns} = 8.2\mu\text{s} \end{aligned}$$

This is a slowdown by a factor of $\frac{8.2\text{us}}{200\text{ns}} = 40!!$

Performance of Demand Paging

- Example
  - Memory access time $= 200$ns
  - Average page-fault service time $= 8$ms

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2. If we want performance degradation $< 10\%$, then

$$\begin{aligned} \mathsf{EAT} = 200 + \mathsf{p} \times 7,999,800 &< 200\,(1+10\%) = 220 \\ \mathsf{p} \times 7,999,800 &< 20 \\ \mathsf{p} &< 20/7,999,800 \approx 0.0000025 \end{aligned}$$

Method for better performance

- To keep the fault time low
  1. Swap space, faster then file system
  2. Only dirty page is swapped out, or
  3. Demand paging only from the swap space, or
  4. Initially demand paging from the file system, swap out to swap space, and all subsequent paging from swap space
- Keep the fault rate extremely low
  - Localization of program executing
    - Time, space

Outline

Process Creation

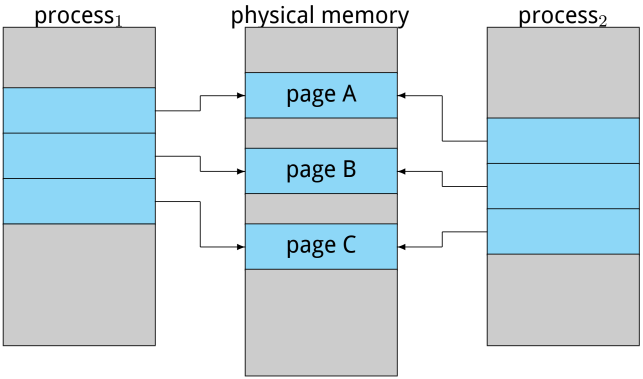
- Virtual memory allows other benefits during process creation:
  1. Copy-on-Write (写时复制)
  2. Memory-Mapped Files (later)

Copy-on-Write (写时复制)

- Copy-on-Write (COW, 写时复制)
  - allows both parent and child processes to initially share the same pages in memory
  - If either process modifies a shared page, only then is the page copied
- COW allows more efficient process creation as only modified pages are copied
- Free pages are allocated from a pool of zeroed-out pages

Copy-on-Write (写时复制)

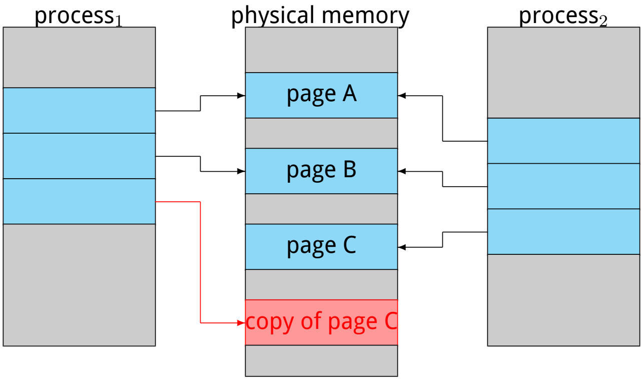
- Example:



Before Process 1 Modifies Page C

Copy-on-Write (写时复制)

- Example:



After Process 1 Modifies Page C

Outline

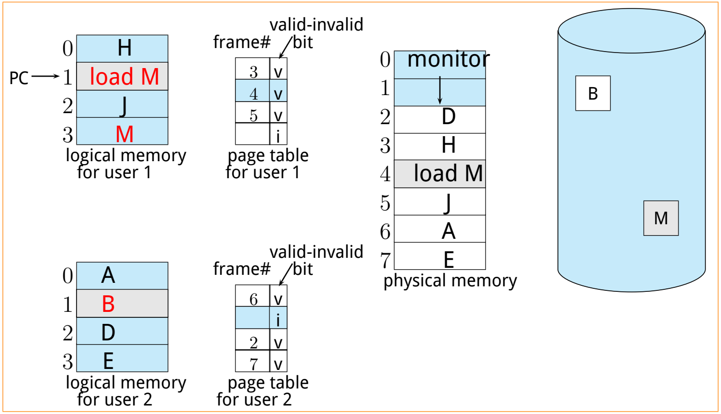
4 Page Replacement (页面置换)
- Basic Page Replacement
- First-In-First-Out (FIFO) Algorithm
- Optimal Algorithm
- Least Recently Used (LRU) Algorithm
- LRU Approximation Algorithms
- Counting Algorithms
- Page-Buffeing Algorithms

What happens if there is no free frame?

- Page replacement (页面置换)
  Find some page in memory, but not really in use, swap it out
  - Algorithm?
  - Performance?
    want an algorithm which will result in minimum number of page faults
  - Same page may be brought into memory several times

Need of Page Replacement (页面置换) I

- Free page frame is managed by OS using free-frame-list
- Over-allocation: No free frames; All memory is in use.



Example of over-allocation

Need of Page Replacement (页面置换) II

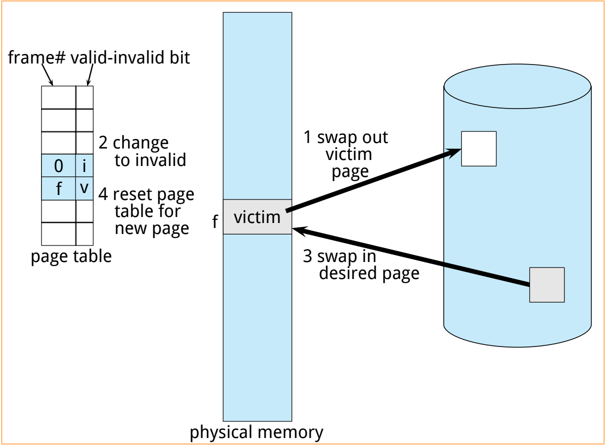
- What happens if there is no free frame?
- Solution:
  Page replacement (页面置换)
  Prevent over-allocation of memory by modifying page-fault service routine to include page replacement

Outline

Basic Page Replacement

- Basic Page Replacement
  1. Find the location of the desired page on disk
  2. Find a free frame:
     - If there is a free frame, use it
     - If there is no free frame, use a page replacement algorithm to select a victim frame
  3. Bring the desired page into the (newly) free frame; Update the page and frame tables
  4. Restart the process

Basic Page Replacement



Basic Page Replacement

- NO MODIFY, NO WRITTEN (to disk/swap space)
  - Use modify (dirty) bit to reduce overhead of page transfers
    - Only modified pages are written to disk
  - This technique also applies to read-only pages
    - For example, pages of binary code
- Page replacement completes separation between logical memory and physical memory
  - Large virtual memory can be provided on a smaller physical memory
- Demand paging, to lowest page-fault rate, two major problems
  1. Frame-allocation algorithms
  2. Page-replacement algorithms

Page Replacement Algorithms

- GOAL: to lowest page-fault rate
- Different algorithms are evaluated by running it on a particular string of memory references (reference string) and computing the number of page faults on that string

1. A reference string is
   a sequence of addresses referenced by a program
   Example:
   - An address reference string:
     0100 0432 0101 0612 0102 0103 0104 0101 0611 0103 0104 0101 0610 0102 0103 0104 0101 0609 0102 0105
   - Assuming page size = 100 B, then its corresponding page reference string is:
     1 4 1 6 1 6 1 6 1 6 1

Page Replacement Algorithms

2. How many page faults?
   - Determined by the number of page frames assigned to the process
   - For the upper example: 1 4 1 6 1 6 1 6 1 6 1
     - If ≥ 3, then only 3 page faults
     - If $= 1$, 11 pages faults

Page Replacement Algorithms

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   - For the upper example: 1 4 1 6 1 6 1 6 1 6 1
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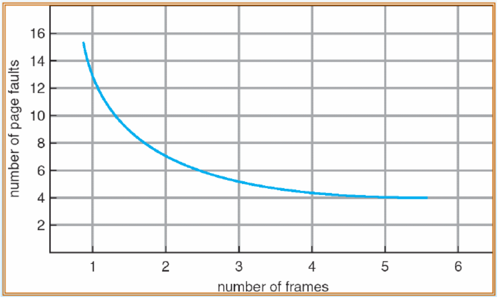


Graph of Page Faults Versus The Number of Frames

Page Replacement Algorithms

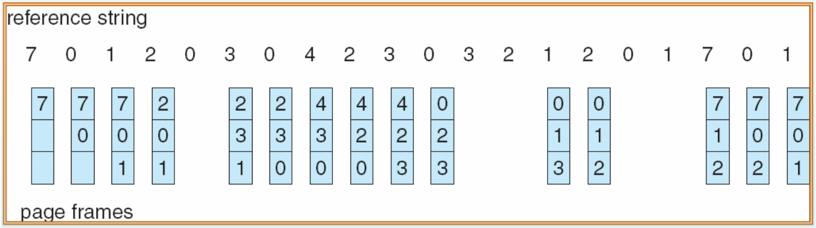
- In all our examples, the reference strings are
  1. 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
  2. 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2, 1, 2, 0, 1, 7, 0, 1

Outline

First-In-First-Out (FIFO) Algorithm

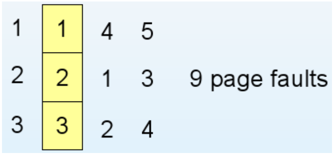
- The simplest page-replacement algorithm: FIFO
  - For each page: a time when it was brought into memory
  - For replacement: the oldest page is chosen
  - Data structure: a FIFO queue
    - Replace the page at the head of the queue
    - Insert a new page at the end of the queue

1. Example 1: 15 page faults, 12 page replacements

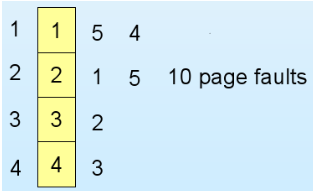


First-In-First-Out (FIFO) Algorithm

2. Reference string:
   1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
   - If 3 frames

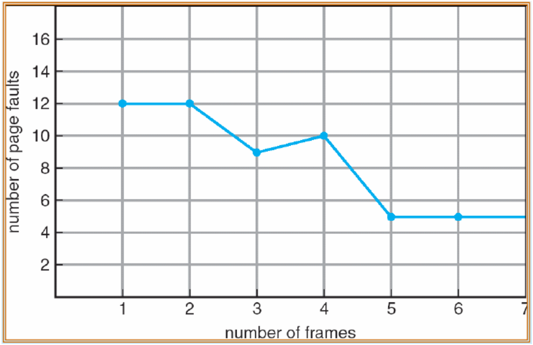


   - If 4 frames



First-In-First-Out (FIFO) Algorithm

- More memory, better performance? MAY BE NOT!!
  - Belady’s anomaly (贝莱迪异常现象):
    more frames $\Rightarrow$ more page faults

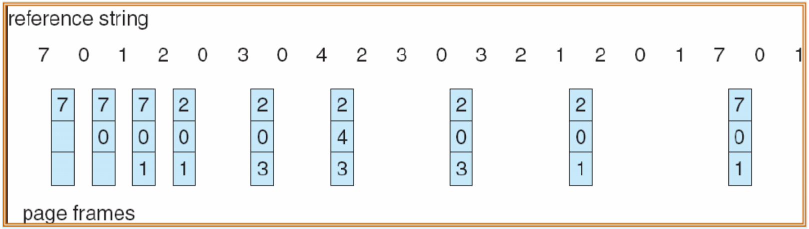


FIFO illustrating Belady’s Anomaly

Outline

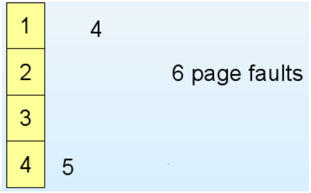
Optimal Algorithm

- Optimal page-replacement algorithm:
  Replace page that will not be used for longest period of time
  - It has the lowest page-fault rate
  - It will never suffer from Belady’ s anomaly
- Example1: 9 page faults, 6 page replacements



Optimal Algorithm

- 4 frames example
  1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



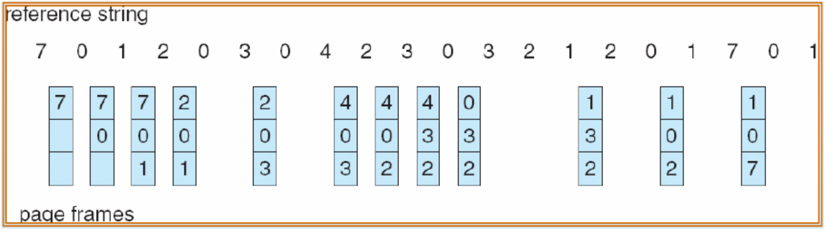
- OPT: Difficult to implement
  - How to know the future knowledge of the reference string?
- So, it is only used for measuring how well other algorithm performs

Outline

Least Recently Used (LRU) Algorithm

- LRU: an approximation of the OPT algorighm
  Use the recent past as an approximation of the near future
  - To replace the page that has not been used for the longest period of time
  - For each page: a time of its last use
  - For replace: the oldest time value

1. Example1: 12 page faults; 9 page replacements



Least Recently Used (LRU) Algorithm

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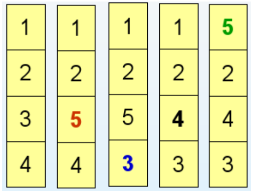
  Use the recent past as an approximation of the near future
  - To replace the page that has not been used for the longest period of time
  - For each page: a time of its last use
  - For replace: the oldest time value

2. Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5



1	1	1	1	**5**
2	2	2	2	2
3	**5**	5	**4**	4
4	4	**3**	3	3

Least Recently Used (LRU) Algorithm

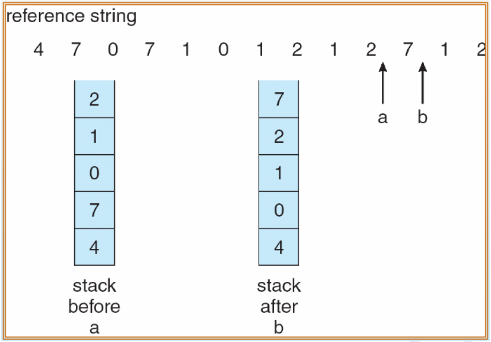
HOW to implement LRU replacement?

1. Counter implementation
   - Every page entry has a counter;
     every time page is referenced through this entry, copy the clock into the counter
   - When a page needs to be changed, look at the counters to determine which are to change

Least Recently Used (LRU) Algorithm

HOW to implement LRU replacement?

2. Stack implementation – keep a stack of page numbers in a double link form:
   - When page referenced: Move it to the top
     - Requires 6 pointers to be changed
   - No search for replacement



Outline

LRU Approximation Algorithms

- Reference bit
  - With each page associate a bit, initially = 0
  - When page is referenced bit set to 1
  - Replace the one which is 0 (if one exists)
    - We do not know the order, however

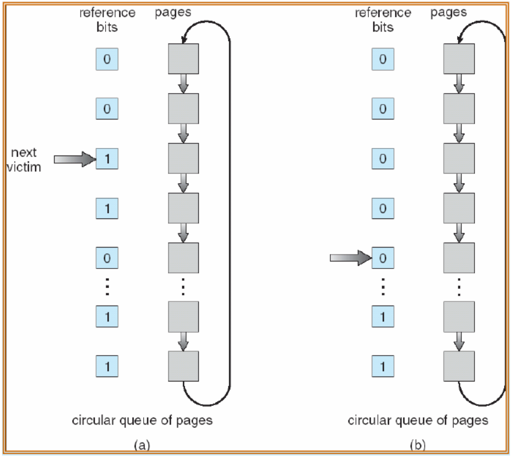
1. Additinal-Reference-Bits Algorithm:
   Reference bits + time ordering, for example: 8 bits
   - HW modifies the highest bit, only
   - Periodically, right shift the 8 bits for each page
   - 00000000, ..., 01110111, ..., 11000100, ..., 11111111

LRU Approximation Algorithms

2. Second chance (clock) Algorithm
   - Need only 1 reference bit, modified FIFO algorithm
     - First, a page is selected by FIFO
     - Then, the reference bit of the page is checked:
       $0 \Rightarrow$ replace it
       $1 \Rightarrow$ not replace it, get a second chance with reference bit: $1 \rightarrow 0$, and time $\rightarrow$ current

LRU Approximation Algorithms

2. Second chance (clock) Algorithm
   - Implementation: Clock replacement
     - Clock order



LRU Approximation Algorithms

3. Enhanced Second-Chance Algothm
   - Reference bit + modify bit
   - 4 page classes (访问位，修改位)
     - (0, 0) – best page to replace
     - (0, 1) – not quite as good
     - (1, 0) – probably be used again soon
     - (1, 1) – probably be used again soon, and be dirty
   - Replace the first page encountered in the lowest nonempty class.
     1. Scan for (0, 0)
     2. Scan for (0, 1), & set reference bits to 0
     3. Loop back to step (a)

Outline

Counting Algorithms

- Counting algorithms:
  Keep a counter of the number of references that have been made to each page

1. LFU Algorithm: replaces page with smallest count
2. MFU Algorithm: based on the argument that the page with the smallest count was probably just brought in and has yet to be used

Outline

Page-Buffeing Algorithms

- System commonly keep a pool of free frames
- When replacement occurs, two frames are involved
  1. A free frame from the pool is allocated to the process
     - The desired page is read into the frame
  2. A viction frame is chosen
     - Written out later and the frame is added to the free pool

  - NO NEED to write out before read in

1. An expansion
   - Maintain a list of modified pages
   - When a paging device is idle, select a modified page, write it out, modify bit$\rightarrow$0

Page-Buffeing Algorithms

2. Another modification
    - Free frame with old page
    - The old page can be reused
        - Less write out and less read in
    - VAX/VMS
    - Some UNIX: + second chance
    - ...

Outline

Allocation of Frames

1. Minimum number of pages
   - Each process needs minimum number of pages
   - Determined by ISA (Instruction-Set Architecture)
     - We must have enough frames to hold all the different pages that any single instruction can reference
   - Example: IBM 370
     6 pages to handle SS MOVE instruction:
     - Instruction is 6 bytes, might span 2 pages
     - 2 pages to handle from
     - 2 pages to handle to
2. Two major allocation schemes
   - Fixed allocation; priority allocation
3. Two replacement policy
   - Global vs. local

Allocation scheme 1: Fixed Allocation

1. Equal allocation
   For example, if there are 100 frames and 5 processes, give each process 20 frames.

$$\begin{aligned}\text{frame number for any process} &= \frac{m}{n}\\ m &= \text{total memory frames}\\ n &= \text{number of processes}\end{aligned}$$

Allocation scheme 1: Fixed Allocation

2. Proportional allocation
   Allocate according to the size of process

- example:

$$\begin{aligned} s_i &= \text{size of process } p_i \\ S &= \Sigma s_i \\ m &= \text{total number of frames} \\ a_i &= \text{allocation for } p_i = \frac{s_i}{S} \times m \end{aligned}$$

$$\begin{aligned} m &= 64 \\ S_1 &= 10 \\ S_2 &= 127 \\ a_1 &= \frac{10}{137} \times 64 \approx 5 \\ a_2 &= \frac{127}{137} \times 64 \approx 59 \end{aligned}$$

Allocation scheme 1: Priority Allocation

- Use a proportional allocation scheme using priorities rather than size
- If process P_i generates a page fault,
  1. Select for replacement one of its frames
  2. Select for replacement a frame from a process with lower priority number

Replacement policy: Global vs. Local Allocation

- Global replacement
  process selects a replacement frame from the set of all frames; one process can take a frame from another
  - Problem: a process cannot control its own page-fault rate
- Local replacement
  each process selects from only its own set of allocated frames
  - Problem?

Outline

6 Thrashing (抖动)

- Cause of trashing
- Working-Set Model (工作集模型)
- Page-Fault Frequency (缺页频率)

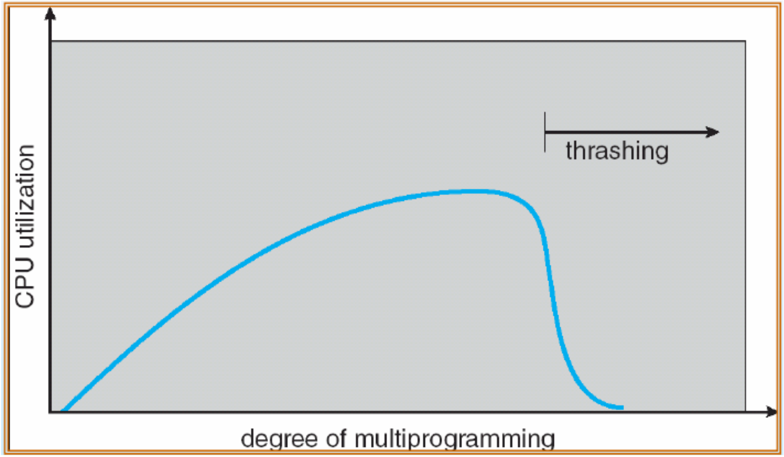
Outline

Thrashing (抖动)

- If a process does not have “enough” pages, the page-fault rate is very high. This leads to:
  - Low CPU utilization
  - OS thinks that it needs to increase the degree of multiprogramming
  - Another process added to the system, getting worse!
- Thrashing $\equiv$ a process is busy swapping pages in and out

Thrashing (抖动)

- Cause of trashing: unreasonable degree of multiprogramming (不合理的多道程序度)



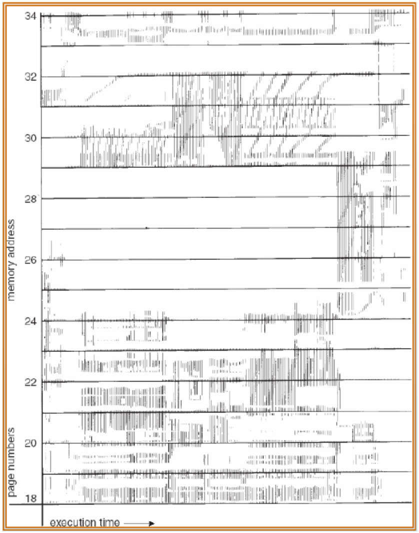
Thrashing (抖动)

- How to limit the effects of thrashing
  - Local replacement algorithm? not entirely sloved.
  - We must provide a process with as many frames as it needs–locality
  - How do we know how many frames is needed?
    - working-set strategy $\Leftarrow$Locality model

- Locality model: This is the reason why demand paging works
  1. Process migrates from one locality to another
  2. Localities may overlap

- Why does thrashing occur?
  Σsize of locality $>$ total memory size

Thrashing (抖动)



Locality In A Memory-Reference Pattern

Outline

6 Thrashing (抖动)
- Cause of trashing
- Working-Set Model (工作集模型)
- Page-Fault Frequency (缺页频率)

Working-Set Model (工作集模型)

- The working-set model is based on the assumption of locality.
- let

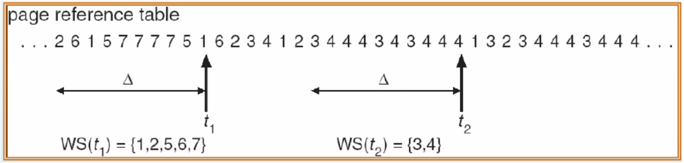
$$\begin{aligned}\Delta &\equiv \text{working} - \text{set window}\\ &\equiv \text{a fixed number of page references}\end{aligned}$$

  For example: 10,000 instructions

- Working set (工作集):
  The set of pages in the most recent Δ page references.
  - An approximation of the program' s locality.

Working-Set Model (工作集模型)

- Example: $\Delta = 10$



- Working set size:

$$\text{WSS}_i(\text{working set of Process } P_i)$$
$$= \text{total number of pages referenced in the most recent } \Delta$$

  - Varies in time, depend on the selection of Δ
    1. if Δ too small will not encompass entire locality
    2. if Δ too large will encompass several localities
    3. if $\Delta = \infty \Rightarrow$ will encompass entire program

Working-Set Model (工作集模型)

- For all processes in the system, currently

$$D = \Sigma WSS_i \equiv \text{total demand frames}$$

  - $D > m \Rightarrow$ Thrashing
  - Policy:
    if $D > m$, then suspend one of the processes

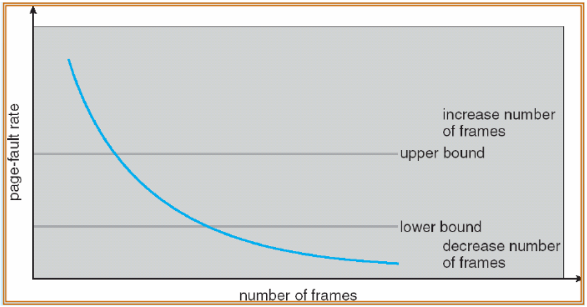
Keeping Track of the Working Set

- Approximate with: interval timer $+$ reference bits
- Example: $\Delta = 10{,}000$
  - Timer interrupts after every 5000 time units
  - 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 $\Rightarrow$ page in working set
- Why is this not completely accurate?
  - IN!! But where?
- Improvement:
  - 10 bits and interrupt every 1000 time units

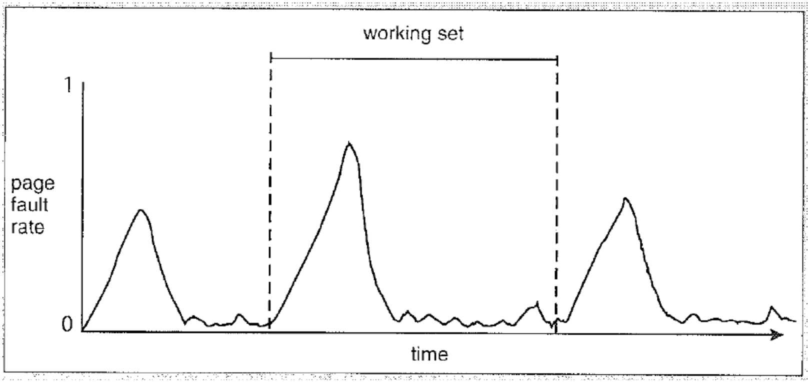
Outline

Page-Fault Frequency Scheme

- Page-Fault Frequency: helpful for controlling trashing
  - Trashing has a high page-fault rate.
  - Establish "acceptable" page-fault rate
    - If actual rate too low, process loses frame
    - If actual rate too high, process gains frame



Working sets and page fault rates



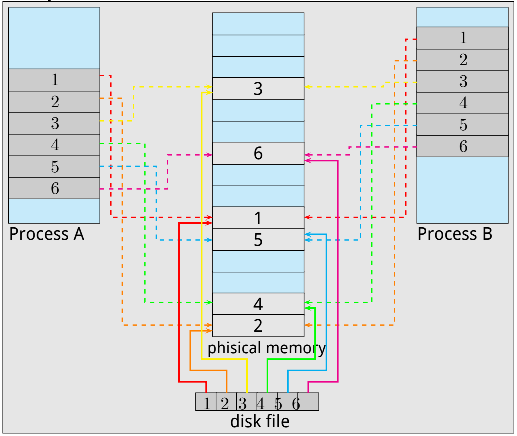
Outline

Memory-Mapped Files

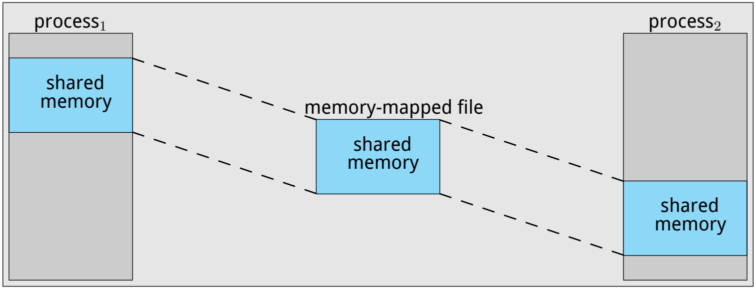
- Memory-mapped file I/O
  allows file I/O to be treated as routine memory access by mapping a disk block to a page in memory
- A file is initially read using demand paging. A page-sized portion of the file is read from the file system into a physical page. Subsequent reads/writes to/from the file are treated as ordinary memory accesses.
- Simplifies file access by treating file I/O through memory rather than read() write() system calls

Memory-Mapped Files

- Also allows several processes to map the same file allowing the pages in memory to be shared



Shared Memory in Windows using Memory-Mapped I/O



Memory－mapped I/O

- Many computer architectures provide memory-mapped I/O
  - Ranges of memory addresses are set aside and are mapped to the device registers.
  - Directly read/write the mapped range of memory address for transfer data from/to device registers
  - Fast response times
  - For example: video controler
    - Displaying text on the screen is almost as easy as writing the text into the appropriate memory-mapped locations.

Outline

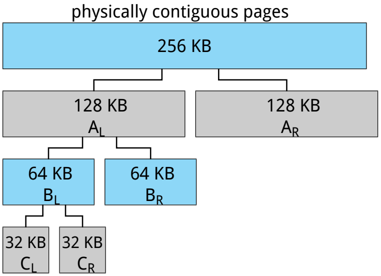
Allocating Kernel Memory

- Kernel memory
  Treated differently from user memory
  - Process’ s logical (virtual) address space VS. kernel address space
    - different privilege
    - allow page fault or not?
- Often allocated from a free-memory pool
  - Kernel requests memory for structures of varying sizes
  - Some kernel memory needs to be contiguous

1. Buddy system (伙伴系统)
2. Slab allocator (slab分配器)

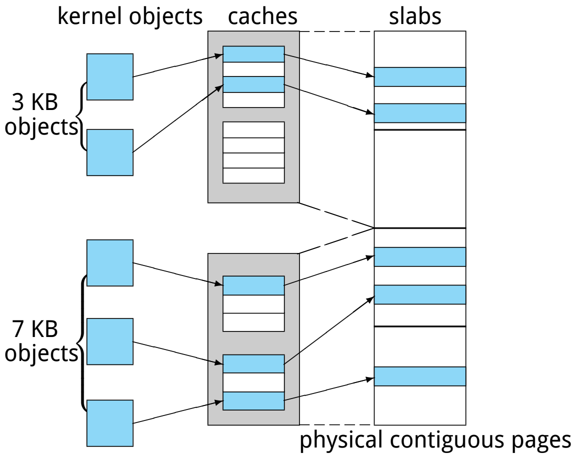
1. Buddy System (伙伴系统)

- Allocates memory from fixed-size segment consisting of physically-contiguous pages
- Memory allocated using power-of-2 allocator
    - Satisfies requests in units sized as power of 2
    - Request rounded up to next highest power of 2
    - When smaller allocation needed than current size is available, current chunk split into two buddies of next-lower power of 2, continue until appropriate sized chunk available



2. Slab Allocator (slab分配器) I

- Slab allocator: Alternate strategy



2. Slab Allocator (slab分配器) II

- Slab is one or more physically contiguous pages
  - Cache consists of one or more slabs
  - Single cache for each unique kernel data structure
    - Each cache filled with objects – instantiations of the data structure
  - When cache created, filled with objects marked as free
  - When structures stored, objects marked as used
  - If slab is full of used objects, next object allocated from empty slab
    - If no empty slabs, new slab allocated
- Benefits: no fragmentation, fast memory request satisfaction

Outline

Other Issues

1. Prepaging
    - To reduce the large number of page faults that occurs at process startup
    - Prepage all or some of the pages a process will need, before they are referenced
    - But if prepaged pages are unused, I/O and memory was wasted
    - Assume s pages are prepaged and α of the pages is used
        - Is cost of s $* \alpha$ save pages faults > or < than the cost of prepaging s $* (1 - \alpha)$ unnecessary pages?
        - α near zero $\Rightarrow$ prepaging loses
2. Page Size
    - Page size selection must take into consideration:
        1. Fragmentation
        2. Table size
        3. I/O overhead
        4. Locality

Other Issues

3. TLB Reach - The amount of memory accessible from the TLB
   - TLB Reach = $(\text{TLB Size}) \times (\text{Page Size})$
     - Ideally, the working set of each process is stored in the TLB, Otherwise there is a high degree of page faults
     - Increase the Page Size.
       This may lead to an increase in fragmentation as not all applications require a large page size
     - Provide Multiple Page Sizes.
       This allows applications that require larger page sizes the opportunity to use them without an increase in fragmentation

4. Inverted page tables
   - This can reduce the memory used to store page tables.
   - Need an external page table (one per process) for the infomation of the logical address space

Other Issues

5. Program structure

int[128,128] data; // Each row is stored in one page

Program 1

```
for (j = 0; j <128; j++)
    for (i = 0; i < 128; i++)
        data[i,j] = 0;
```

128 x 128 = 16,384 page faults

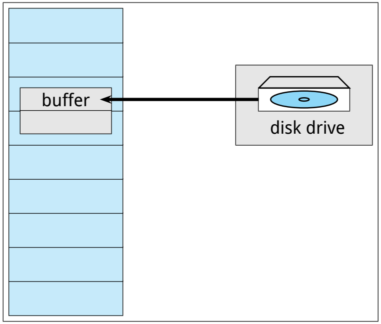
Program 2

```
for (i = 0; i < 128; i++)
    for (j = 0; j < 128; j++)
        data[i,j] = 0;
```

128 page faults

Other Issues

6. I/O Interlock – Pages must sometimes be locked into memory
   - Consider I/O – Pages that are used for copying a file from a device must be locked from being selected for eviction by a page replacement algorithm



Reason why frames used for I/O must be in memory

Outline

Operating System Examples

- Windows XP
- Solaris

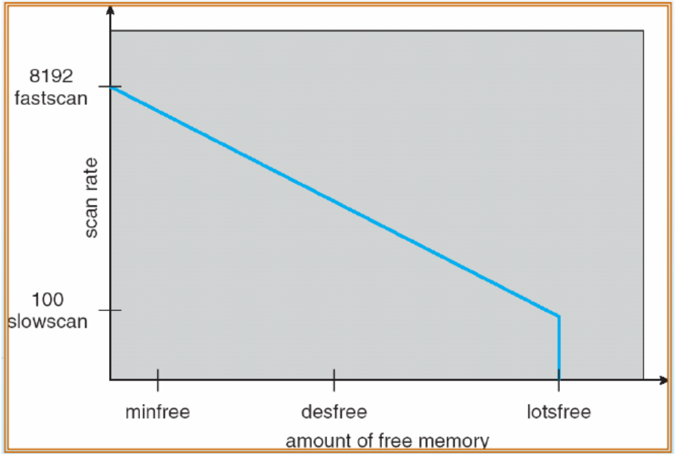
Windows XP

- Uses demand paging with clustering. Clustering brings in pages surrounding the faulting page.
- Processes are assigned working set minimum and working set maximum
    - 50~345 pages
    - Working set minimum is the minimum number of pages the process is guaranteed to have in memory,
    - A process may be assigned as many pages up to its working set maximum
    - When page fault:
        - if < working set maximum, allocates a new page
        - if =max, uses local page-replacement policy
- When the amount of free memory in the system falls below a threshold, automatic working set trimming is performed to restore the amount of free memory
    - Working set trimming removes pages from processes that have pages in excess of their working set minimum

Solaris I

- Maintains a list of free pages to assign faulting processes
  - Parameter lotsfree– threshold (amount of free memory) to begin paging, 1/64 the size of physical memory
  - check the amount of free pages 4 times per second
- Paging is performed by pageout process using modified second-chance algorithm (with two hands)
  - Desfree– threshold parameter to increasing paging
  - Minfree– threshold parameter to being swapping
  - Scanrate is the rate at which pages are scanned. This ranges from slowscan to fastscan
  - Pageout is called more frequently depending upon the amount of free memory available

Solaris II



Solaris 2 page scanner

Outline

小结

谢谢！