Chapter 9: Virtual Memory

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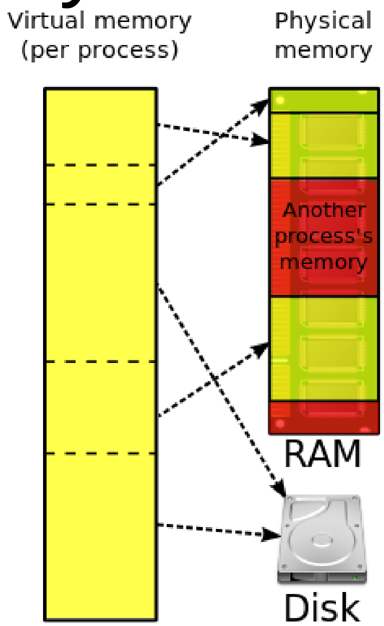
Chapter 9: Virtual Memory

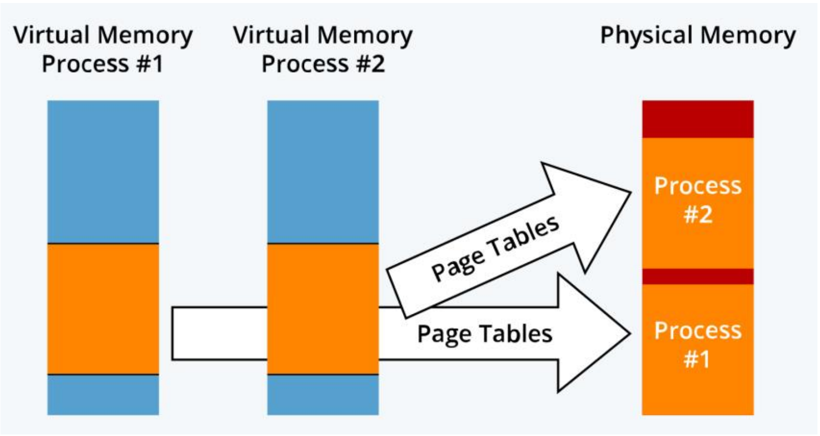
- Background
- Demand Paging
- Copy-on-Write
- Page Replacement within a Process
- Allocation of Frames among Processes
- Thrashing and Working Set Model
- Memory-Mapped Files
- Allocating Kernel Memory
- Other Considerations
- Operating-System Examples

Background

- **Virtual memory is different from the idea of memory virtualization**. The former is to abstract disk as memory. The later is to separate memory address spaces of all user processes.



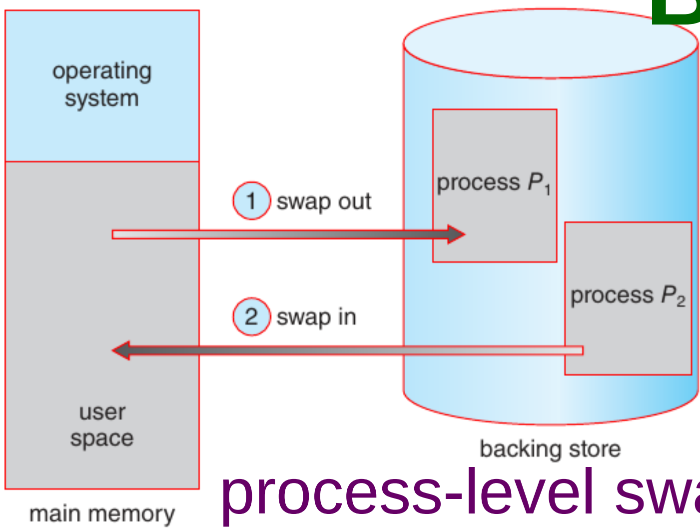
virtual memory



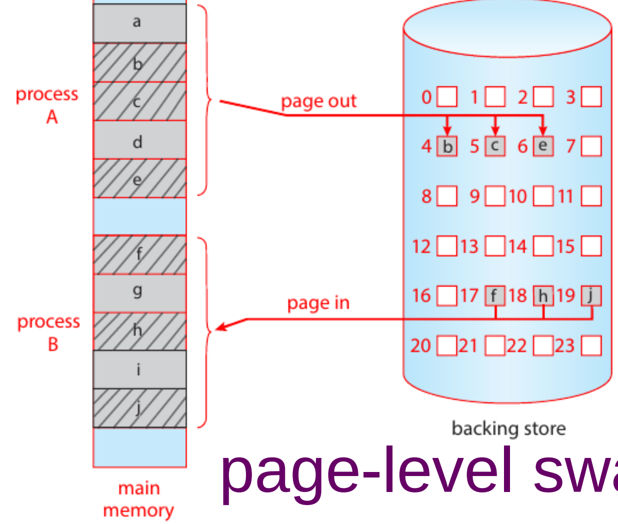
memory virtualization

- We previously talked about an entire process swapping into or out of main memory

Background



process-level swapping

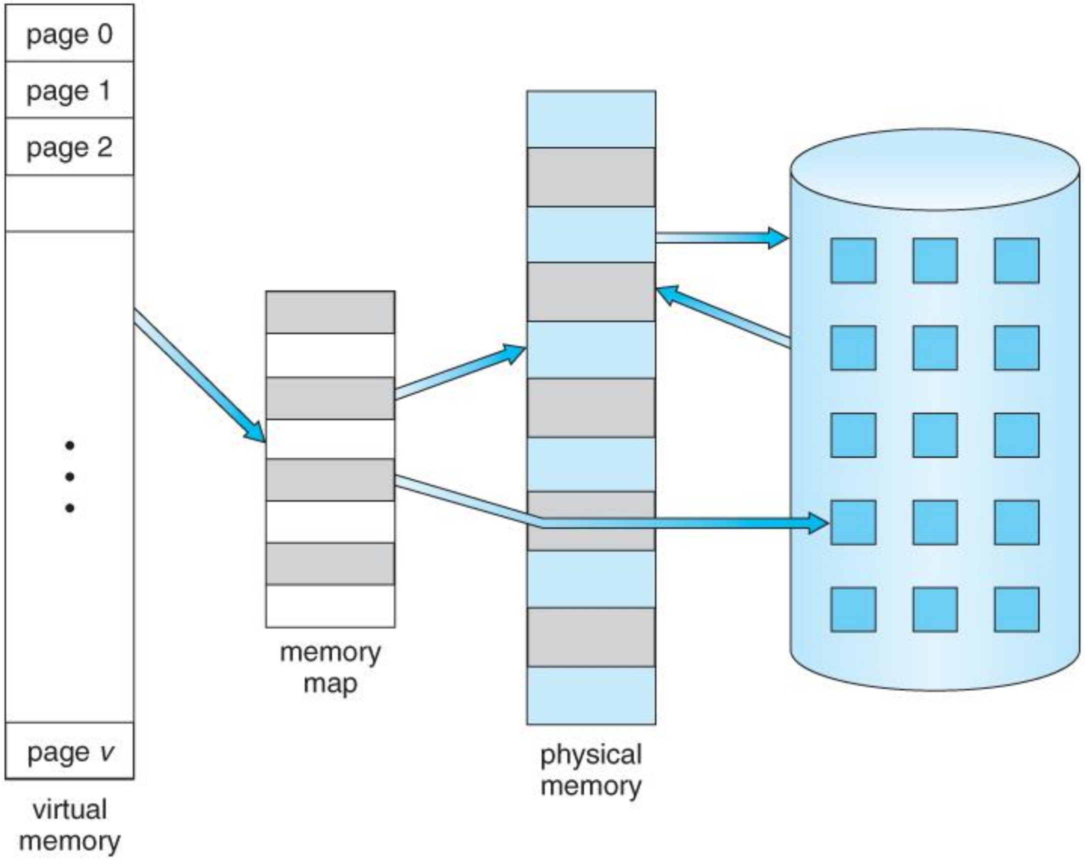


page-level swapping

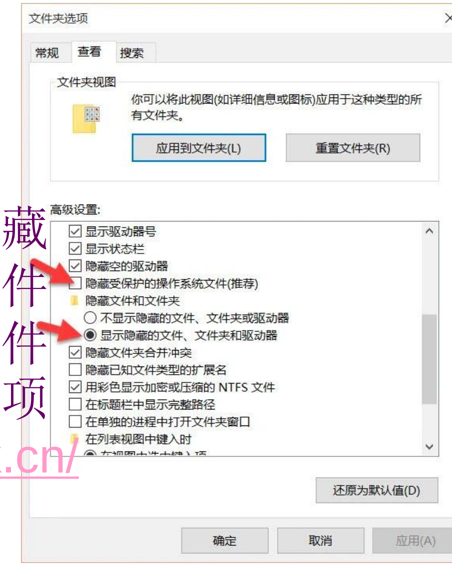
- **Virtual memory**: Separation of logical memory from physical memory by page-level swapping
  - Only part of the program needs to be kept in memory for execution. Used pages can be swapped out.
  - Logical address space can therefore be much larger than physical address space.
  - More programs can be run at the same time.
  - Less I/O is needed than loading or swapping.

Two Kinds of Implementation for Virtual Memory

- **Virtual memory can be implemented via:**
  - Demand paging （按需调页）
  - Demand segmentation（按需调段）



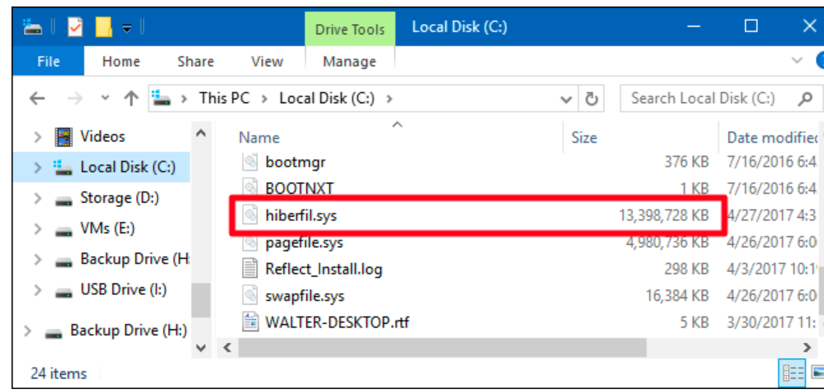
Hibernation, Page, Swap Files on Windows



文件夹选项中取消隐藏受保护的操作系统文件并打开显示隐藏的文件、文件夹和驱动器选项

https://www.sysgeek.cn/swapfile-sys/

- hiberfil.sys 休眠文件是 Windows 休眠时用于向磁盘写入内存内容的
  - mirror copy for physical memory data on disk
  - same size as the physical memory

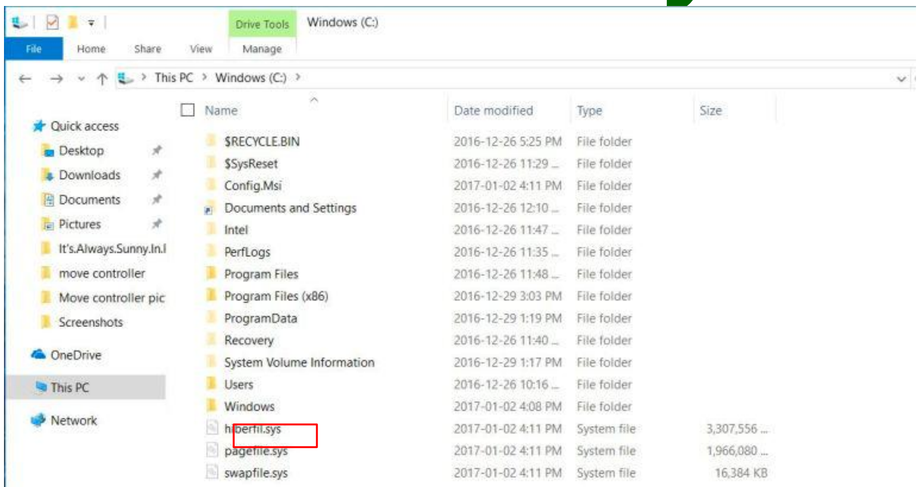


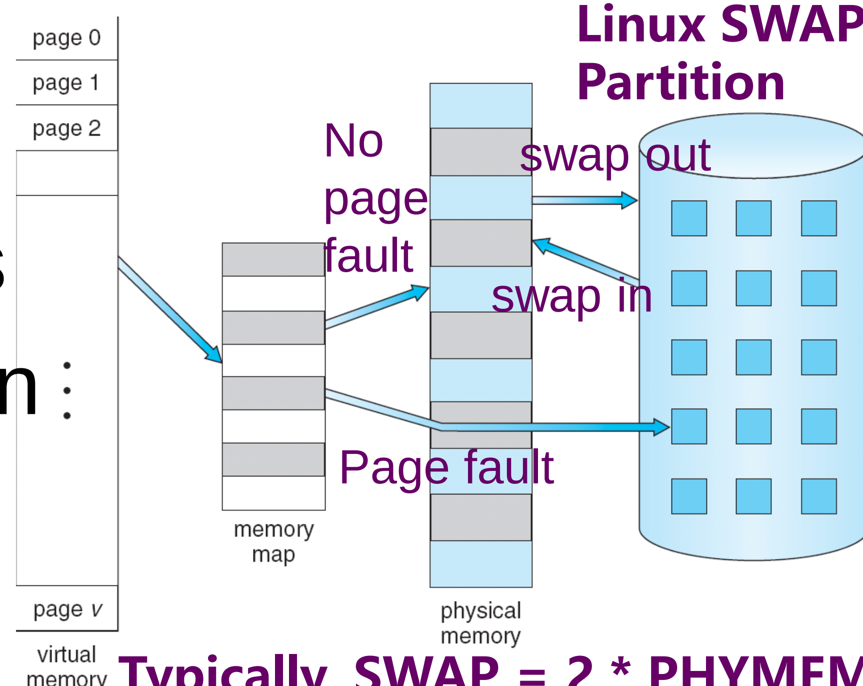
- pagefile.sys 页面文件是用于在操作系统内存不足时临时交换数据的
- swapfile.sys 文件用于交换 Universal Apps 的相关数据

Depending on the version of Windows you're using, you have several options for conserving power when you're not using your PC. Obviously, you can just shut it down. But, you can also send it into a sleep or hibernate mode, where it uses dramatically less power but is still available quickly when you need it.

Paging-based Virtual Memory

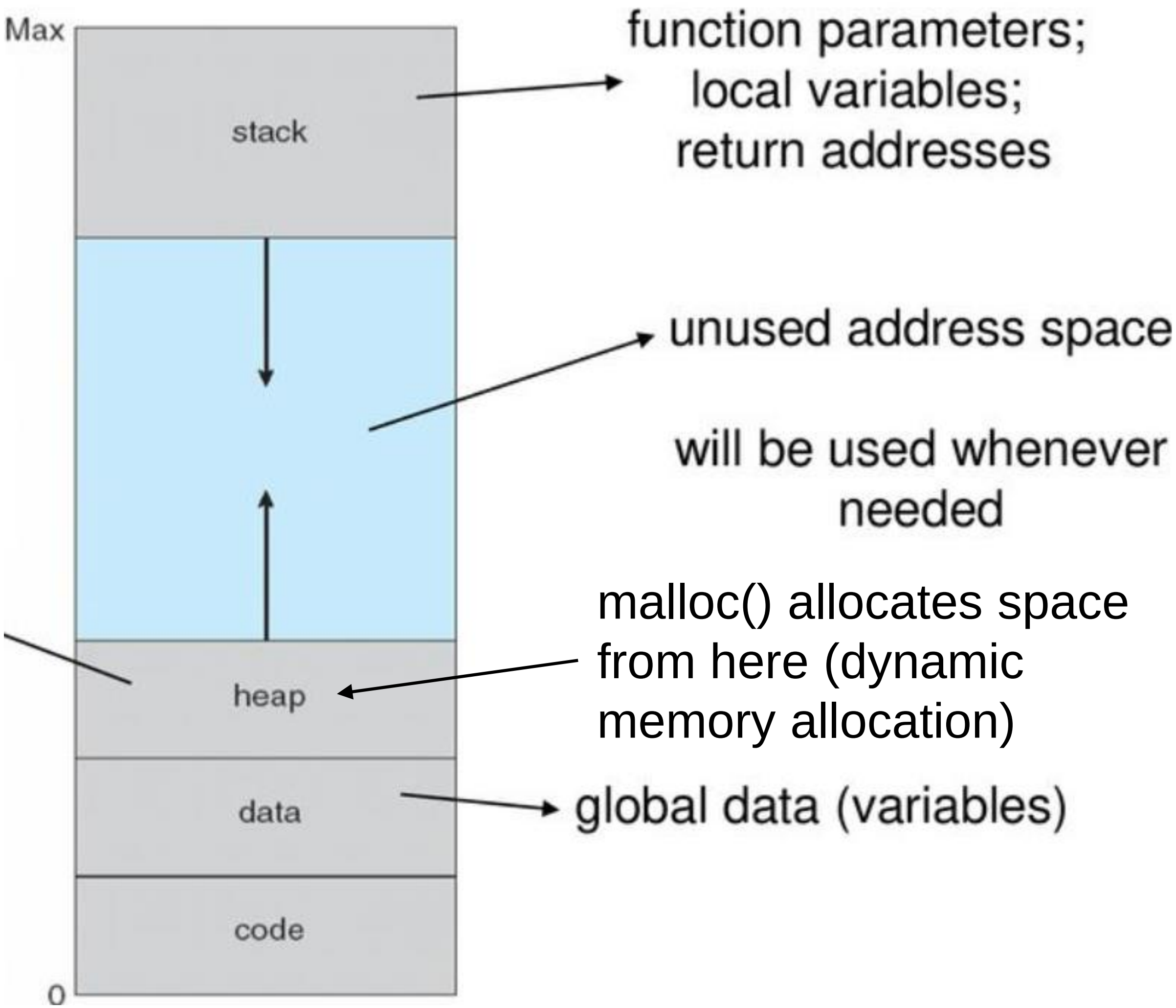
- Temporary storage for physical memory data on disk to provide more “virtual” memory for applications
- On Windows, in the root directory, C:/pagefile.sys
- On Linux, SWAP partition：
- may be greater than the size of physical memory



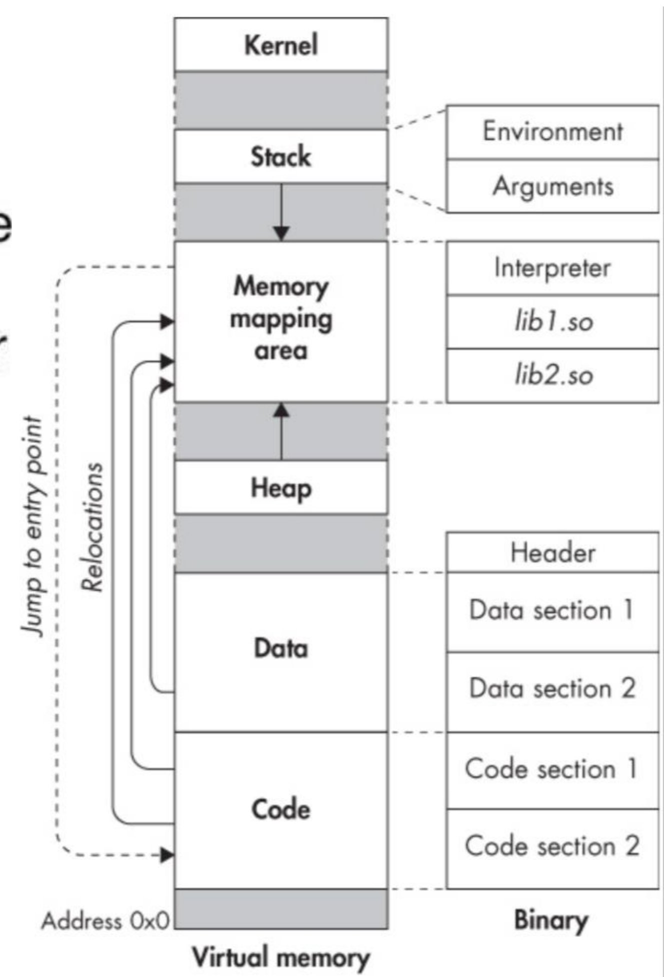


Typically, SWAP = 2 * PHYMEM

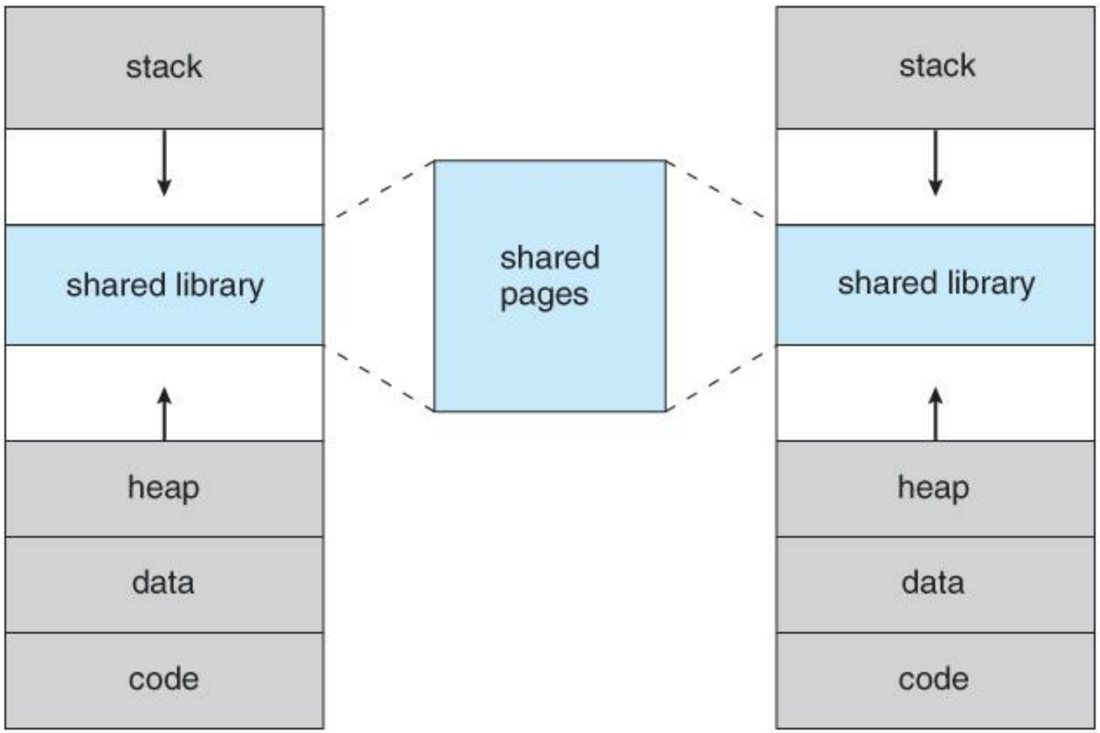
Virtual Address Space with Segmentation



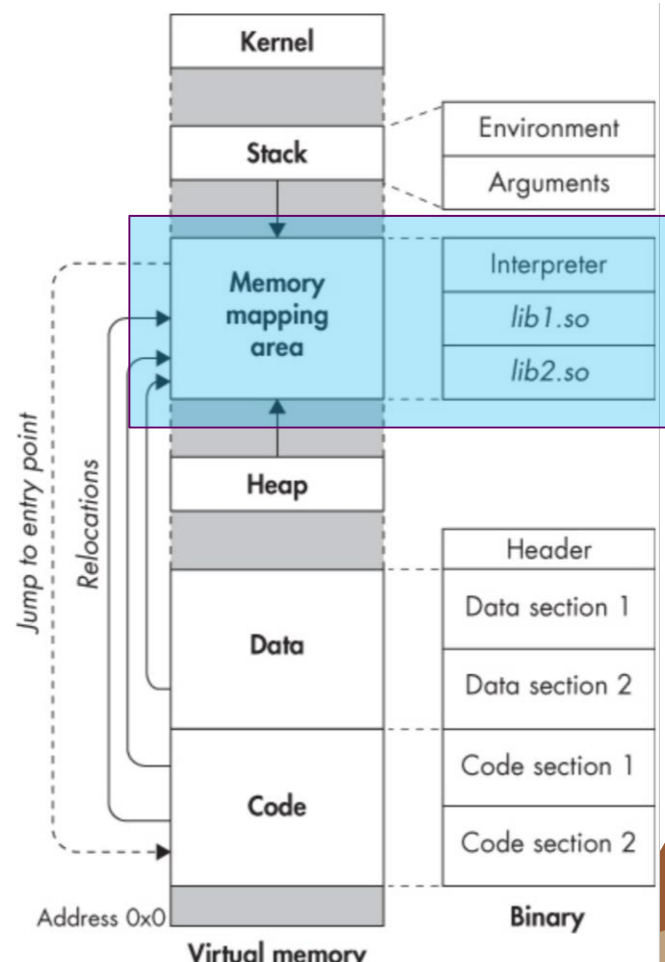
ELF (Executable and Linkable Format) on Linux System



Shared Library Using Virtual Memory with a Shared Segment



ELF (Executable and Linkable Format) on Linux System



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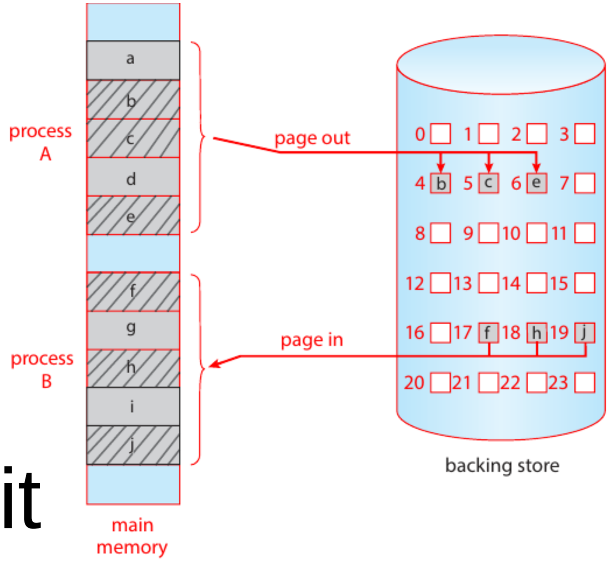
Demand Paging

- Bring a page into memory only when it is needed
  - Less I/O needed
  - Less memory needed
  - Faster response
  - More users
- Page is needed ⇒ reference to it
  - invalid reference ⇒ abort
  - not-in-memory ⇒ bring to memory
- **Pure demand paging** – never bring a page into memory unless page will be needed



page-level swapping

Valid-Invalid Bit

- With each page table entry, a valid-invalid bit is associated
  - 1 ⇒ in-memory, 0 ⇒ not-in-memory
- Initially, valid-invalid bit is set to 0 on all entries.
- During address translation, if valid-invalid bit in page table entry is 0 ⇒ page fault (缺页中断)

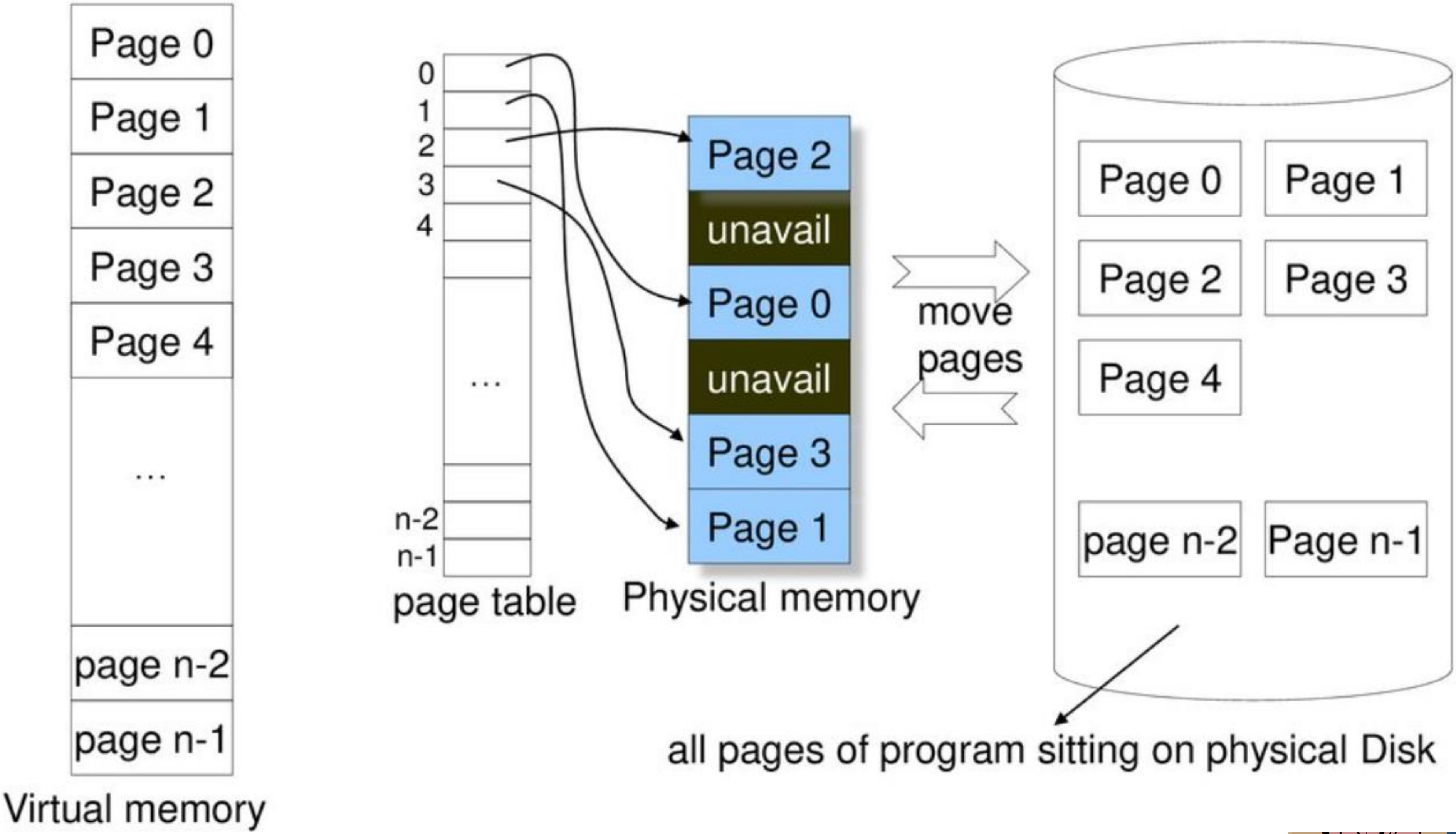
TLB

Valid	Tag	Physical Page Number	Time Since Last Access
1	0xb	12	4
1	0x7	4	1
1	0x3	6	3
0	0x4	9	7

Page table

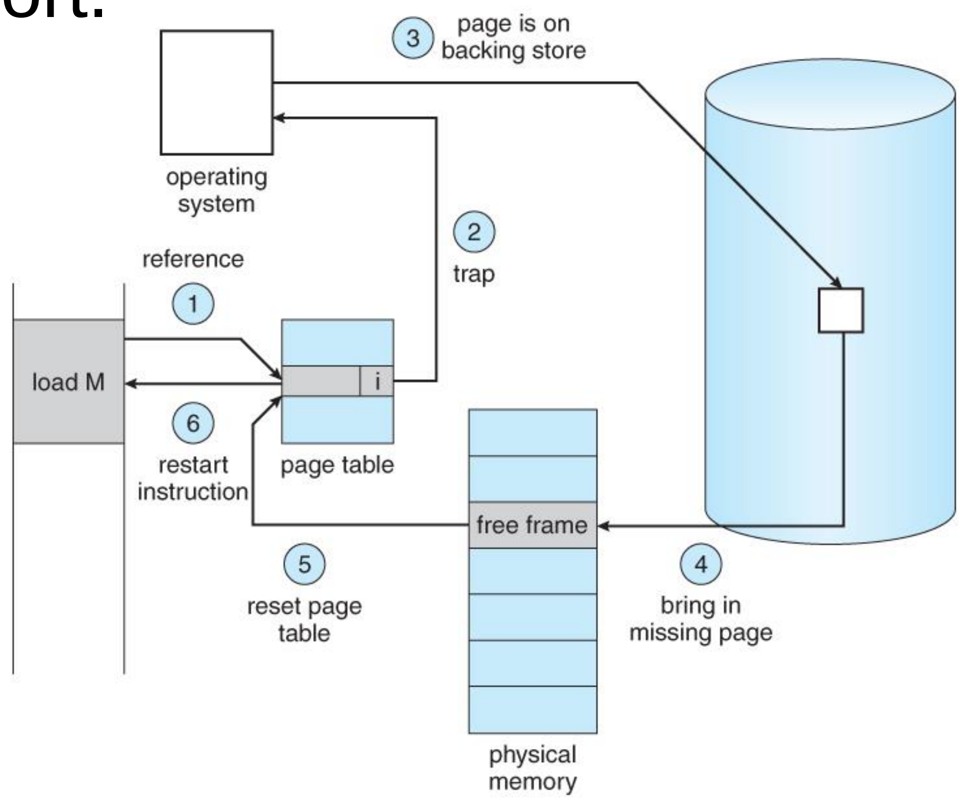
Index	Valid	Physical Page or in Disk
0	1	5
1	0	Disk
2	0	Disk
3	1	6
4	1	9
5	1	11
6	0	Disk
7	1	4
8	0	Disk
9	0	Disk
a	1	3
b	1	12

Page Table When Some Pages Are Not in Main Memory



Steps in Handling a Page Fault

- If there is ever a reference to a page, first reference will trap to OS kernel ⇒ page fault
- OS looks at another table to decide:
  - Invalid reference ⇒ abort.
  - Just not in memory.
- Get empty frame.
- Swap page into frame
- Reset tables, validation bit = 1.
- Restart instruction



More Details about Restarting an Instruction

- The restart will require fetching instruction again, decoding it again, fetching the two operands again, and applying it again
- Restarting Instruction after Page Fault (Worst-Case Example)

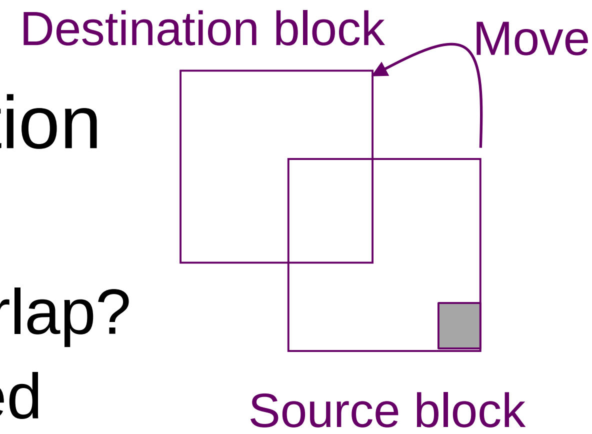
$$C \leftarrow A + B$$

1. Fetch and decode the instruction (ADD)
2. Fetch *A* to a register
3. Fetch *B* to another register
4. ADD *A* and *B*
5. Store the sum in *C* (Page fault)

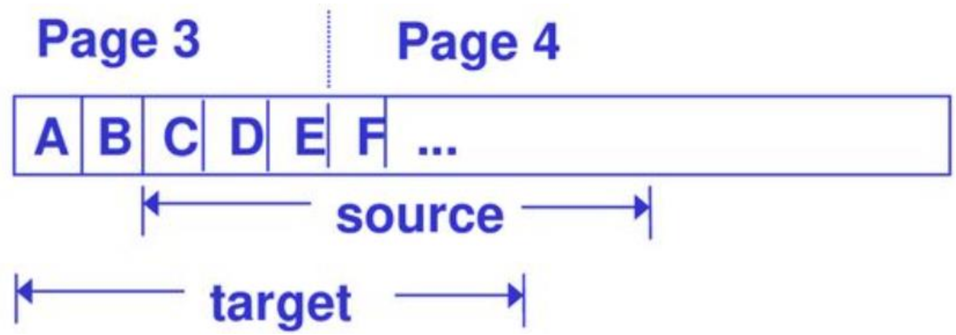
Restart

Restarting Instruction after Page Fault (Block-Move Example)

- Difficulty arises when an instruction may modify multiple virtual pages
  - For example, block move operation
  - Restart the whole operation?
    - ✓What if source and destination overlap?
    - ✓The source may have been modified



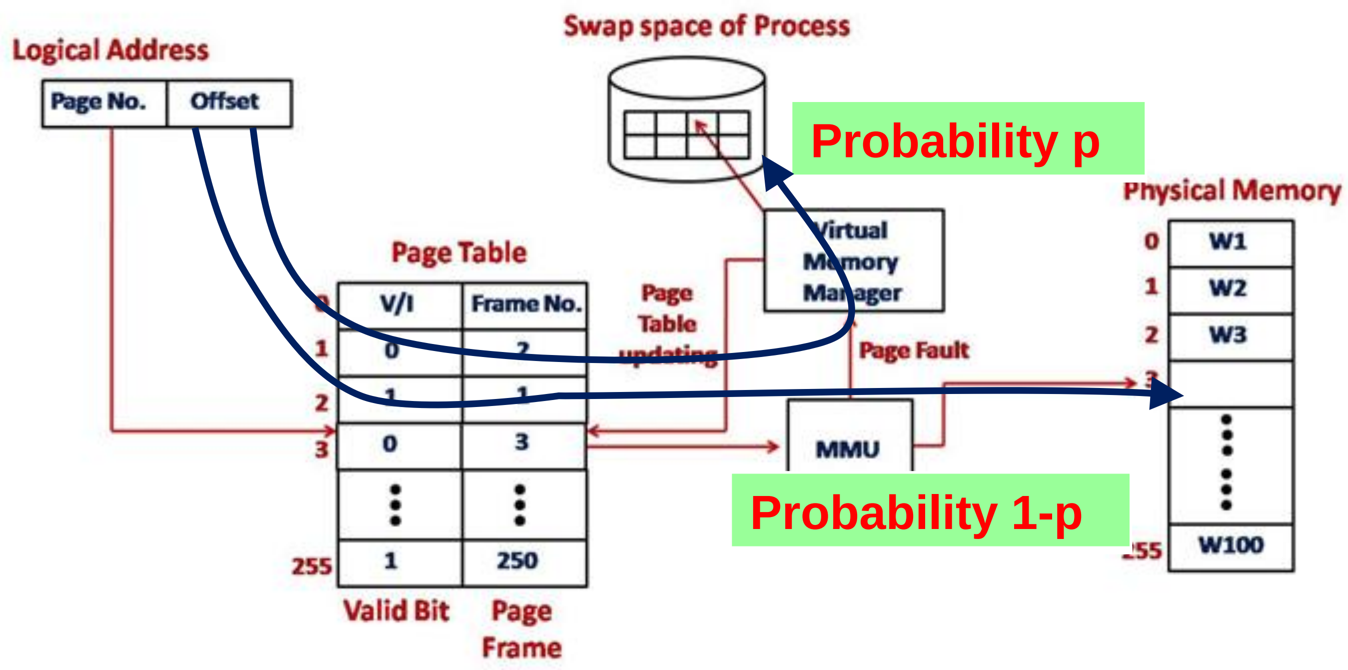
MVS: move up to 256 characters from source to target



- Solution:
  - Access both ends of both blocks before execution
  - Using temporal registers to hold the values of overwritten locations

Performance of Demand Paging

- Page Fault Rate $0 \leq p \leq 1.0$
  - if $p = 0$, no page faults
  - if $p = 1$, every reference is a fault



Performance of Demand Paging

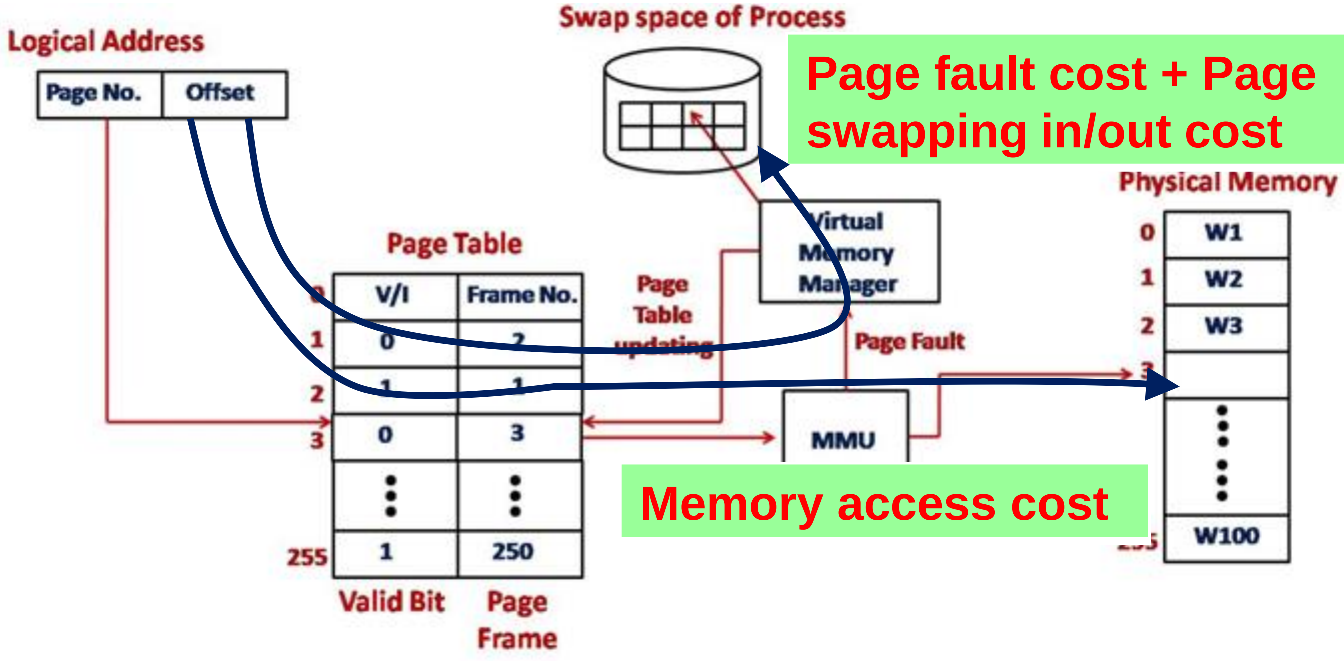
- Effective Access Time (EAT)

EAT = (1 – *p*) x memory access

+ *p* x (page fault overhead

[+swap page out]+swap page in

+ instruction restart overhead)



Example of Demand Paging Performance

- Memory access time = 1 microsecond
- Swap Page Time = 10 millisec = 10000 microsec
- Assume 50% of the time the page that is being replaced has been modified and therefore needs to be swapped out.
- Ignore the cost of restarting an instruction.

- EAT = (1 - p) x 1 + p x (10000*50%+20000*50%)
  = (1 - p) x 1 + p x (15000)
  = 1 + 14999 x p (in microsecond)

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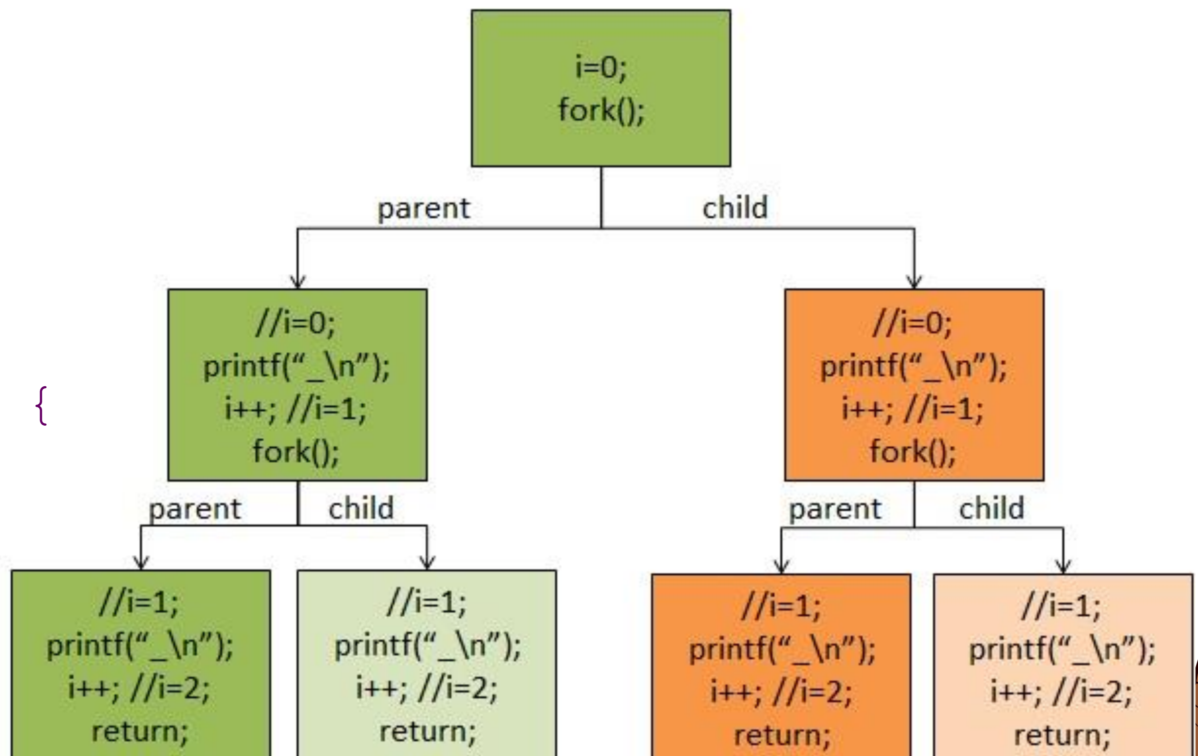
复习Linux fork系统调用

- 问题：Linux fork()系统调用实现了什么功能，返回值含义是什么？请问下面的代码一共输出多少个“_”？请解释原因。

```
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

int main(void) {
    int i;
    for(i=0; i<2; i++) {
        fork();
        printf("_\n");
    }
    wait(NULL);
    wait(NULL);
}
```

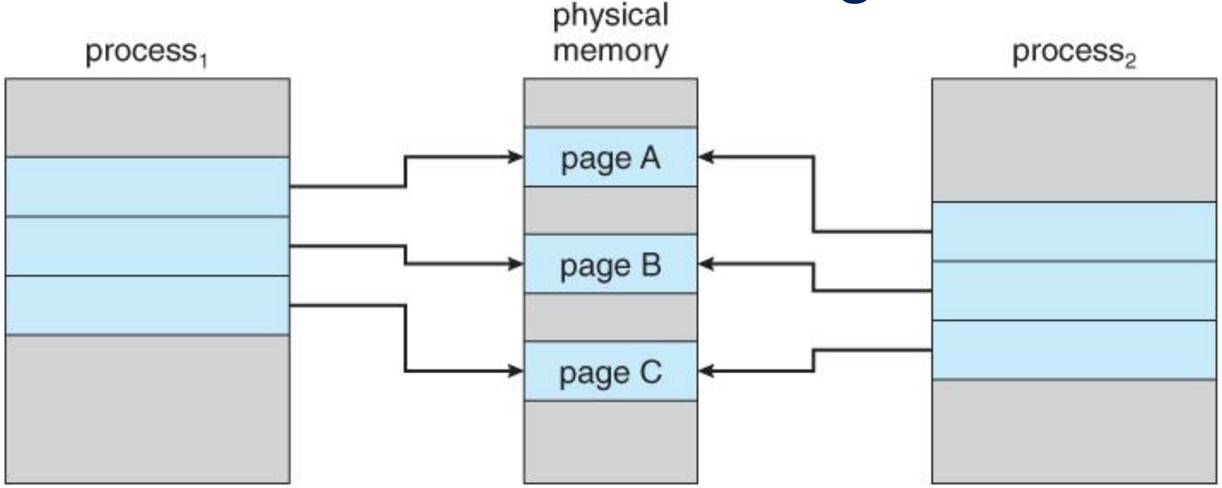


What if we remove the \n symbol? Give your reason.

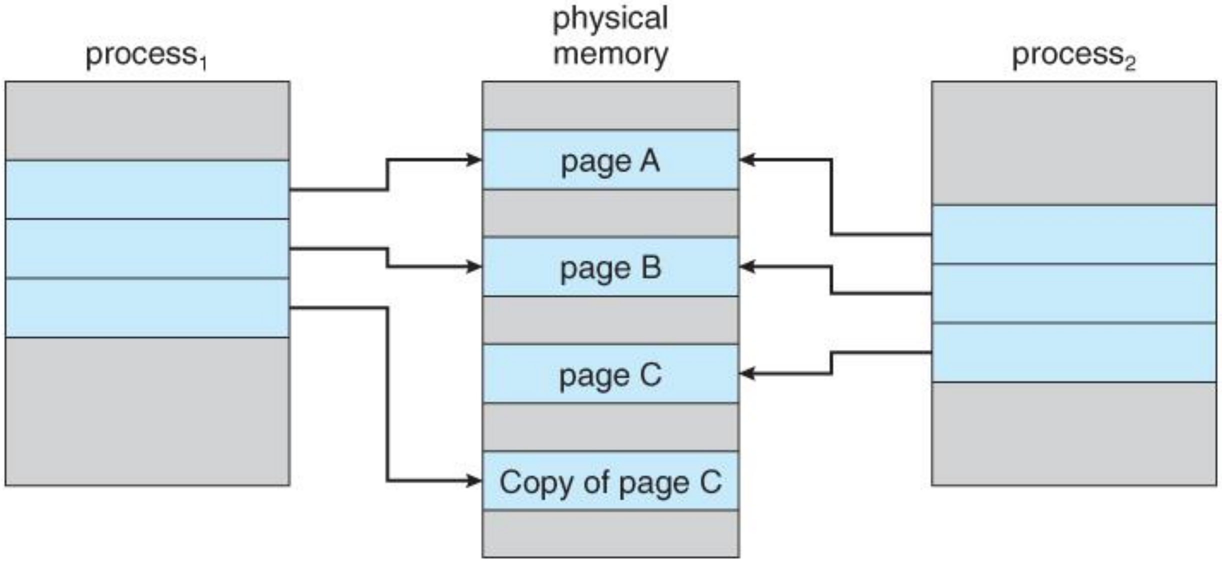
Copy-on-Write

- **Copy-on-Write** (COW) 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 **zero-fill-on-demand** pages
  - Why do we need to zero-out a page before allocating it to a process?
  - The pool should always have free frames for fast demand page execution

Before Process 1 Modifies Page C



After Process 1 Modifies Page C



fork() and vfork()

- `vfork()`, a variation of `fork()` system call, has the parent suspend and the child without copying the page table of the parent
  - Useful in performance-sensitive applications where a child is created which then immediately issues an `execve()`.
- 以前的fork很低效，它创建一个子进程时，将会创建一个新的地址空间，并且拷贝父进程的资源，而往往在子进程中会执行exec调用，这样，前面的拷贝工作就是白费了。于是，设计者就想出了vfork，它产生的子进程刚开始暂时与父进程共享地址空间（其实就是线程的概念了）。因为这时候子进程在父进程的地址空间中运行，所以子进程不能进行写操作，并且在儿子“**霸占**”着老子的房子时候，要委屈父亲一下了，让他在外面歇着（阻塞），一旦儿子执行了execve 或者exit 后，相于儿子买了自己的房子了，这时候就相于分家了。

http://linux.die.net/man/2/vfork

An Example of fork() and vfork()

```
int main() {
    pid_t pid;
    int cnt = 3;
    pid = fork();
    if(pid<0)
        printf("error in fork!\n");
    else if(pid == 0) {
        cnt++;
        printf("Child process %d, ",getpid());
        printf("cnt=%d\n",cnt);
    }  else {
        cnt++;
        printf"Parent process %d,",getpid());
        printf("cnt=%d\n",cnt);
    }
    return 0;
}
```

Execution Result:

Child process 5077, cnt=4

Parent process 5076, cnt=4

If we replace line 4 by pid = vfork(), then

Execution Result:

Child process 5077, cnt=4

Parent process 5076, cnt=1

Segmentation fault: 11

Question: If the cnt variable on stack is shared between parent and child processes, why do we still see cnt =1?

Answer: vfork() differs from fork() in that the calling thread is suspended until the child terminates (either normally by exit() or abnormally after a fatal signal), or it makes a call to execve(). Until that point, the child shares all memory with its parent, including the stack.

Question: What if we insert a command exit(0) before the line "} else {" ?

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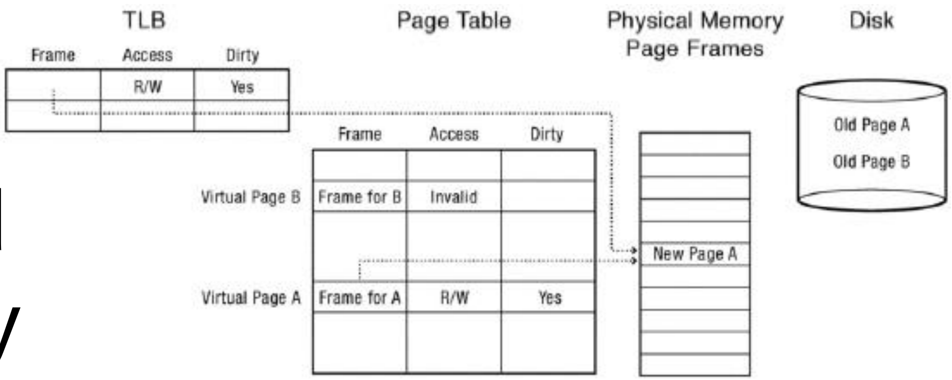
What Happens if There are no Free Frames?

- Used up by process pages
- Also in demand by the kernel, I/O buffers, …
- How much to allocate to each?
- Same page may be brought into memory several times
- Page replacement – find some page in memory, but not really in use, swap it out
  - Algorithm: terminate? swap out? replace the page?
  - Performance: want an algorithm which will result in minimum number of page faults

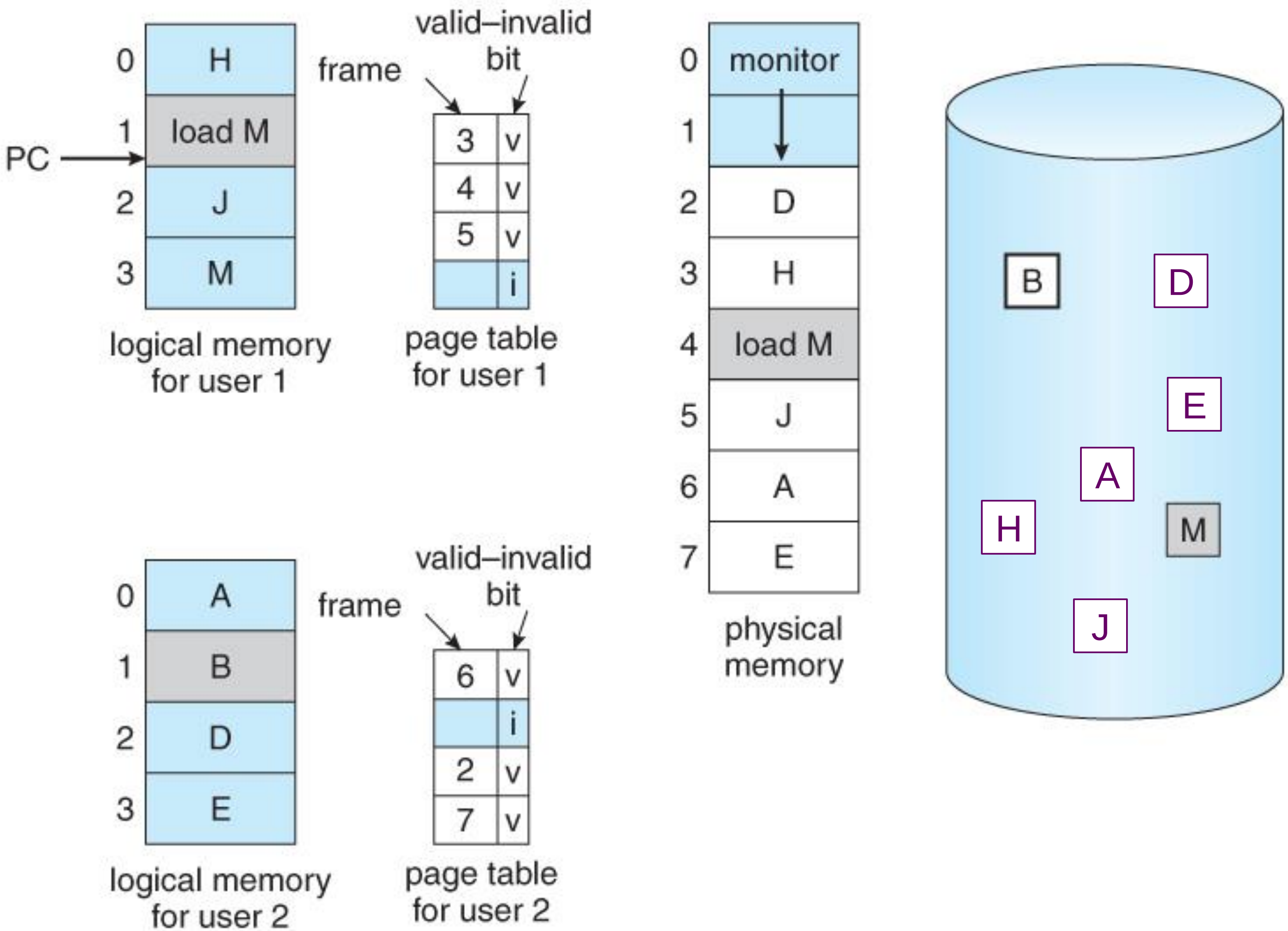
Page Replacement

- Prevent over-allocation of memory by modifying page-fault service routine to include page replacement.
- Use *modify* (*dirty*) *bit* to reduce the overhead of page transfers – only modified pages are written to disk.



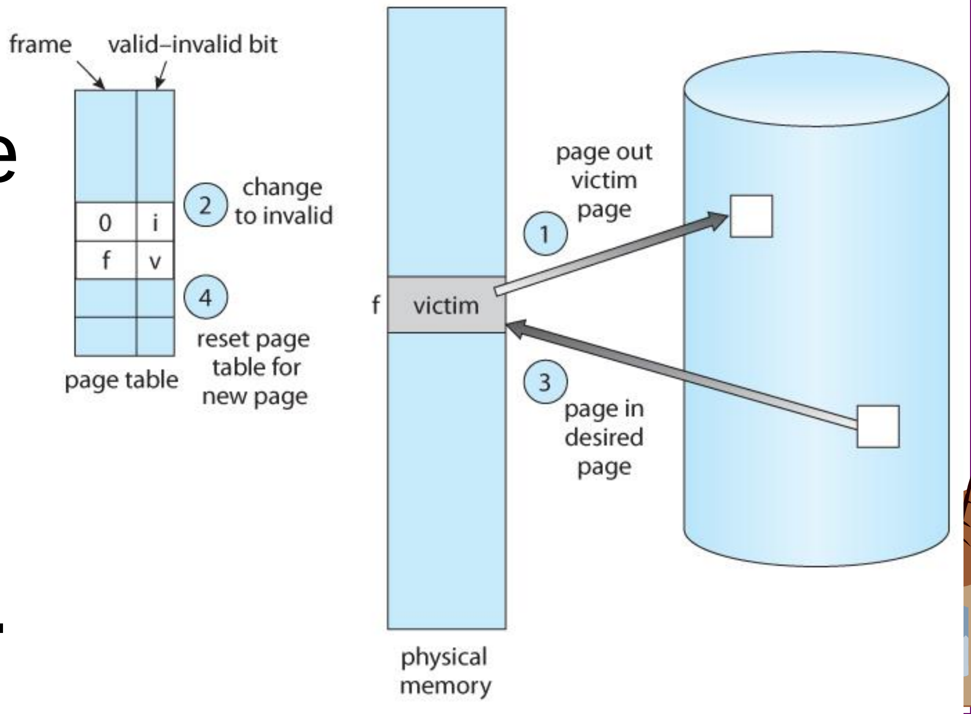
- Page replacement completes separation between logical memory and physical memory – large virtual memory can be provided on a smaller physical memory.

Need For 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 and swap it out
3. Read the desired page into the free frame.
4. Update the page and frame tables.
5. Restart the instruction.



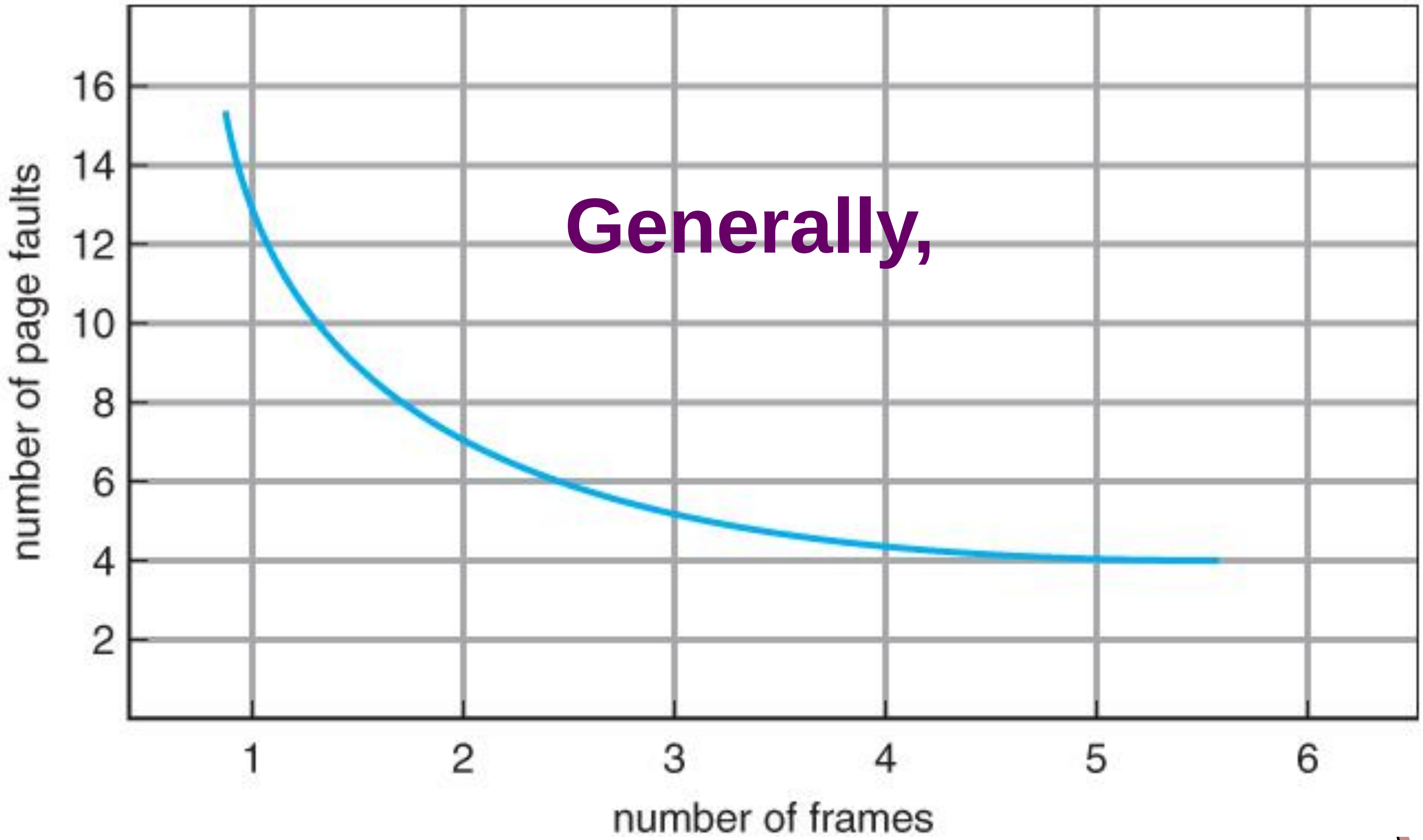
Page Replacement Algorithms

- Key objective: Want the lowest page-fault rate
- Evaluate algorithm by running it on a particular string of memory references (reference string) and computing the number of page faults.
- In all our examples, the reference string is

  1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5.

- See program trace files on my course web page
  - Address sequence recorded for a certain program
    - 0100, 0432, 0101, 0612, 0102, 0103, 0104, 0611, 0102, 0103, 0601, 0102, 0104, 0609, 0100, 0105
    - Page size = 100 $\Rightarrow$ reference string 1, 4, 1, 6, 1, 6, 1, 6, 1, 6, 1

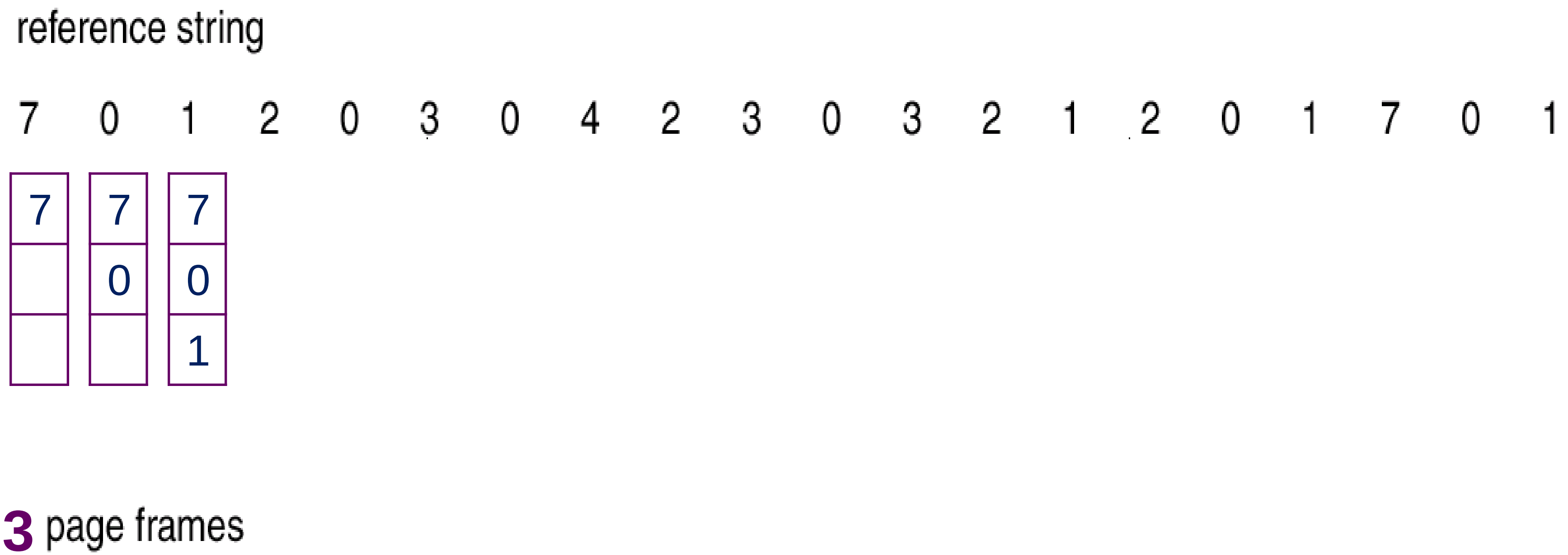
The Number of Page Faults vs. The Number of Frames



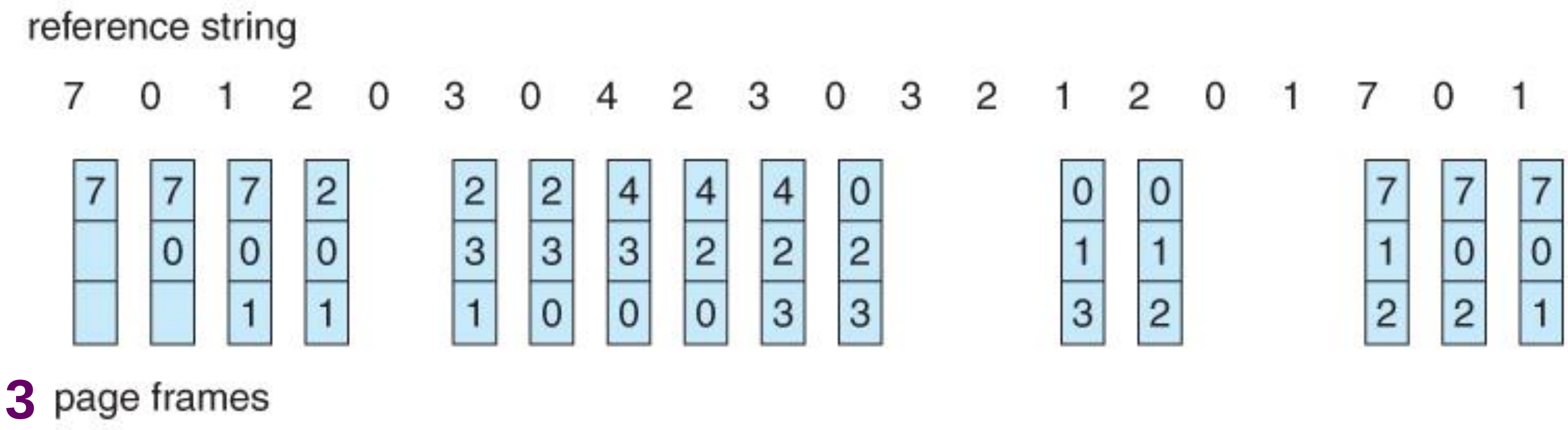
Generally,

First-In-First-Out (FIFO) Page Replacement

- Reference string: 7, 0, 1, 2, 0, 3, 0, 4, 2, 3, 0, 3, 2, 1, 2, 0, 1, 7, 0, 1
- 3 frames (3 pages can be in memory at a time per process)



FIFO Page Replacement



Belady's Anomaly for FIFO Algorithm

- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5
- In all our examples, the reference string is

  1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5.

- Where there are 3 frames (3 pages can be in memory at a time per process), 9 page faults. But when there are 4 frames, 10 page faults.

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

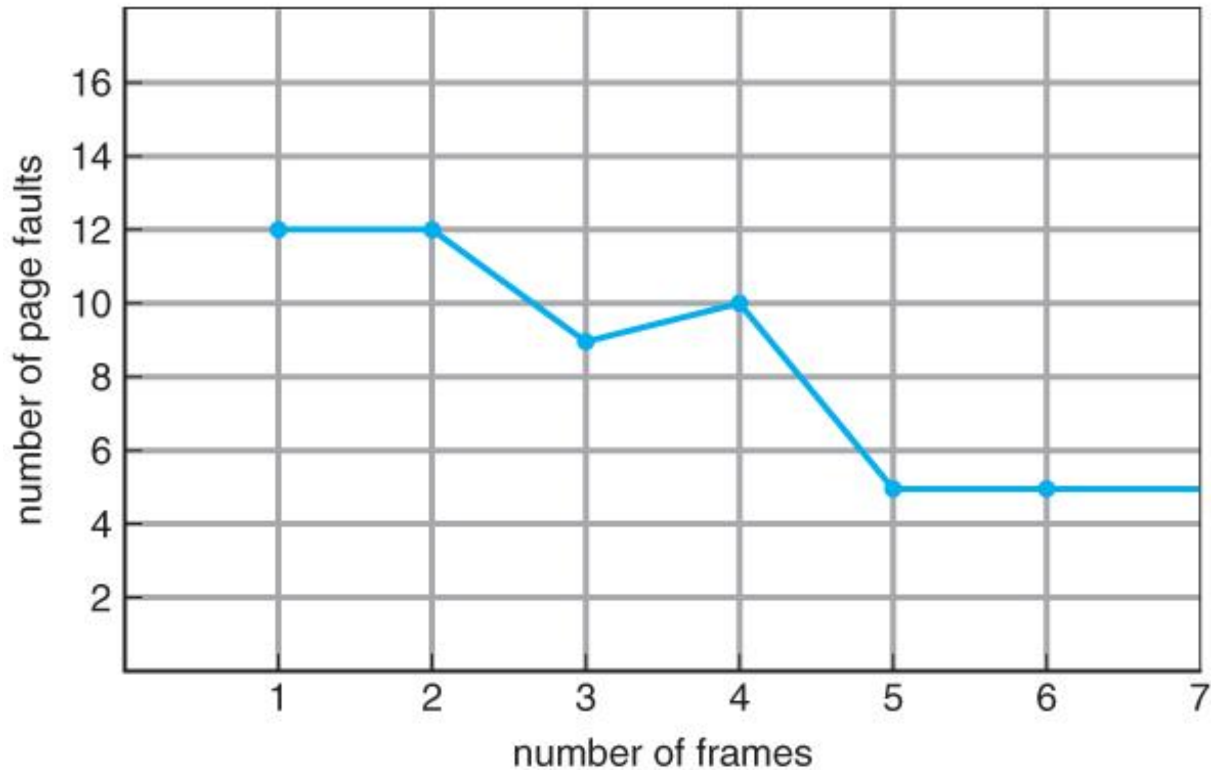
9 page faults

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

10 page faults

Belady's Anomaly for FIFO Algorithm

- FIFO Replacement – Belady's Anomaly
  - Supposedly, more frames $\Rightarrow$ less page faults
  - However, see the following illustration



Optimal Algorithm

- Replace the page that will not be used for the longest period of time in future.
- An example of allocating 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

FIFO Algorithm

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

10 page faults

Optimal Algorithm

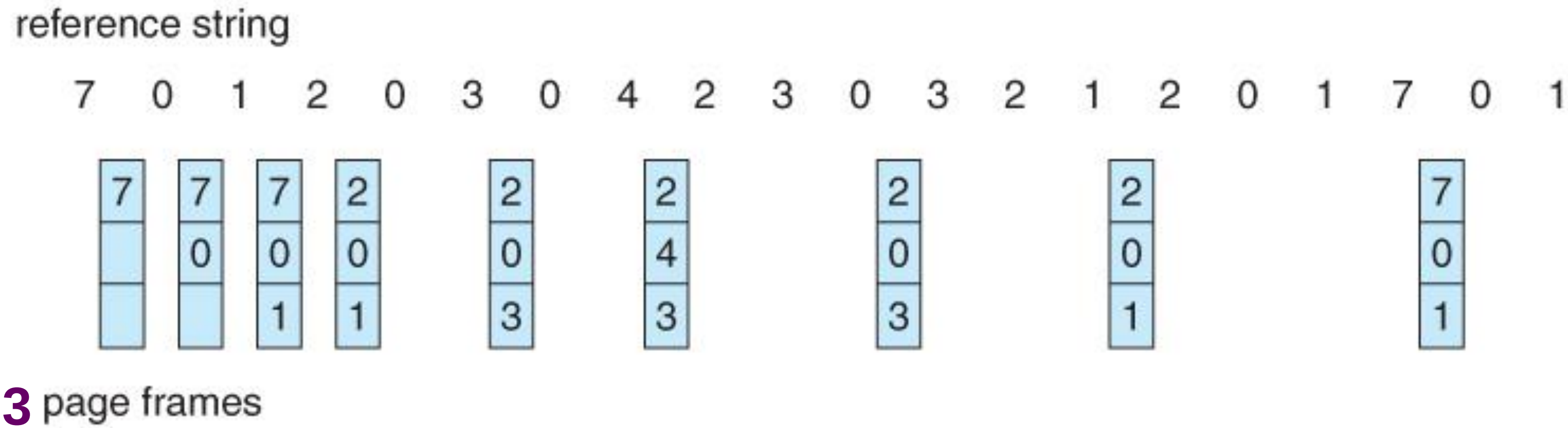
1	1	4
2	2	
3	3	
4	4	5

6 page faults

- Need to know the pattern of future memory accesses. So used only for measuring how well your page replacement algorithm performs.

Optimal Page Replacement

- Another example of allocating 3 frames



- Its idea is to replace the page that will not be used for the longest period of time in future.
- But how to know the future memory access pattern? Only the past history is known.

Least Recently Used (LRU) Algorithm

- Replace the page that is the least recently used.
- Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

Optimal Algorithm

1	1	4
2	2	
3	3	
4	4	5

6 page faults

LRU Algorithm

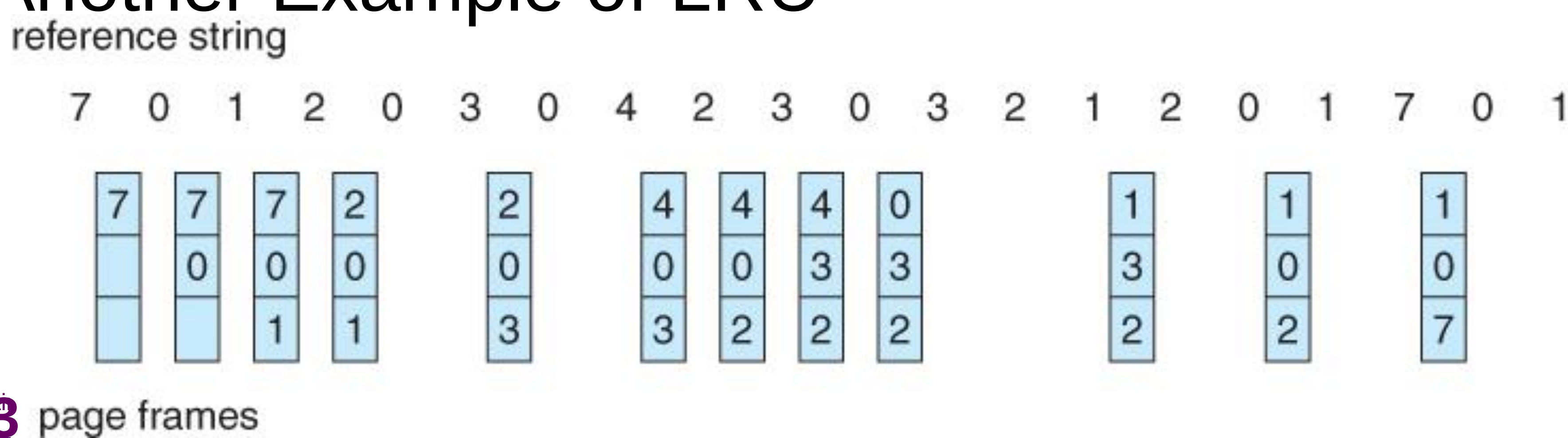
1	5
2	
3	5 4
4	3

8 page faults,

better than FIFO (10 faults) and

worse than the optimal (6 faults)

- Another Example of LRU



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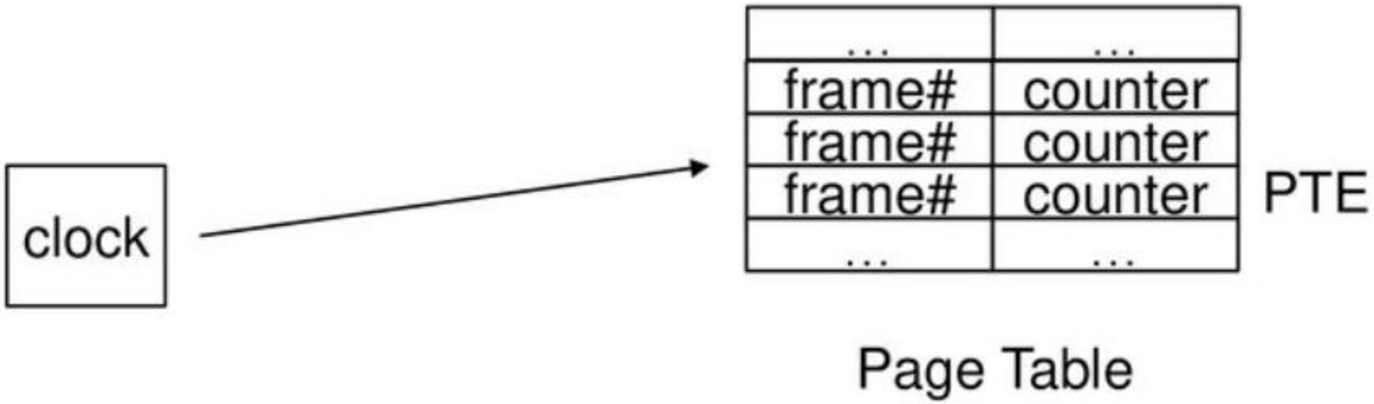
LRU Algorithm Implementations

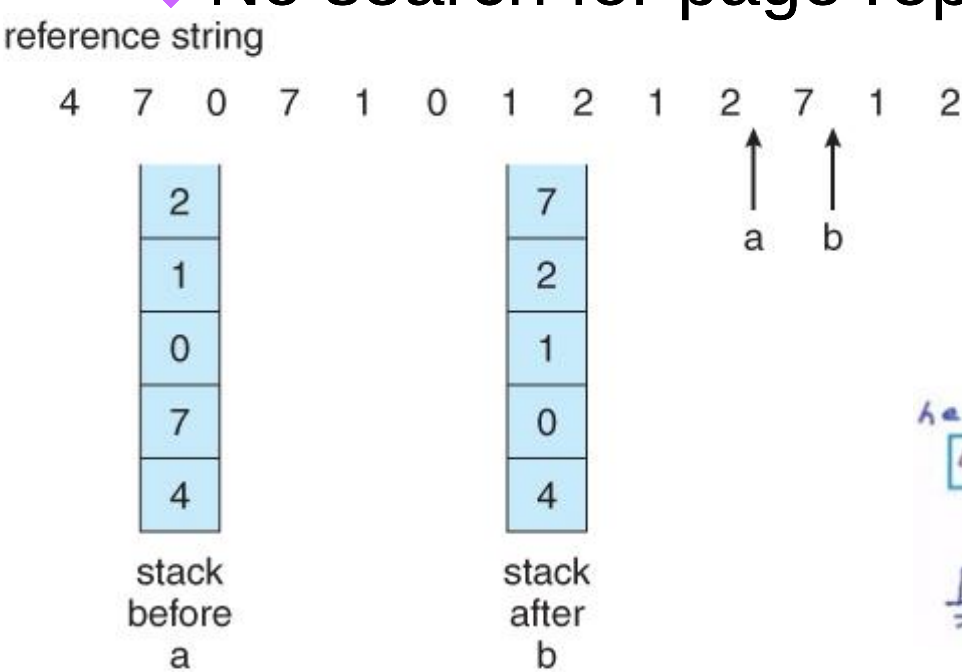
- Counter implementation
  - Every page entry has a counter; every time page is referenced through this entry, copy the clock into the counter.
  - When a page needs to be changed, look at the counters to determine which are to change.



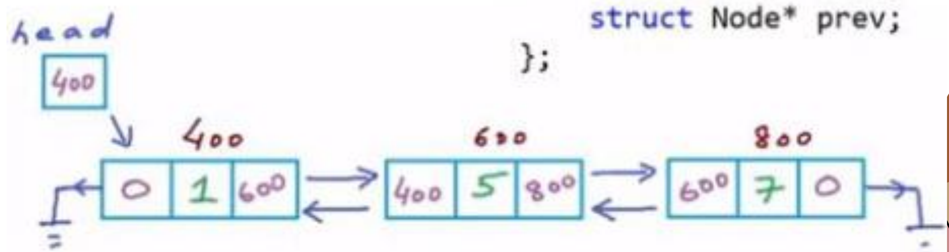
Use A Stack to Record The Most Recent Page References

- Stack implementation – keep a stack of page numbers in a doubly linked list:
  - When a page is referenced:
    - ✓move it to the top
    - ✓requires 6 pointers to be changed
  - No search for page replacement

访问特定页面号之后，调整栈里面顺序的计算复杂度是多少？ 是O(1)还是O(n)？假设n是栈里的页面个数。

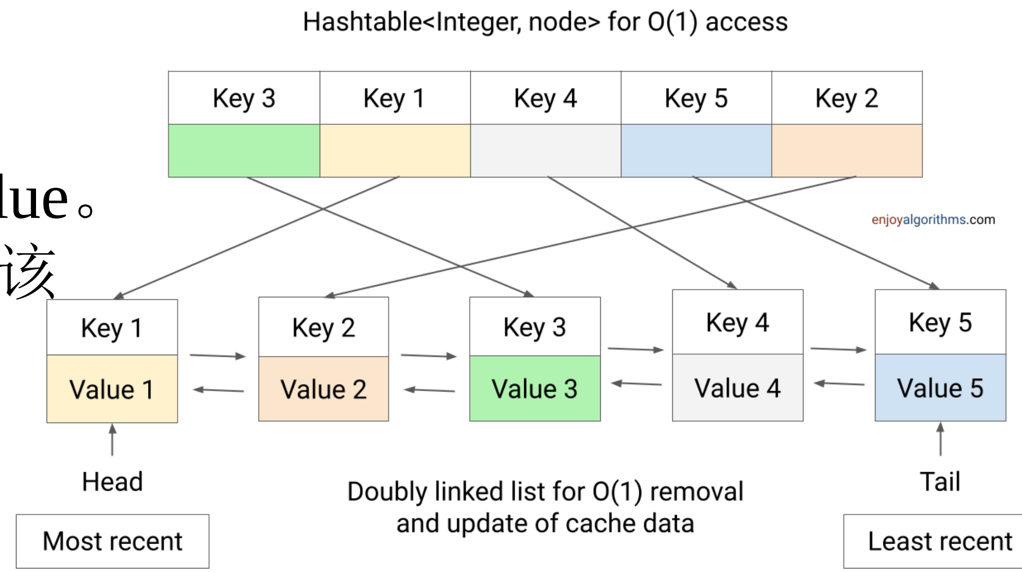



```
struct Node  {
      int data;
      struct Node* next;
      struct Node* prev;
};
```



设计和实现O(1)计算复杂度的 LRU 缓存机制的数据结构

- 问题：设计和实现一个 LRU（最近最少使用）的键值对缓存结构，支持 get 和 put 操作，要求O(1)复杂度
  - get(key) - 如果 key 存在于缓存中，则获取 key 的 value（总是正数），否则返回 -1。
  - put(key, value) - 如果 key 不存在，请设置或插入value。当缓存达到容量时，它应该在插入新项目之前使最近最少使用的项目作废



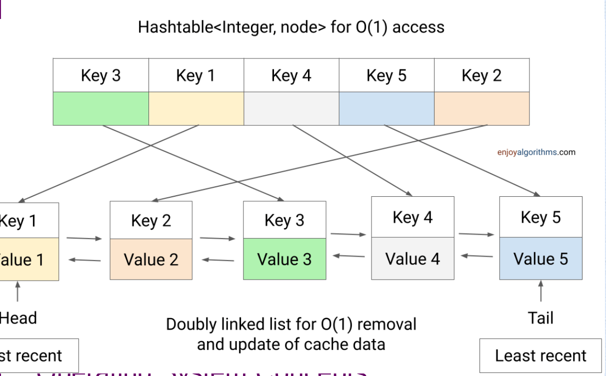
- 分析：
  - 需要使用的数据结构是哈希表（Hash Table）。基础的哈希表虽具备读写 key-value 数据的功能，但是 key 的存储是无序的。
  - 而本题中当 LRU 存满且存储新key时，需要删除掉最久未使用的旧key。
  - 所以，用哈希表和链表两个数据结构。当进行 set & get 操作时，只需把当前节点调整到链表头部，而需要 pop 操作的时候，将链表尾部弹出。

关于LRU算法的动手小实验

- 该O(1)复杂度的LRU问题来自于leetcode：https://leetcode.com/problems/lru-cache
- 一个可能解法来自Github网站 https://github.com/lamerman/cpp-lru-cache
- 请用git clone同步该项目到本地，并把该代码仓库编译运行起来。
  - 提示：该代码需要gcc和cmake工具链编译。由于引用了单元测试框架googletest，需要命令行下的梯子代理才能解决googletest的下载问题

- 请问这段代码中这个iterator是什么作用？

- 分析get和put方法的算法复杂度




```cpp
class lru_cache {
public:
    typedef typename std::pair<key_t, value_t> key_value_pair_t;
    typedef typename std::list<key_value_pair_t>::iterator list_iterator_t;

    lru_cache(size_t max_size) :
        _max_size(max_size) {
    }

    void put(const key_t& key, const value_t& value) {
        auto it = _cache_items_map.find(key);
        _cache_items_list.push_front(key_value_pair_t(key, value));
        if (it != _cache_items_map.end()) {
            _cache_items_list.erase(it->second);
            _cache_items_map.erase(it);
        }
        _cache_items_map[key] = _cache_items_list.begin();

        if (_cache_items_map.size() > _max_size) {
            auto last = _cache_items_list.end();
            last--;
            _cache_items_map.erase(last->first);
            _cache_items_list.pop_back();
        }
    }

    const value_t& get(const key_t& key) {
        auto it = _cache_items_map.find(key);
        if (it == _cache_items_map.end()) {
            throw std::range_error("There is no such key in cache");
        } else {
            _cache_items_list.splice(_cache_items_list.begin(), _cache_items_list, it->second);
            return it->second->second;
        }
    }

    bool exists(const key_t& key) const {
        return _cache_items_map.find(key) != _cache_items_map.end();
    }

    size_t size() const {
        return _cache_items_map.size();
    }

private:
    std::list<key_value_pair_t> _cache_items_list;
    std::unordered_map<key_t, list_iterator_t> _cache_items_map;
    size_t _max_size;
```

- 这段代码中的put方法任何情况都首先push_front。
- 最后的if语句中再判断是或否缓存溢出；如果是，则移除lru项目。
- 尝试将put代码逻辑修改：首先判断key是否存在；存在则更新其val并返回。下一步插入新的<key, val>对。先判断缓存是否已满；如果是，则移除lru项目腾出空间给新的键值对。

```cpp
class lru_cache {
public:
    typedef typename std::pair<key_t, value_t> key_value_pair_t;
    typedef typename std::list<key_value_pair_t>::iterator list_iterator_t;

    lru_cache(size_t max_size) :
        _max_size(max_size) {
    }

    void put(const key_t& key, const value_t& value) {
        auto it = _cache_items_map.find(key);
        _cache_items_list.push_front(key_value_pair_t(key, value));
        if (it != _cache_items_map.end()) {
            _cache_items_list.erase(it->second);
            _cache_items_map.erase(it);
        }
        _cache_items_map[key] = _cache_items_list.begin();

        if (_cache_items_map.size() > _max_size) {
            auto last = _cache_items_list.end();
            last--;
            _cache_items_map.erase(last->first);
            _cache_items_list.pop_back();
        }
    }

    const value_t& get(const key_t& key) {
        auto it = _cache_items_map.find(key);
        if (it == _cache_items_map.end()) {
            throw std::range_error("There is no such key in cache");
        } else {
            _cache_items_list.splice(_cache_items_list.begin(), _cache_items_list, it->second);
            return it->second->second;
        }
    }

    bool exists(const key_t& key) const {
        return _cache_items_map.find(key) != _cache_items_map.end();
    }

    size_t size() const {
        return _cache_items_map.size();
    }

private:
    std::list<key_value_pair_t> _cache_items_list;
    std::unordered_map<key_t, list_iterator_t> _cache_items_map;
    size_t _max_size;
```

LRU代码的改进方法

- 如果map中找不到的key，代码不用改变；如果map中找到该key，首先将结点的value赋予新值，然后使用splice函数将结点移动到链表头。

```
void put(const key_t& key, const value_t& value) {
    auto it = _cache_items_map.find(key);
    if (it != _cache_items_map.end()) {
        it->second->second = value;
        _cache_items_list.splice(_cache_items_list.begin(), _cache_items_list, it->second);
    }
    else{
        _cache_items_list.push_front(key_value_pair_t(key, value));
    }
    _cache_items_map[key] = _cache_items_list.begin();

    if (_cache_items_map.size() > _max_size) {
        auto last = _cache_items_list.end();
        last--;
        _cache_items_map.erase(last->first);
        _cache_items_list.pop_back();
    }
}
```

Problems of Previous LRU Implementations

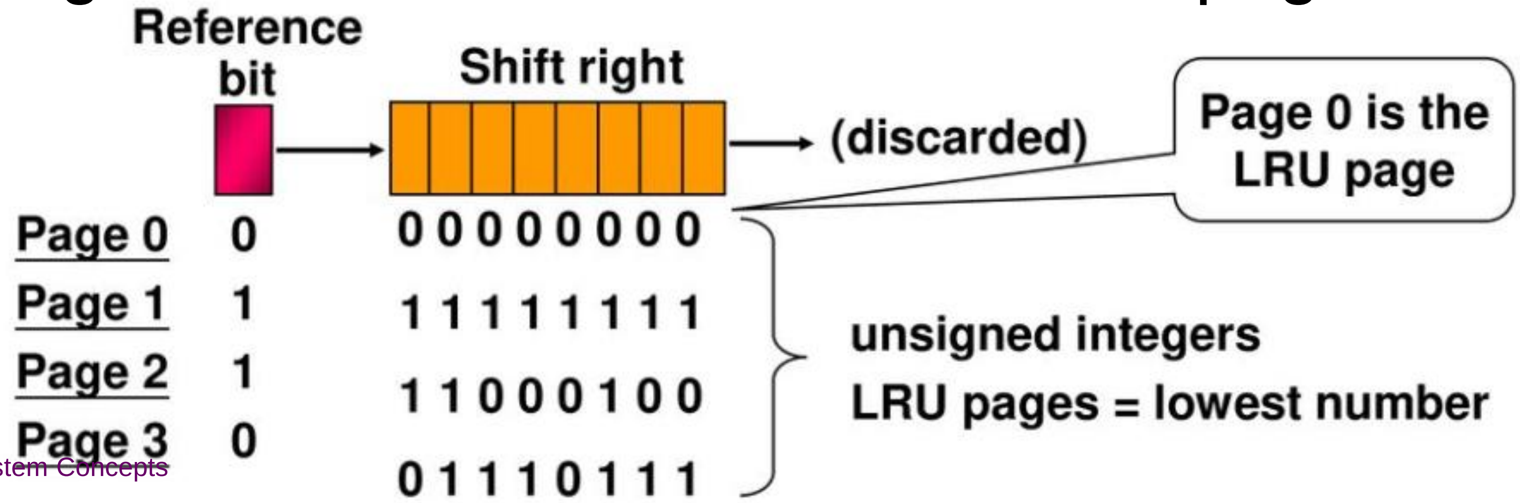
- As to the previous two LRU implementations,
  - Clock: Every page entry has a counter; every time page is referenced through this entry, copy the clock into the counter.
  - Stack: Whenever a page is referenced, it is removed from the stack and put on the top.
- The updating of the clock fields or stack must be done for every memory reference
- Would slow every memory access by a factor of at least ten

LRU Approximation Algorithms

- Reference bit per page (Hardware maintained)
  - Each page is associated with a bit in the page table
  - Initially 0; When page is referenced, set the bit to 1.
  - Replace the one which is 0 (if one exists)
- However, we do not know the order of use.
- This information is the basis for many page-replacement algorithms that approximate LRU replacement

LRU Approximation Algorithms

- Idea: Gain additional ordering information by recording the reference bits at regular intervals
- Additional-Reference-Bits Algorithm
  - Keep an 8-bit bytes for each page in main memory
  - At regular intervals, shifts the bits right 1 bit, shift the reference bit into the lower-order bit
  - Interpret these 8-bit bytes as unsigned integers, the page with lowest number is the LRU page



An Example of Additional-Reference-Bits Algorithm (1)

- Assume the following page reference string, where T marks the end of each time interval: 3, 2, 3, T, 8, 0, 3, T, 3, 0, 2, T, 6, 3, 4, 7
- Assume there are 5 frames in memory, and each frame has a Page field (P) and 4 used bits (U3, U2, U1, and U0).
- Initial State

P	U3	U2	U1	U0
–	0	0	0	0
–	0	0	0	0
–	0	0	0	0
–	0	0	0	0
–	0	0	0	0

An Example of Additional-Reference-Bits Algorithm (2)

- Assume the following page reference string: 3, 2, 3, T, 8, 0, 3, T, 3, 0, 2, T, 6, 3, 4, 7
- During the first time interval, pages 3, 2, and 3 are referenced.

P	U3	U2	U1	U0
3	1	0	0	0
2	1	0	0	0
–	0	0	0	0
–	0	0	0	0
–	0	0	0	0

P	U3	U2	U1	U0
3	0	1	0	0
2	0	1	0	0
–	0	0	0	0
–	0	0	0	0
–	0	0	0	0

- At the end of the first time interval, all U bits are shifted right one position.

An Example of Additional-Reference-Bits Algorithm (3)

- Assume the following page reference string: 3, 2, 3, T, 8, 0, 3, T, 3, 0, 2, T, 6, 3, 4, 7
- During the second time interval, pages 8, 0, and 3 are referenced.

P	U3	U2	U1	U0
3	1	1	0	0
2	0	1	0	0
8	1	0	0	0
0	1	0	0	0
–	0	0	0	0

P	U3	U2	U1	U0
3	0	1	1	0
2	0	0	1	0
8	0	1	0	0
0	0	1	0	0
–	0	0	0	0

- At the end of the second time interval, all U bits are shifted right one position.

An Example of Additional-Reference-Bits Algorithm (4)

- Assume the following page reference string: 3, 2, 3, T, 8, 0, 3, T, 3, 0, 2, T, 6, 3, 4, 7
- During the third time interval, pages 3, 0, and 2 are referenced.

P	U3	U2	U1	U0
3	1	1	1	0
2	1	0	1	0
8	0	1	0	0
0	1	1	0	0
–	0	0	0	0

→

P	U3	U2	U1	U0
3	0	1	1	1
2	0	1	0	1
8	0	0	1	0
0	0	1	1	0
–	0	0	0	0

- At the end of the third time interval, all U bits are shifted right one position.

An Example of Additional-Reference-Bits Algorithm (5)

- Assume the following page reference string: 3, 2, 3, T, 8, 0, 3, T, 3, 0, 2, T, 6, 3, 4, 7
- During the fourth time interval, pages 6, 3, 4, and 7 are referenced.

P	U3	U2	U1	U0
3	1	1	1	1
2	0	1	0	1
8	**0**	**0**	**1**	**0**
0	0	1	1	0
6	1	0	0	0

→

P	U3	U2	U1	U0
3	1	1	1	1
2	0	1	0	1
4	**1**	**0**	**0**	**0**
0	0	1	1	0
6	1	0	0	0

After pages 6, 3, 4 are referenced,
page 8 has been replaced by 4

http://www2.cs.uregina.ca/~hamilton/courses/330/notes/memory/page_replacement.html

An Example of Additional-Reference-Bits Algorithm (6)

- Assume the following page reference string: 3, 2, 3, T, 8, 0, 3, T, 3, 0, 2, T, 6, 3, 4, 7
- During the fourth time interval, pages 6, 3, 4, and 7 are referenced.

P	U3	U2	U1	U0
3	1	1	1	1
2	**0**	**1**	**0**	**1**
4	1	0	0	0
0	0	1	1	0
6	1	0	0	0

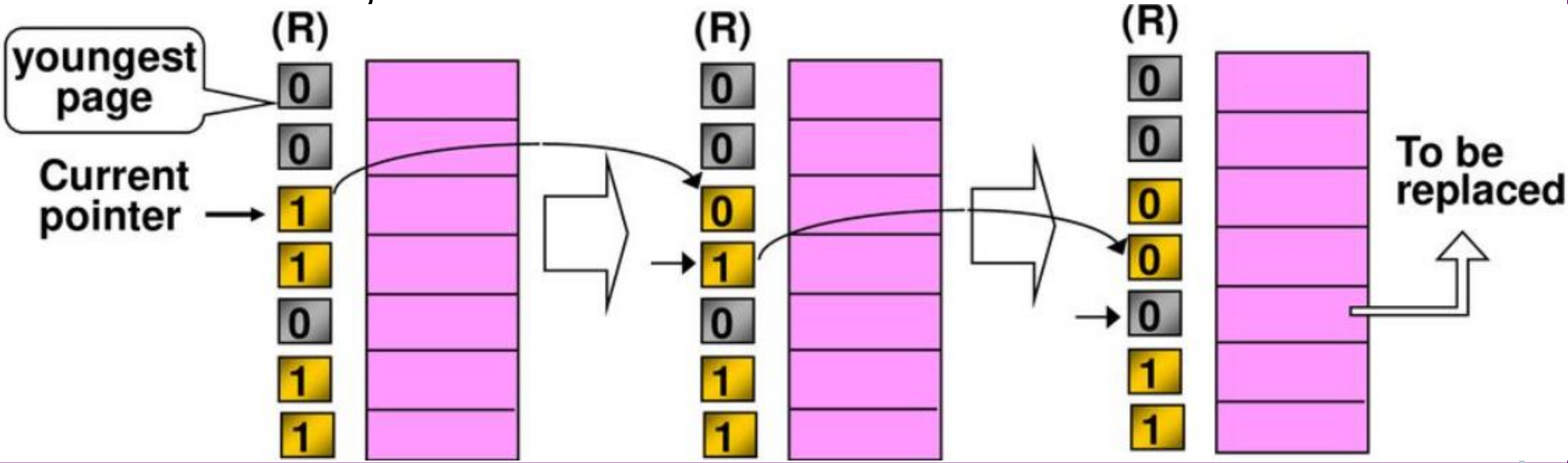
P	U3	U2	U1	U0
3	1	1	1	1
7	**1**	**0**	**0**	**0**
4	1	0	0	0
0	0	1	1	0
6	1	0	0	0

After page 7 is referenced, page 2 has been replaced by 7

http://www2.cs.uregina.ca/~hamilton/courses/330/notes/memory/page_replacement.html

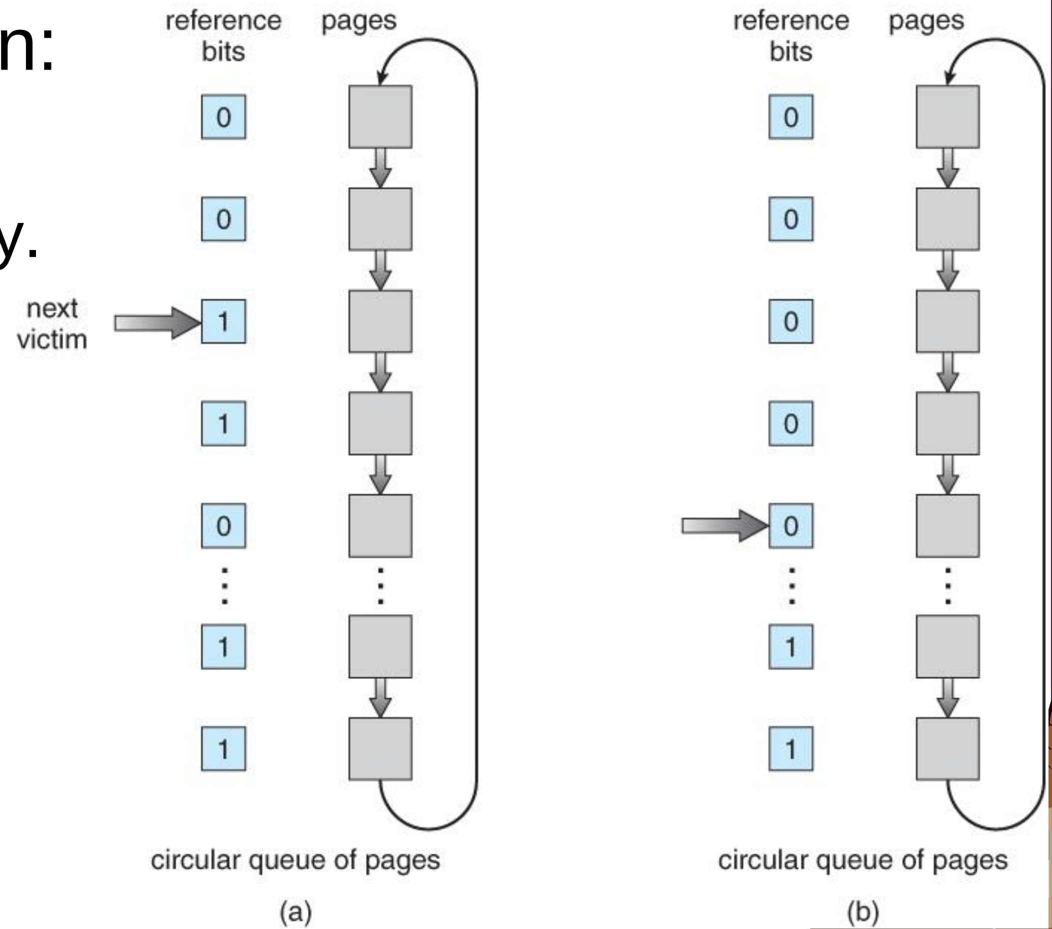
LRU Approximation Algorithms

- Second-Chance Algorithm (FIFO+reference bit)
  - When a page has been selected for replacement, we inspect its reference bit.
  - If the value is 0, we proceed to replace this page;
  - If the reference bit is set to 1, give the page a second chance and move on to pick the next FIFO page.
  - When a page gets a second chance, its reference bit is cleared, and its arrival time is reset to current time.



LRU Approximation Algorithms

- Second-Chance Algorithm (clock+reference bit)
  - Given a circular queue, called clock
  - If page to be replaced (in clock order) has reference bit = 1, then:
    - ✓ set reference bit 0.
    - ✓ leave page in memory.
    - ✓ replace next page (in clock order), subject to same rules.



Counting Algorithms

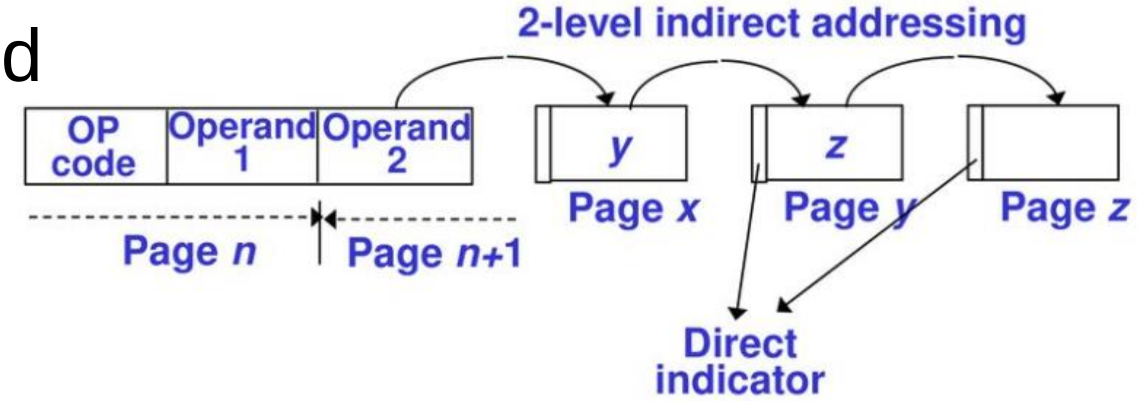
- Keep a counter of the number of references that have been made to each page.
- **Least Frequently Used (LFU) Algorithm**: replaces page with the smallest count.
- **Most Frequently Used (MFU) Algorithm**: based on the argument that the page with the smallest count was probably just brought in and has yet to be used.

Chapter 9: Virtual Memory

- Background
- Demand Paging
- Copy-on-Write
- Page Replacement within a Process
- Allocation of Frames among Processes
- Thrashing and Working Set Model
- Memory-Mapped Files
- Allocating Kernel Memory
- Other Considerations
- Operating-System Examples

Allocation of Frames among Processes

- Each process needs a **minimum** number of pages.
- 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**.
- If n-level indirect addressing is allowed
  - n+1 frame needed



Fixed Allocation

- Two major allocation schemes.
  - fixed allocation
  - priority allocation
- Equal allocation – e.g., if 100 frames and 5 processes, give each process 20 pages.
- Proportional allocation – Allocate pages to a process according to the size of the process.

$$s_i = \text{size of process } p_i$$

$$S = \sum s_i$$

$$m = \text{total number of frames}$$

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

$$m = 64$$

$$s_1 = 10$$

$$s_2 = 127$$

$$a_1 = \frac{10}{137} \times 64 \approx 5$$

$$a_2 = \frac{127}{137} \times 64 \approx 59$$

Priority Allocation

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

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.

- **Local** replacement – each process selects from only its own set of allocated frames.

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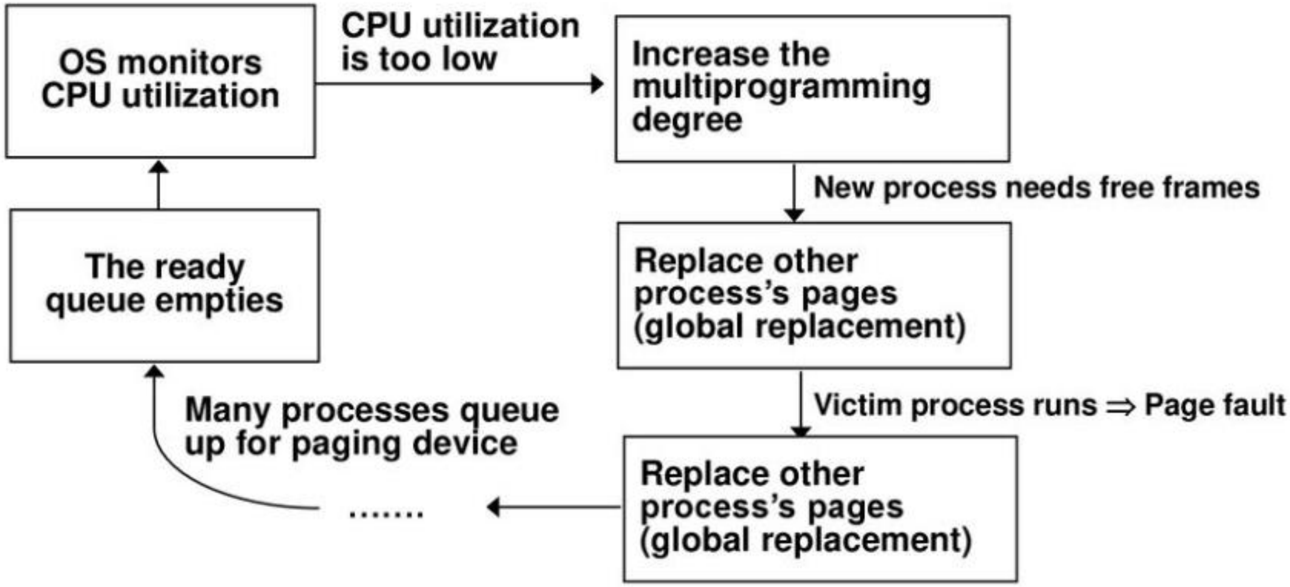
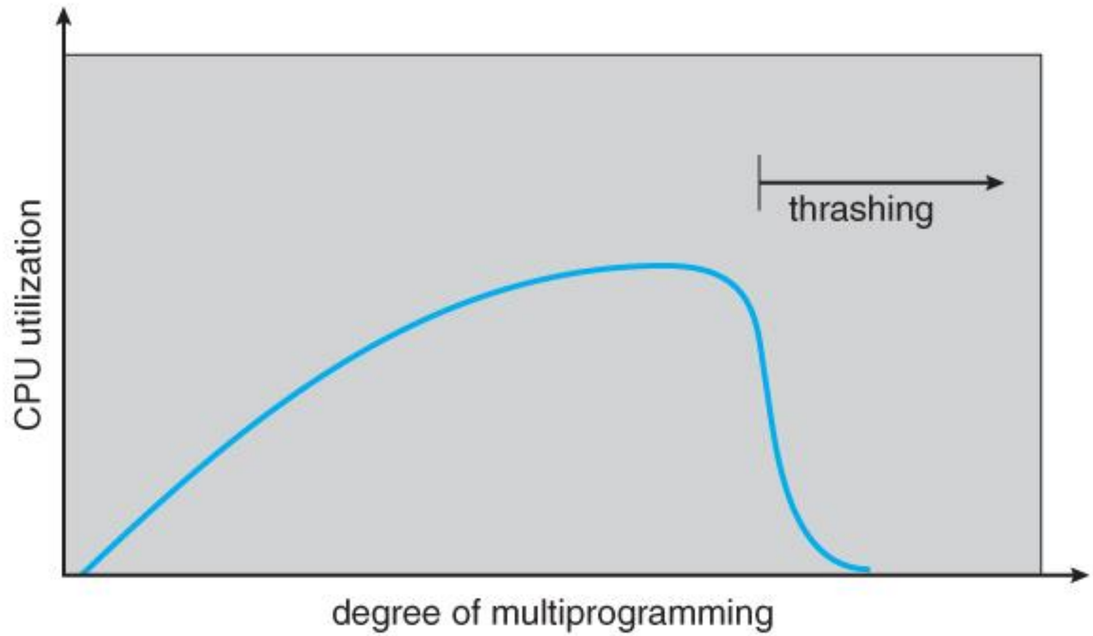
Thrashing

- If a process does not have "enough" frames, the page-fault rate is very high. This leads to:
  - low CPU utilization.
  - operating system thinks that it needs to increase the degree of multiprogramming.
  - another process added to the system.
- **Thrashing** ≡ a process is busy swapping pages in and out.



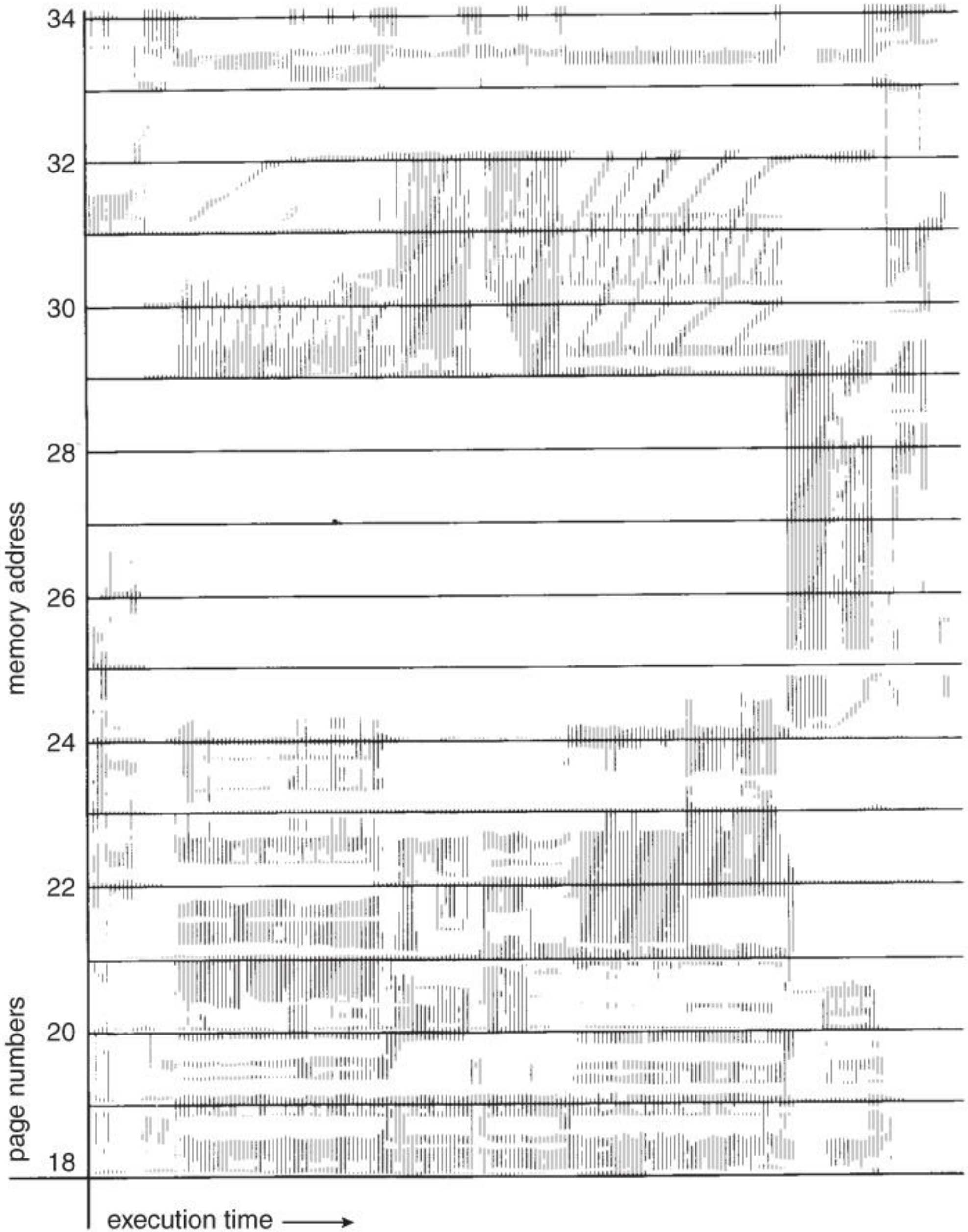
Thrashing

- Why does paging work?
  Locality model
  - Process migrates from one locality to another.
  - Localities may overlap.
- Why does thrashing occur?
  Σ size of locality > total physical memory size



Locality In Memory-Reference Pattern

Locality in a memory-reference pattern



Working-Set Model

- The pages used by a process within a window of time are called its working set
  - Δ ≡ size of working-set window ≡ a fixed number of page references. Example: 10000 instructions
- The working-set model is based on the assumption of locality

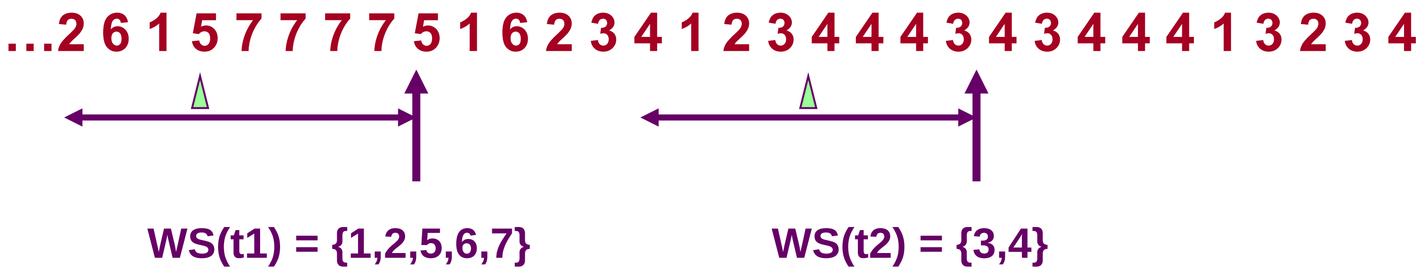
…2 6 1 5 7 7 7 7 5 1 6 2 3 4 1 2 3 4 4 4 3 4 3 4 4 4 1 3 2 3 4

WS(t1) = {1,2,5,6,7} **WS(t2) = {3,4}**

- Changes continuously - hard to maintain an accurate number
- How can the system use this number to give optimum memory to the process?

Working-Set Model (cont.)

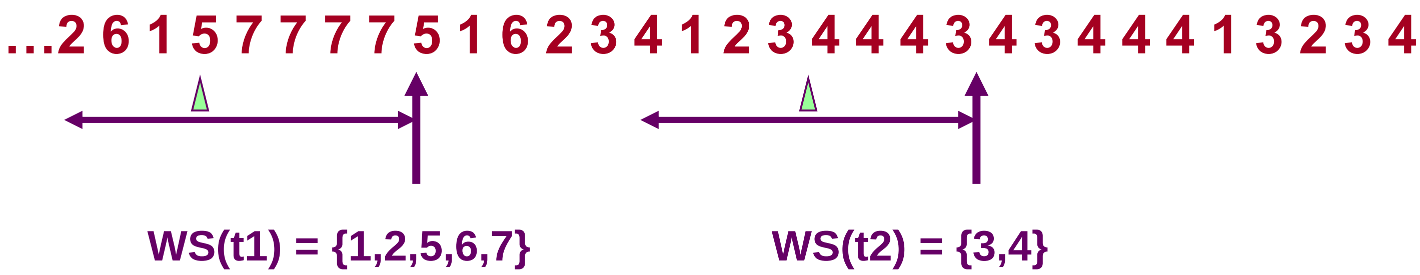
- Δ defines the size of working set window
  - If a page is in active use, it will be in the working set
  - If it is not in the use, it will be dropped from the working set



- Working-set is the approximation of the program's locality
- The accuracy of the working set depends on the selection of the Δ

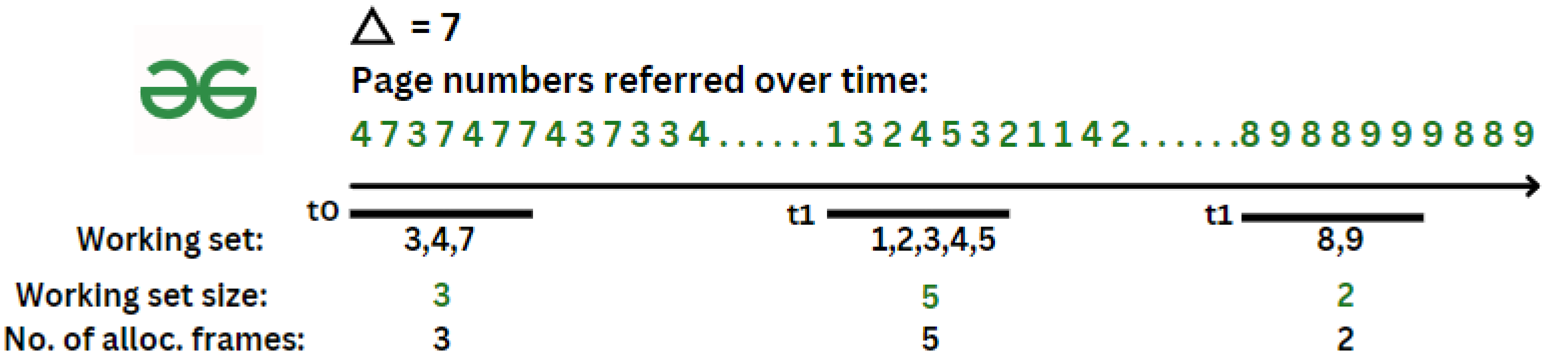
Working-Set Model (cont.)

- Important property of the working set is the size
- Compute working set size for each process P_i in the system, i.e., WSS_i
- WSS_i (working set of process P_i) = total number of pages referenced in the most recent Δ (varies in time)
  - if Δ = ∞, the window will cover the entire program.
  - if Δ too small, it will not encompass entire locality.
  - if Δ too large, it will encompass several localities.



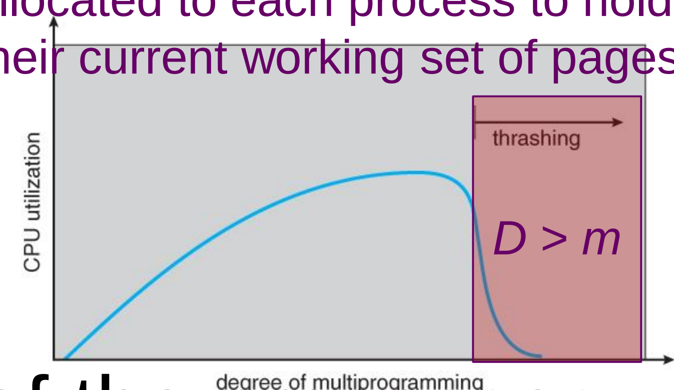
Working-Set Model (cont.)

- The operating system monitors the working-set WSS_i of each process P_i, and allocates them enough frames



- if $D > m \Rightarrow$ Thrashing.
  - $D = \Sigma\ WSS_i \equiv$ total demand in number of frames
  - m $\equiv$ total physical memory size

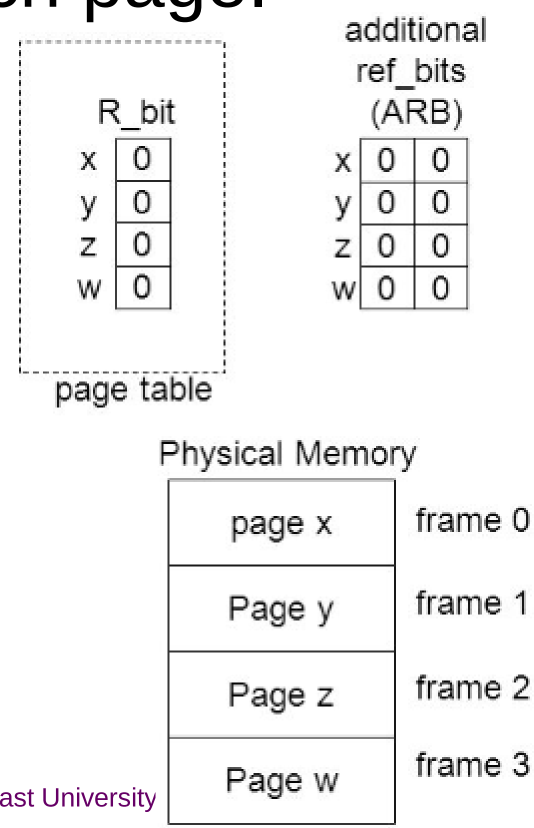
so many processes in memory that not enough page frames are allocated to each process to hold their current working set of pages



- Policy: if D>m, suspend one of the processes.

Keeping Track of the Working Set WSS_i

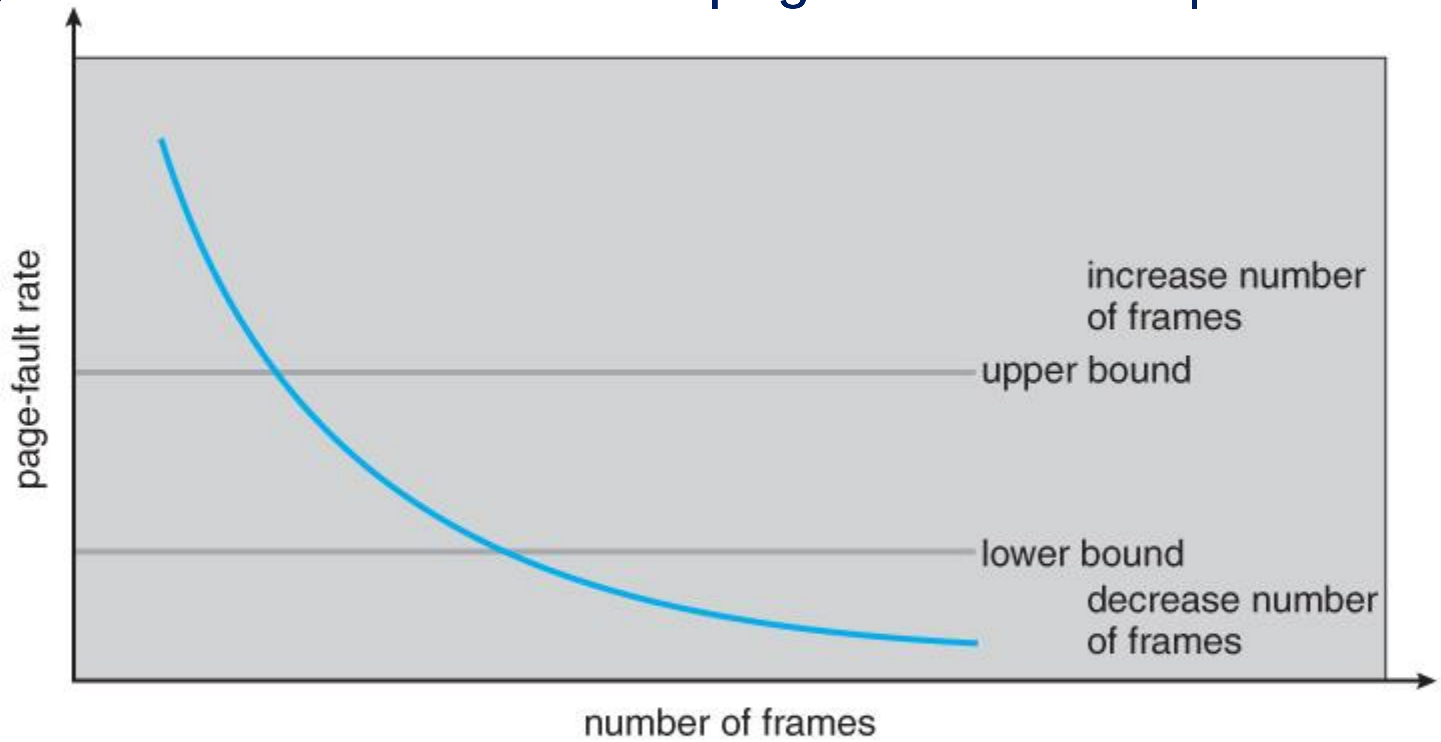
- Approximate with interval timer + a reference bit
- Example: Δ = 10,000
  - Timer interrupts after every T=5,000 time units.
  - Keep in memory Δ/T=2 bits for each page.
  - Whenever a timer interrupts, copy and set the values of reference bits of all pages to 0.
  - If any one of the bits in memory = 1 $\Rightarrow$ page in working set.



- Improvement: interrupt every T=1,000 time units, and keep Δ/T=10 bits for each page

Page-Fault Frequency Scheme

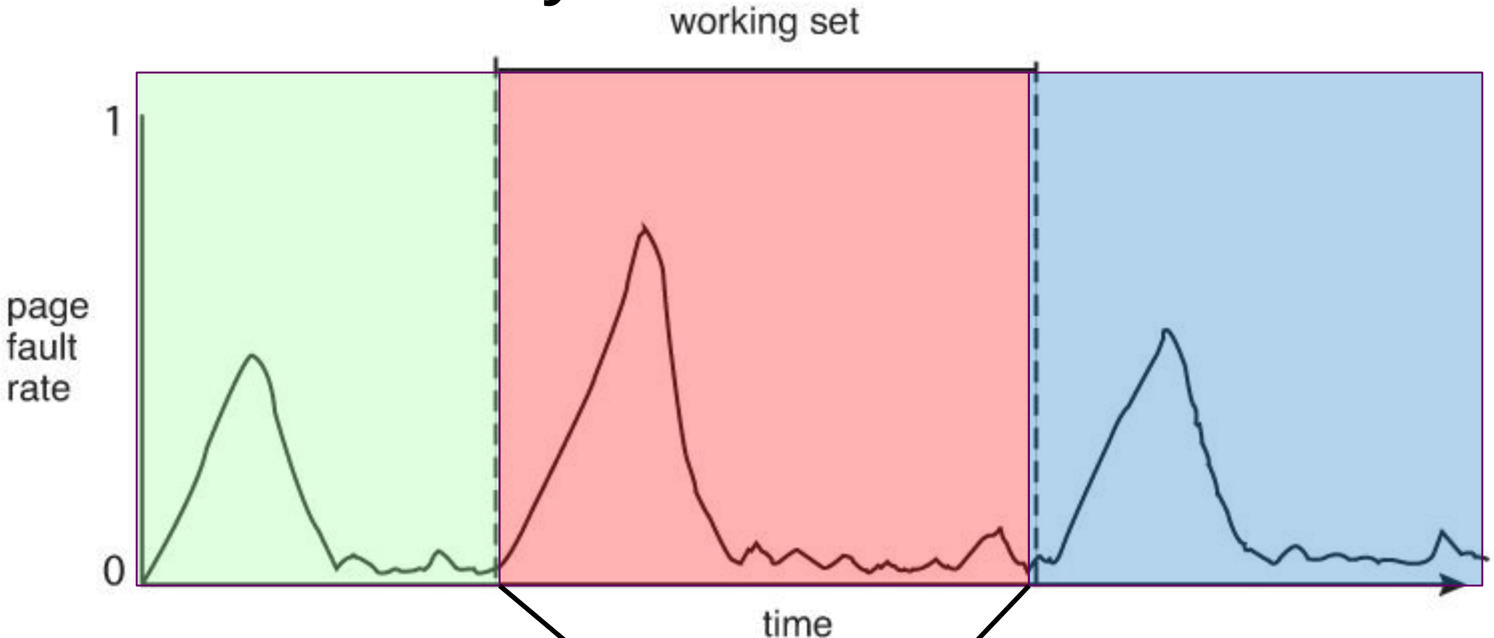
Directly measure and control the page-fault rate to prevent thrashing



- Establish “acceptable” page-fault rate.
  - If actual rate is too low, process loses frame.
  - If actual rate is too high, process gains frame.

Working Sets and Page Fault Rates

- Direct relationship between working set of a process and its page-fault rate
- Working set changes over time
- Peaks and valleys over time



Transition from one working set to another

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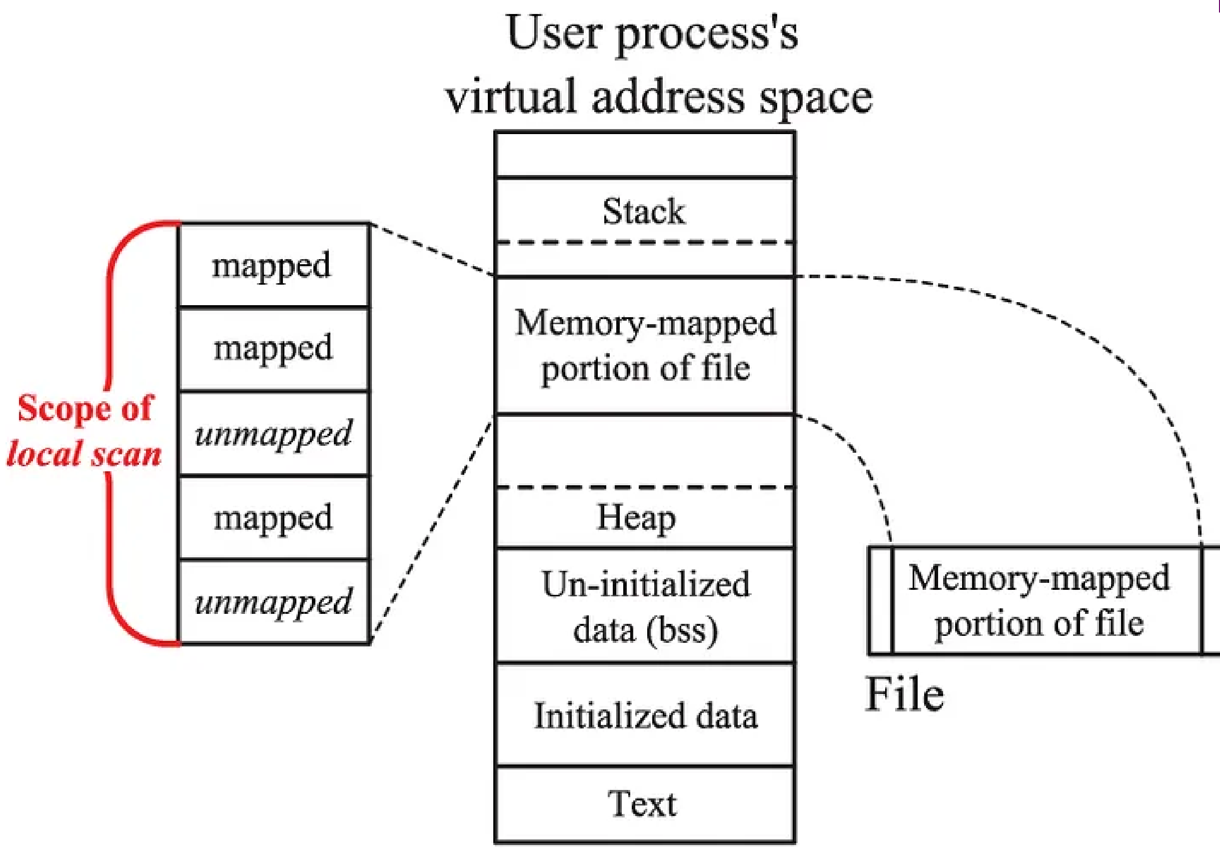
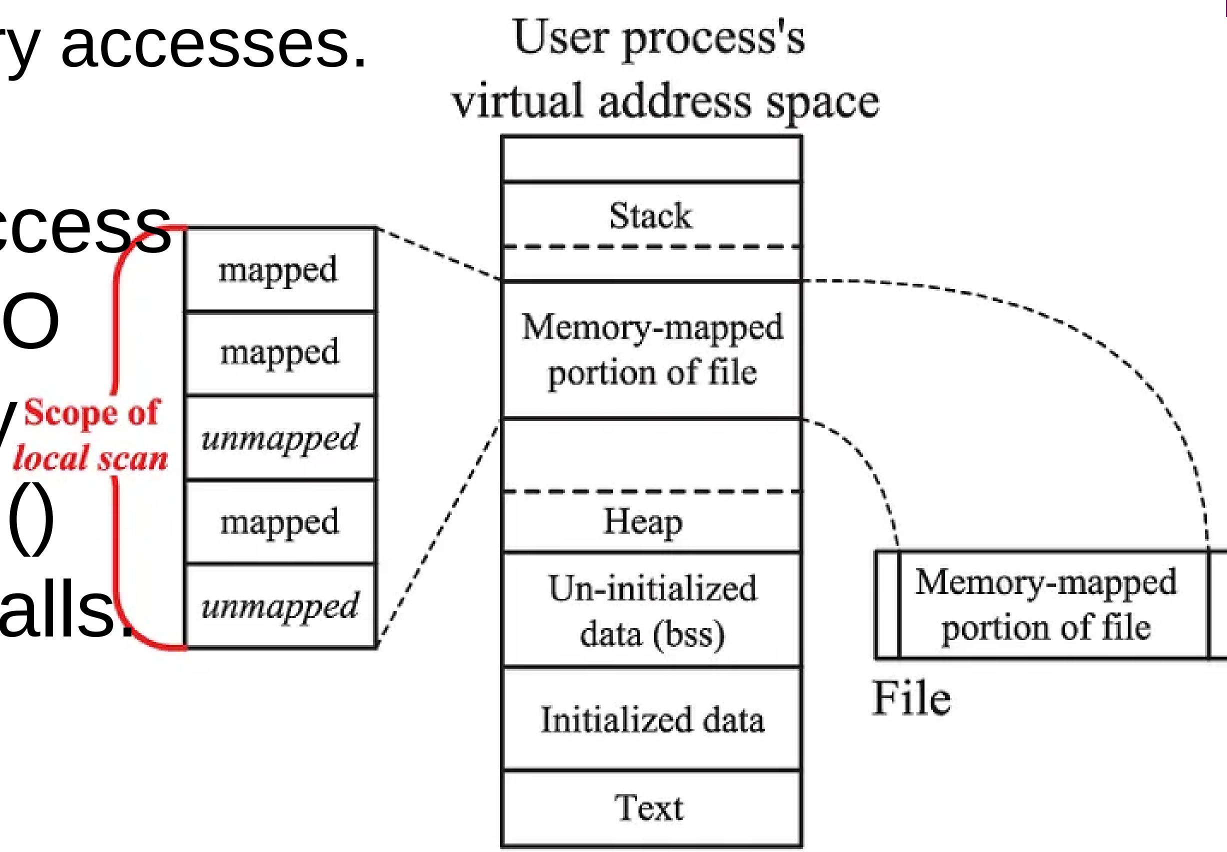
Memory-Mapped Files

- Memory-mapped file I/O allows a part of virtual address space to be logically associate with a file
  - File I/O to be treated as routine memory access by *mapping* a disk block to a page in memory.



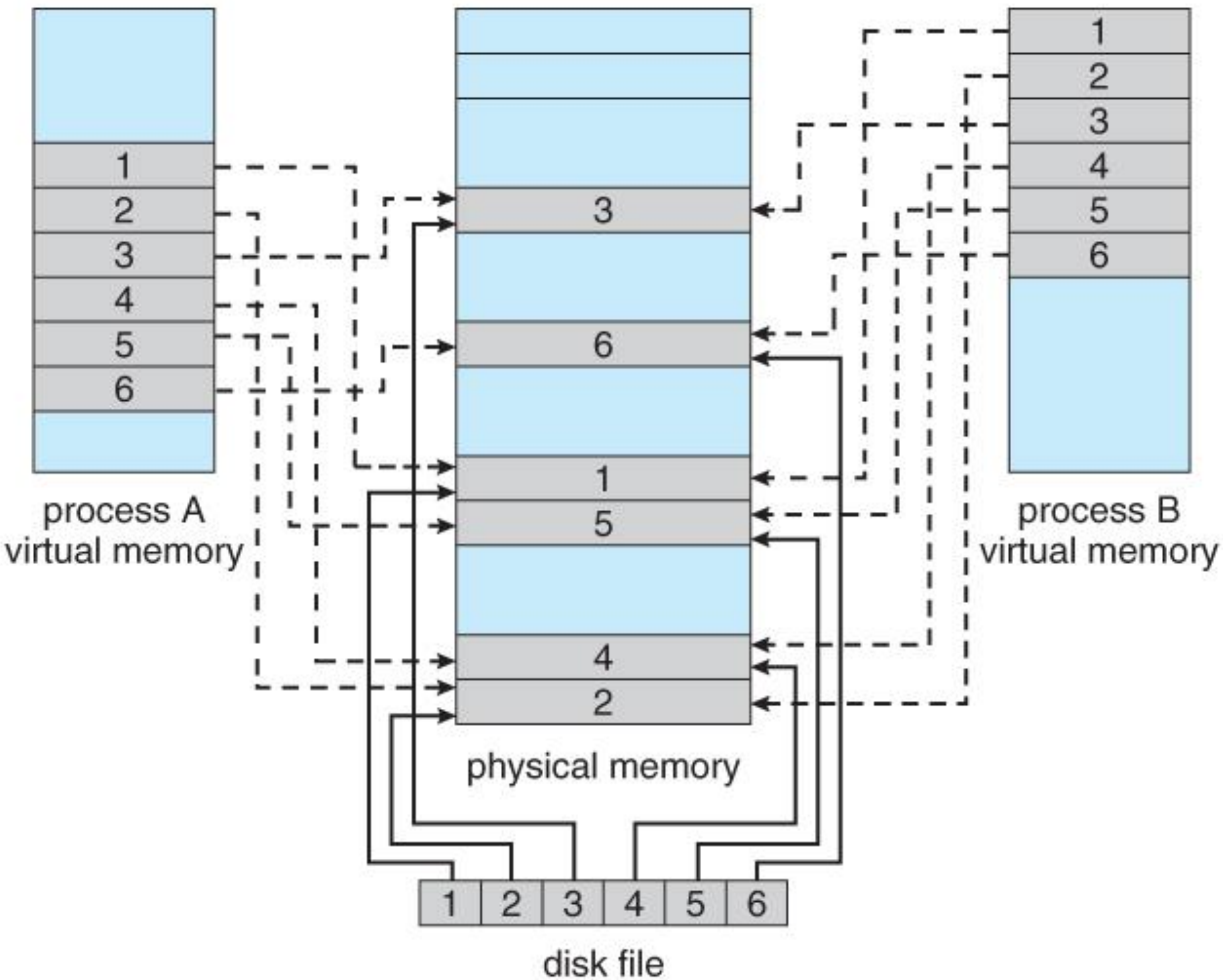
Memory-Mapped Files

- 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.



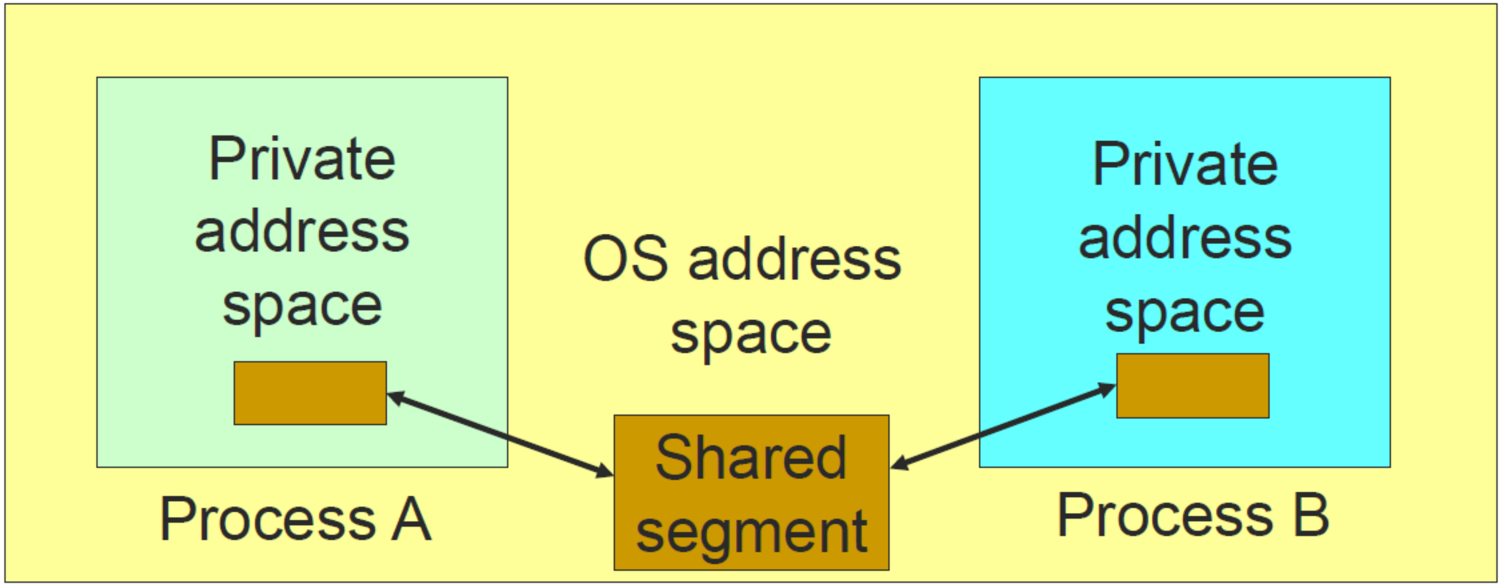
Memory-Mapped Files

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



Memory-Mapped Shared Memory

- Processes request the shared segment
- OS maintains the shared segment
- Processes can attach/detach the segment
- Can mark segment for deletion on last detach



Chapter 9: Virtual Memory

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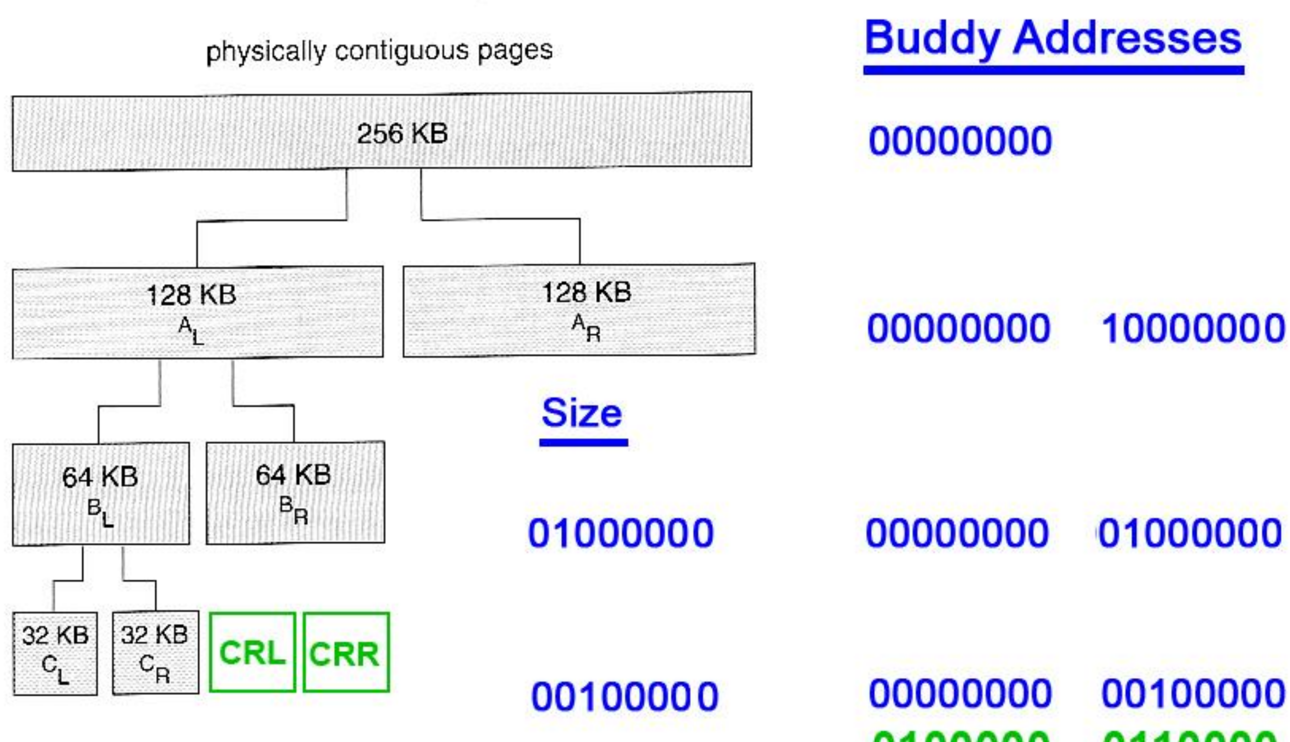
Allocating Kernel Memory

- Treated differently from user memory
- Often allocated from a free-memory pool
  - Kernel requests memory for structures of varying sizes
  - Some kernel memory needs to be contiguous
- Question: Can kernel memory management adopt contiguous memory allocation methods, similar to user-space memory management?

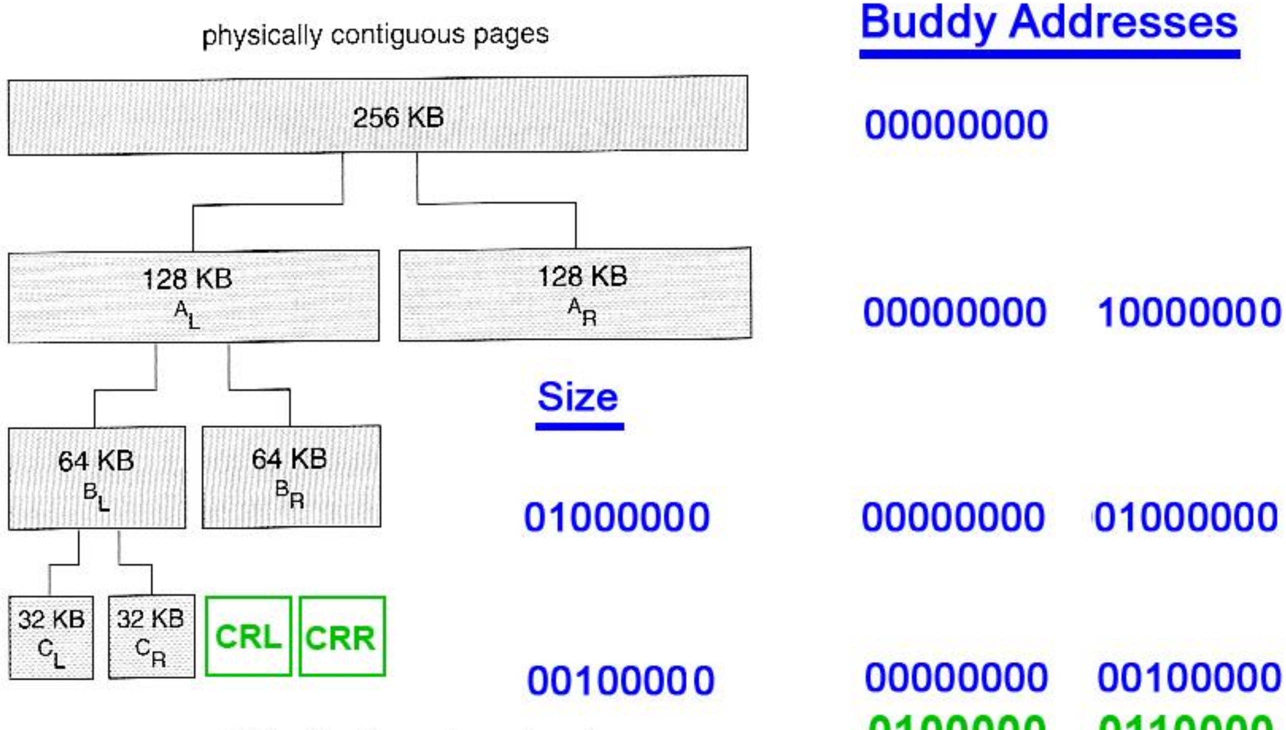
Buddy System

- 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

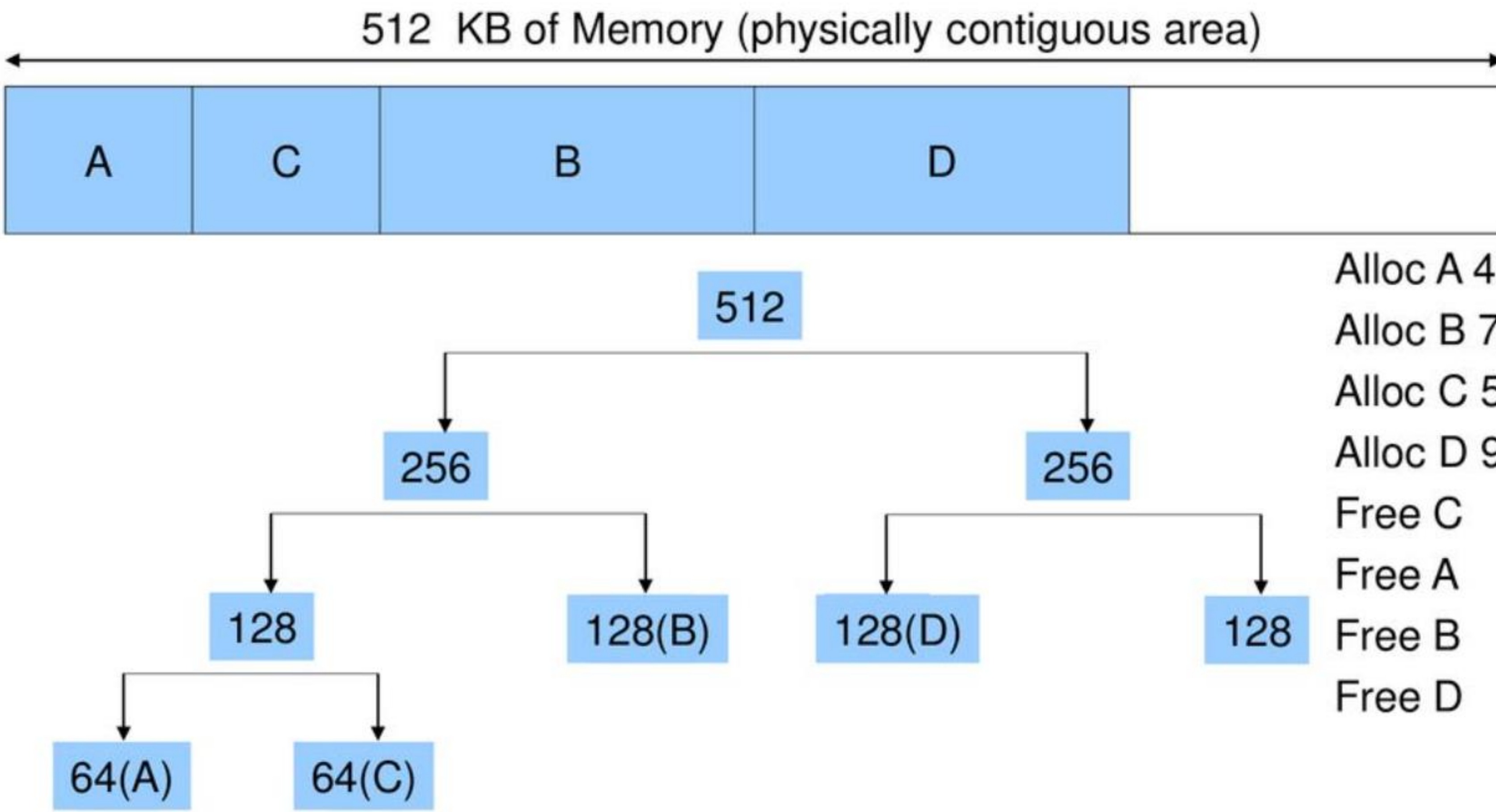


Buddy System

- This algorithm is used to give best fit
  - ✓ *Example* – If the request of 25Kb is made then block of size 32Kb is allocated.
- When smaller allocation needed than available, current chunk split into two buddies of next-lower power of 2
  - ✓ Continue until appropriate sized chunk available



Example



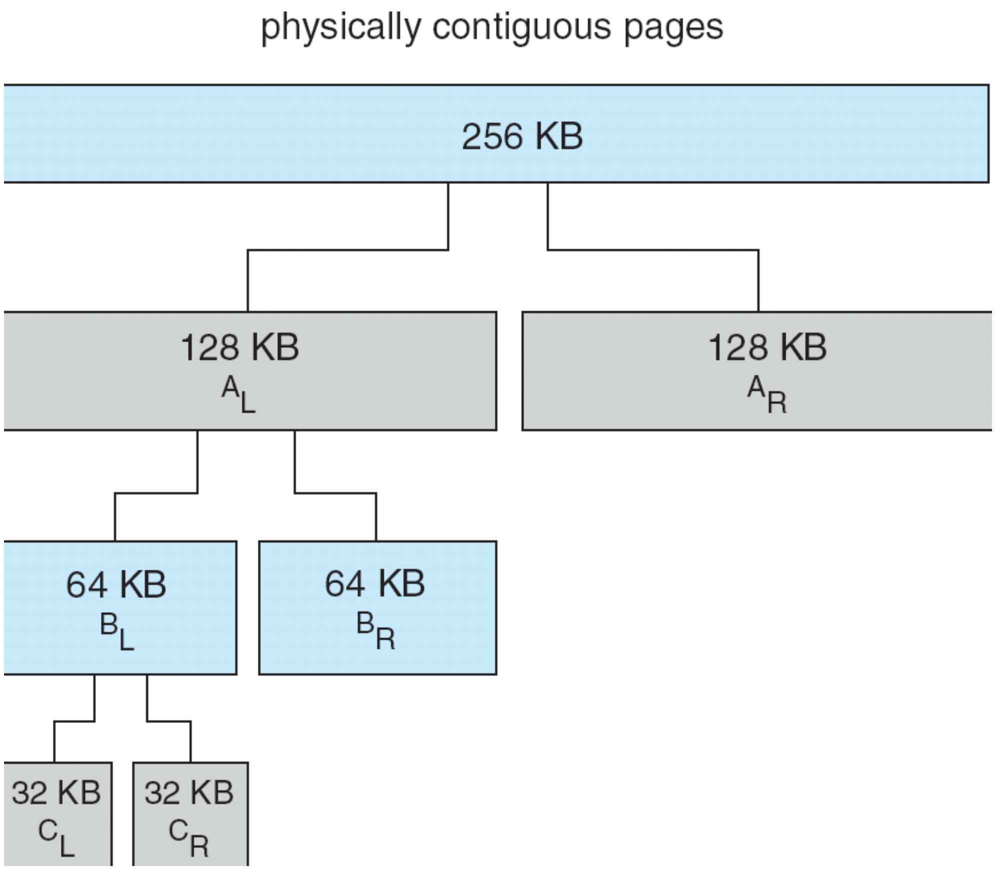
Alloc A 45 KB
Alloc B 70 KB
Alloc C 50 KB
Alloc D 90 KB
Free C
Free A
Free B
Free D

Advantages of Buddy System

- In comparison to other simpler techniques such as dynamic allocation, the buddy memory system has little external fragmentation.
- The buddy memory allocation system is implemented with the use of a binary tree to represent used or unused split memory blocks.
- The buddy system is very fast to allocate or deallocate memory.
- In buddy systems, the cost to allocate and free a block of memory is low compared to that of best-fit or first-fit algorithms.

https://www.geeksforgeeks.org/operating-system-allocating-kernel-memory-buddy-system-slab-system/

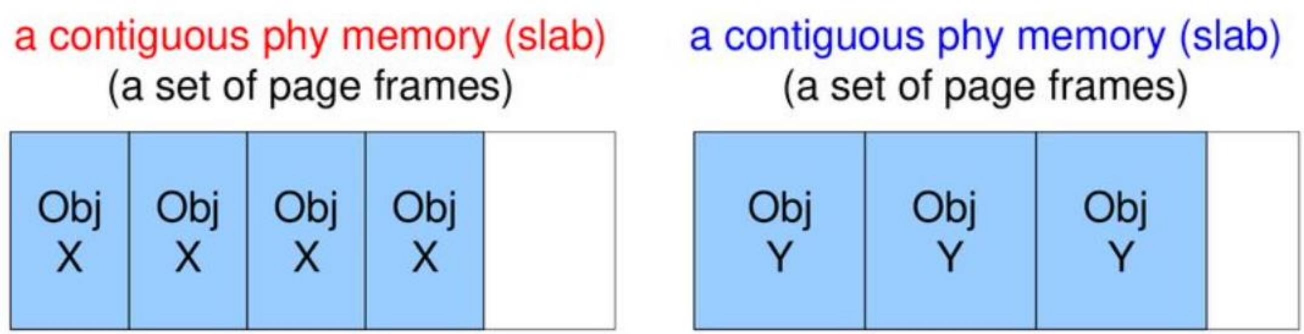
Buddy System Allocator



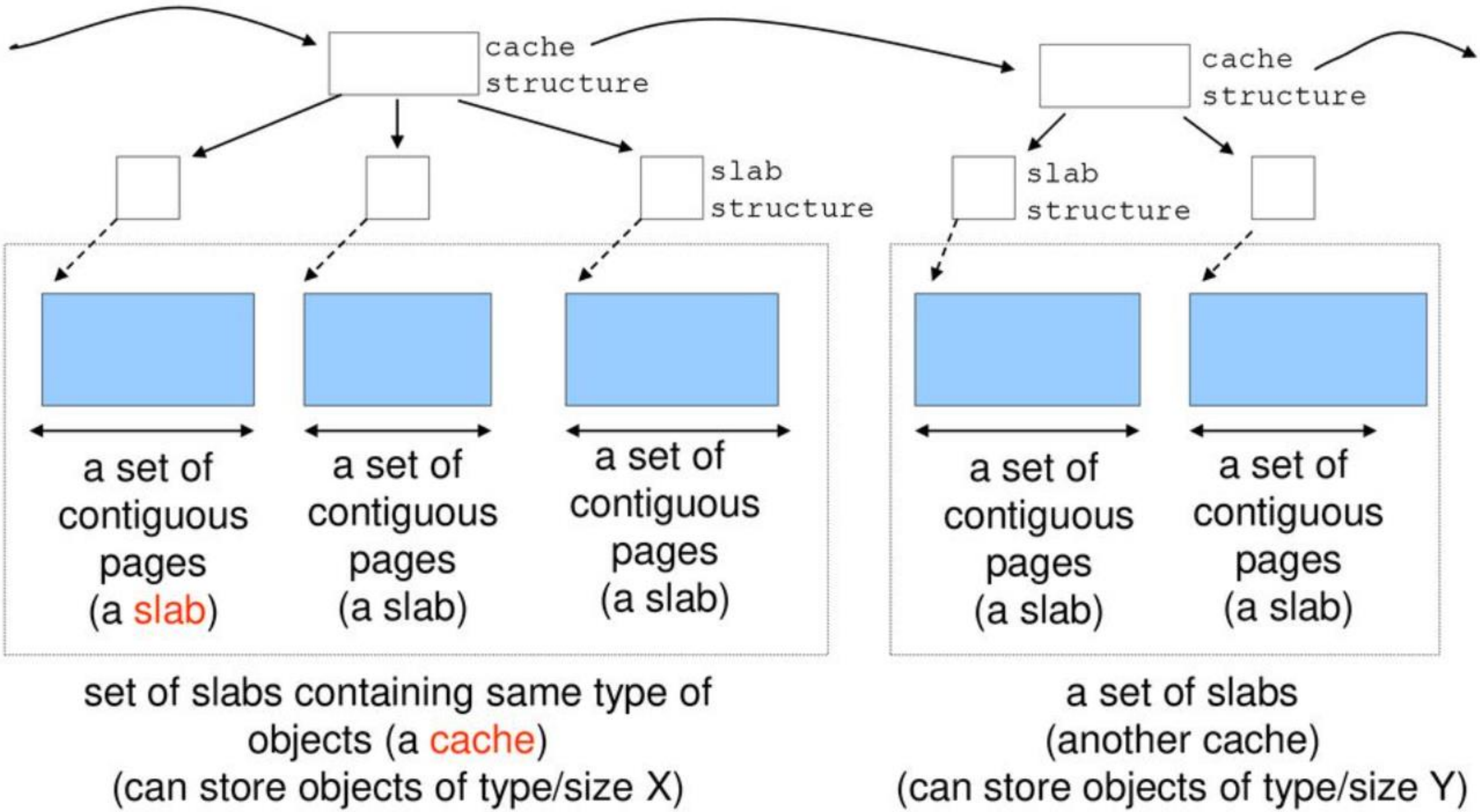
- Question: What is the key inadequacy of this power-of-2 allocator?
- Internal fragmentation
- When the size of an allocated block is x, the expected size of wasted memory is about $\frac{\sqrt{2}}{2}x$?

Slab Allocator

- Alternate strategy: With kernel, a considerable amount of memory is allocated for a finite set of object types, such as process descriptors, file descriptors and other common objects.
- **Slab** is one or more physically contiguous pages
- **Cache** consists of one or more slabs
- Single cache for each unique kernel data structur
  - Each cache filled with **objects** – instantiations of the data structure

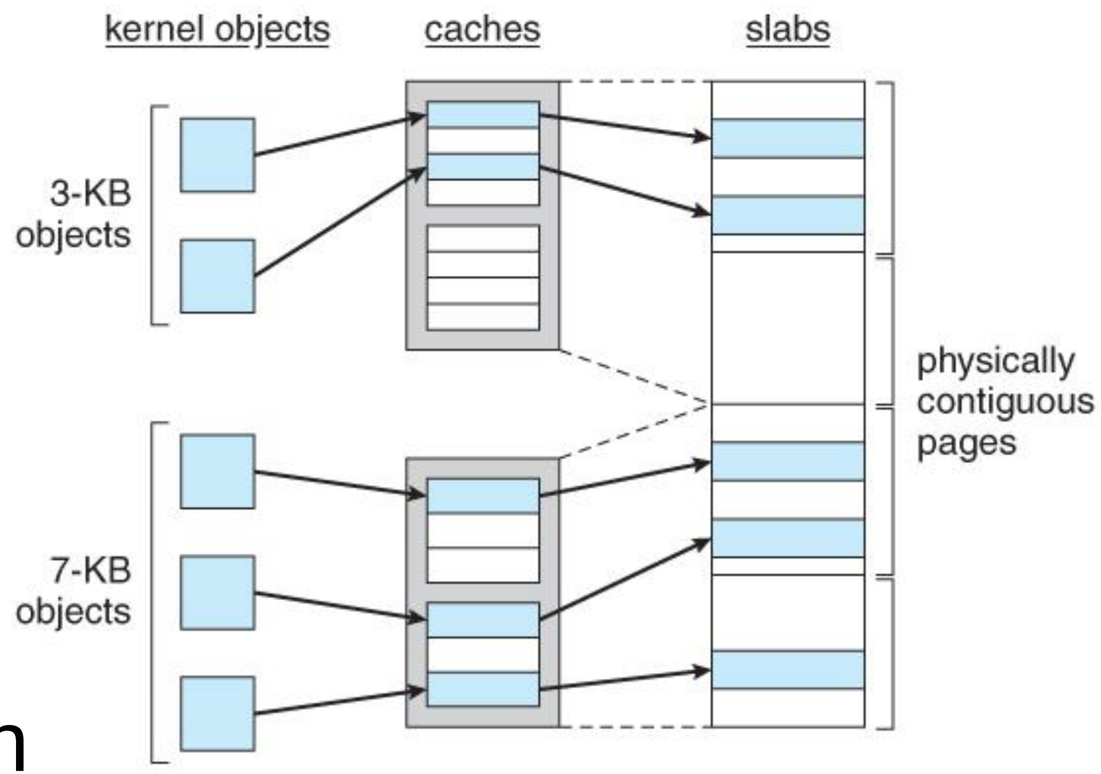


Slabs and Caches



Slab Allocator

- 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 include no fragmentation, fast memory request satisfaction



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Other Issues -- Prepaging

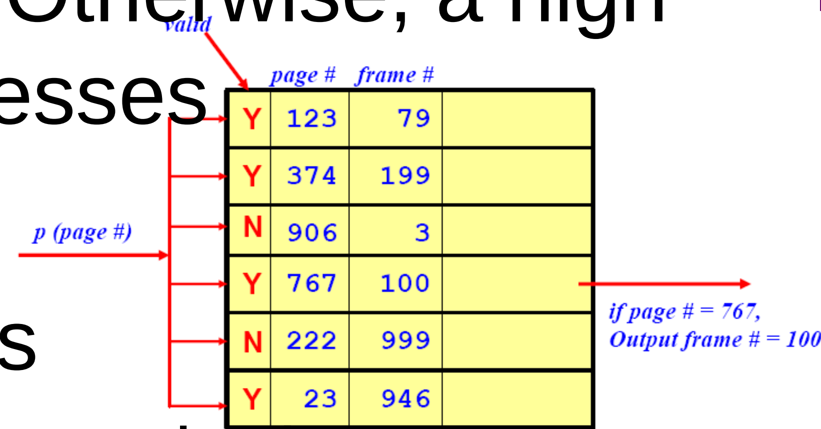
- Prepaging (预调页)
  - To reduce the large number of page faults that occur at process startup
  - Prepage all or some of the pages a process will need, before they are referenced
  - But if prepaged pages are unused, I/O and memory was wasted
  - Assume *s* pages are prepaged and *α* of the pages is used
    - ✓ Is the benefit of *s* * *α* save pages faults larger or smaller than the cost of prepaging *s* * *(1- α)* unnecessary pages?
    - ✓ *α* near zero ⇒ prepaging loses

Other Issues – Page Size

- ***Continue: Windows Prefetch***
  - introduced in Windows XP and used in Windows 10
  - stores specific data about the applications you run in order to help them start faster
  - .pf files in Windows/Prefetch
- Page size selection must take into consideration
  - fragmentation
  - table size
  - I/O overhead
  - locality

Other Issues – TLB Reach

- TLB Reach - The amount of memory accessible from the TLB
- TLB Reach = (TLB Size) X (Page Size)
- Ideally, the working set of each process is stored in main memory and its corresponding page table items is in TLB. Otherwise, a high degree of two-memory accesses



- Increase the Page Size
- Provide Multiple Page Sizes
  - This allows applications that require larger page sizes the opportunity to use them without a significant increase in fragmentation

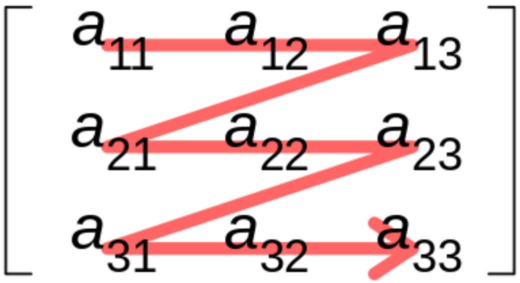
Other Issues – Program Structure

- Program structure：
  - **int A[][] = new int[2048][1024];**
  - Each row is stored in one page
  - Program 1 **for (int j = 0; j < A.length; j++)**

```
for (int j = 0; j < A.length; j++)
    for (int i = 0; i < A.length; i++)
        sum += A[i,j];
```

Assume only one page can be held in mem,
2048 x 1024 page faults

Row-major order

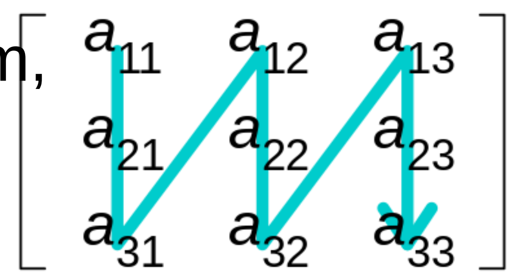


  - Program 2 **for (int i = 0; i < A.length; i++)**

```
for (int i = 0; i < A.length; i++)
    for (int j = 0; j < A.length; j++)
        sum += A[i,j];
```

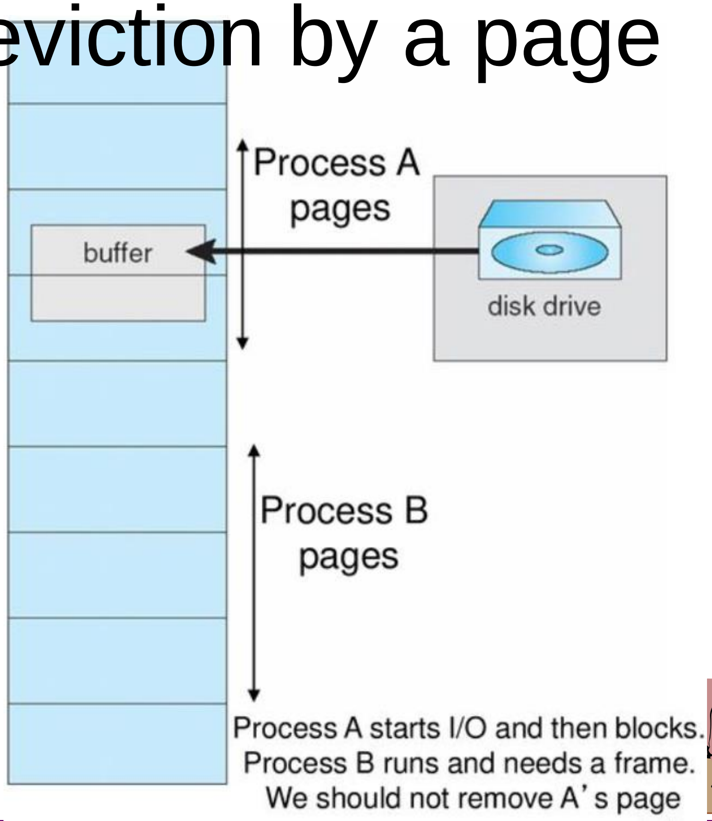
  - Assume only one page can be held in mem,
2048 page faults

Column-major order



Other Issues – I/O interlock

- **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



Why Frames Used For I/O Must Be Kept in Memory?

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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**
- Working set minimum is the minimum number of pages the process is guaranteed to have in memory

Windows XP (Cont.)

- A process may be assigned as many pages up to its working set maximum

- 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

- Maintains a list of free pages to assign faulting processes
- *Lotsfree* – threshold parameter (amount of free memory) to begin paging
- *Desfree* – threshold parameter to increasing paging
- *Minfree* – threshold parameter to being swapping

Solaris (Cont.)

- Paging is performed by *pageout* process
- Pageout scans pages using modified clock algorithm
- *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 2 Page Scanner