

Lecture 10

Virtual Memory

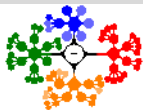
Lecture Information

Ceng328 *Operating Systems* at April 27, 2010

Virtual Memory

- Background
- Demand Paging
 - Basic Concepts
 - Performance of Demand Paging
- Copy-on-Write
- Page Replacement
 - Basic Page Replacement
 - FIFO Page Replacement
 - Optimal Page Replacement
 - LRU Page Replacement
- Allocation of Frames
 - Allocation Algorithms
 - Global versus Local Allocation
- Thrashing
 - Cause of Thrashing

Dr. Cem Özdoğan
Computer Engineering Department
Çankaya University



1 Virtual Memory

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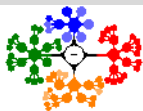
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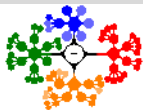
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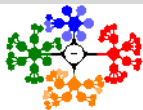
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 - One major advantage of this scheme is that programs can be larger than physical memory.

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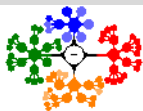
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 - Further, virtual memory abstracts main memory into an extremely large, uniform array of storage, *separating logical memory as viewed by the user from physical memory*.

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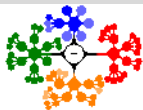
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- Virtual memory also allows processes to share files easily and to implement shared memory.
- Virtual memory is not easy to implement, however, and may substantially decrease performance if it is used carelessly.

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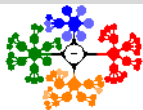
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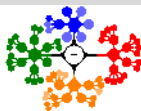
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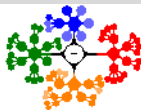
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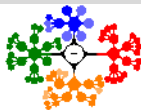
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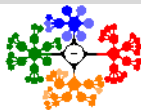
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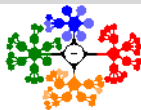
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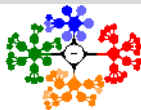
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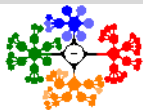
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 - Because each user program could take less physical memory, more programs could be run at the same time,
 - with a corresponding increase in CPU utilization and throughput
 - with no increase in response time or turnaround time.
 - **Less I/O would be needed to load or swap each user program into memory, so each user program would run faster.**



Background II

- **Virtual memory** involves the separation of logical memory as perceived by users from physical memory.



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- This separation allows an extremely large virtual memory to be provided for programmers when only a smaller physical memory is available (see Fig. 1).

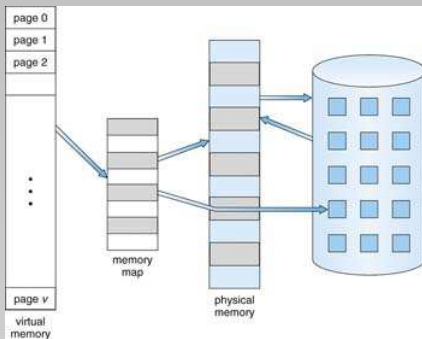
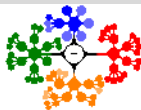


Figure: Diagram showing virtual memory that is larger than physical memory.



Background III

- The **virtual address space** of a process refers to the logical (or virtual) view of how a process is stored in memory.

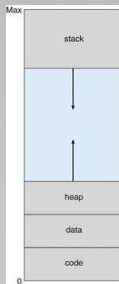
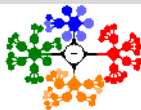


Figure: Virtual address space.



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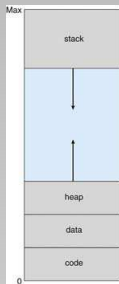
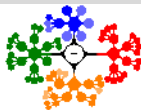


Figure: Virtual address space.

- The large blank space (or hole) between the heap and the stack is part of the virtual address space but will require actual physical pages only if the heap or stack grows.



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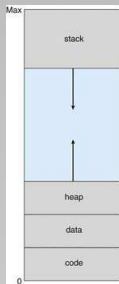
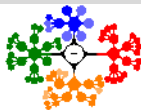


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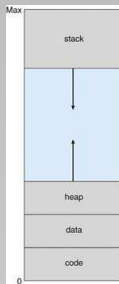
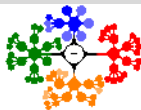


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 - heap** to grow upward in memory as it is used for dynamic memory allocation
 - stack** to grow downward in memory through successive function calls



Background IV

- Using a sparse address space is beneficial because the holes can be filled as the stack or heap segments grow



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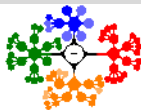
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- or if we wish to dynamically link libraries (or possibly other shared objects) during program execution.
- In addition to separating logical memory from physical memory,
- **virtual memory also allows files and memory to be shared by two or more processes through page sharing.**

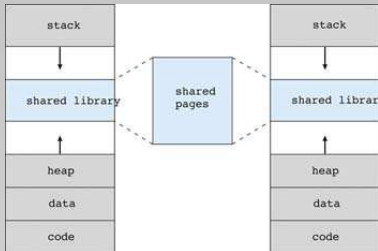
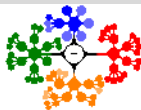
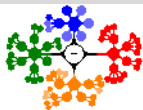


Figure: Shared library using virtual memory.



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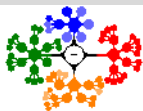
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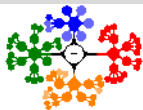


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 - System libraries can be shared by several processes through mapping of the shared object into a virtual address space. Actual pages where the libraries reside in physical memory are shared by all the processes (see Fig. 3).

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 - Similarly, virtual memory enables processes to share memory. Two or more processes can communicate through the use of shared memory (see Fig. 3).

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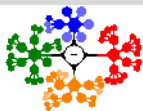
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 - **Virtual memory can allow pages to be shared during process creation with the *fork()* system call, thus speeding up process creation.**

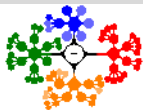
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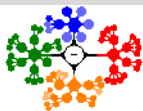
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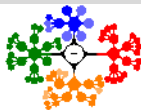
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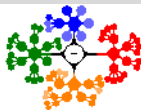
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- When we want to execute a process, we swap it into memory.



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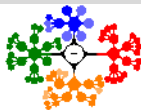
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Demand Paging I

- Consider how an executable program might be loaded from disk into memory.
 - One option is to load the entire program in physical memory at program execution time. However, a problem with this approach is that we may not initially need the entire program in memory.
 - An alternative strategy is to initially load pages only as they are needed. This technique is known as demand paging and is commonly used in virtual memory systems.
- When we want to execute a process, we swap it into memory.
- **Rather than swapping the entire process into memory, however, we use a **lazy swapper**.**



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- When we want to execute a process, we swap it into memory.
- Rather than swapping the entire process into memory, however, we use a **lazy swapper**.
- A lazy swapper never swaps a page into memory unless that page will be needed.



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Demand Paging II

- A demand-paging system is similar to a paging system with swapping (see Fig. 4) where processes reside in secondary memory (usually a disk).

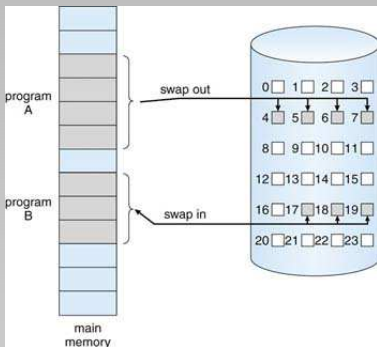
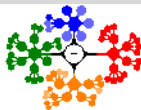


Figure: Transfer of a paged memory to contiguous disk space.



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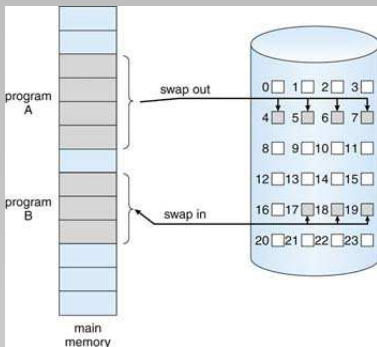
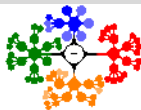


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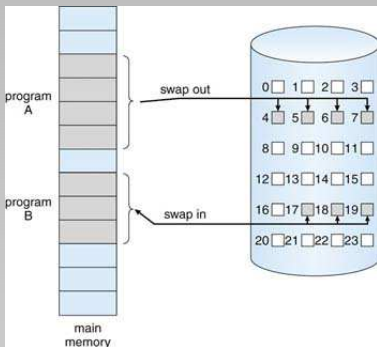
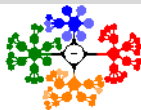


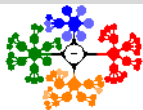
Figure: Transfer of a paged memory to contiguous disk space.

- A swapper manipulates entire processes, whereas a pager is concerned with the individual pages of a process.
- We thus use **pager**, rather than swapper, in connection with demand paging.



Basic Concepts I

- When a process is to be swapped in, the pager guesses which pages will be used before the process is swapped out again.



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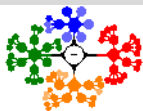
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- When a process is to be swapped in, the pager guesses which pages will be used before the process is swapped out again.
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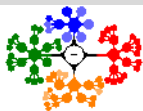
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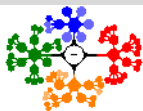
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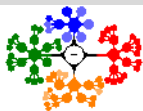
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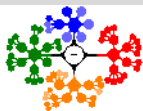
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 - **The page-table entry for a page that is brought into memory is set as usual,**



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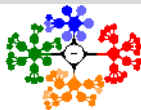
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- The valid -invalid bit scheme can be used for this purpose.
 - This time however, when this bit is set to “valid”, the associated page is both legal and in memory.
 - If the bit is set to “invalid”, the page either is not valid (that is, not in the logical address space of the process) or is valid but is currently on the disk.
 - The page-table entry for a page that is brought into memory is set as usual,
 - **but the page-table entry for a page that is not currently in memory is either simply marked invalid or contains the address of the page on disk (see Fig. 5).**



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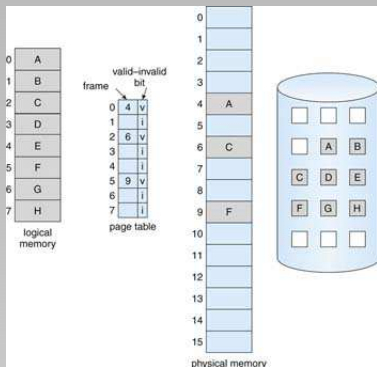
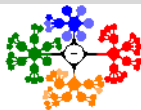


Figure: Page table when some pages are not in main memory.

- While the process executes and accesses pages that are memory resident, execution proceeds normally.



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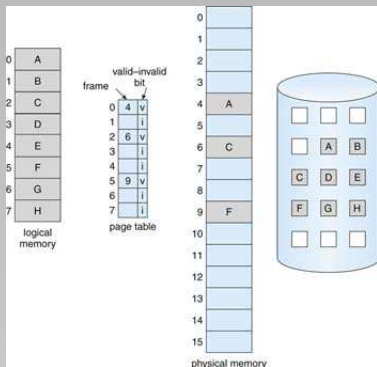
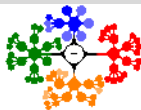


Figure: Page table when some pages are not in main memory.

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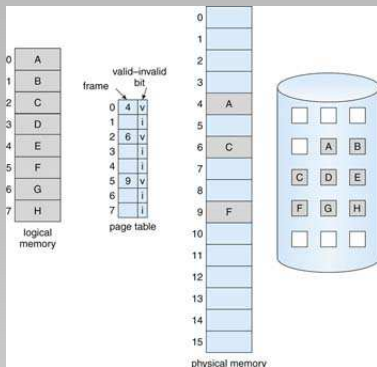
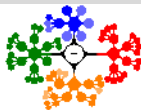


Figure: Page table when some pages are not in main memory.

- While the process executes and accesses pages that are memory resident, execution proceeds normally.
- But what happens if the process tries to access a page that was not brought into memory?
- Access to a page marked invalid causes a **page-fault trap**.



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Basic Concepts III

The paging hardware, in translating the address through the page table, will notice that the invalid bit is set, causing a trap to the OS.

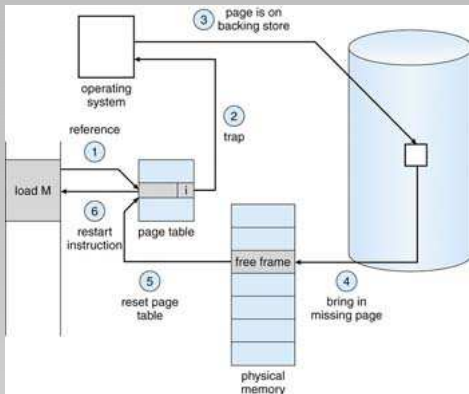
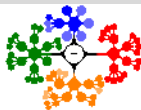
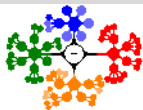


Figure: Steps in handling a page fault.



- The procedure for handling this page fault is straightforward (see Fig. 6).



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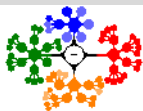
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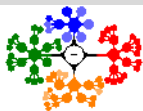
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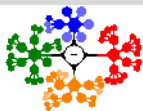
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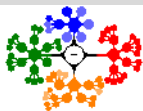
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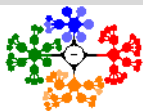
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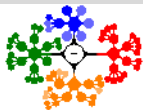
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 - 6 We restart the instruction that was interrupted by the trap.

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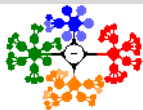
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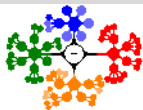
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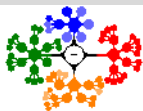
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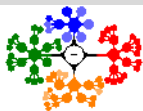
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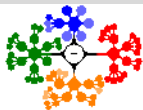
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 - After this page is brought into memory, the process continues to execute, faulting as necessary until every page that it needs is in memory.
- At that point, it can execute with no more faults.
- This scheme is **pure demand paging**: *Never bring a page into memory until it is required.*

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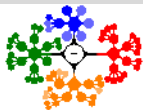
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- Theoretically, some programs could access several new pages of memory with each instruction execution (one page for the instruction and many for data), possibly causing multiple page faults per instruction.



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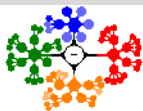
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Basic Concepts VI

- Theoretically, some programs could access several new pages of memory with each instruction execution (one page for the instruction and many for data), possibly causing multiple page faults per instruction.
- This situation would result in unacceptable system performance (but fortunately this behavior is exceedingly unlikely).



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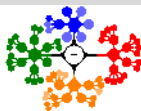
Global versus Local Allocation

Thrashing

Cause of Thrashing

Basic Concepts VI

- Theoretically, some programs could access several new pages of memory with each instruction execution (one page for the instruction and many for data), possibly causing multiple page faults per instruction.
- This situation would result in unacceptable system performance (but fortunately this behavior is exceedingly unlikely).
- Programs tend to have **locality of reference** which results in reasonable performance from demand paging.



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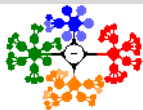
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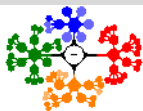
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- Because we save the state (registers, condition code, instruction counter) of the interrupted process when the page fault occurs, we must be able to restart the process in exactly the same place and state.
 - If the page fault occurs on the instruction fetch, we can restart by fetching the instruction again.



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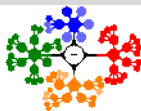
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- Because we save the state (registers, condition code, instruction counter) of the interrupted process when the page fault occurs, we must be able to restart the process in exactly the same place and state.
 - If the page fault occurs on the instruction fetch, we can restart by fetching the instruction again.
 - **If a page fault occurs while we are fetching an operand, we must fetch and decode the instruction again and then fetch the operand.**



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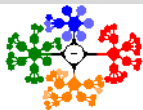
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Performance of Demand Paging I

- Demand paging can significantly affect the performance of a computer system.



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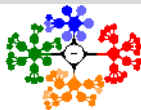
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Performance of Demand Paging II

- *Service the page-fault interrupt and Restart the process tasks may take from 1 to 100 microseconds each.*



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- We see, then, that the effective access time is directly proportional to the **page-fault rate**.



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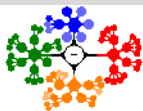
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Performance of Demand Paging III

- We see, then, that the effective access time is directly proportional to the **page-fault rate**.
- If one access out of 1,000 causes a page fault, the effective access time is 8.2 microseconds.



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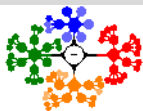
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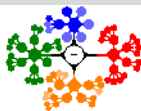
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- If one access out of 1,000 causes a page fault, the effective access time is 8.2 microseconds.
- It is important to keep the page-fault rate low in a demand-paging system.



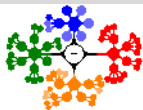
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- We see, then, that the effective access time is directly proportional to the **page-fault rate**.
- If one access out of 1,000 causes a page fault, the effective access time is 8.2 microseconds.
- It is important to keep the page-fault rate low in a demand-paging system.
- **Otherwise, the effective access time increases, slowing process execution dramatically.**



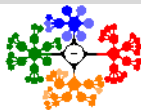
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- **An additional aspect of demand paging is the handling and overall use of swap space.**



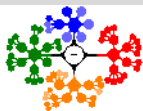
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- An additional aspect of demand paging is the handling and overall use of swap space.
 - **Disk I/O to swap space is generally faster than that to the file system.**



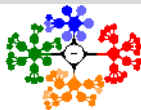
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- An additional aspect of demand paging is the handling and overall use of swap space.
 - Disk I/O to swap space is generally faster than that to the file system.
 - The system can therefore gain better paging throughput by copying an entire file image into the swap space at process startup and then performing demand paging from the swap space.



Performance of Demand Paging III

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 - Disk I/O to swap space is generally faster than that to the file system.
 - The system can therefore gain better paging throughput by copying an entire file image into the swap space at process startup and then performing demand paging from the swap space.
 - Another option is to demand pages from the file system initially but to write the pages to swap space as they are replaced.



Copy-on-Write I

- Process creation using the *fork()* system call may initially bypass the need for demand paging.



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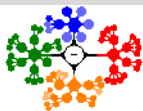
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Copy-on-Write I

- Process creation using the *fork()* system call may initially bypass the need for demand paging.
- Recall that the *fork()* system call creates a child process as a duplicate of its parent.



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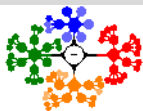
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 - Traditionally, *fork()* worked by creating a copy of the parent's address space for the child, duplicating the pages belonging to the parent.



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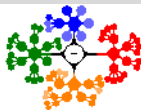
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 - However, considering that many child processes invoke the *exec()* system call immediately after creation, the copying of the parent's address space may be unnecessary.



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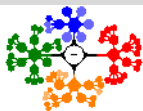
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- Alternatively, we can use a technique known as **copy-an-write**, which works by allowing the parent and child processes initially to share the same pages.



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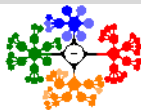
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- These shared pages are marked as **copy-an-write pages**, meaning that if either process writes to a shared page, a copy of the shared page is created (see Figs. 7 and 8).



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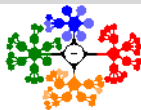
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- These shared pages are marked as copy-an-write pages, meaning that if either process writes to a shared page, a copy of the shared page is created (see Figs. 7 and 8).
- **Only pages that can be modified need be marked as copy-on-write. Pages that cannot be modified (pages containing executable code) can be shared by the parent and child.**



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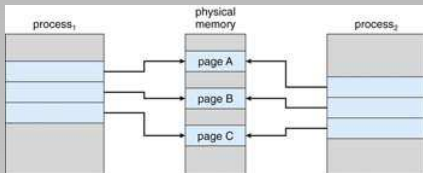


Figure: Before process 1 modifies page C.

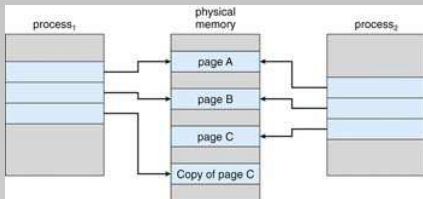
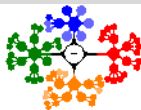


Figure: After process 1 modifies page C.

Copy-on-write is a common technique used by several OSs, including Windows XP, Linux, and Solaris.



- If we increase our degree of multiprogramming, we are over-allocating memory.



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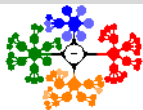
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- If we increase our degree of multiprogramming, we are over-allocating memory.
- Further, consider that system memory is not used only for holding program pages.



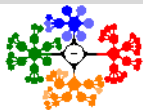
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- If we increase our degree of multiprogramming, we are over-allocating memory.
- Further, consider that system memory is not used only for holding program pages.
- **Buffers for I/O also consume a significant amount of memory.**



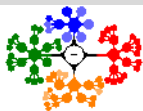
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- If we increase our degree of multiprogramming, we are over-allocating memory.
- Further, consider that system memory is not used only for holding program pages.
- Buffers for I/O also consume a significant amount of memory.
- Over-allocation of memory manifests itself as follows (see Fig. 9).



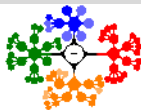
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 - While a user process is executing, a page fault occurs.



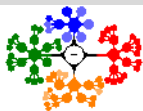
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- Further, consider that system memory is not used only for holding program pages.
- Buffers for I/O also consume a significant amount of memory.
- Over-allocation of memory manifests itself as follows (see Fig. 9).
 - While a user process is executing, a page fault occurs.
 - The OS determines where the desired page is residing on the disk but then finds that there are no free frames on the free-frame list; all memory is in use.



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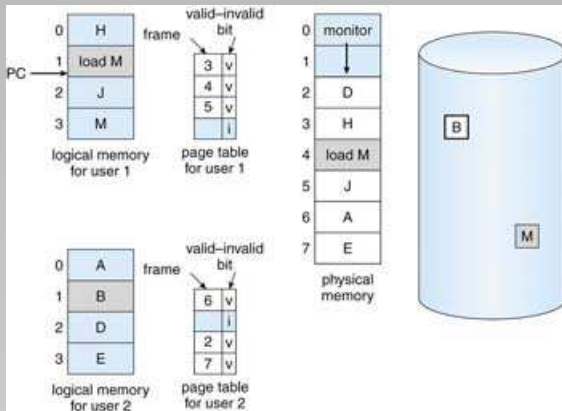
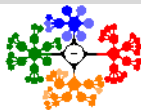


Figure: Need for page replacement.

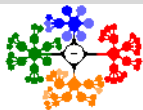
The OS could swap out a process, freeing all its frames and reducing the level of multiprogramming.

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Basic Page Replacement I

- Page replacement takes the following approach (see Fig. 10).



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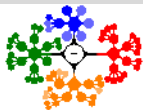
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Basic Page Replacement I

- Page replacement takes the following approach (see Fig. 10).
- We modify the page-fault service routine to include page replacement:



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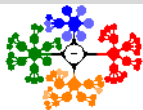
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Basic Page Replacement I

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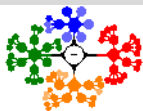


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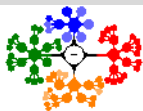


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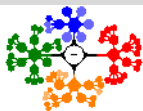


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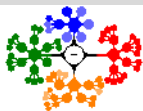
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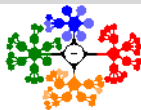
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 - 3 Read the desired page into the newly freed frame; change the page and frame tables.



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 - 3 Read the desired page into the newly freed frame; change the page and frame tables.
 - 4 Restart the user process.

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Basic Page Replacement II

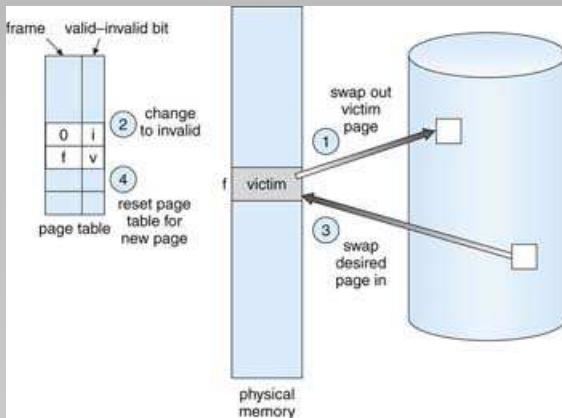
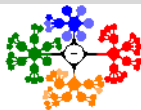


Figure: Page replacement.

- Notice that, if no frames are free, two page transfers (one out and one in) are required.



Basic Page Replacement II

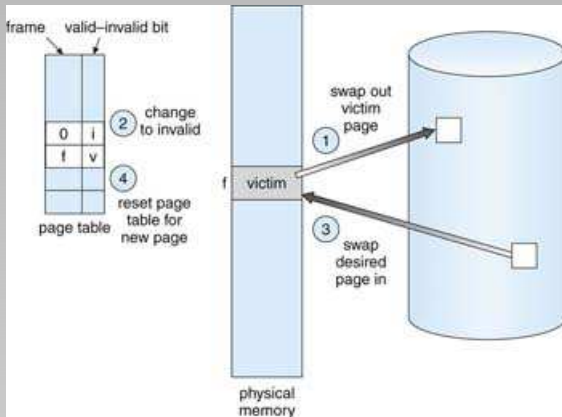
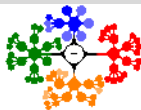


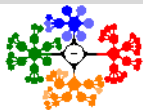
Figure: Page replacement.

- Notice that, if no frames are free, two page transfers (one out and one in) are required.
- We can reduce this overhead by using a **modify bit** (or **dirty bit**).



Basic Page Replacement III

- The modify bit for a page is set by the hardware whenever any word or byte in the page is written into, indicating that the page has been modified.



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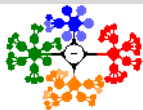
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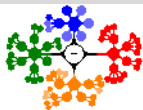


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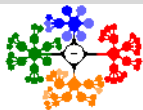


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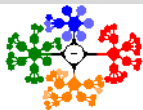


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- This technique also applies to read-only pages (for example, pages of binary code).

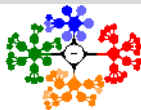


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- This technique also applies to read-only pages (for example, pages of binary code).
- This scheme can significantly reduce the time required to service a page fault, since it reduces I/O time by one-half if the page has not been modified.



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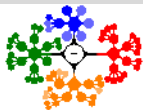
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Basic Page Replacement IV

- Page replacement is basic to demand paging. It completes the separation between logical memory and physical memory.



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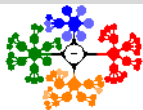
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Basic Page Replacement IV

- Page replacement is basic to demand paging. It completes the separation between logical memory and physical memory.
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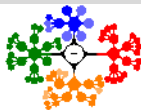


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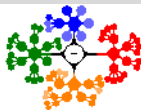


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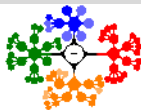


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- Designing appropriate algorithms to solve these problems is an important task, because disk I/O is so expensive.



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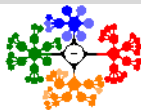
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- Designing appropriate algorithms to solve these problems is an important task, because disk I/O is so expensive.
- Even slight improvements in demand-paging methods yield large gains in system performance.

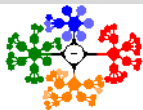


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Basic Page Replacement V

- Second major problem will be discussed firstly.



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Basic Page Replacement VI

- As the number of frames increases, the number of page faults drops to some minimal level (see Fig. 11).

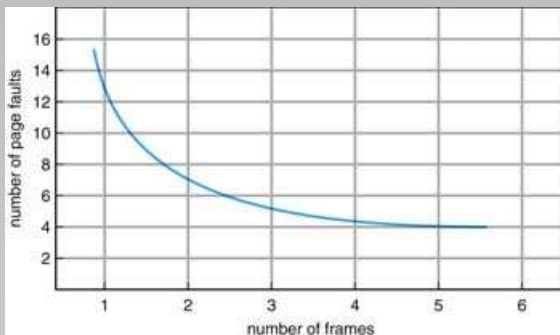
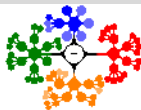


Figure: Graph of page faults versus number of frames.

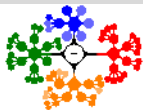


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FIFO Page Replacement I

- The simplest page-replacement algorithm is a first-in, first-out (FIFO) algorithm.



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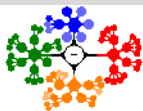
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FIFO Page Replacement I

- The simplest page-replacement algorithm is a first-in, first-out (FIFO) algorithm.
- A FIFO replacement algorithm *associates with each page the time when that page was brought into memory.*



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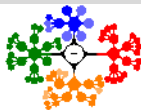
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- For our example reference string, our three frames are initially empty.

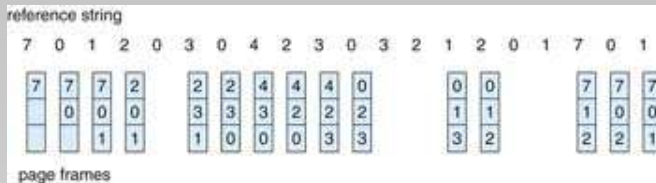
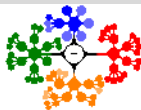


Figure: FIFO page-replacement algorithm.



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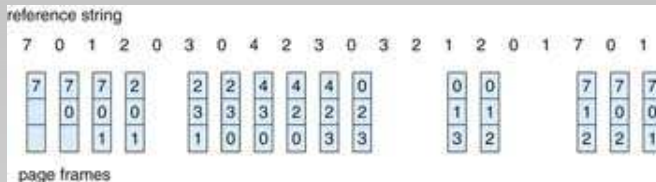
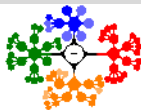


Figure: FIFO page-replacement algorithm.

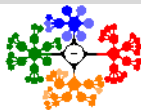
- There are 15 faults altogether.



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FIFO Page Replacement II

- The FIFO page-replacement algorithm is easy to understand and program. However, its performance is not always good.



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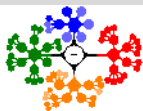
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FIFO Page Replacement II

- The FIFO page-replacement algorithm is easy to understand and program. However, its performance is not always good.
- On the one hand, the page replaced may be an initialization module that was used a long time ago and is no longer needed.

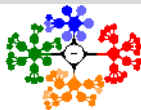


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- Notice that, even if we select for replacement a page that is in active use, everything still works correctly.



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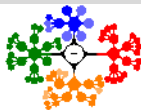


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 - After we replace an active page with a new one, a fault occurs almost immediately to retrieve the active page.
 - **Some other page will need to be replaced to bring the active page back into memory.**

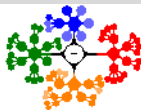


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 - After we replace an active page with a new one, a fault occurs almost immediately to retrieve the active page.
 - Some other page will need to be replaced to bring the active page back into memory.
 - Thus, a bad replacement choice increases the page-fault rate and slows process execution.

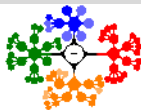


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 - After we replace an active page with a new one, a fault occurs almost immediately to retrieve the active page.
 - Some other page will need to be replaced to bring the active page back into memory.
 - Thus, a bad replacement choice increases the page-fault rate and slows process execution.
 - **It does not cause incorrect execution.**



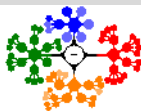
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Optimal Page Replacement I

- An optimal page-replacement algorithm has the lowest page-fault rate of all algorithms (called OPT or MIN). It is simply this:

Replace the page that will not be used for the longest period of time.

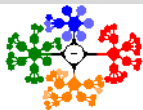


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Optimal Page Replacement II

- If we ignore the first three, which all algorithms must suffer, then optimal replacement is twice as good as FIFO replacement.



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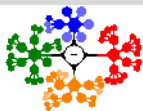
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Optimal Page Replacement II

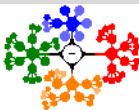


- If we ignore the first three, which all algorithms must suffer, then optimal replacement is twice as good as FIFO replacement.
- Unfortunately, the optimal page-replacement algorithm is difficult to implement, because it requires future knowledge of the reference string (similar situation with the SJF CPU-scheduling algorithm).

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Optimal Page Replacement II



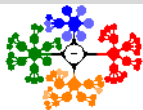
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- Unfortunately, the optimal page-replacement algorithm is difficult to implement, because it requires future knowledge of the reference string (similar situation with the SJF CPU-scheduling algorithm).
- As a result, the optimal algorithm is used mainly for comparison studies.

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LRU Page Replacement I

- The key distinction between the FIFO and OPT algorithms (other than looking backward versus forward in time) is that



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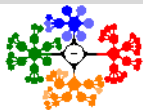
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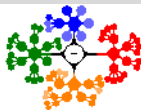


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LRU Page Replacement I

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 - the FIFO algorithm uses the time when a page was brought into memory,
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- The key distinction between the FIFO and OPT algorithms (other than looking backward versus forward in time) is that
 - the FIFO algorithm uses the time when a page was brought into memory,
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- If we use the recent past as an approximation of the near future, then we can replace the page that has not been used for the longest period of time (see Fig. 14).

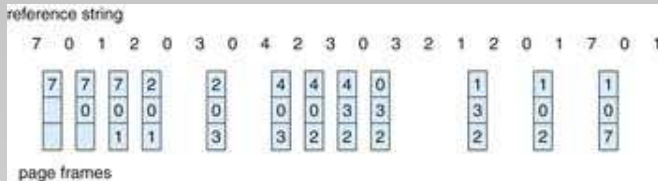
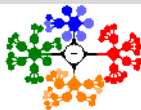


Figure: LRU page-replacement algorithm.



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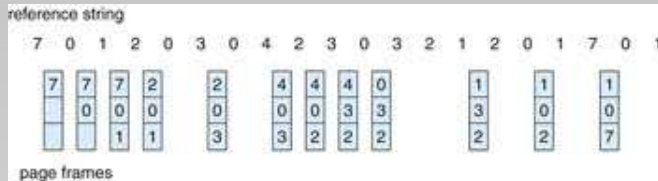
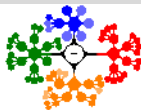


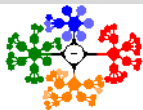
Figure: LRU page-replacement algorithm.

- This approach is the **least-recently-used (LRU) algorithm**.



LRU Page Replacement II

- The result of applying LRU replacement to our example reference string is shown in Fig. 14. The LRU algorithm produces 12 faults.



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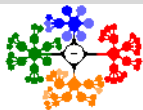
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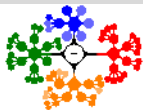


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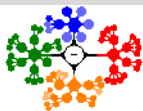


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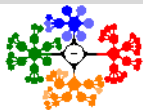


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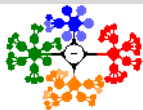


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 - Thus, the LRU algorithm replaces page 2, not knowing that page 2 is about to be used.
 - When it then faults for page 2, the LRU algorithm replaces page 3, since it is now the least recently used of the three pages in memory.
- Despite these problems, LRU replacement with 12 faults is much better than FIFO replacement with 15.

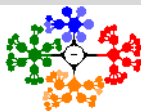


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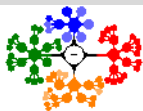


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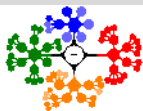


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- If we have 93 free frames and two processes, how many frames does each process get?

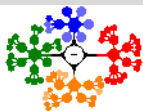


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 - When a user process started execution, it would generate a sequence of page faults.

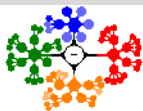


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 - **The first 93 page faults would all get free frames from the free-frame list.**

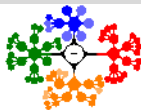


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- Under pure demand paging, all 93 frames would initially be put on the free-frame list.
 - When a user process started execution, it would generate a sequence of page faults.
 - The first 93 page faults would all get free frames from the free-frame list.
 - When the free-frame list was exhausted, a page-replacement algorithm would be used to select one of the 93 in-memory pages to be replaced with the 94th, and so on.

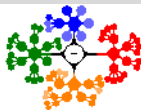


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- Under pure demand paging, all 93 frames would initially be put on the free-frame list.
 - When a user process started execution, it would generate a sequence of page faults.
 - The first 93 page faults would all get free frames from the free-frame list.
 - When the free-frame list was exhausted, a page-replacement algorithm would be used to select one of the 93 in-memory pages to be replaced with the 94th, and so on.
 - When the process terminated, the 93 frames would once again be placed on the free-frame list.

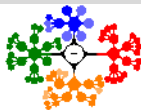


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Allocation of Frames

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- We can require that the OS allocate all its buffer and table space from the free-frame list.

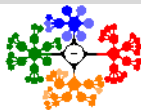


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- **When this space is not in use by the OS, it can be used to support user paging.**

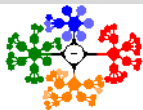


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- The easiest way to split m frames among n processes is to give everyone an equal share, m/n frames. This scheme is called **equal allocation**.



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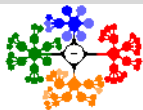
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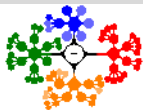


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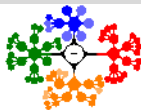
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 - Consider a system with a 1-KB frame size.

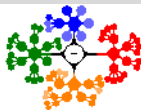


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- An alternative is to recognize that various processes will need differing amounts of memory.
 - Consider a system with a 1-KB frame size.
 - If a small student process of 10 KB and an interactive database of 127 KB are the only two processes running in a system with 62 free frames, it does not make much sense to give each process 31 frames.

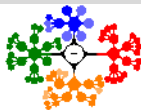


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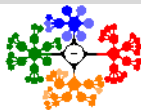
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 - The student process does not need more than 10 frames, so the other 21 are, strictly speaking, wasted.
- To solve this problem, we allocate available memory to each process according to its size (proportional allocation).



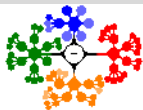
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Allocation Algorithms II

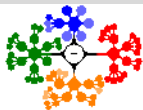
- Let the size of the virtual memory for process p_i be s_i , and define

$$S = \sum s_i$$



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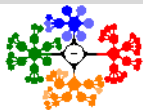
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- In both equal and proportional allocation, of course, the allocation may vary according to the multiprogramming level.

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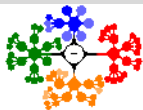
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 - If the multiprogramming level is increased, each process will lose some frames to provide the memory needed for the new process.
 - If the multiprogramming level decreases, the frames that were allocated to the departed process can be spread over the remaining processes.

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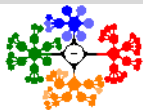
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- With multiple processes competing for frames, we can classify page-replacement algorithms into two broad categories:



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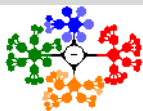
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- With multiple processes competing for frames, we can classify page-replacement algorithms into two broad categories:

① **Global replacement.** Global replacement allows a process to select a replacement frame from the set of all frames, even if that frame is currently allocated to some other process; that is, one process can take a frame from another.



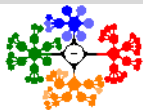
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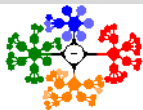
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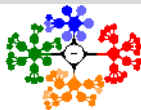


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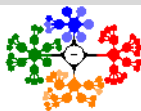
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- With global replacement, a process may happen to select only frames allocated to other processes, thus increasing the number of frames allocated to it (assuming that other processes do not choose its frames for replacement).
- **Global replacement generally results in greater system throughput and is therefore the more common method.**



Thrashing

- If the number of frames allocated to a low-priority process falls below the minimum number required, we must suspend that process's execution.



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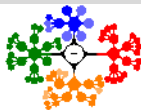


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- If the number of frames allocated to a low-priority process falls below the minimum number required, we must suspend that process's execution.
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- **In fact, look at any process that does not have “enough” frames.**

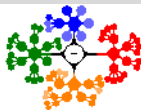


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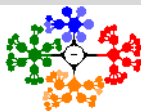


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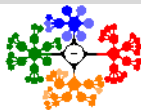


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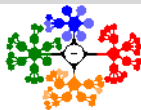
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 - **Consequently, it quickly faults again, and again, and again, replacing pages that it must bring back in immediately.**



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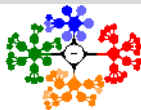
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 - Consequently, it quickly faults again, and again, and again, replacing pages that it must bring back in immediately.
- This high paging activity is called **thrashing**.



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Thrashing

- If the number of frames allocated to a low-priority process falls below the minimum number required, we must suspend that process's execution.
- We should then page out its remaining pages, freeing all its allocated frames.
- In fact, look at any process that does not have “enough” frames.
 - If the process does not have the number of frames it needs to support pages in active use, it will quickly page-fault.
 - At this point, it must replace some page.
 - However, since all its pages are in active use, it must replace a page that will be needed again right away.
 - Consequently, it quickly faults again, and again, and again, replacing pages that it must bring back in immediately.
- This high paging activity is called **thrashing**.
- A process is thrashing if it is spending more time paging than executing.



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Cause of Thrashing I

- Thrashing results in severe performance problems. Consider the following scenario (see Fig. 15);

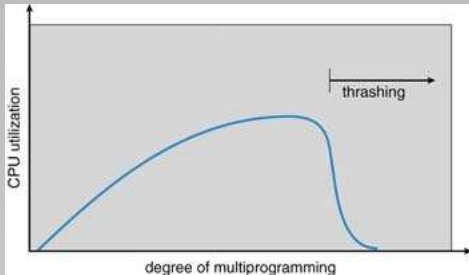
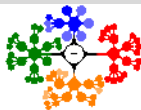


Figure: Thrashing.



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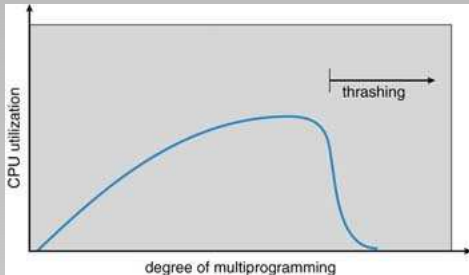
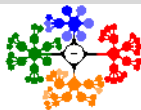


Figure: Thrashing.

- Thrashing has occurred. The page-fault rate increases tremendously.



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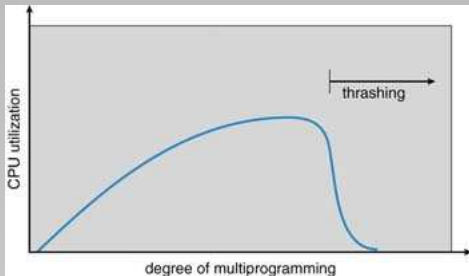
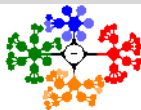


Figure: Thrashing.

- Thrashing has occurred. The page-fault rate increases tremendously.
- No work is getting done, because the processes are spending all their time paging.



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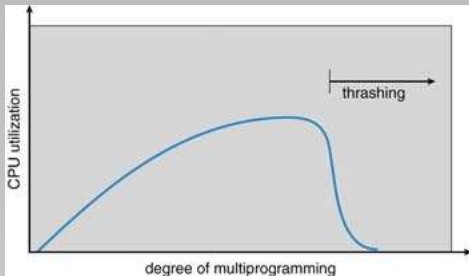
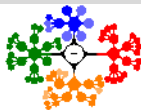


Figure: Thrashing.

- Thrashing has occurred. The page-fault rate increases tremendously.
- No work is getting done, because the processes are spending all their time paging.
- At this point, to increase CPU utilization and stop thrashing, we must decrease the degree of multiprogramming.

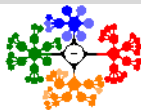


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Cause of Thrashing II

- The OS monitors CPU utilization. If CPU utilization is too low, we increase the degree of multiprogramming by introducing a new process to the system.



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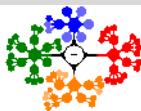
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Cause of Thrashing

Cause of Thrashing II

- The OS monitors CPU utilization. If CPU utilization is too low, we increase the degree of multiprogramming by introducing a new process to the system.
 - Now suppose that a process enters a new phase in its execution and needs more frames.

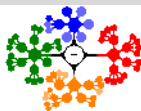


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- The OS monitors CPU utilization. If CPU utilization is too low, we increase the degree of multiprogramming by introducing a new process to the system.
 - Now suppose that a process enters a new phase in its execution and needs more frames.
 - It starts faulting and taking frames away from other processes (global page-replacement algorithm).

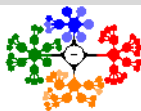


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 - Now suppose that a process enters a new phase in its execution and needs more frames.
 - It starts faulting and taking frames away from other processes (global page-replacement algorithm).
 - **These processes need those pages, however, and so they also fault, taking frames from other processes.**

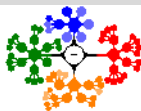


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 - Now suppose that a process enters a new phase in its execution and needs more frames.
 - It starts faulting and taking frames away from other processes (global page-replacement algorithm).
 - These processes need those pages, however, and so they also fault, taking frames from other processes.
 - **These faulting processes must use the paging device to swap pages in and out.**

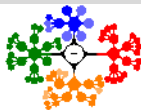


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 - These processes need those pages, however, and so they also fault, taking frames from other processes.
 - These faulting processes must use the paging device to swap pages in and out.
 - **As processes wait for the paging device, CPU utilization decreases.**

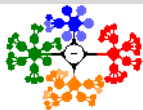


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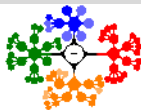
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 - As processes wait for the paging device, CPU utilization decreases.
- The CPU scheduler sees the decreasing CPU utilization and increases the degree of multiprogramming as a result.



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 - The new process tries to get started by taking frames from running processes, causing more page faults and a longer queue for the paging device.

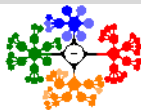


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 - These faulting processes must use the paging device to swap pages in and out.
 - As processes wait for the paging device, CPU utilization decreases.
- The CPU scheduler sees the decreasing CPU utilization and increases the degree of multiprogramming as a result.
 - The new process tries to get started by taking frames from running processes, causing more page faults and a longer queue for the paging device.
 - **As a result, CPU utilization drops even further, and the CPU scheduler tries to increase the degree of multiprogramming even more.**



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