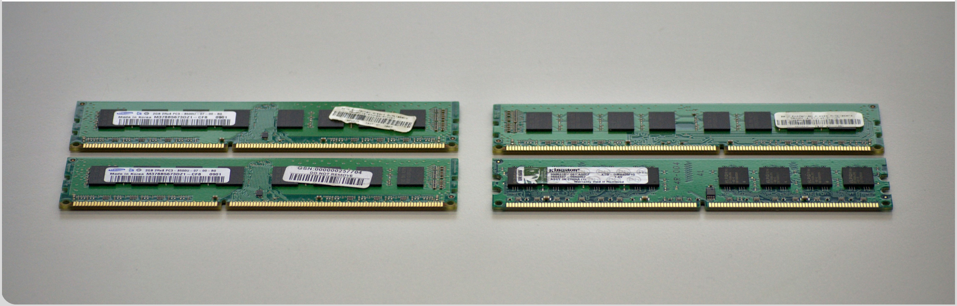
Betriebssysteme

12. Page Faults

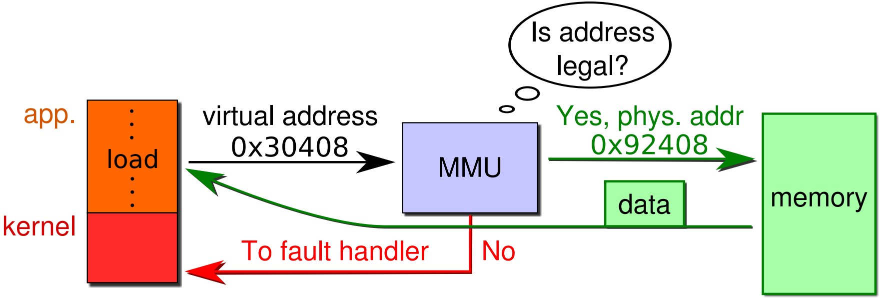
Prof. Dr.-Ing. Frank Bellosa | WT 2016/2017

KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT) – OPERATING SYSTEMS GROUP



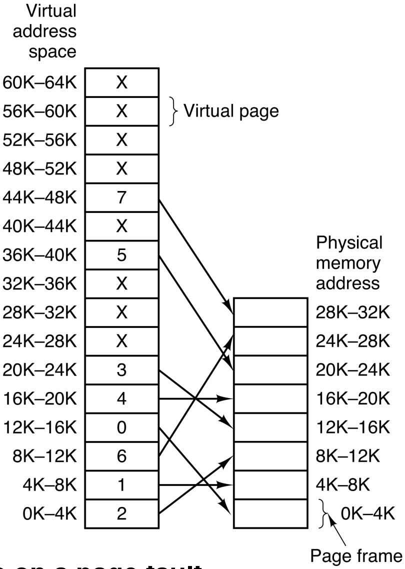
Memory-Management Unit (MMU)

- Need hardware support to achieve safe and secure protection
- Hardware device maps virtual to physical address
- The user program deals with virtual addresses
  - It never sees the real physical addresses



Paging

- A Present Bit in the page table indicates if a virtual page is currently mapped to physical memory
- MMU reads the page table and autonomously translates valid mappings
- If a process issues an instruction to access a virtual address that is currently not mapped, the MMU calls the OS to bring in the data (page fault)

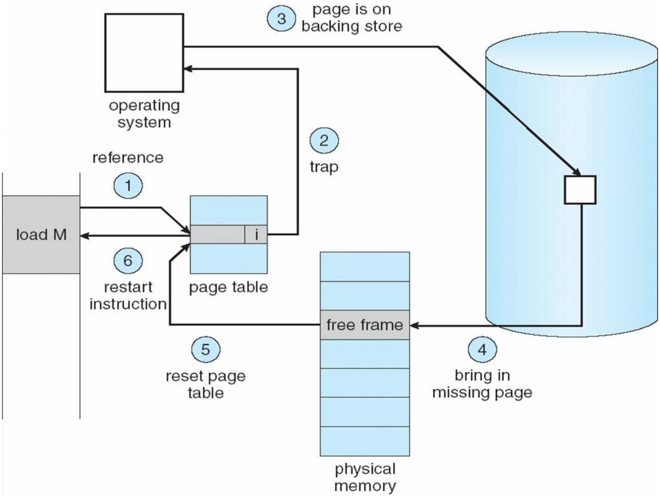


Today: What happens on a page fault

Page Fault Handling

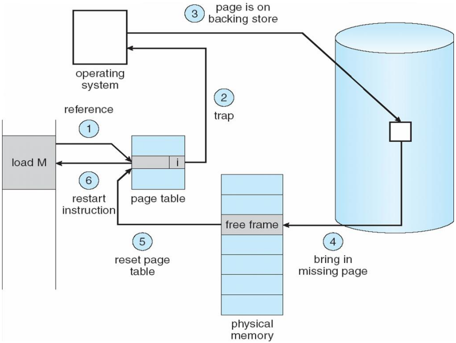
Paging

- Use disk to simulate virtual memory that is larger than physical memory



Page Fault Handling

- Access to page that is currently not present in main memory causes page fault (exception that invokes OS)



1. OS checks validity of access (requires additional info)
2. Get empty frame
3. Load contents of requested page from disk into frame
4. Adapt page table
5. Set present bit of respective entry (a.k.a. as setting valid-invalid bit to **v**)
6. Restart instruction that caused the page fault

Page Fault Latency

- Page Fault Rate $0 \leq p \leq 1.0$
  - $p = 0$: No page faults
  - $p = 1$: Every reference is a page fault
- Effective Access Time (EAT)

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

Performance Impact of Page Faults

- Memory access time = 200 nanoseconds
- Average page fault service time = 8 milliseconds
- $$\begin{aligned} \text{EAT} &= (1-p)\times 200 + p(8\text{ms}) \\ &= (1-p)\times 200 + p \times 8,000,000 \\ &= 200 + p\times 7,999,800 \end{aligned}$$
- If one access out of 1,000 causes a page fault, then EAT = 8.2 microseconds. $\Rightarrow$ Slowdown by a factor of 40!

Page Fault Challenges

- What to eject?
  - How to allocate frames among processes?
  - Which particular process's pages to keep in memory?
  - See 2^{nd} part of this lecture (page frame allocation)
- What to fetch?
  - What if block size not the same as page size?
  - Just one page needed? Prefetch more?
- How to resume a process after a fault?
  - Need to save state and resume
  - Process might have been in the middle of an instruction!

What to fetch?

- Bring in page that caused page fault
- Pre-fetch surrounding pages?
  - Reading two disk blocks is approximately as fast as reading one
  - As long as no track/head switch, seek time dominates (disk)
  - If application exhibits spatial locality → big win
- Pre-zero pages?
  - Don't want to leak information between processes
  - Need 0-filled pages (0-pages) for stack, heap, .bss, ...
  - Zero on demand?
  - Keep a pool of 0-pages that is filled in the background when the CPU is idle?

How to resume a process after a fault?

- Hardware provides info about page fault
  - Faulting virtual address: **`%cr2`** on intel

- OS needs to figure out context of fault. Was the instruction a
  - Read or write?
  - Instruction fetch?
  - User access to kernel memory?

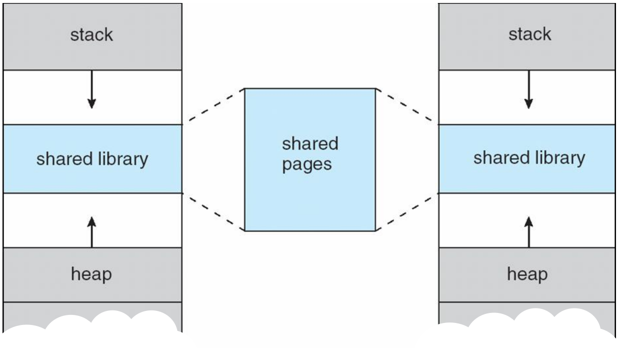
- Idempotent instructions are easy
  - Just re-do load/store instructions
  - Just re-execute instructions that only access one address

Complex instructions must be re-started, too

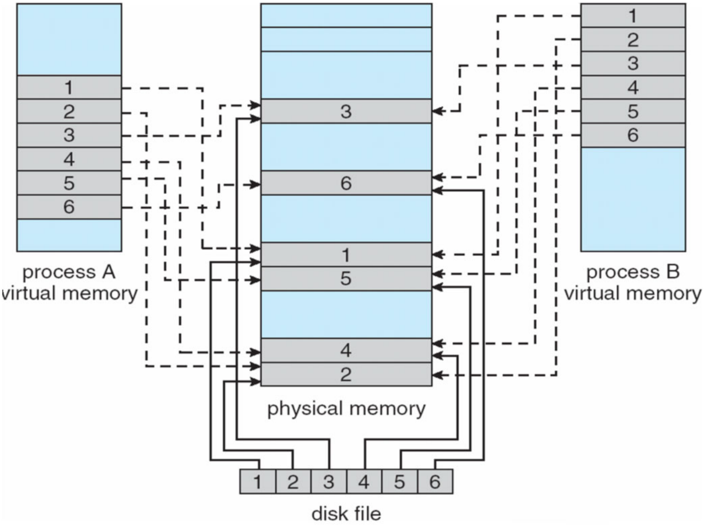
- Some CISC instructions are difficult to restart such as
  - Block move of overlapping areas, string move instructions
  - Auto-increments/decrements of multiple locations
  - Instructions that keep and update state in source **`%esi`**, destination **`%edi`**, and counter **`%ecx`** registers

- Possible Solutions
  - Touch all relevant pages before operation starts
  - Keep modified data in registers so that page faults can't take place
  - Design ISA such that complex operations can execute partially and leave consistent state on a page fault (easy job for the OS)

Shared Library/Code Using Virtual Memory



Memory-Mapped Files

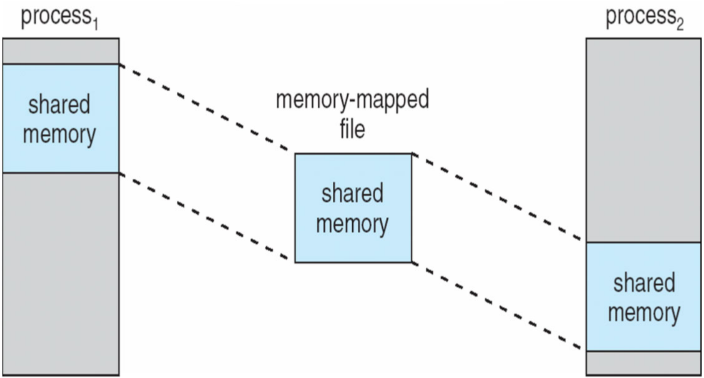


Other Issues – Memory-Mapped Files

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

Shared Data Segments

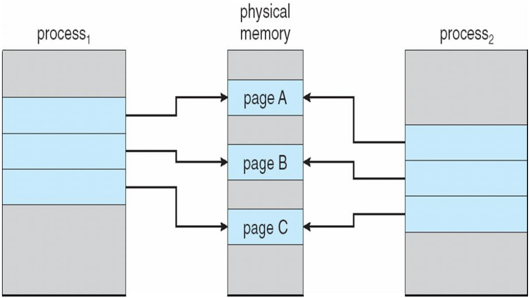
- Shared data segements are often implemented with
  - temporary, anonymous memory-mapped files
  - shared pages (with allocated space on backing store)



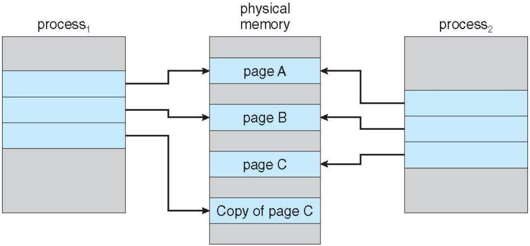
Copy-On-Write

- Copy-on-Write (COW) allows both parent and child process to initially share the same pages in memory
  A page is copied only if one of the processes attempts to modify it
- COW allows more efficient process creation as only modified pages are copied

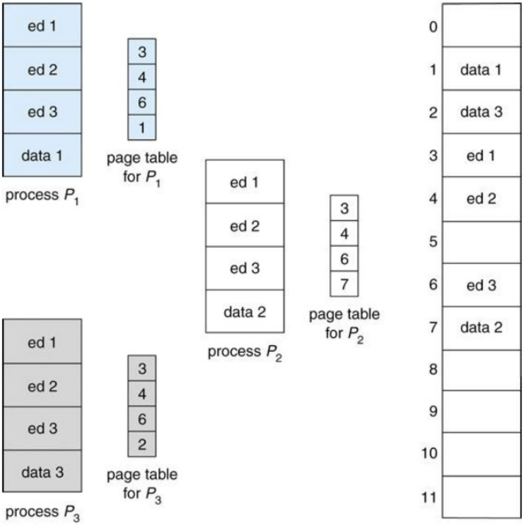
COW: Before Process 1 Modifies Page C



COW: After Process 1 Modifies Page C



Shared Pages Example



Page Frame Allocation

Local vs. Global Allocation

- Global allocation: All frames are considered for replacement
  - Does not consider page ownership
  - One process can get another process's frame
  - Does not protect process from a process that hogs all memory

- Local allocation: Only frames of the faulting process are considered for replacement
  - Isolates processes (or users)
  - Separately determine how many frames each process gets

Fixed Allocation

- Equal allocation: All processes get the same amount of frames
  - e.g., there are 100 frames and 5 processes → each process gets 20 frames

- Proportional allocation: Allocate according to the size of the process

$s_i =$ size of process p_i
$S = \sum s_i$
$m =$ total number of frames

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

Example: $m = 64$
$s_1 = 10$
$s_2 = 127$

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

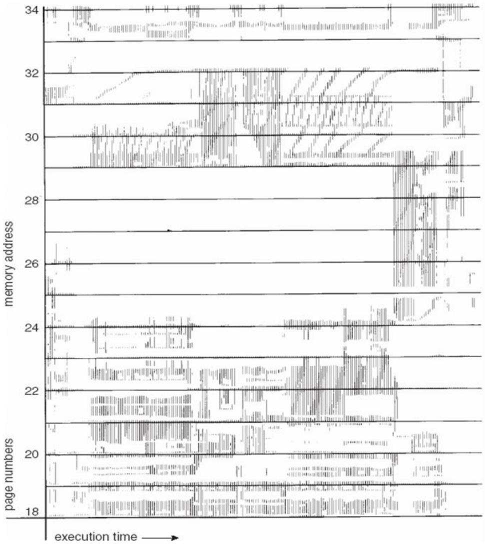
Priority Allocation

- Priority Allocation (global replacement)
  - Proportional allocation scheme using priorities rather than size
- If process P_i generates a page fault
  - Select one of its frames for replacement or
  - Select a frame from a process with lower priority

Memory Locality

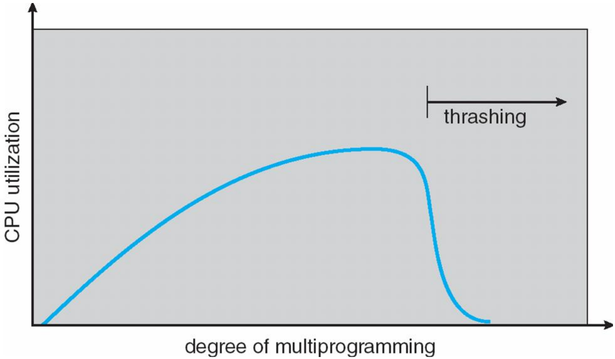
- Background storage is much slower than memory
  - Paging extends memory size using background storage
  - Goal: Run near memory speed, not near background storage speed
- Pareto principle applies to working sets of processes
  - 10% of memory gets 90% of the references
  - Goal: Keep those 10% in memory, the rest on disk
- Problem: How do we identify those 10%?

Locality in a Memory-Reference Pattern



Thrashing

- Thrashing: The system is busy swapping pages in and out
  - Each time one page is brought in, another page, whose contents will soon be referenced, is thrown out
  - Effect: Low CPU utilization, processes wait for pages to be fetched from disk
  - Consequence: OS “thinks” that it needs higher degree of multiprogramming



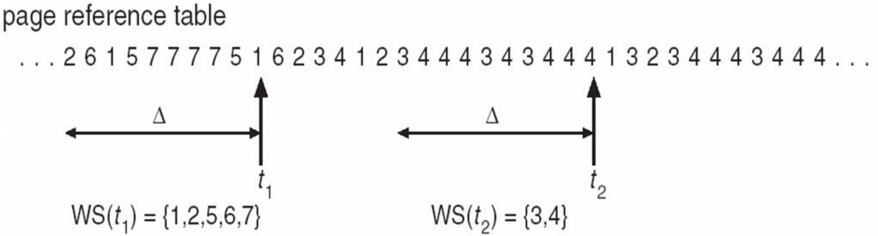
Reasons for Thrashing

- Access pattern has no temporal locality
  - Process doesn't follow the pareto principle
  - Past $\neq$ future
- Each process fits individually, but too many for system
  - Degree of multiprogramming too high
- Memory too small to hold hot memory of a single process (the 10%)
- Page replacement policy doesn't work well
  - We will talk about page replacement policies at length next lecture
  - For now we'll just establish the concepts

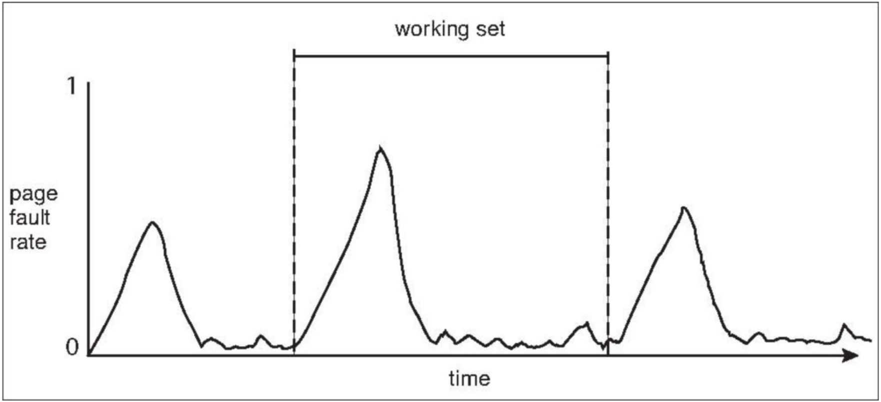
Working-Set Model

- Δ: Working-set window
  - A fixed number of page references
  - Example: 10,000 instructions ($\#$instruction $=$ $\#$page ref?)
- WSS$_i$: Working set of process P_i
  - Total number of pages referenced in the most recent Δ (varies in time)
  - Δ too small: Will not encompass entire locality
  - Δ too large: Will encompass several localities
  - $\Delta = \infty$: Will encompass entire program
- $D = \sum \text{WSS}_i$: Total demand for frames
- If $D > m$: Thrashing
  - Policy: If $D > m$, suspend a process

Working-Set Model



Working Set and Page Fault Rates



Keeping Track of the Working Set

- Ideally: Replace page that is referenced furthest in the future (oracle)
  - Problem: Cannot predict the future
- Idea: Predict future from past
  - Record page references from the past and extrapolate them into the future (we will see how in the next lecture)
  - Problem: Too expensive to make an ordered list of all page references at run-time
- Idea: Sacrifice precision for speed
  - The MMU automatically sets the reference bit in the respective page table entry every time a page is referenced
  - Set a timer to scan all page table entries for reference bits

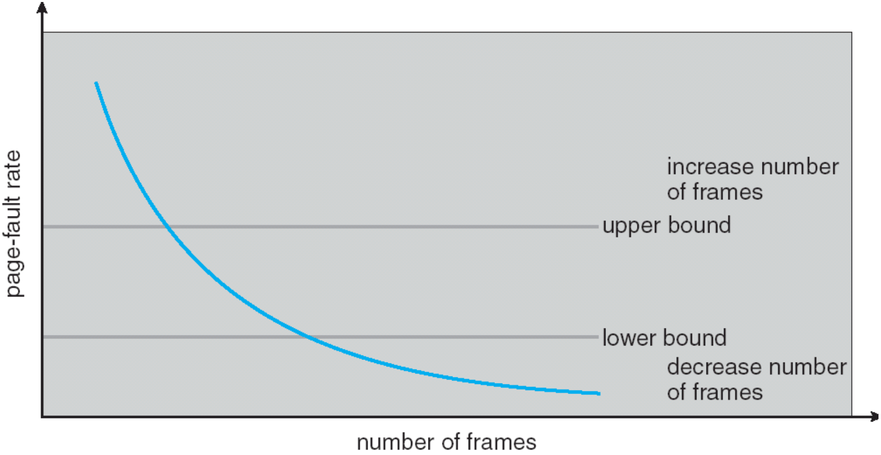
Example: Keeping Track of the Working Set

- $\Delta = 10,000$
- Timer interrupts after every 5,000 time units
- Keep 2-bit history for each page in addition to the reference-bit
  On timer interrupt, do for each page:
  - Shift reference bit into the 2-bit history
  - Reset reference bit
- If history $\neq$ 0: Page is in working set

- Not accurate, because window is moving in large steps
  - Improvement: 10 bits and interrupt every 1000 time units

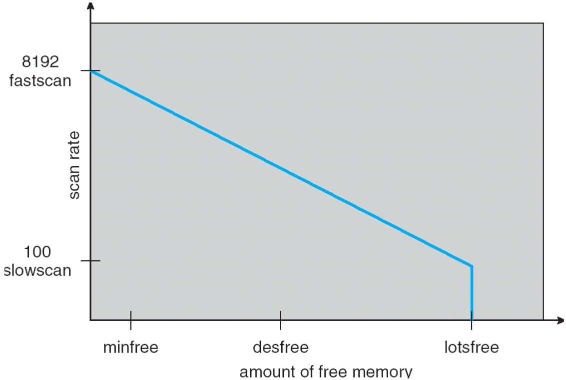
Page Fault Frequency Allocation Scheme

- Establish “acceptable” page fault rate
  - If actual rate too low, give frames to other process
  - If actual rate too high, allocate more frames to process



Solaris

- Maintains a list of free pages to assign to faulting processes
- Paging is performed by *pageout* process
  - Scans pages using modified clock algorithm
  - *Scanrate* ranges from *slowscan* to *fastscan*
- Free memory thresholds determine the behavior of *pageout*
  - *Lotsfree*: Begin paging
  - *Desfree*: Increase paging
  - *Minfree*: Begin swapping



Page Fetch Policy: Demand-Paging

- When should the OS allocate new pages?
  - Two possibilities: Pre-paging and demand-paging

- Demand-Paging: Transfer only pages that raise page faults

+ Only transfer what is needed
+ Less memory needed per process
  (higher degree of multiprogramming possible)

– "Many" initial page faults when a task starts
– More I/O operations → More I/O overhead

Page Fetch Policy: Pre-Paging

- Pre-Paging: Speculatively transfer pages to RAM
  - At every page fault: speculate what else should be loaded
  - E.g., load entire text section when starting process

\+ Improves disk I/O throughput by reading chunks

– Wastes I/O bandwidth if page is never used

– Can destroy the working set of other processes in case of page stealing

Summary

- Paging simulates a memory size of the size of virtual memory
- When pages are filled via page faults some questions need to be answered by the OS
  - What to eject?
  - What to fetch?
  - How to resume a process after a fault?
- When allocating frames and replacing pages different strategies can be followed
  - Local vs. global allocation
  - Fixed vs. proportional vs. priority allocation
- The working sets of the active processes need to be taken into account to prevent thrashing
  - In an ideal world the pager would know all future references
  - In the real world pagers track references in the past to predict the future