Memory management

- Programs use logical addresses of their own address space (0..MAX)
- OS kernel usually in a fixed location using physical memory addresses directly
- Rest of the physical memory for user processes and other OS parts
- OS task: memory allocation and process relocation
- Hardware task: address translation (to protect memory)
  - MMU - memory management unit

Basic Memory Management: One program
Monoprogramming without Swapping or Paging

- No memory abstraction, no address space, just an operating system with one user process

Fixed partitions

- Process queue for partition on disk
- In shared queue for all partitions or
- In multiple queues for different sizes,
- No free partition, OS can swap
- Move one process to disk
- PCB always in memory
- Program too large for any partition; programmer has to design solution
- Overlaying: keep just part of the program in memory
- Write the program to control the part swapping between memory and disk
Relocation and Protection
- Cannot be sure where program will be loaded in memory
  - Address locations of variables, code routines cannot be absolute
  - Must keep a program out of other processes' partitions
- Use base and limit values
  - Address locations added to base value to map to physical address locations larger than limit value is an error
- Address translation by MMU (hardware)

Sharing
- Access to shared code / data
  - No violation of the protections!
- Shared code
  - Must be reentrant, not to change during execution
  - Just one copy of the shared code (e.g., library)
- Shared data
  - Processes co-operate and share data structures
  - E.g., shared buffer of producer and consumer
- Solution: system calls between processes, threads within a process (more solutions in virtual memory)

Swapping (1)
- Memory allocation changes as processes come into memory and leave memory
- Shaded regions are unused memory

Swapping (2)
- (a) Allocating space for growing data segment
- (b) Allocating space for growing stack & data segment

Fragmentation (pirstoutuminen)
- No fixed predetermined partition sizes
- External fragments: $6M + 6M + 4M = 14M$
- OS could occasionally reorganize the memory (compaction)

Memory Management: bookkeeping allocations and free areas
- Part of memory with 5 processes, 3 holes
  - Tick marks show allocation units
  - Shaded regions are free
- (b) Corresponding bit map
- (c) Same information as a list
Combining freed areas

Four neighbor combinations for the terminating process X

Allocation

Where to place the new process?

Goal: avoid external fragmentation and compaction

Some alternatives:
- Best-fit
- First-fit
- Next-fit
- Worst-fit
- Quick-fit

Virtual memory (using paging)

Paging

Each process has own page table
- Contains the locations (frame numbers) of allocated frames
- Page table location stored in PCB, copied to PTR for execution
- OS maintains a table (or list) of page frames, to know which are unallocated

Paging: Address Translation

MMU has one special register, Page Table Register (PTR), for address translation
Paging: Address Translation

- Each process has its own page table
- Each entry has a present bit, since not all pages need to be in the memory all the time -> page faults
- Remember the principle of locality
- Logical address space can be much larger than the physical

Page Table

- Typical Page Table Entry, Fig. 3.11

Translation Lookaside Buffer - TLB (osoitteenuunnospuskuri)

Goal is to speed up paging
TLB is a cache in MMU for page table entries (hardware issue)
**TLB - translation lookaside buffer**
- Part of memory management unit (MMU)
  - Cache for used page table entries to avoid extra memory access during address translation
- Associative search
  - Compare with all elements at the same time (fast)
- Each process uses the same page numbers 0, 1, 2, ..., stored on different page frames
  - TLB must be cleared during process switch
  - At least clear the validity bits (this is fast)

**Operation of Paging and TLB**

**Multilevel and Inverted Page Tables**
- Large virtual address space
  - Logical address could be 32- or 64-bits
- Each process has a large page table
  - Using 32-bit address and frame size 4KB (12 bit offset), means $2^{20} = 1M$ of page table entries for a single process
  - Each entry requires several bytes (lets say 4 bytes), so the final size of page table could be for example 4 MB
- Thus the page table is divided to several pages also and part of it can be on the disk
- Only the part of the page table that covers the pages used currently in the execution of the process is in memory
Two-level hierarchical page table
- Top-most level in one page and always in the memory

```
4-K byte-level page table
4-Mbyte-level page table
4-Gbyte-level page table

1 K entries (= 1024 = 2^10)
```

Address translation with two levels
(Fig 4-12 [Tane01])

Address translation with two levels

Inverted Page Tables
Comparison of a traditional page table with an inverted page table

Inverted page table
- Physical memory often smaller than the virtual address space of processes
- Invert booking: Store for each page frame what page (of which process) is stored there
  - Only one global table (inverted page table), one entry for each page frame.
  - Search for the page based on the content of the table
    - Inefficient, if done sequentially.
    - Use hash to calculate the location, start search from there
    - If page not found, page fault
  - Useful, only if TLB is large

Inverted page table
- Frame number
  - Index of the table
  - Not stored in the entry

Figure 8.4 A Two-Level Hierarchical Page Table
Figure 8.6 Inverted Page Table Structure
Virtual memory
Operations and policies
Chapters 3.4. – 3.7

Policies and methods
- Fetch policy (Noutopolitiikka)
  - When to load page to memory?
- Placement policy (Sijoituspolitiikka)
  - Where to place the new page?
- Replacement policy (Korvaus/poistopolitiikka)
  - Which page to be evicted and replaced?
- Cleaning policy (Levylle kirjoituskirjoitus-politiikka)
  - When to evict a modified page?
- Multiprogramming, load control (Majoitusa)l
  - How many processes in the system at the same time?
  - How much memory, how many pages per process?
- Working set (Käyttöjoukko)
  - How many page frames allocated for one process?(resident set)
  - Which areas have been referenced recently?

Page fault (Sivun puutos)
- If the requested page is not in memory, MMU causes interrupt
- OS process the interrupt and notice a page fault
  - Move the process to blocked state
  - Allocate page frame for the new page
  - Start page load from disk using driver to command controller
  - Switch another process for execution
- After the device interrupt
  - OS notices the termination of page transfer
  - Move process to ready state
  - Continue the process now or later (scheduling decision)

Locking pages
- To avoid page fault, page can be locked to memory
  - Kernel pages
  - Key data structures of OS
  - I/O buffers (at least during the transfer)
  - Process pages (at least in real time systems)
- How?
  - Page frame table has a lock bit on the frame
  - Per frame
  - Or page table entry has the lock bit
  - Per process

Page replacement
- When?
  - Page fault
  - Memory too full, no free frames (usually some kept free!)
  - Not enough free unallocated frames (limit value)
- Which page to replace?
  - One, that is not needed in the (near) future
    - Predict based on the past behavior
    - Locality principle helps no more references to the page, process passed that phase
    - Sometimes mistakes happen

See Fig 8.1 [Stal05]

Perform page replacement
- Page fault (Sivun puutos)
  - If the requested page is not in memory, MMU causes interrupt
  - OS process the interrupt and notice a page fault
    - Move the process to blocked state
    - Allocate page frame for the new page
    - Start page load from disk using driver to command controller
    - Switch another process for execution
  - After the device interrupt
    - OS notices the termination of page transfer
    - Move process to ready state
    - Continue the process now or later (scheduling decision)