Management of a limited resource:
(Memory hunger of applications increases with capacity!)
⇒ Sophisticated algorithms needed, together with support from HW and from compiler and loader.

Start by looking at mapping from logical addresses to physical addresses:

- at compile time: absolute references are generated (*e.g.*,MS-DOS `.com`-files)
- at load time: can be done by special program
- at execution time: needs HW support

Address mapping can be taken one step further:
dynamic linking: use only one copy of system library
⇒ OS has to help: same code accessible to more than one process

If memory demand is too high, memory of some processes is transferred to disk
Usually combined with scheduling: low priority processes are swapped out

Problems:

- Big transfer time
- What to do with pending I/O?

First point reason why swapping is not principal memory management technique

exception: MS-Windows 3.1: based on MS-DOS for 8086, which is not sophisticated enough (no MMU).
⇒ user decides which process is swapped out
possible only at few pre-defined moments
⇒ multi-processing severely limited
DOS-mode in Windows 9.x has same limitations!

Swapping raises two problems:

- over time, many small holes appear in memory (external fragmentation)
- programs only a little smaller than hole ⇒ leftover too small to qualify as hole (internal fragmentation)

Strategies for choosing holes:

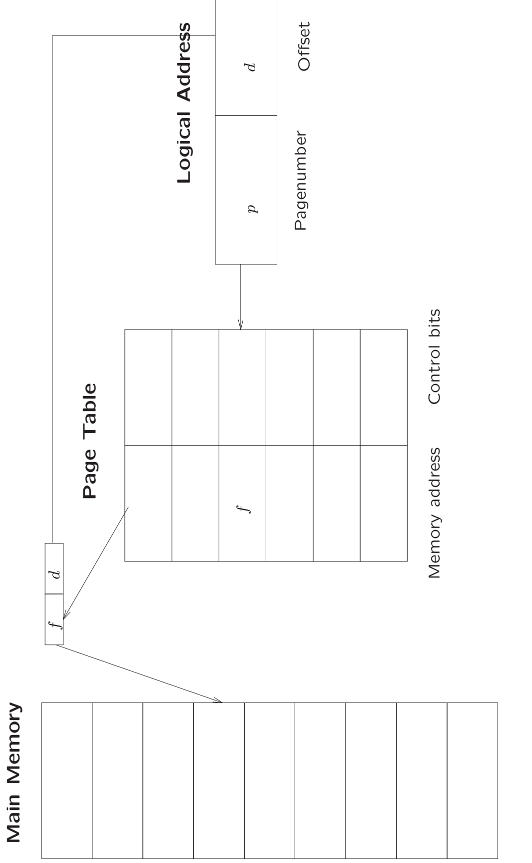
- First-fit: Start from beginning and use first available hole
- Rotating first fit: start after last assigned part of memory
- Best fit: find smallest usable space
- Buddy system: Free holes are administered according to tree structure; smallest possible chunk used

Alternative approach: Assign memory of a fixed size (page)
⇒ avoids external fragmentation
Translation of logical address to physical address done via page table

Hardware support mandatory for paging:
If page table small, use fast registers
Store large page tables in main memory, but cache most recently used entries

Instance of a general principle:
Whenever large lookup tables are required, use cache (small but fast storage) to store most recently used entries

Memory protection easily added to paging:
protection information stored in page table

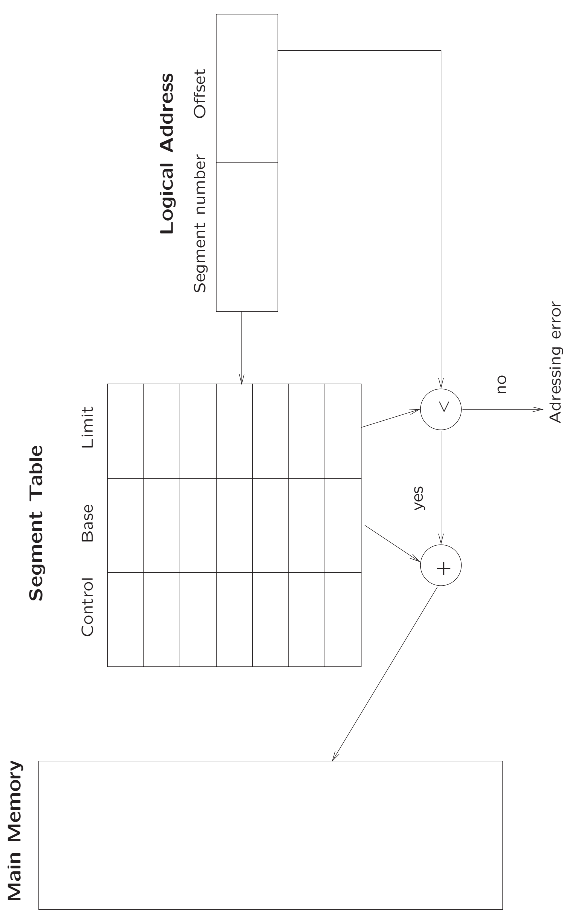


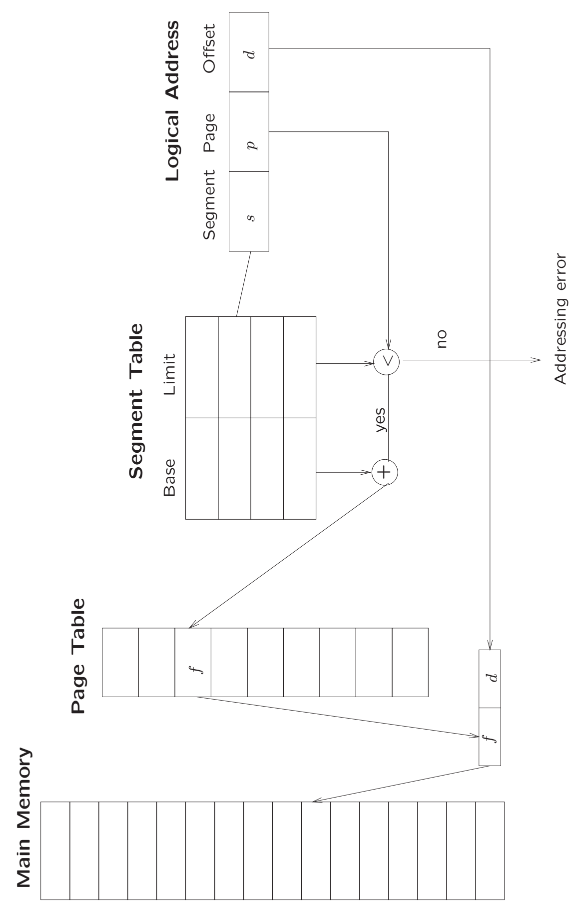
Idea: Divide memory according to its usage by programs:

- Data: mutable, different for each instance
- Program Code: immutable, same for each instance
- Symbol Table: immutable, same for each instance, only necessary for debugging

Requires again HW support
can use same principle as for paging, but have to do overflow check

Paging motivated by ease of allocation, segmentation by use of memory
⇒ combination of both works well (*e.g.*, 80386)





Idea: complete separation of logical and physical memory
⇒ Program can have extremely large amount of virtual memory

Generalisation of paging and segmentation works because most programs use only small fraction of memory intensively.

Efficient implementation tricky
Reason: Enormous difference between
- memory access speed (ca. 60ns)
- disk access speed (ca. 6ms)

Factor 100,000 !!

Virtual memory implemented as demand paging:

memory divided into units of same length (pages), together with valid/invalid bit

Two strategic decisions to be made:

- Which process to "swap out" (move whole memory to disk and block process): done by swapper
- which pages to move to disk when additional page is required: done by pager

Minimisation of rate of page faults (page has to be fetched from memory) crucial

If we want 10% slowdown due to page fault, require fault rate $p < 10^{-6}$!!

1.) FIFO:
easy to implement, but does not take locality into account
Further problem: Increase in number of frames can cause increase in number of page faults (Belady's anomaly)

2.) Optimal algorithm:
select page which will be re-used at the latest time (or not at all)
⇒ not implementable, but good for comparisons

3.) Least-recently used:
use past as guide for future and replace page which has been unused for the longest time

Problem: Requires a lot of HW support
Possibilities:
-Stack in microcode
-Approximation using reference bit: HW sets bit to 1 when page is referenced.
Now use FIFO algorithm, but skip pages with reference bit 1, resetting it to 0
⇒ Second-chance algorithm

If process lacks frames it uses constantly, page-fault rate very high.
$\Rightarrow$ CPU-throughput decreases dramatically.
$\Rightarrow$ Disastrous effect on performance.

Two solutions:
1.) Working-set model (based on locality):
Define working set as set of pages used in the most recent Δ page references
keep only working set in main memory
$\Rightarrow$ Achieves high CPU-utilisation and prevents thrashing

Difficulty: Determine the working set!
Approximation: use reference bits; copy them each 10,000 references and define working set as pages with reference bit set.

2.) Page-Fault Frequency:
takes direct approach:
- give process additional frames if page frequency rate high
- remove frame from process if page fault rate low