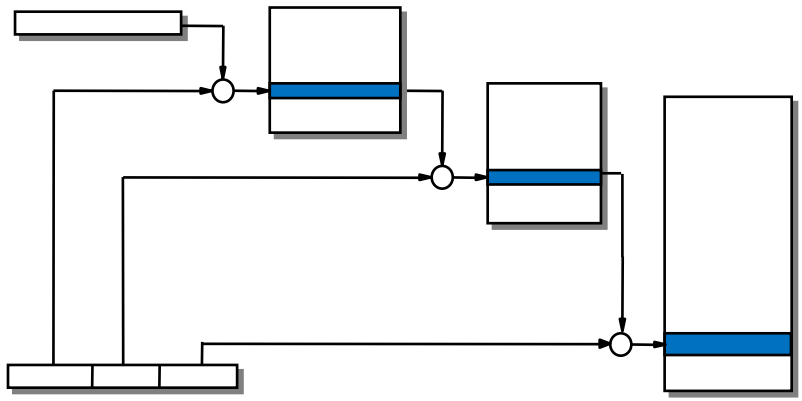
"640 Kilobyte ought to be enough for anybody."
-- Bill Gates, 1981

"Wir haben so viel Speicher, den müssen wir gar nicht managen."

-- Abraham Söyler, 2018

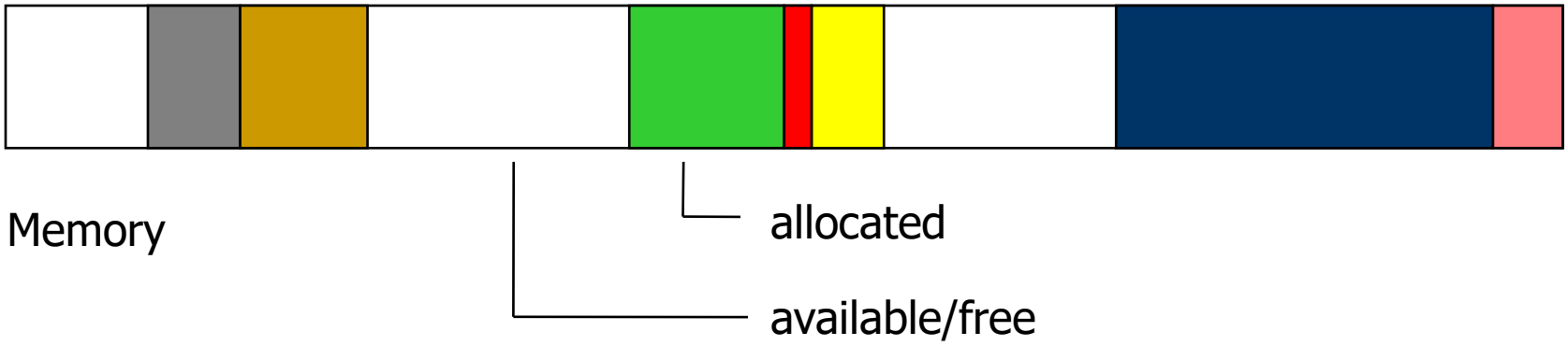
Chapter 7

Memory Management



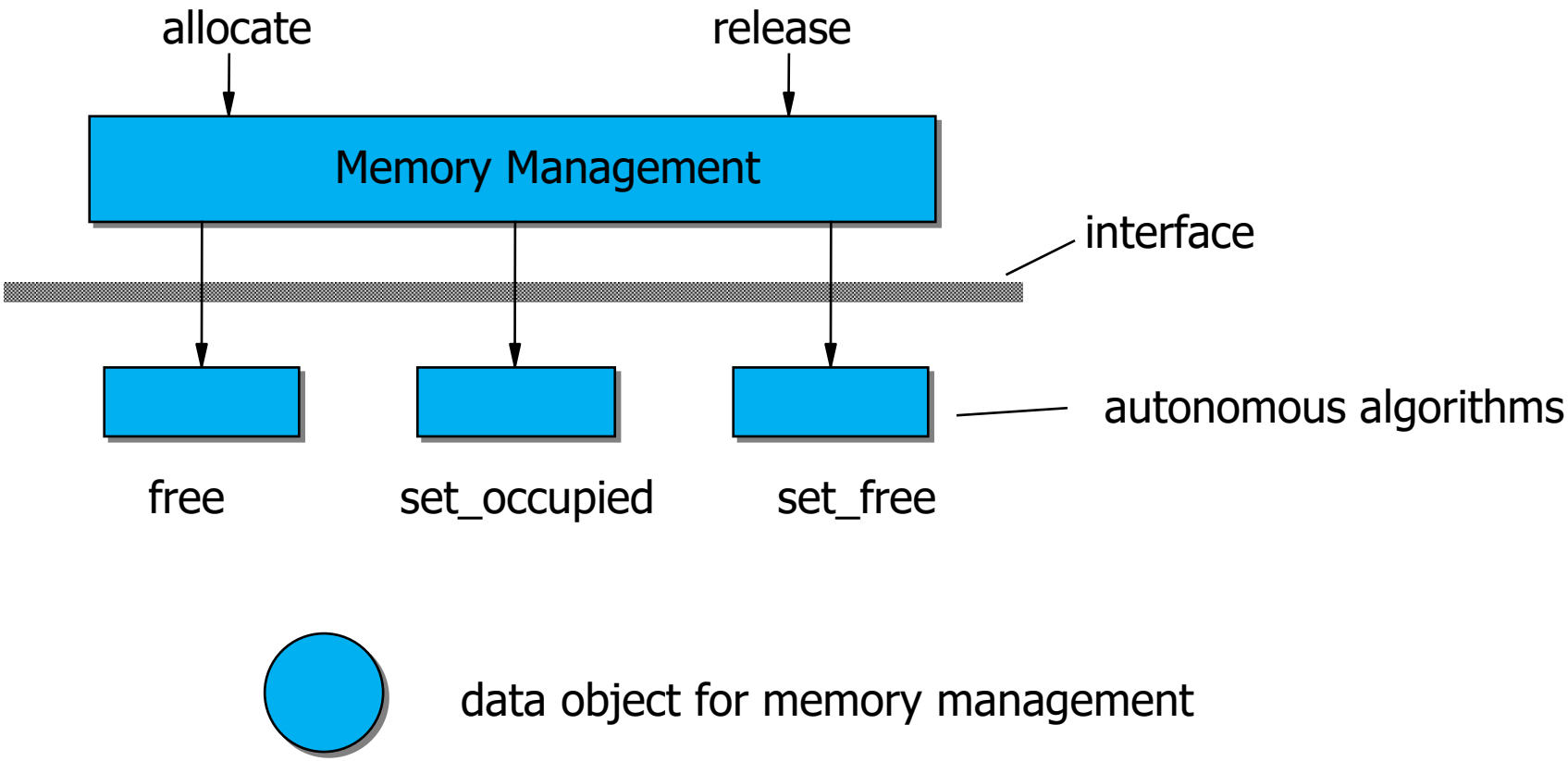
7.1 Allocation strategies

- Problem



- Selection of memory sections/pieces
- Efficiency of algorithms
- Memory usage
- Problem conditions
- Application area: (real) Main Memory (and Swap Space)

Structure of Memory Management



Design parameters

- Memory management strategies can be distinguished based on:
  - Sequence of operation
  - Size of pieces
  - Representation of allocation
  - Fragmentation
  - Allocation strategies (with free pieces)
  - (Re-)integration

Sequence of operation

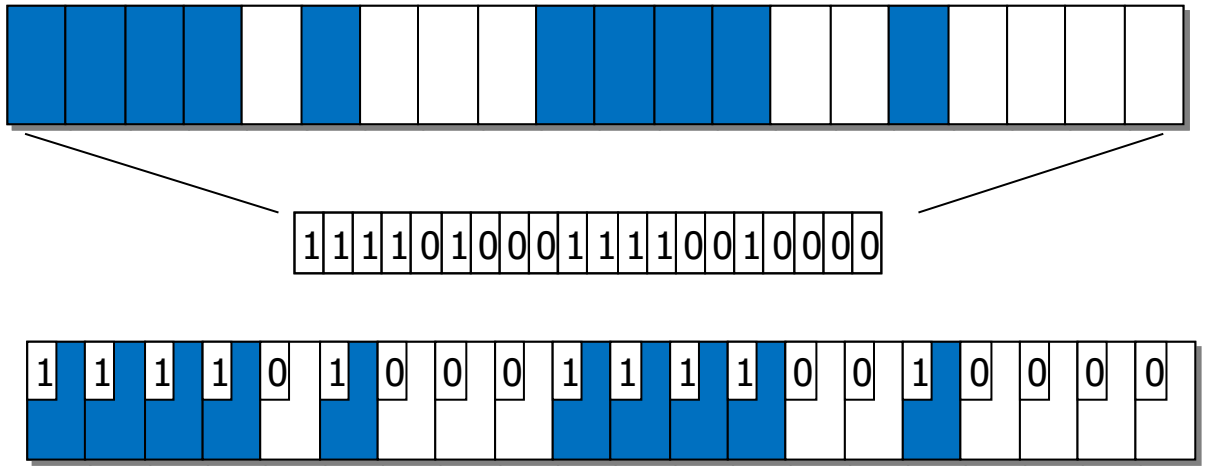
- Allocation and release
  - in same order
    - Queing approaches, FIFO = First In First Out
  - in reverse order
    - Batch approaches, LIFO = Last In First Out
  - in arbitrary order
    - General approach

Size of pieces

- Constant size
  - NUM = 1 (unit size)
- Multiple of constant size
  - NUM = k (unit size)
- Given size of partitions
  - NUM = k_1, k_2, k_3, …
- Arbitrary size
  - NUM = x

Representation of allocation

- How?
  - Vector
  - Table
- Where?
  - Separated
  - Integrated

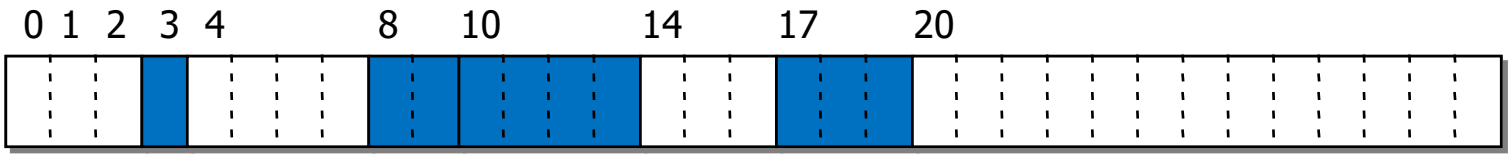


Representation by vector separated and integrated

- Example
  - Main Memory 128 Mbyte (2^{27} Byte)
  - Unit size 512 Byte (2^{9} Byte)
  - Sum 262144 Units (2^{18})
  - Representation with 8192 words with 32 Bit

Representation of allocation

- Representation by table
  - Separated representation
  - Holding information about allocation in table
  - Sorting by address and/or length



Sorted by address

Address	Length
0	3
4	4
14	3
20	13

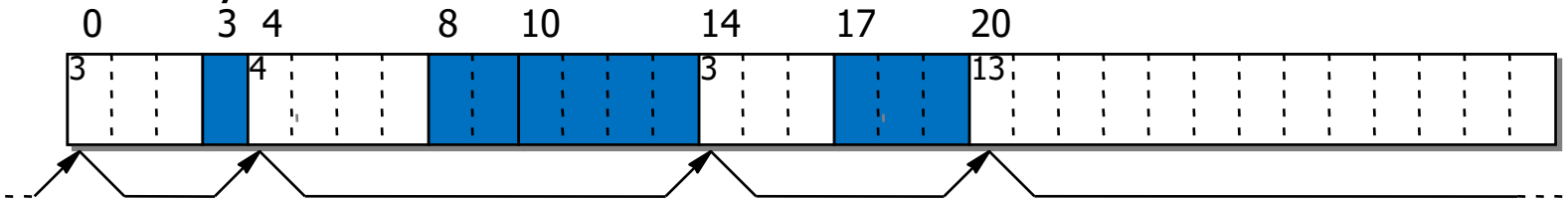
Sorted by length

Length	Address
3	14
3	0
4	4
13	20

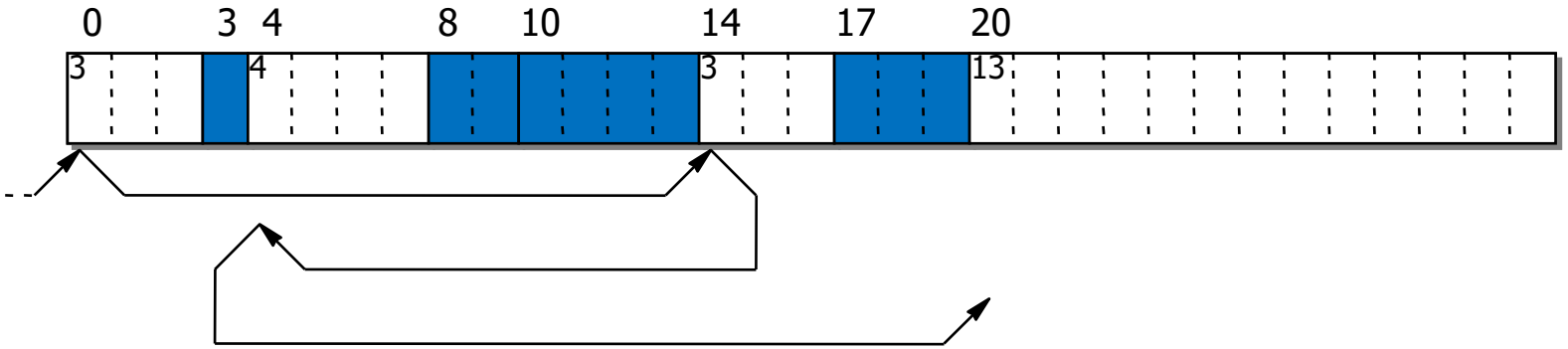
Representation of allocation

- Integrated representation (by table)
  - Pieces identify itself, specify length and provide pointer to next element of free list.

Sorted by address



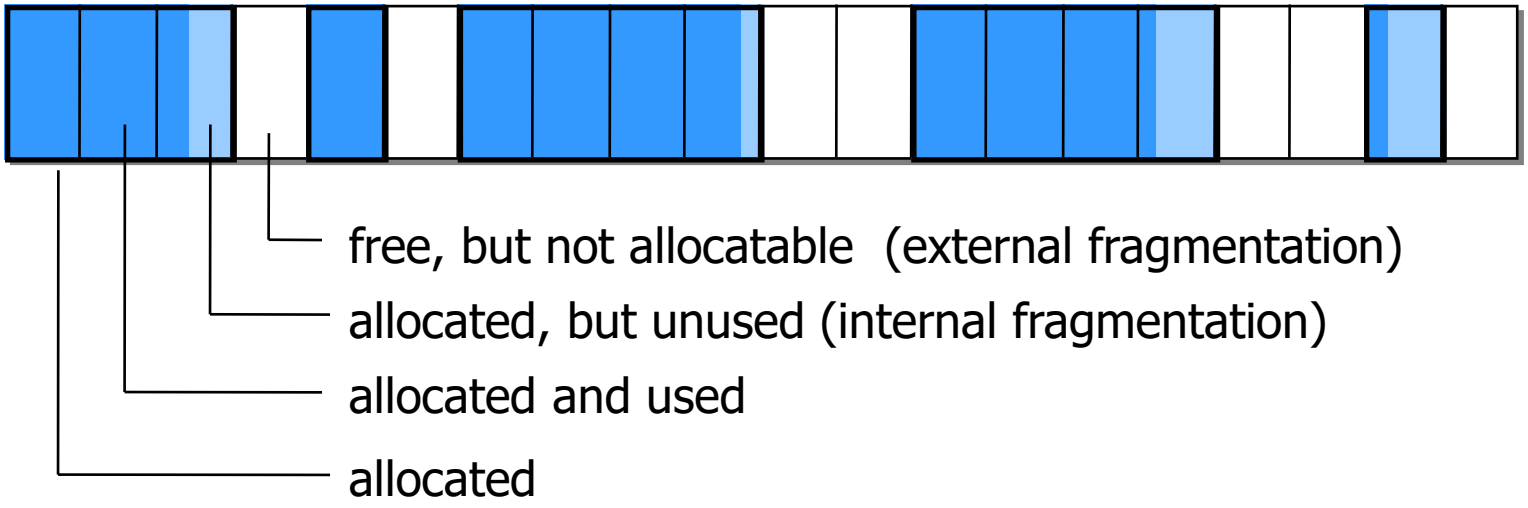
Sorted by length



Fragmentation

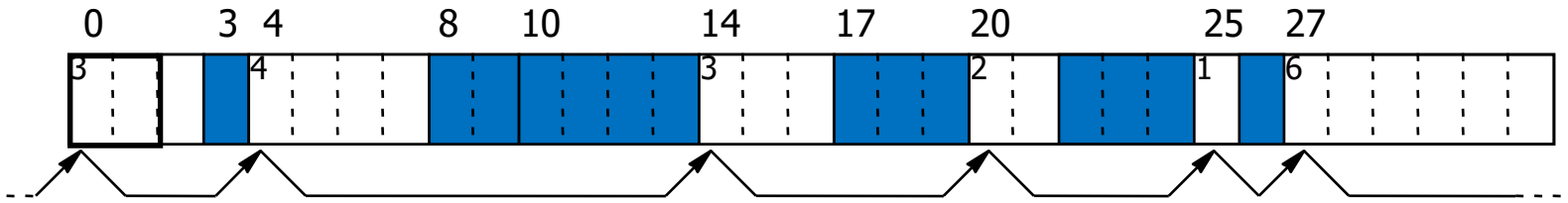
- Usually memory is allocated for multiple of units.
- Requests therefore are rounded up to the next multiple of units.
- This come with unused parts of the allocated memory.
- The unused piece of memory is called **internal fragmentation f_{int}**.
- Due to the dynamic of allocation and release of pieces it may happen the overall amount of free memory can satisfy a request, but because of the layout of all of the pieces of free memory is cannot be fulfilled.
- So free memory is created, which is not suitable to be used for requests.
- This is called **external fragmentation f_{ext}**.

Fragmentation



Allocation strategies

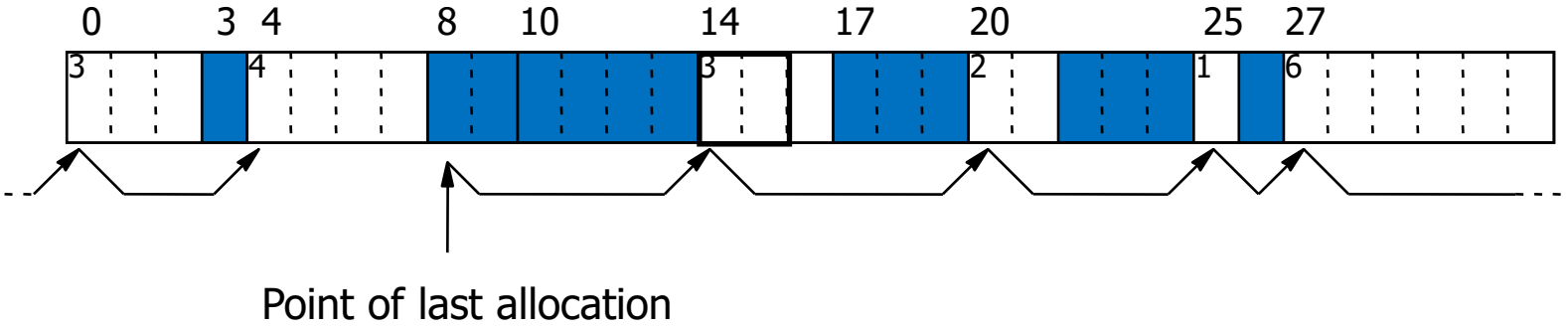
- First Fit strategy



- Search the free list from start.
- Take the first piece of free memory satisfying the request.
- Properties
  - Low search effort (in case of almost empty memory space).
  - External fragmentation
  - Concentration of allocated memory at the begin of the memory space
  - Increased search effort in loaded situations

Allocation strategies

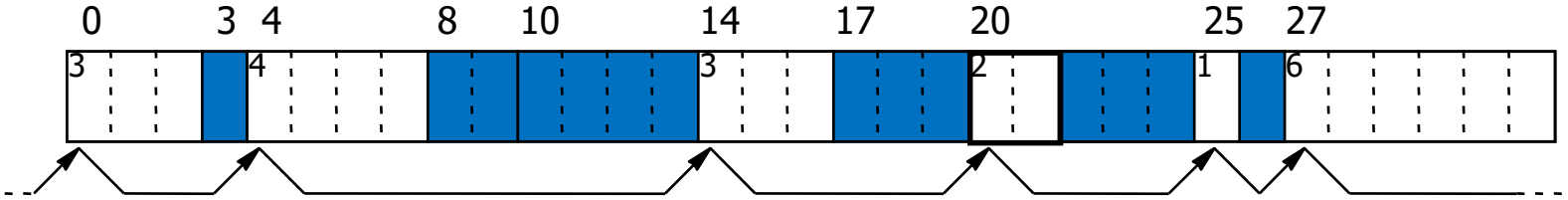
- Next Fit strategy, Rotating First Fit strategy



- Cyclic search of list.
- Search start at the point of last allocation.
- Properties
  - Like First Fit, but without concentration at the begin of the memory space
  - Therefore slightly reduced search effort (memory space not empty).

Allocation strategies

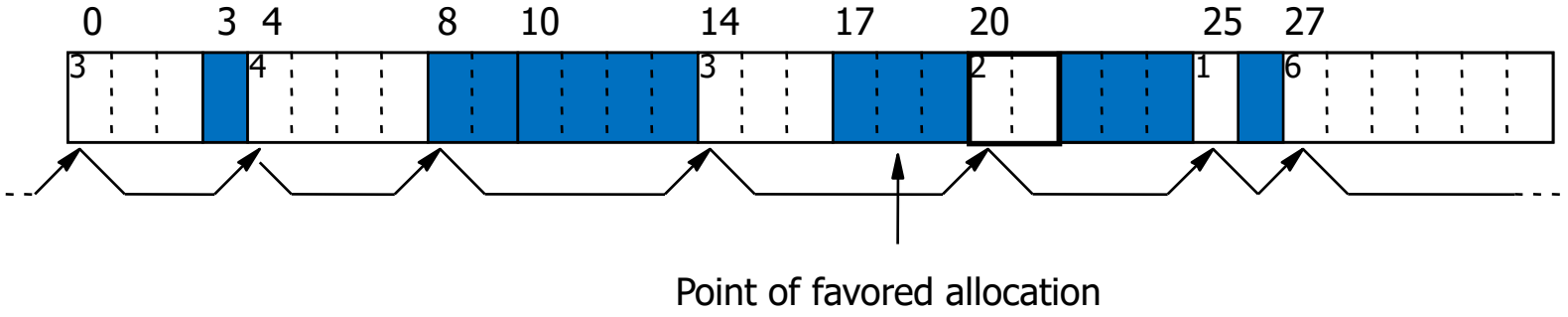
- Best Fit strategy



- Allocation of the smallest piece of memory satisfying the request.
- Properties
  - If sorted by address the whole free list has to be searched.
  - List should be sorted by size of piece of free memory.
  - Usually reduced external fragmentation, because requests for small amount of memory may be served without derogation of larger pieces.
  - But produces very small pieces of free memory unsuitable for any request (external fragmentation).

Allocation strategies

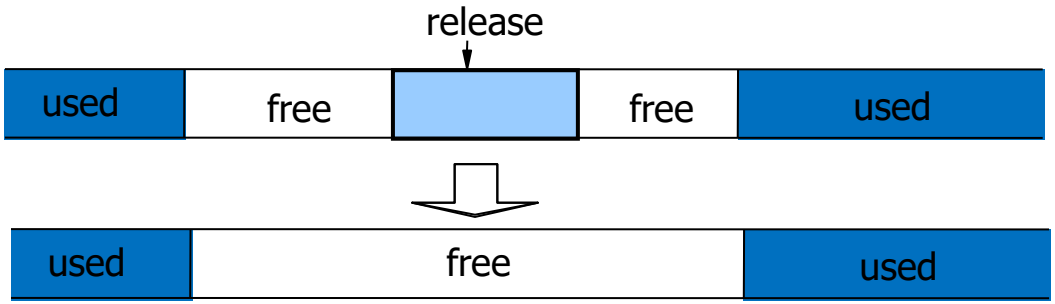
- Nearest Fit strategy



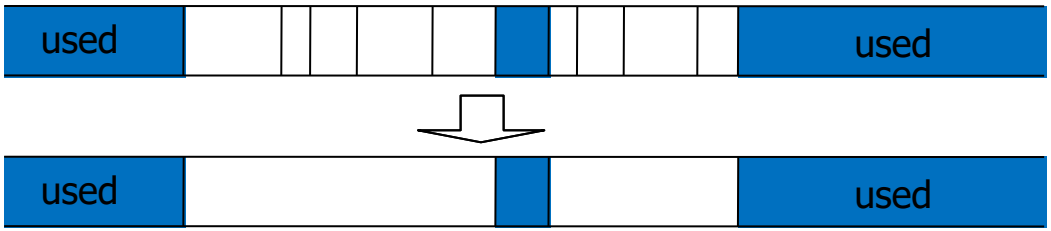
- A favored address is provided.
- Search with First Fit from the point of favored allocation.
- Properties
  - In case of disc space minimizing the movement of disc arm. Especially if the sequence of access is known, the movement of the disc arm can be optimized.
    - File directory information can located in the middle of a cylinder.
    - In case of expansion of files the blocks to be allocated should be located in the neighborhood.

Reintegration

- Instantly after release

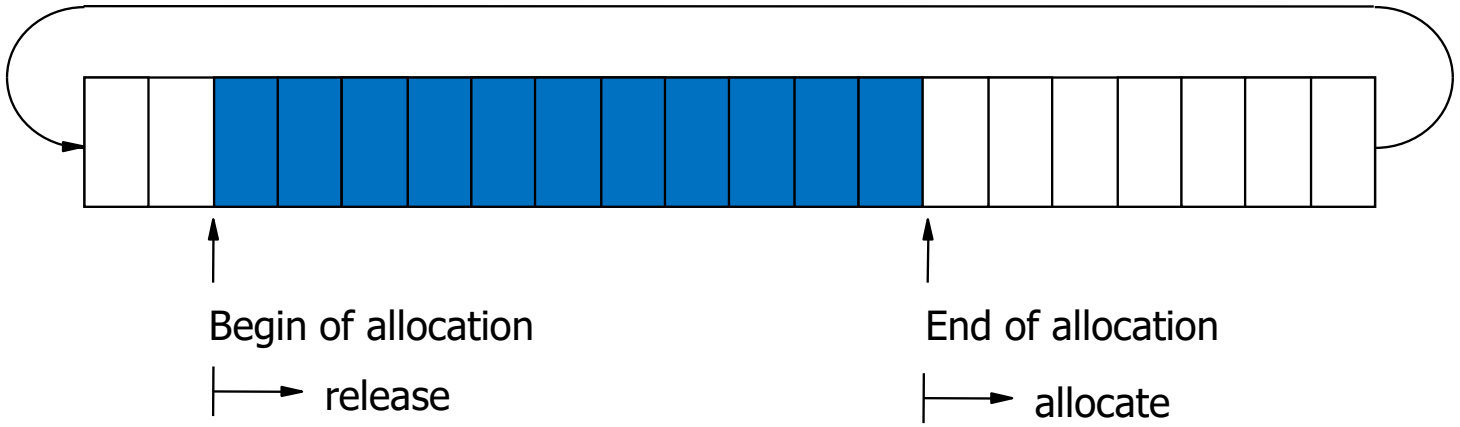


- Delayed aggregation



Examples

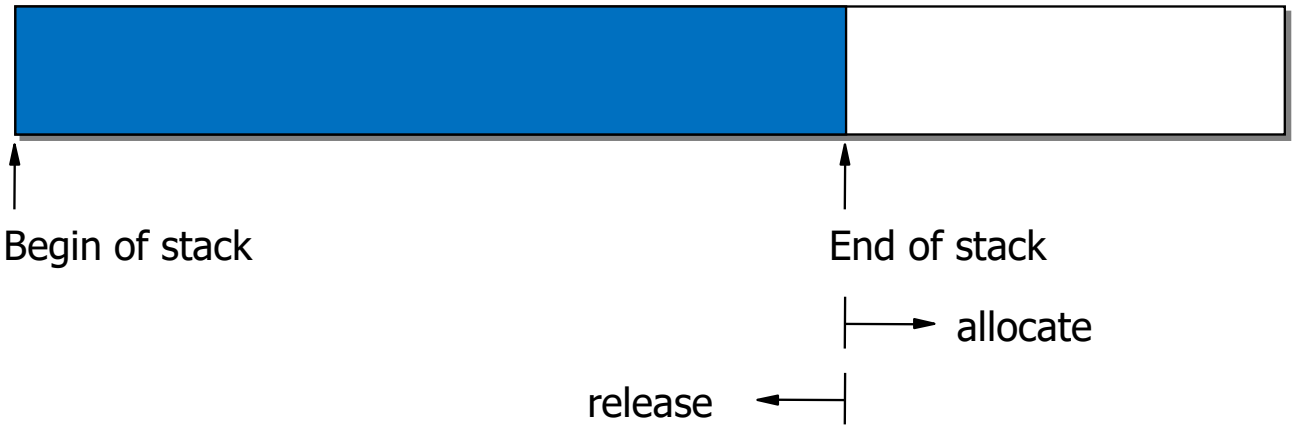
- Ring buffer



- Allocation and release in same direction (FIFO)
- Fix length of pieces
- No search needed
- No external fragmentation
- Automatic and immediate reintegration

Examples

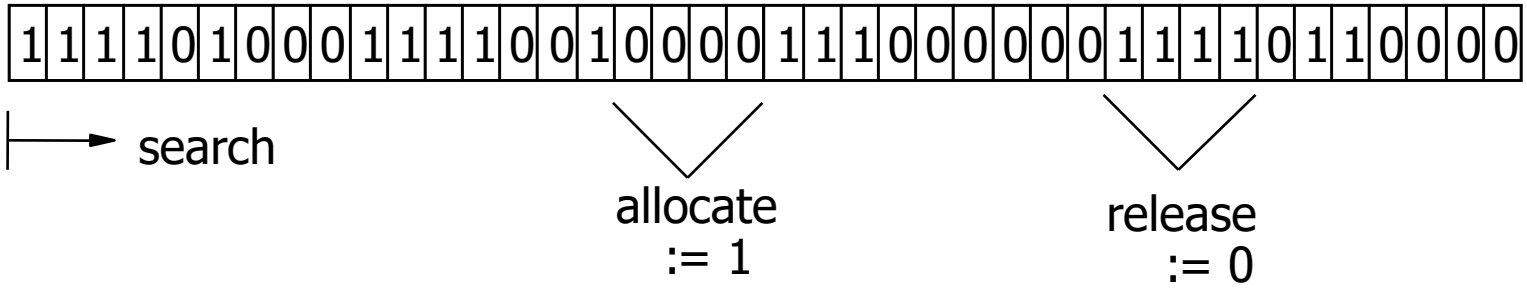
- Stack



- Allocation and release in inverse direction (LIFO)
- Arbitrary length of pieces
- No search needed
- Little external fragmentation
- Automatic and immediate reintegration

Examples

- Vector based approach

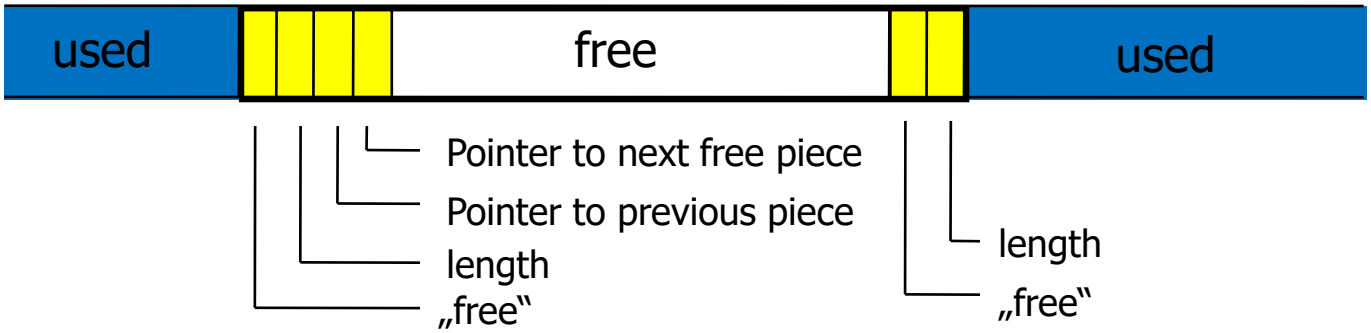


- Allocation and release in arbitrary direction
- Fixed length with k * unit size
- Search for first fitting piece
- Internal and external fragmentation
- Automatic and immediate reintegration

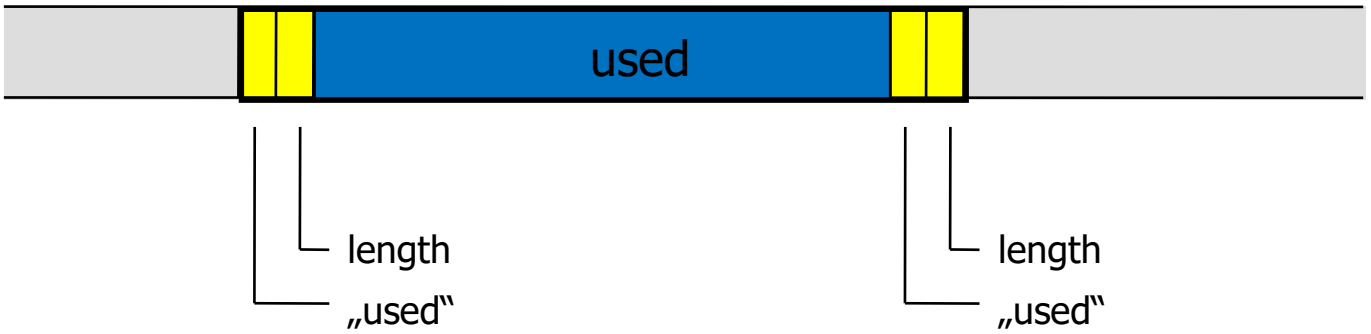
Examples

- Boundary tag system

free piece



used piece

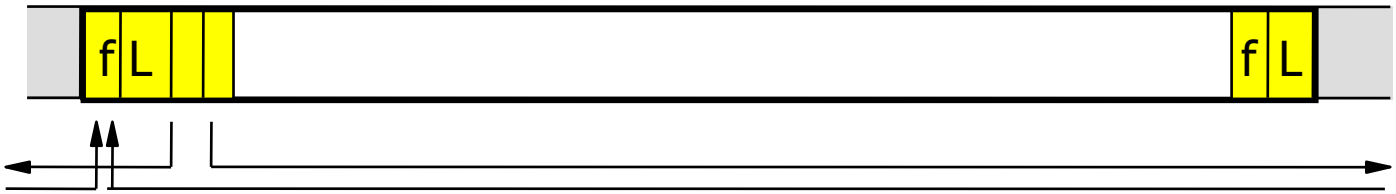


  - Label for pieces
  - Sorted list by size (length)

Boundary tag system

after release

after reintegration



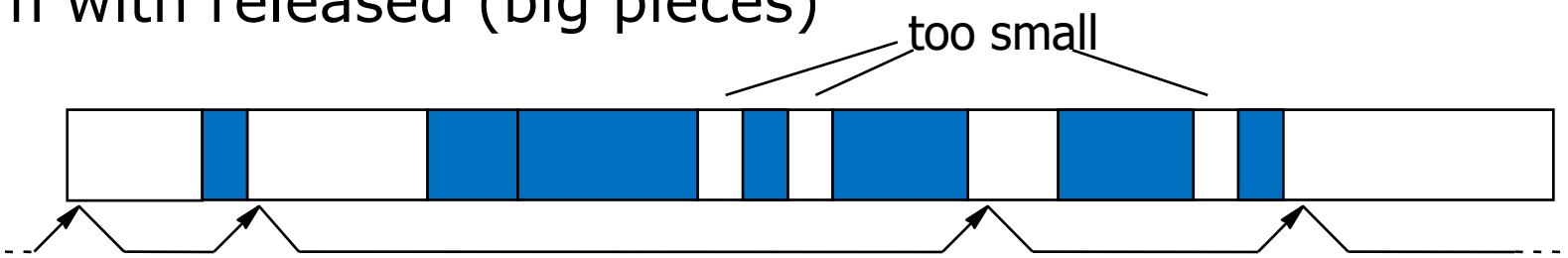
Boundary tag system

- Properties
  - Operation in arbitrary order
  - Allocation of pieces with arbitrary size (length)
  - Integration of management and representation of pieces
    - Doubly linked list sorted by size of pieces
  - Best Fit search strategy
  - External fragmentation
  - Explicit immediate reintegration using length field to check with neighboring pieces
    - Immediate integration into linked list

Optimizations

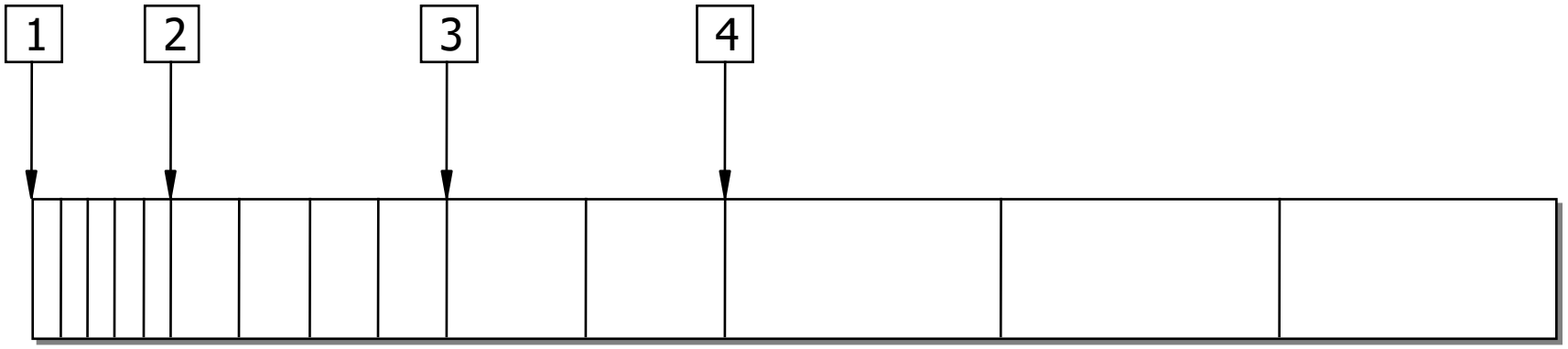
- Reduction of management efforts based on small pieces
- Merge requested piece and small piece (transform external fragmentation into internal fragmentation)

- Avoid integration of small pieces into free list, but merge them with released (big pieces)



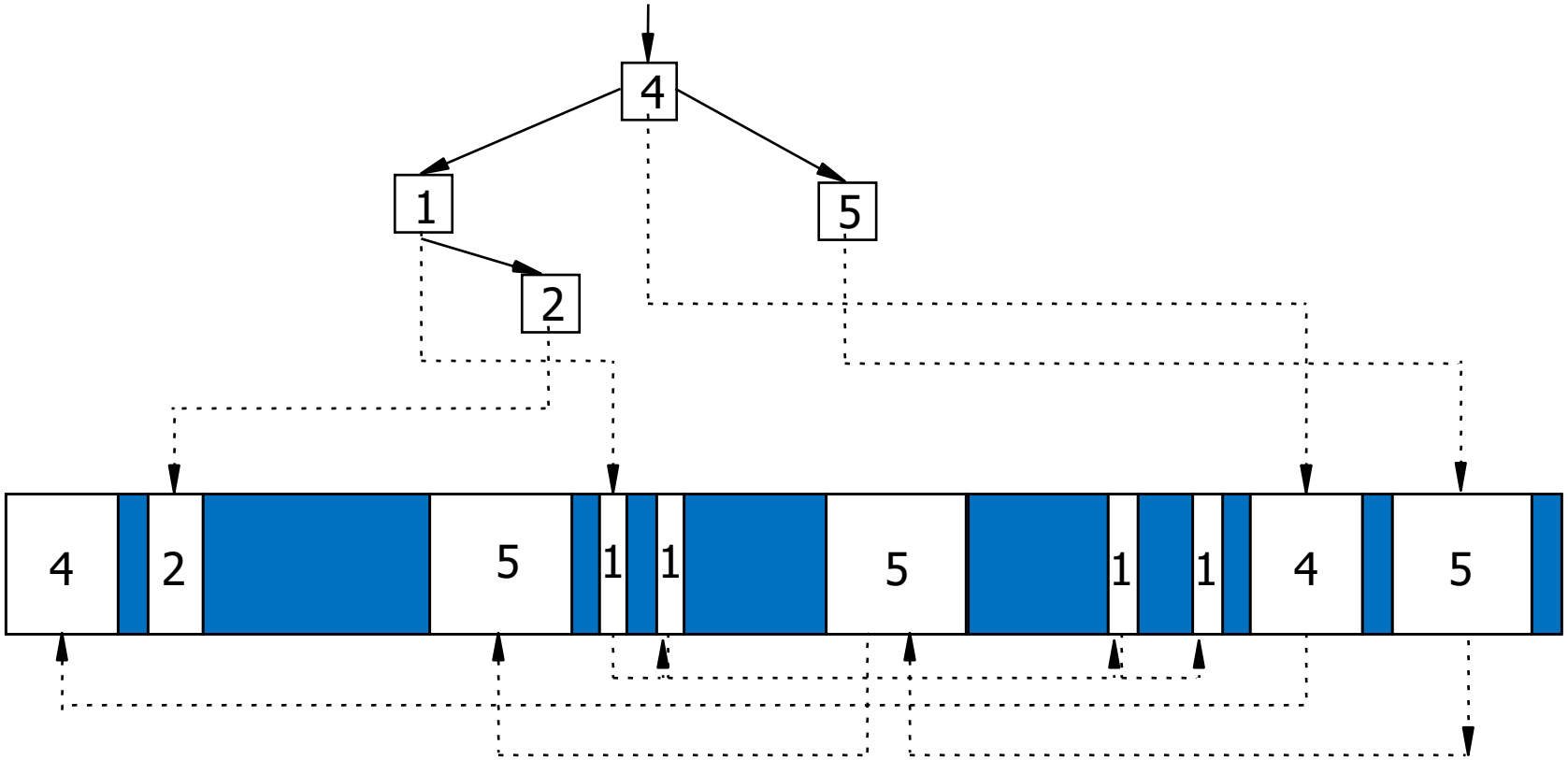
Optimizations

- Cost of search on arbitrary order of allocation and release – O(n)
- Reduce search costs
  - Tailored pieces
    - Given size (length) of pieces
  - Provide number of (statistically) frequently used pieces



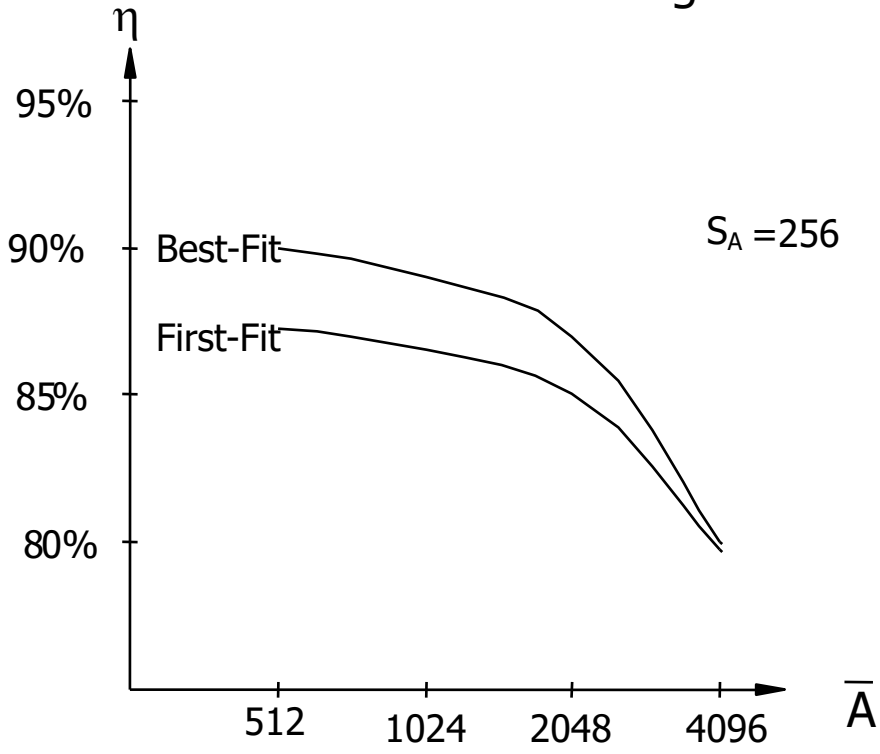
Reduction of search costs

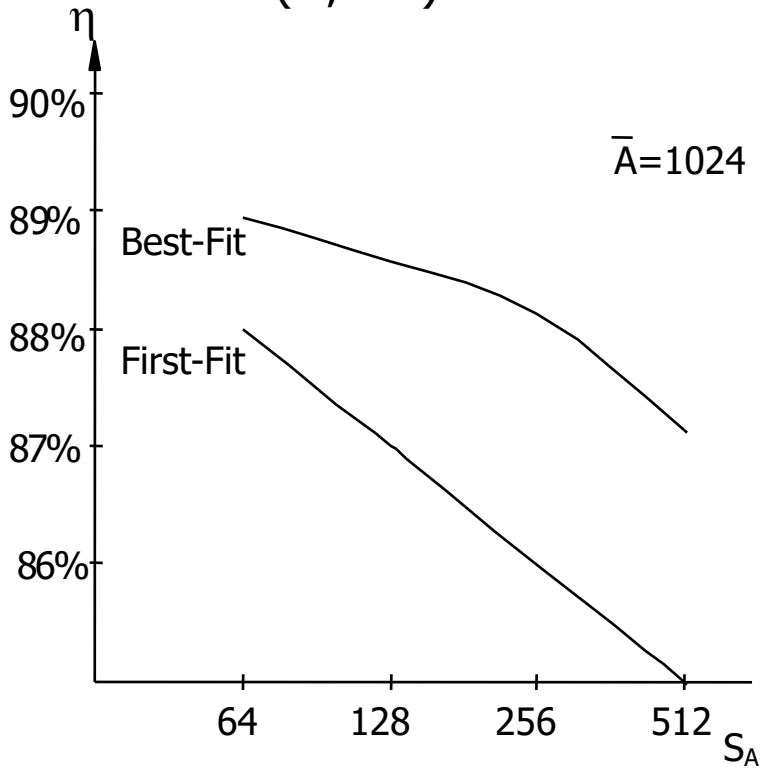
- Example: access by binary tree



Memory usage

- Simulation with 32 K units
- Uniform distribution of requests with mean value A and standard deviation S_A
- Uniform distribution of usage time within interval (5, 15)



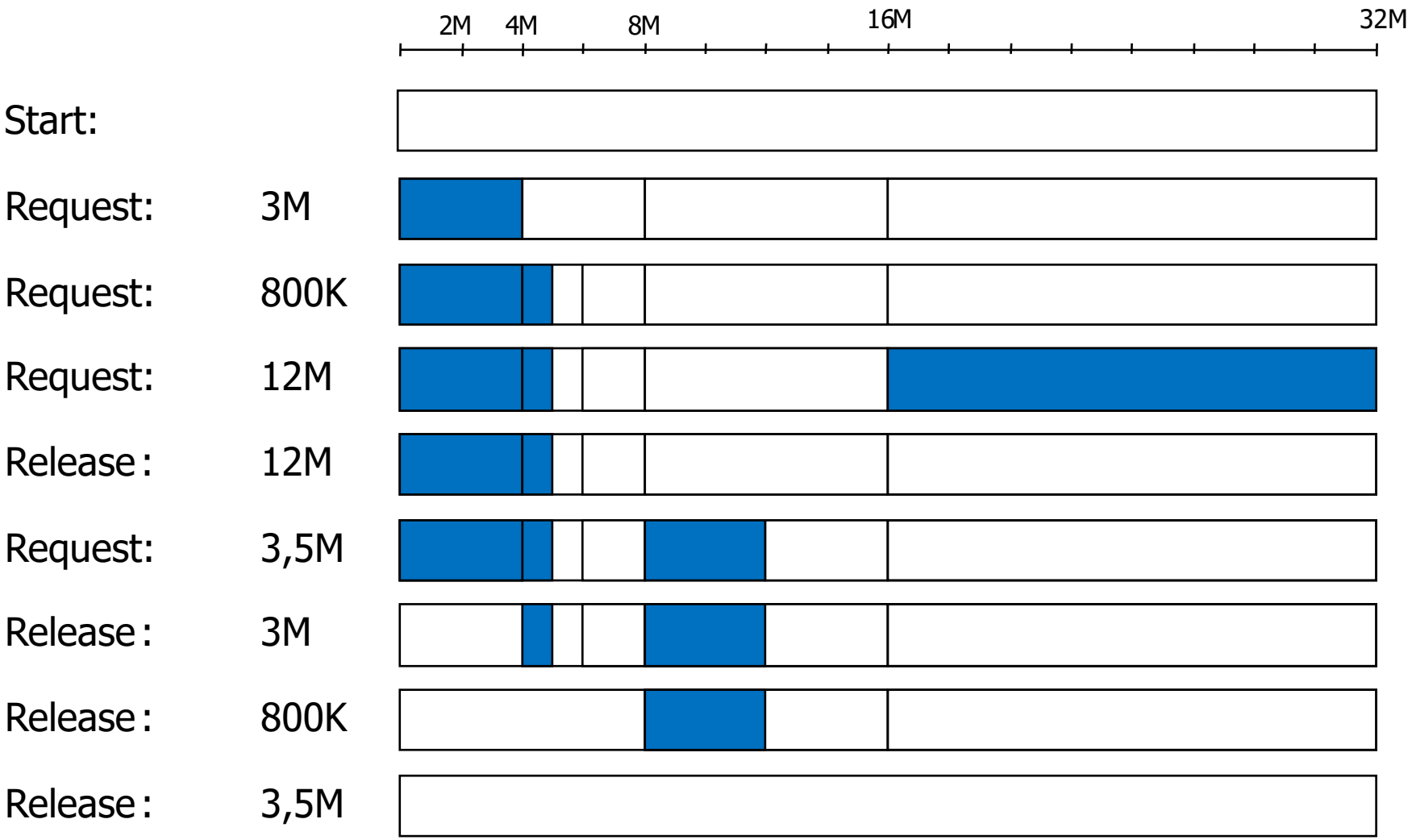


- External fragmentation is increasing with size and variation of request

Buddy system

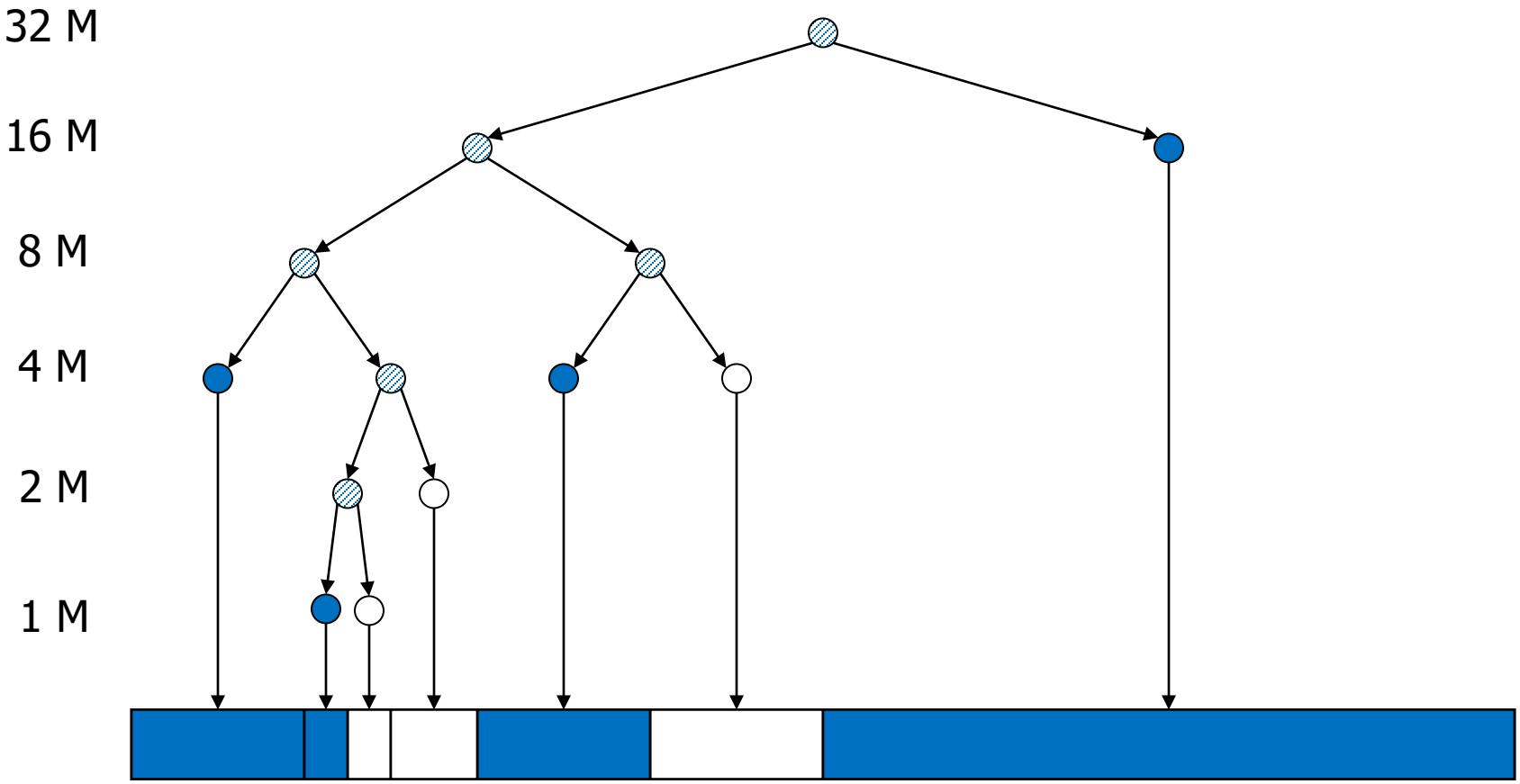
- Memory is separated in 2^{kmax} units
- Smaller pieces are created by (continuously) performed bisection of bigger pieces
- Pieces split in one action can be joined by release
- Properties
  - Allocation and release in arbitrary order
  - Allocation of pieces with unit size of 2^0, 2^1, 2^2, …, 2^k
  - Separated representation
  - Limited search costs
  - Internal and external fragmentation
  - Explicit reintegration

Buddy system



Buddy system

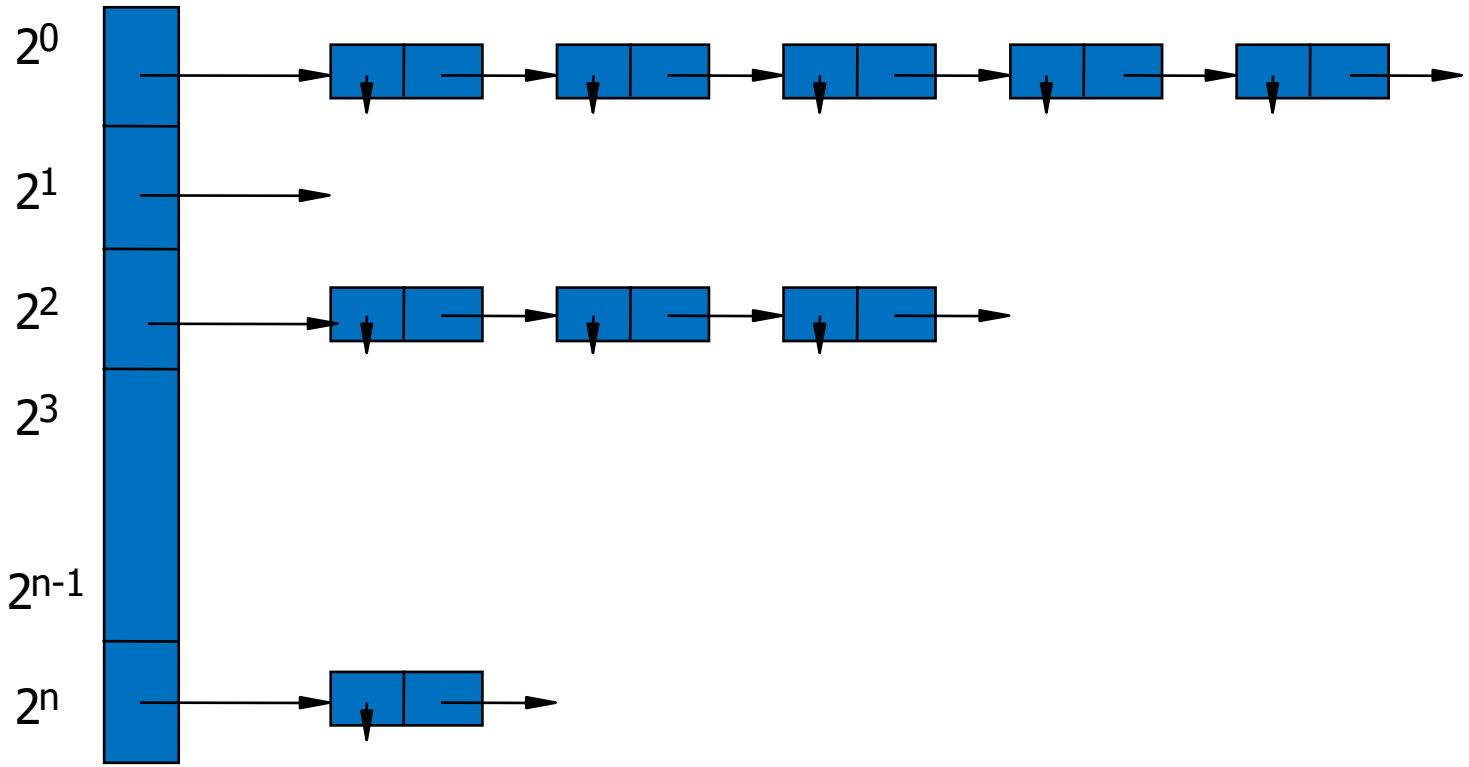
- Representations as tree



Buddies have the same parent node.

Data structures of a Buddy system

- With separated representation



- Array of heads of free lists for pieces with same size

Operation of the Buddy system

- Handling of requests
  - Check for next value with power of two
  - Take first entry of list
  - In case of empty list (recursive):
    - Take first entry of next list with bigger pieces
    - Cut piece in half
    - Insert second half into list of the original size
    - Take remaining piece to satisfy he request
- Handling release
  - Determine buddy of the piece to be released
  - If buddy is used, insert piece into list
  - In case buddy is free: join both (piece and buddy)
  - Insert emerged piece into the next list

Buddy system – internal fragmentation

- Requests of size *a*: 1 2 3 4 5 6 7 8 9 10 …
- Size of allocated pieces *b(a)*: 1 2 4 4 8 8 8 8 16 16 …
- p_a – probability request is of size *a*
- *b(a)* – size of allocated piece for request of size *a*

- Def.: **Internal fragmentation** ratio between the expected value of the number of unused pieces and the expected value of the number of allocated pieces:

$$\frac{\sum_{a=1}^{a_{max}} p_a(b(a)-a)}{\sum_{a=1}^{a_{max}} p_a b(a)}$$

- With $S_b := \sum_{a=1}^{a_{max}} p_a b(a)$ and $S_a := \sum_{a=1}^{a_{max}} p_a a$ as the expected values of the size of the allocated piece *b* or of the size requested respectively the internal fragmentation is $1 - S_a/S_b$.

Buddy system – internal fragmentation

- To determine the internal fragmentation an assumption about the distribution of the requests is needed.
- To simplify matters we assume sizes of request are uniform distributed over the interval [1, 2^n]. So every size of request have the same probability $p_a = 2^{-n}$.

- Approximately the average size requested is

$$S_a = \frac{1}{2^n}\sum_{i=1}^{2^n} i = \frac{1}{2^n}\frac{2^n\left(2^n+1\right)}{2} = 2^{n-1} + \frac{1}{2} \approx 2^{n-1}$$

Buddy system – internal fragmentation

- Keeping in mind the size of the allocated pieces is based on the next value with power of two:

$$S_b = \frac{1}{2^n}\left(1+2+4+4+8+8+8+8+\ldots+\underbrace{2^n+\ldots+2^n}_{2^{n-1}\text{ times}}\right)$$

$$= \frac{1}{2^n}\left(1+1\cdot 2+2\cdot 4+4\cdot 8+\ldots+2^{n-1}2^n\right)$$

$$= \frac{1}{2^n}\left(1+2\sum_{i=0}^{n-1}2^{2i}\right) = \frac{1}{2^n}\left(1+2\frac{2^{2n}-1}{2^2-1}\right)$$

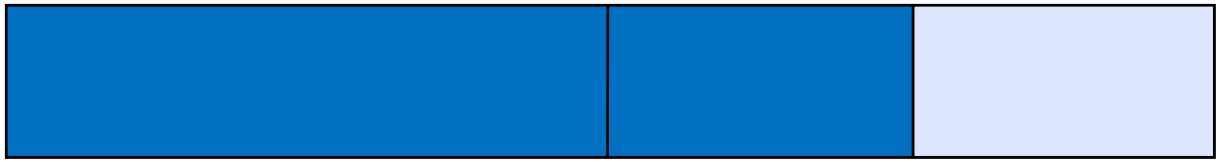
$$= \frac{1}{2^n}\frac{2^{2n+1}+1}{3} \approx \frac{2^{n+1}}{3}$$

- Therefore the ratio $S_a / S_b \approx 3\cdot 2^{n-1} / 2^{n+1} = 3/4$

  so the allocated pieces are used by ¾ and the internal fragmentation is 25%.

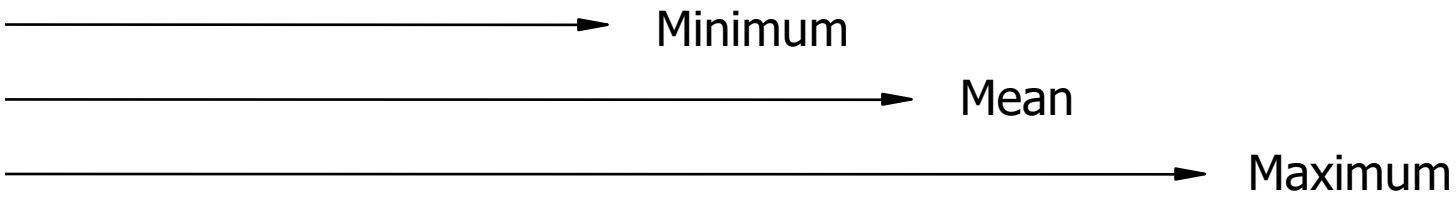
Buddy system

- Fast operation with O(1)
- Adaption to distribution of requests
- Only limited number of split and join operations after transient oscillation.
- Amount of internal fragmentation fairly large.



25% int. fragmentation

Requests with uniform distribution:



- An address space is a contiguous set of addresses.
- It holds all necessary instructions and data structures needed to execute a program.
- Parts of the address space may be undefined. Access to undefined parts of the address space leads to an error.
- We distinguish:
  - Logical address space, program address space (from the view of the thread/program)
  - Physical address space (defined by the width of the address bus)
- For higher efficiency and security, logical address spaces are decomposed into segments (of different size) which in turn are cut into pages (equal size)

Address Spaces: Examples

- Address spaces of, e.g., 64 bit machines are not always as expected:

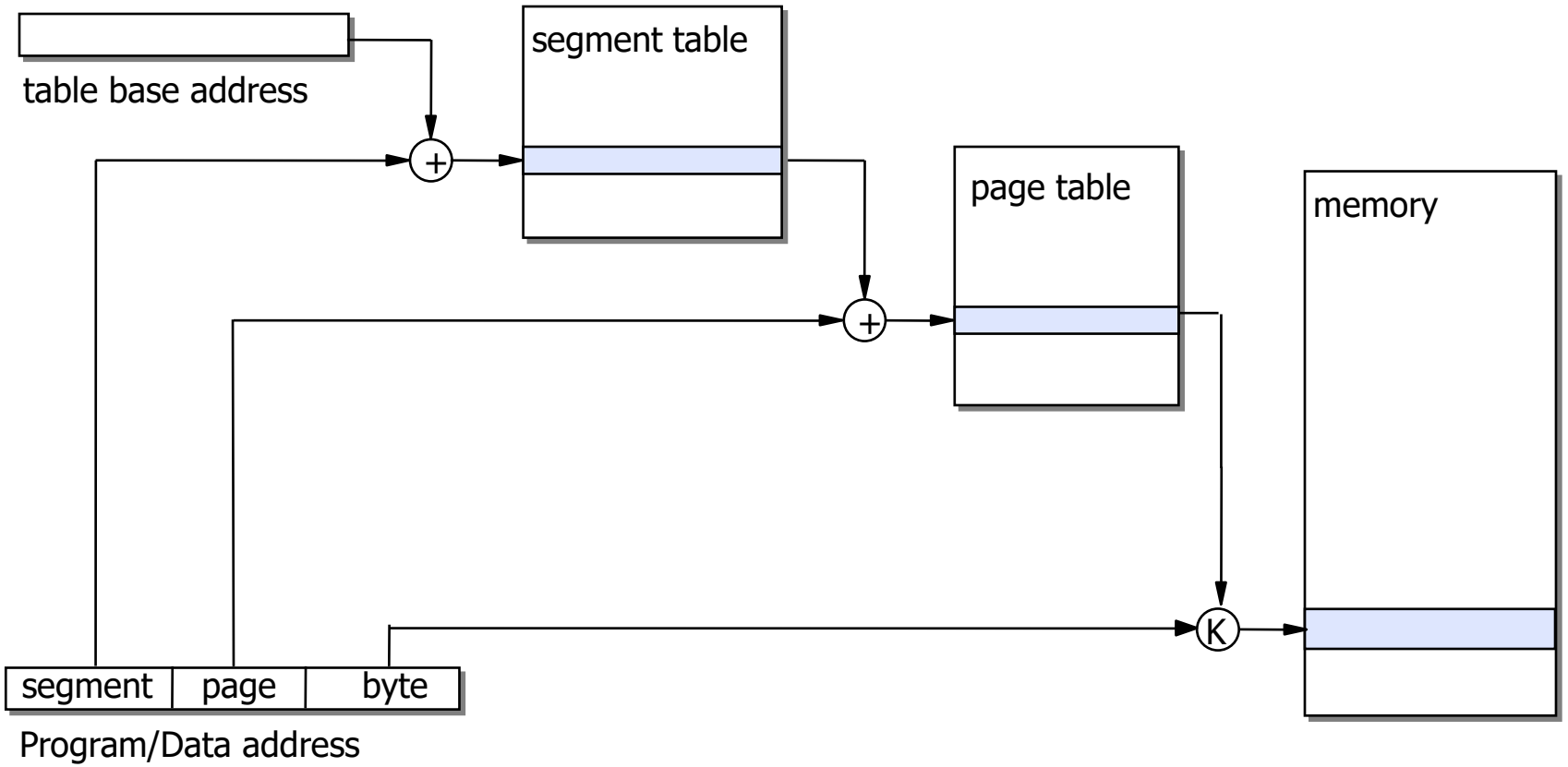
- Linux: `cat /proc/cpuinfo`
  Here: only small snippets from some example machines

- Intel, mobile CPU, 2007
```
model name      : Intel(R) Core(TM)2 Duo CPU     L7700  @ 1.80GHz
address sizes   : 36 bits physical, 48 bits virtual
```
- Intel, desktop CPU, 2011
```
model name      : Intel(R) Core(TM) i7-2600 CPU @ 3.40GHz
address sizes   : 36 bits physical, 48 bits virtual
```
- Intel, entry server CPU, 2009
```
model name      : Intel(R) Xeon(R) CPU           X3470  @ 2.93GHz
address sizes   : 36 bits physical, 48 bits virtual
```
- Intel, server CPU, 2009
```
model name      : Intel(R) Xeon(R) CPU           X5570  @ 2.93GHz
address sizes   : 40 bits physical, 48 bits virtual
```

- AMD, desktop CPU, 2008
```
model name      : AMD Athlon(tm) 64 X2 Dual Core Processor 5600+
address sizes   : 40 bits physical, 48 bits virtual
```
- AMD, desktop CPU, 2011
```
model name      : AMD FX(tm)-6100 Six-Core Processor
address sizes   : 48 bits physical, 48 bits virtual
```
- AMD, server CPU, 2009
```
model name      : Six-Core AMD Opteron(tm) Processor 8435
address sizes   : 48 bits physical, 48 bits virtual
```

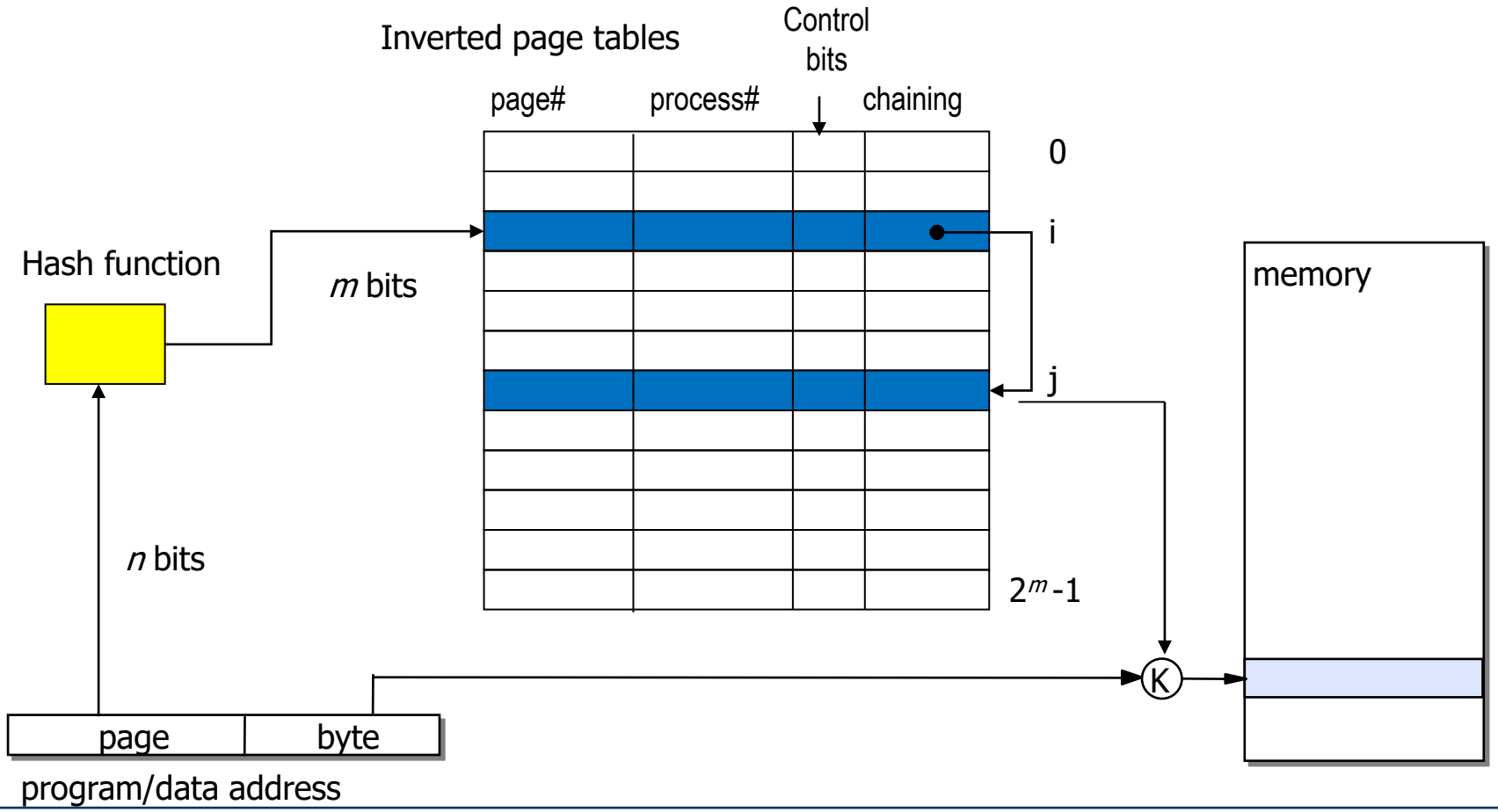
Two-stage hierarchical address translation

- Each segment consists of a variable number of pages.



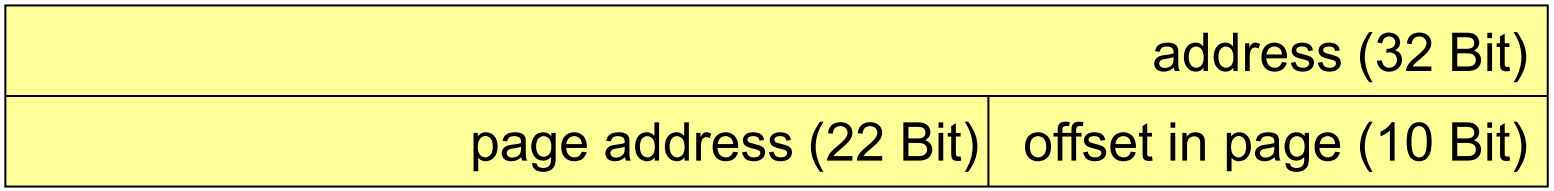
Inverted page table

- While the Intel I32 processors or ARM processors support multistage segment / page tables, PowerPC and UltraSPARC-processors use **inverted page tables**.



Page Table: Theoretical Example

- 32 Bit addresses
- 4 GB logical address space
- 64 MB RAM (physical)
- Pages of 1 KB
- One page table for the whole logical address space



- Offset (inside pages): 10 Bit (2^10 = 1 KB)
- Page addresses: 22 Bit (32-10)
- Number of entries in page table: 2^22 = 4M
- Size of an entry: 16 Bit = 2 Byte
  (64 MB = 2^26 B = 2^16 frames)
- Size of page table (ignoring managament information such as dirty bits etc. and ignoring alignment): 8 MB (4M x 2 Byte)

Inverted Page Table: Theoretical Example

Freie Universität Berlin

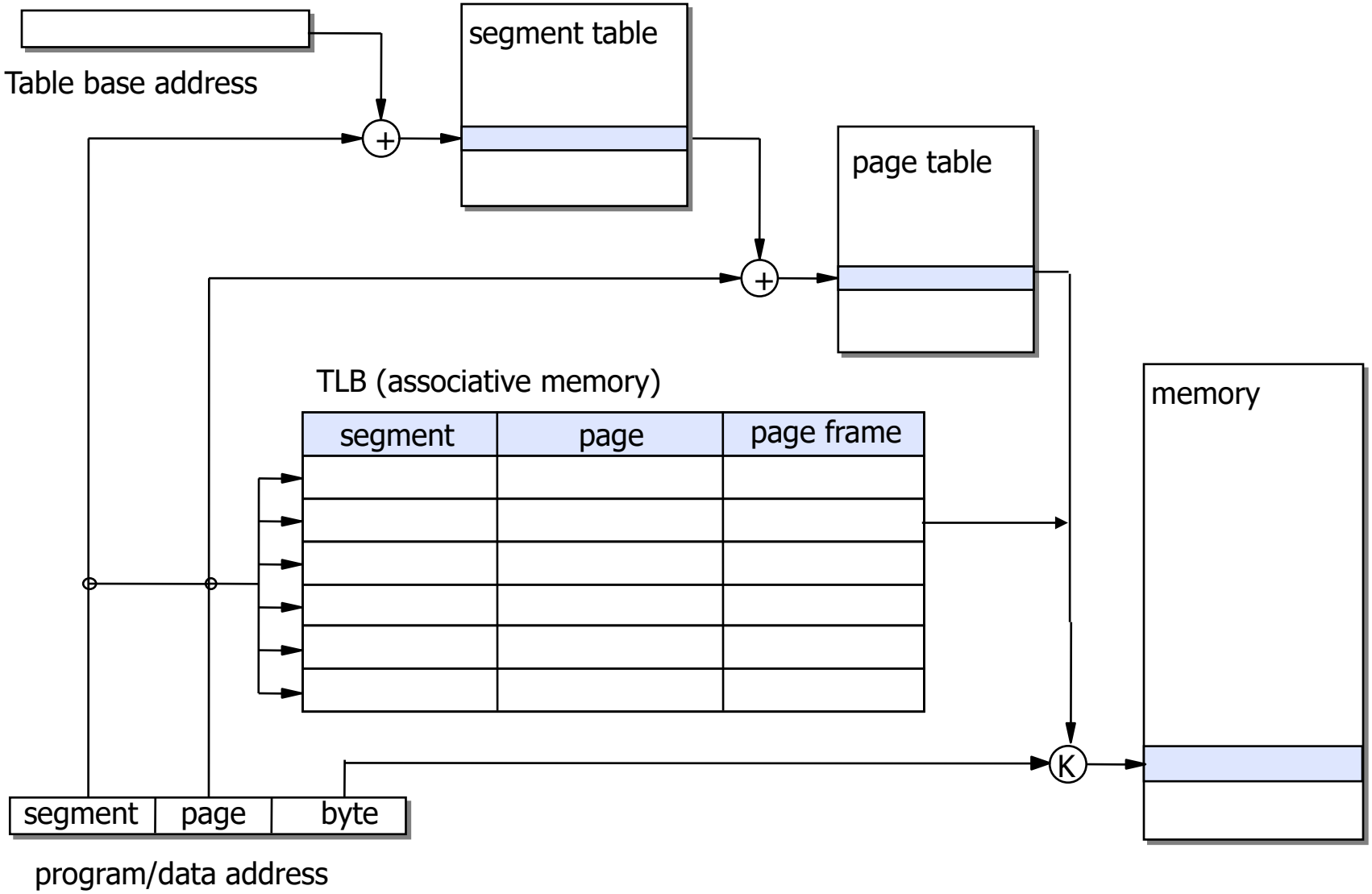
- 32 Bit addresses
- 4 GB logical address space
- 64 MB RAM (physical)
- Pages of 1 KB
- One page table for the whole logical address space
- Offset (inside pages): 10 Bit (2^10 = 1 KB)
- Number of frames: 65536 = 2^16
- Frame addresses: 16 Bit
- Number of entries in inverted page table: 2^16 = 64K
- Size of an entry: 22 Bit = 2.75 Byte
  (page addresses are 22 bit (32-10))
- Size of page table (ignoring managament information such as dirty bits etc. and ignoring alignment): 176 KB (64K x 2.75 Byte)
- But: Search is much more complicated (e.g. hash function)!

Acceleration of address translation

Problem:

- Segment and page tables are so large that they have to be kept in main memory.
- To build an effective main memory address, we first need to get the page and/or segment address.
- For each address (instruction or data) we need at least two accesses to main memory.
- Thus, the processing speed is reduced by a factor of 2.
- To prevent that, the currently used parts of the segment/page tables are stored in a fast set of registers. (TLB = Translation Lookaside Buffer, part of MMU)
- The TLB is an associative memory, i.e. a table in which the entry to be found is being searched simultaneously in all lines of the table.
- It is used as a sort of cache for page/segment tables.
- Usually, the search can be performed in one processor cycle.

Two stage hierarchical address translation with associative register

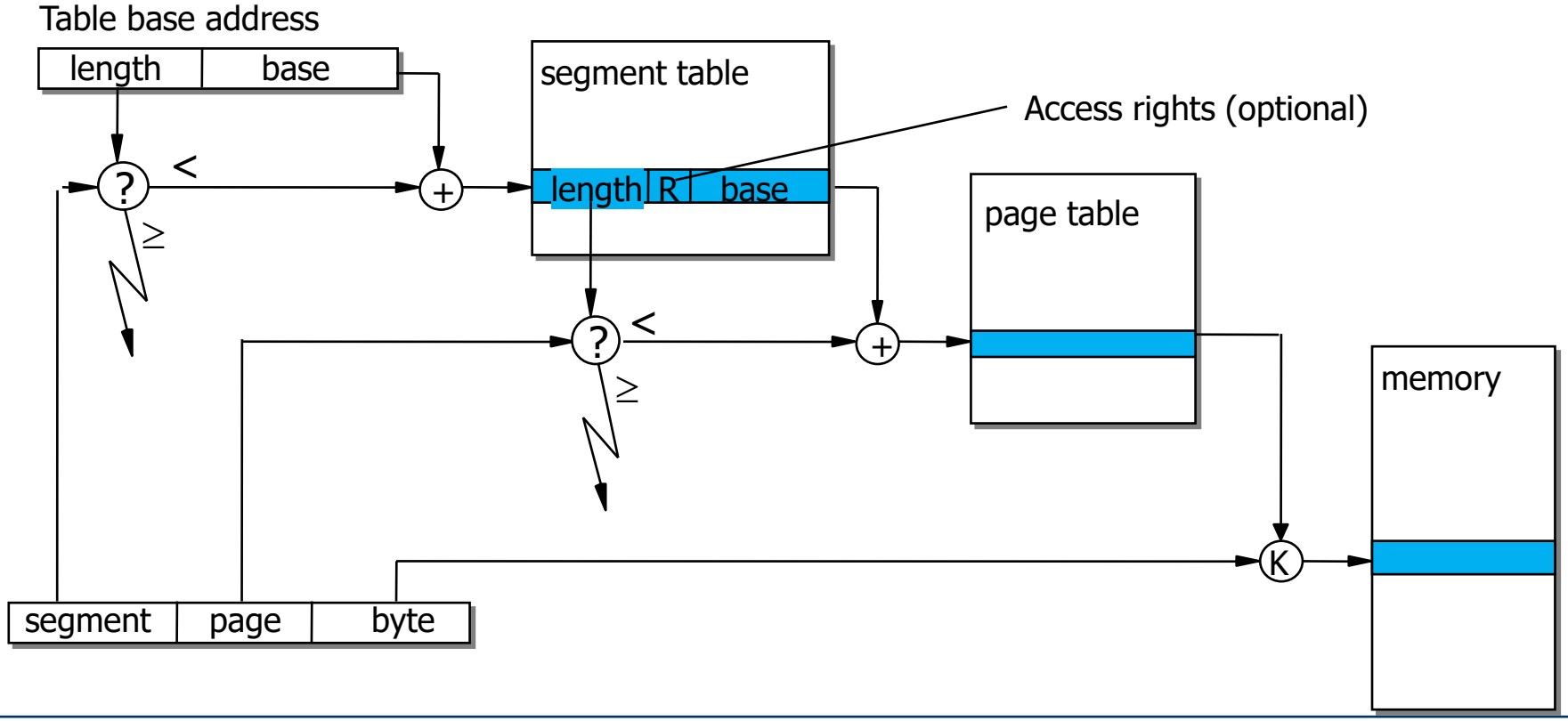


Typical properties of a TLB

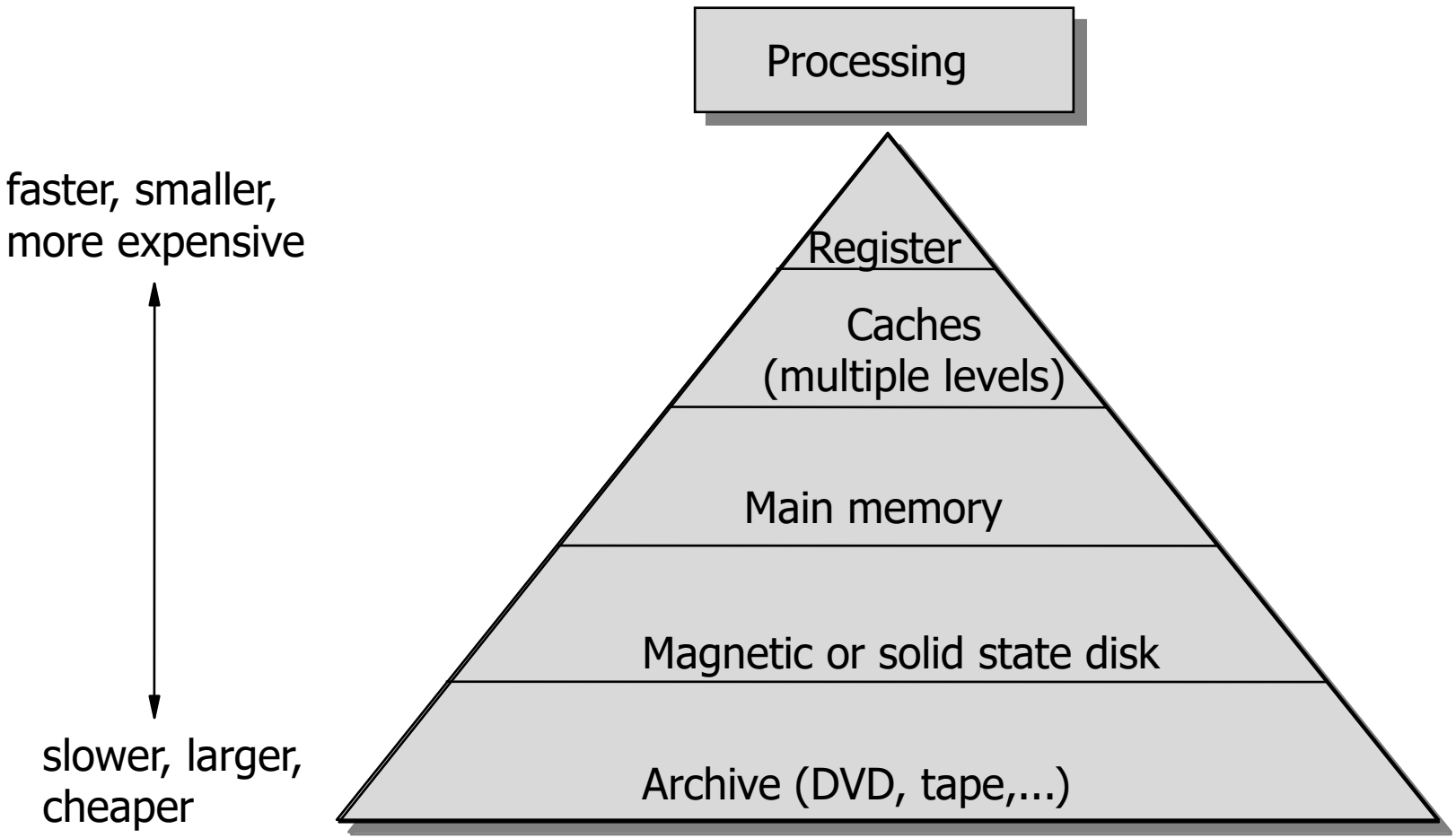
- Line width : 4-8 bytes: Logical page/segment-no., page frame no., Management bits
- Time for address translation:
  - hit: ≤ 1 processor cycle
  - miss: 10 - 200 processor cycles (depending on memory speed)
- Hit rate: 99.0% - 99.99%
- TLB-size: 32 – 1024 lines (entries)

Memory protection for hierarchical address translation

- Table base register and segment table entries are complemented by a length field indicating the appropriate amount of memory.
- Exceeding the length triggers an interrupt (segmentation fault).
- It is possible to differentiate between read and write access and/or different processor modes.

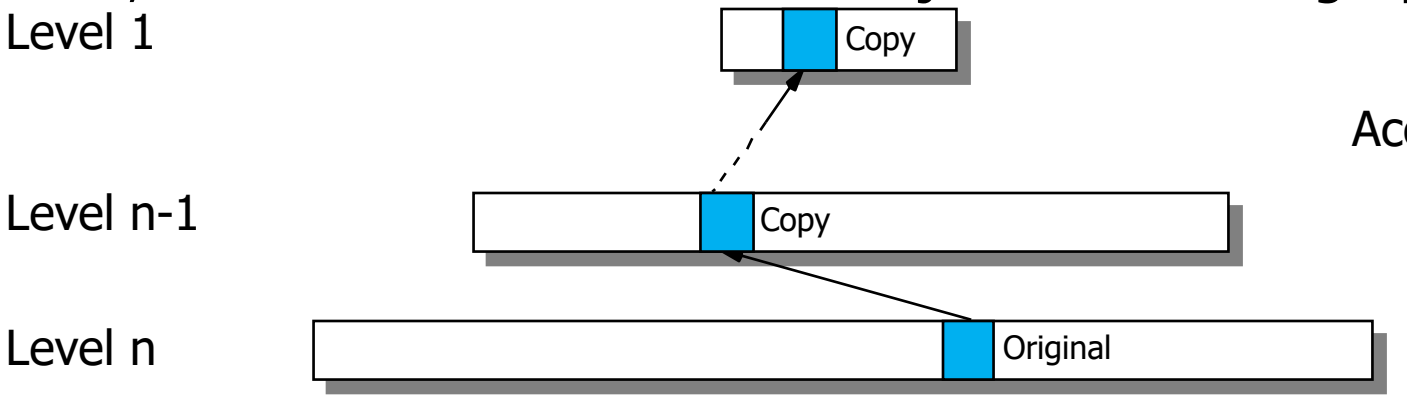


7.3 Memory Hierarchy and Locality

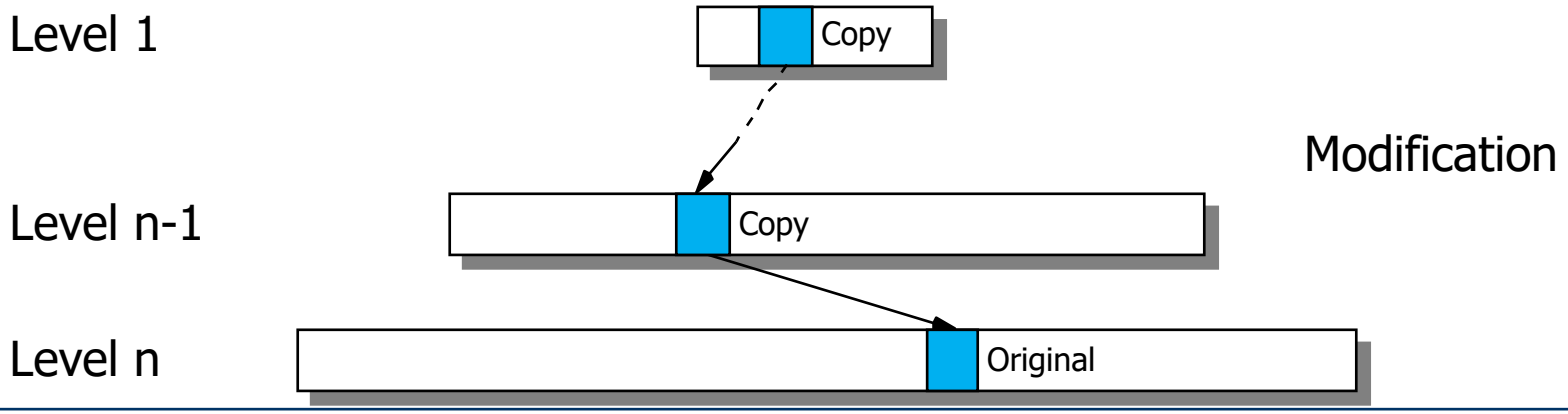


Operation of Memory Hierarchy

- Copies of the data object will be generated at time of (first) access, so it seems that the data object is “climbing up”.



- After modification of the data object changes will be propagated (step-by-step, delayed) downwards.



Locality

The memory hierarchy is based on the

Principle of locality

- A program limits its accesses within a small time interval Δt to only a small subset of its address space *A*.
  - Spatial locality: when a program accesses an address *a*, then another access to a nearby address is very likely.
  - Temporal locality: When a program accesses an address *a,* then a repeated access to the same address within short time is very likely.

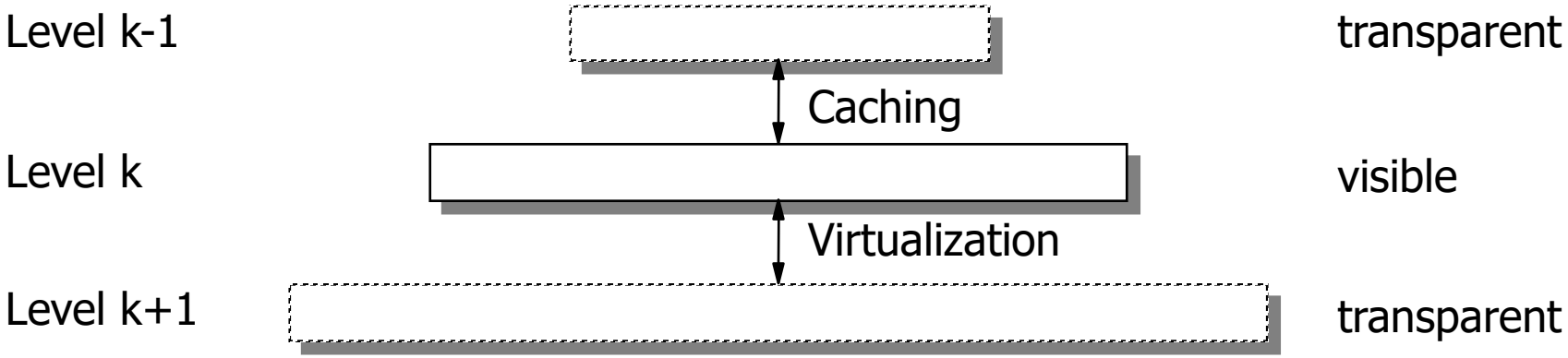
Why ?

- Mostly, instructions are executed sequentially.
- Programs spend the most time in loops.
- Some parts of the program are executed only in exceptional cases.
- Many arrays are only partially filled.
- 90/10-Rule: A thread spends 90% of its time in 10% of its address space.

Design parameters of Memory Hierarchy

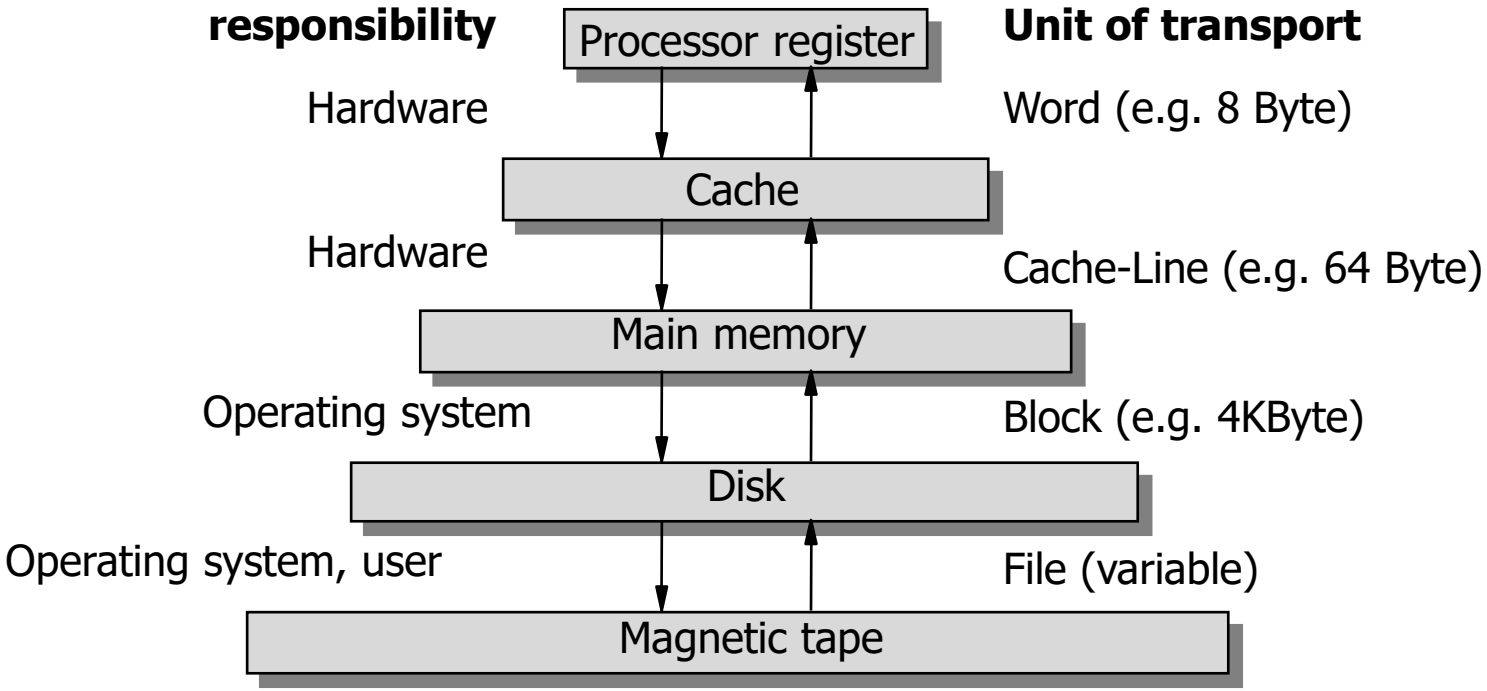
- Goal
  - Hold data needed on highest level as possible.
- Problem
  - Capacity is shrinking on the way up.
- Questions
  - How it can be known what data object is accessed next?
    Knowledge about the program behavior
  - Who is responsible for data transport between levels?
    User/Programmer, Compiler, OS, Hardware
  - What is the size of the data objects feasible for transportation?
    Bytes, Words, Blocks, Files
  - Is there an automatic mechanism for transportation between levels?
  - Is there an acceleration of the data access (Caching) or enlargement of capacity (Virtualization)?

Caching vs. Virtualization



- Usually not all of the levels are recognizable for the programmer or user – some are hidden or transparent.
- So the user has the impression to access Level k only.
- In case of Caching the access is performed on Level k-1 and Level k is visible.
- In case of Virtualization the access is performed on Level k+1, but the user has the impression to access Level k.
- Cashing is used to accelerate the data access, Virtualization is used to enlarge the capacity.

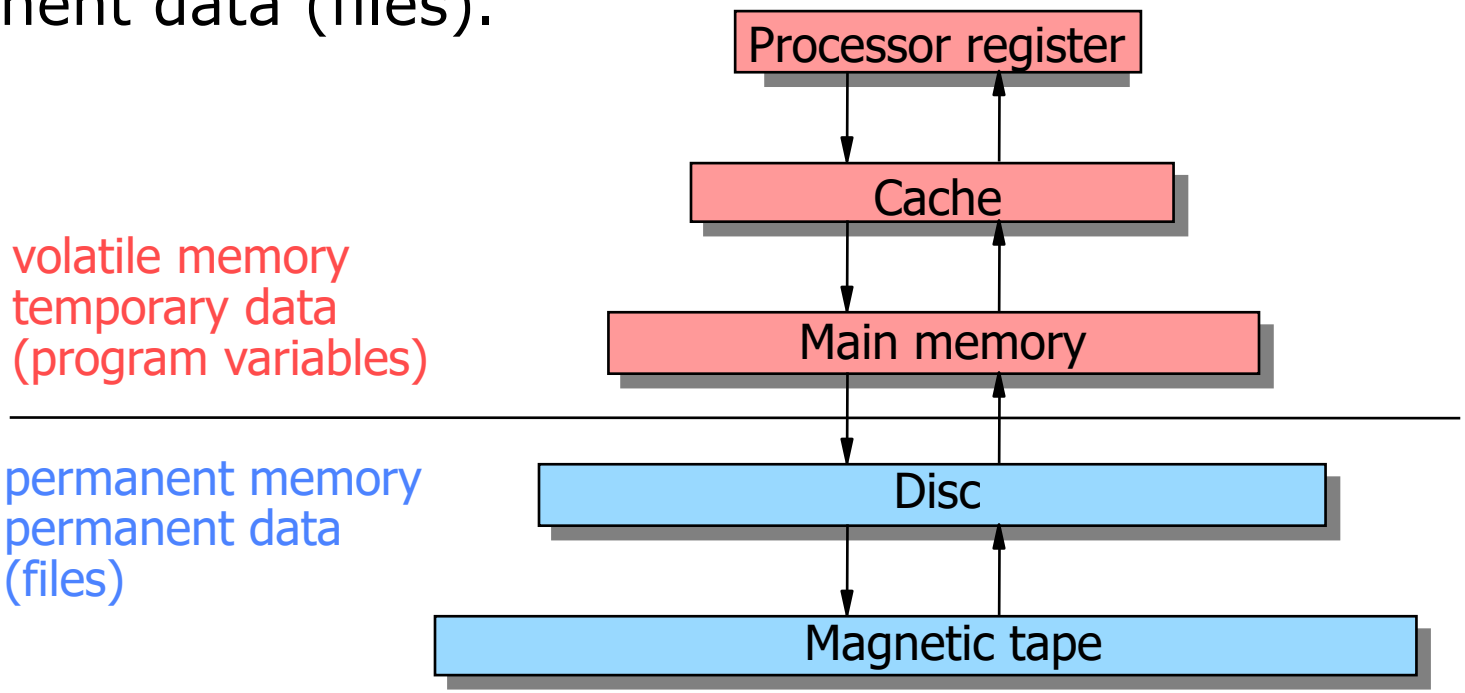
Responsibilities



- During the runtime of the program the transport of data and instructions between main memory, cache, and processor is done by the hardware (transparent to software).
- Accesses to the disk are performed by the operating system.
- Writing files to and reading from archive memory can be done either explicitly by the user or automatically by the operating system (file system).

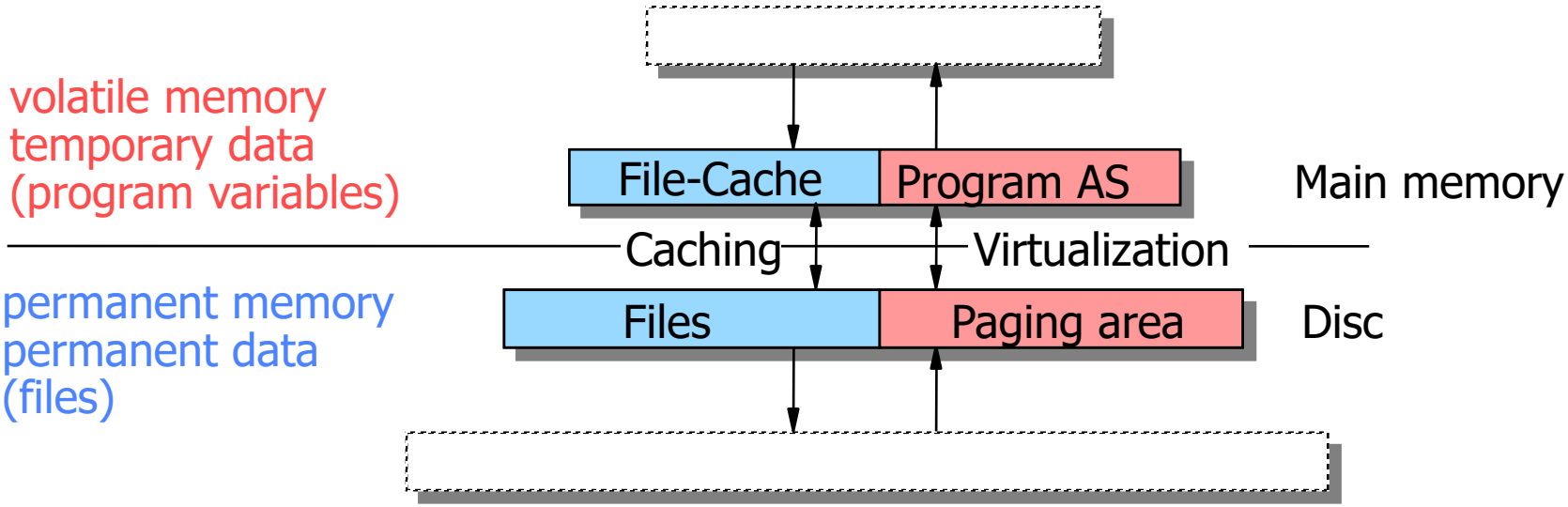
Volatile vs. permanent Memory

- Due to the used media the memory on higher levels usually is implemented as volatile memory. So the data stored within this memory is lost after power cutoff.
- Therefore higher levels are used to hold temporary data (program variables), while the other levels hold permanent data (files).



Volatile vs. permanent Memory

- Using Caching and Virtualization led to weaken the difference between Main memory (for address spaces only) and Disc space (for files only).



- Due to the principle of locality, only those parts of the address space that is currently in use by the program, needs to be present in the physical memory.
- The pages needed are loaded only when addressed (*demand paging*).
- The copy-out and copy-in operations of the pages can be automated (by some hardware support).
- For the user / programmer all these activities are transparent.
- Programmer has the impression that main memory is available in (almost) unlimited size.
- But this unlimited memory is only *virtually* existent.

Requirements for efficient operation:

- Noncontiguous allocation (page tables)
  - Pages are the units of transfer.
- Automatic detection of missing pages
  - Access to missing page triggers interrupt.
  - Loading of page from disk is initiated as part of the interrupt handling.

Involved components (Data structures)

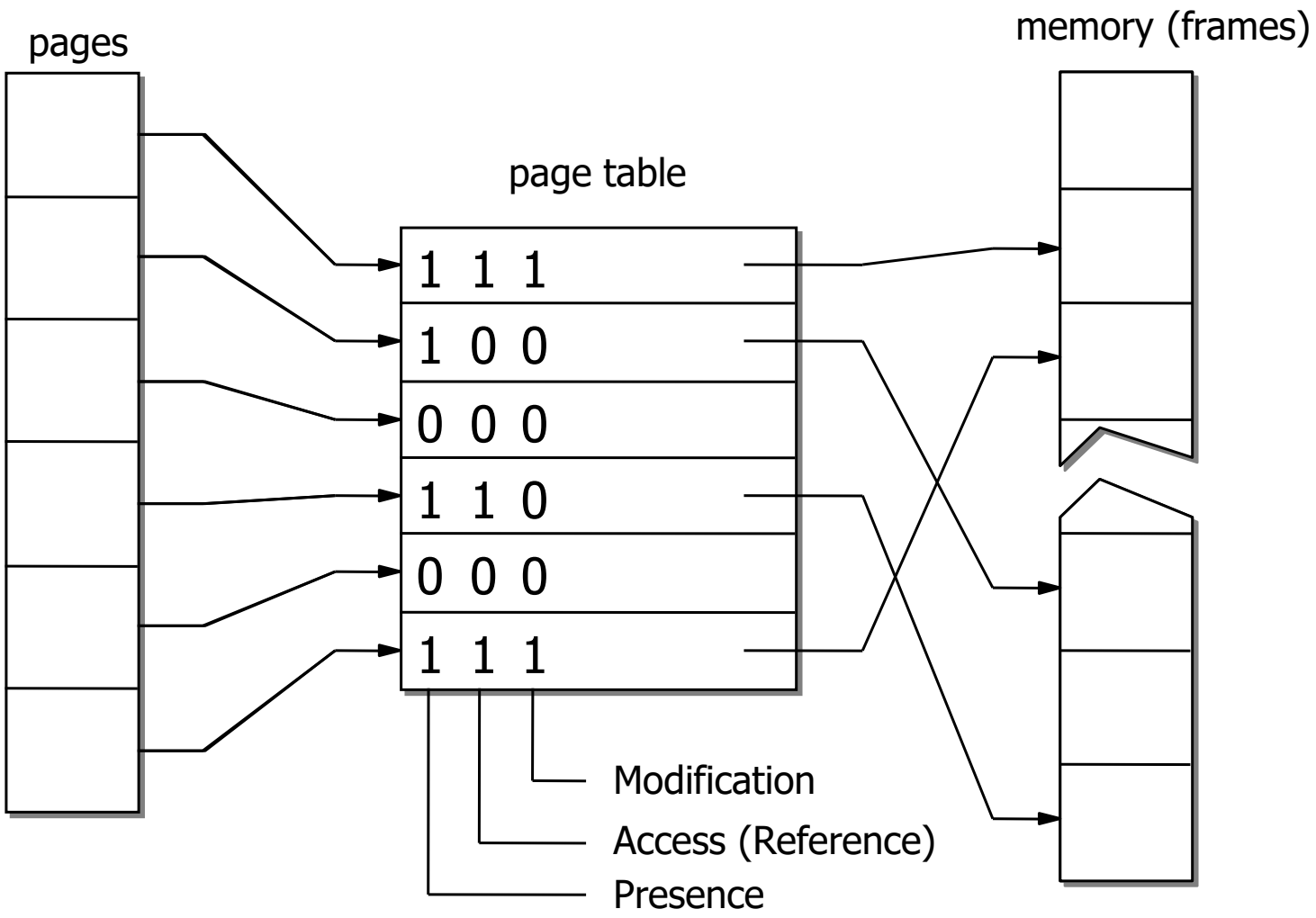
- Page table
  - Function: address transformation
  - Content: for each page
    - usage and presence information
    - physical address (page frame number)
- Page frame table, inverted page table
  - Function: memory management
  - Content: for each page frame
    - state (free / occupied)
    - owner
    - occupying page
- Swap area (paging area)
  - Function: areas of storage to store the pages that are swapped out
    - Usually mass storage such as magnetic or solid state disks
    - Seldom network devices

Page table for virtual memory

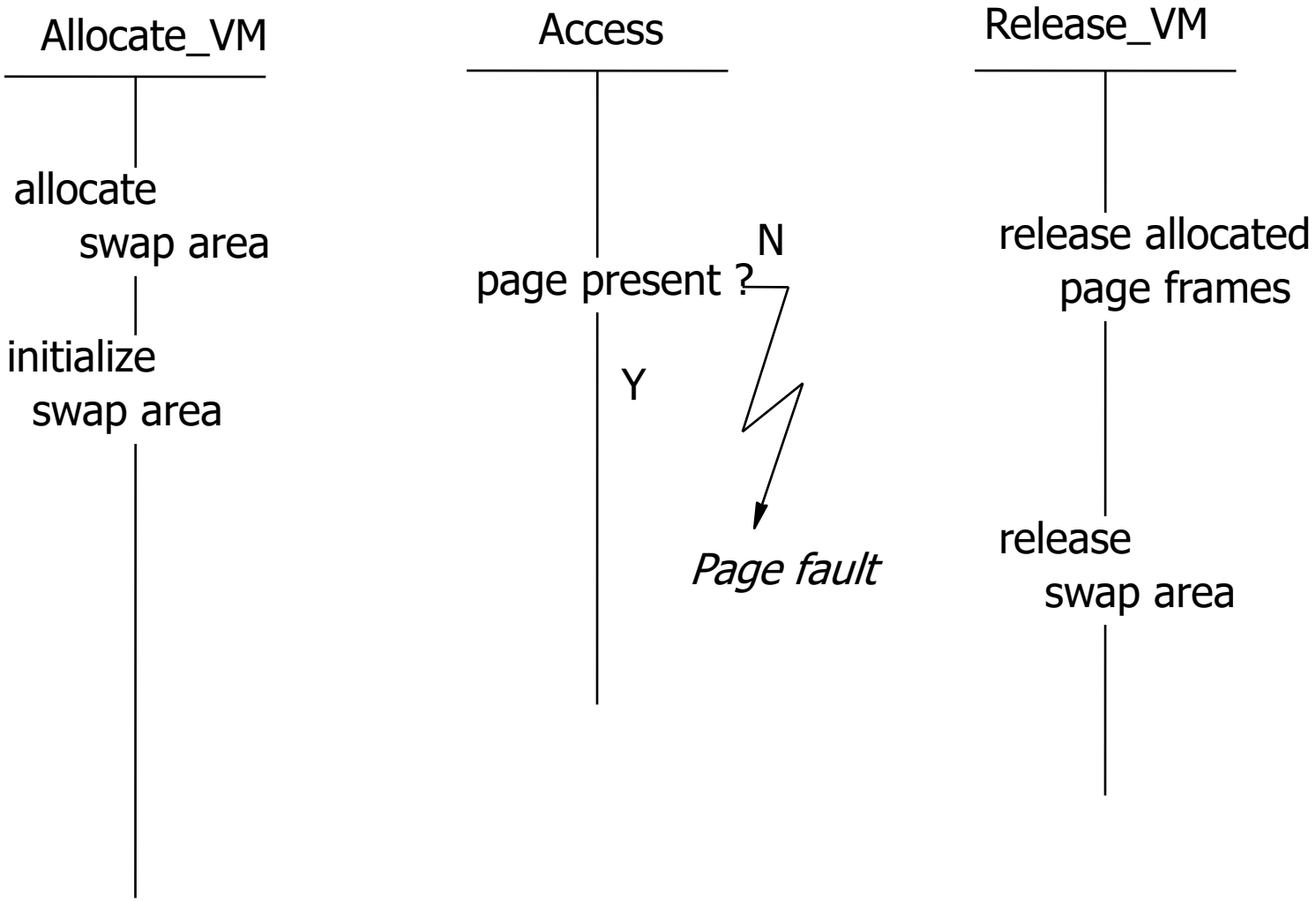
In addition to the physical address, each entry provides information whether

- the page is present in main memory:
  - presence bit, valid bit
- the page has been accessed:
  - reference bit
- the page has been modified (write access):
  - modification bit, dirty bit

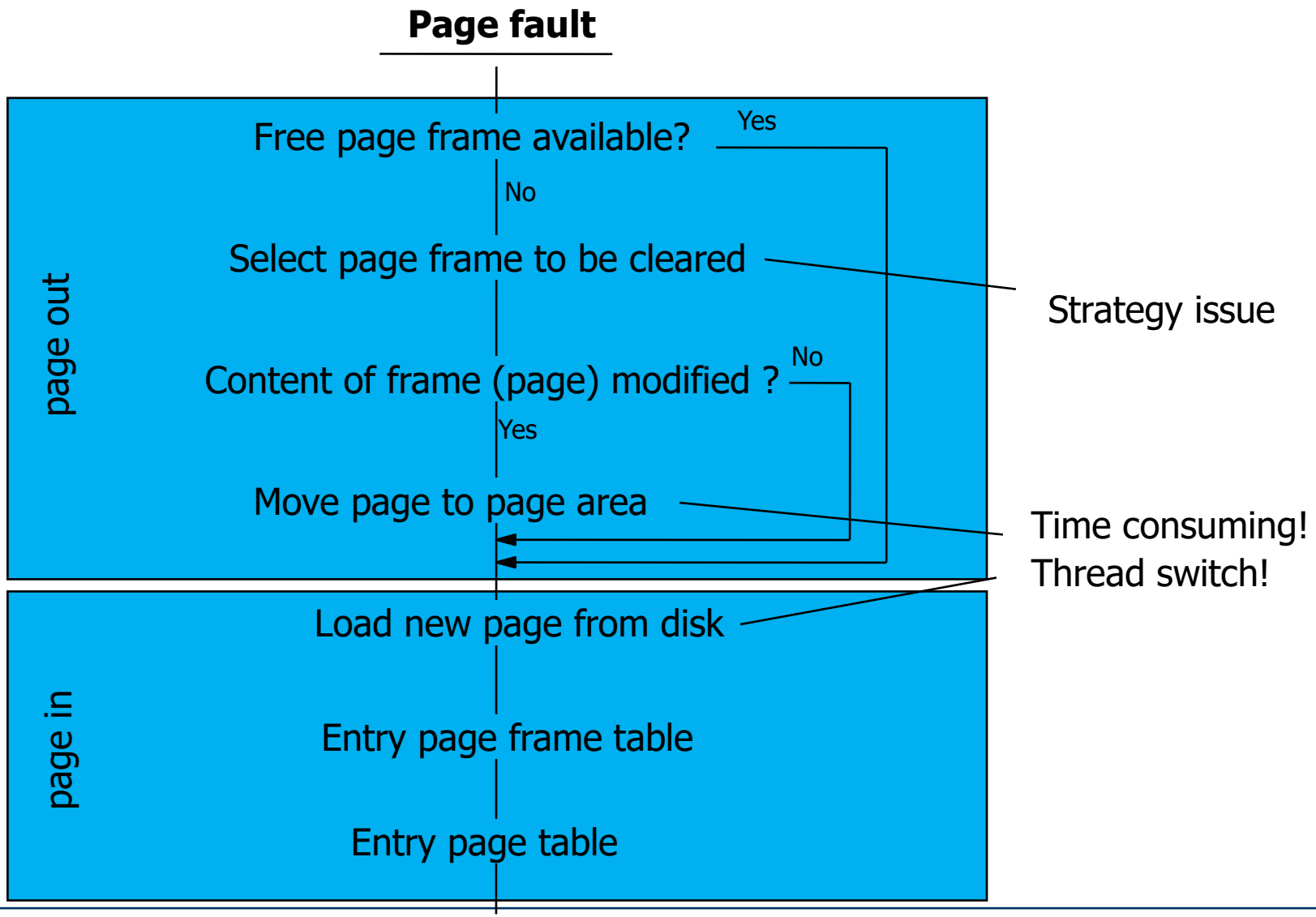
Page table for virtual memory



Tasks for virtual memory management

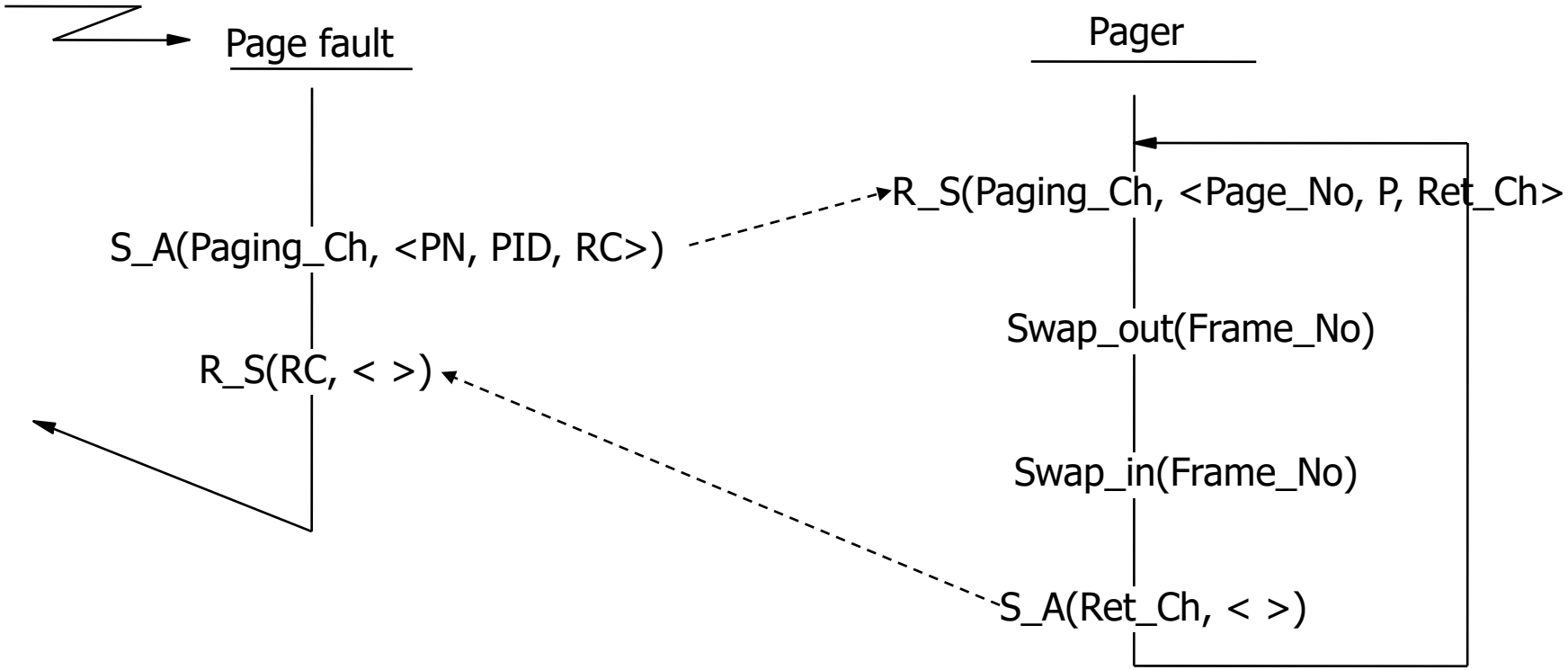


Page fault


Page fault
page out
Free page frame available?
Yes
No
Select page frame to be cleared
Strategy issue
Content of frame (page) modified ?
No
Yes
Move page to page area
Time consuming!
Thread switch!
page in
Load new page from disk
Entry page frame table
Entry page table

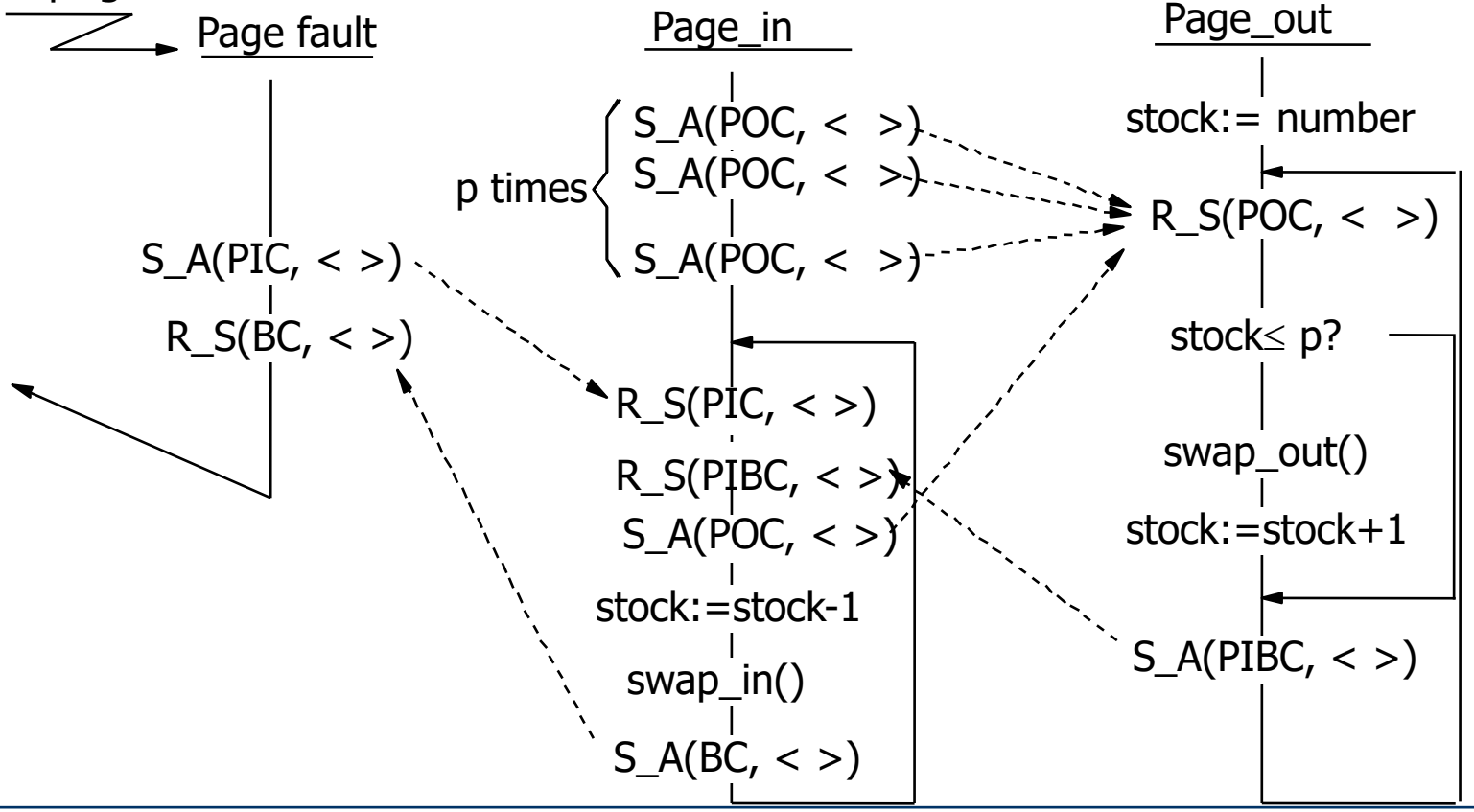
Parallelization of paging

- Paging is a time-critical component, we therefore try to speed it up by parallelization.



Buffering

- Since page faults often occur in bulks, it is recommend to have some amount of free page frames available to avoid costly page-out operations when time is tight.
- To that purpose we parallelize by applying the buffering principle to get a stock of free page frames.



A small calculation:

- Let p_{pf} be the probability of a page fault, t_m the memory access time and t_{pf} the time needed for handling a page fault.
- Then we obtain as effective memory access time t_{eff} in the virtual memory:

$$t_{eff} := (1 - p_{pf}) \cdot t_m + p_{pf} \cdot t_{pf}$$

- Using roughly realistic numbers, e.g. t_m = 20 nsec and t_{pf} = 20 msec

$$\begin{aligned} t_{eff} &= (1 - p_{pf}) \cdot 20 + p_{pf} \cdot 20.000.000 \\ &= 20 + 19.999.980 \cdot p_{pf} \end{aligned}$$

- With a page fault probability of p_{pf} = 0.001, we get an effective access time of 20 μsec, i.e. a slow-down by a factor of 1000!
- Even with a value of $p_{pf} = 10^{-6}$ the effective access time doubles.
- Thus it is of utmost importance to keep the number of page faults extremely low.

Selection strategy

- The page fault rate strongly depends on which pages are kept in real memory and which are stored on disk.

- Selection strategy:

  When a page fault occurs and no page frame is free, which page frame should be emptied?

- Differentiation
  - Local selection strategy:

    We clear a page frame of that process that caused the page fault.
  - Global selection strategy:

    An arbitrary page frame (belonging to other processes) is cleared.

Classical Strategies

- **FIFO** (First-In-First-Out)
  The page that is longest in memory is swapped out.

- **LFU** (Least Frequently Used)
  The page that has been least frequently referenced is swapped out.

- **LRU** (Least Recently Used)
  The page not been referenced for the longest period is swapped out.

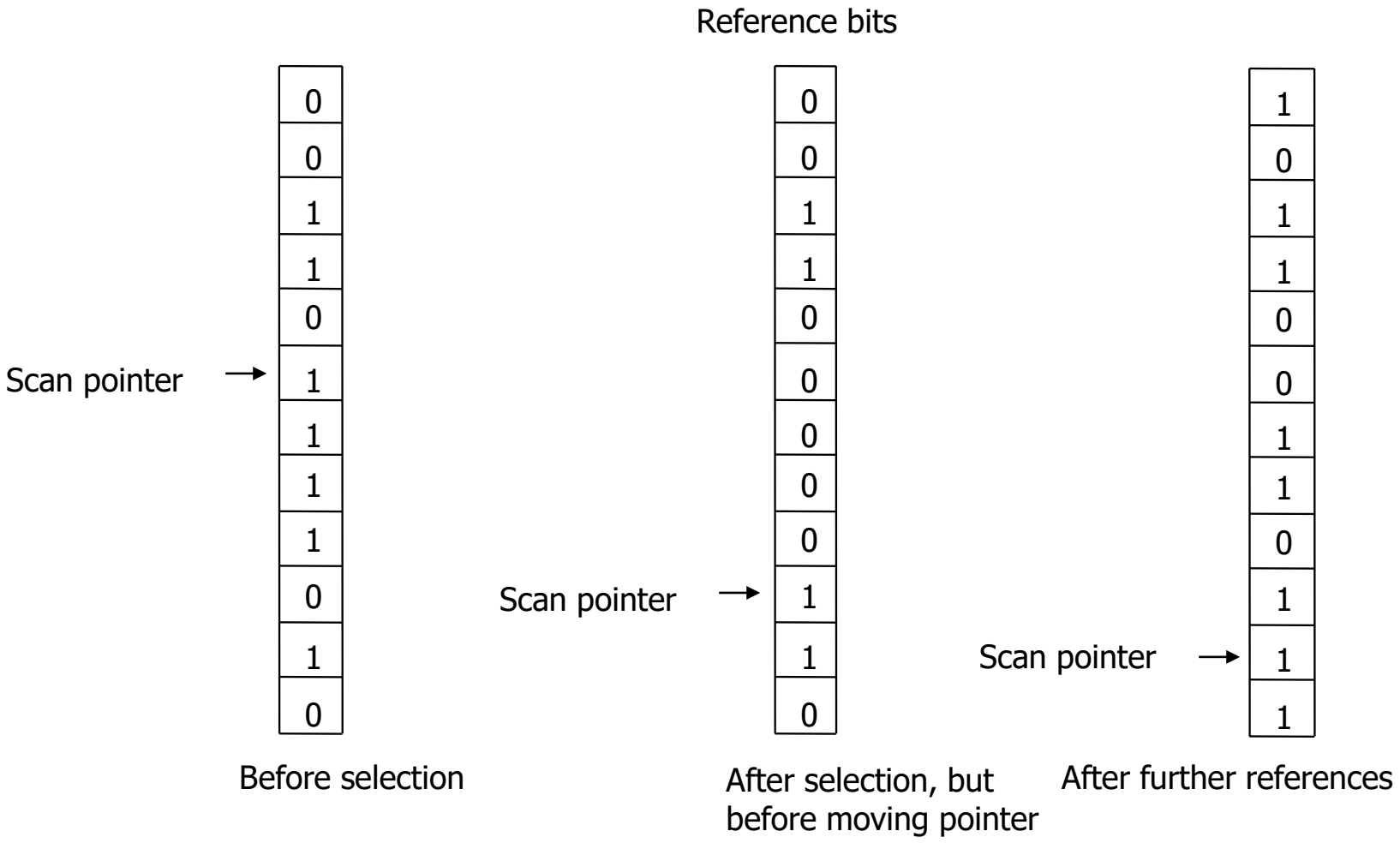
- **RNU** (Recently Not Used)
  The page not been referenced within some specified time period is swapped out.

Second-Chance-Algorithm (Clock-Algorithm)

The Clock- Algorithm is smarter, since it resets the reference bits not all at once but only smaller subsets:

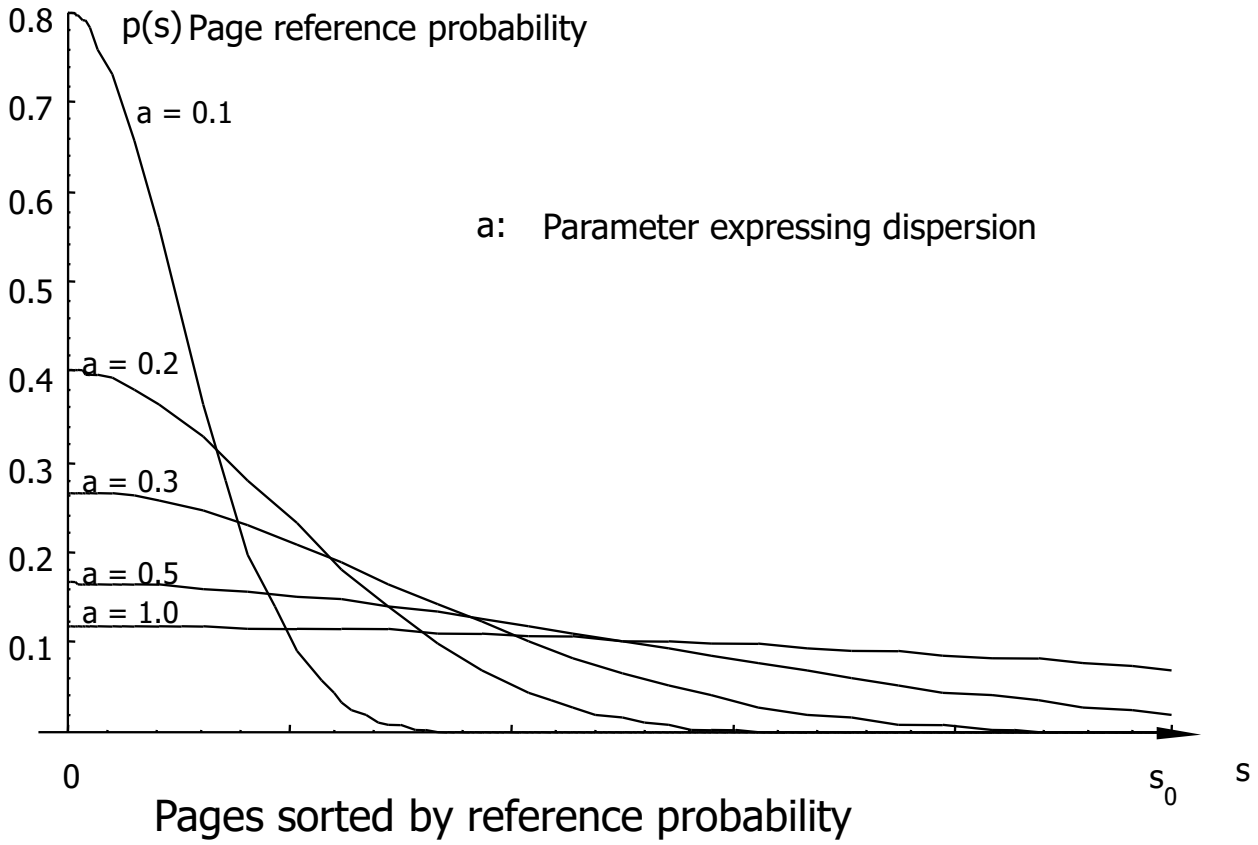
- The vector of reference bits is scanned cyclically.
- For searching the next candidate to be swapped out, the next page is selected which has a reference bit of 0.
- During this linear search all visited reference bits are reset to 0.
- They have – until the scan pointer revisits the page again during the next cycle – a second chance to be referenced and stay in memory.
- That means that the selected page has the property that it has not been referenced during the last scan cycle.

Second-Chance-Algorithm



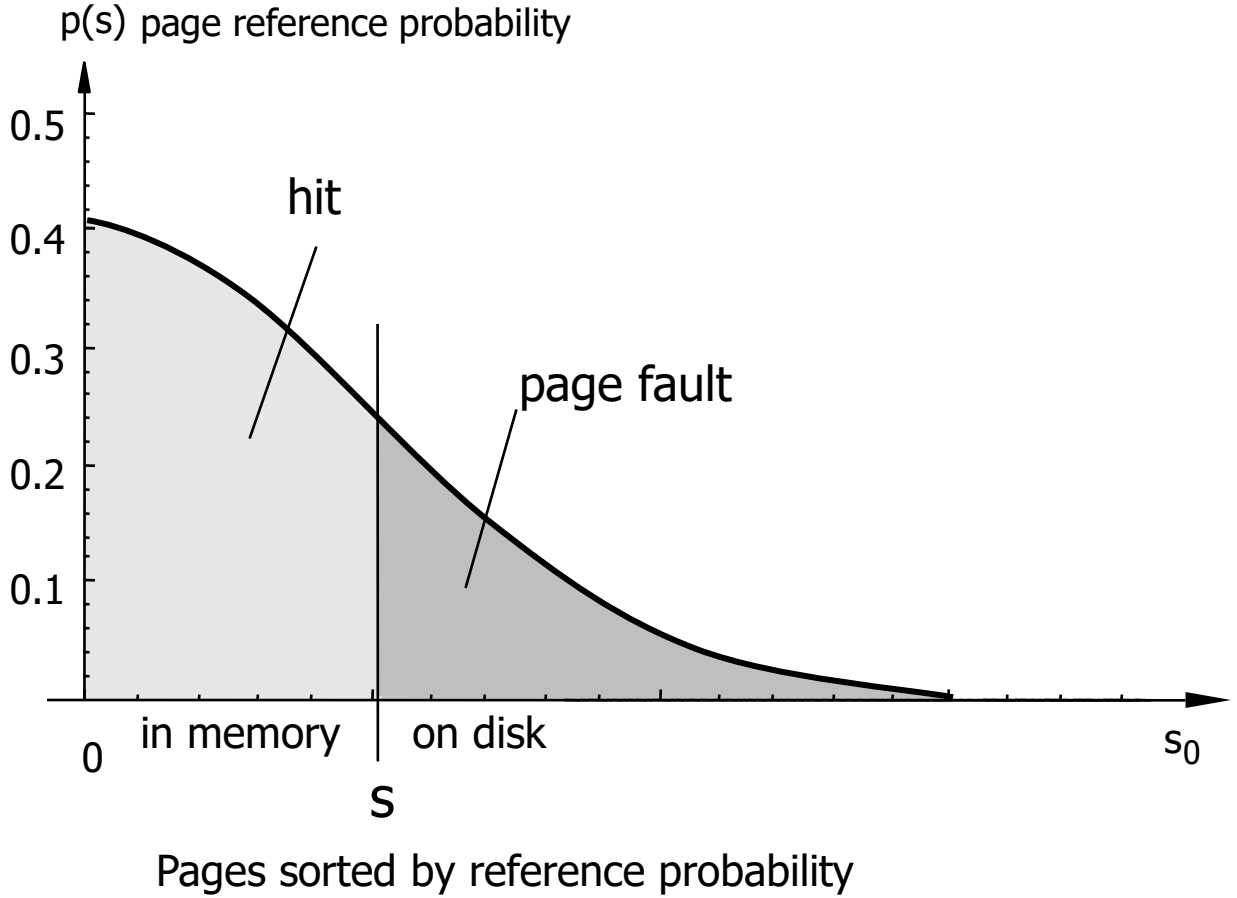
7.6 Performance aspects of virtual memory

- The virtual memory works the better, the higher the programs‘ locality.
- Locality is good, if few pages are referenced with high probability, and many pages with low probability (small a).



7.6.1 Modeling paging

- In memory should only be those pages that are referenced with high probability.



Modeling paging

- Let be
  - s number of available frames
  - s_0 size of address space
- The s most frequently referenced pages are assumed to be in memory (i.e., in the s available frames).

Then we have:

- Hit probability

$$p_{hit}(s) = \int_0^s p(z)\,dz$$

- Page fault probability

$$p_{pf}(s) = 1 - p_{hit}(s)$$

Normalized to size of address space:

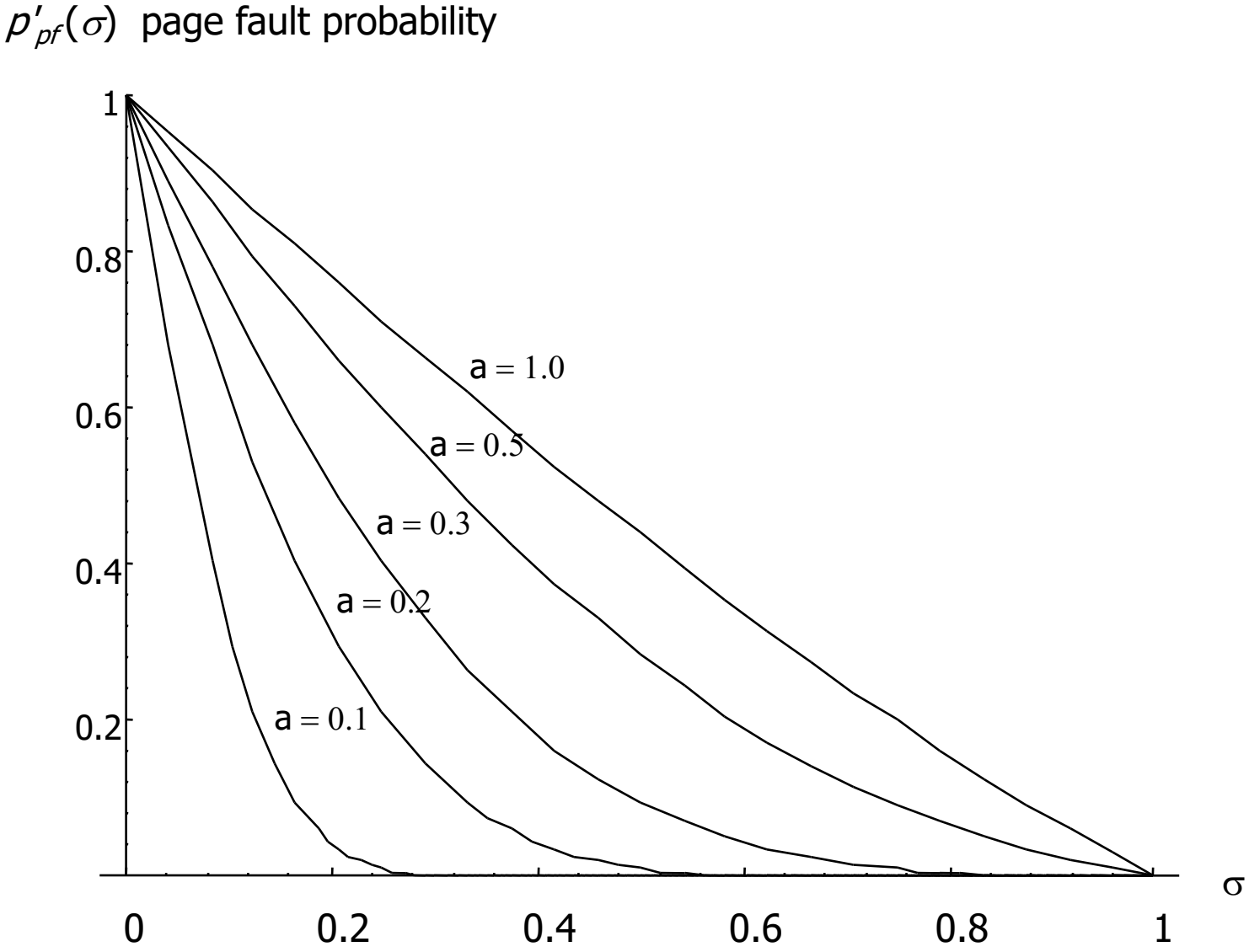
- Memory offer

$$\sigma = s / s_0$$

- Normalized page fault probability

$$p'_{pf}(\sigma) = p_{pf}(s)$$

Dependence of page fault probability on memory offer

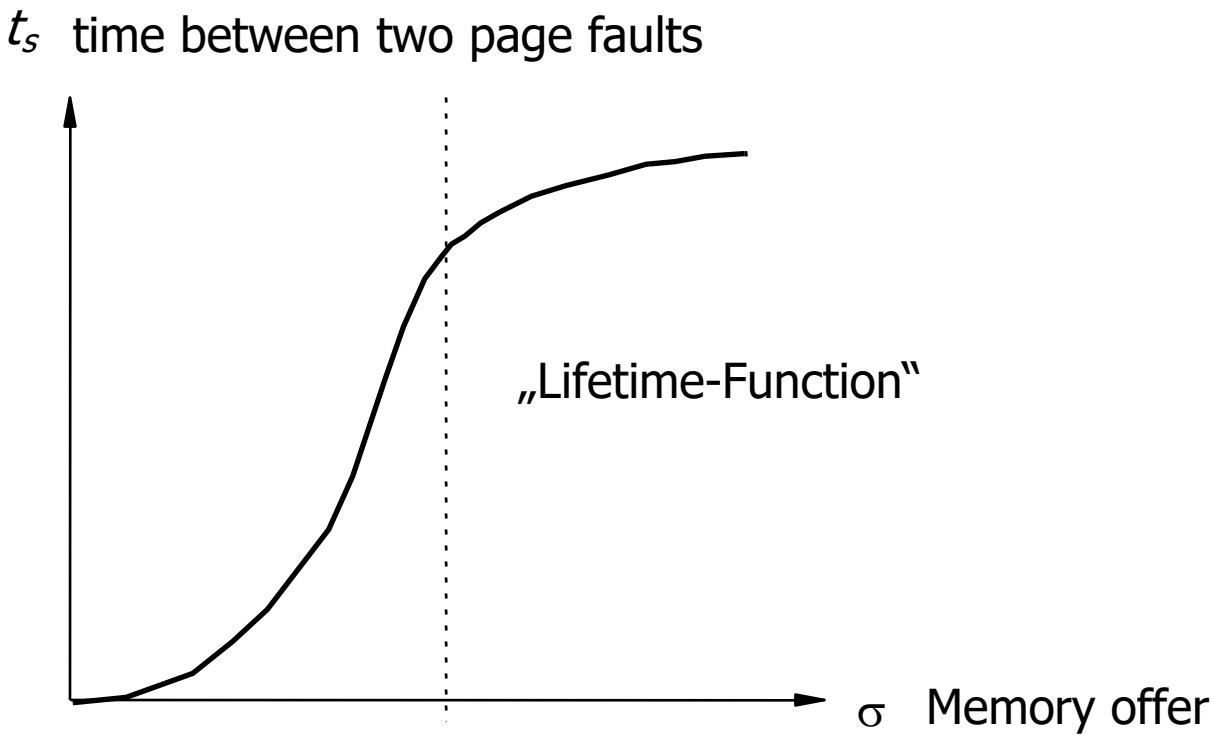


K	number of memory frames
n	number of programs in memory (*Multiprogramming Level, MPL*)
s_0	size of program address space (in pages)
t_s	time between two page faults
t_T	page transfer time
s	memory offer in pages
$\sigma = s/s_0$	memory offer normalized to program address space

- For n identical programs the following holds:

  $s(n) = K / n$ or $\sigma(n) = K / (n\, s_0)$, *resp.*

Inter page fault time

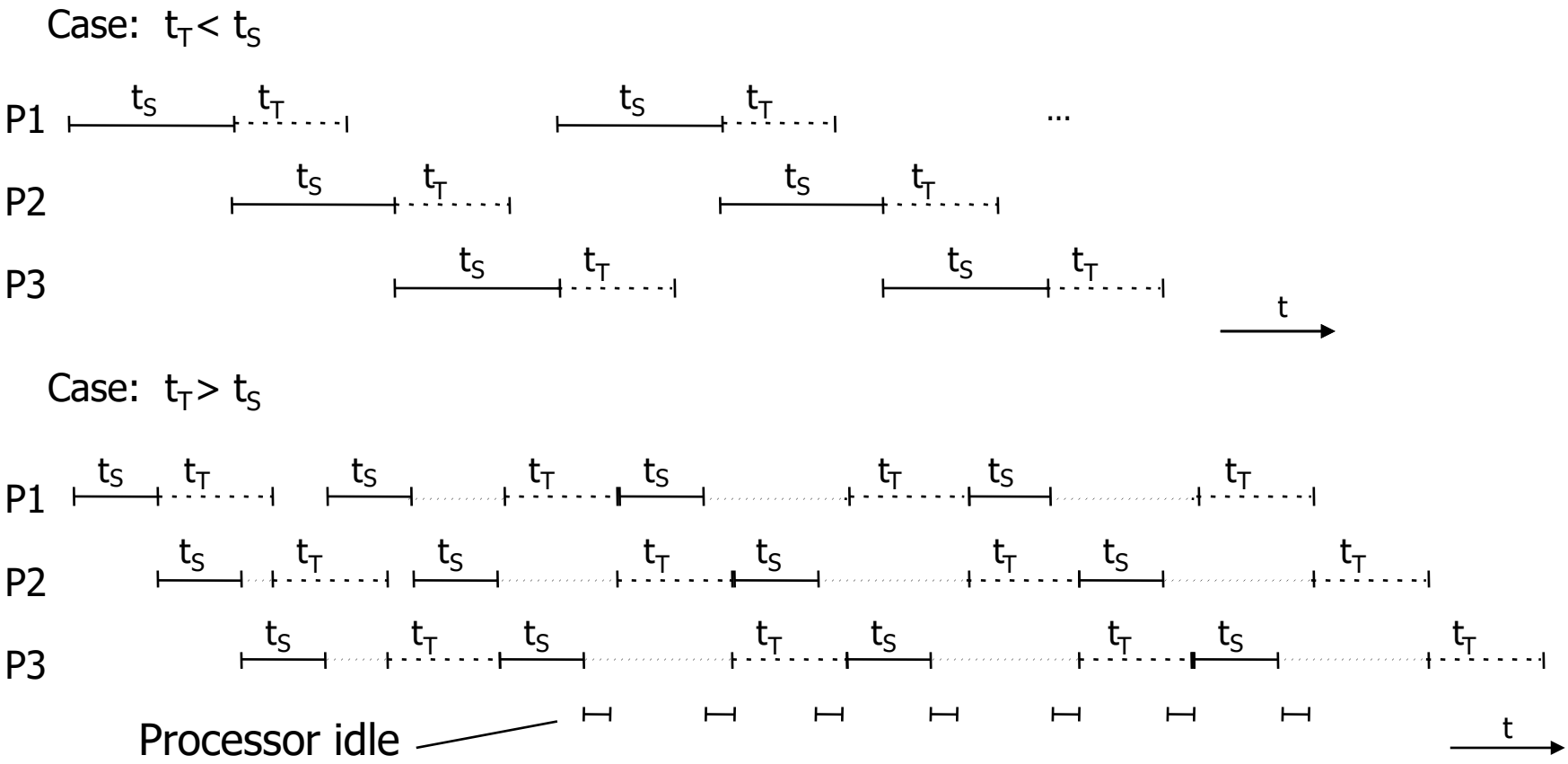


- The time between two page faults depends on the amount of available memory
- Left of the „knee“ the function can be approximated by a parabola:

$$t_s \approx a \cdot \sigma^2 = a \cdot \left(\frac{K}{n \cdot s_0} \right)^2$$

i.e. t_s decreases with growing n

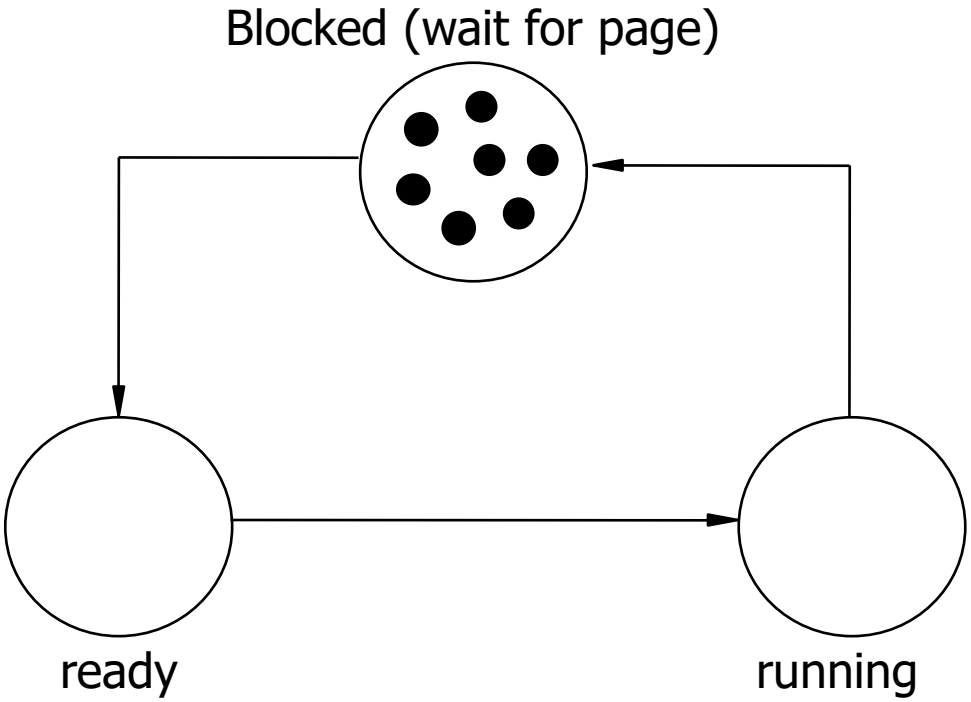
Interleaving of compute and page transfer phases



- In the second case, we experience phases where the processor is idle since all processes wait for their pages to be swapped in.

7.6.2 Thrashing Effect

- The system is completely occupied with paging and cannot perform regular useful work.



Thrashing

Goal: High processor utilization

↓

Many programs executed simultaneously

↓

High multiprogramming degree n

↓

Low memory space s per process

↓

Short time between successive page faults

↓

Congestion at paging device (disk)

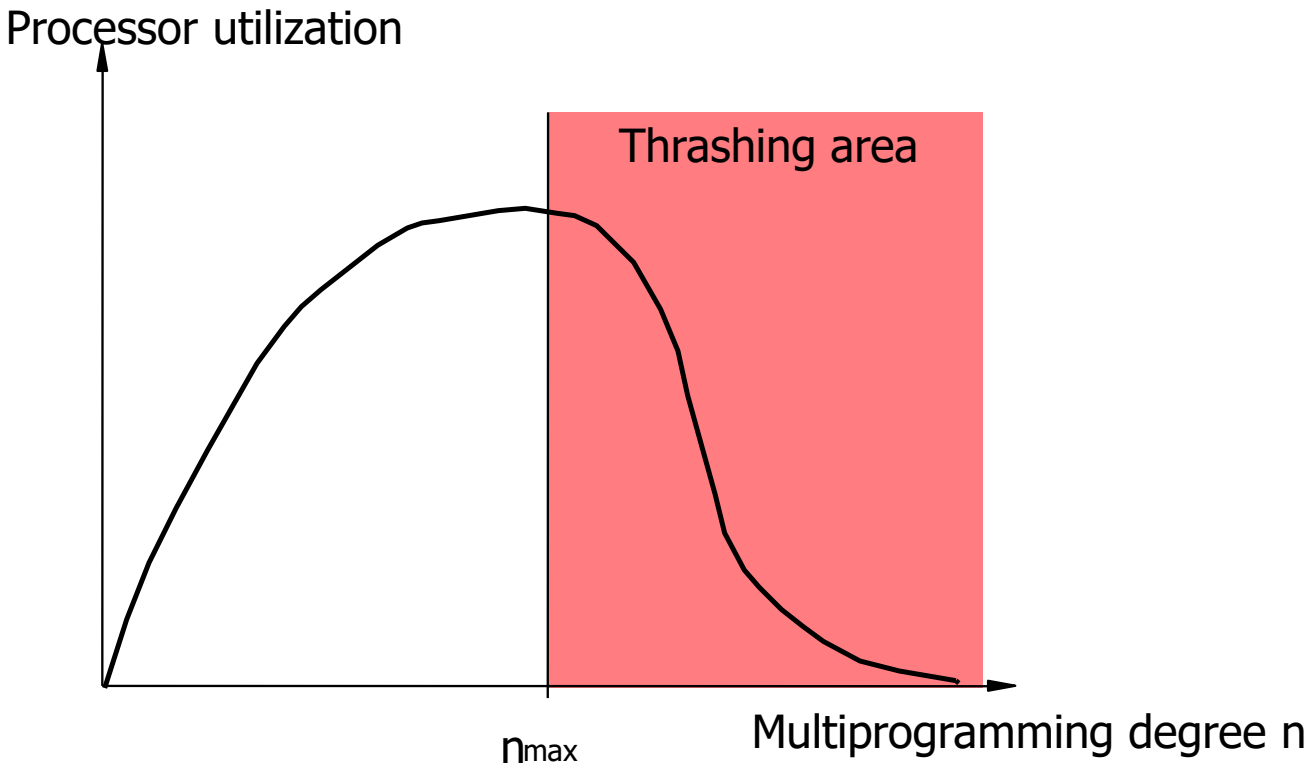
↓

Almost all processes blocked

↓

Result: poor processor utilization

Thrashing Curve



- We have to take care that the system does not enter the overload region.

Overload phenomena

- Thrashing is a special variant of an overload phenomenon that can be found in many areas (not only in computer science) and always leads to a performance collapse.

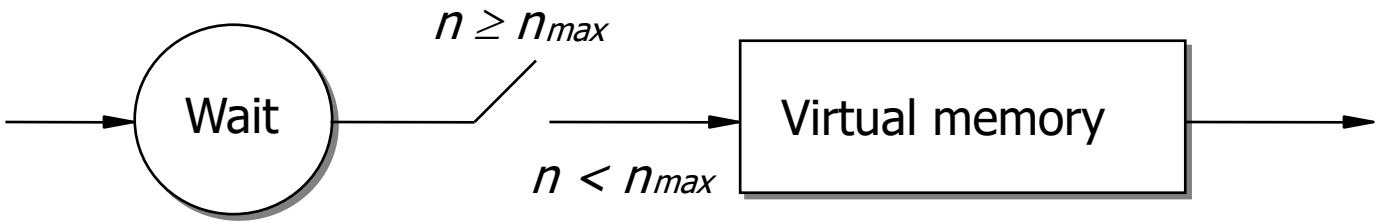
- Examples:
  - Computer networks — too many packets
  - Telephone networks: — too many calls
  - Database systems: — too many transactions
  - Road traffic — too many cars
  - Parallel computing — too many processors

- Reason:

  Overhead for coordination grows overlinearly.

Overload prevention

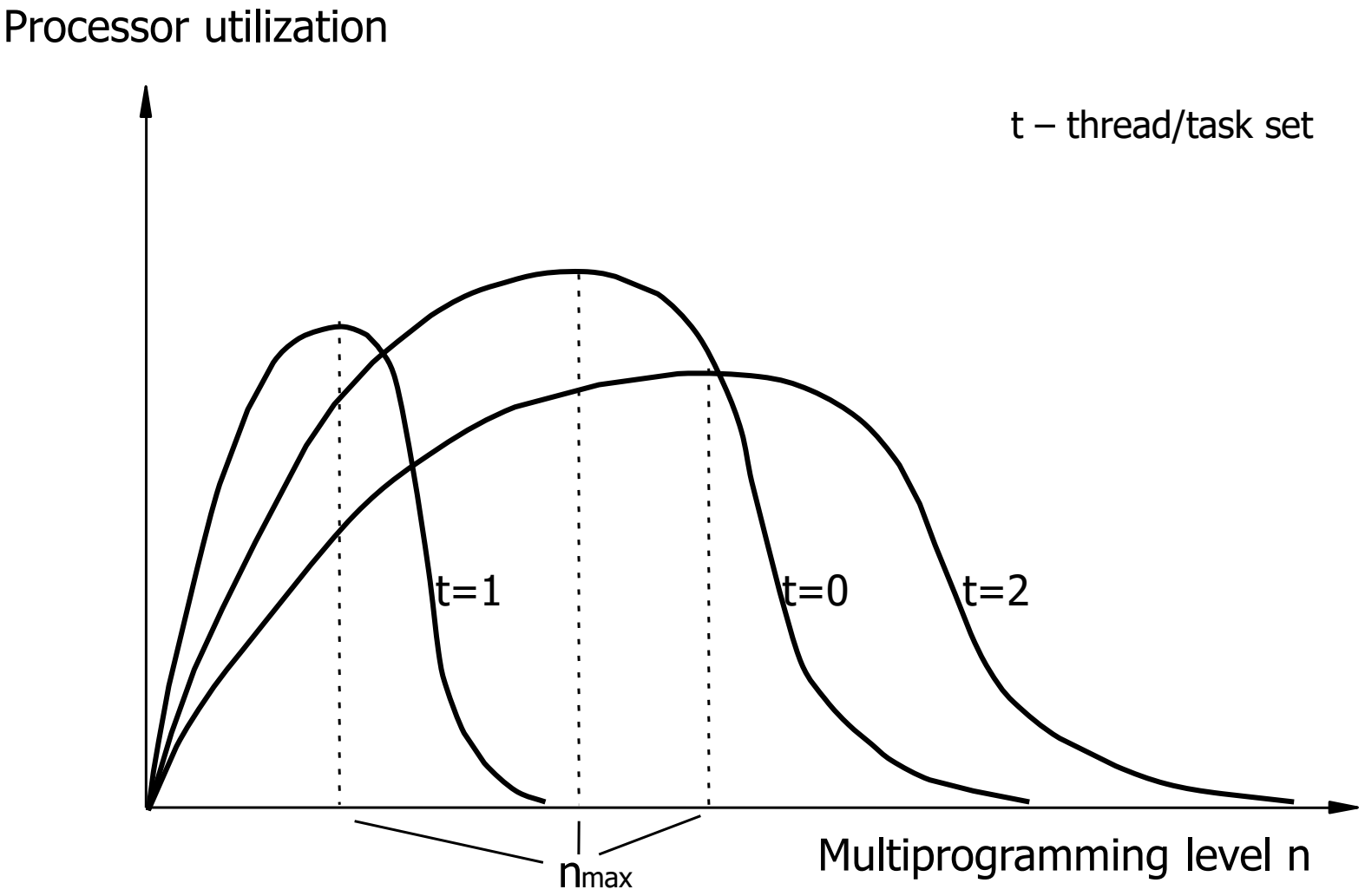
- To prevent the thrashing effect, the multiprogramming level must be limited.



- Problem: How to find an optimal n_{max} ?
- Difficulty:

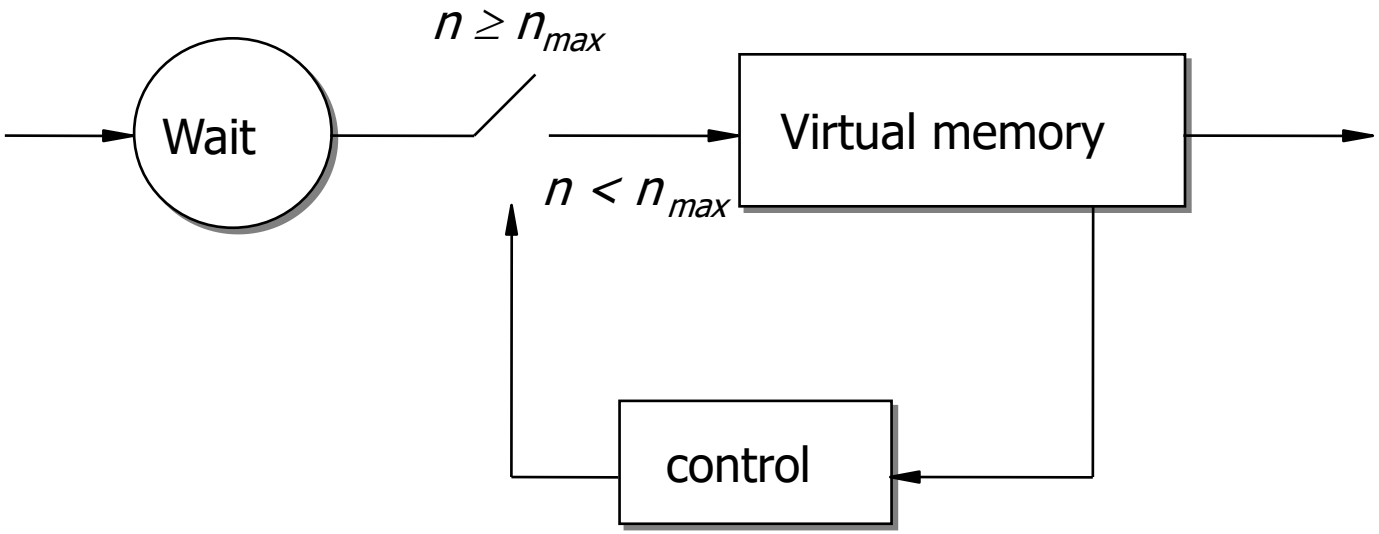
  Program behavior changes over time:
  - Individual program behavior changes
  - Combination of program set in memory changes (multiprogramming mix)

Thrashing curve dynamics



Thrashing prevention

- The optimal n_{max} turns out in operation and has to be adopted dynamically.
- Thrashing prevention is therefore done by feedback control.



Thrashing prevention

Two strategic approaches:

- *Indirect* or *local* strategy

  For each process *i* a reasonable number of frames s_i is determined dynamically.

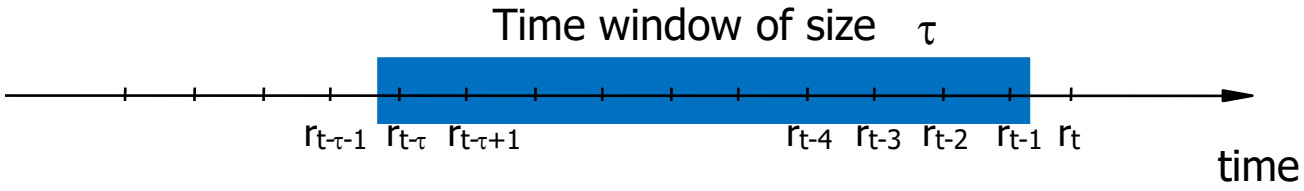
  The maximum multiprogramming level can be found indirectly:

$$n_{max} := max\left\{ n \;\middle|\; \sum_{i=1}^{n} s_i \leq K \right\}$$

- *Direct* or *global* strategy

  The measurement of the global paging activity leads to the calculation of an optimal n_{max}.

- **The Working-Set Model**
- The Working-Set of a program *i* is defined as the set of pages that have been referenced within the last τ time units.

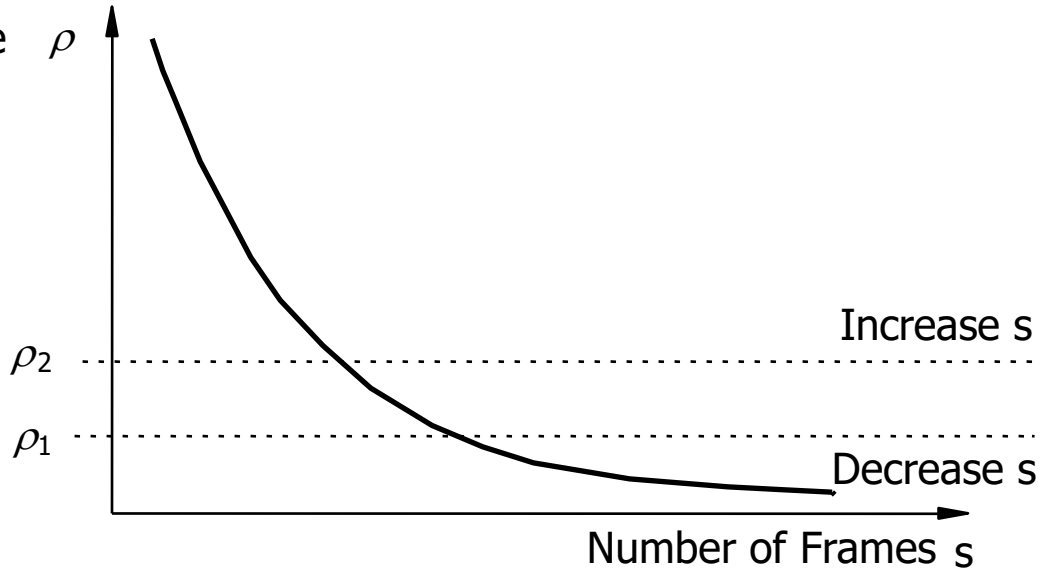


- With suitable choice of *t* the size of the working set $w_i(t,\tau) := |W_i(t,\tau)|$ indicates the number of page frames that the process needs for efficient work.
- $w_i(t,\tau)$ is estimated using the reference information for each process.
- A new process *x* is loaded into memory, only if

$$w_x \leq K - \sum_{i=1}^{n} w_i(t,\tau)$$

- It is the goal of the algorithm that all processes can accommodate their particular working sets in the memory.

The Page-Fault-Frequency Model (PFF)

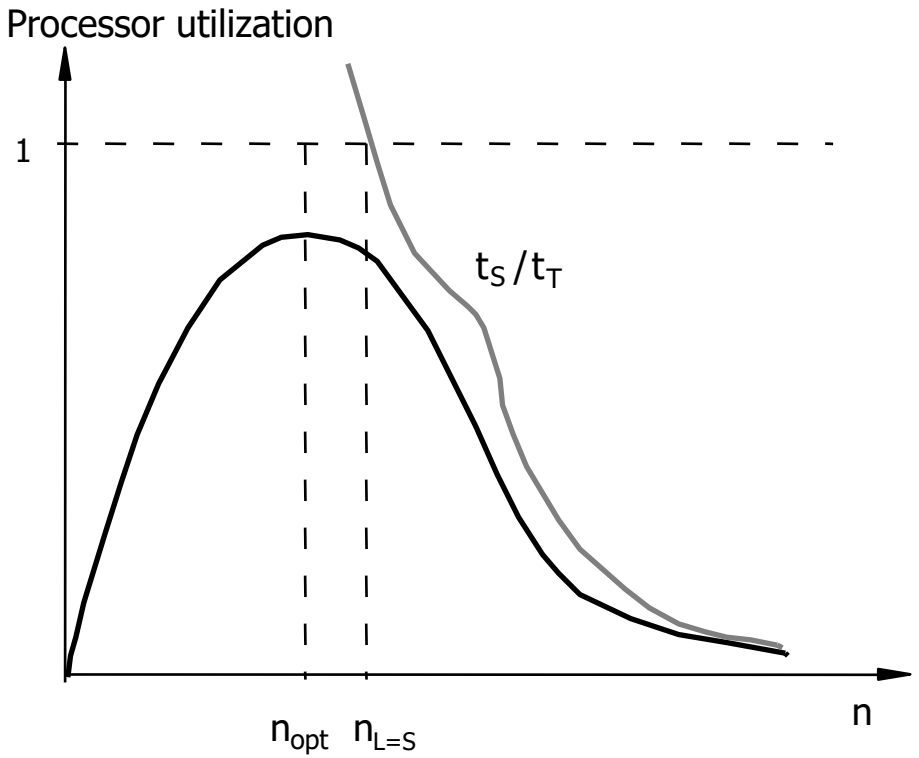


- For each process, the page fault rate (#page faults per time unit) is measured and serves to adjust the number of frames.
- Control mechanism: $\rho < \rho_1 : \quad s =: s - 1$
  $\rho > \rho_2 : \quad s =: s + 1$
- The multiprogramming level can be calculated indirectly as with the Working-Set algorithm.

The criterion of the interpagefault time (L=S-criterion)

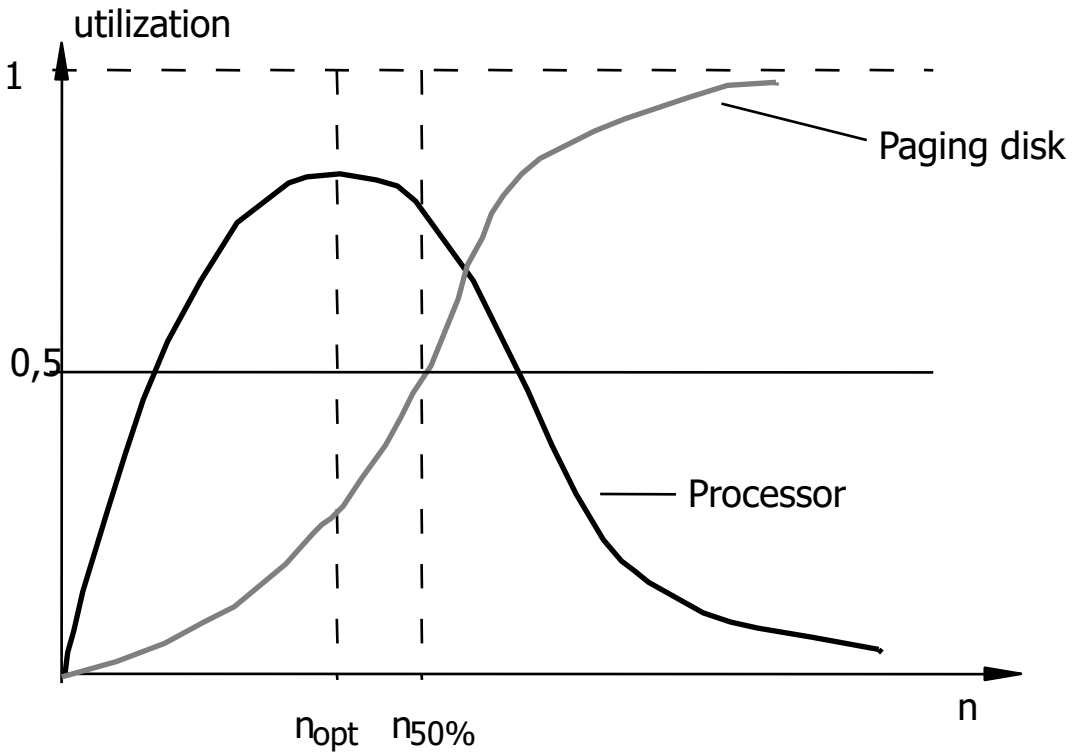
- The time between two page faults t_s (or *L resp.*) should be roughly the same as the page transfer time t_T (or *S, resp.*).

The resulting operation point is in most cases too far at the right which can be taken into account in the control laws.



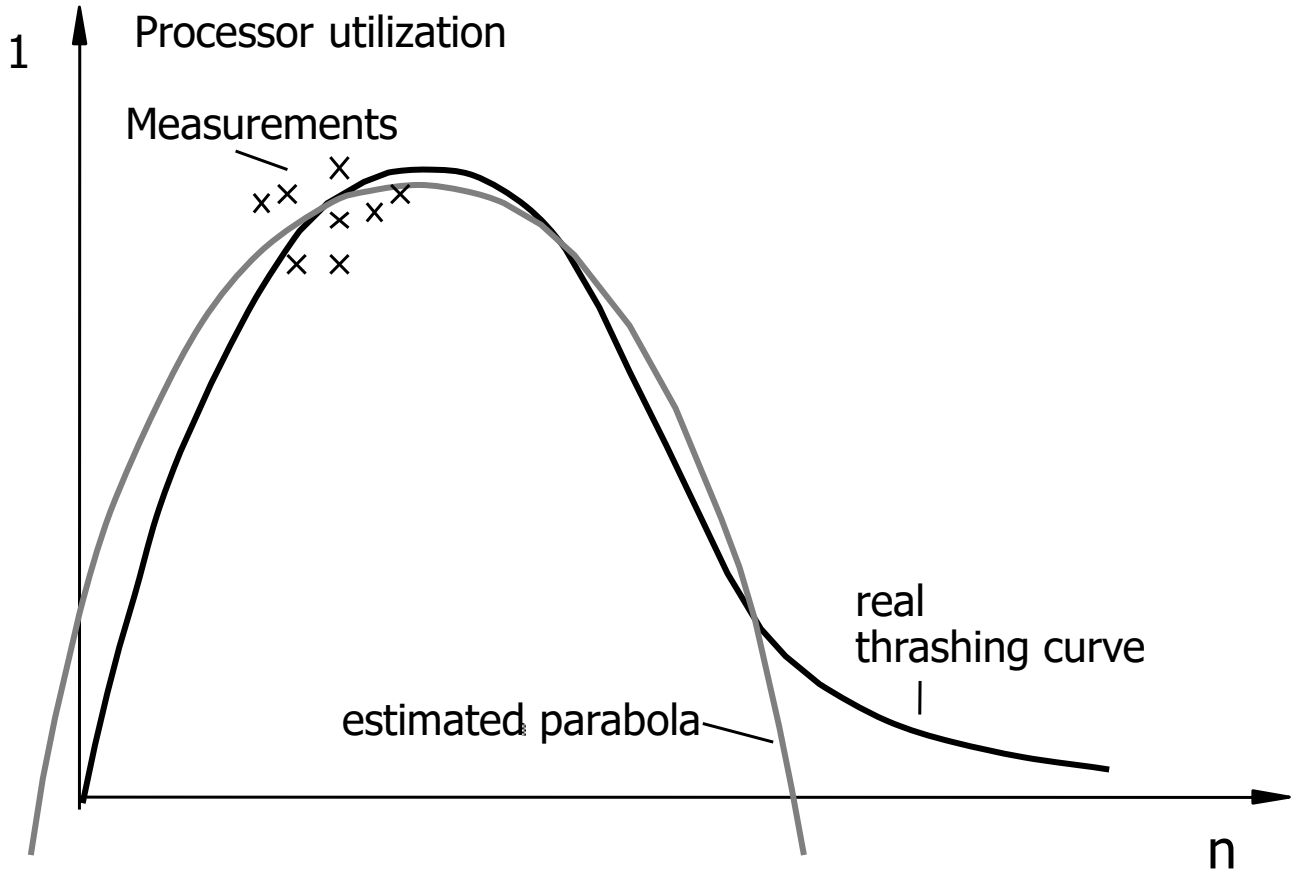
The 50%-Rule

- Thrashing happens, when many processes are blocked due to paging, i.e. when the mean queue length at the paging device is larger than 1.
- According to queuing theory this corresponds to a device utilization of > 50%.
- New processes are loaded to main memory only if the utilization of the disk (measured over a longer time period) is below 50%.



Parabola approximation

- The thrashing curve can be approximated by a parabola in the region of the maximum.



Parabola approximation

- Approximation formula $\eta = a_0 + a_1 n + a_2 n^2$

- The coefficients a_0, a_1, a_2 are dynamically estimated based on measurements (η_t, n_t).
- The apex n^* of the parabola can be calculated and used as upper bound of the multiprogramming level.
- If the estimation results in parabola that opens upward, the apex (extreme point) cannot be used as optimum.
- In this case the first derivative indicates the slope, i.e. whether we are left or right of the optimum.
- The current upper bound can then be incremented or decremented.

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Swapping

- Early Unix systems did not have a virtual memory.
- The main memory had been managed as a resource with preemption, i.e. processes and their address spaces were swapped to disk, if
  - No space for process generation (fork) was available,
  - A dynamic memory request could not be satisfied.
- The process to be swapped out was chosen according to the following criteria:
  - State – blocked processes were favored for swapping out
  - Priority and residence time in memory
- Priority and time since its last swap-in are added.
- The process with the highest value is swapped out.
- Management of memory and swap area is done using a separate list-based mechanism with First-Fit.

Paging

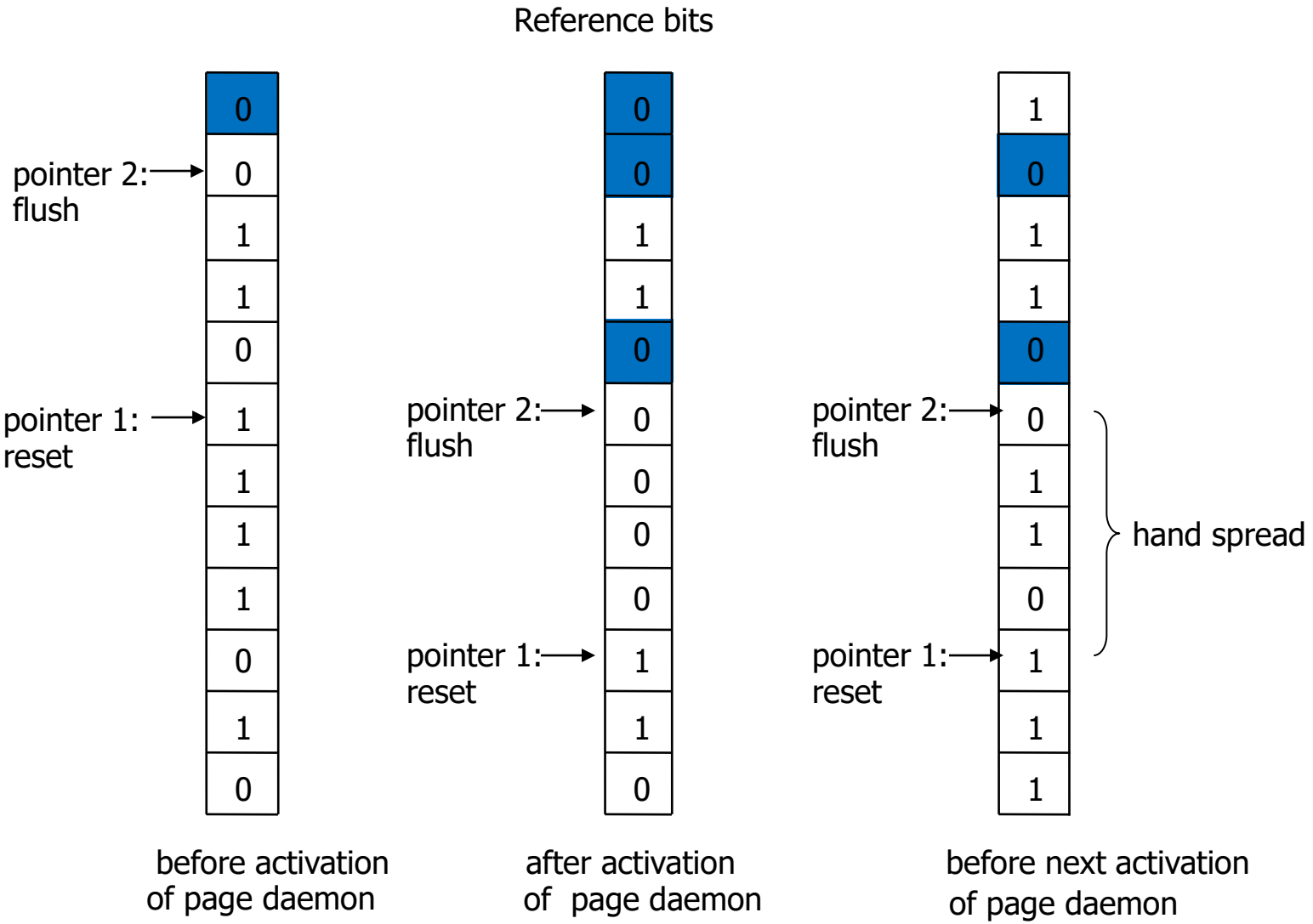
- Today‘s Unix Systems all provide virtual memory (demand paging).
- When a page fault occurs the missing page is loaded into an empty page frame.
- A special server process (*page-daemon*) has to take care that a sufficient number of empty frames (*lotsfree*) is always available.
- If there are too few empty frames available, the page daemon starts to flush pages to disk.
- For that, a *global* Second-Chance-Algorithm is used.
- The different Unix-systems use different variants.
- To prevent thrashing, Unix uses swapping, i.e. entire processes (address spaces) are swapped out.

Activating the Page daemon

- **AT&T System V**:
  - Original Second-chance-Algorithm
  - Instead of *lotsfree* two parameters *min* and *max* are used
    - Activation, if current no. of frame < *min*
    - stop, if current no. of frame > *max*

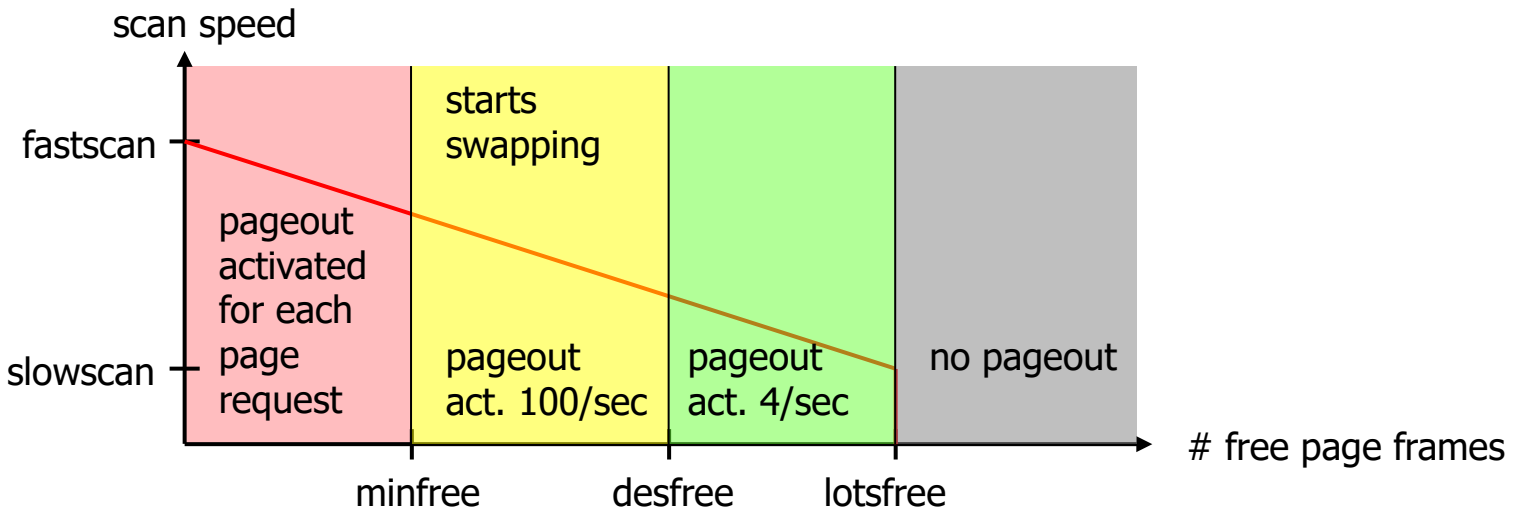
- **4.3BSD**:
  - Modified Second-chance-Algorithm (Two-Hand-Clock-Algorithm)
  - Parameter *lotsfree*
    - Activation, if current no. of frame < *lotsfree*
    - stop, if current no. of frame > *lotsfree*

Modified "Second Chance"-Algorithm (Two-Hand-Clock-Algorithm, Unix 4.2BSD)



Solaris

- Solaris (Sun Microsystems/Oracle) also uses the 2-Hand-Clock (page out) with the following parameters
  - hand spread: difference between the two hands (# Frames)
  - scan speed: speed of frame scanning
    (slow: 100 frames/sec, fast: 8192 frames/sec)
  - lotsfree: amount at which paging sets in
    (e.g. 1/64 of total number of frames)
  - desfree: desirable amount of empty frames
  - minfree: minimal amount of empty frames



7.7.2 Memory management in Windows

In contrast to Unix, Windows uses a *local paging strategy* :

- If, as a consequence of a page fault, a page needs to be swapped out, always a page of that process which caused the page fault is chosen.
- Not only the missing page, but also some more of the „neighborhood" of that page is swapped in (*clustering*).
- The set of all currently loaded pages of a process is called working set.

Memory management in Windows

- The paging strategy depends on the hardware:
  - *FIFO* (modified) for Alpha processors and Intel multiprocessor systems
  - *Clock* for Intel monoprocessors

- The size of the working sets is initialized by default values (Min and Max).
- On demand Working Sets can grow beyond the maximum (*Working set expansion*) and shrink again (*Working set trimming*).
- Both are dependent on the page fault rate and on the number of free frames.
- For the OS itself also a working set mechanism is used.

Further reading

- Stallings,W.: *Operating Systems*, 5th ed., Prentice Hall, 2005, Chapter 7 (7.1+7.2) , Chapter 8
- Tanenbaum, A.: *Moderne Betriebssysteme*, 2.Aufl., Hanser, 1995, Kapitel 3, Abschnitt 3.1+3.2
- Knuth, D.E.: *The Art of Computer Programming*, Vol. 1, 3rd ed., 1997, pp. 435-451
- Peterson, J.; Norman T. A.: *Buddy systems*. CACM 20, 6 (June 1977, pp. 421-431
- Shore, J.E.: *Anomalous behavior of the fifty-percent rule in dynamic memory allocation*. CACM 20, 11 (Nov. 1977) pp. 812 - 820
- Denning,P.J.: *Working Sets Past and Present*, IEEE TOSE, Vol 6, (Jan. 1980) pp. 64-84.

Further reading

- Heiss, H.-U.: *Verhinderung von Überlast in Rechensystemen*, Springer (Informatik-Fachberichte), 1988
- Heiss, H.-U.: *Overload Effects and their Prevention*. Performance Evaluation Vol.12, No.4 (July 1991), S. 219-235.
- Markatos, E.: *Visualizing Working Sets*, ACM Operating Systems Review 31,4 (1997), pp.3-11
- Megiddo,N.; Modha,D.S.: *Outperforming LRU with an Adaptive Replacement Cache Algorithm*, IEEE Computer, April 2004