Operating Systems

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VI. Memory Management
May 17, 2023 (Summer Term 2023)

RUB Faculty of Computer Science

RUHR UNIVERSITÄT BOCHUM RUB

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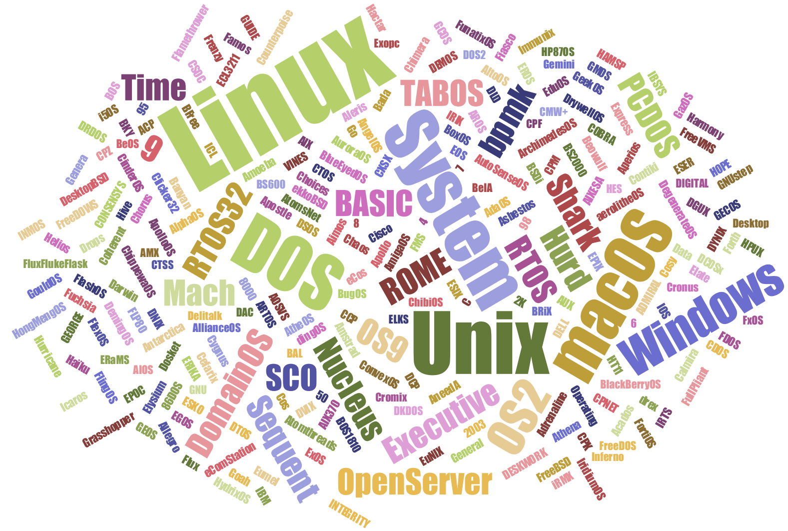
Chair of Operating Systems and System Software

Agenda



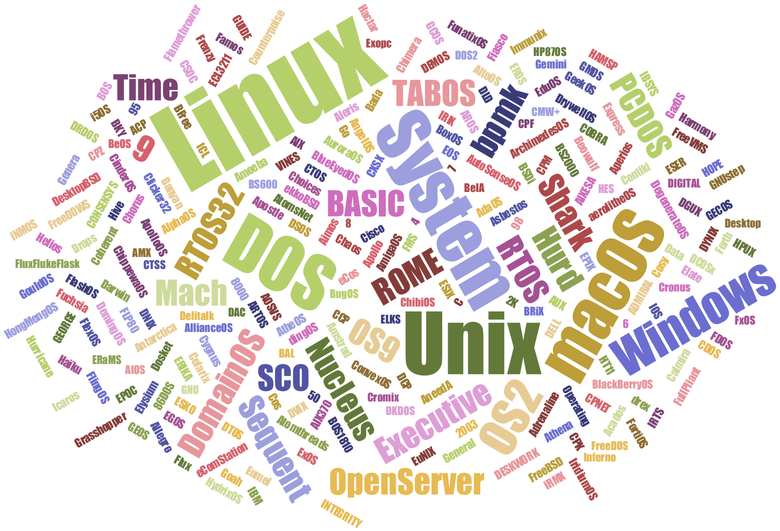
- Recap
- Organizational Matters
- Principles of Memory Management
  - Motivation
  - Requirements
  - Strategies
- Memory Allocation Schemes
- Memory Management for Multi-Program Operation
  - Segmentation
  - Paging
- Summary and Outlook

Literature References

Silberschatz, Chapter 9

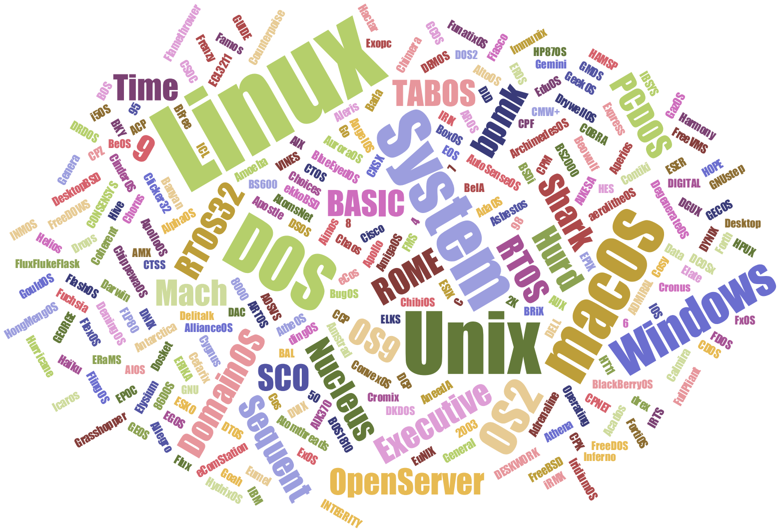
Tanenbaum, Chapter 3

⏮ Recap



- **process deadlocks**
  - **mutual blocking** of concurrent but independent processes
- **variants** and **necessary conditions**
  - deadly embrace: **deadlocks** and **livelocks**
  - **four deadlock conditions**
- deadlock **handling** and **countermeasures**
  - dining philosophers
  - prevention, avoidance, detection and recovery

Agenda



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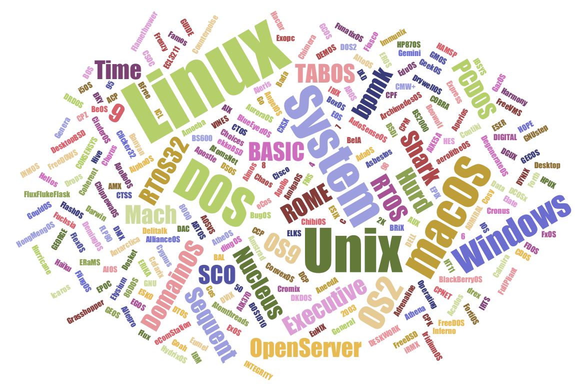
Organizational Matters



- lecture
  - Wednesday, 10:15 – 11:45
  - format: synchronous, **hybrid**
    - → in presence (Room HID, Building ID)
    - → online lecture (Zoom)
  - **exam:** August 7, 2023 (first appointment)
    September 25, 2023 (retest appointment)

- exercises: **group allocation ~~almost~~ complete**
  - make use of group work - for your own benefit!
- manage course material, asynchronous communication: Moodle
- `https://moodle.ruhr-uni-bochum.de/course/view.php?id=50698`

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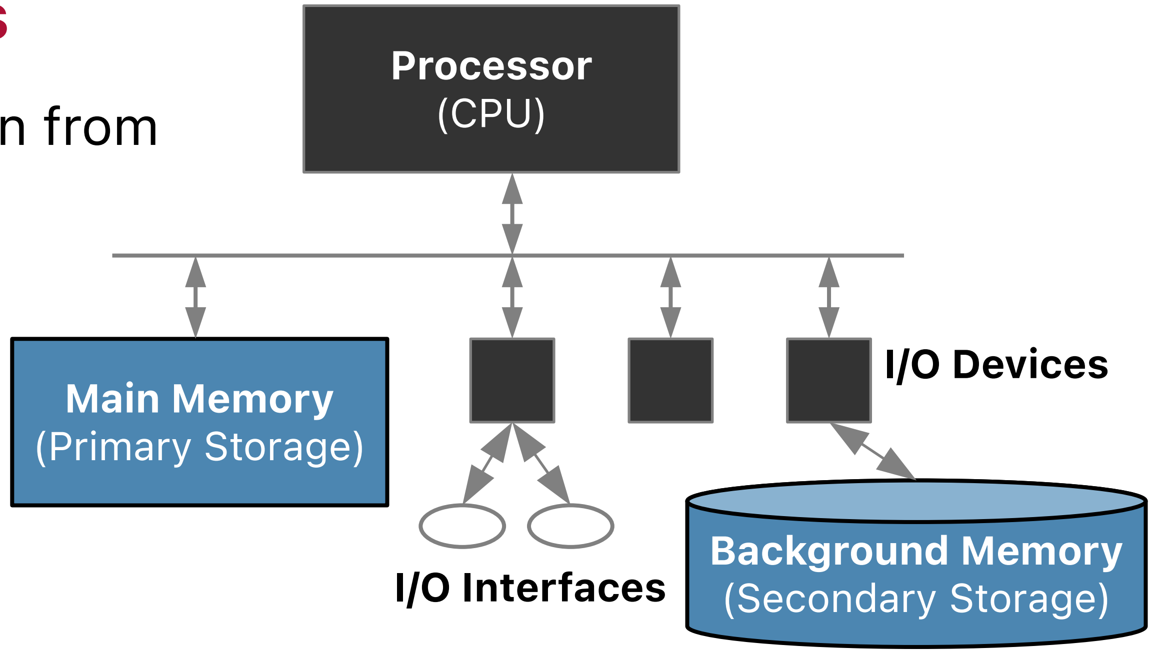
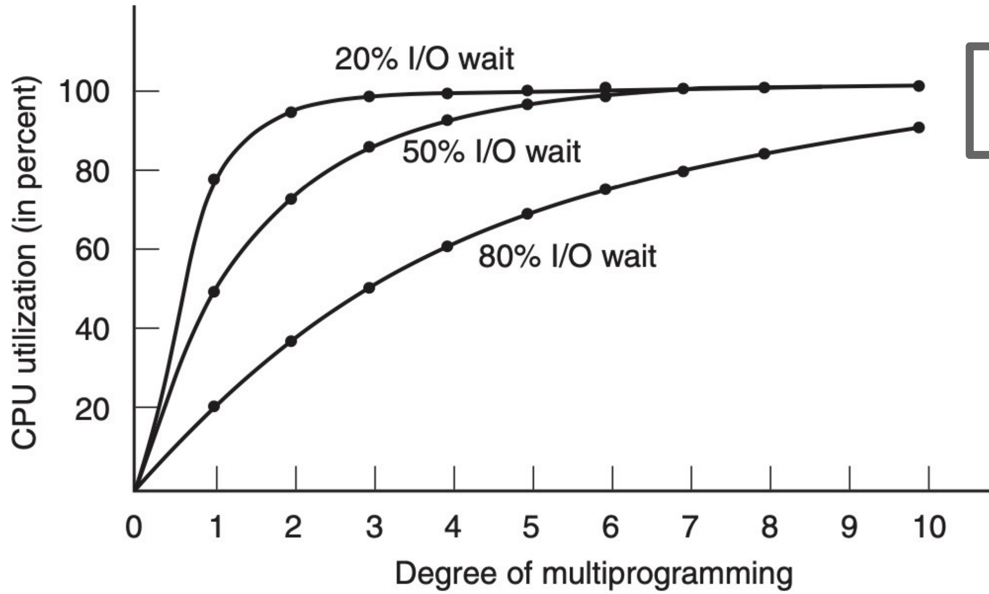
Operating Resources (Recap)

- the operating system has the following responsibilities:
  - management of the computers' operating resources
  - **creation of abstractions** that allow applications to handle operating resources (more) easily and efficiently
- up to now: **processes**
  - concept for abstraction from the real CPU
- now: **memory**
  - management of main and background memory



Motivation: Memory for Multi-Program Operation

- CPU utilisation assuming a certain I/O wait probability:



$$\boxed{A = 1-p^n}$$

A: CPU utilization
p^n: probability all n processes waiting for I/O

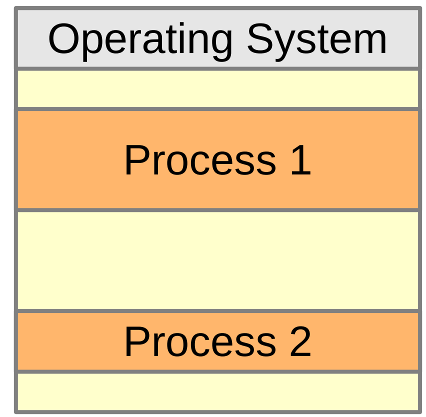
Source: Tanenbaum, Modern Operating Systems

→ **multi-program operation is essential for a high utilisation of the CPU**

- upon starting and terminating the processes, memory must be dynamically allocated or deallocated!

Requirements for Memory Management

- multiple processes require main memory
  - processes are located at different places in the main memory
  - need for protection of the operating system and the processes among each other
  - memory may not be sufficient not enough for all processes



➔ **know, manage and allocate free memory areas**

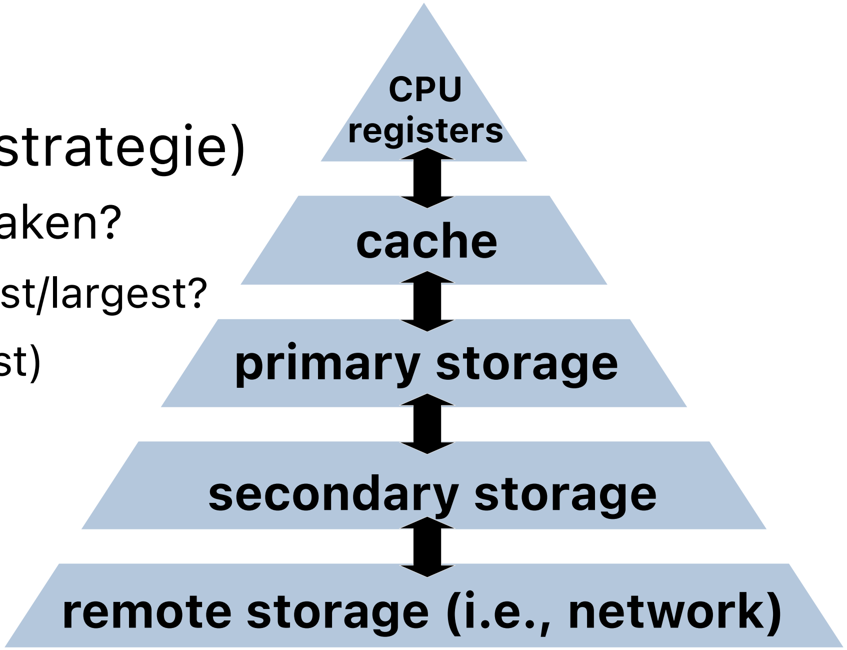
➔ **swap-in and swap-out of processes**

➔ **relocation of program code**

➔ **exploit hardware support (i.e., memory management unit)**

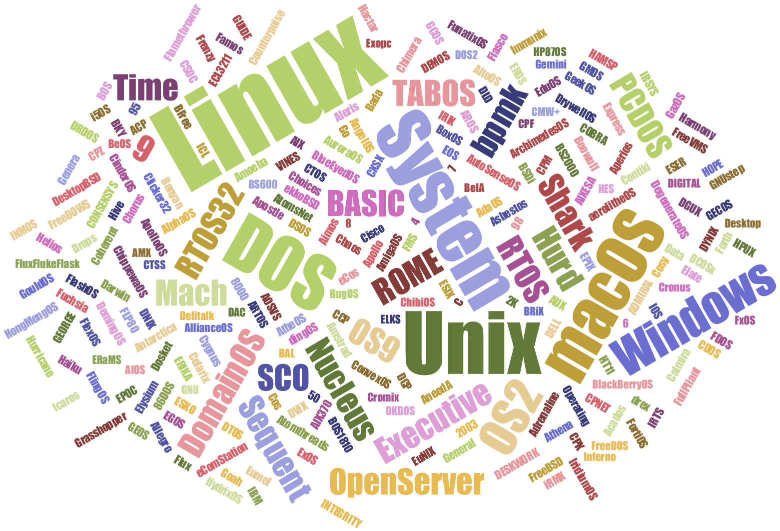
Strategies for Memory Management

Fundamental strategies at each level of the memory hierarchy:



- **placement strategy** (dt. Platzierungsstrategie)
  - **from where** should required memory be taken?
    - where is leftover (dt. Verschnitt) the smallest/largest?
    - do not care (leftover is of secondary interest)
- **fetch strategy** (dt. Ladestrategie)
  - **when** should data be loaded to memory?
    - on demand
    - anticipatory (i.e., in advance)
- **replacement strategy** (dt. Ersetzungsstrategie)
  - **which** memory contents are to be replaced, if any, if the memory is running low?
    - the oldest, most rarely used memory
    - the longest unused memory

Agenda



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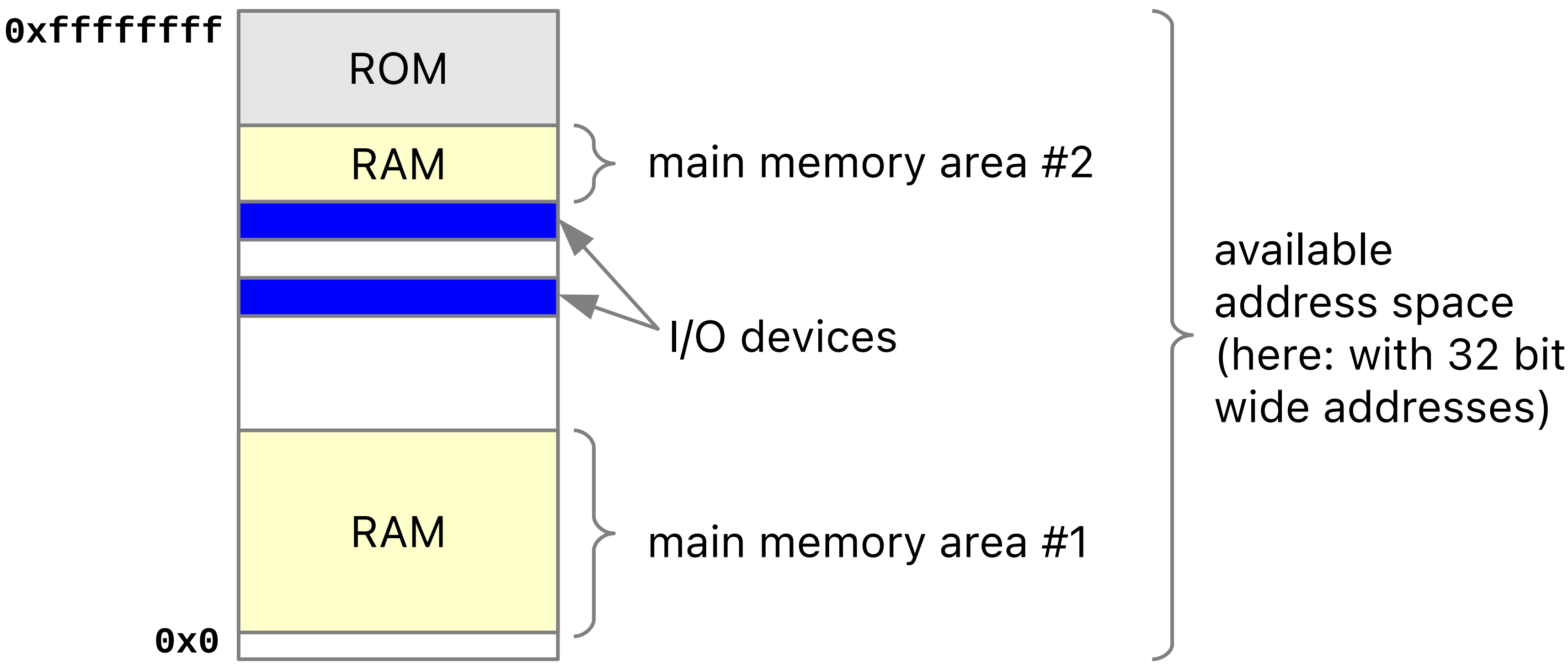
Memory Allocation - Problem Statement

- available memory is non-contiguous and has holes



memory map of a (hypothetical) 32 bit system

Static Memory Allocation

- fixed memory areas for operating system and user programs
- **problems**
  - degree of multiprogram operation limited
  - limitation of other resources (e.g., bandwidth for input/output due to too small buffers)
  - unused memory of the operating system cannot be used by application programs and vice versa

➔ **<u>dynamic</u> memory management is mandatory**

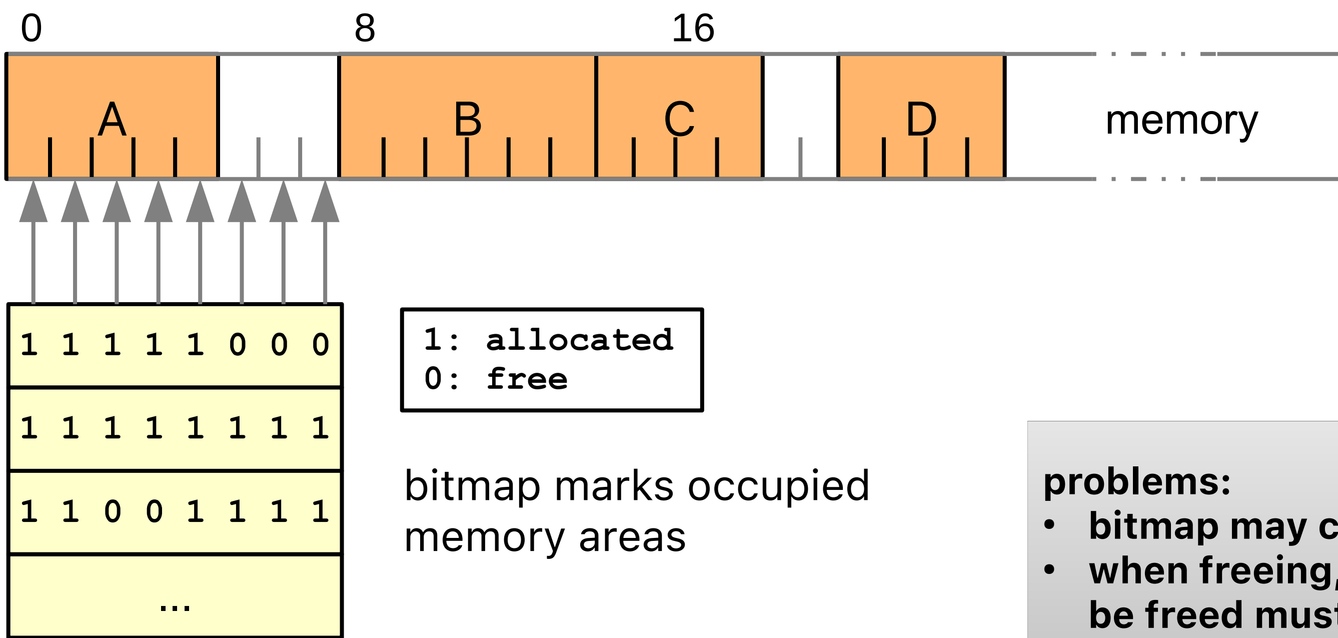
Dynamic Memory Allocation

- **segments**
  - **contiguous memory** area (i.e., memory range with consecutive addresses)
  - **variable size**
- **allocation** (dt. Belegung) und **deallocation** (dt. Freigabe) of memory segments
- an application program usually has the following segments:
  - text segment
  - data segment
  - stack segment (local variables, parameters, return addresses, ...)
- search for suitable memory areas for allocation
  - especially at program start

➔ **placement strategies are necessary necessary**
  - especially important:
    efficient free-space management (dt. Freispeicherverwaltung)

Free-Space Management – Bitmap

- free (possibly also allocated) segments of the memory must be represented
- **bitmap (or bit vector)**




```
1: allocated
0: free
```

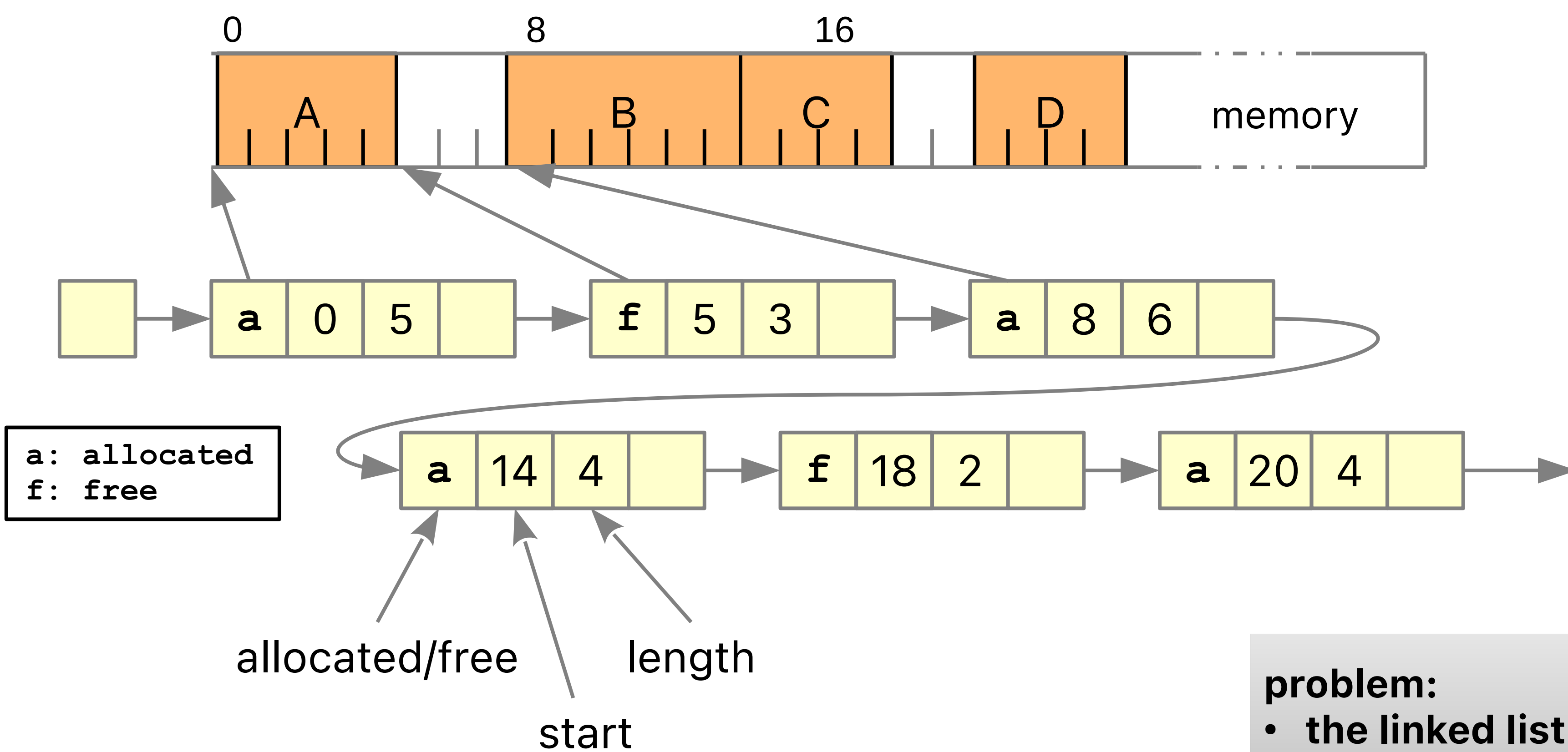
bitmap marks occupied memory areas

memory units of the same size (e.g., 1 byte, 64 bytes, 1024 bytes)

problems:
- **bitmap may cost a lot of memory**
- **when freeing, size of the memory to be freed must be known/specified**
- **linear search necessary (→ runtime overhead)**
- **handling of high memory pressure**

Free-Space Management – Linked List (V1)

- **linked list**

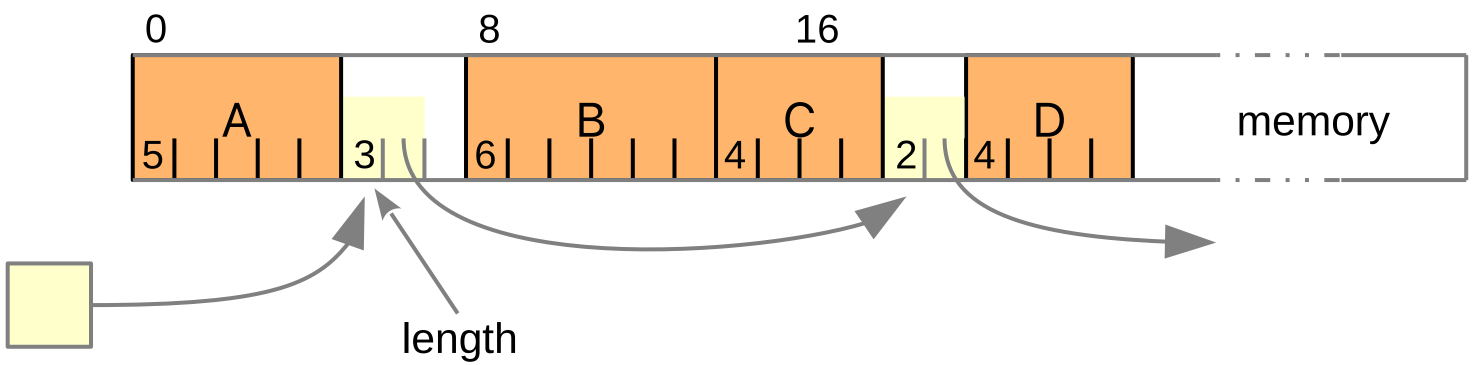


representation of allocated (used) and free (unused) segments

problem:
- **the linked list itself requires (dynamically allocated) memory**

Free-Space Management – Linked List (V2)

- **keep linked list in unused (i.e., free) memory**

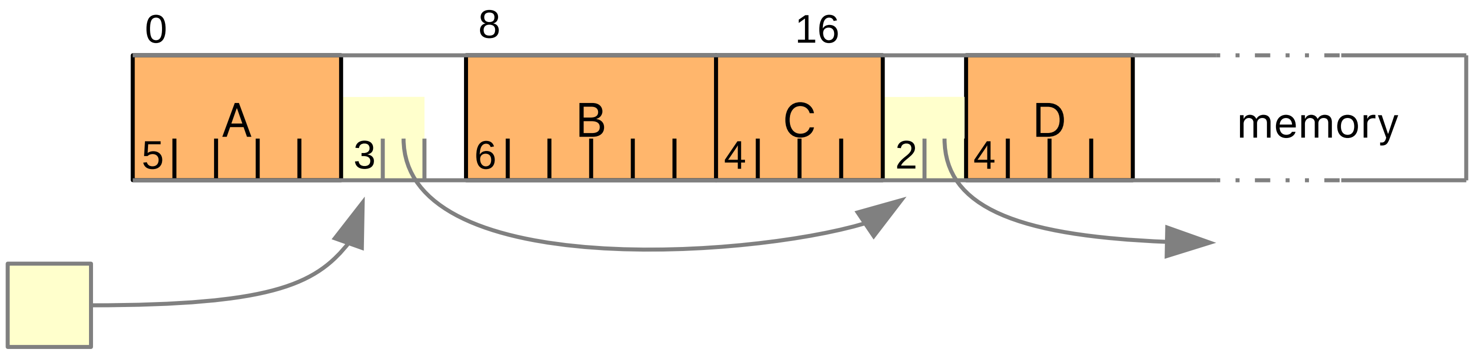


minimum hole size must be guaranteed

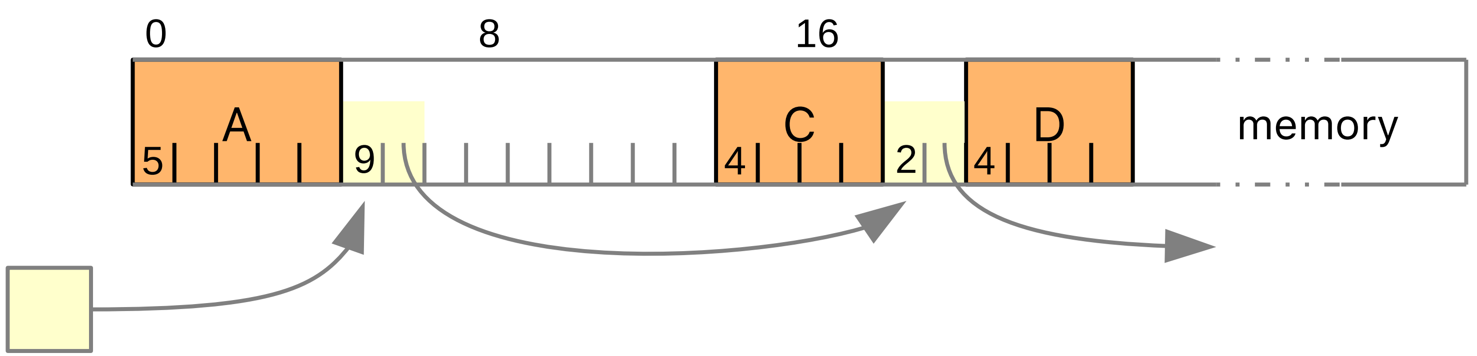
- backward linking may be necessary to increase efficiency
- representation ultimately also dependent on the allocation strategy

Free-Space Management - Freeing Memory

- **merging leftover holes**



after freeing of B



Placement Strategies – List-based Strategies

depending on the individual strategy, hole lists are sorted differently:

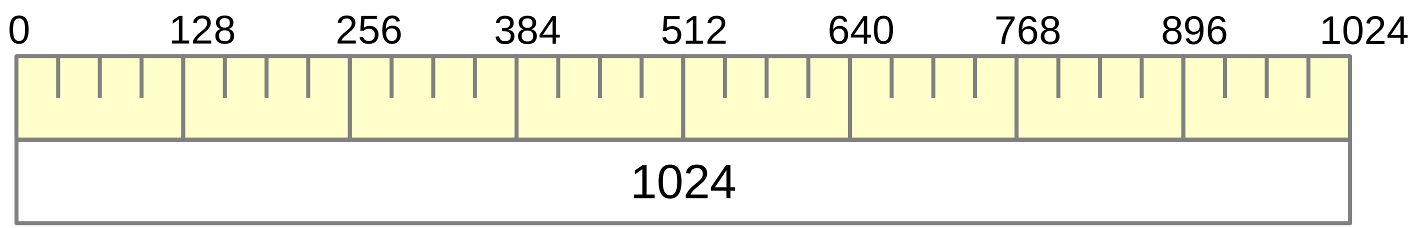
- **First Fit** (sorting: **by memory address**)
  - linear search, first matching hole is used
- **Rotating First Fit / Next Fit** (sorting: **by memory address**)
  - like First Fit, but start at the last assigned hole
  - avoids many small holes at the beginning of the list (like First Fit)
- **Best Fit** (sorting: **by hole size** – smallest hole first)
  - linear search, smallest matching hole is searched
- **Worst Fit** (sorting: **by hole size** – largest hole first)
  - largest matching hole is searched
- **common problem**:
  - when holes are too small → memory fragmentation

Placement Strategies – Buddy System

- memory allocation algorithm: buddy system
- operating principle
  - allocation: split available memory into **partitions of size 2^n bytes**
  - try to fit memory request:
    - ➔ splitting memory into halves
    - ➔ best fit
  - free: recursively merge any free buddy partitions
- practical importance
  - Linux (Buddy System variant which addresses external fragmentation)
  - FreeBSD (jemalloc, which implements the Buddy System)

Placement Strategies – Buddy System

- the **buddy system** partitions memory into dynamic areas of size 2^n



A: request 70
B: request 35
C: request 80
release A
D: request 60
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release C

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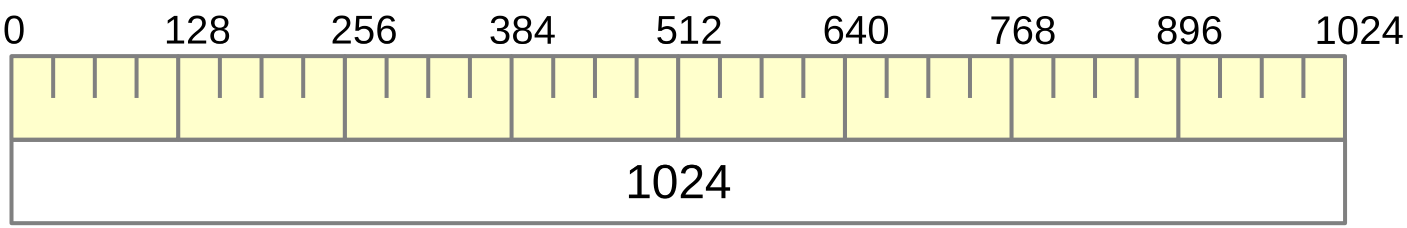

A: → request 70
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bucket size	free list	allocated list
1024 (2^10)	0	
512 (2^9)		
256 (2^8)		
128 (2^7)		
64 (2^6)		

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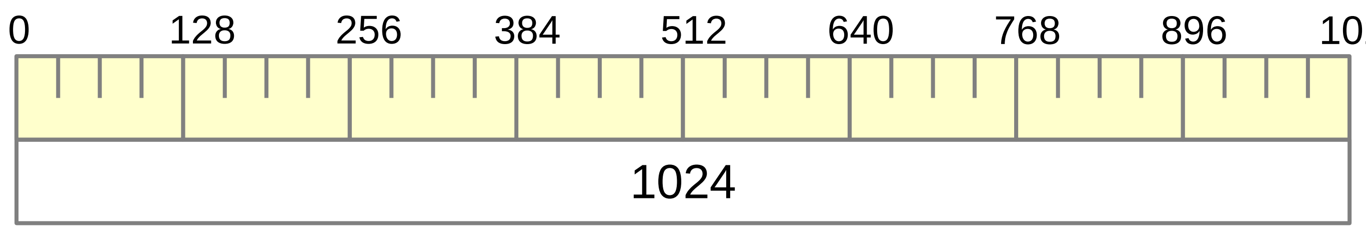

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bucket size	free list	allocated list
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512 (2^9)	0, 512	
256 (2^8)		
128 (2^7)		
64 (2^6)		

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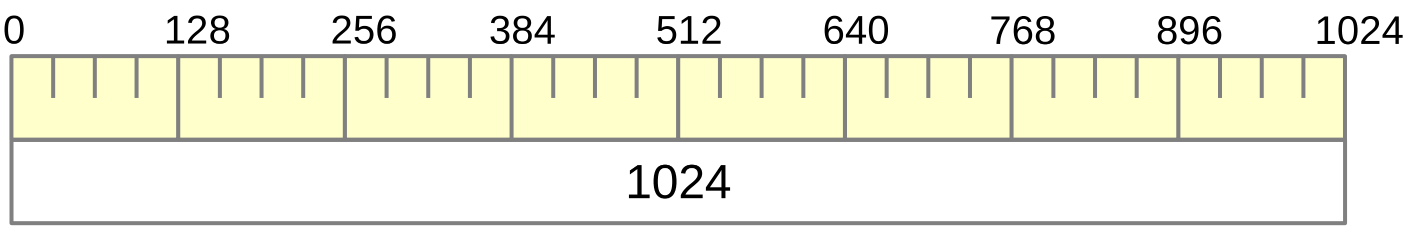

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bucket size	free list	allocated list
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512 (2^9)	512	
256 (2^8)	0, 256	
128 (2^7)		
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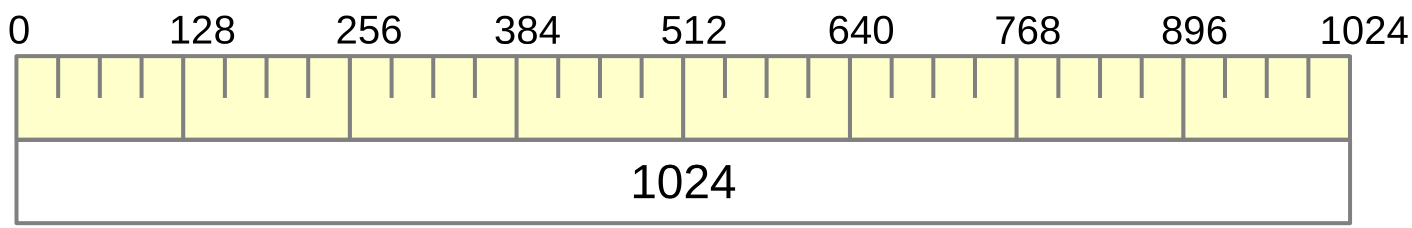

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bucket size		free list	allocated list
1024	(2^10)		
512	(2^9)	512	
256	(2^8)	256	
128	(2^7)	0, 128	→ allocate A at 0
64	(2^6)		

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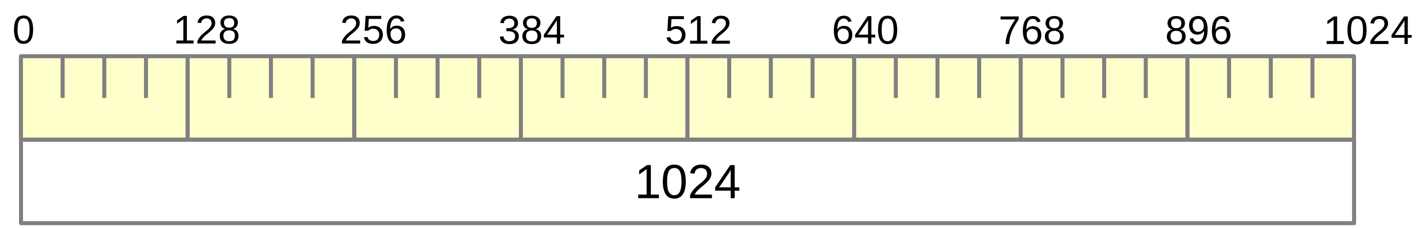

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bucket size		free list	allocated list
1024	(2^10)		A: 0 (128)
512	(2^9)	512	
256	(2^8)	256	
128	(2^7)	128	
64	(2^6)		

address
size

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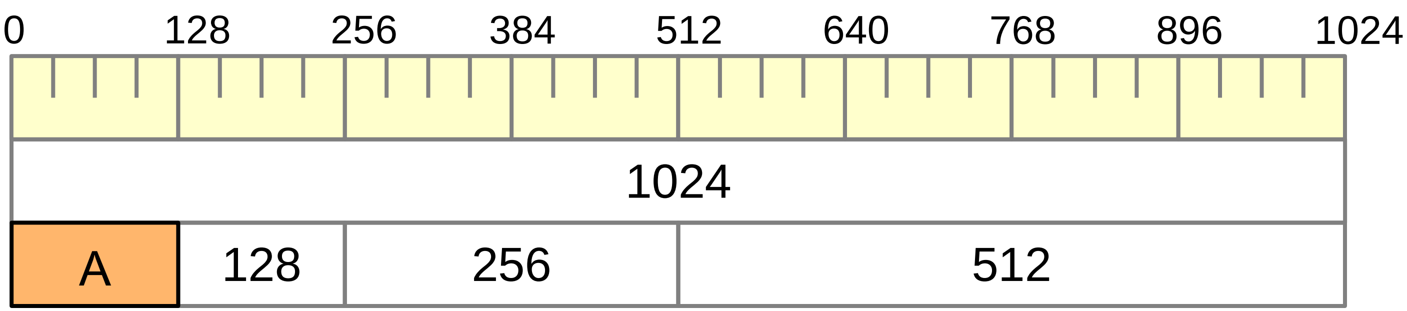

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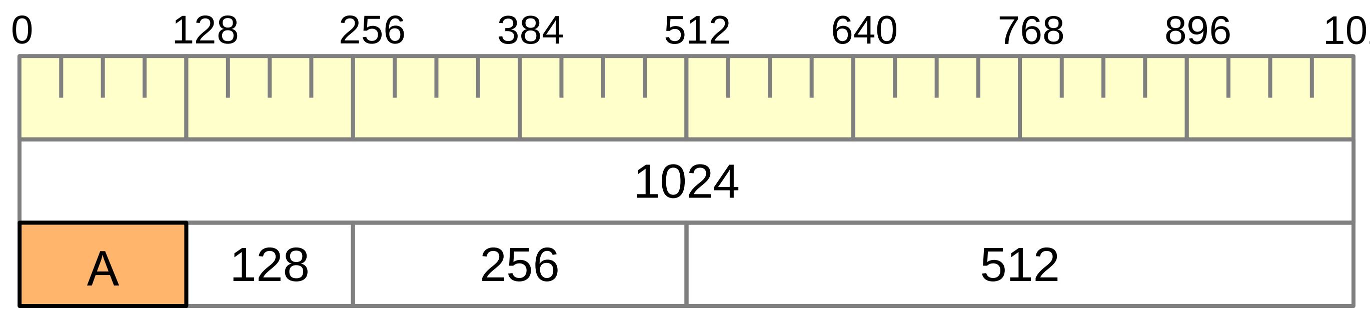

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512 (2^9)	512	
256 (2^8)	256	
128 (2^7)	128	
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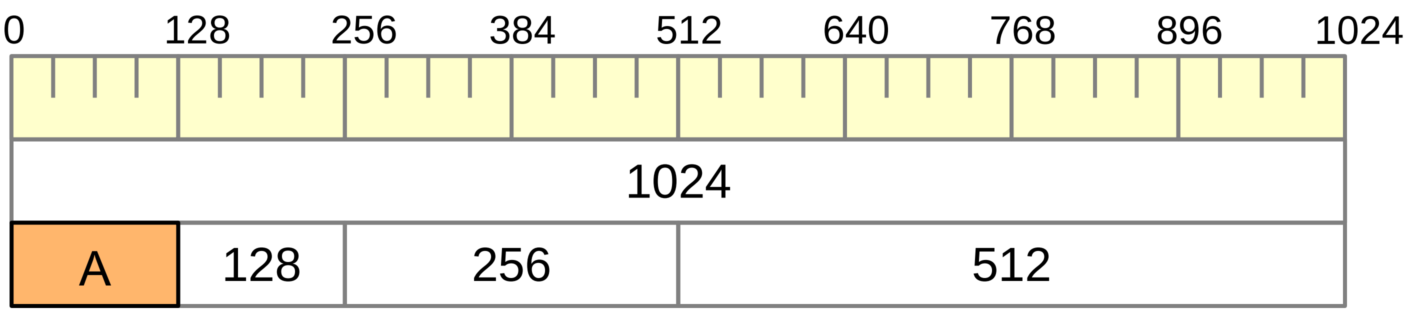

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bucket size		free list	allocated list
1024	(2^10)		A: 0 (128)
512	(2^9)	512	
256	(2^8)	256	
128	(2^7)		
64	(2^6)	128, 192	→ allocate B at 128

Placement Strategies – Buddy System

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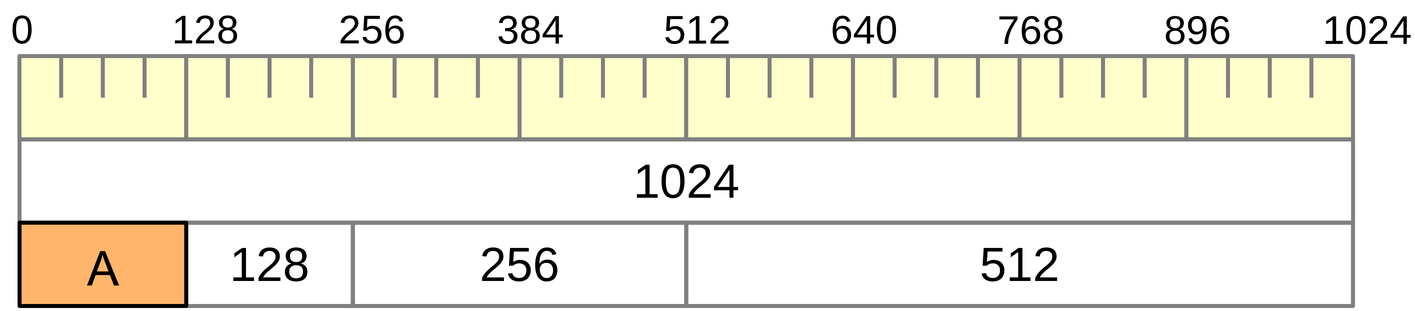

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release C

bucket size	free list
1024 (2^10)	
512 (2^9)	512
256 (2^8)	256
128 (2^7)	
64 (2^6)	192

allocated list

A: 0 (128)
B: 128 (64)

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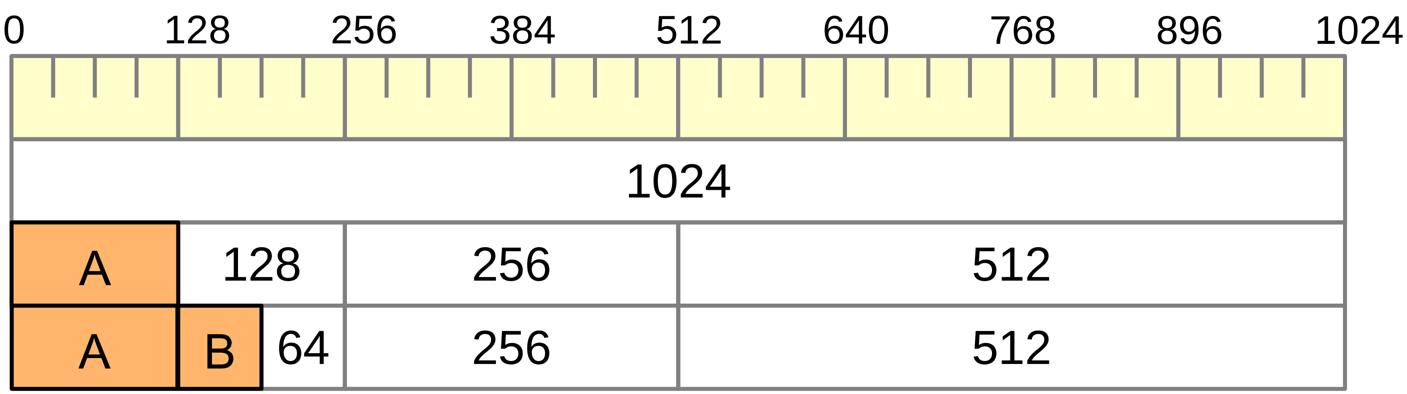

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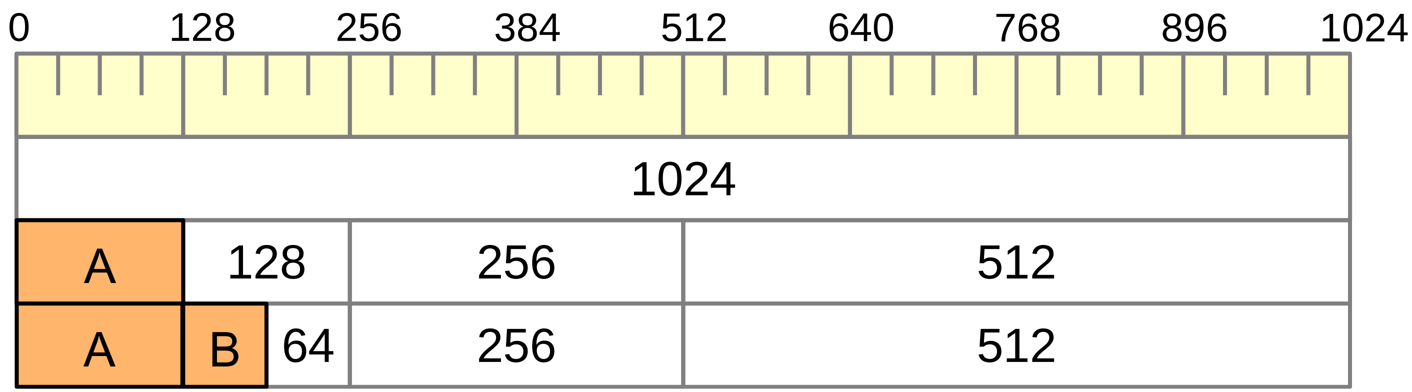

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512 (2^9)	512
256 (2^8)	256
128 (2^7)	
64 (2^6)	192

allocated list

A: 0 (128)
B: 128 (64)

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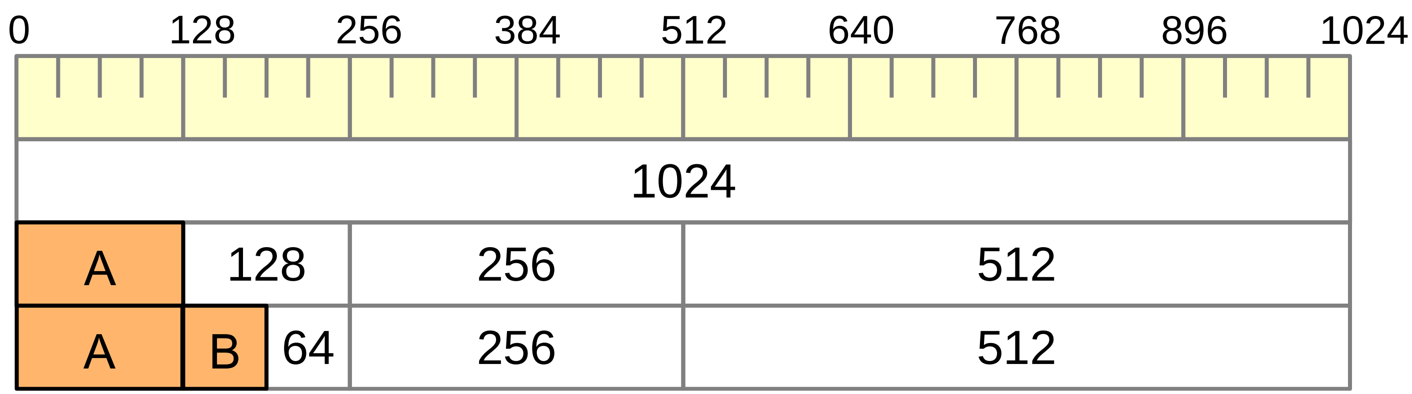

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bucket size	free list	allocated list
1024 (2^10)		A: 0 (128)
512 (2^9)	512	B: 128 (64)
256 (2^8)		
128 (2^7)	256, 384	→ allocate C at 256
64 (2^6)	192	

Placement Strategies – Buddy System

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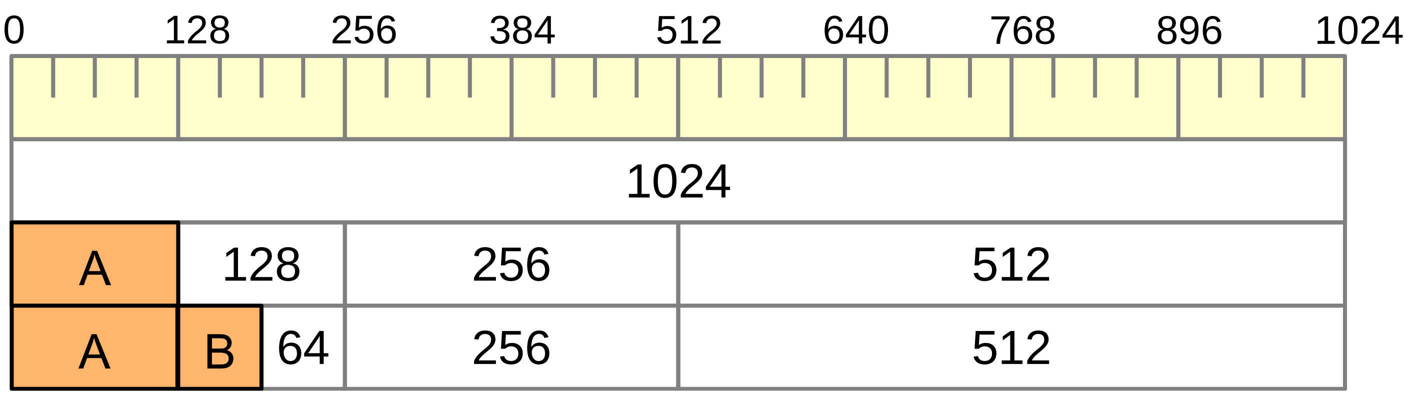

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bucket size	free list
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512 (2^9)	512
256 (2^8)	
128 (2^7)	384
64 (2^6)	192

allocated list

A: 0 (128)
B: 128 (64)
C: 256 (128)

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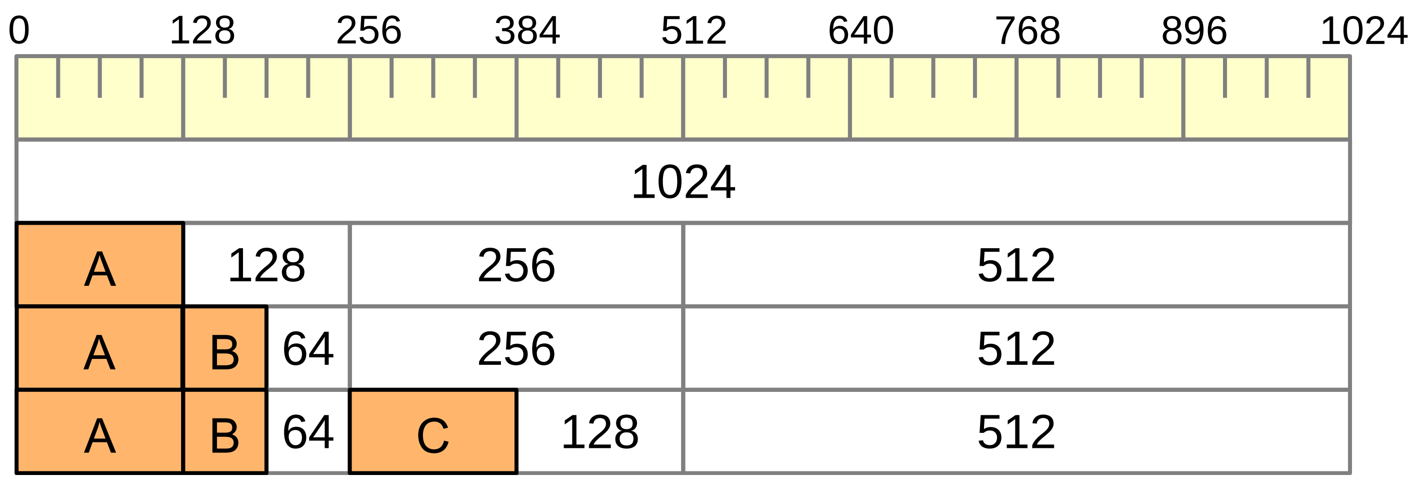

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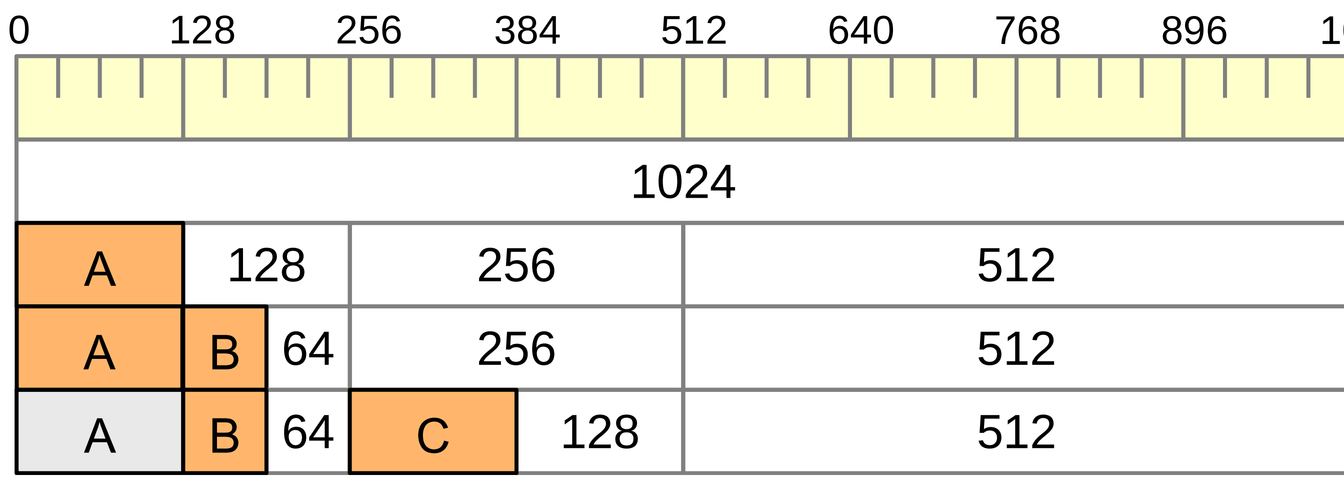

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512	(2^9)	512
256	(2^8)	
128	(2^7)	384
64	(2^6)	192

allocated list

A: 0 (128)
B: 128 (64)
C: 256 (128)

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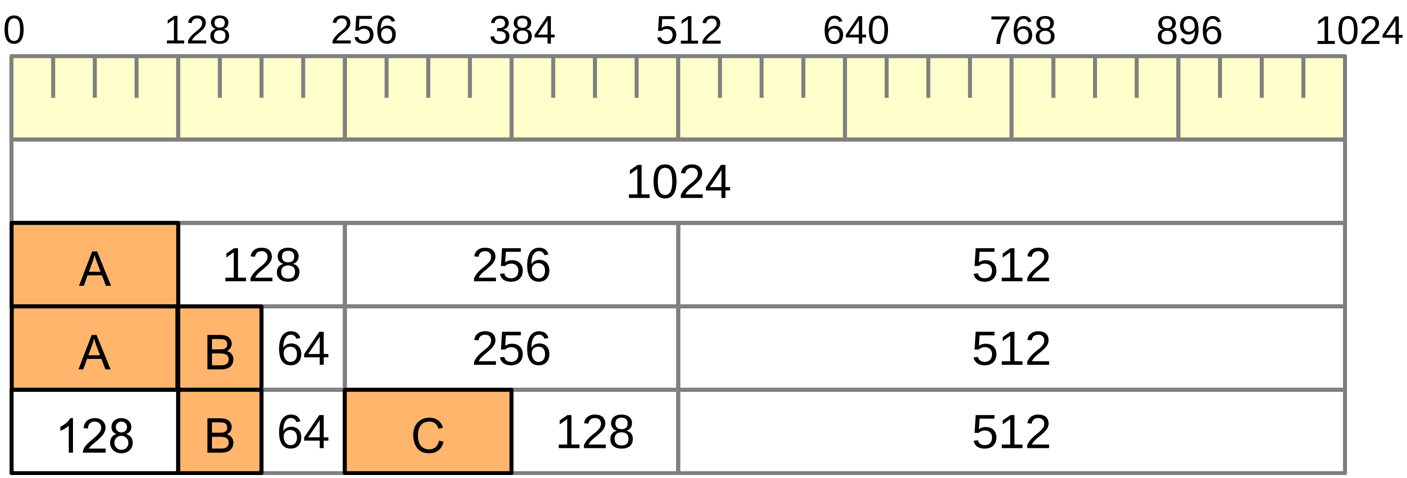

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allocated list

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B: 128 (64)
C: 256 (128)

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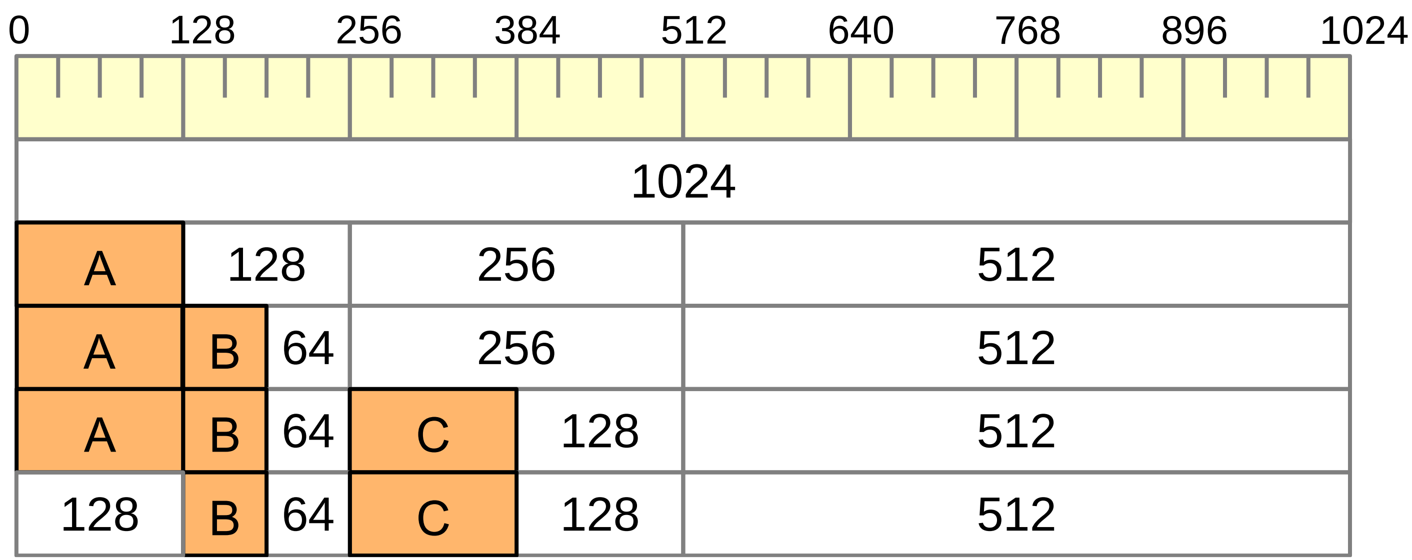

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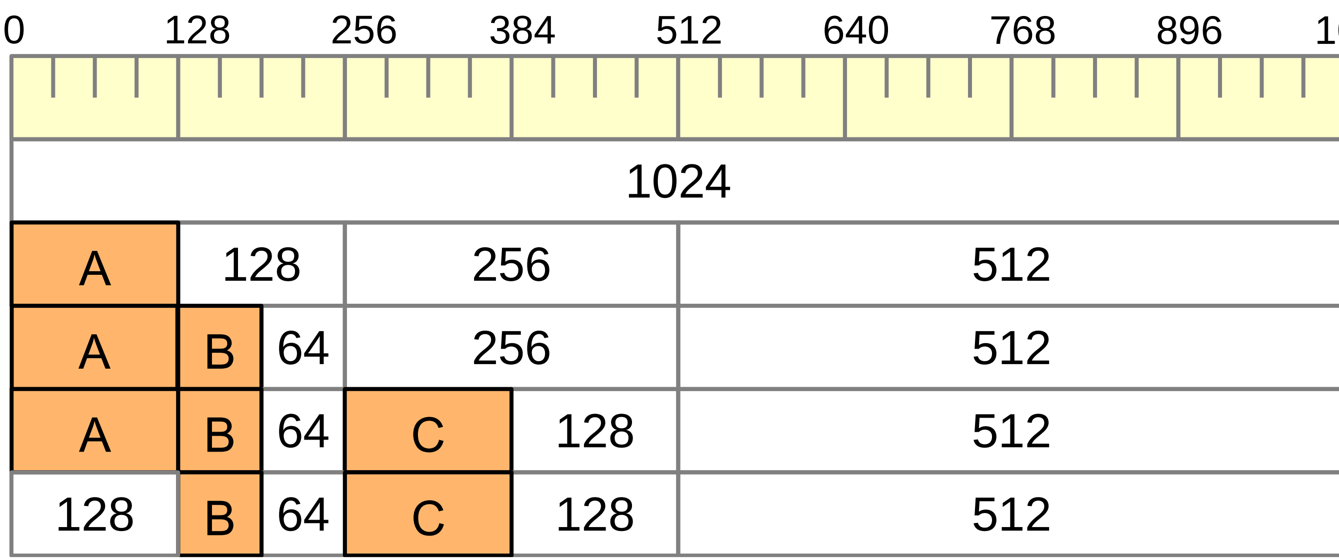

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128	(2^7)	0, 384
64	(2^6)	192

<u>allocated list</u>

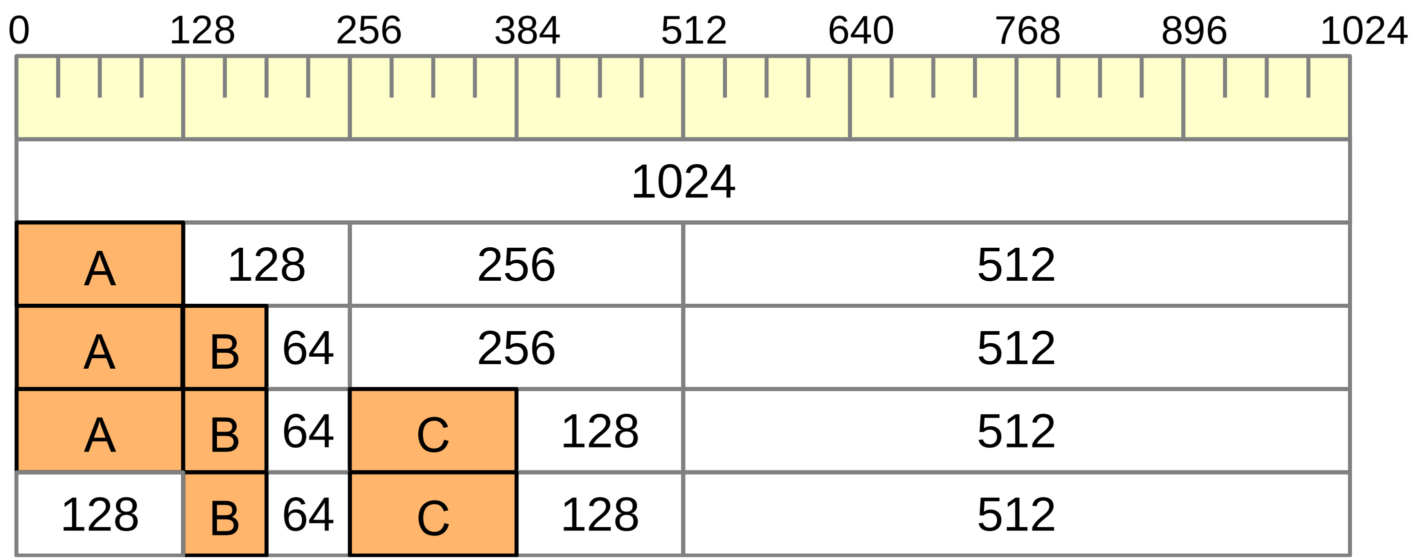
~~A: 0 (128)~~
B: 128 (64)
C: 256 (128)

→ allocate D at 192

Placement Strategies – Buddy System

- the **buddy system** partitions memory into dynamic areas of size 2^n

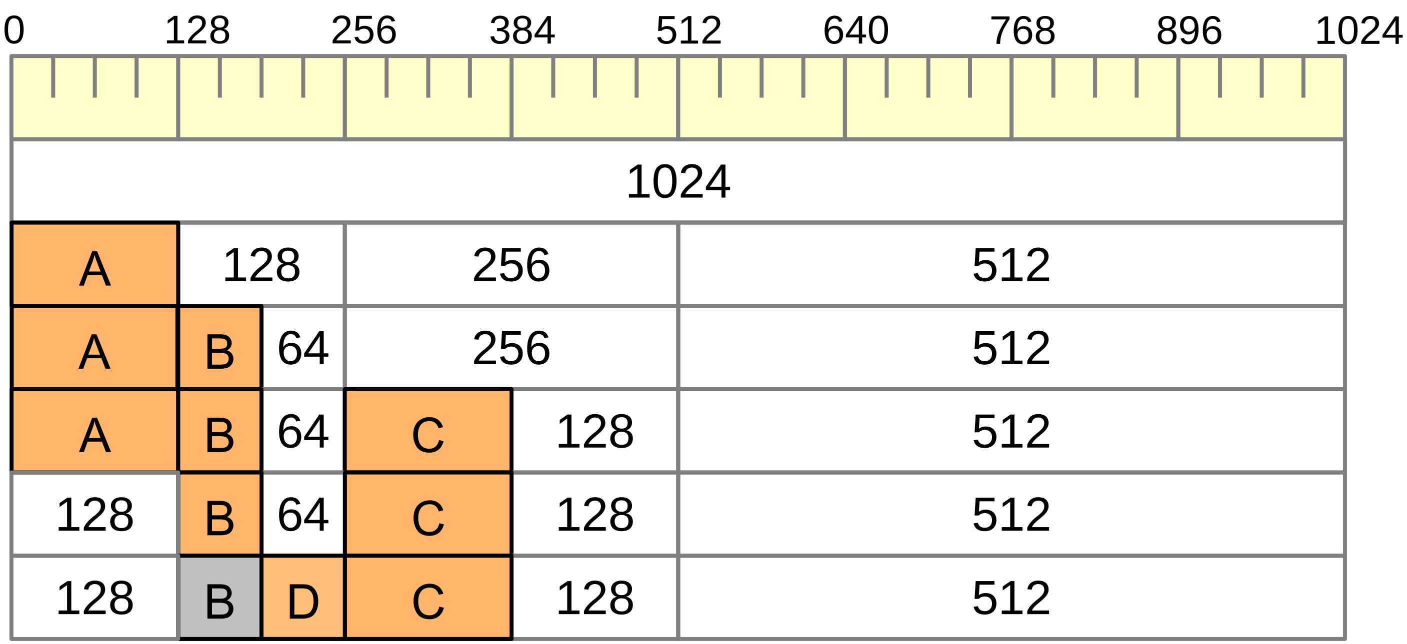
~~A: request 70~~
~~B: request 35~~
~~C: request 80~~
~~release A~~
D: → request 60
release B
release D
release C



bucket size		free list	allocated list
1024	(2^10)		
512	(2^9)	512	~~A: 0 (128)~~
256	(2^8)		B: 128 (64)
128	(2^7)	0, 384	C: 256 (128)
64	(2^6)		D: 192 (64)

Placement Strategies – Buddy System

- the **buddy system** partitions memory into dynamic areas of size 2^n

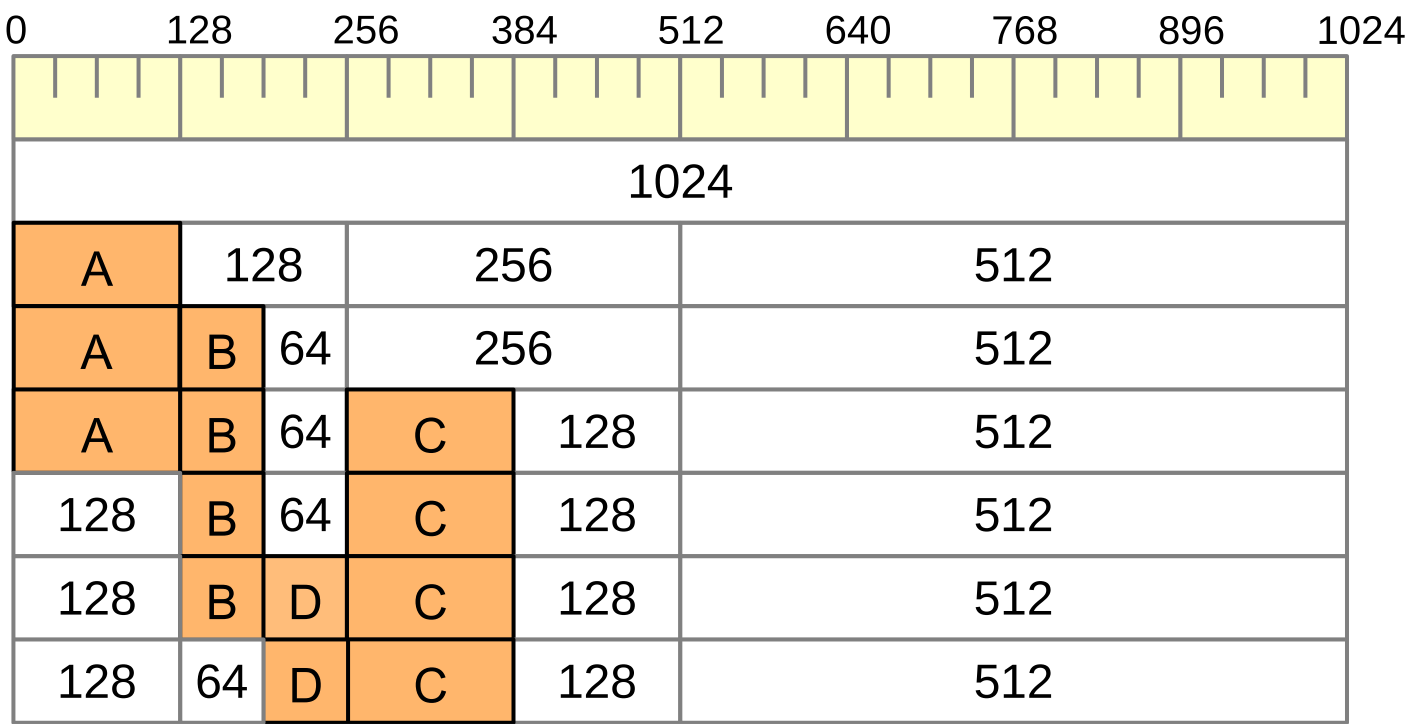


~~A: request 70~~
~~B: request 35~~
~~C: request 80~~
~~release A~~
~~D: request 60~~
→ release B
release D
release C

- freeing the memory allocated for request B
- buddy (D) remains allocated
- no merging of leftover holes

Placement Strategies – Buddy System

- the **buddy system** partitions memory into dynamic areas of size 2^n



~~A:~~ ~~request 70~~

~~B:~~ ~~request 35~~

~~C:~~ ~~request 80~~

~~release A~~

~~D:~~ ~~request 60~~

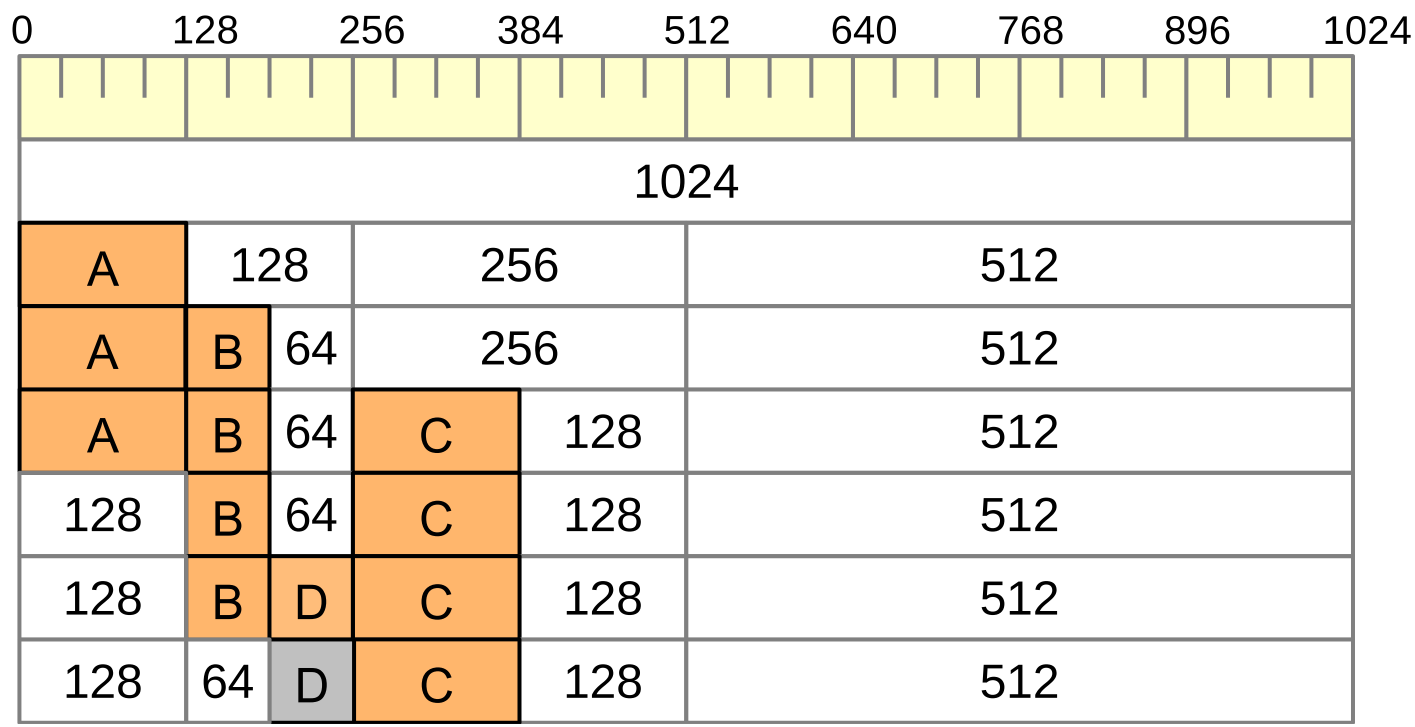
→ release B

release D

release C

Placement Strategies – Buddy System

- the **buddy system** partitions memory into dynamic areas of size 2^n



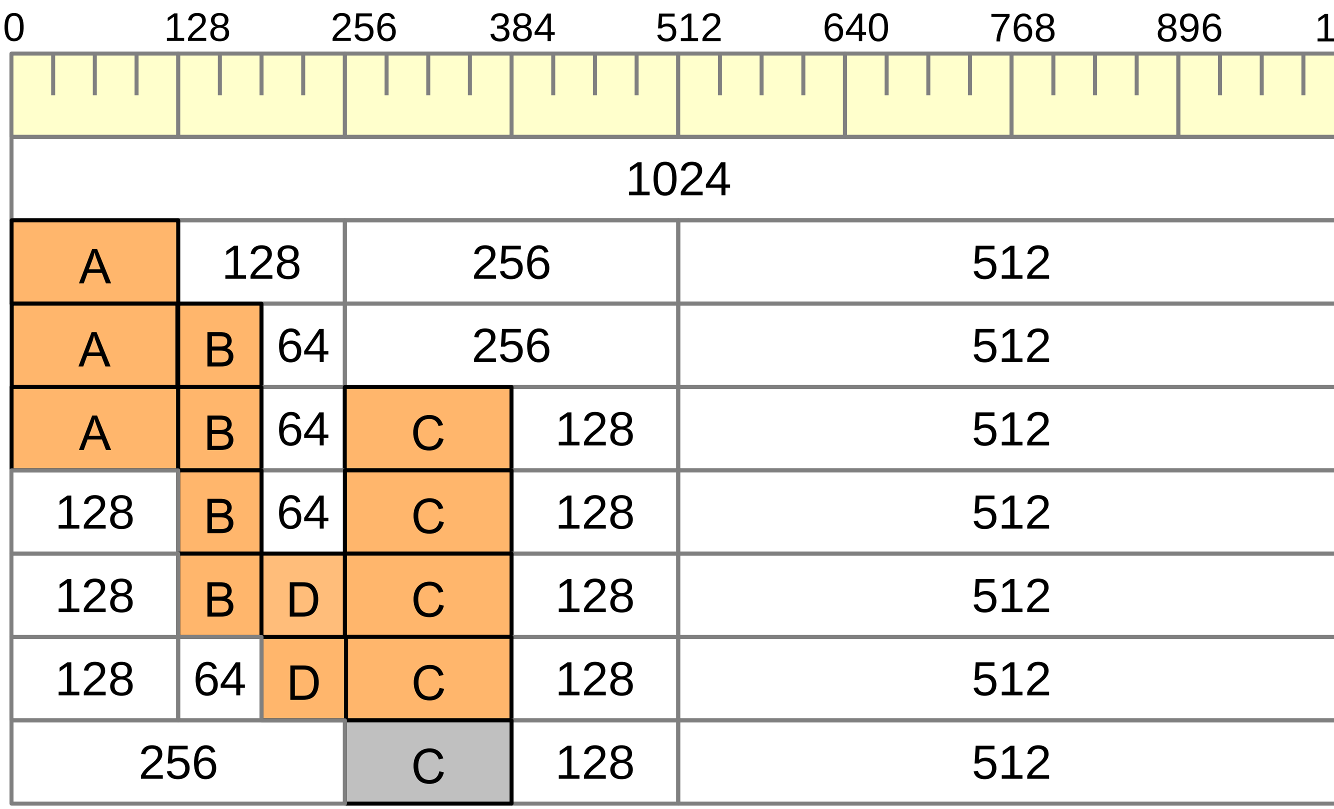
~~A:~~ ~~request 70~~
~~B:~~ ~~request 35~~
~~C:~~ ~~request 80~~
~~release A~~
~~D:~~ ~~request 60~~
~~release B~~
→ release D
release C

- freeing the memory allocated for request D
- no buddy allocation present
- merge leftover holes, recursively (2 times)

Placement Strategies – Buddy System

- the **buddy system** partitions memory into dynamic areas of size 2^n

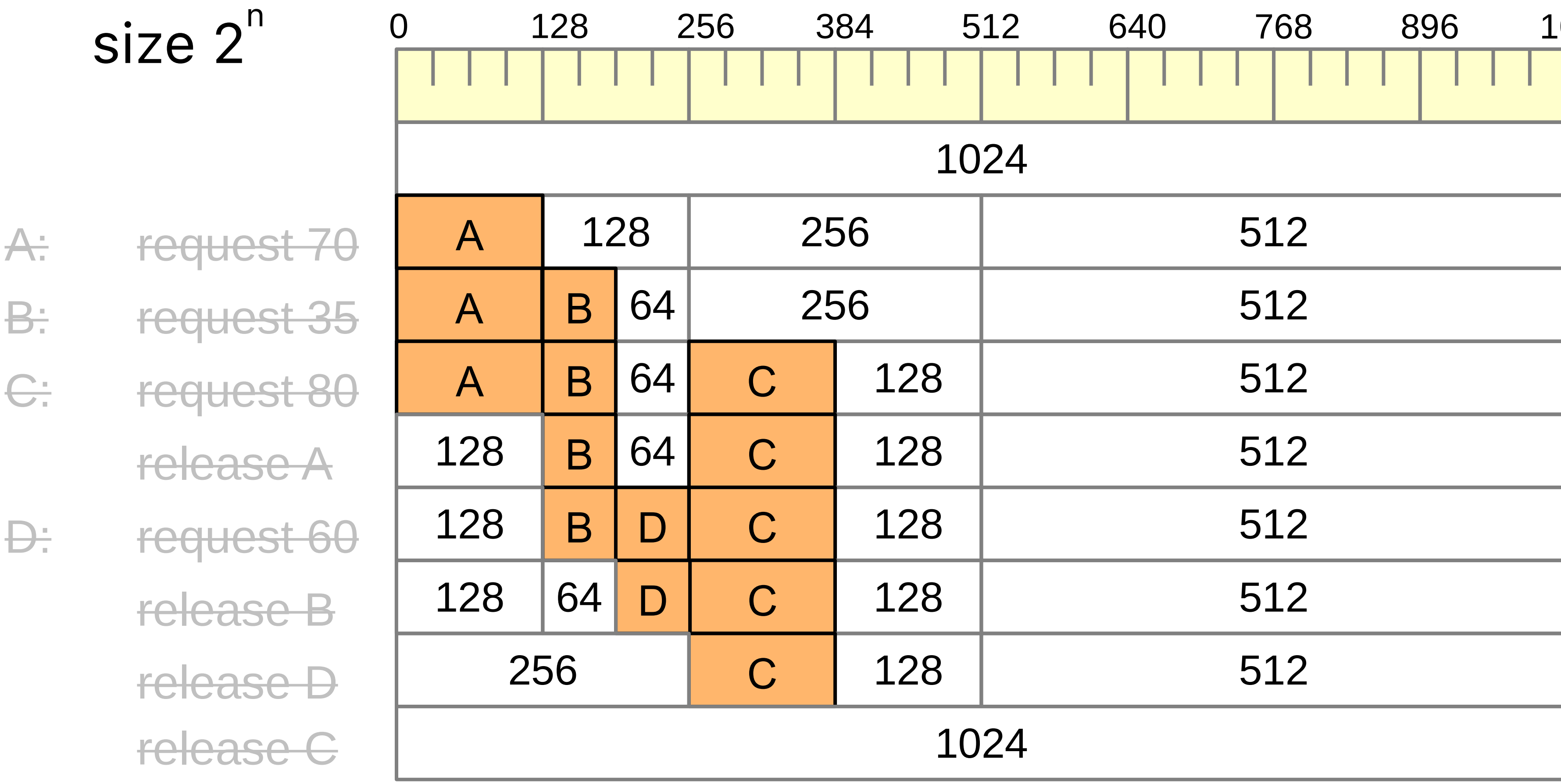
~~A: request 70~~
~~B: request 35~~
~~C: request 80~~
~~release A~~
~~D: request 60~~
~~release B~~
~~release D~~
→ release C



- freeing the memory allocated for request C
- no buddy allocation present
- merge leftover holes, recursively (3 times)

Placement Strategies – Buddy System

- the **buddy system** partitions memory into dynamic areas of size 2^n



Discussion – Fragmentation

- **external fragmentation**
  - **outside** the allocated memory area, memory fragments are created that can no longer be used
  - occurs when using **list-based strategies** such as (first fit, best fit, etc.) and also buddy system when merge of buddies is not possible
  - **countermeasures:** merge leftover holes, relocate memory areas
- **internal fragmentation**
  - there is unused memory **within** the allocated memory areas
  - occurs when using the **Buddy system**, for example, as the requirements are rounded up to the next larger power of two
  - undiscoverable, **invalid pointers** accessing fragmented areas
  - **countermeasures:** difficult to address; alter granularity of memory allocation or different memory allocation scheme that better fits to the observed memory allocation patterns

Active Use of the Discussed Methods

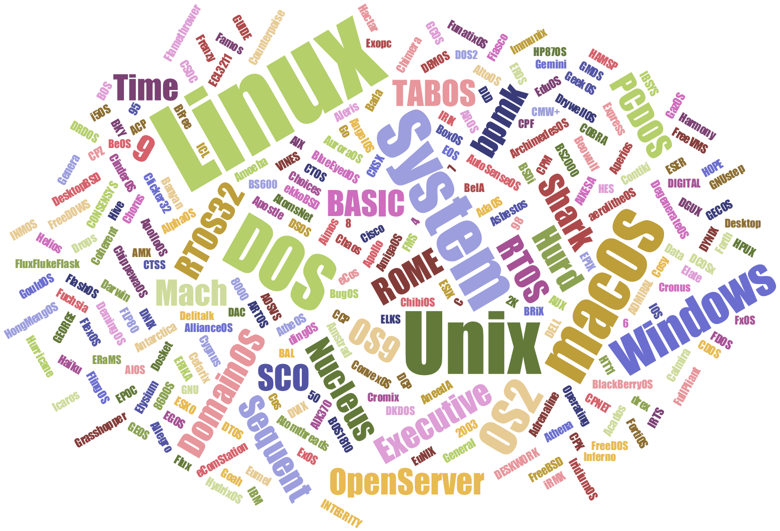
- use in the operating system
  - management of the system memory
  - allocation of memory to processes **and** the operating system
- use within a process
  - management of the heap memory
  - allows dynamic allocation of memory areas processes (malloc and free)
- use for secondary storage
  - management of specific sections of secondary storage, for example, memory areas for process swap data (swap space)

Buddy allocator in Linux

typically list-based

often with implemented with bitmaps

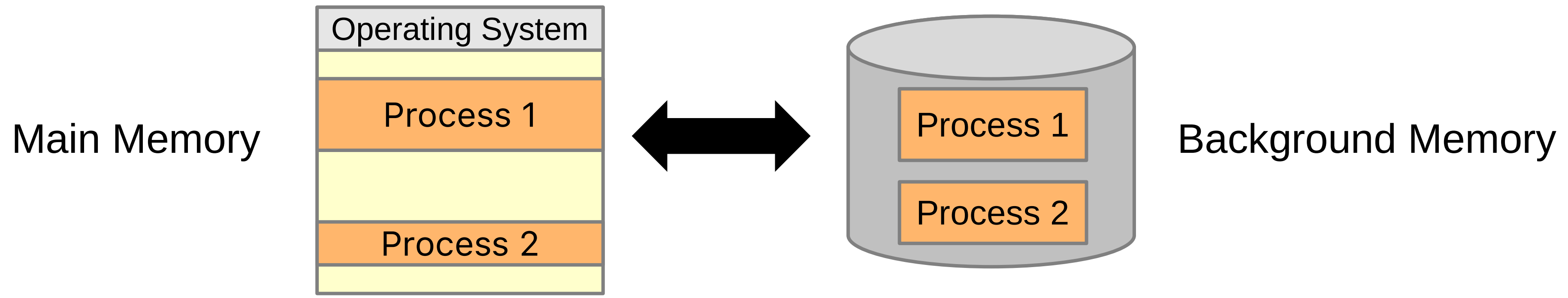
Agenda



- Recap
- Organizational Matters
- Principles of Memory Management
  - Motivation
  - Requirements
  - Strategies
- Memory Allocation Schemes
- **Memory Management for Multi-Program Operation**
  - **Segmentation**
  - **Paging**
- Summary and Outlook

Memory Management – Swapping

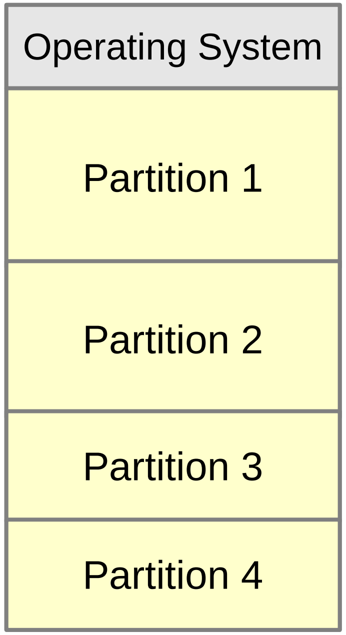
- segments of a process are swapped out to background memory and then freed in main memory
  - for example, to bridge waiting times for I/O
- swapping-in of the segments to the main memory at the end of the waiting time



- considerations: <u>start/stop</u> programs, <u>swap-in/out</u> processes
  - **when** (aligned to scheduling policy, consider overheads)?
  - **where** to place processes in main memory?

Memory Management – Swapping

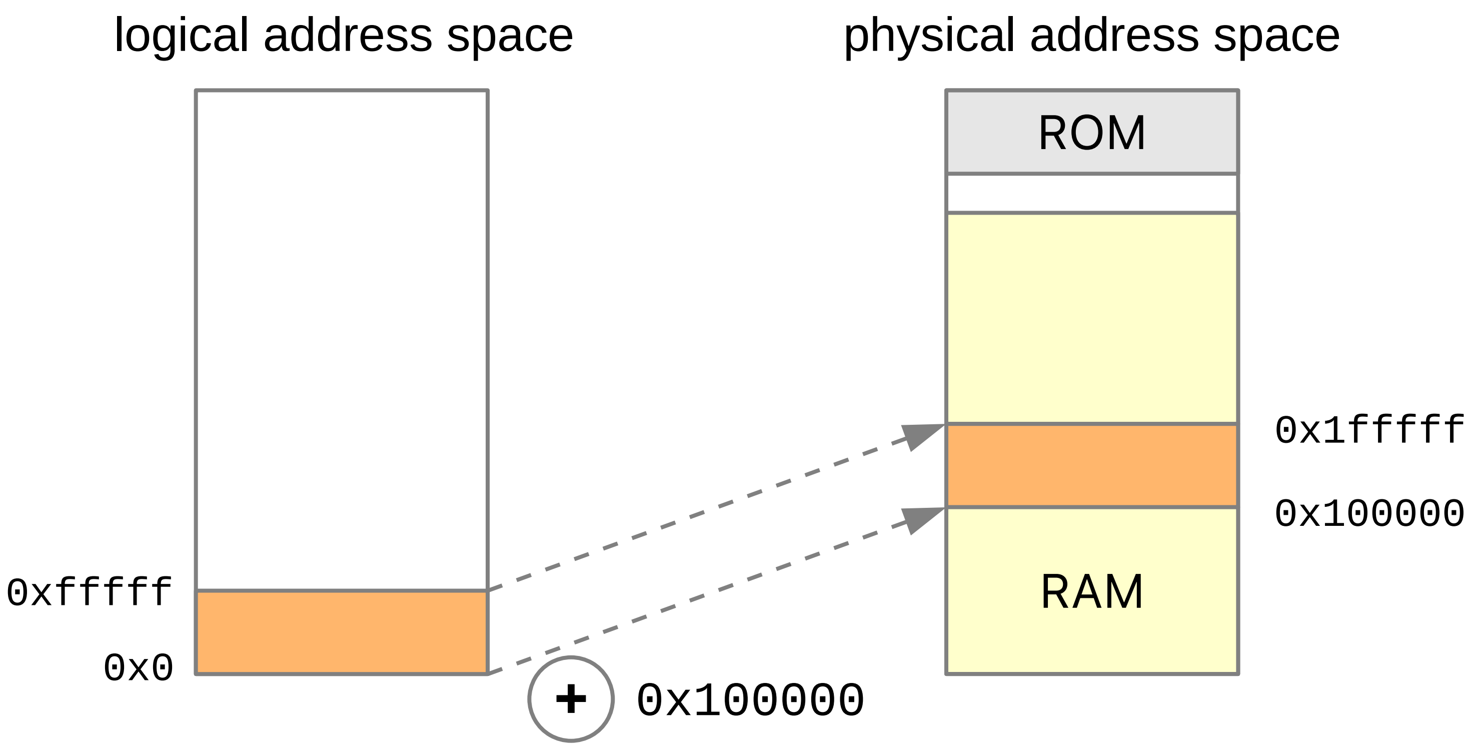
- addresses in the processes are usually statically bound
  - can only be loaded to the same place in the main memory
  - collisions with segments that may be new in the main memory
- possible solution 1: **static partitioning** of the main memory
  - only one process is running in each partition
  - swapped in processes are placed again into the same partition
  - memory can not be used optimally
- possible solution 2: **program relocation**
  - at load time (static linking)
  - during execution time (dynamic linking)



→ focus: **dynamic memory allocation** with hardware support

Memory Management – Segmentation

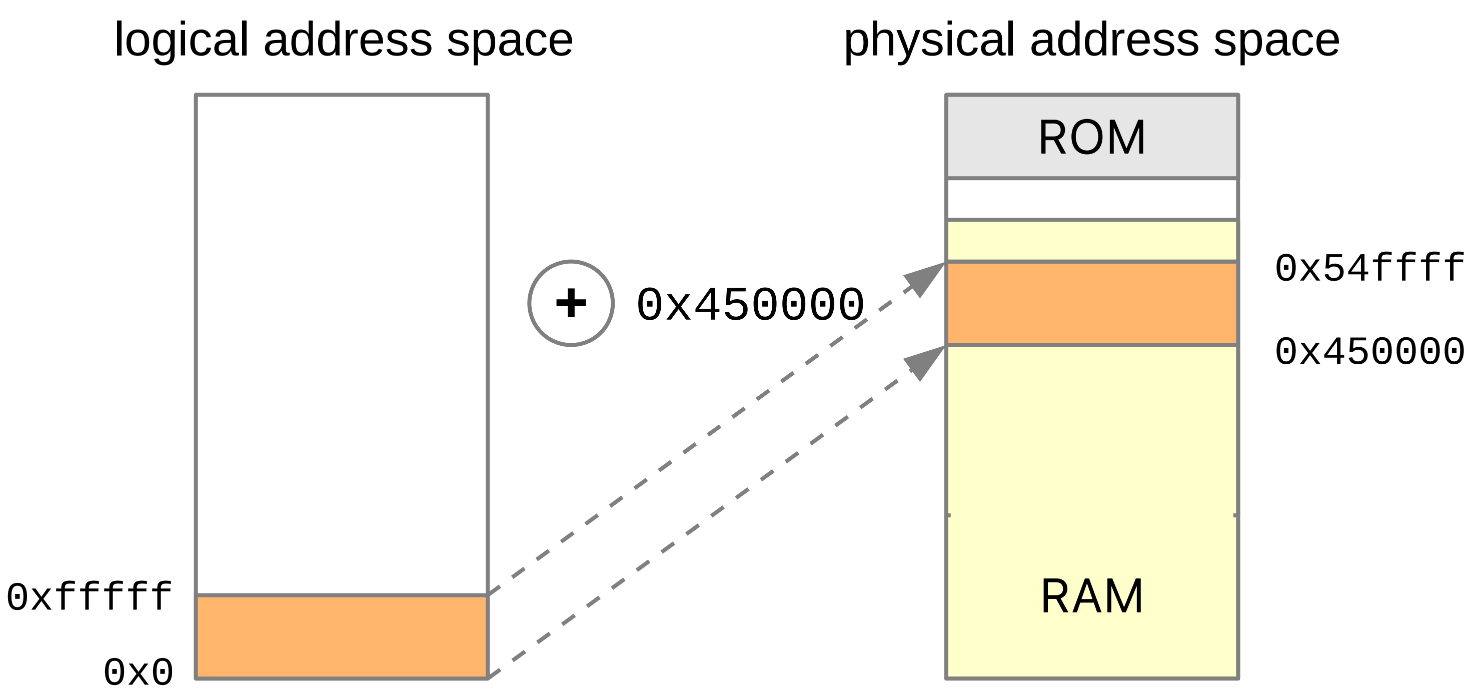
- map logical to physical addresses with hardware support



- a segment of the logical address space can be located at any position in the physical address space
- **size of segments is variable**
- OS determines where a segment should actually be located in the physical address space

Memory Management – Segmentation

- map logical to physical addresses with hardware support



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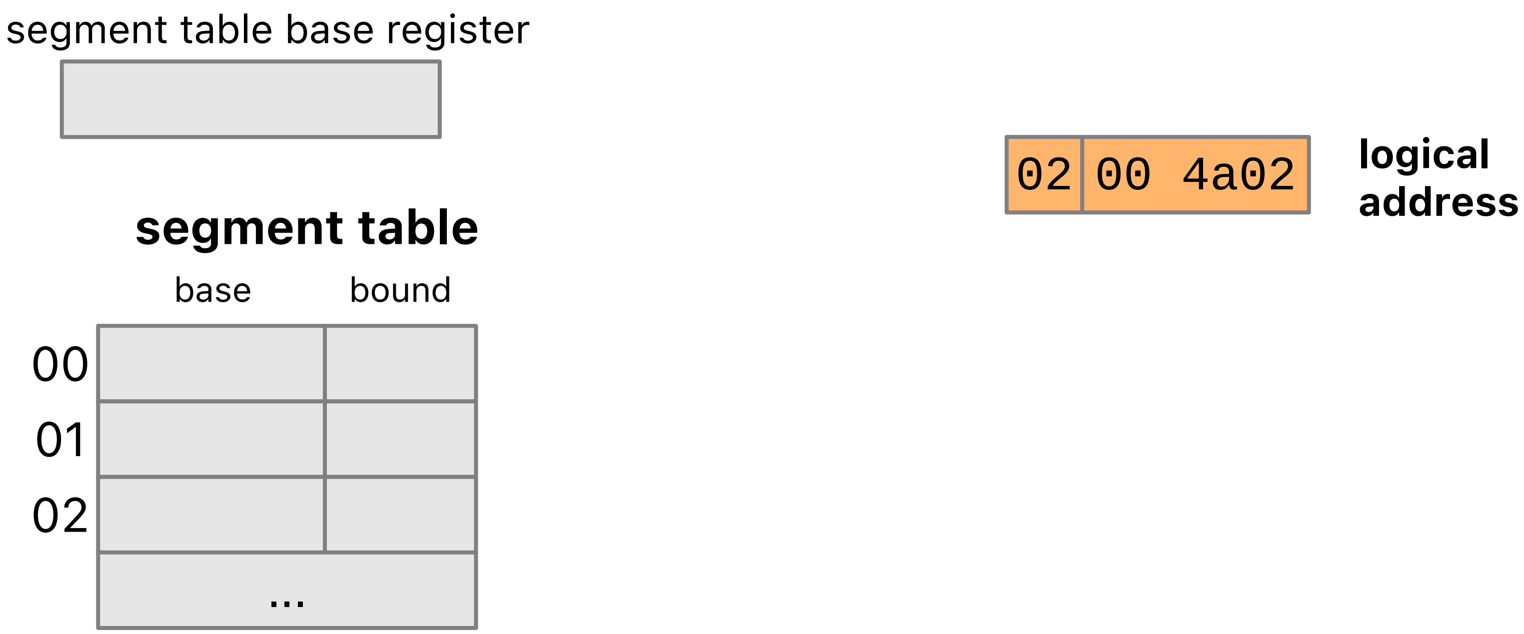
Memory Management – Segmentation

- realisation with translation table (per process)



Memory Management – Segmentation

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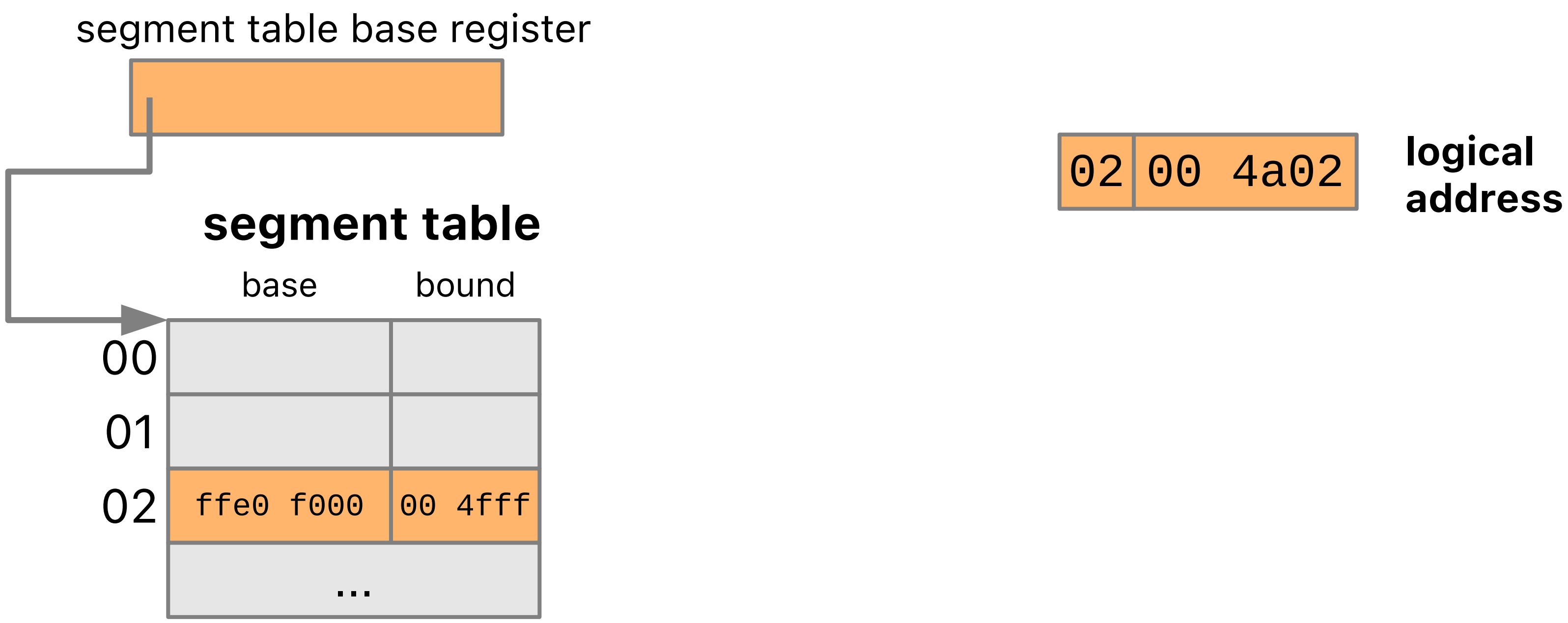

Memory Management – Segmentation

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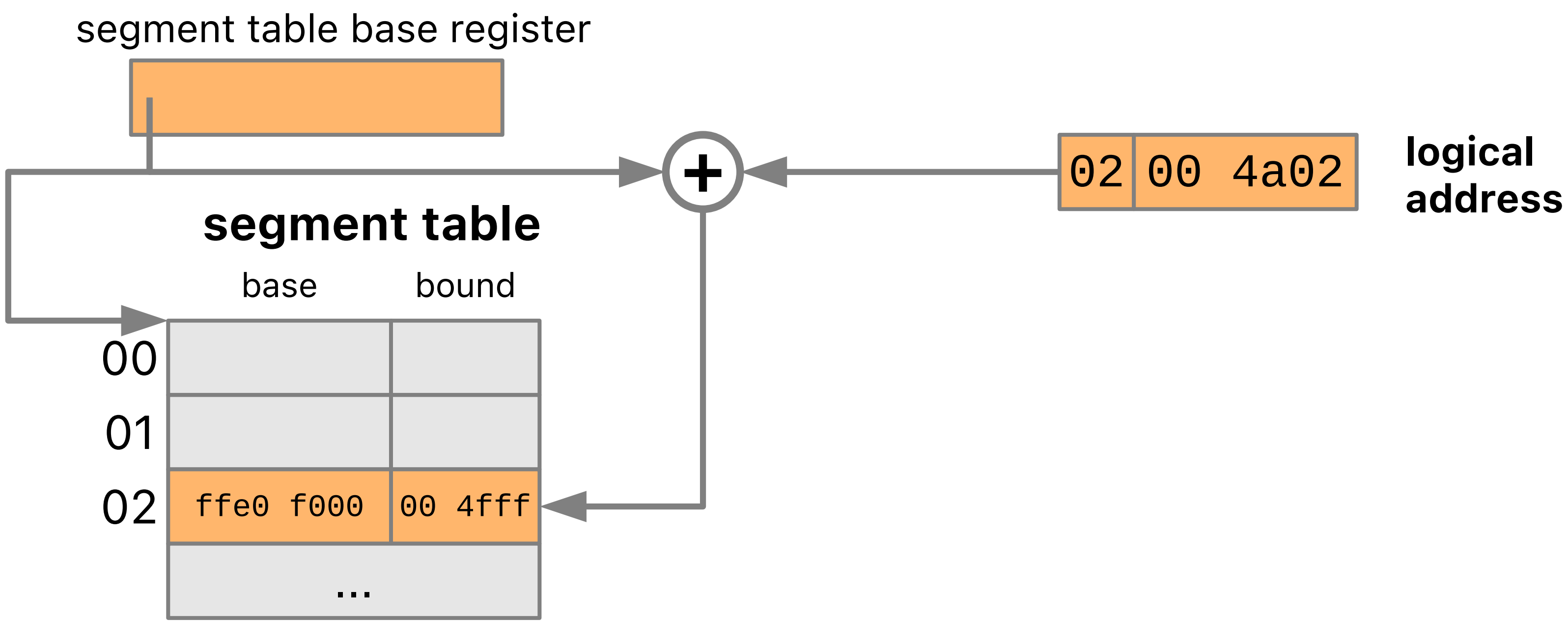

Memory Management – Segmentation

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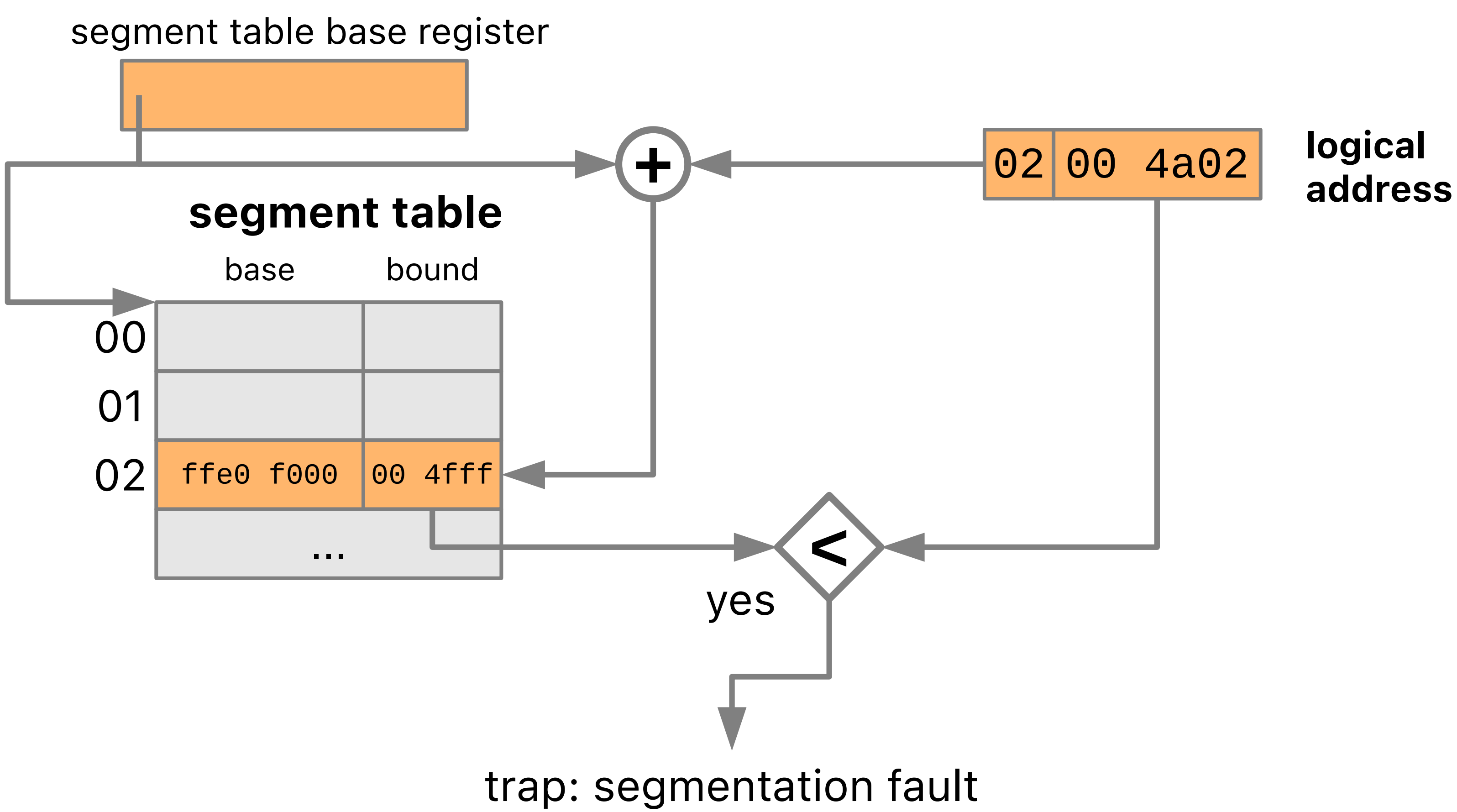

Memory Management – Segmentation

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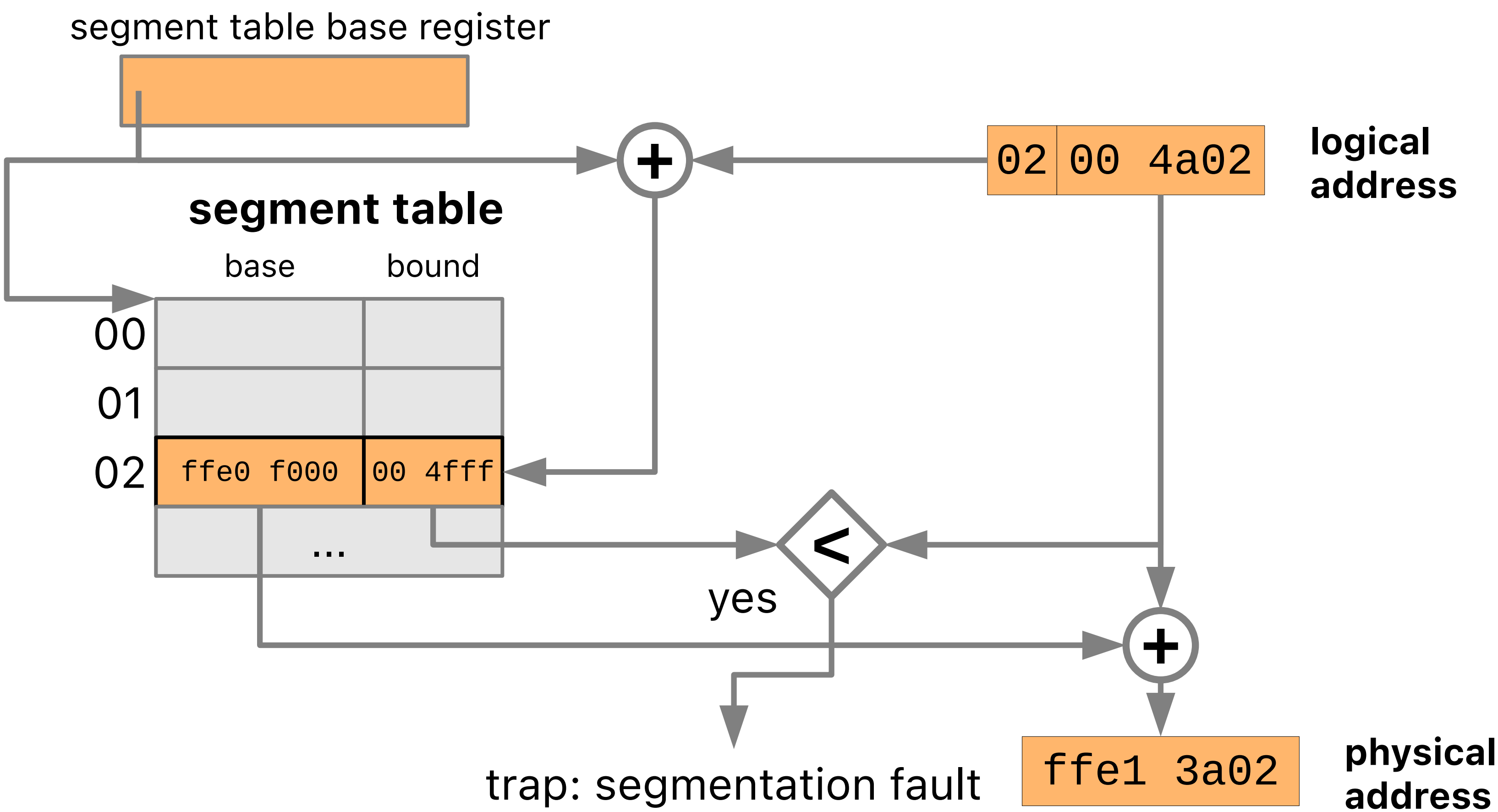


Memory Management – Segmentation

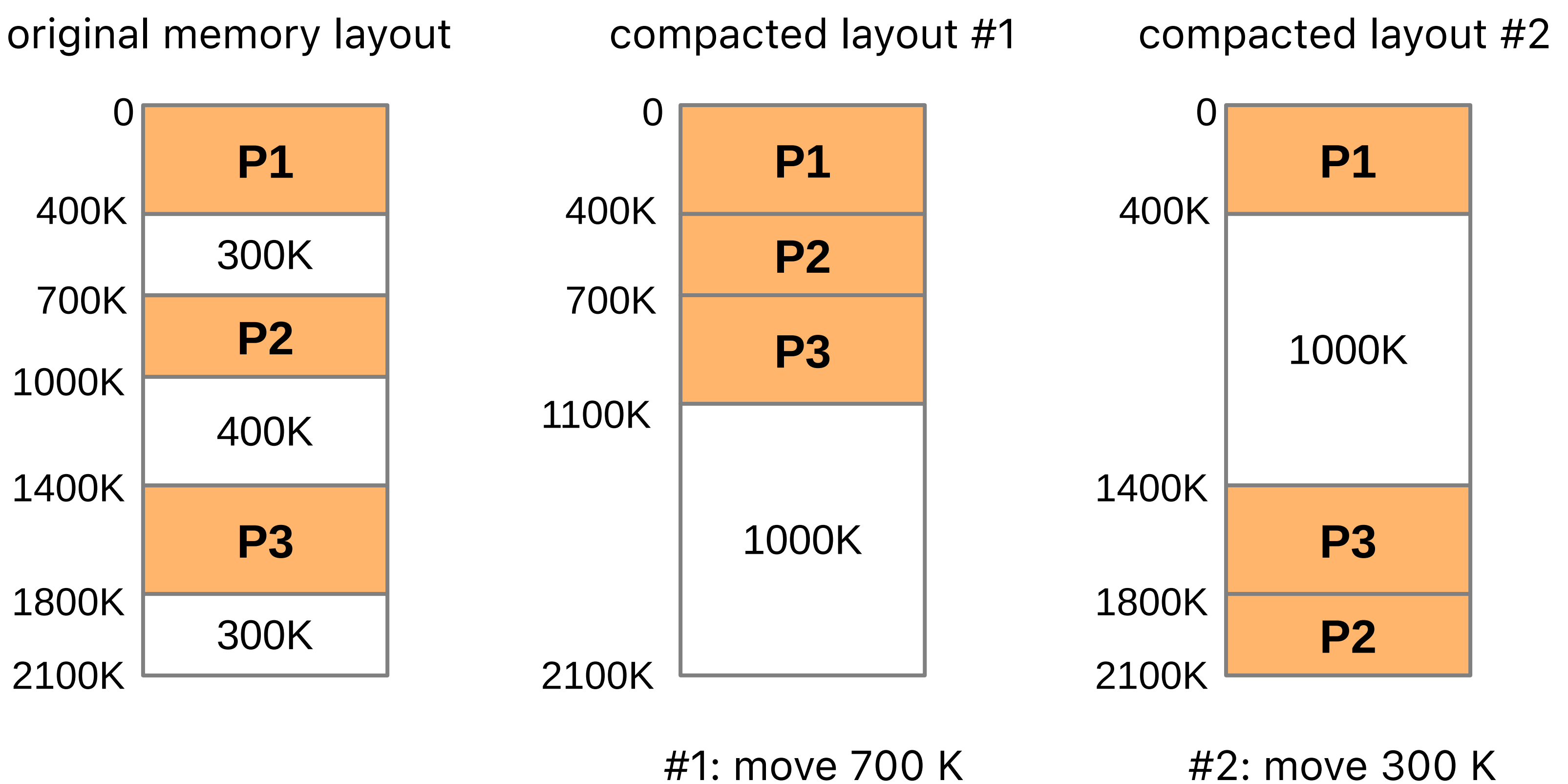
- hardware support is provided and implemented by the **memory management unit (MMU)**
- the MMU provides protection for segmentation violations
  - verification of access rights to **read**, **write** and **execute** commands depending on segments
  - **traps** indicate segmentation violations (→ segmentation fault)
  - programs and operating system are protected from each other
- replacing the segment base on each context switch
  - processes have their own translation table (→ stored in its PCB)
- simplification of swapping
  - after swapping-in only the segment table must be adjusted
- shared segments for text (program code) and data (shared memory) are possible

Segmentation – Problems

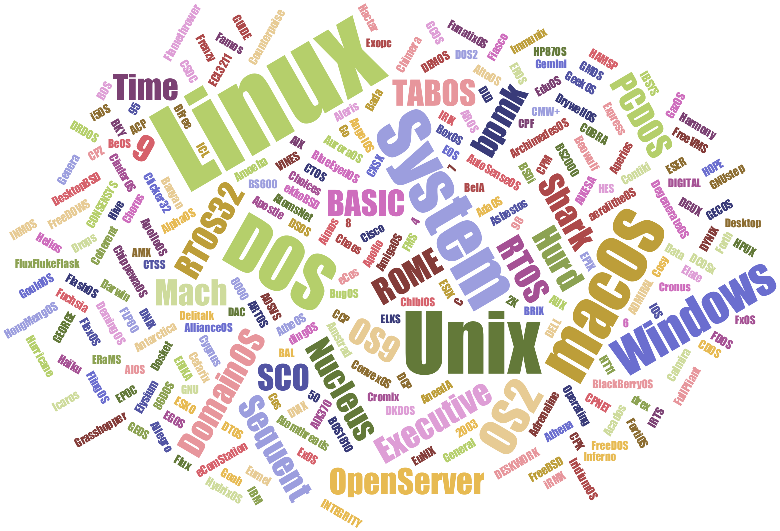
- **memory fragmentation** due to frequent swapping-in/out (or start/termination) of processes
  - small, unusable holes occur (external fragmentation)
- **solution: compacting**
  - segments are moved to close holes
  - segment table needs to be adjusted and updated
  - performance penalty
- issue: **long I/O time overhead** due to swapping-in/out
  - not all parts of a segment are used equally often

Segmentation – Compacting

- move segments to defragment memory
  - creating fewer but larger gaps to reduce fragmentation
  - complex operation, depending on the size of the segments



Agenda



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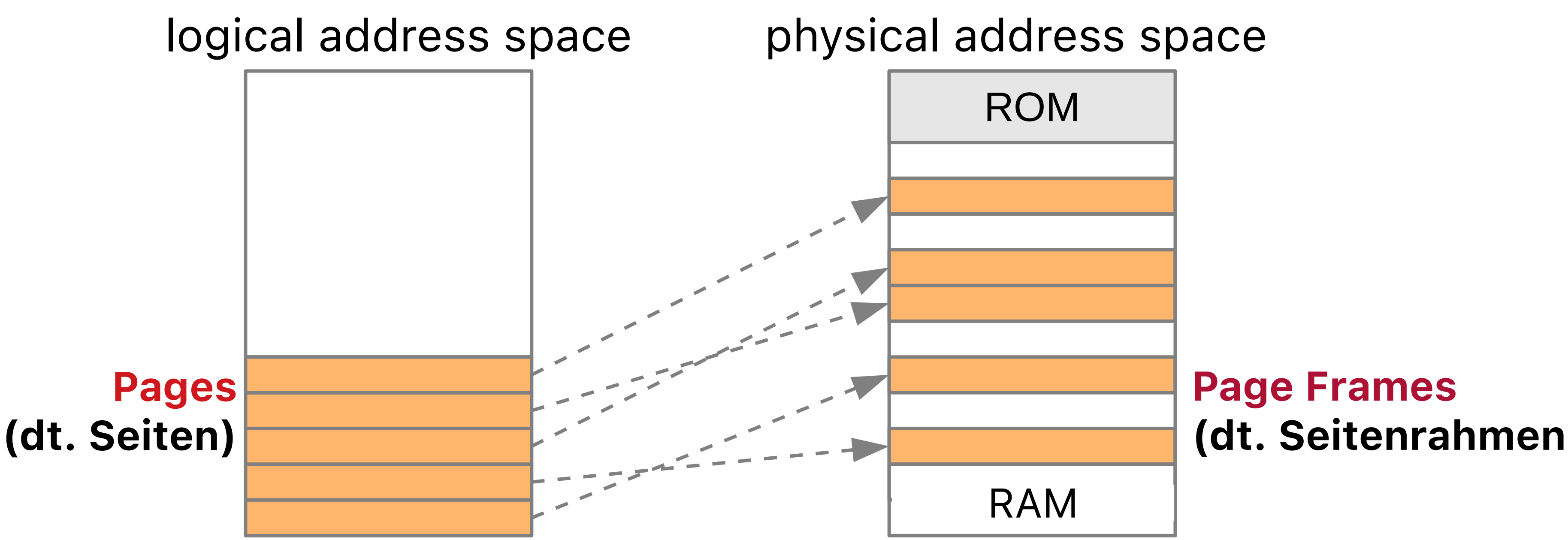
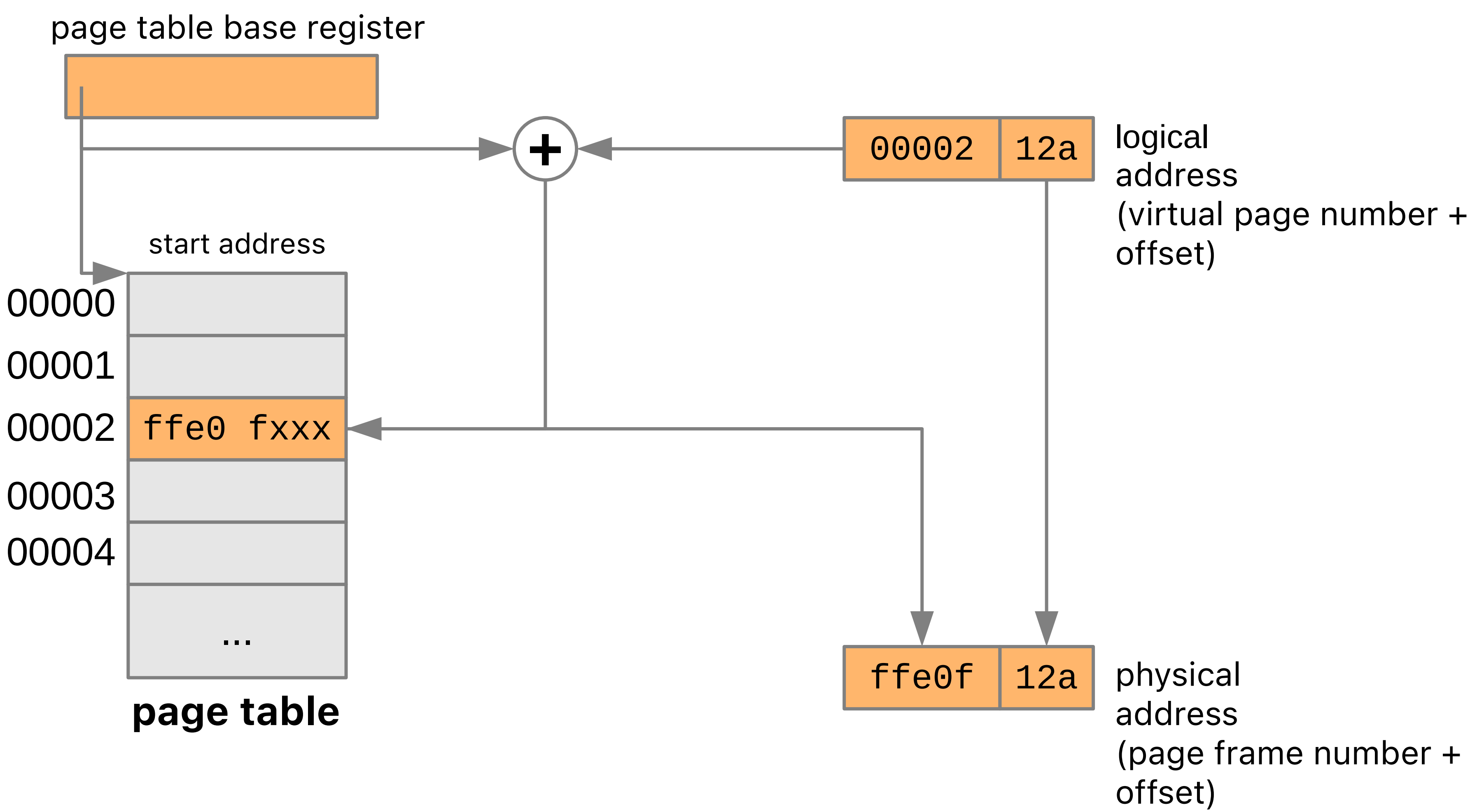
Memory Management – Paging

- paging (dt. Seitenadressierung): organisation of the logical address space in pages of equal, **fixed size** (e.g., 4 K, 8 K)
- pages can be located at any position in the physical address space
  - solves the fragmentation problem
  - no more compacting necessary
  - simplifies memory allocation and swapping in/out



Memory Management – Paging

- MMU translates logical (virtual page) to physical addresses (page frame)



Paging – Problems

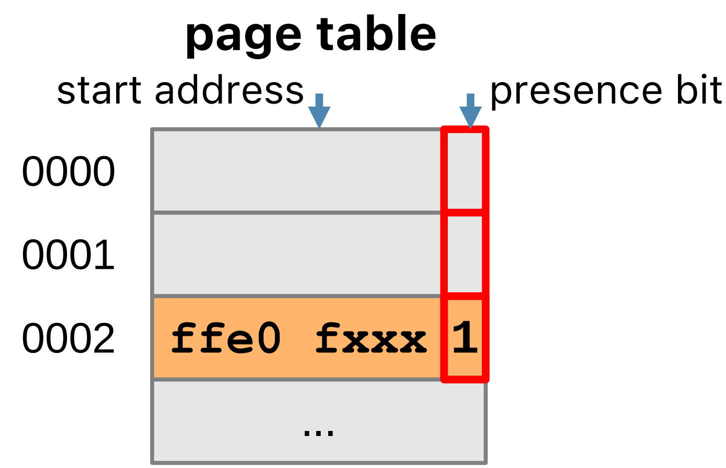
- paging leads to internal fragmentation
  - last page may not be used completely
- page size
  - small pages reduce internal fragmentation, but increase size of page table (and vice versa)
  - common sizes: 512 bytes to 8192 bytes
- large table that must be kept in memory
- many implicit memory accesses necessary

- advanced paging: segmented paging, paged segmentation, inverted page tables

Paging – Swapping In/Out of Pages

- it is no longer necessary to swap-in/out an entire segment
  - pages can be swapped in and out individually

- page faults, hardware support
  - if the presence bit is set, everything remains as before
  - if the presence bit is cleared, a trap is triggered (**page fault**)
  - trap handling can now be used for loading the page from the background memory and repeat the memory access afterwards (requires hardware support in the CPU)

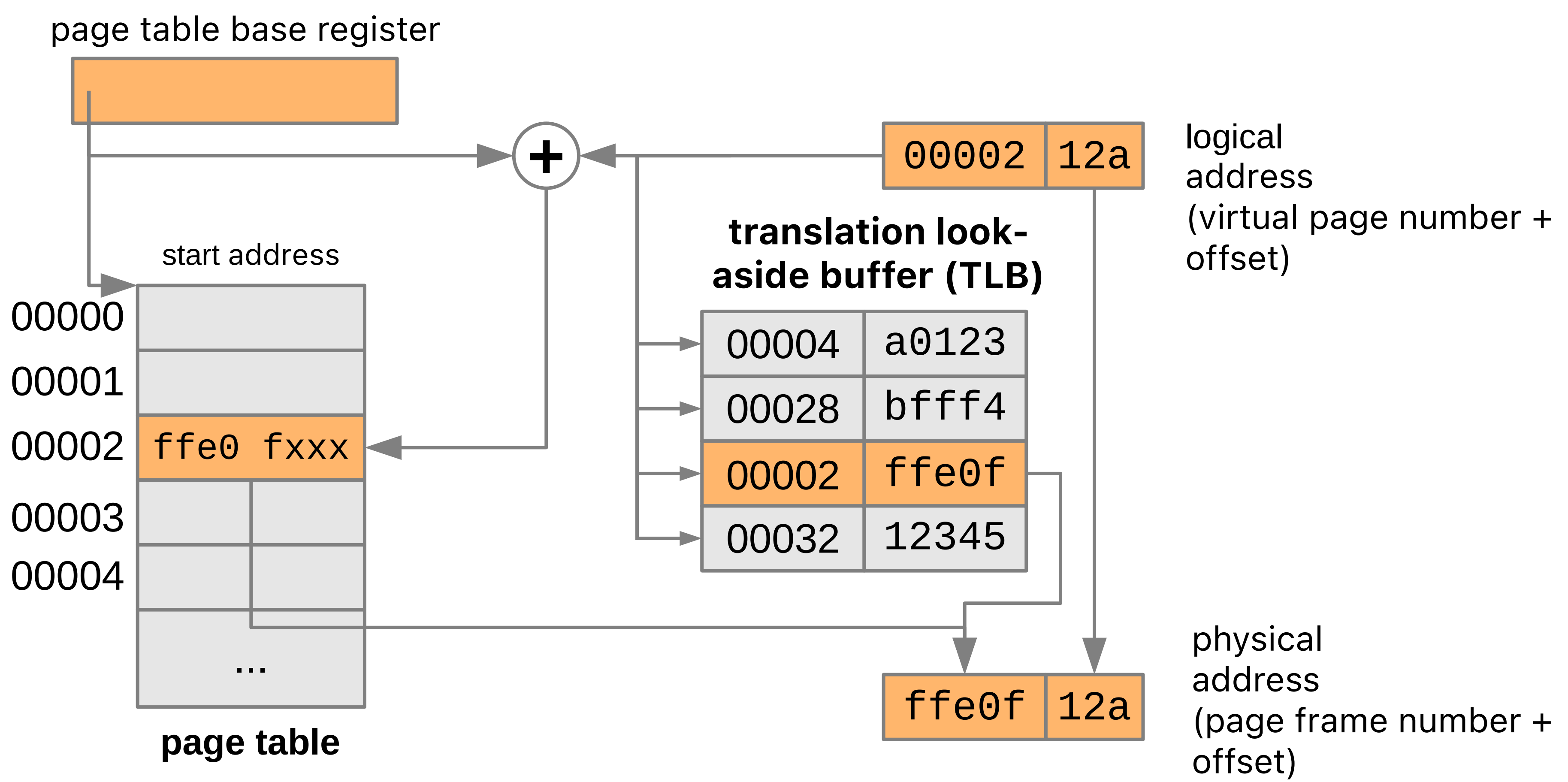


Paging – Discussion on Operational Costs

- page faults may occur very frequently
  - depends on program and its I/O activity pattern(s)
  - Linux: `ps -eo min_flt,maj_flt,cmd`
- page translations (virtual to physical addresses) are expensive
  - example: memory reference
  - `movl 0x14711222, %eax`
    1. lookup page table base register (PTBR)
    2. extract virtual page number (VPN), here: `0x14711`
    3. read page table entry, here: `PTBR + 0x14711 * 8`
    4. extract page frame number (PFN), here: `0x222`
    5. read the memory at location `PFN << 12 + 0x222`
- translation lookaside buffer (TLB): **hardware cache**, stores recent **translations of virtual memory to physical memory addresses**

Paging – Translation Lookaside Buffer (TLB)

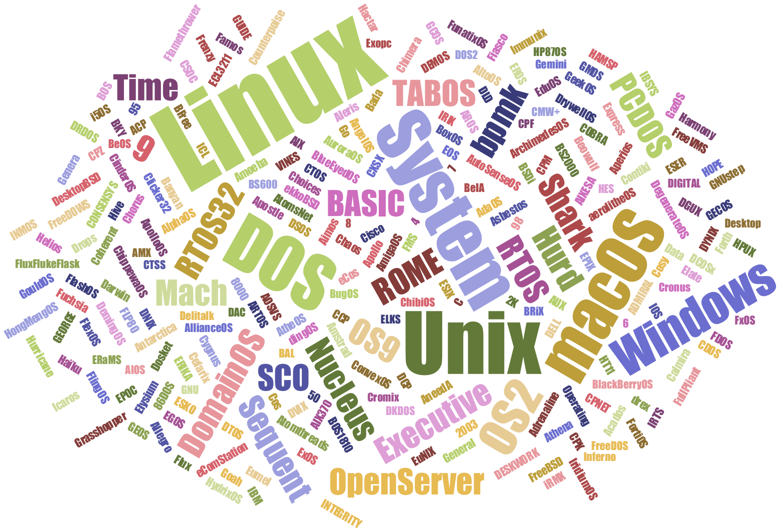
- fast register set is consulted before accessing the page table:



Paging – Translation Lookaside Buffer (TLB)

- fast access to pages if information is in TLB's memory
  - fully associative cache
  - TLB hit: no implicit memory accesses necessary
- TLB content must be replaced for context changes (TLB flush)
- when accessing a page not included in the TLB, the corresponding access information is entered into the TLB
  - an old entry must be selected for replacement
- typical TLB sizes
  - Intel Core i7: 512 entries, page size 4K
  - UltraSPARC T2: data TLB = 128, code TLB = 64, page size 8K
  - larger TLBs not possible at the usual clock rates at present

Agenda



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⏭ Summary and Outlook

- **summary**
  - operating systems work closely with the hardware in terms of memory management
    - ➔ **segmentation** and/or **paging**
    - ➔ due to implicit indirection in memory access, programs and data can be moved arbitrarily during runtime under the control of the OS
  - in addition, various strategic decisions are made
    - ➔ **placement strategy** (**first fit**, **best fit**, **buddy**, ...)
    - ➔ differences with regard to fragmentation as well as allocation and relocation costs
    - ➔ strategy selection depends on the usage pattern
- **outlook: virtual memory**
  - methods and strategies how/when segments or pages should be swapped in/out
  - fetch strategies, replacement strategies

References and Acknowledgments

Lecture

- Systemnahe Programmierung in C (SPiC), Betriebssysteme (Jürgen Kleinöder, Wolfgang Schröder-Preikschat)
- Betriebssysteme und Rechnernetze (Olaf Spinczyk, Embedded Software Systems Group, Universität Osnabrück)

Teaching Books and Reference Book

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[2] Andrew Tanenbaum, Herbert Bos: *Modern Operating Systems*, Pearson, 2015.

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