Operating Systems

Timo Hönig
Bochum Operating Systems and System Software (BOSS)
Ruhr University Bochum (RUB)

VI. Memory Management

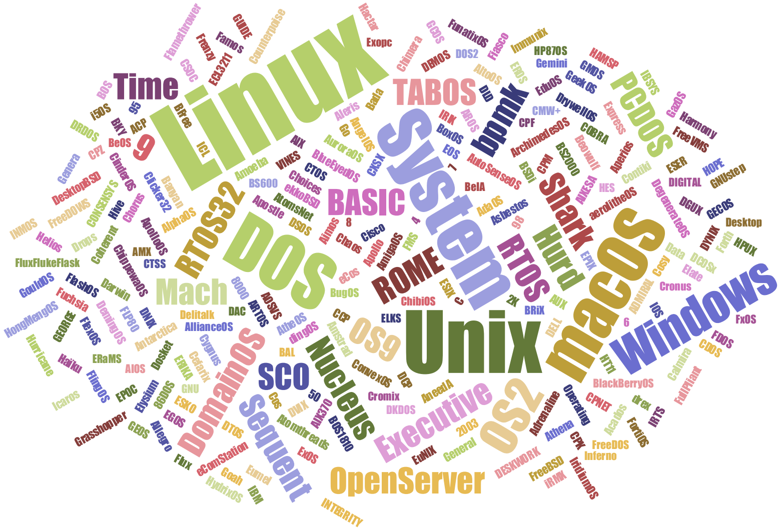
May 17, 2023 (Summer Term 2023)

RUB Faculty of Computer Science

RUHR UNIVERSITÄT BOCHUM RUB

www.informatik.rub.de
Chair of Operating Systems and System Software

Agenda



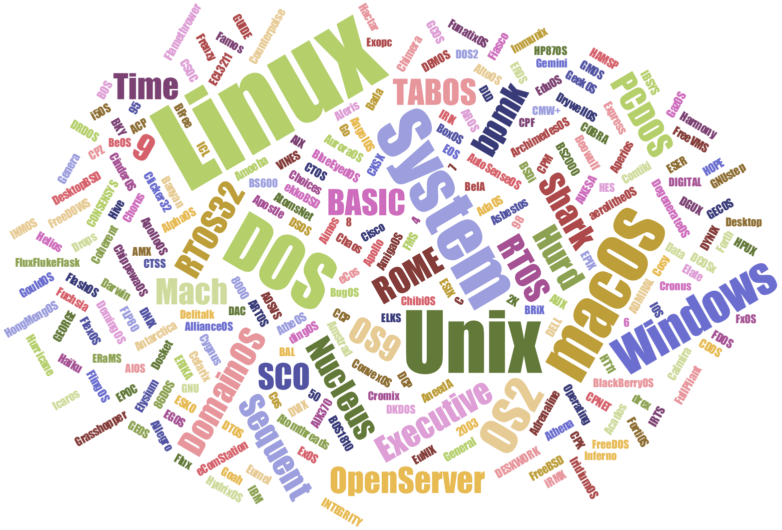
- Recap
- Organizational Matters
- Principles of Memory Management
  - Motivation
  - Requirements
  - Strategies
- Memory Allocation Schemes
- Memory Management for Multi-Program Operation
  - Segmentation
  - Paging
- Summary and Outlook

Literature References

Silberschatz, Chapter 9

Tanenbaum, Chapter 3

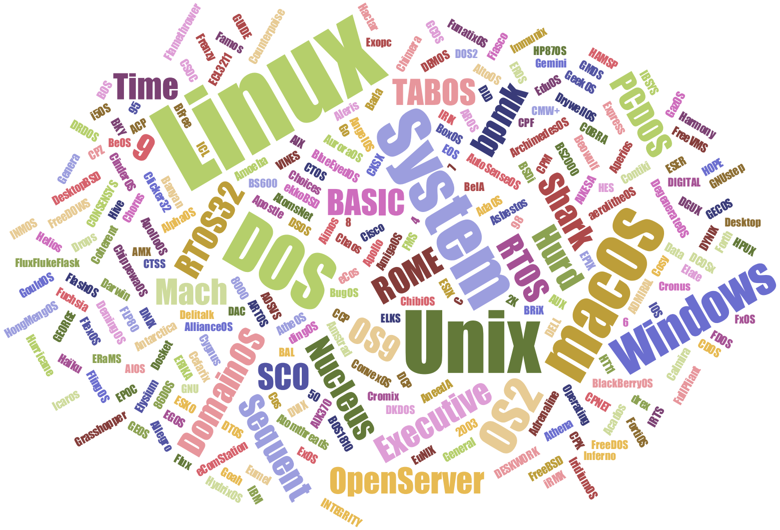
⏮ Recap



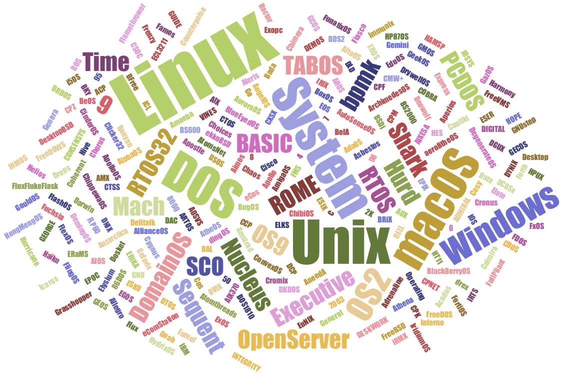
- **process deadlocks**
  - **mutual blocking** of concurrent but independent processes
- **variants** and **necessary conditions**
  - deadly embrace: **deadlocks** and **livelocks**
  - **four deadlock conditions**
- deadlock **handling** and **countermeasures**
  - dining philosophers
  - prevention,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

Agenda

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



Organizational Matters



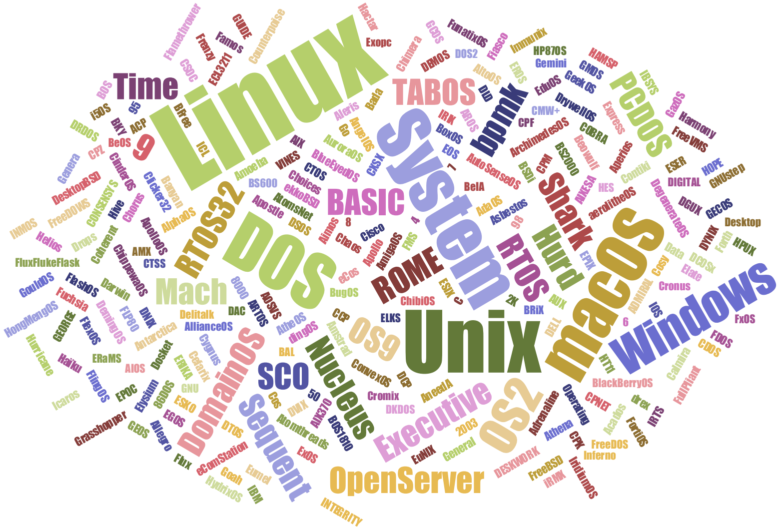
- lecture
  - Wednesday, 10:15 – 11:45
  - format: synchronous, **hybrid**

    → 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`

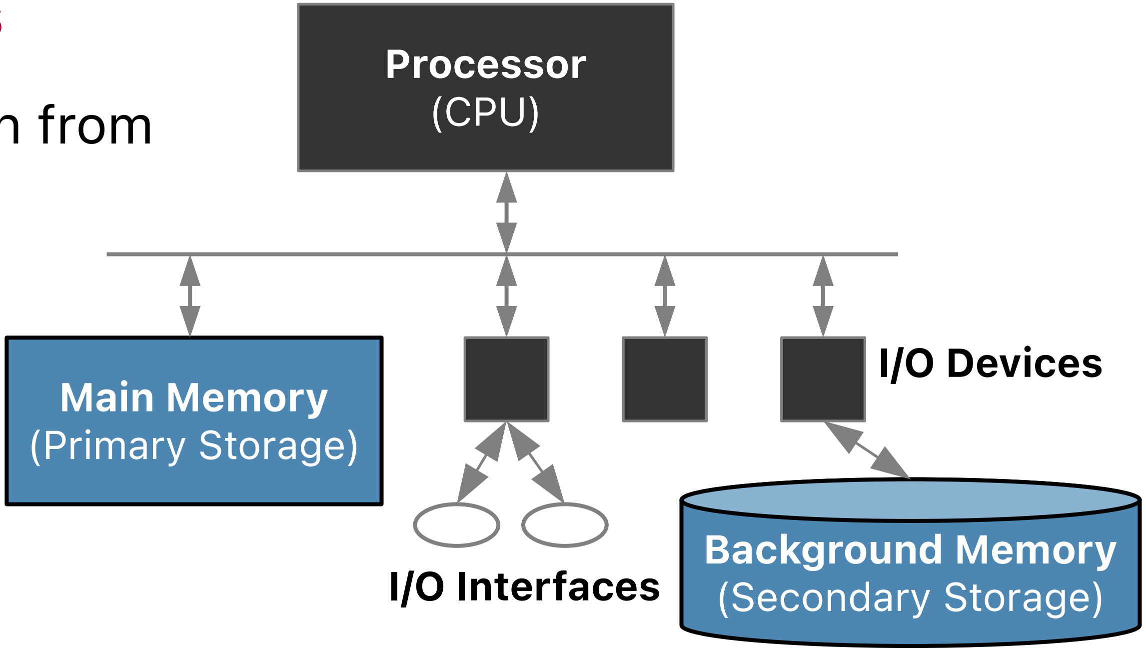
Agenda



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

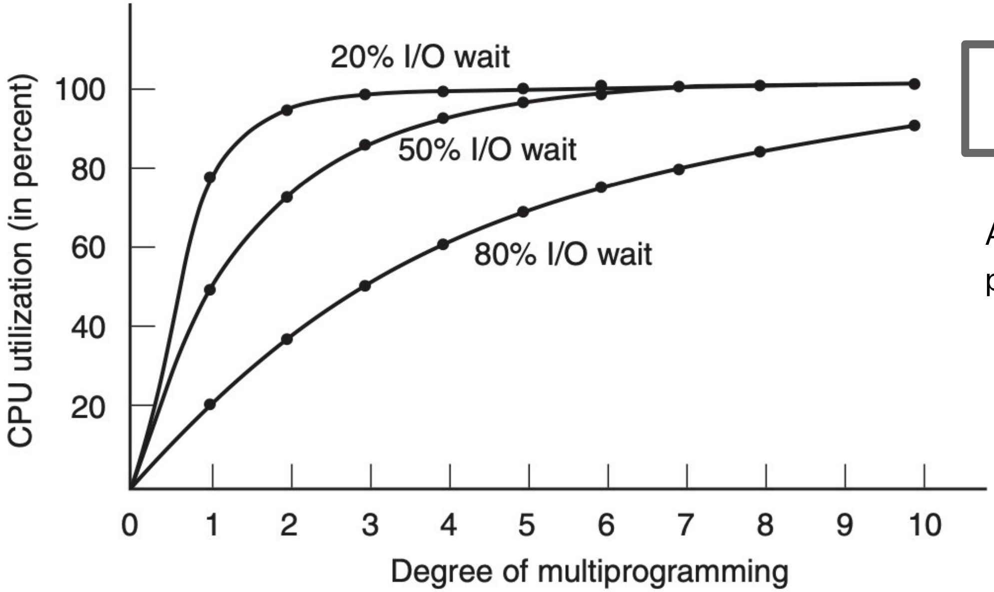
Operating Resources (Recap)

- 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

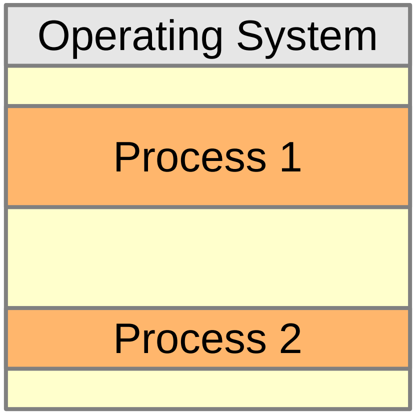
Source: Tanenbaum, Modern Operating Systems

➔ **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

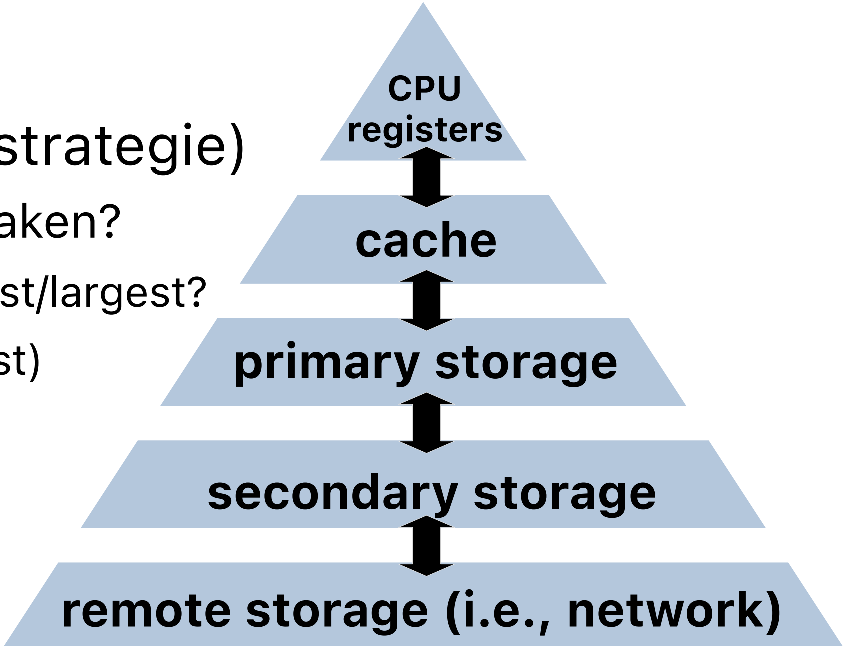
➔ swap-in and swap-out of processes

➔ relocation of program code

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

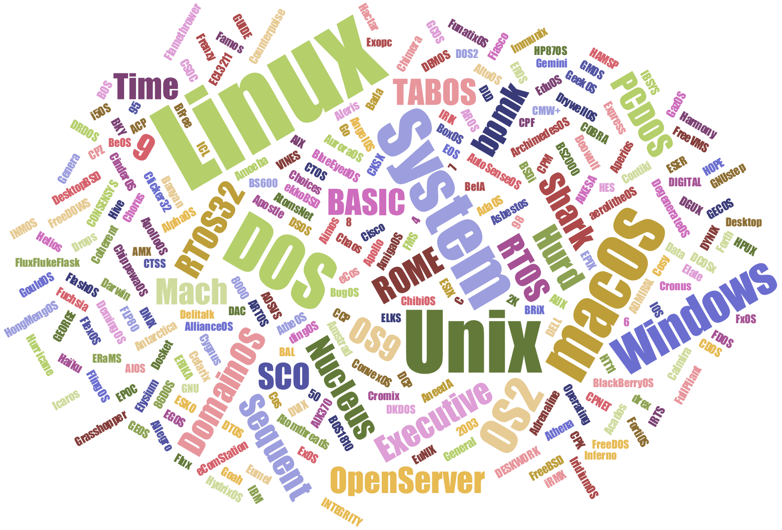
Strategies for Memory Management

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

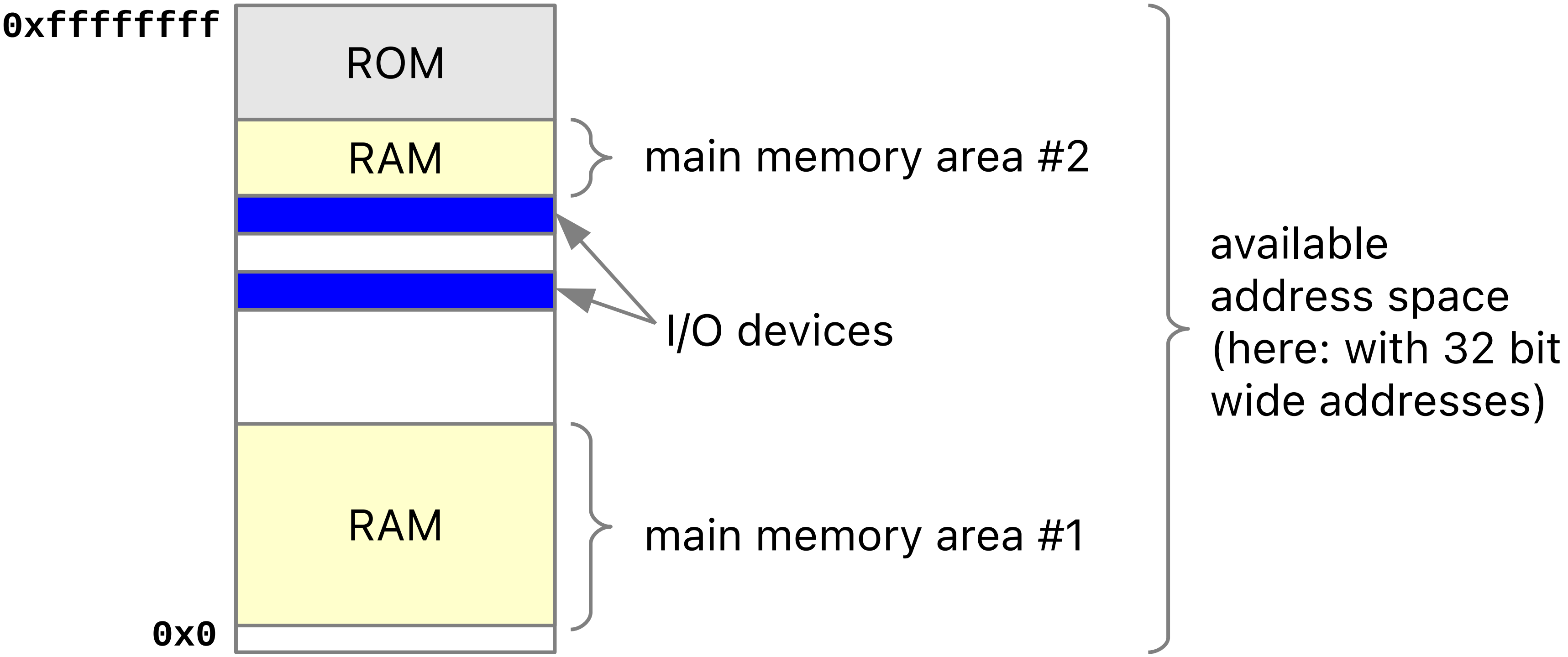
Agenda



- 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 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

➔ **dynamic memory management is mandatory**

Dynamic Memory Allocation

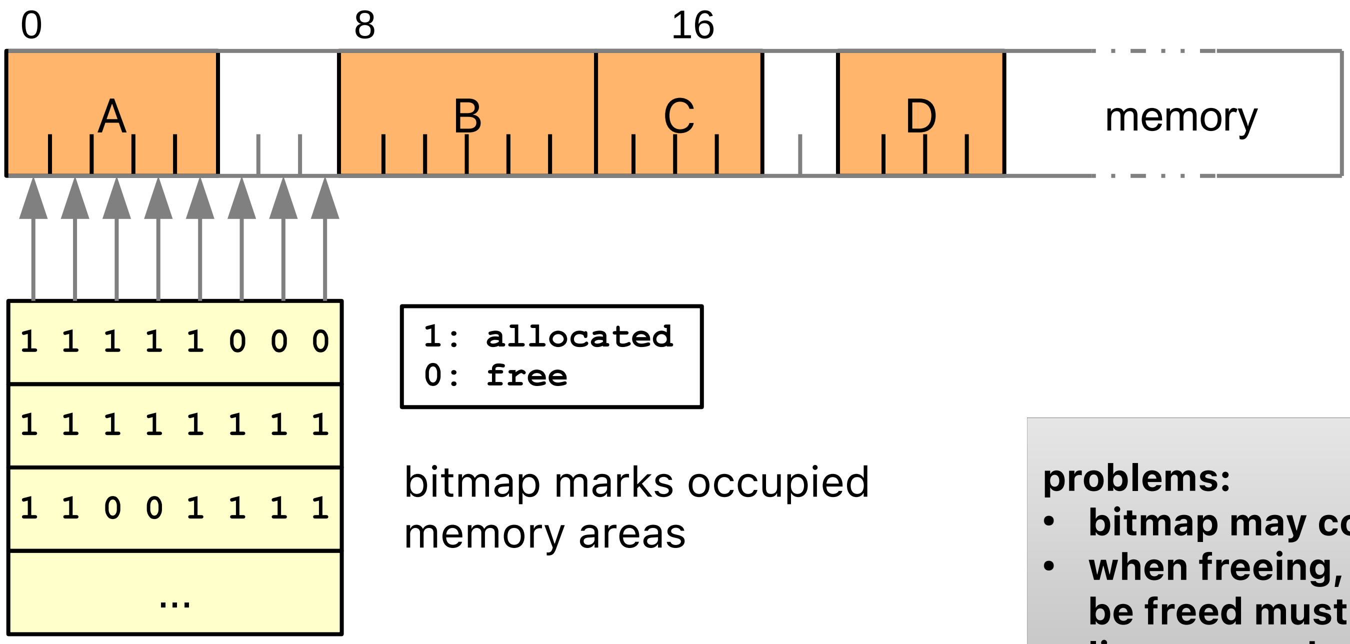
- **segments**
    - **contiguous memory** area (i.e., memory range with consecutive addresses)
    - **variable size**
- **allocation** (dt. Belegung) und **deallocation** (dt. Freigabe) of memory segments
- an application program usually has the following segments:
    - text segment
    - data segment
    - 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 1 1 1 1 0 0 0
1 1 1 1 1 1 1 1
1 1 0 0 1 1 1 1
...
```

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

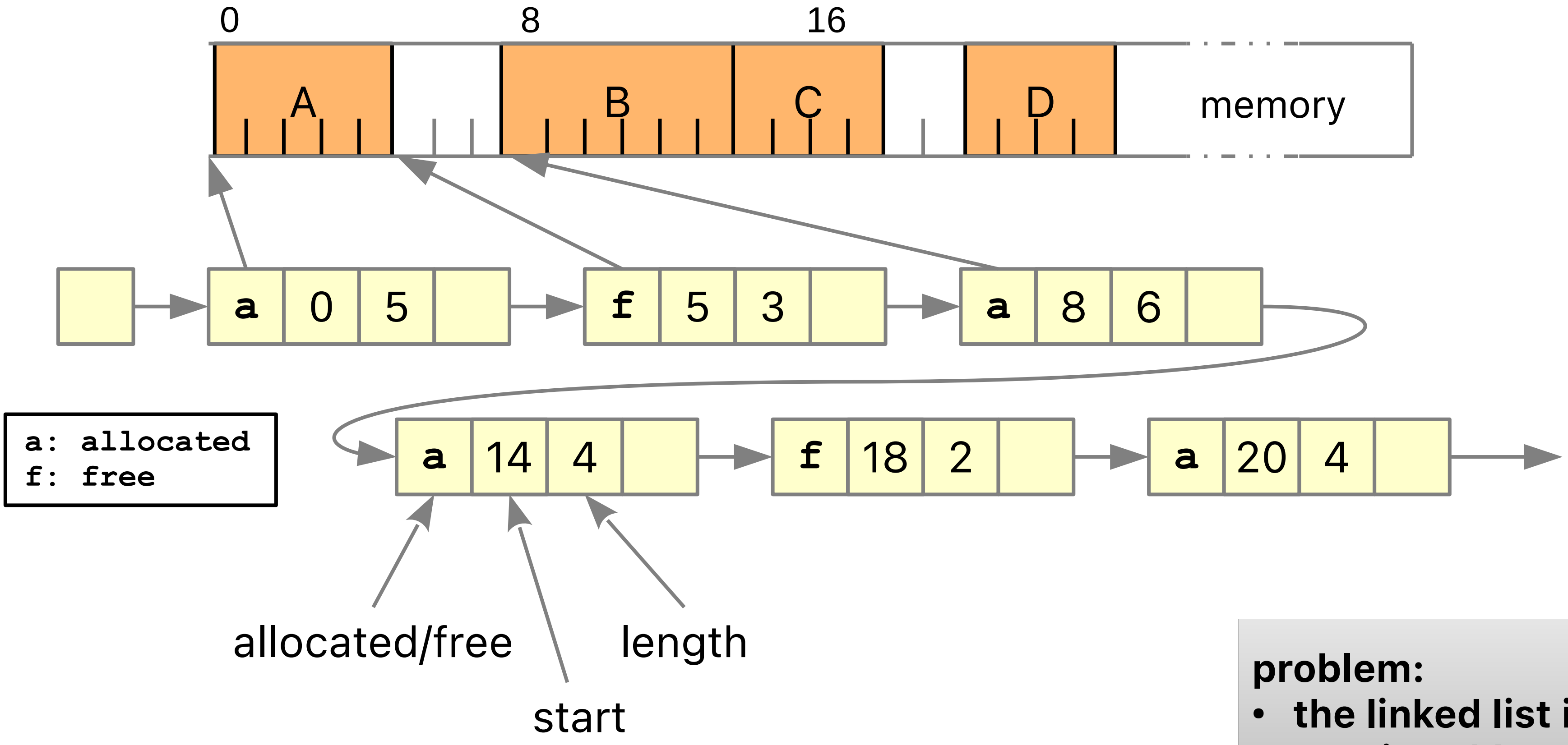
bitmap marks occupied memory areas

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**

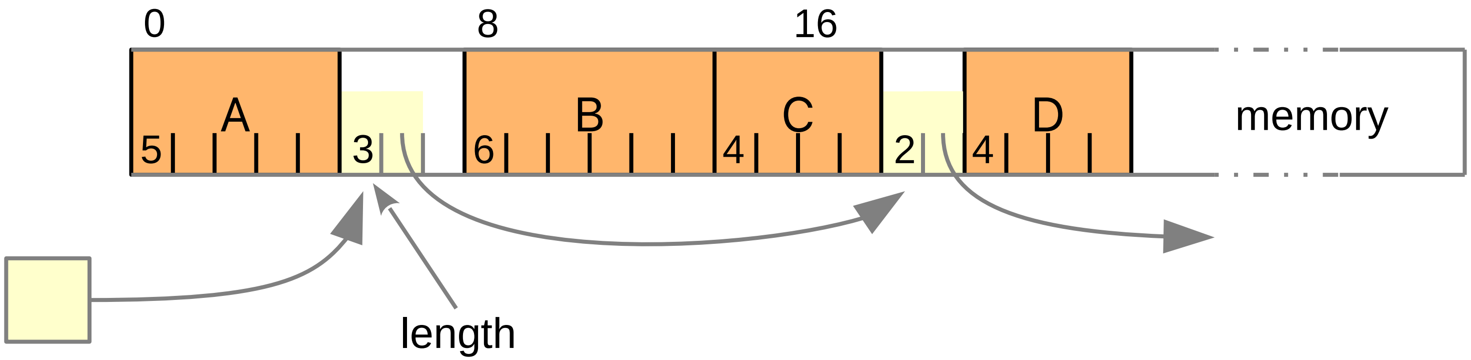


representation of allocated (used) and free (unused) segments

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

Free-Space Management – Linked List (V2)

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

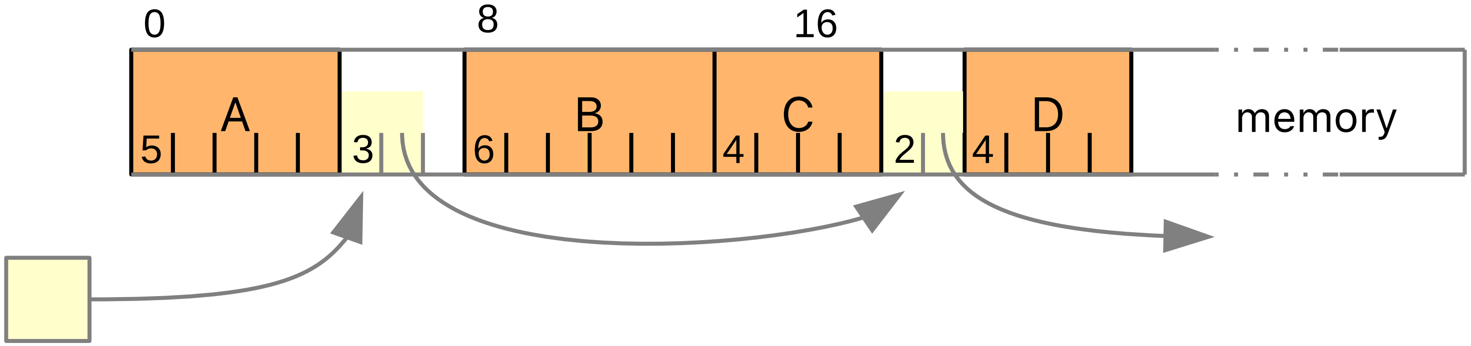


minimum hole size must be guaranteed

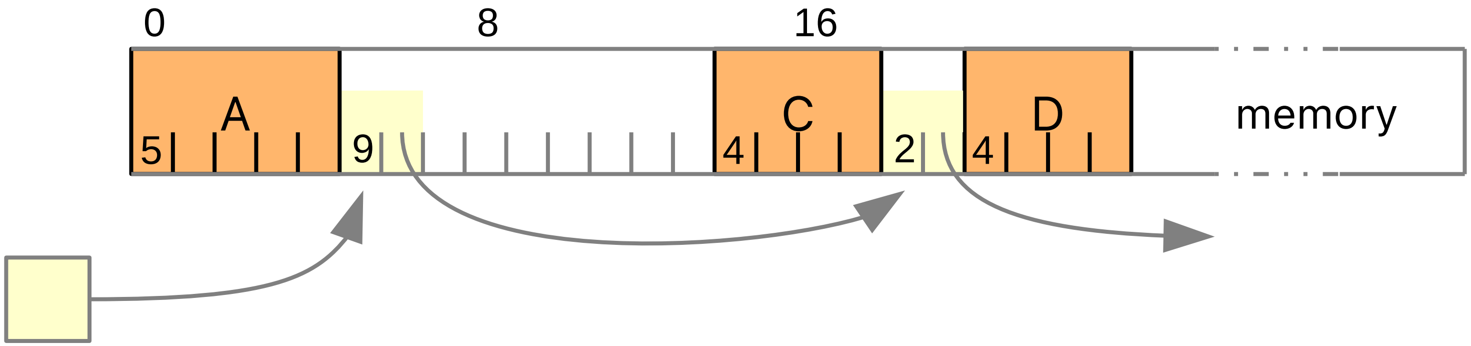
- backward linking may be necessary to increase efficiency
- representation ultimately also dependent on the allocation strategy

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:

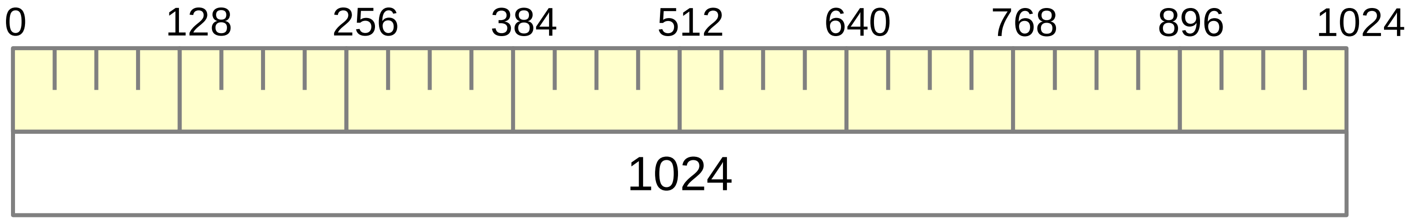
- **First Fit** (sorting: **by memory address**)
  - linear search, first matching hole is used
- **Rotating First Fit / Next Fit** (sorting: **by memory address**)
  - like First Fit, but start at the last assigned hole
  - avoids many small holes at the beginning of the list (like First Fit)
- **Best 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

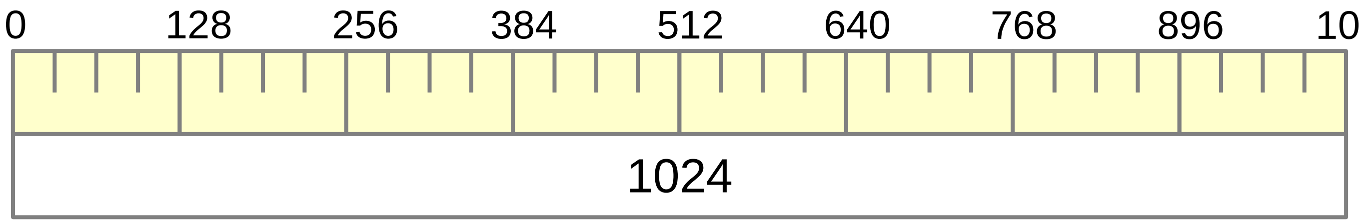
release B

release D

release C

Placement Strategies – Buddy System

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

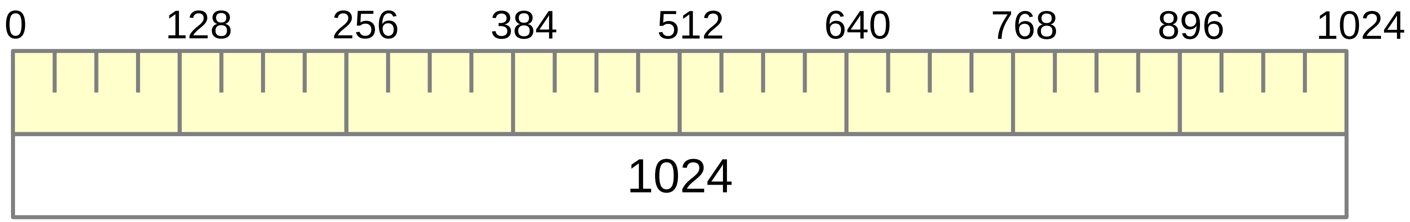


A: → request 70
B: request 35
C: request 80
release A
D: request 60
release B
release D
release C

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

Placement Strategies – Buddy System

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

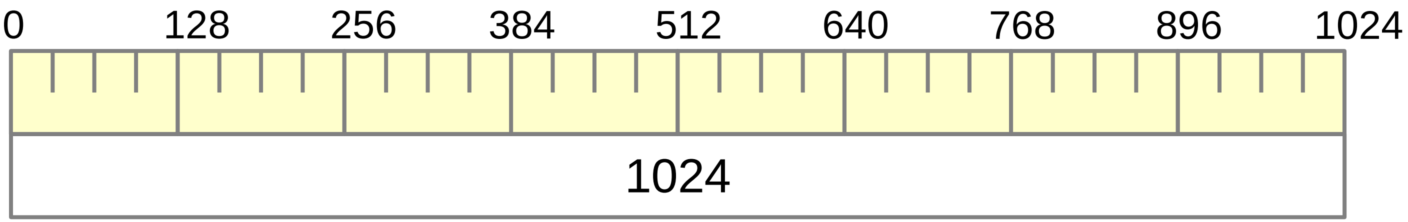


A: → request 70
B: request 35
C: request 80
release A
D: request 60
release B
release D
release C

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

Placement Strategies – Buddy System

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

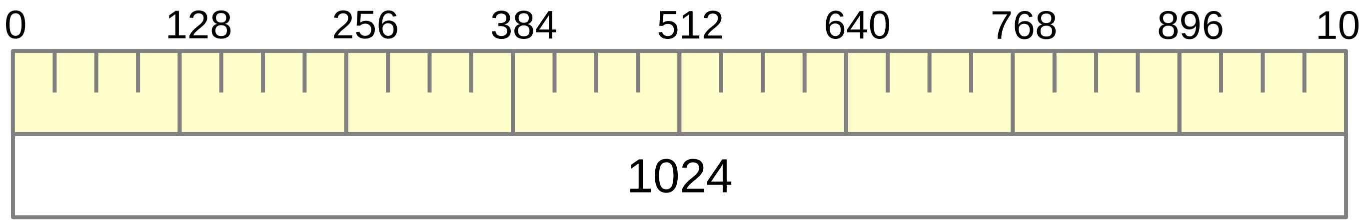


A: → request 70
B: request 35
C: request 80
release A
D: request 60
release B
release D
release C

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

Placement Strategies – Buddy System

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

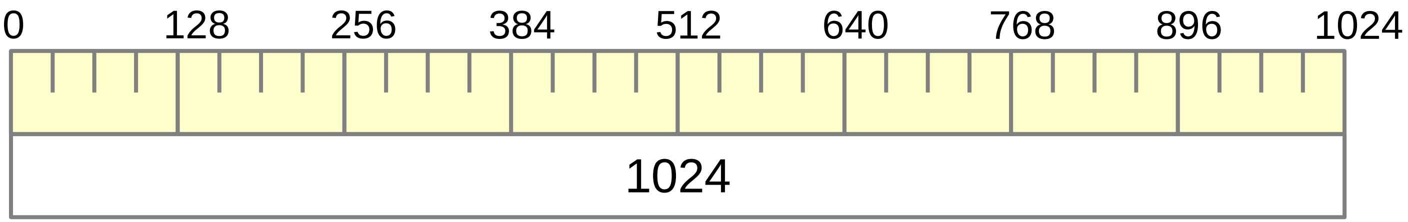


A: → request 70
B: request 35
C: request 80
release A
D: request 60
release B
release D
release C

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

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
1024	(2^10)	
512	(2^9)	512
256	(2^8)	256
128	(2^7)	128
64	(2^6)	

address

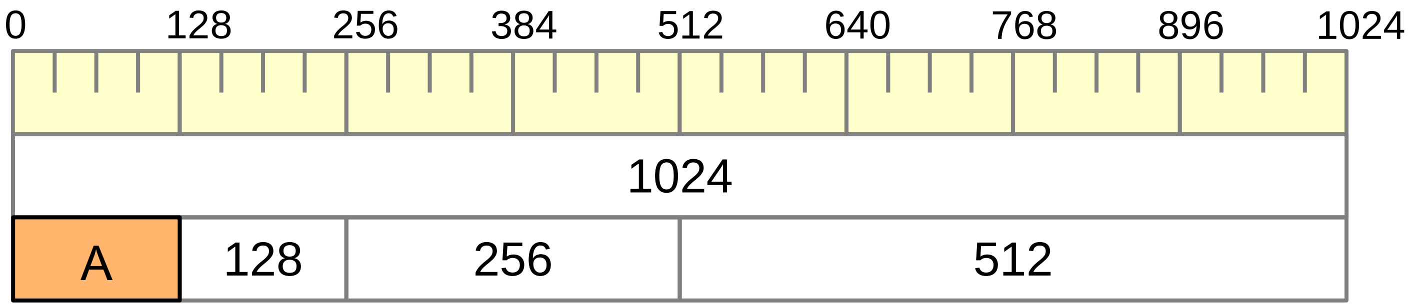
allocated list

size

`A: 0 (128)`

Placement Strategies – Buddy System

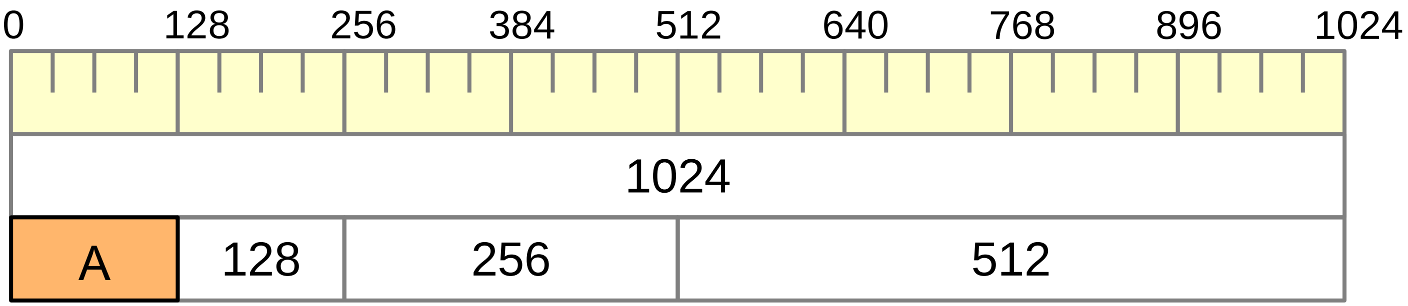
- the **buddy system** partitions memory into dynamic areas of size 2^n



~~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



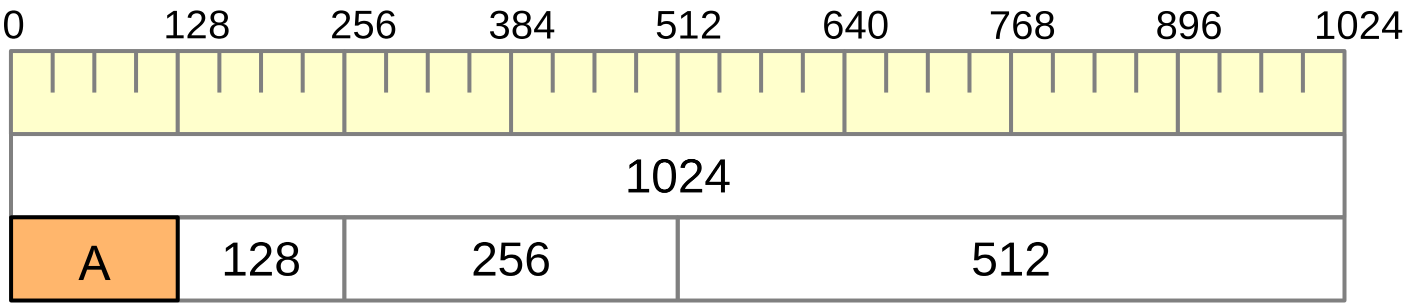
~~A: request 70~~
B: → request 35
C: request 80
release A
D: request 60
release B
release D
release C

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)		

Placement Strategies – Buddy System

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

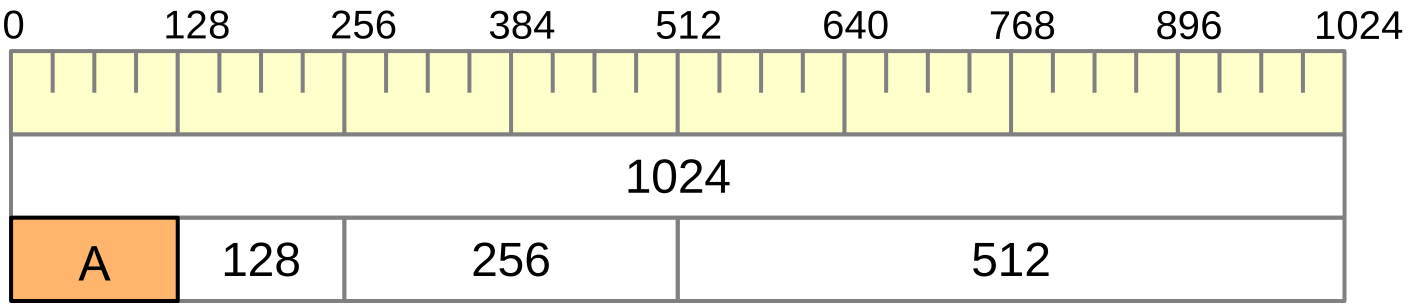
~~A: request 70~~
B: → request 35
C: request 80
release A
D: request 60
release B
release D
release C



bucket size		free list	allocated list
1024	(2^10)		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

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

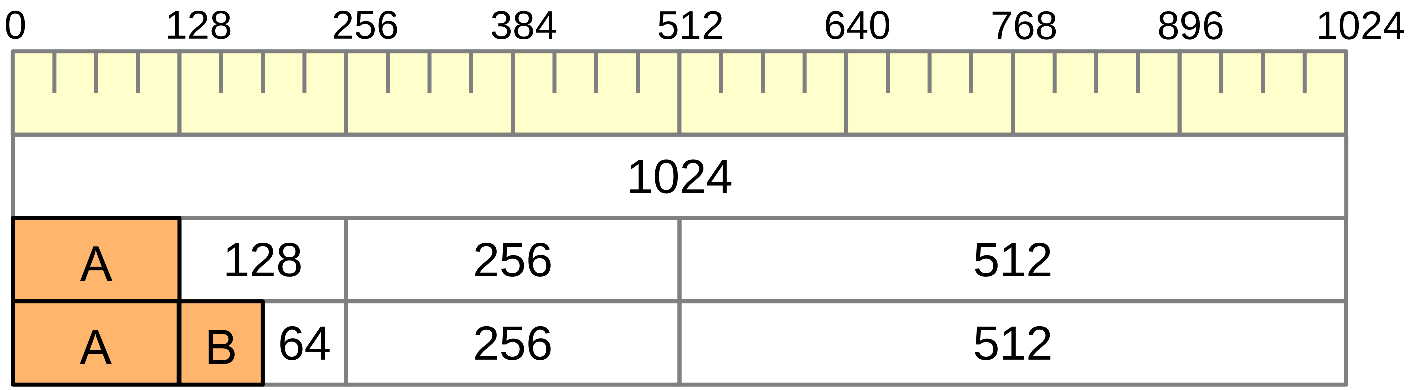


~~A:~~ ~~request 70~~
B: → request 35
C: request 80
release A
D: request 60
release B
release D
release C

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

Placement Strategies – Buddy System

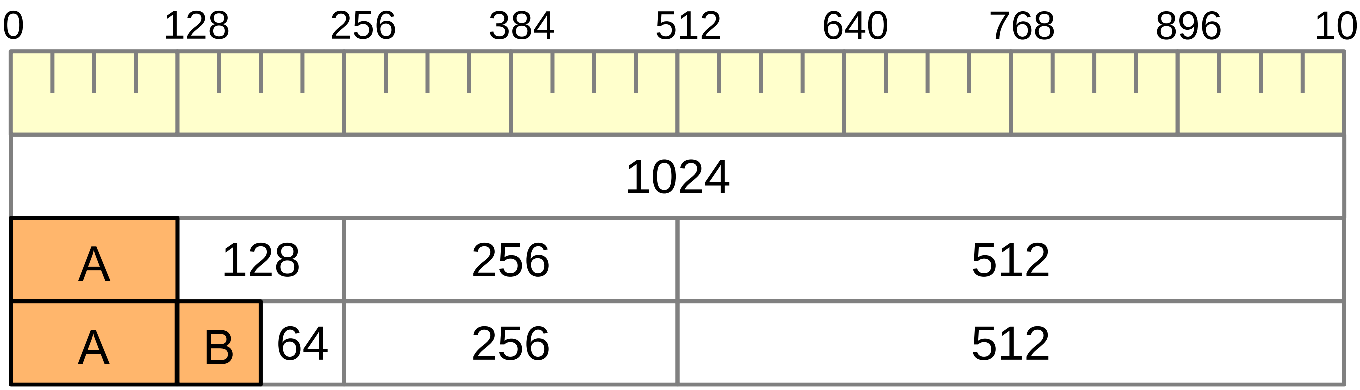
- the **buddy system** partitions memory into dynamic areas of size 2^n



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

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

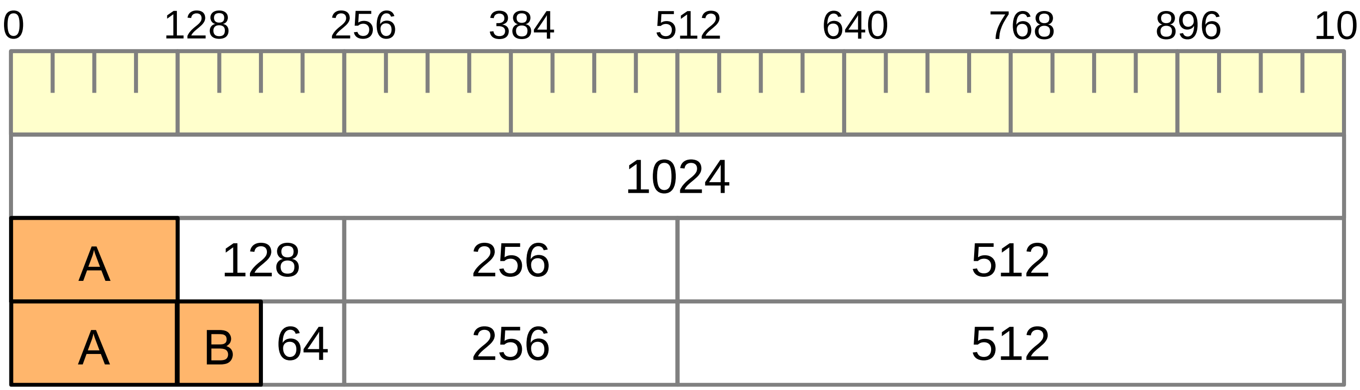
bucket size	free list
1024 (2^10)	
512 (2^9)	512
256 (2^8)	256
128 (2^7)	
64 (2^6)	192

allocated list

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

Placement Strategies – Buddy System

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



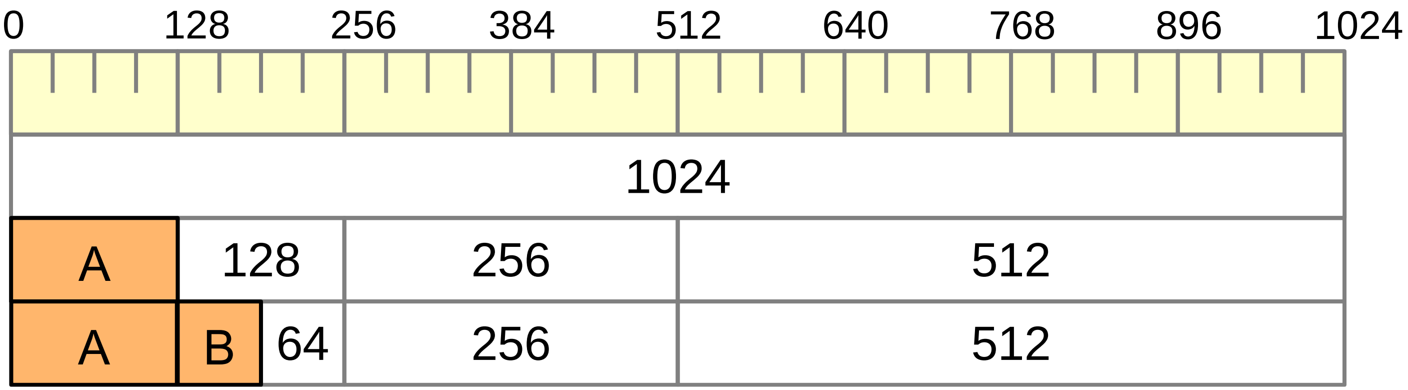
~~A:~~ ~~request 70~~
~~B:~~ ~~request 35~~
C: → request 80
release A
D: request 60
release B
release D
release C

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



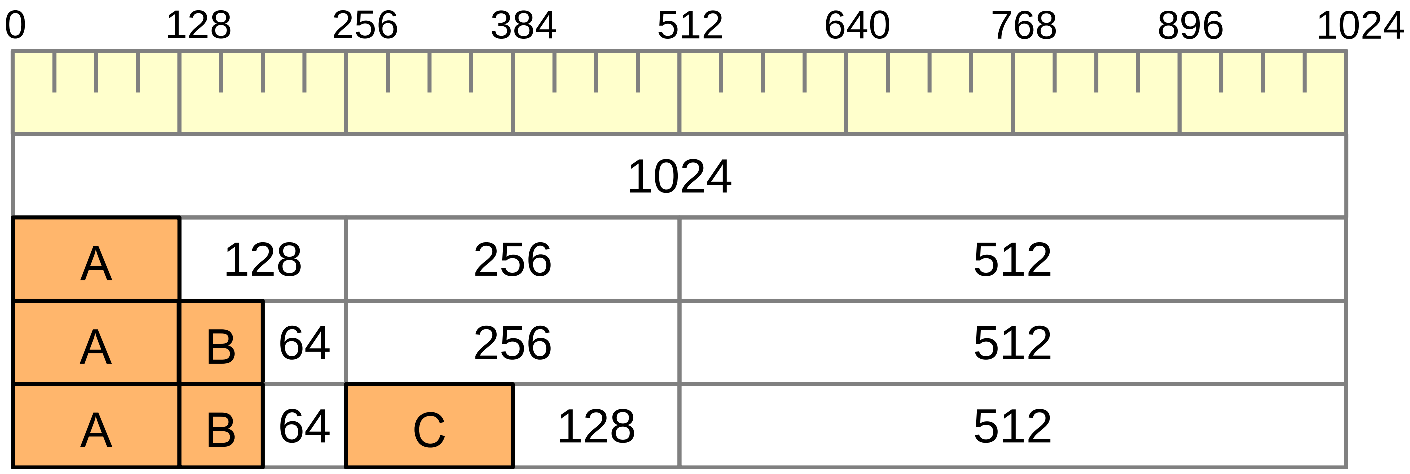
bucket size	free list
1024 (2^10)	
512 (2^9)	512
256 (2^8)	
128 (2^7)	384
64 (2^6)	192

allocated list

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

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

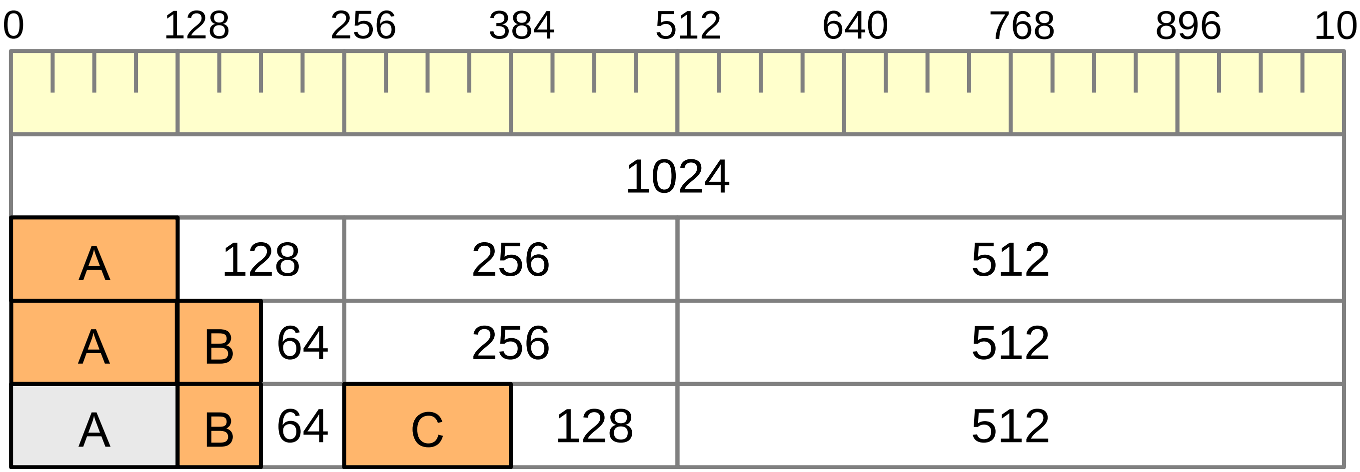
release B

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

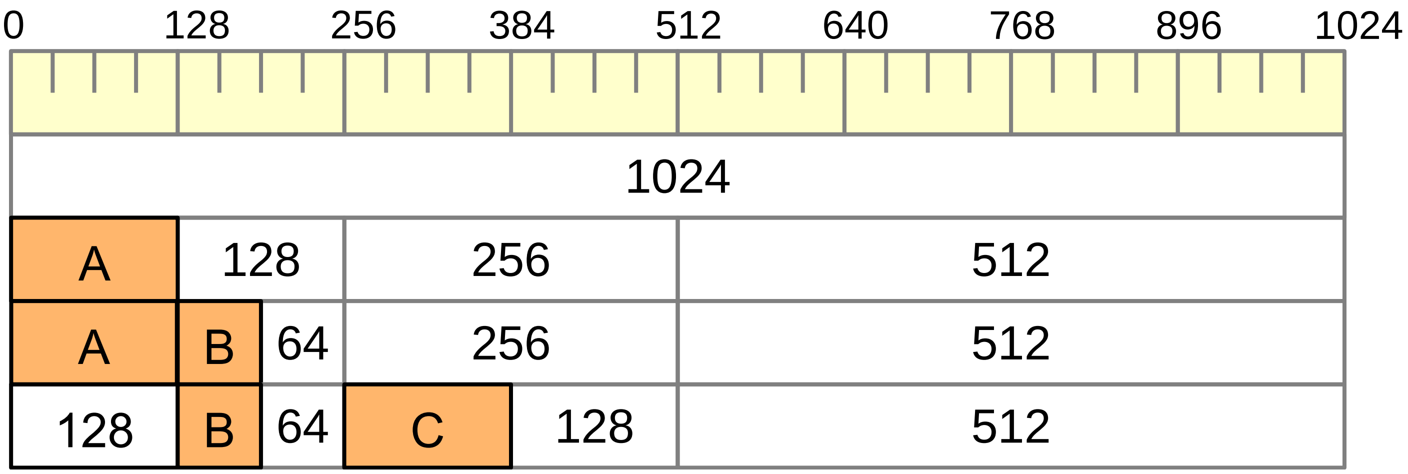
bucket size	free list
1024 (2^10)	
512 (2^9)	512
256 (2^8)	
128 (2^7)	384
64 (2^6)	192

allocated list

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

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

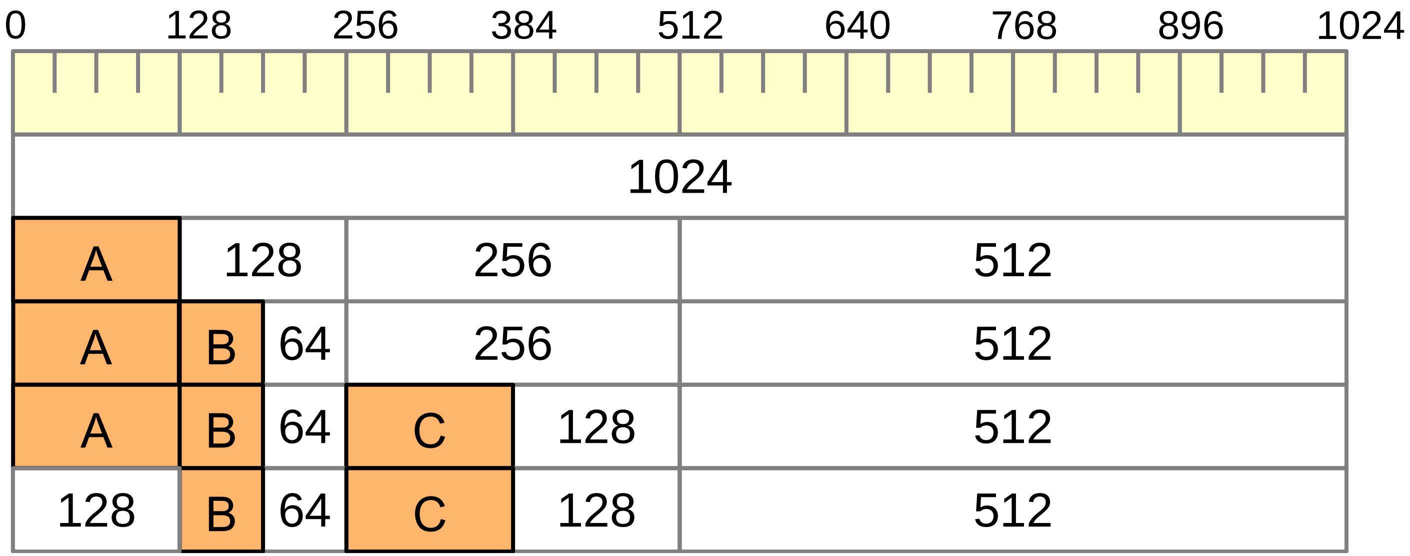
bucket size	free list
1024 (2^10)	
512 (2^9)	512
256 (2^8)	
128 (2^7)	0, 384
64 (2^6)	192

allocated list

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

Placement Strategies – Buddy System

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

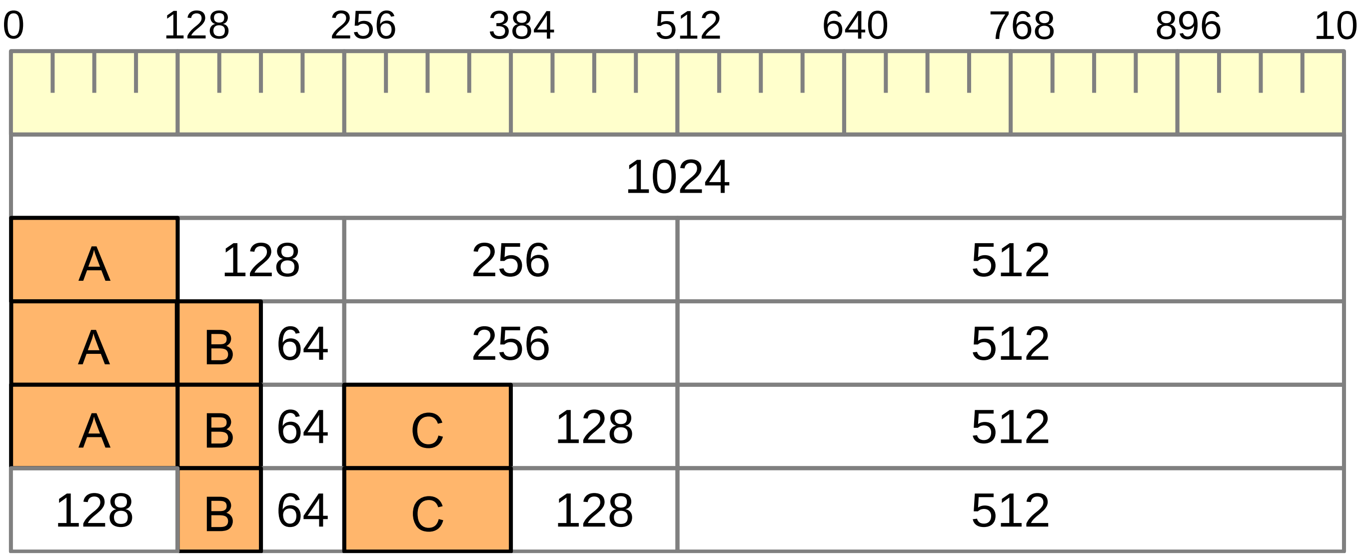


~~A:~~ ~~request 70~~
~~B:~~ ~~request 35~~
~~C:~~ ~~request 80~~
~~release A~~
D: → request 60
release B
release D
release C

Placement Strategies – Buddy System

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

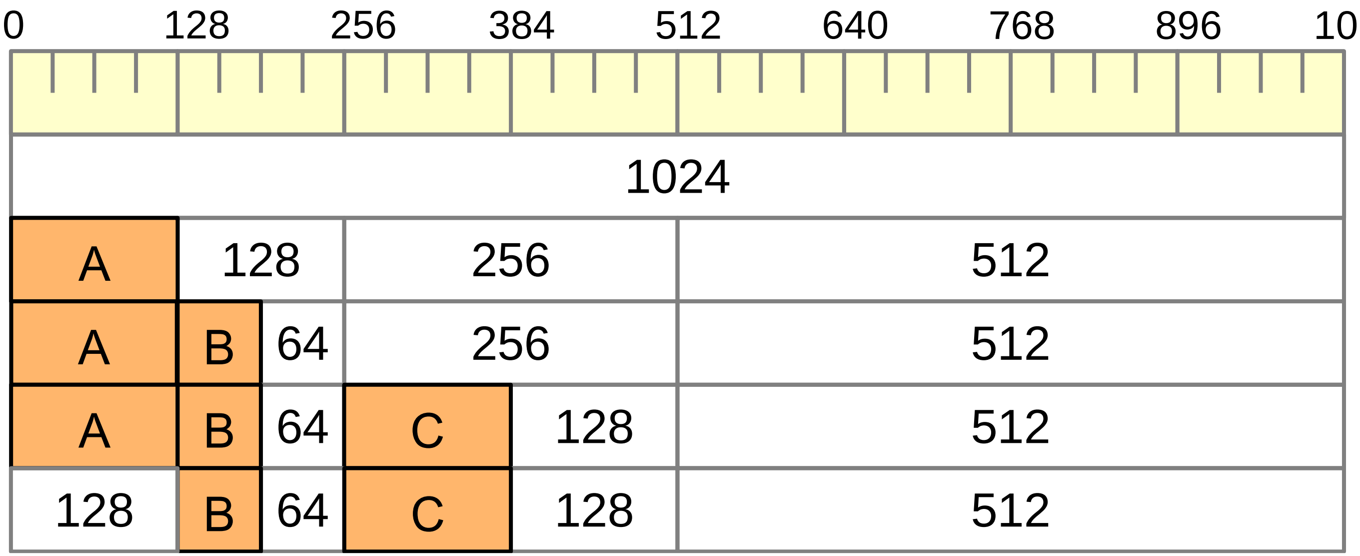
~~A:~~ ~~request 70~~
~~B:~~ ~~request 35~~
~~C:~~ ~~request 80~~
~~release A~~
D: → request 60
release B
release D
release C



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

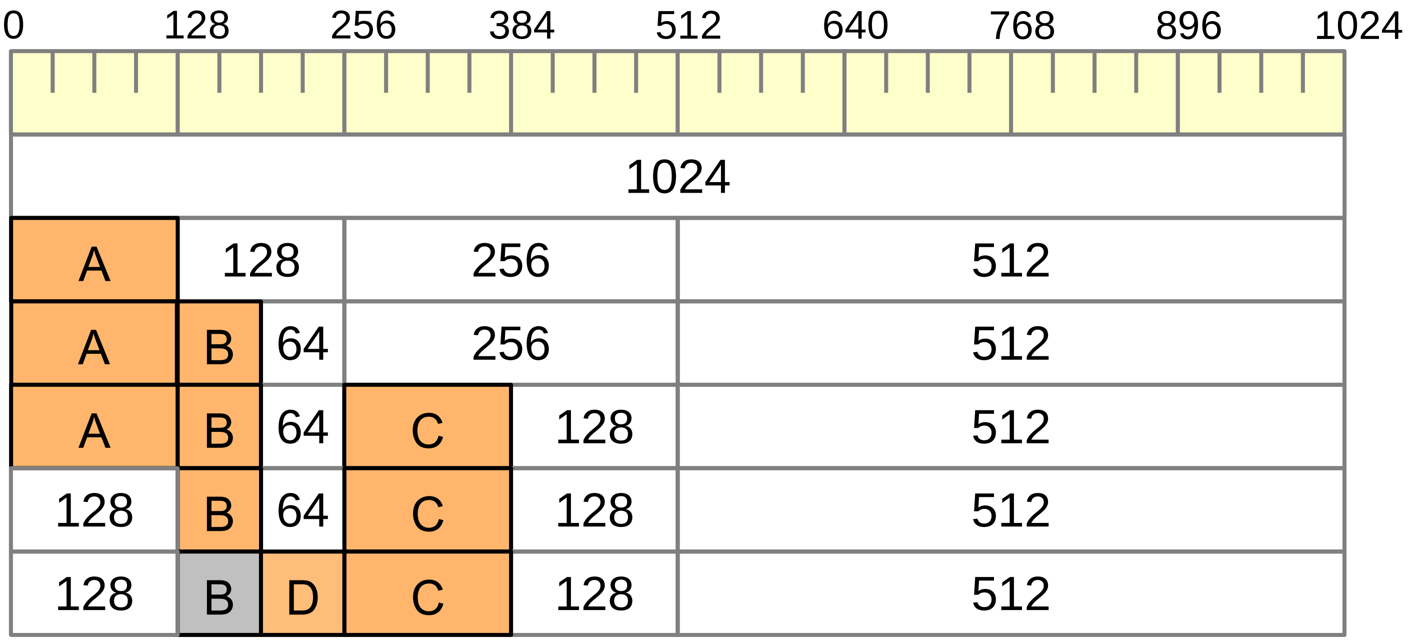
bucket size		free list
1024	(2^10)	
512	(2^9)	512
256	(2^8)	
128	(2^7)	0, 384
64	(2^6)	

allocated list

~~A: 0 (128)~~
B: 128 (64)
C: 256 (128)
D: 192 (64)

Placement Strategies – Buddy System

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



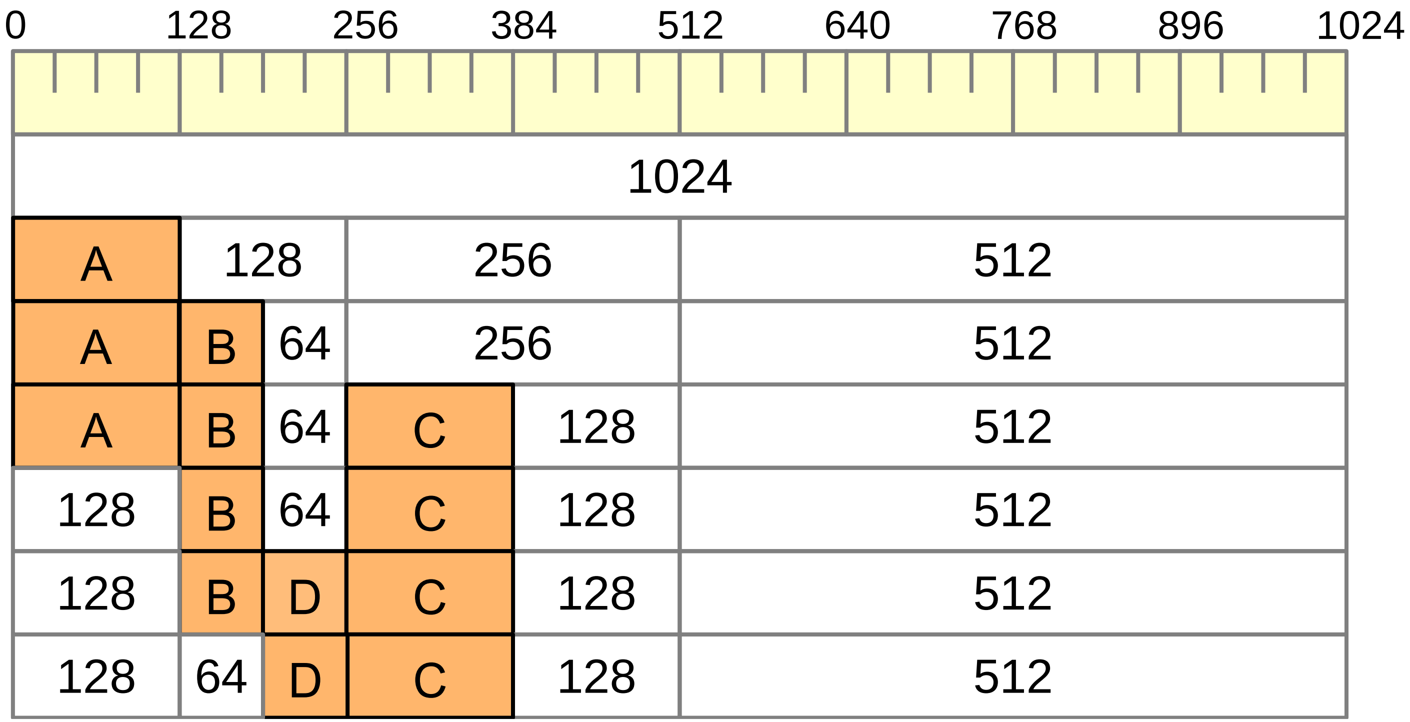
~~A:~~ ~~request 70~~
~~B:~~ ~~request 35~~
~~C:~~ ~~request 80~~
~~release A~~
~~D:~~ ~~request 60~~
→ release B
release D
release C

- 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

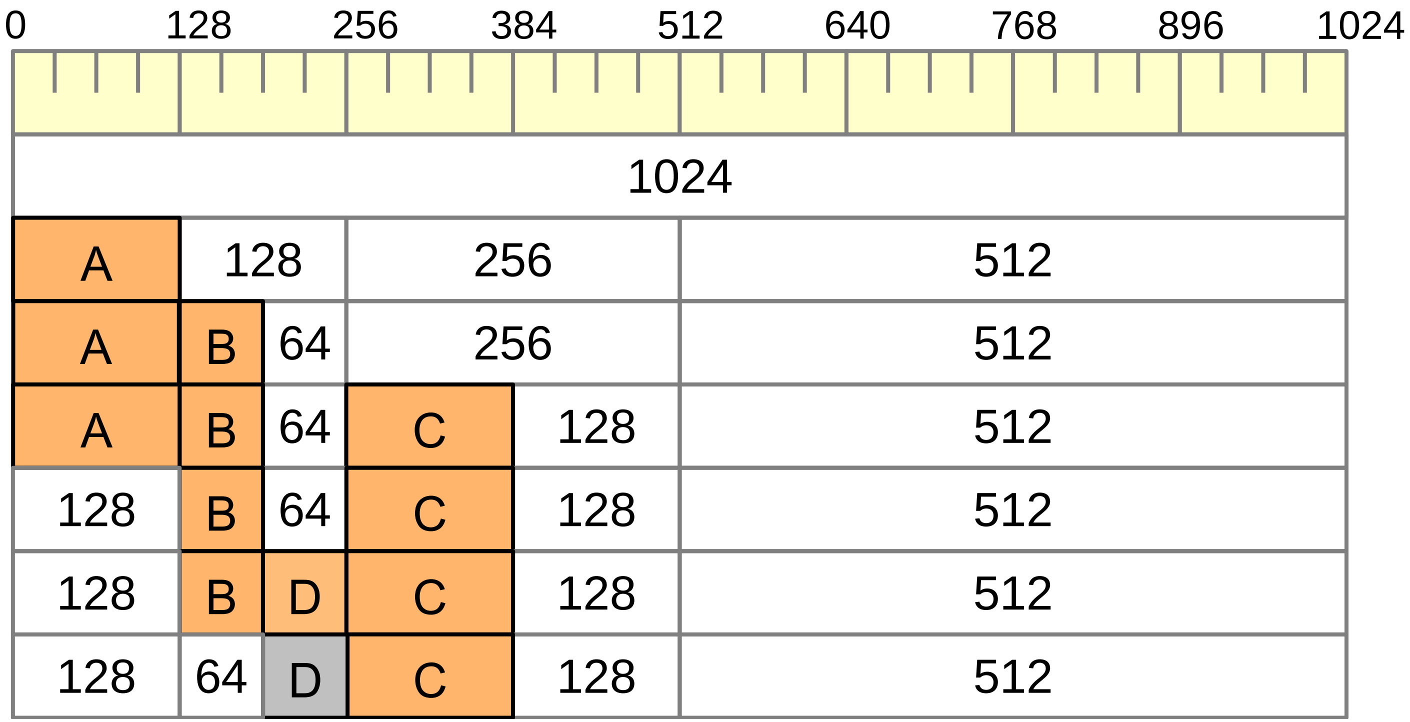


1024
A | 128 | 256 | 512
A | B | 64 | 256 | 512
A | B | 64 | C | 128 | 512
128 | B | 64 | C | 128 | 512
128 | B | D | C | 128 | 512
128 | 64 | D | C | 128 | 512

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

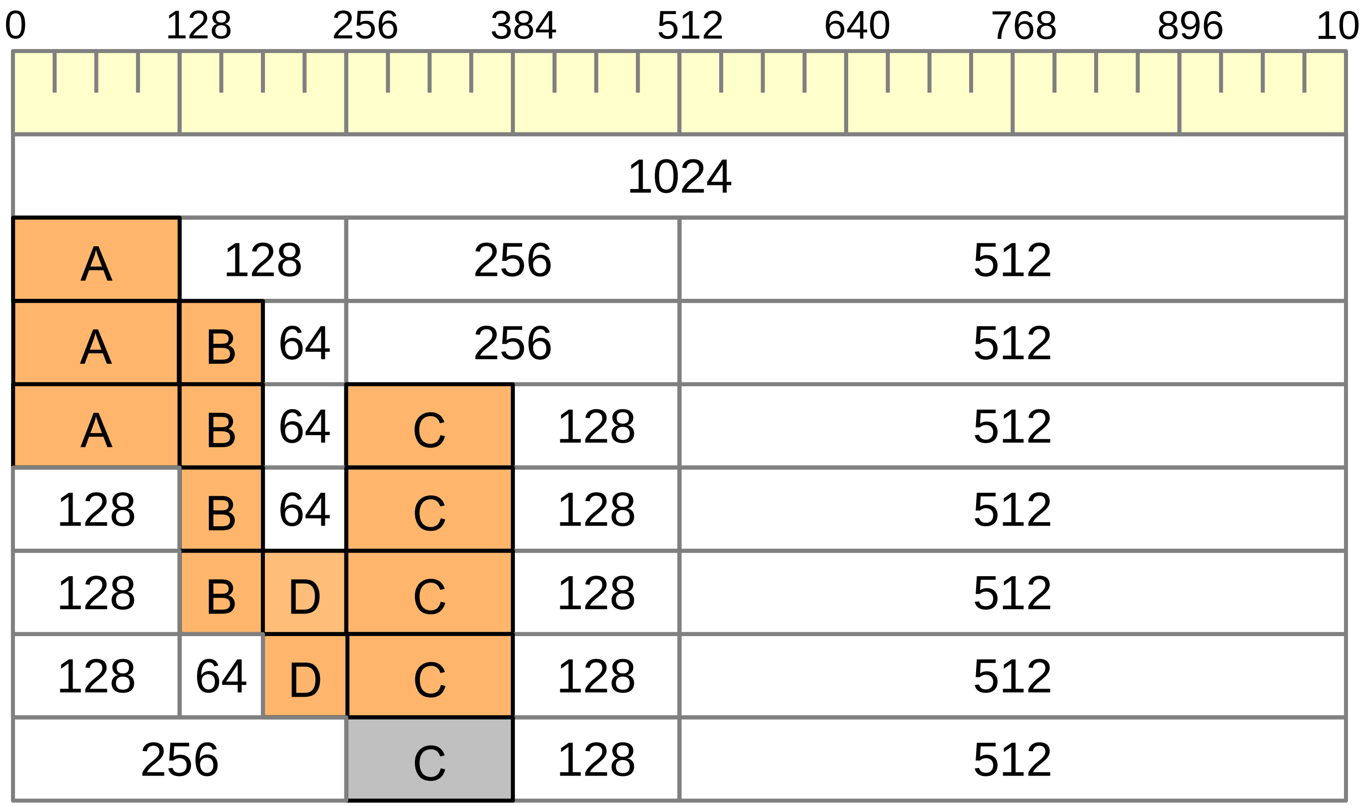


- freeing the memory allocated for request D
- no buddy allocation present
- merge leftover holes, recursively (2 times)

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

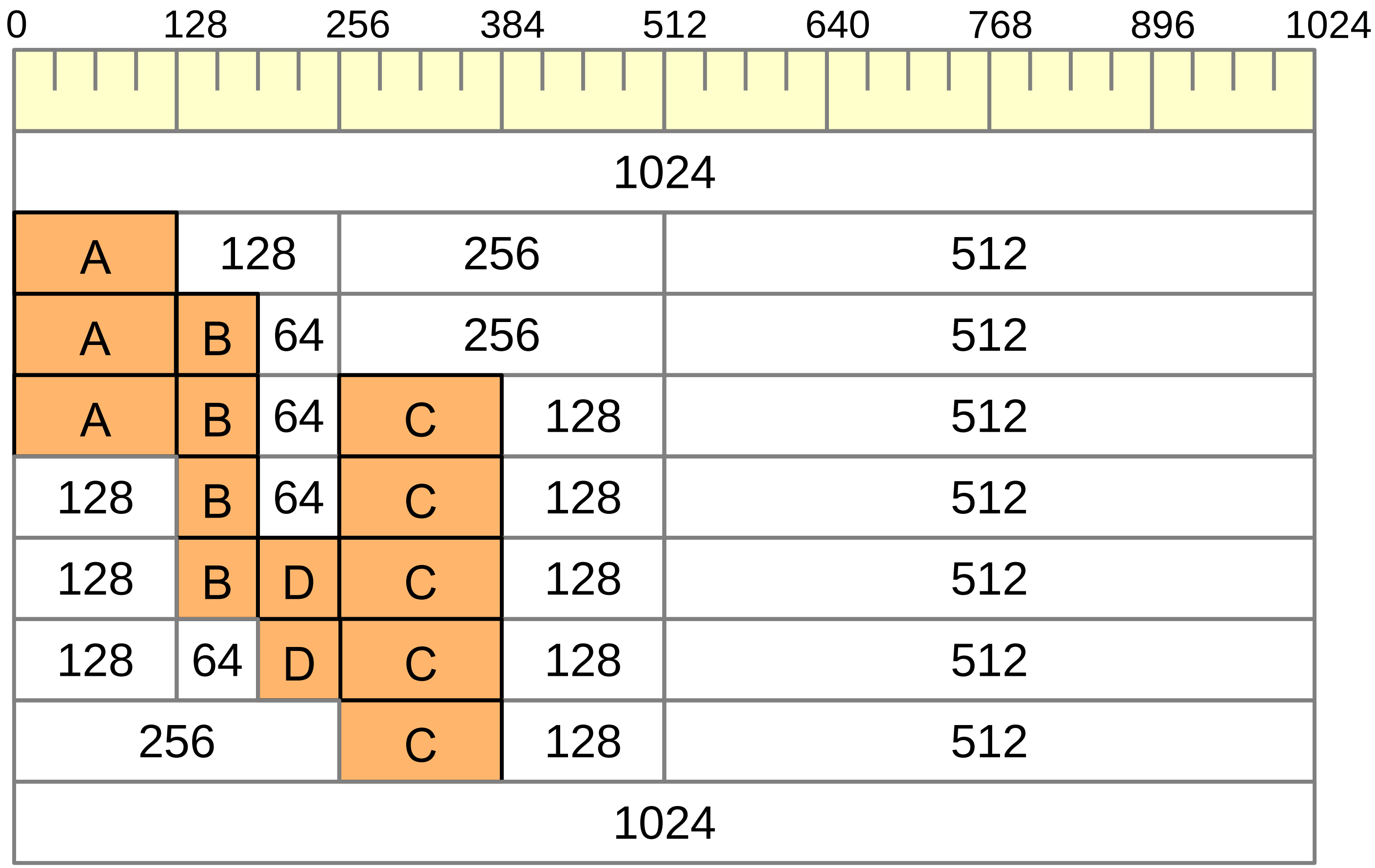


- freeing the memory allocated for request C
- no buddy allocation present
- merge leftover holes, recursively (3 times)

Placement Strategies – Buddy System

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

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



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

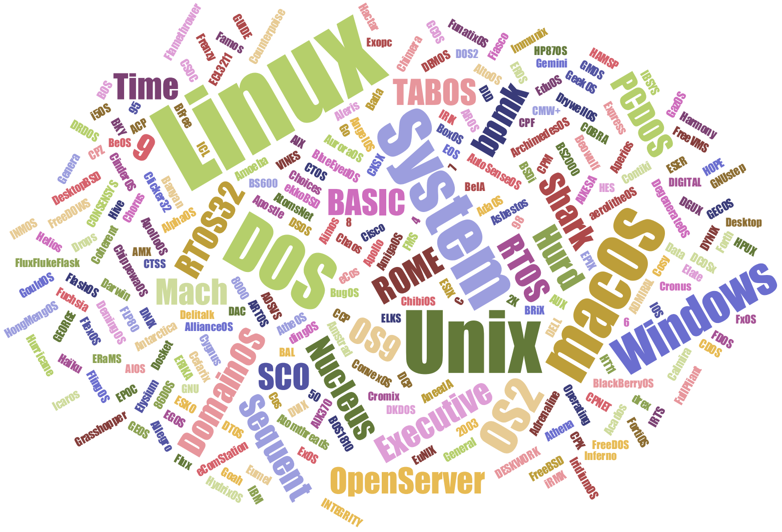
Buddy allocator in Linux

- use within a process
    - management of the heap memory
    - allows dynamic allocation of memory areas processes (malloc and free)

typically list-based

- use for secondary storage
    - management of specific sections of secondary storage, for example, memory areas for process swap data (swap space)

often with implemented with bitmaps

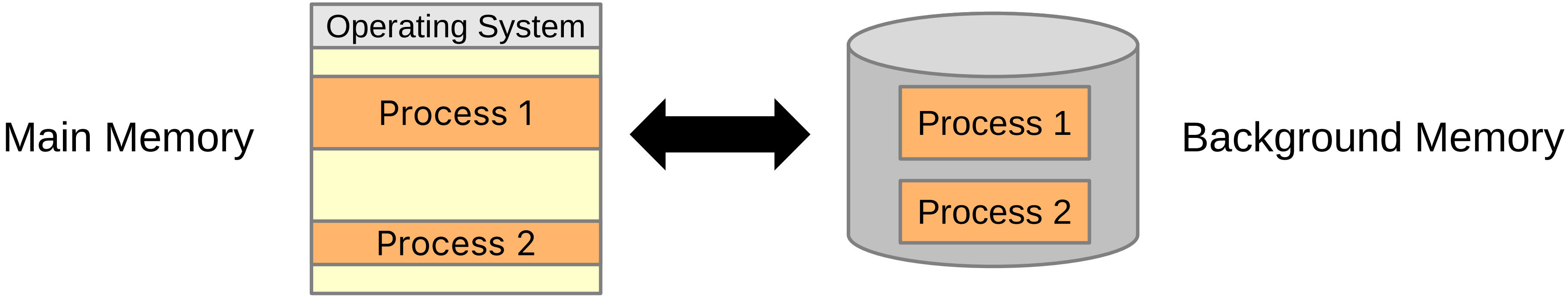


Agenda

- 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

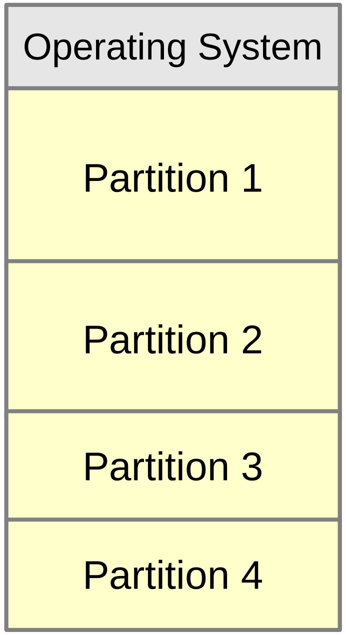
- segments of a process are swapped out to background memory and then freed in main memory
    - for example, to bridge waiting times for I/O
- swapping-in of the segments to the main memory at the end of the waiting time



- 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

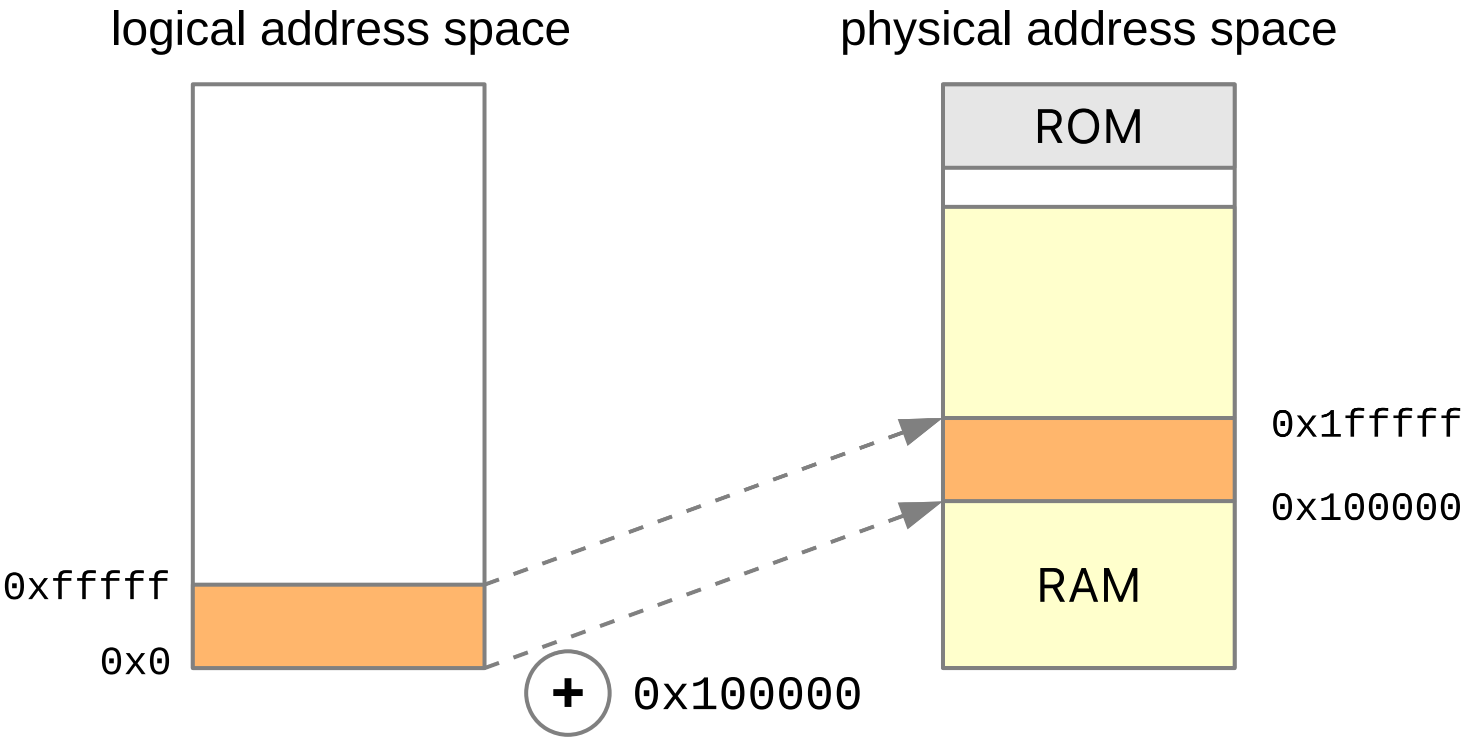
- addresses in the processes are usually statically bound
  - can only be loaded to the same place in the main memory
  - collisions with segments that may be new in the main memory
- possible solution 1: **static partitioning** of the main memory
  - only one process is running in each partition
  - 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

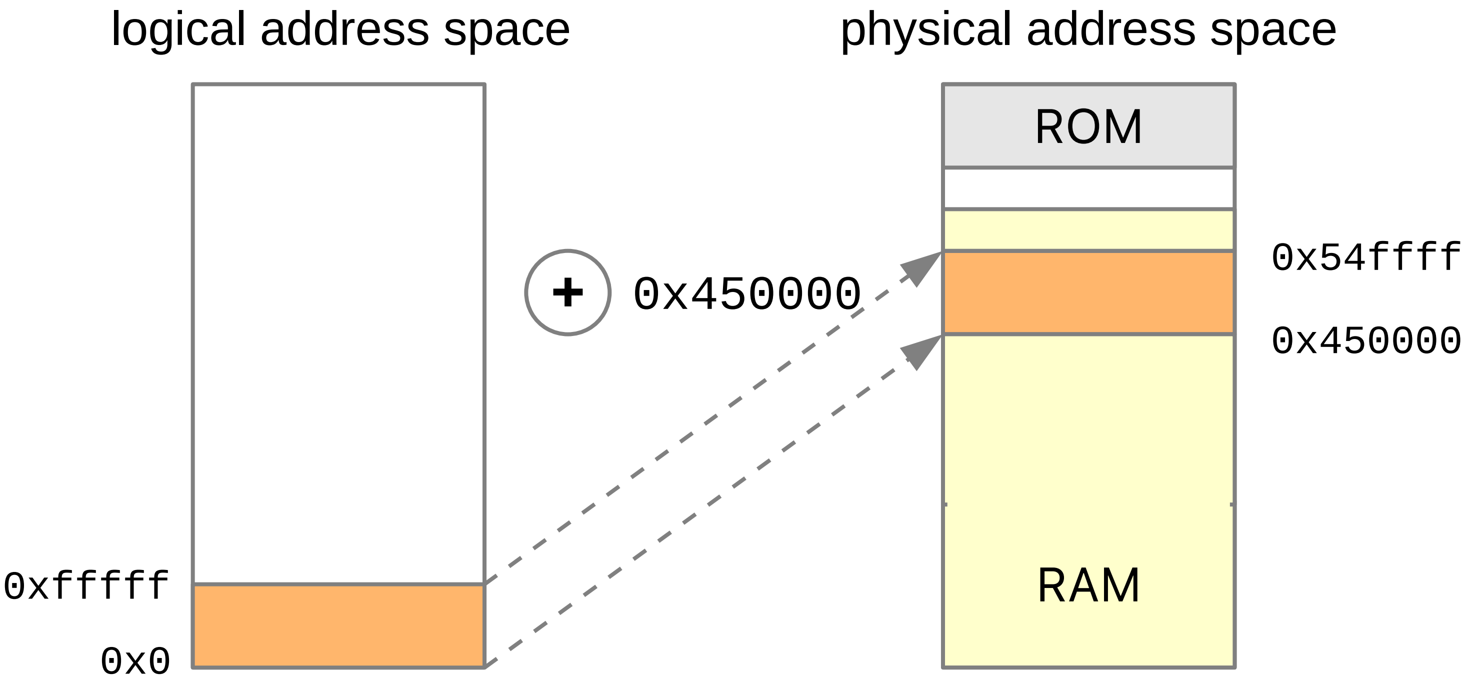
- map logical to physical addresses with hardware support



- 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

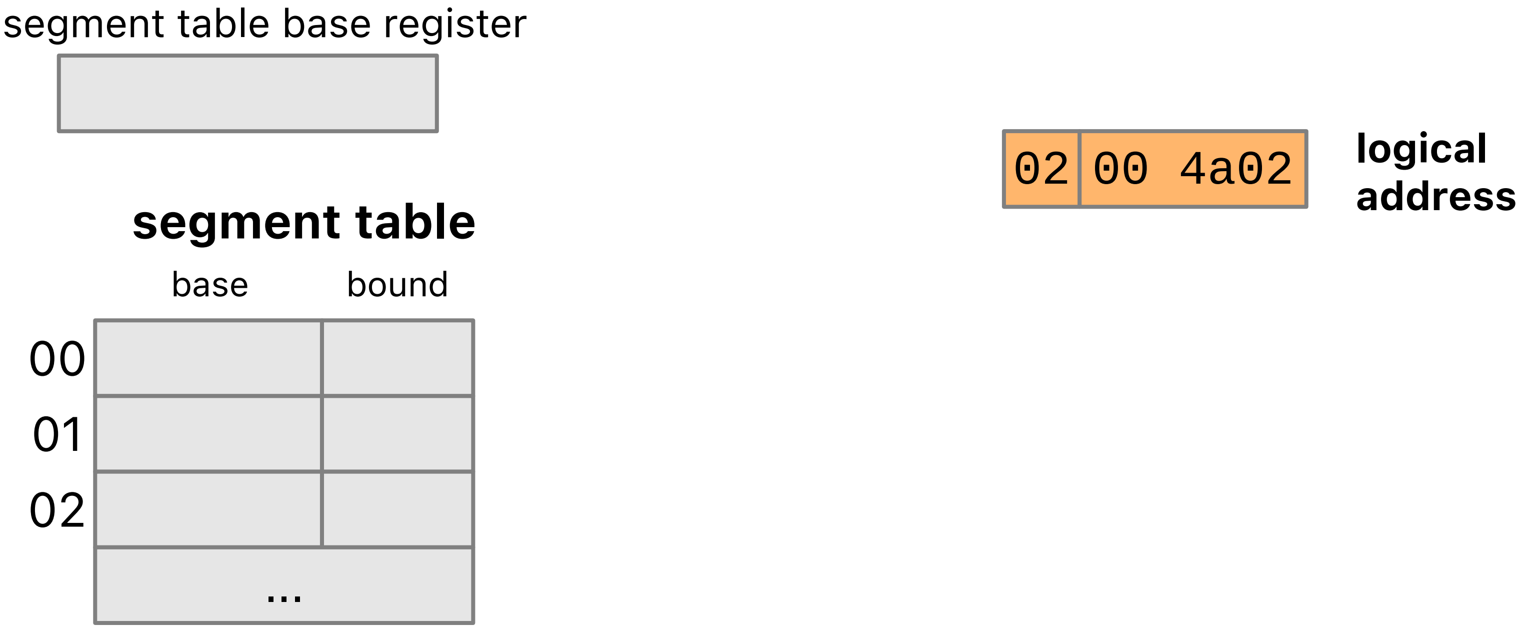
- map logical to physical addresses with hardware support



- 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

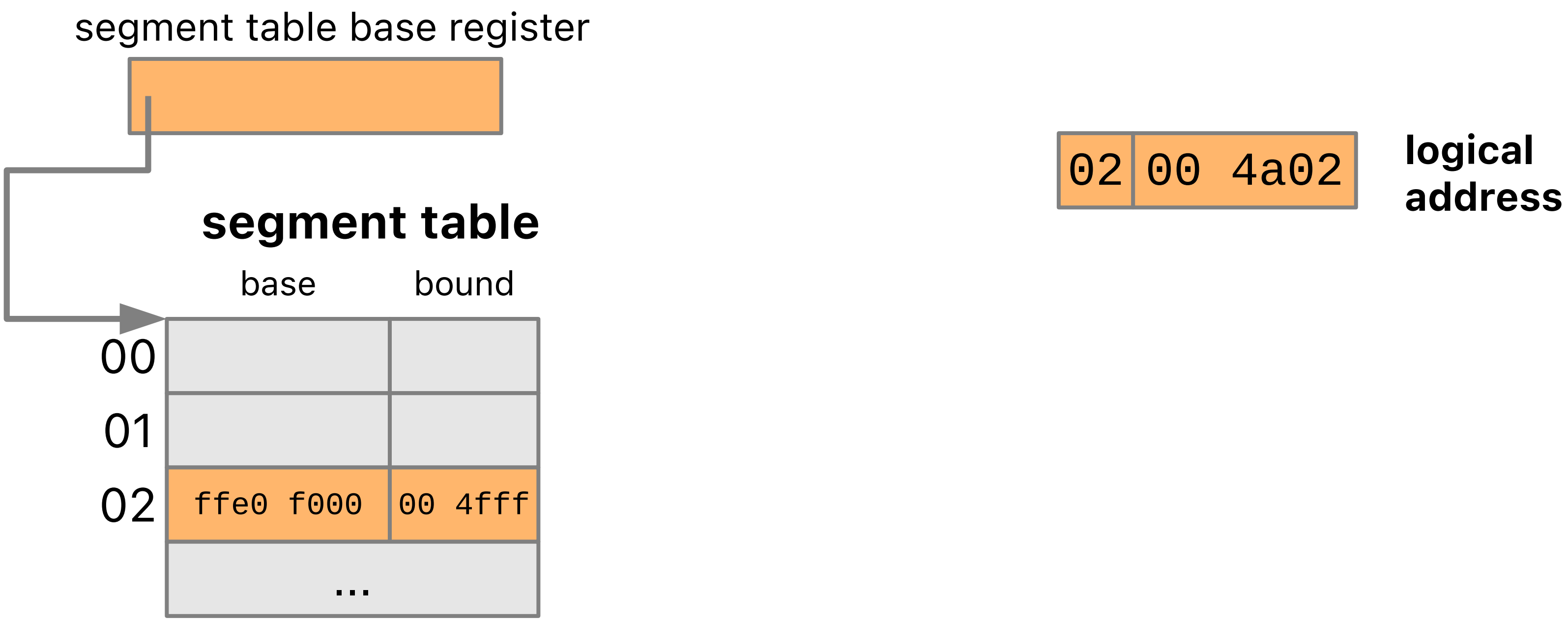
- realisation with translation table (per process)



	base	bound
00		
01		
02		
	...	

Memory Management – Segmentation

- realisation with translation table (per process)



segment table base register

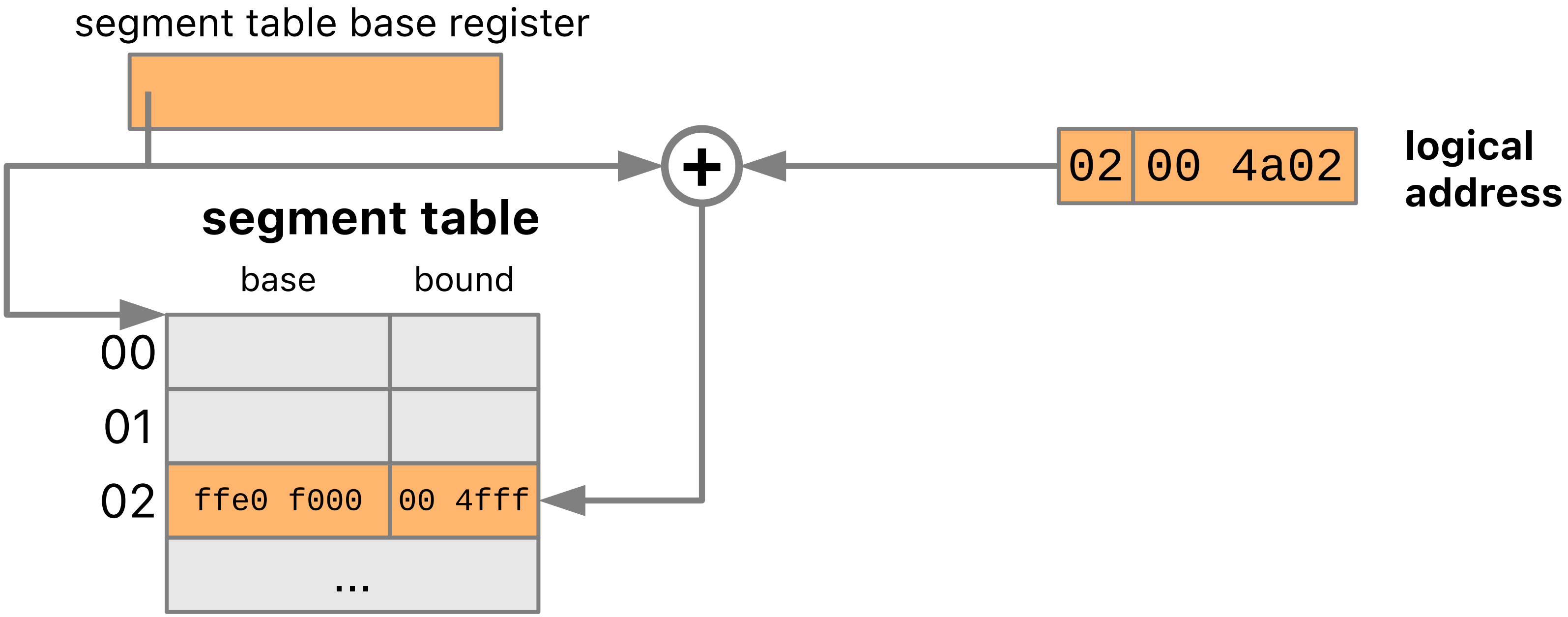
segment table

	base	bound
00		
01		
02	`ffe0 f000`	`00 4fff`
...		

`02` `00 4a02` **logical address**

Memory Management – Segmentation

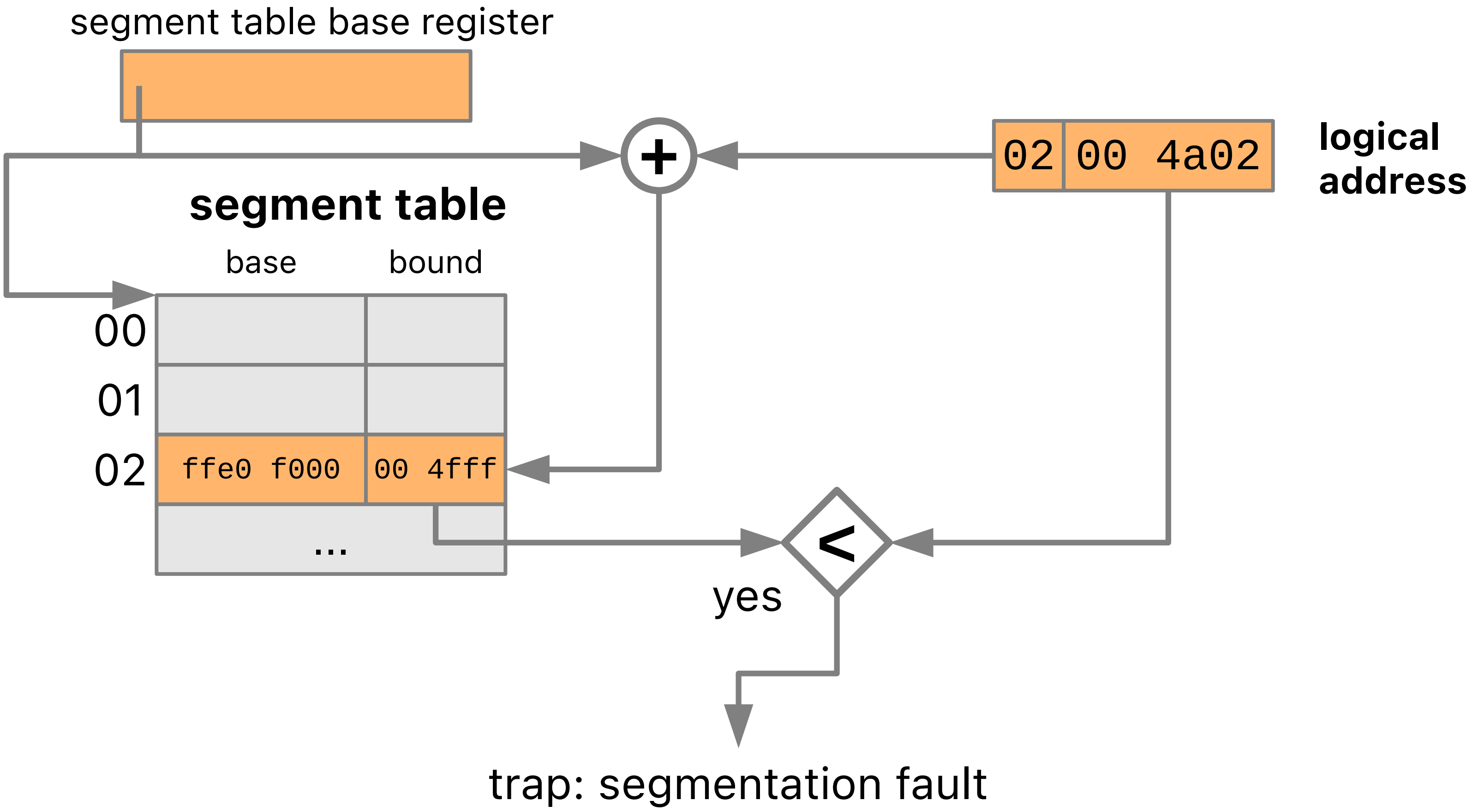
- realisation with translation table (per process)



	base	bound
00		
01		
02	ffe0 f000	00 4fff
	...	

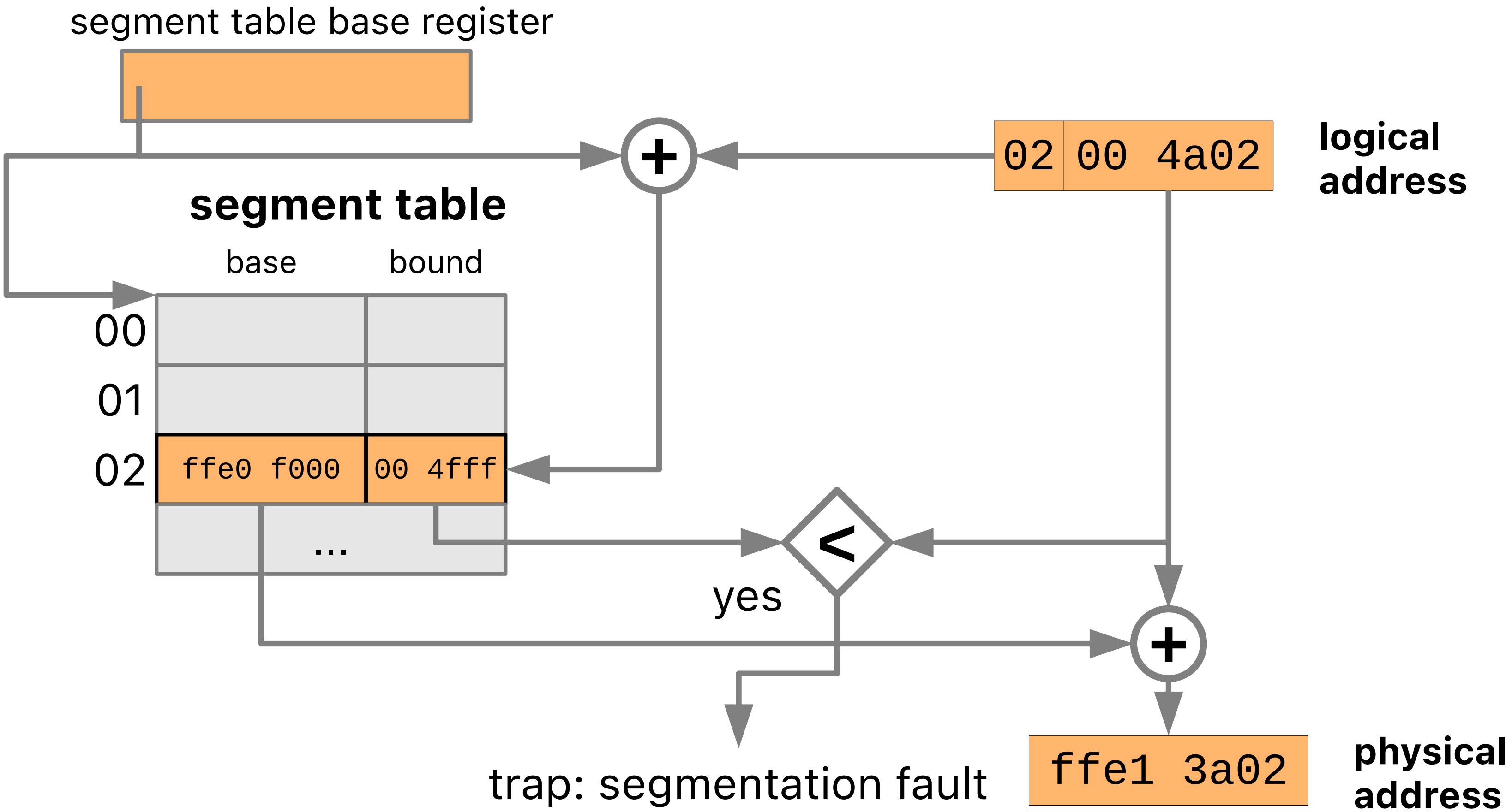
Memory Management – Segmentation

- realisation with translation table (per process)



Memory Management – Segmentation

- realisation with translation table (per process)



Memory Management – Segmentation

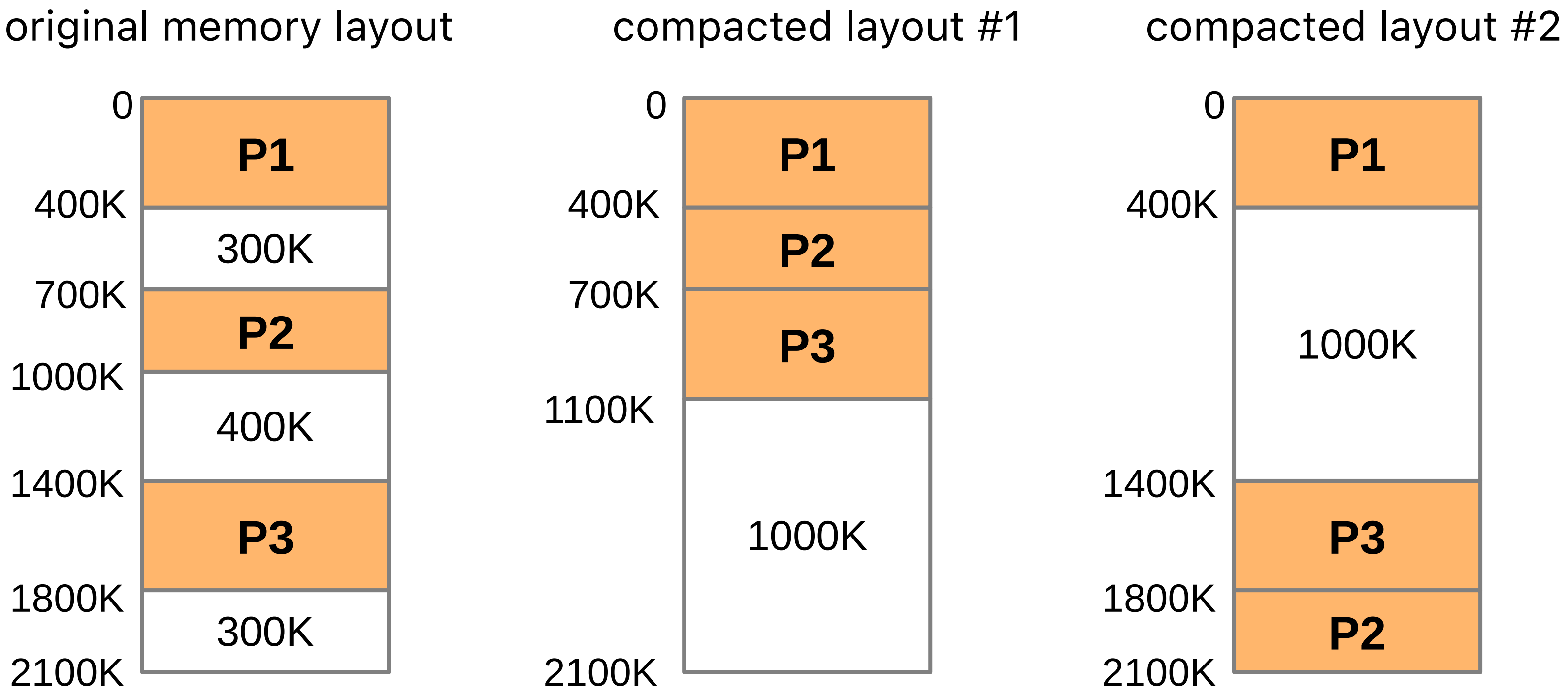
- hardware support is provided and implemented by the **memory management unit (MMU)**
- the MMU provides protection for segmentation violations
  - verification of access rights to **read**, **write** and **execute** commands depending on segments
  - **traps** indicate segmentation violations (→ segmentation 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



original memory layout

0
P1
400K
300K
700K
P2
1000K
400K
1400K
P3
1800K
300K
2100K

compacted layout #1

0
P1
400K
P2
700K
P3
1100K
1000K
2100K

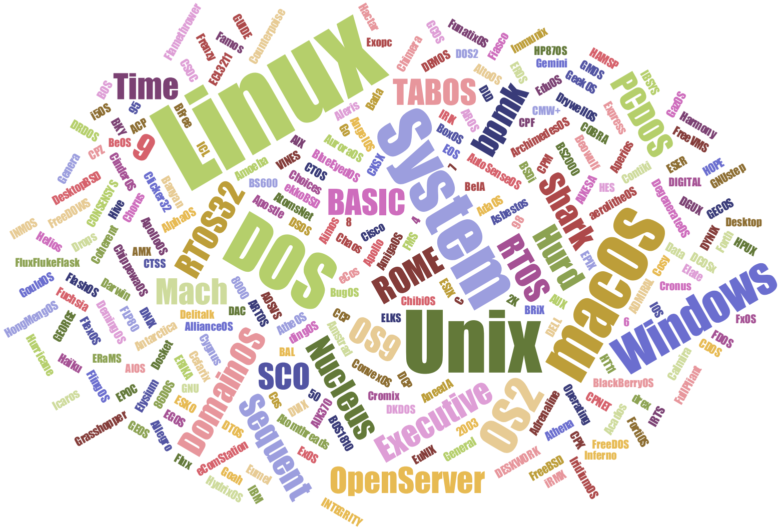
compacted layout #2

0
P1
400K
1000K
1400K
P3
1800K
P2
2100K

#1: move 700 K

#2: move 300 K

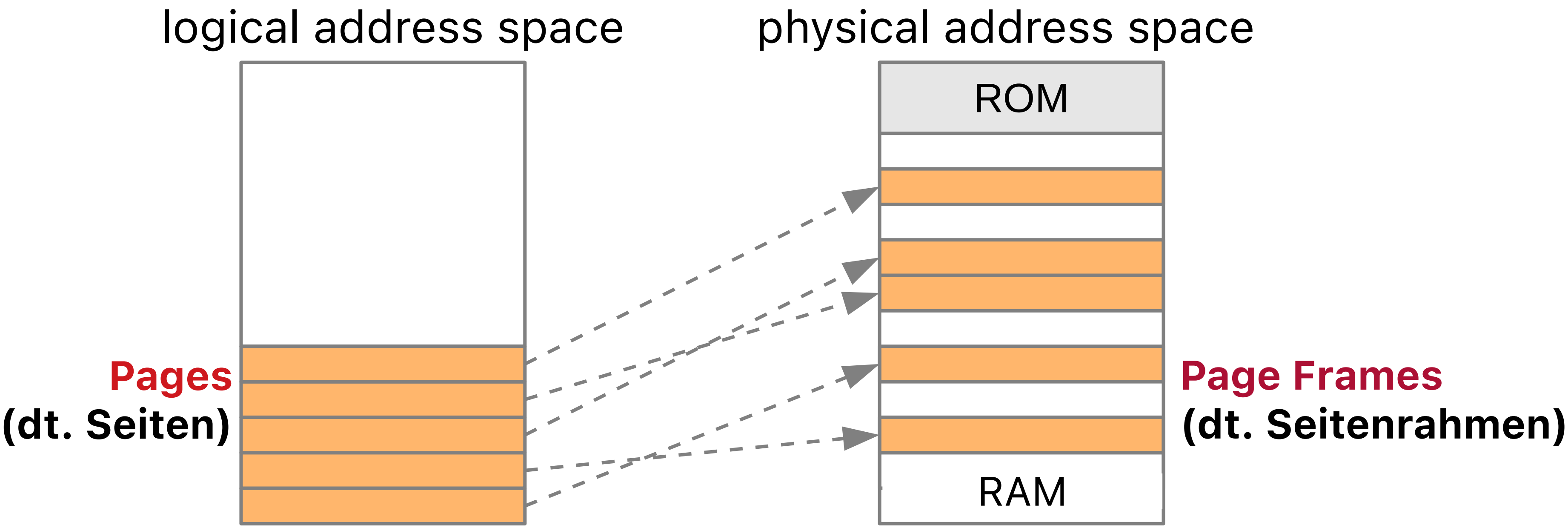
Agenda



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

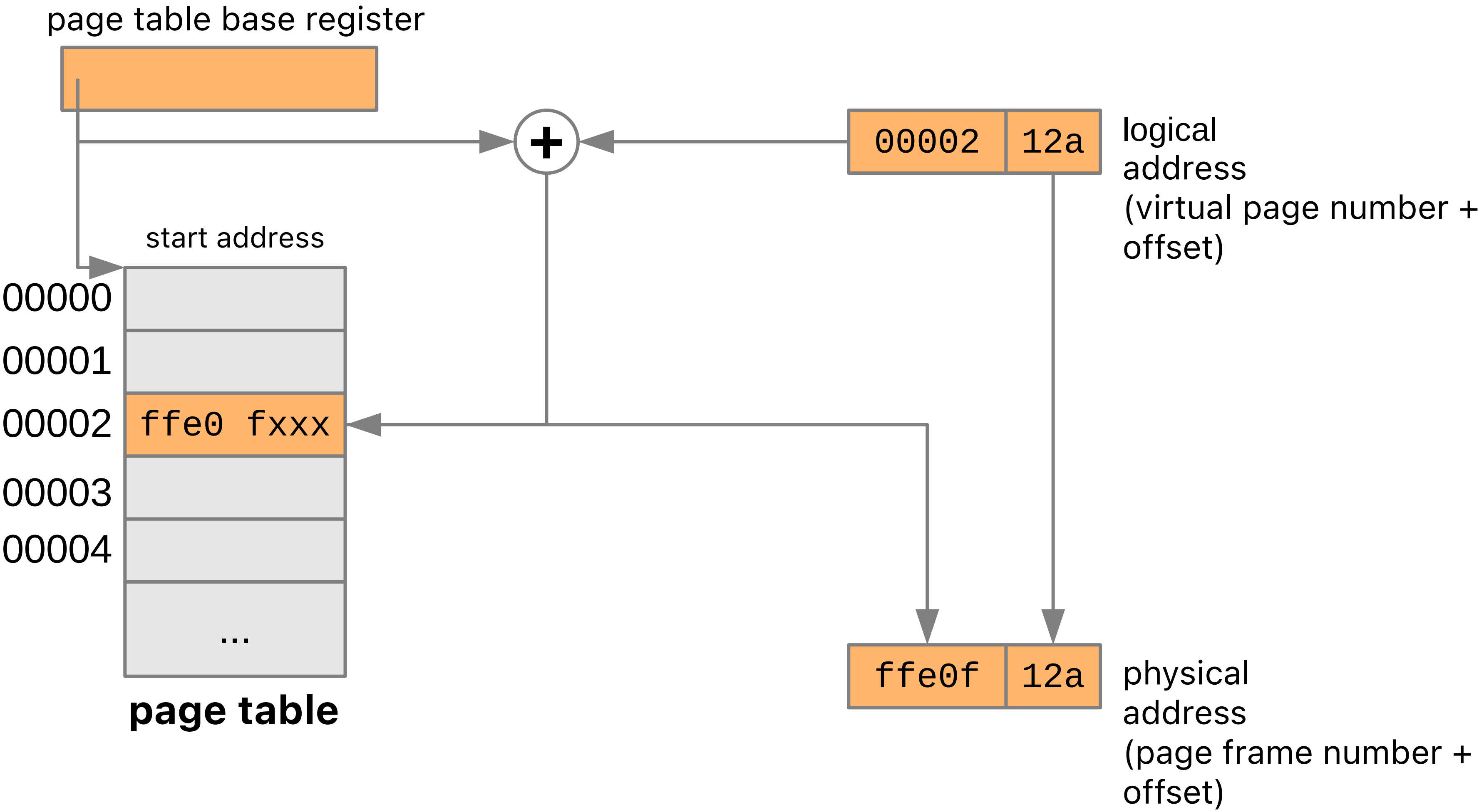
Memory Management – Paging

- 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)



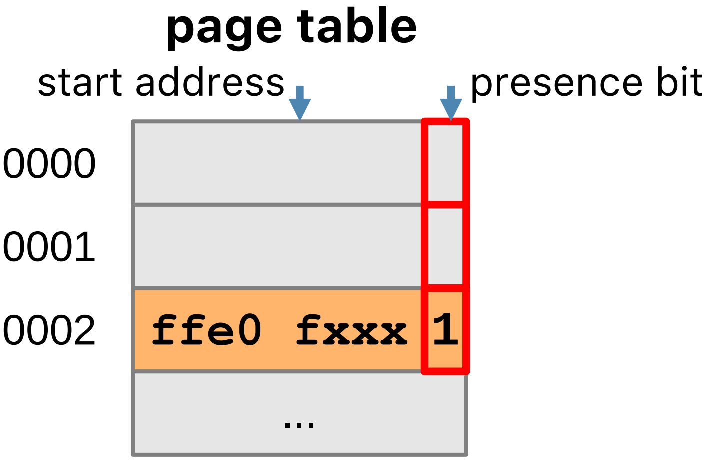
Paging – Problems

- 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)

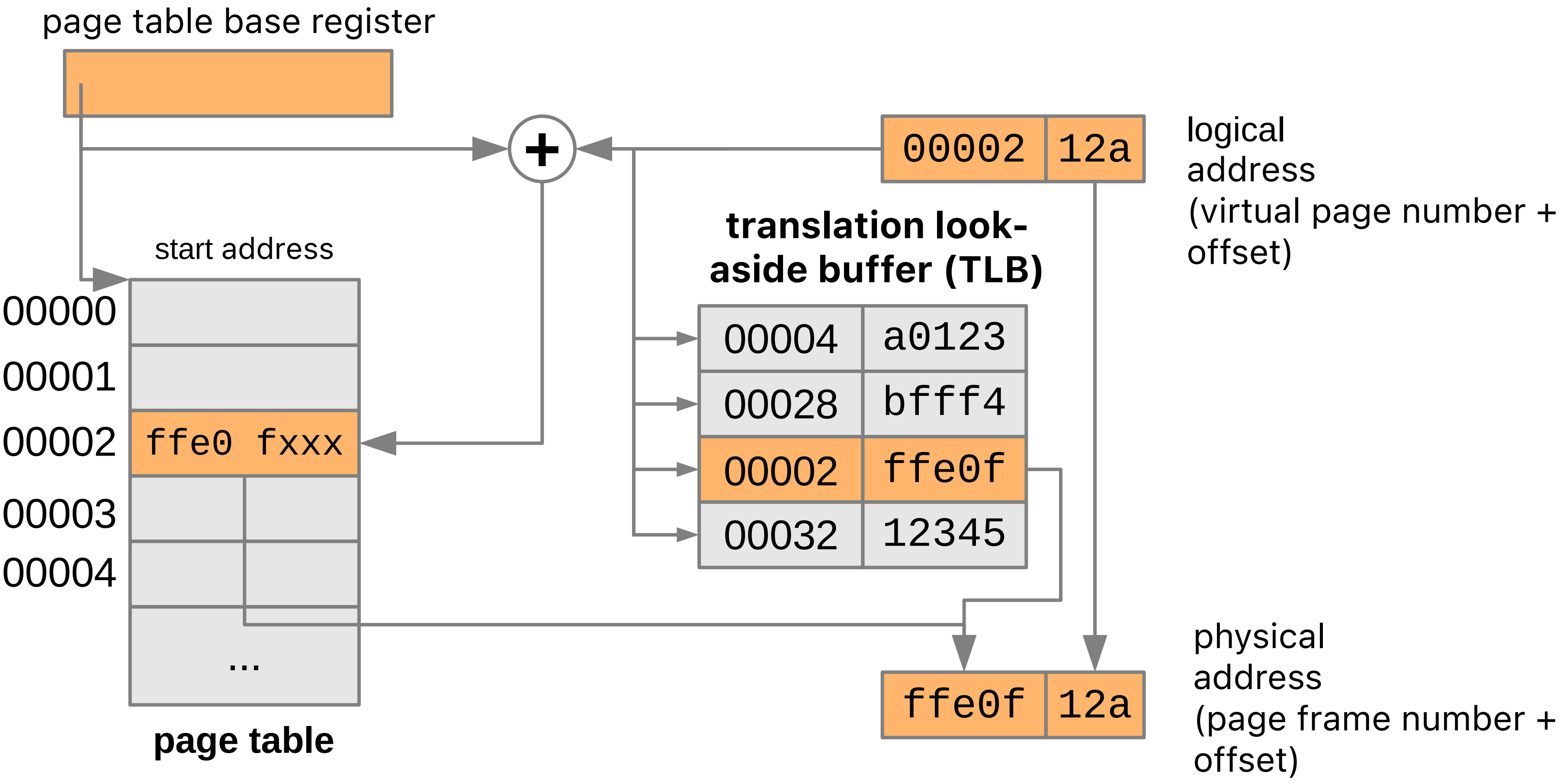


Paging – Discussion on Operational Costs

- 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)

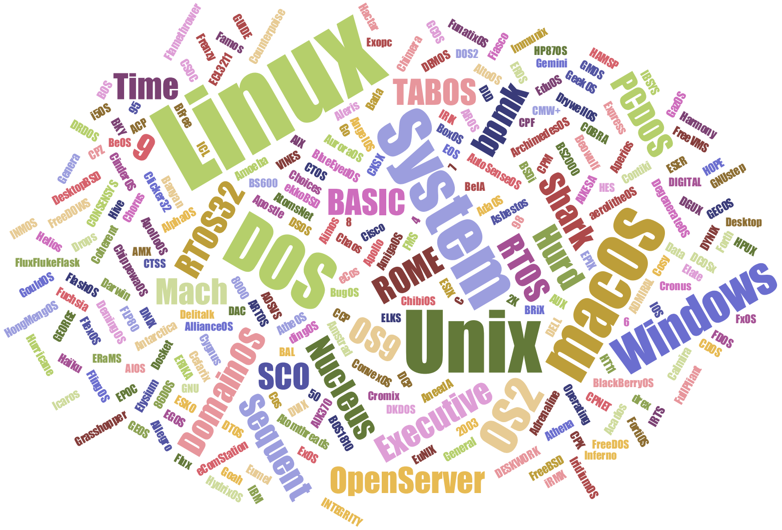
- fast register set is consulted before accessing the page table:



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



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

⏭ 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

[1] Avi Silberschatz, Peter Baer Galvin, Greg Gagne: *Operating System Concepts*, John Wiley & Sons, 2018.

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

[3] Wolfgang Schröder-Preikschat: *Grundlage von Betriebssystemen – Sachwortverzeichnis*, 2023.
`https://www4.cs.fau.de/~wosch/glossar.pdf`