NTNU | Norwegian University of Science and Technology

Operating Systems

Lecture 9: Memory management

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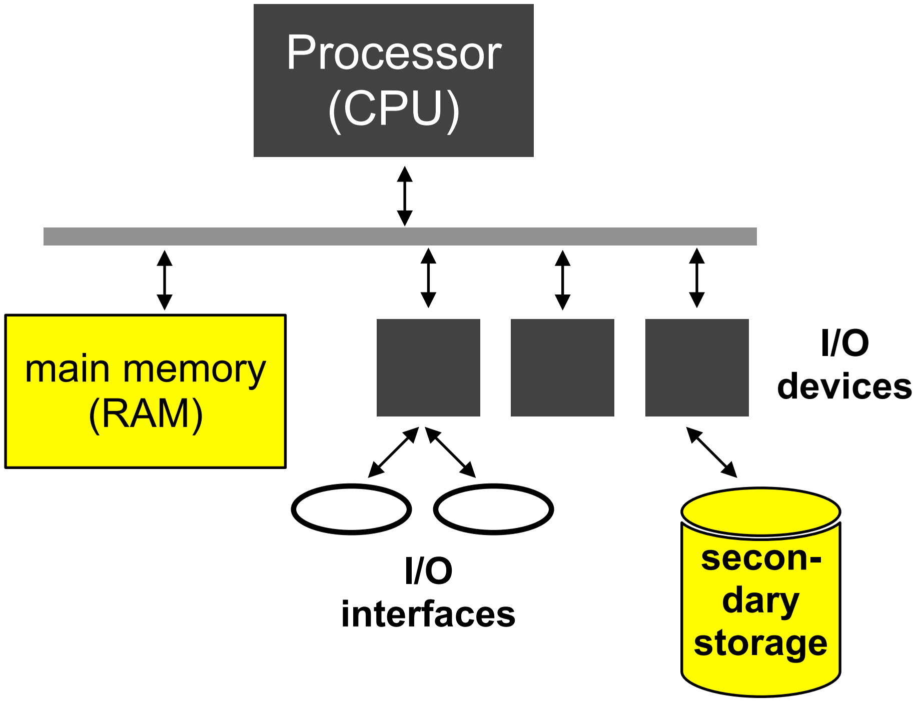
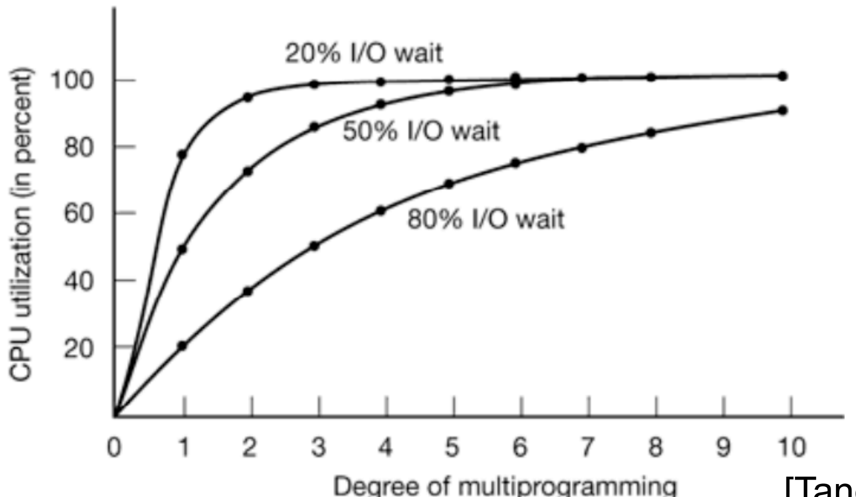
Resources (again)

- Tasks of an operating system:
  - **Administering the resources** of a computer
  - **Creating abstractions** that allow applications to easily and efficiently use these resources
- So far: **processes**
  - Concept to abstract from a real CPU
- Now: **memory**
  - Administration of main and background memory (secondary storage)



Multiprogramming (again)

- CPU load under the assumption of a given probability to wait for I/O:



Load $L = 1 - p^n$

[Tanenbaum: Modern Operating Systems]

➢ **Multiprogramming is essential to guarantee a high CPU utilization**

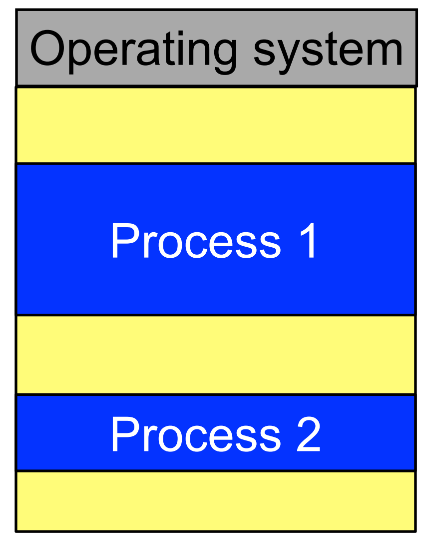
- When processes are started and terminated, memory has to be allocated and released dynamically!

Memory management requirements

- Multiple processes need main memory
  - Processes are located in different positions in main memory
  - Protection requirements:
    - Protect the OS from processes
    - Protect processes against accesses from other processes
  - Size of main memory may not suffice for all processes together

➢ OS has to know about free memory areas, administer and allocate them
  - ➢ *Swapping* of processes
  - ➢ *Relocation* of instructions in programs
  - ➢ Use hardware support

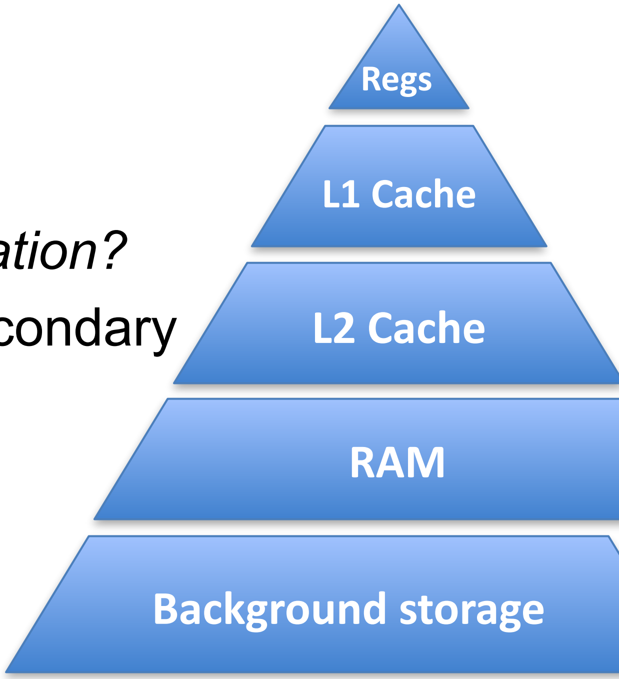
The OS and two applications in main memory



Basic policies and strategies

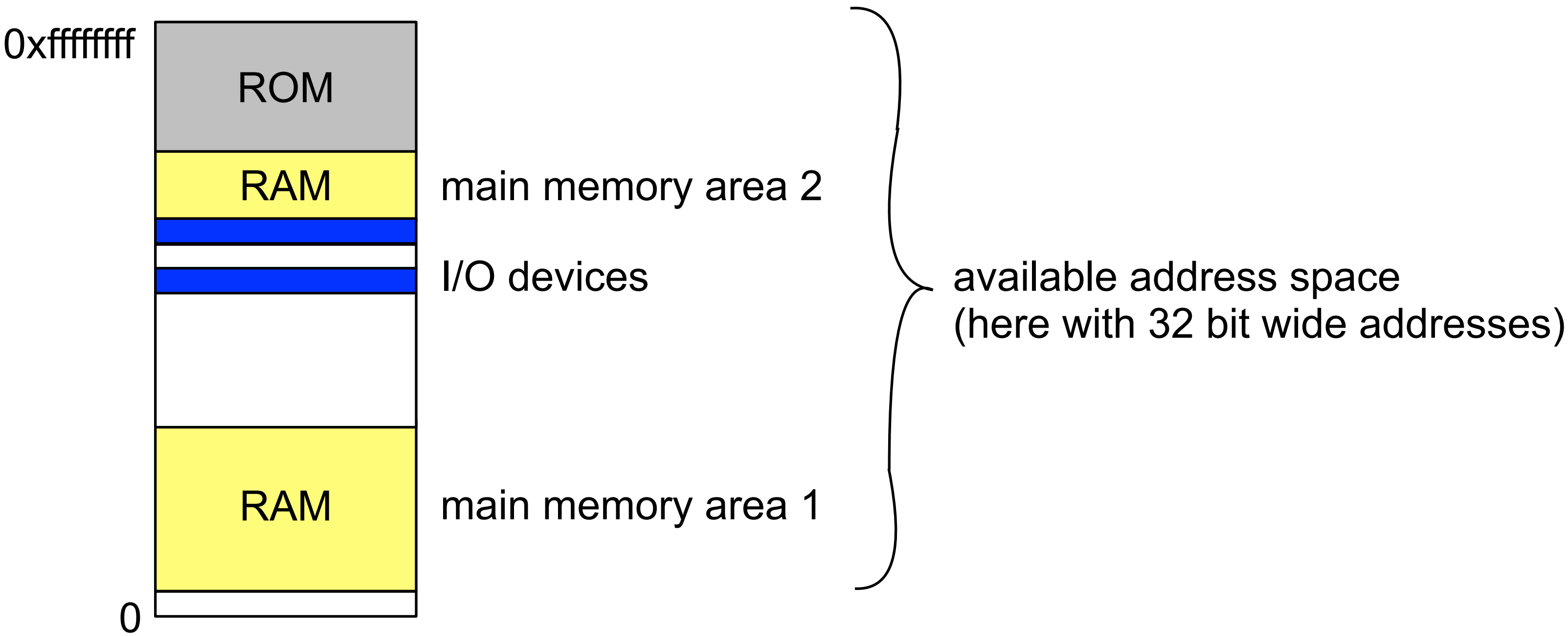
… on all levels of the memory hierarchy:

- **Placement policy:**
  - ***Which*** area of memory should be allocated?
    - The one with the largest/smallest *fragmentation?*
    - Not that relevant, since fragmentation is secondary
- **Fetch policy:**
  - ***When*** should we swap in memory contents?
    - On demand or predictive
- **Replacement policy:**
  - Which memory contents should be swapped out if the system is running out of free memory?
    - The oldest, least used one
    - The one that is used for the longest amount of time



Memory allocation: problem

- Available memory



Memory map of a simple 32 bit system

Memory allocation: problem

The available main memory is used by…

- User processes
  - Program code (text)
  - Program data (data)
  - Dynamic memory allocations (stack, heap)
- Operating system
  - Operating system code and data
  - Process control blocks
  - Data buffers for input/output
  - ...
- Memory allocation is necessary!

Static memory allocation

- Idea:
  use fixed memory areas for the OS and for user processes

- **Problems**
  - Limited degree of multiprogramming
  - Limitation of other resources
    e.g. I/O bandwidth due to buffers that are too small
  - Unused OS memory cannot be used by application processes (and vice versa)

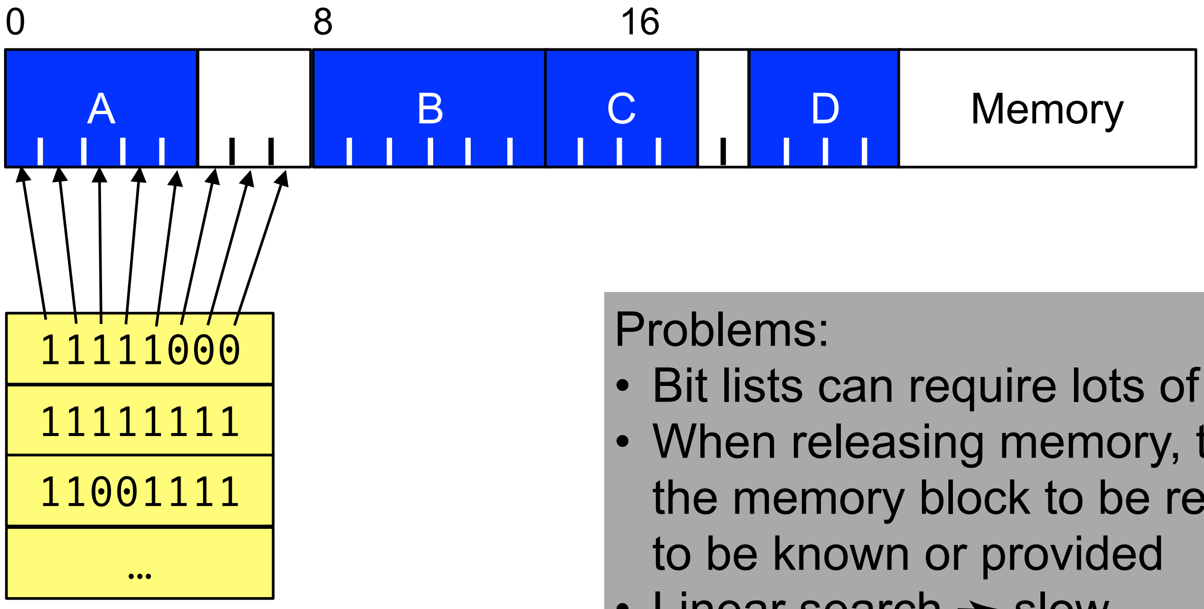
➢ Use dynamic memory allocation

Dynamic memory allocation

- **Segments**
  - *contiguous* area of memory
    (memory area with successive addresses)
- **Allocation** and **release** of segments
- All the segments that are part of a program we have seen already:
  - text segment(s)
  - data segment(s)
  - stack segment (local variables, parameters, return addresses, ...)
- Search for suitable memory areas for allocation
  - especially when a program is started
- **Placement policies required**
  - especially important: management of free memory

Memory allocation

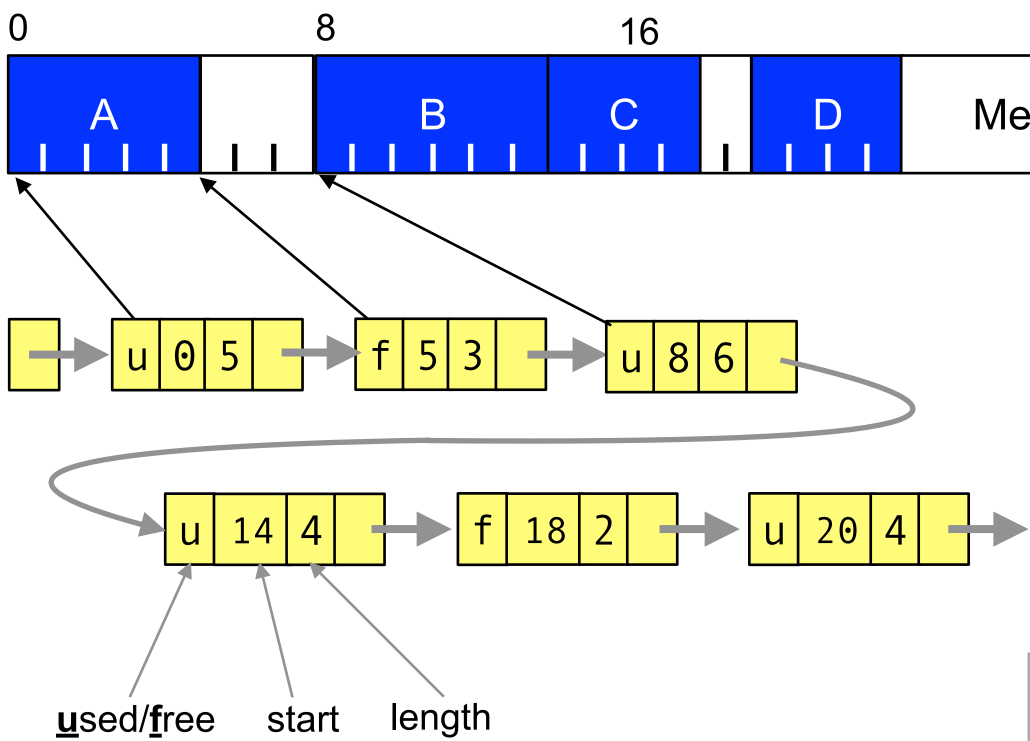
- Free (sometimes also allocated) segments of main memory have to be represented
- Simple approach: **Bit lists**



Problems:
- Bit lists can require lots of memory
- When releasing memory, the size of the memory block to be released has to be known or provided
- Linear search ➛ slow

Memory allocation (2)

- **Linked list**

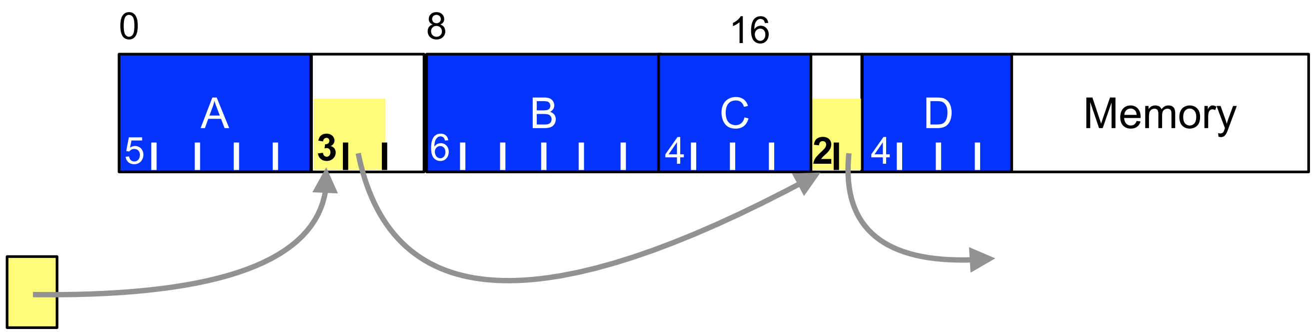


Representation of used and free segments

Problem:
- Memory required for the list has to be allocated (dynamically)

Memory allocation (3)

- **Linked list in *free memory***

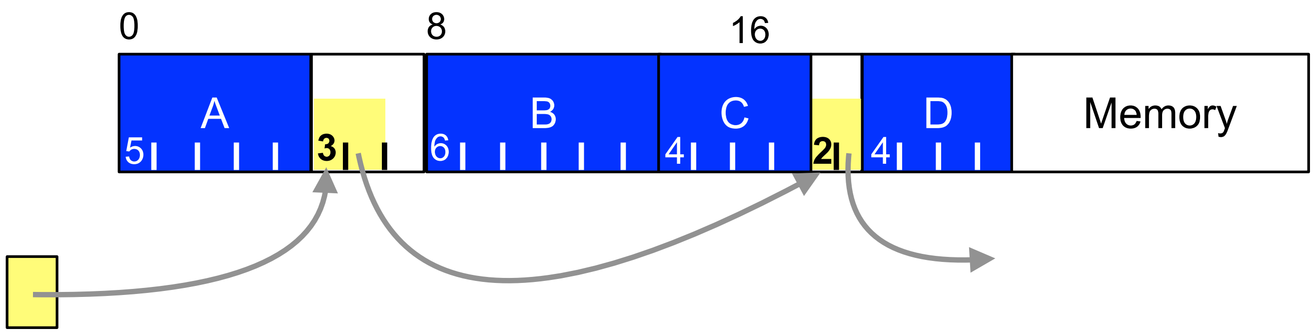


A minimum gap size has to be guaranteed to store the length of and the pointer to the next free gap!

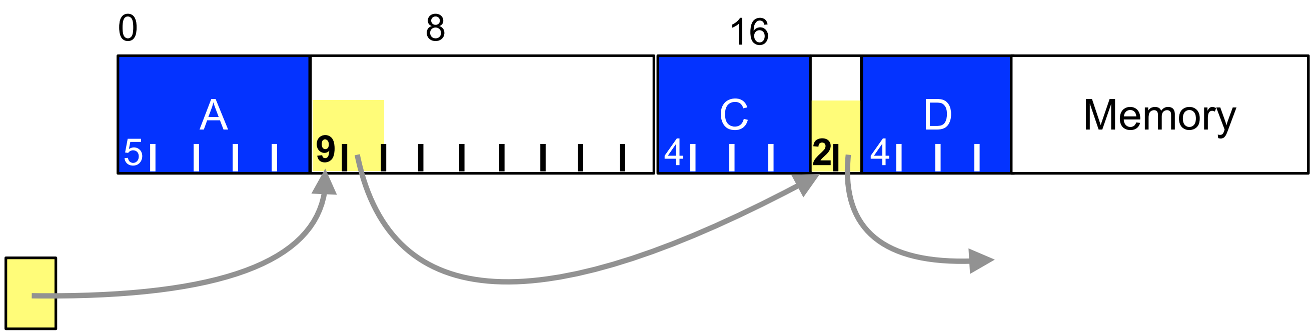
Problems:
- To increase efficiency, backwards links might be required in addition
- This representation is dependent on the allocation strategy

Releasing memory

- **Combine the gaps**



After releasing B:



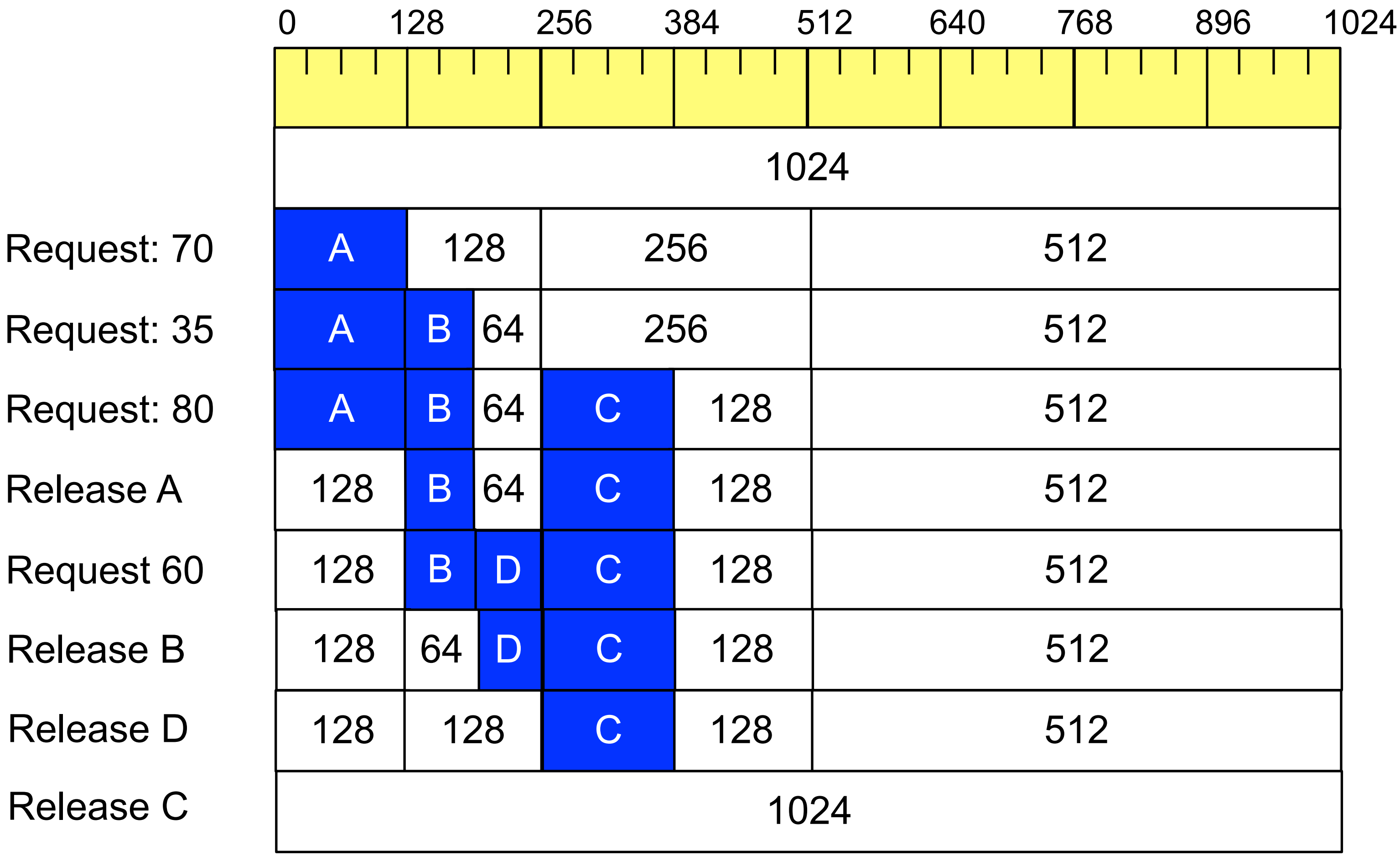
Placement strategies

…based on different sorting policies for the list of gaps:

- **First Fit** (sorted after memory address)
  - use the first fitting gap
- **Rotating First Fit / Next Fit** (sorted after memory address)
  - like first fit, but start with the most recently allocated gap
  - avoids the generation of a large number of small gaps at the beginning of the list (which happens with first fit)
- **Best Fit** (sorted after gap size – smallest first)
  - find the smallest fitting gap
- **Worst Fit** (sorted after gap size – largest first)
  - find the largest fitting gap
- **Problems:**
  - gaps that are too small, *fragmentation*

Placement strategies (2)

- **Buddy method:** split memory dynamically into areas of a size 2^n



Efficient representation of gaps and efficient algorithms to handle allocation

Discussion: fragmentation

- **External fragmentation**
  - Allocations creates *memory fragments* outside of the allocated memory areas which cannot be used
  - Problem with all list based strategies, e.g. first fit, best fit, ...

- **Internal fragmentation**
  - Unused memory *inside of* allocated memory areas
  - Problem e.g. with the buddy allocator
    - since request sizes are rounded up to the next power of 2

Use of the different methods

- In the operating system (kernel) itself
  - Management of system memory
  - Allocation of memory to processes and the operating system itself

e.g. Buddy allocator in Linux

- Inside of processes
  - Management of heap memory
  - Enables dynamic allocation of memory areas by the process (using the malloc und free libc functions)

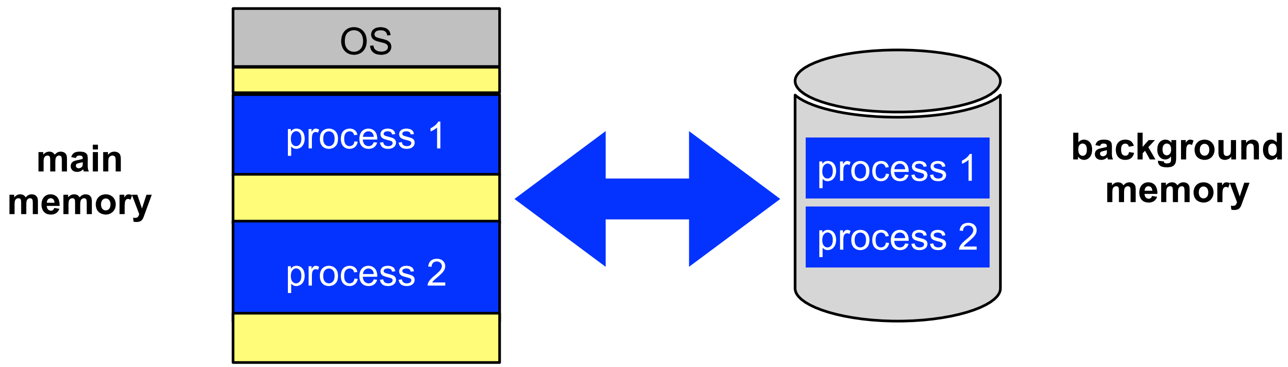
typically using linked lists

- Areas of secondary storage
  - Management of certain sections of secondary memory
    - e.g. the area used for process swapping (swap space)

often using bitmaps

Multiprogramming: swapping

- Segments of a process are *swapped out* to background memory and *released* in main memory
  - e.g. if I/O waiting times hinder a process from running
- Segments are *swapped in* back into main memory when the waiting time ends



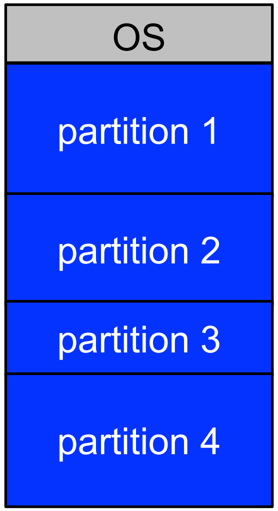
- Large amount of time required for swapping in and out
  - Latency of the disk (e.g. positioning of a read/write head of a hard disk, not a big problem with SSDs)
  - Transfer time

Swapping (2)

- Addresses in processes are usually *linked statically*
  - Can only be swapped into the *same location in main memory*
  - Collisions with new segments allocated in memory after the process was swapped out

- Possible solution: *partitioning* of main memory
  - Only one process per partition
  - Swapping in into the same partition as before
  - Memory cannot be used *optimally*

- Better approach:
  Dynamic allocation and ***program relocation***



Address linking and relocation

- **Problem**: Machine instructions use addresses
  - e.g. a jump instruction that changes control flow into a function
  - or a load instruction to read a variable value from the data segment

Different approaches to link the address used as the operand of an instruction:

- **Absolute linking** (at compile/link time)
  - Addresses are fixed
  - The program can only execute correctly at a certain location in memory
- **Static linking** (at load time)
  - Absolute addresses are adapted (*relocated*) when a program is loaded (started)
  - Relocation information has to be provided by the compiler/assembler
- **Dynamic linking** (at execution time)
  - Code accesses operands only *indirectly*
  - The program can be relocated in memory at any time
  - Resulting programs are slightly larger and slower

Address linking and relocation (2)

- **Translation process**
  (creation of relocation information)

test.c

C program

```
int main() {
  exit (0);
}
```

test.s

Assembler

```
main:
  pushl %ebp
  movl %esp,%ebp
  pushl $0
  call exit
  addl $4, %esp
  popl %ebp
  ret
```

test.o

Linker module (obj. file)

```
0000 55
0001 89E5
0003 6A00
0005 E800000000
000a 83C404
000d 89EC
000f 5D
0010 C3

main: 0

0006: exit ADDR32
```

Created during compilation

Address linking and relocation (3)

- **Linking and loading**

test.o

Linker module

```
0000 55
0001 89E5
0003 6A00
0005 E800000000
000a 83C404
000d 89EC
000f 5D
0010 C3

main: 0

0006: exit ADDR32
```

Replace address of exit

test

Loader module

```
…
0030 55
0031 89E5
0033 6A00
0035 E848010000
003a 83C404
003d 89EC
003f 5D
0040 C3
…

0036: ADDR32 TXT
```

=0x0148

Replace address *relative* to the text segment

process

Memory contents

```
…
2130 55
2131 89E5
2133 6A00
2135 E848220000
213a 83C404
213d 89EC
213f 5D
2140 C3
…
```

=0x2248

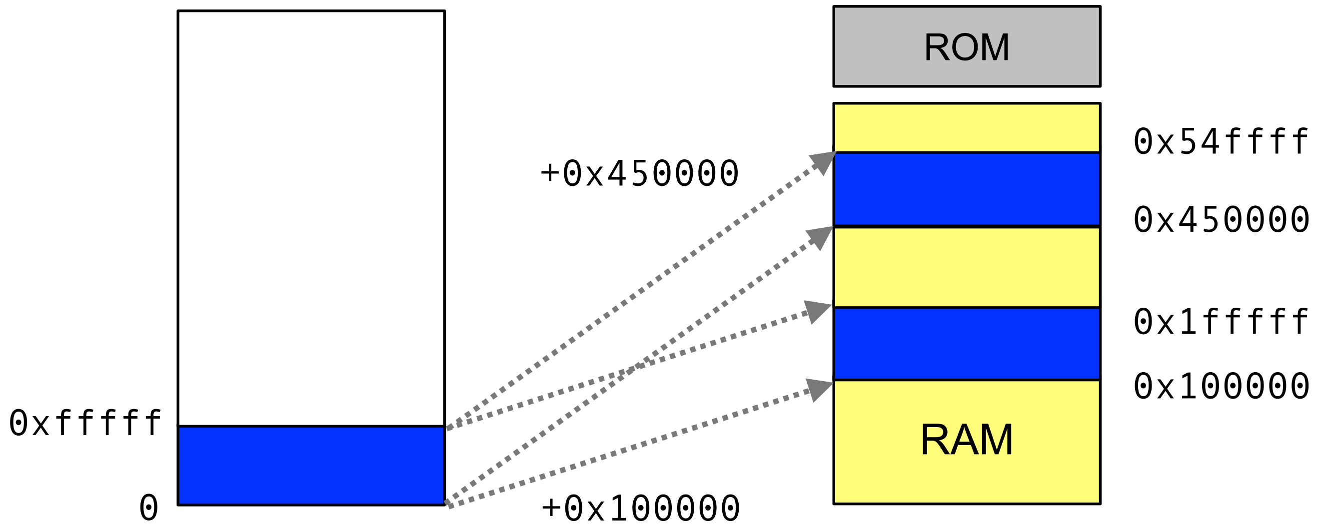
Address now is *absolute*
Text segment at 0x2100

Address linking and relocation (4)

- Relocation information in the linker module (object file)
  - allows the linking of modules into arbitrary programs
- Relocation information in the loader module
  - allows loading of the program at arbitrary locations in memory
  - absolute addresses are generated only at load time
- Dynamic linking with compiler support
  - Program does not use absolute addresses and can thus always be loaded to arbitrary memory locations
    - *position independent code* (PIC)
- Dynamic linking with MMU support
  - Mapping from “logical” to “physical“ addresses
    - Relocation at link time is sufficient
      (except for *shared libraries*)

Segmentation

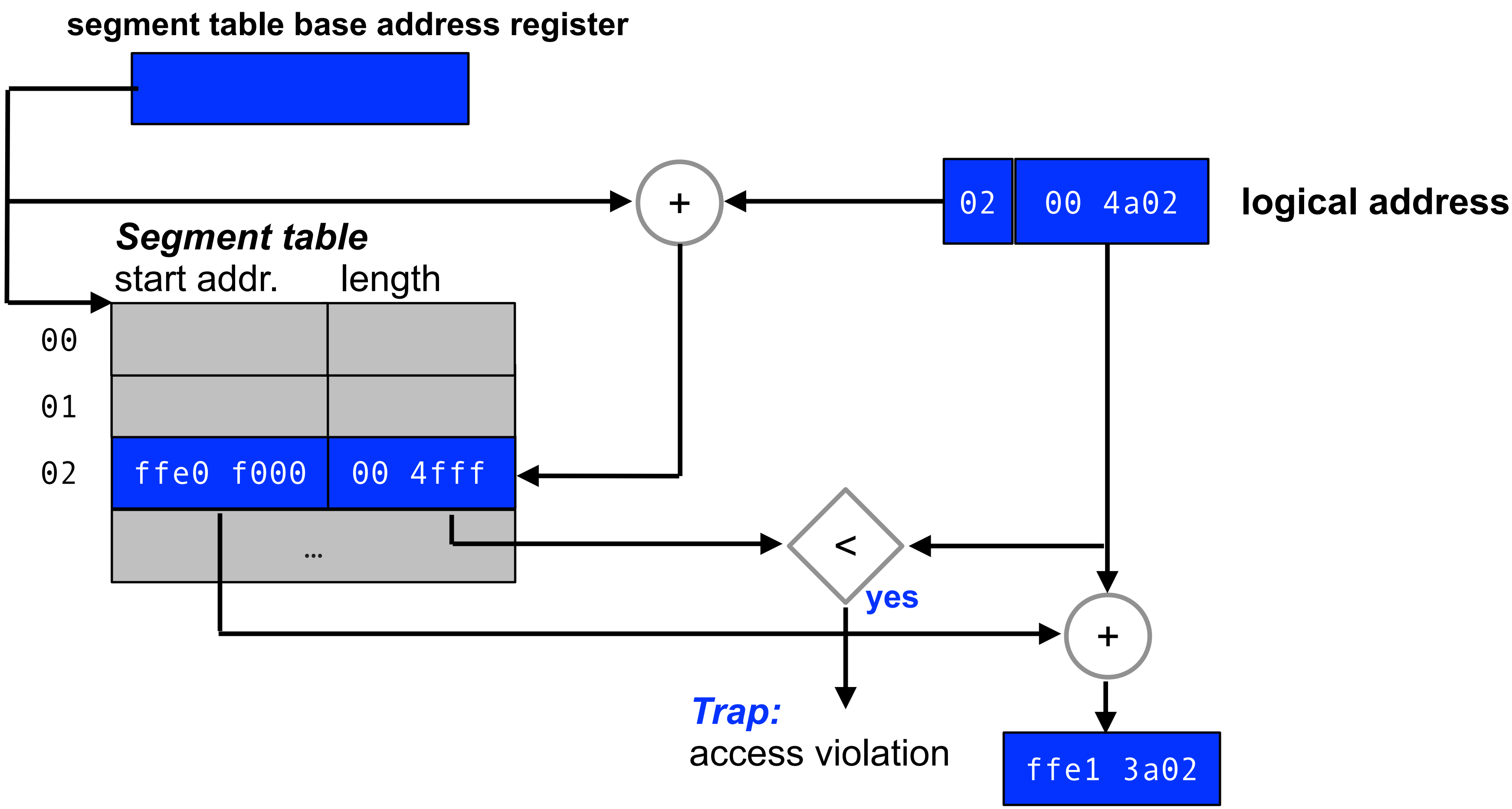
- **Hardware support: map *logical* to *physical* addresses**



The segment in the logical address space can be located at an arbitrary position in the physical address space.
The OS controls where a segment is located in physical memory.

Segmentation (2)

- **Using a translation table** (per process)



Segmentation (3)

- Hardware component translating addresses: **MMU** (Memory Management Unit)
- Protects against overstepping the segment limits
  - MMU checks read/write/execute permissions
  - *Trap* indicates a *violation* (a process attempts to access non permitted memory location)
  - Programs and operating system are protected against each other
- Process switching by exchanging the segment base
  - each process has its own translation table
- Easier swapping
  - after swapping a process into an arbitrary memory location, only the translation table has to be modified
- Shared segments are possible
  - Instruction (text) segments
  - Data segments (*shared memory*)

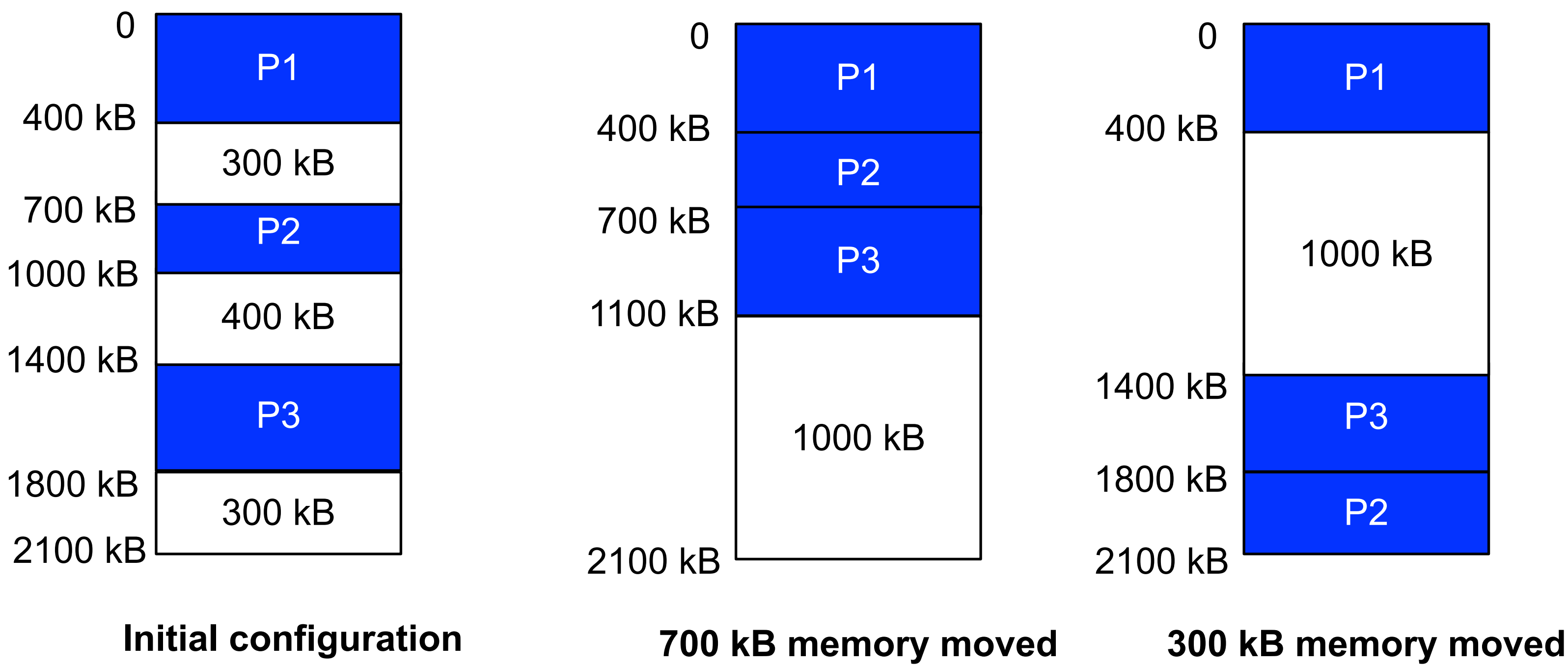
Segmentation (4)

Problems...

- **Fragmentation** of main memory due to frequent swapping or starting/ termination of processes
  - This results in small unusable gaps: *external fragmentation*
- **Compacting** helps
  - Segments are moved to close gaps
  - Segment table is modified accordingly
  - Time consuming…
- **Long running I/O operations** required for swapping
  - Not all parts of a segment are used with the same frequency

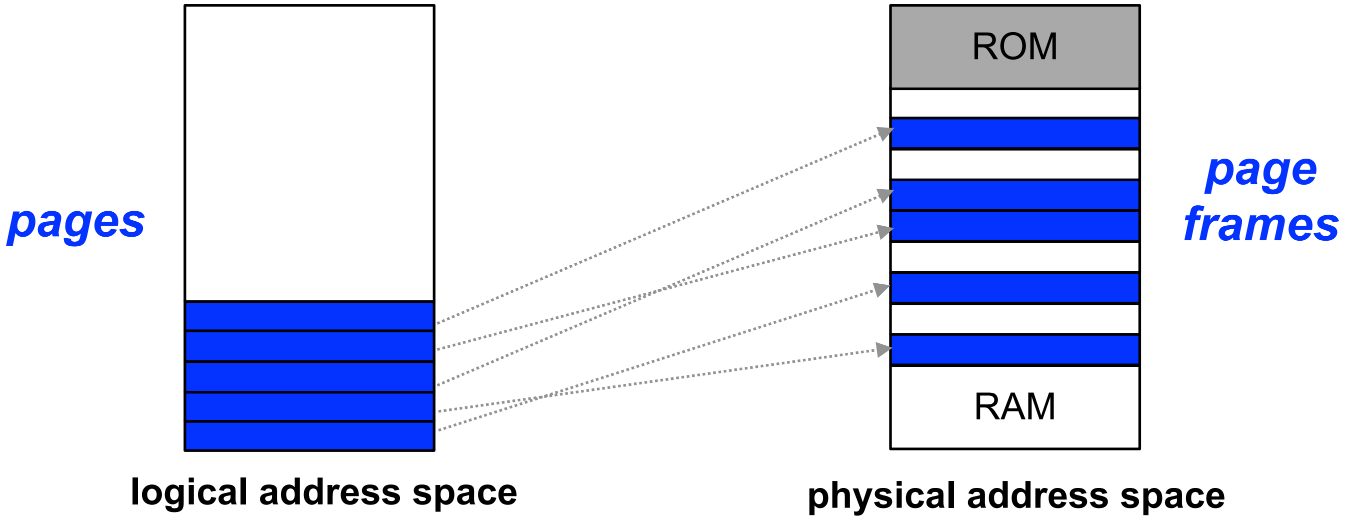
Compaction

- Moving of segments
  - Creates fewer but larger gaps
  - Reduced fragmentation
  - Operation with large overhead
    - Specific overhead depends on the size of the segments that are moved



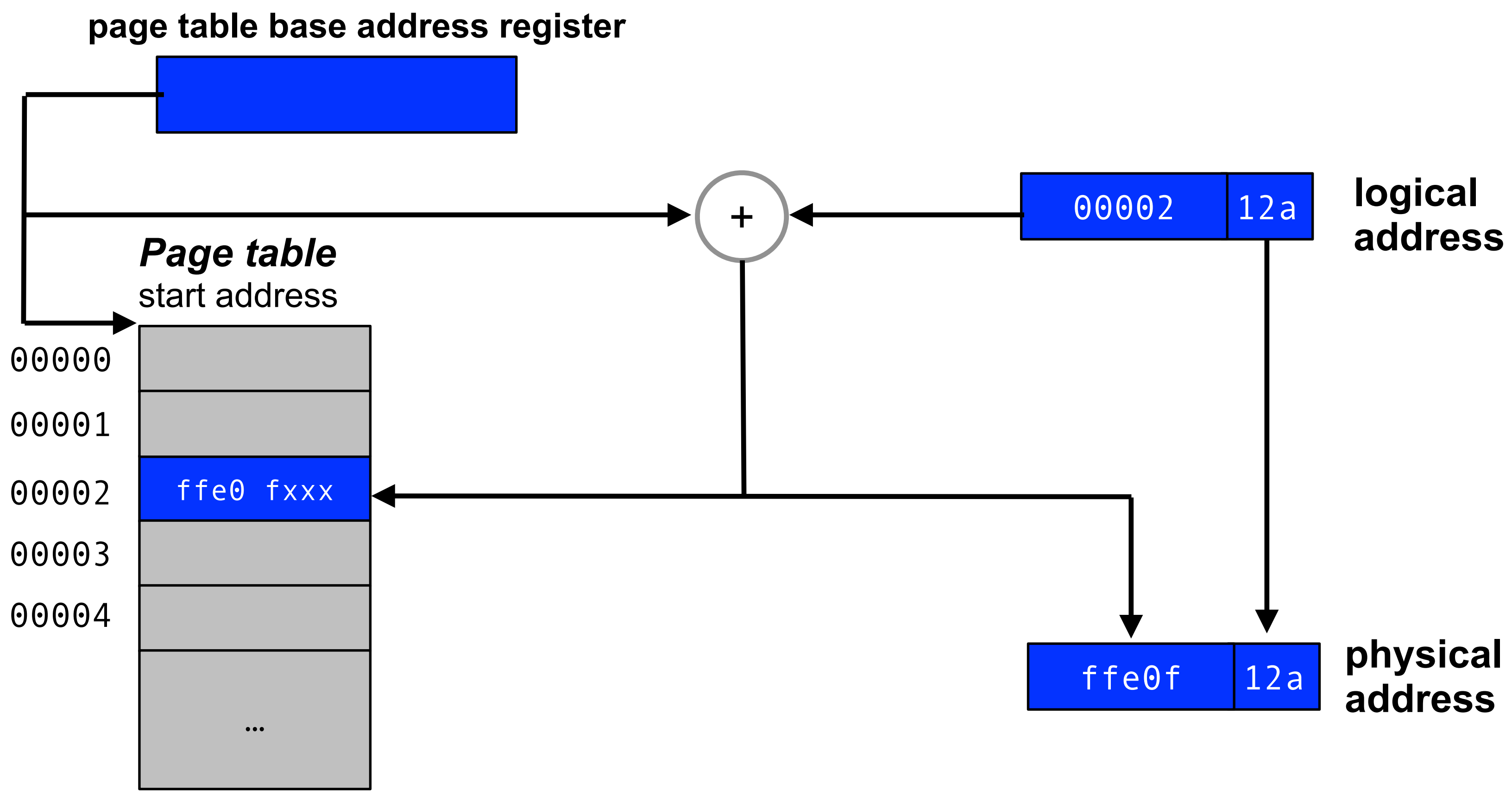
Paging

- Logical address space is split into *pages* of identical size
  - Pages can be located at arbitrary positions in the physical memory address space
  - Solves the fragmentation problem
  - no compaction necessary
  - Simplified memory allocation and swapping



MMU with page table

- A table is used to translate *page addresses* into *page frame addresses*

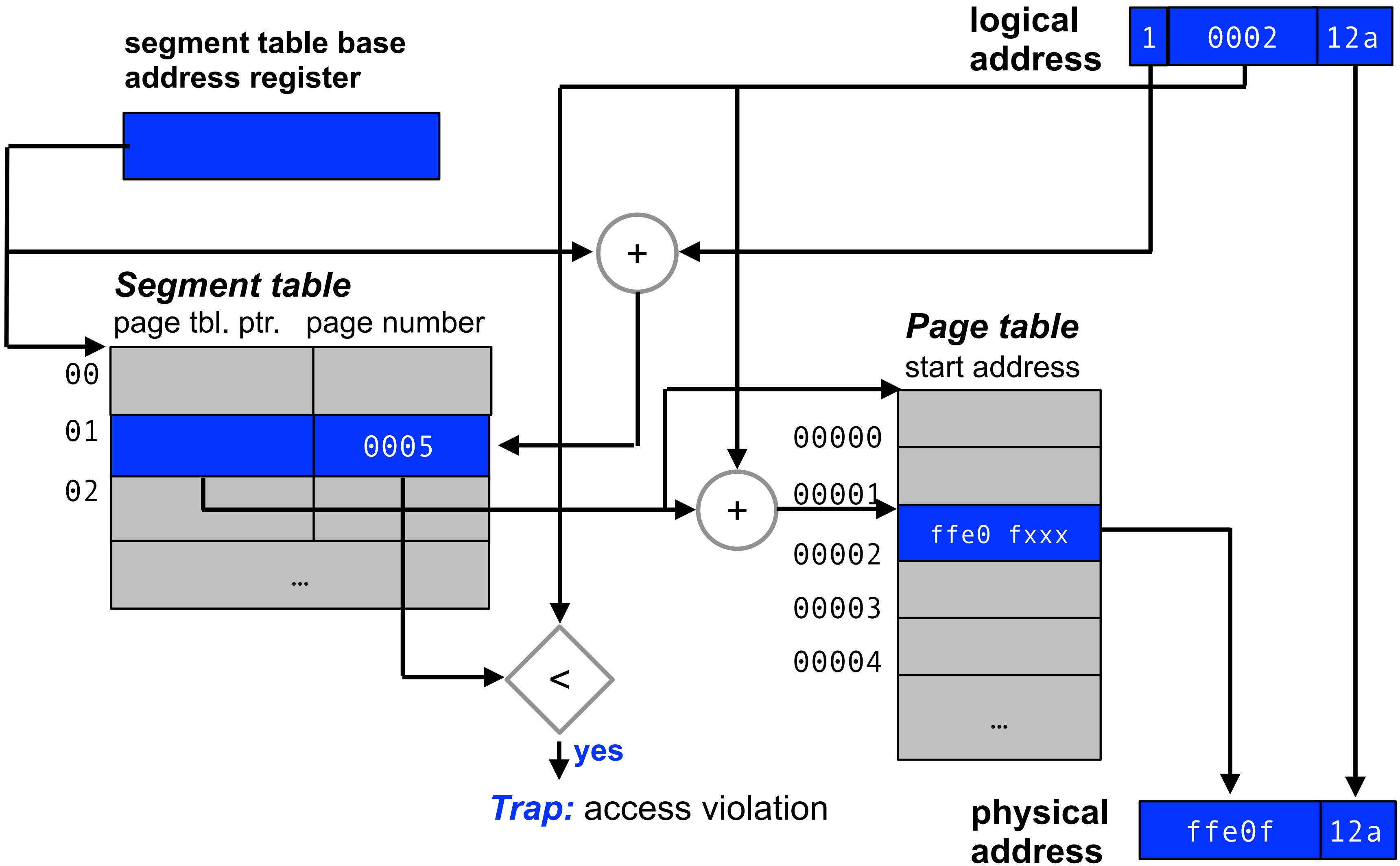


MMU with page table (2)

- Page-based addressing creates ***internal*** fragmentation
  - The last page is often not used completely
- Page size
  - small pages reduce internal fragmentation, but increase the size of the page table (and vice versa)
  - common page sizes: 512 bytes — 8192 bytes
- Page tables are large and have to be kept in main memory
- Large number of implicit page accesses required to map an address
- Only one “segment” per context
  - Makes the “appropriate” use of memory difficult to control
    - e.g. ensuring push/pop only on “stack”, execution only of “text”

➢ **Combine paging with segmentation**

Segmentation and page addressing



Segmentation and page addressing (2)

- This requires even more implicit memory accesses
- Large tables in main memory

- Mixup of the different concepts

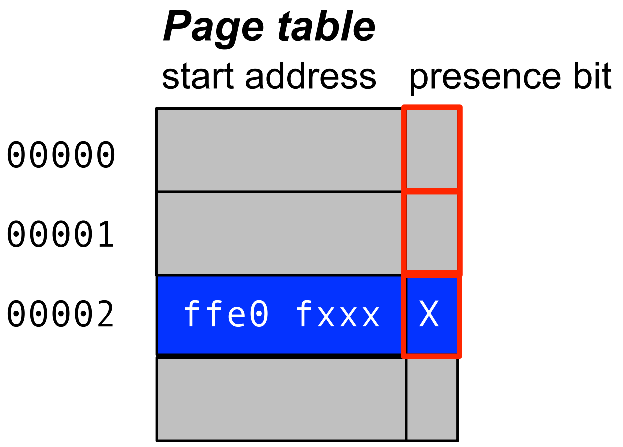
- Still swapping of complete segments

➢ **Multi-level page addressing with paging**

Paging

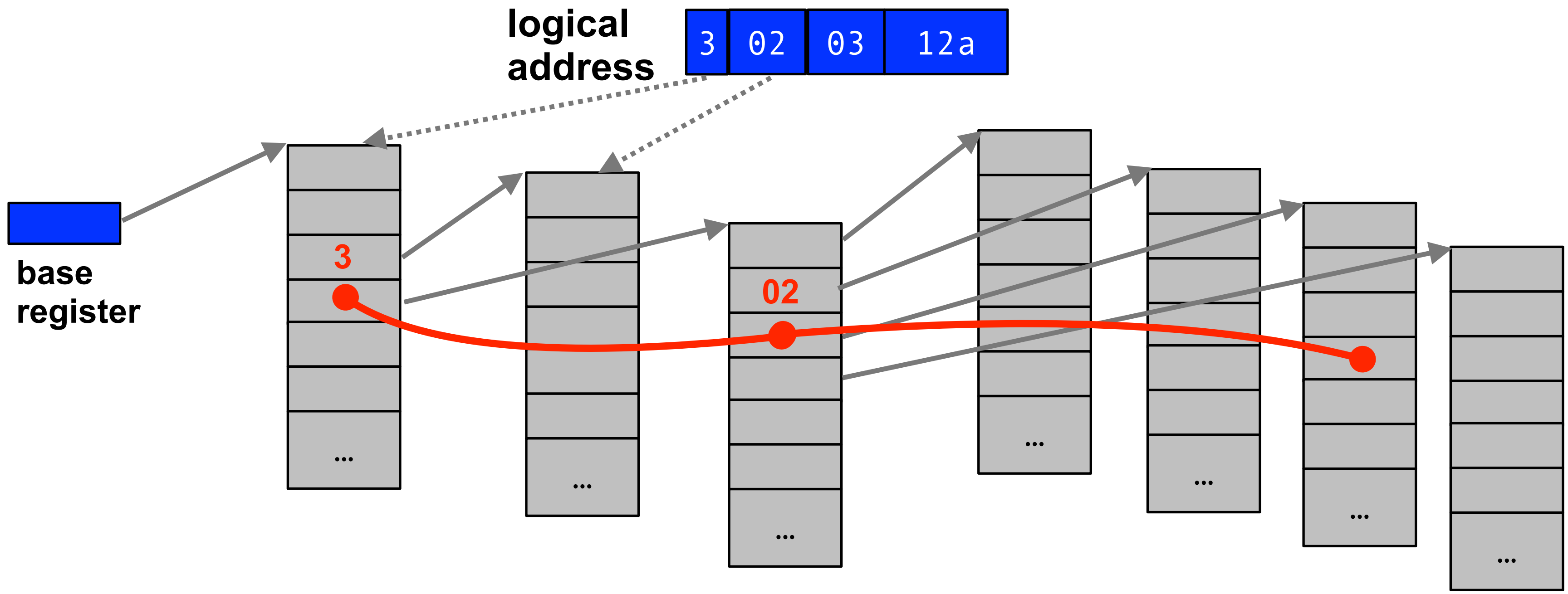
- Swapping complete segments is not necessary
  - Single pages can now be swapped (***paged***)

- Hardware support
  - If the ***presence bit*** is *set*, nothing changes
  - If the ***presence bit*** is *cleared*, a *trap* is invoked (***page fault***)
  - The *trap handler* (part of the OS) can now initiate the loading of the page from background storage (this requires hardware support in the CPU)



Multi-level page addressing

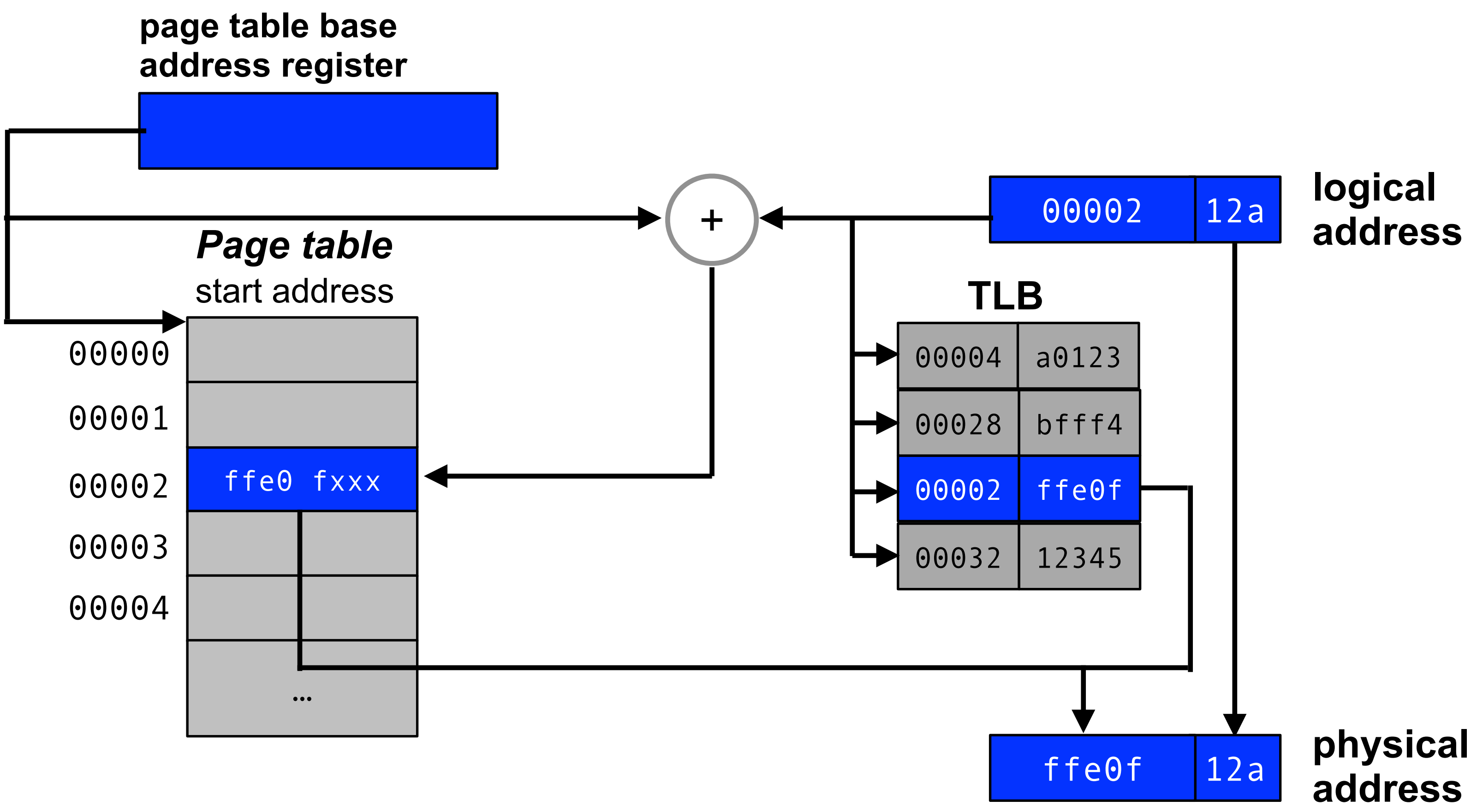
- Example: two-level page addressing



- Presence bit also for all entries in higher levels
  - This enables the swapping of page tables
  - Tables can be created at access time (*on demand*) – saves memory!
- However: even more implicit memory accesses required

Translation lookaside buffer (TLB)

- Fast cache which is consulted before a (possible) lookup in the page table:



Translation lookaside buffer (2)

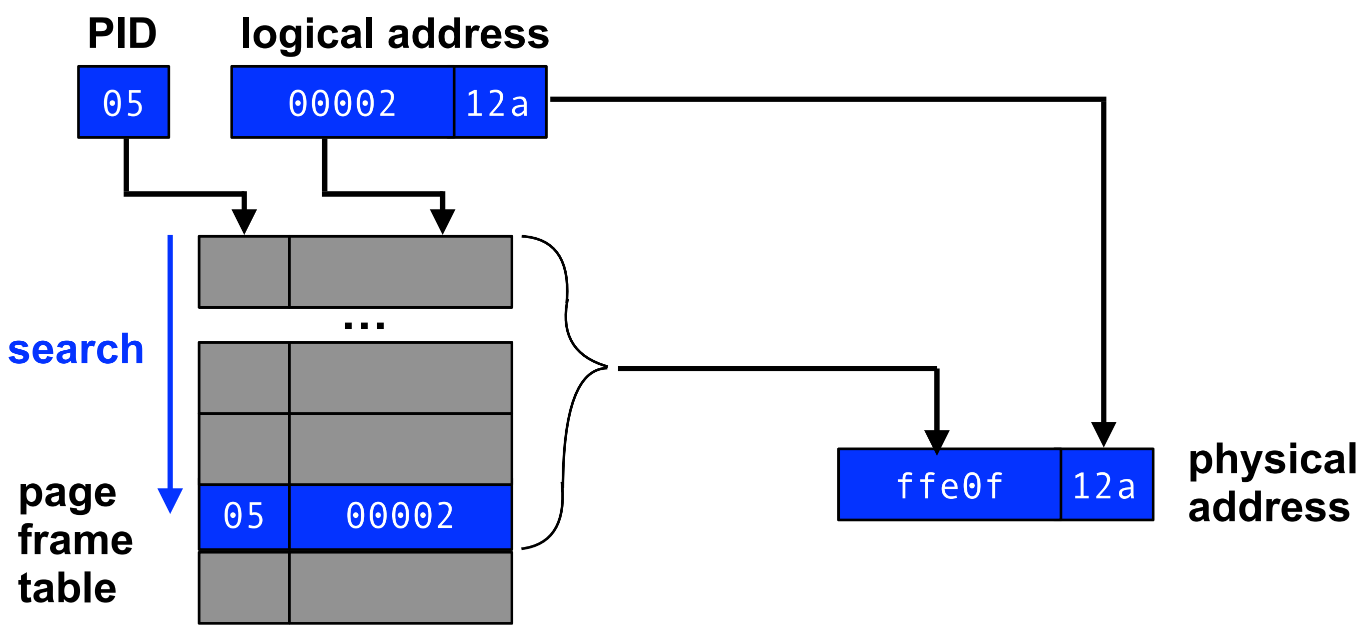
- Fast access to page address mapping, the information is contained in the (fully associative) TLB memory
  - no implicit page accesses required
- TLB has to be *flushed* when the OS switches context
- If a page not contained in the TLB is accessed, the related access information is entered into the TLB
  - An old TLB entry has to be selected to be replaced by the new one

- TLB sizes:
  - Intel Core i7: 512 entries, page size 4 kB
  - UltraSPARC T2: data TLB = 128, Code TLB = 64, page size 8 kB
  - Larger TLBs are currently not implementable due to timing and cost considerations

Inverted page tables

- For large logical address spaces (e.g. 64 bit addresses):
  - Classical page tables are very large ***or***
  - Large number of address translation levels
  - Page tables are often only sparsely populated

➛ **Inverted Page Tables**



Inverted page tables (2)

- **Advantages**
  - required little memory space to store address mappings
  - table can always be kept in main memory
- **Disadvantages**
  - sharing of page frames is difficult to implement
  - process-local data structures are used for pages that are swapped out
  - Lookups in the page table have large overhead
    - Use of *associative memories* and *hash functions*

- Despite these disadvantages, many 64 bit processors use this approach to address translation:
  - Sun UltraSparc, IBM PowerPC, intel Itanium (IA-64), (DEC Alpha), ...

Conclusions

- The OS has to work in close cooperation with the hardware to enable efficient memory management
  - Segmentation and/or page-based addressing
  - The implicit indirection of memory accesses allows to arbitrarily move code and data of running processes under the control of the OS (at page size granularity)
- Additional strategic decisions have to be taken
  - Placement strategy (first fit, best fit, buddy, ...)
    - These differ with regard to fragmentation and the required overhead for allocation and release
    - Selection of an appropriate strategy depends on the expected application profile
  - When swapping segments or pages:
    - Loading strategy
    - Replacement strategy ⇒ *more on this in the next lecture*