Additional details about virtual memory

M1 MOSIG – Operating System Design

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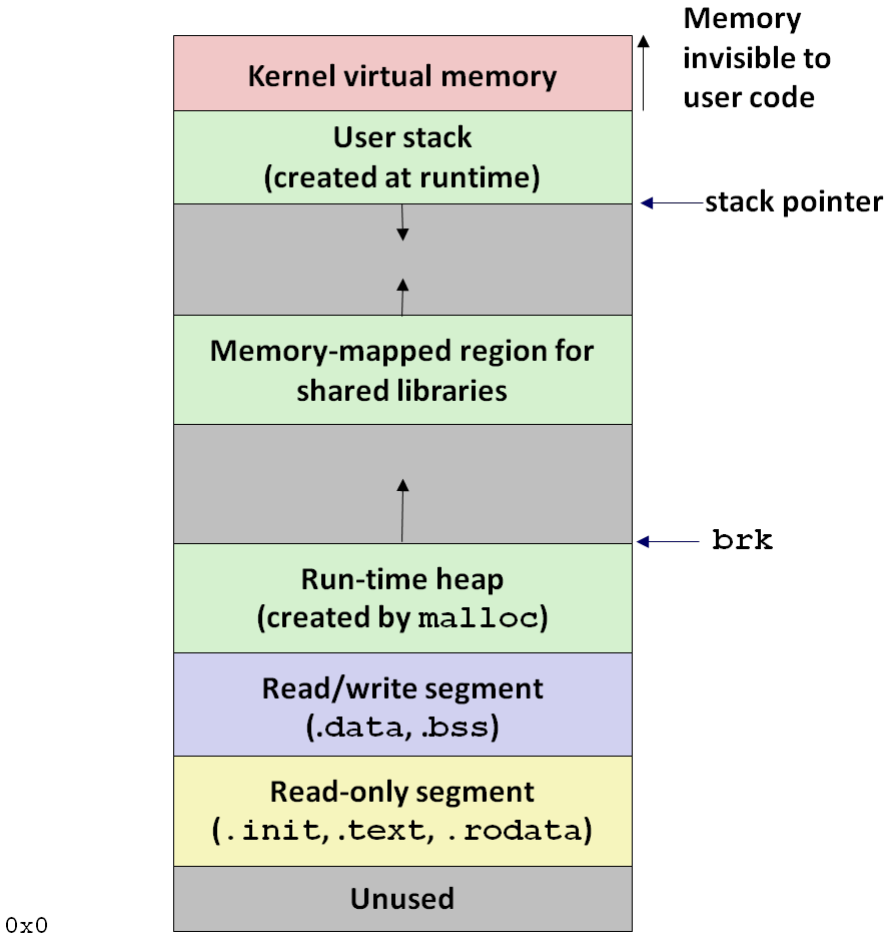
Acknowledgments

- Many ideas and slides in these lectures were inspired by or even borrowed from the work of others:
  - Arnaud Legrand, Noël De Palma, Sacha Krakowiak
  - David Mazières (Stanford)
    - (many slides/figures directly adapted from those of the CS140 class)
  - Remzi and Andrea Arpaci-Dusseau (U. Wisconsin)
  - Randall Bryant, David O'Hallaron, Gregory Kesden, Markus Püschel (Carnegie Mellon University)
    - Textbook: Computer Systems: A Programmer's Perspective (2nd Edition)
    - CS 15-213/18-243 classes
  - Textbooks (Silberschatz et al., Tanenbaum)

Outline

- Systems calls related to virtual memory
- Copy-on-Write
- Hardware/OS paging extensions
- Exposing page faults to applications

Recall typical virtual address space



- Dynamically allocated memory goes in heap
- Top of heap called "breakpoint" (**`brk`**)
  - (Do not confuse with debugging breakpoints)

Early VM system calls

- OS keeps “breakpoint” – top of data segment (heap)
  - Memory addresses between breakpoint and next region trigger fault on access

- **`char *brk(const char addr);`**
  - Set and return new value of breakpoint

- **`char *sbrk(int incr);`**
  - Increment value of breakpoint and return old value

- On modern systems, applications should not directly use such calls
  - They will be called indirectly through invocations of **`malloc`** or the **`mmap`** system call (described next)

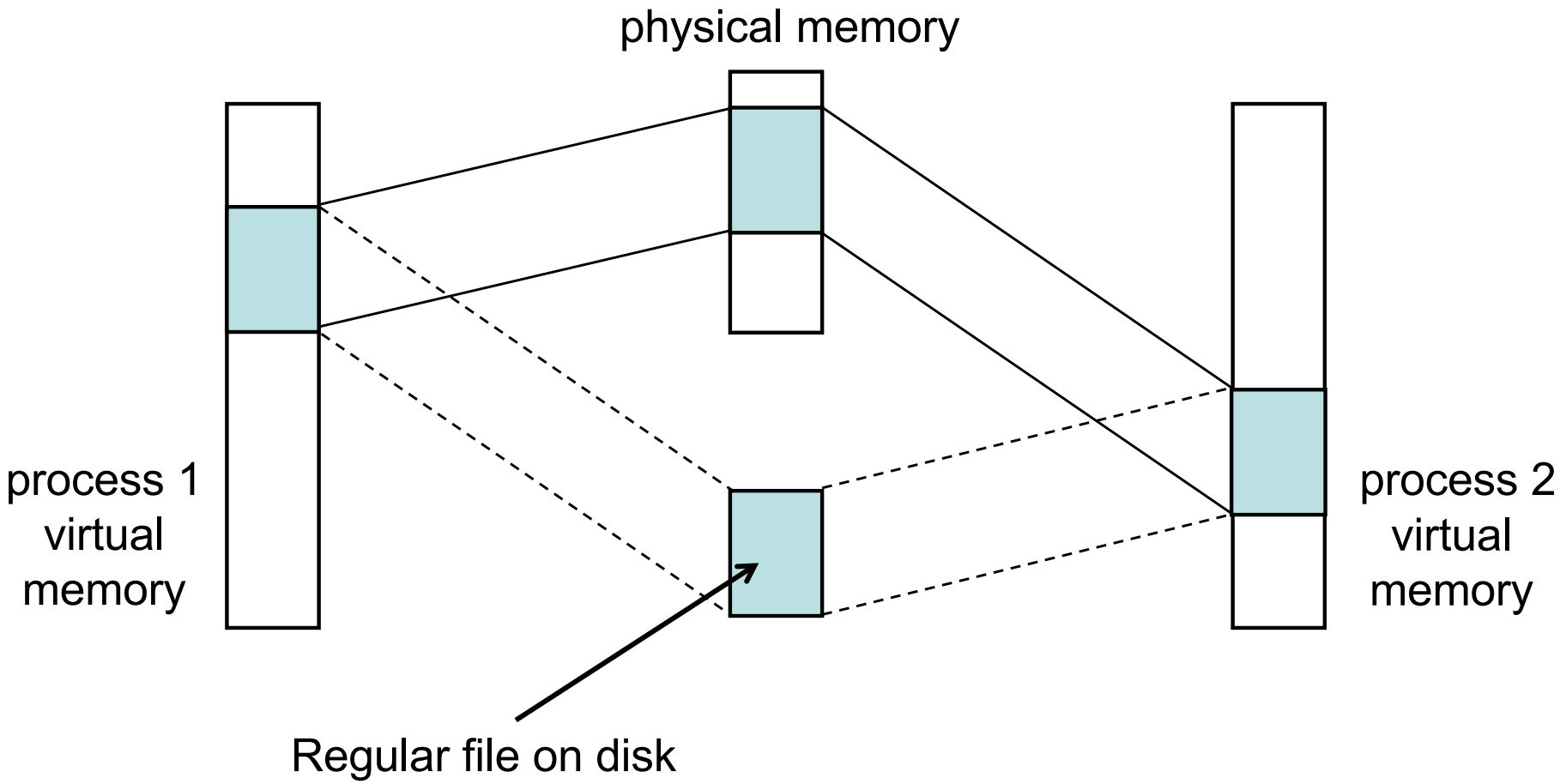
Memory-mapped files

- **Key idea**: **associate an address range within an address space** (a.k.a. *"memory area"/"region"/"zone"*, and sometimes *"segment"*) **with the contents of a "backing" file** (or a portion of a backing file)
- **Useful for different needs:**
  - For the OS itself, when building the contents of an address space
  - For the application programmers (makes code simpler and/or more efficient)
  - See details in the next slides
- **Two different kinds of backing files**
  - **Regular (persistent) file**
    - Initial page bytes come from this file
    - Updated bytes may (or may not, depending on settings) be propagated to the backing file (and become persistent)
  - **"Anonymous" file** (a.k.a. "demand-zero"): **fake file full of zeros**
    - Does not need to be read from disk
    - Once the page is modified (dirtied), treated like any other page
    - Updates are not persistent

Memory-mapped files (continued)

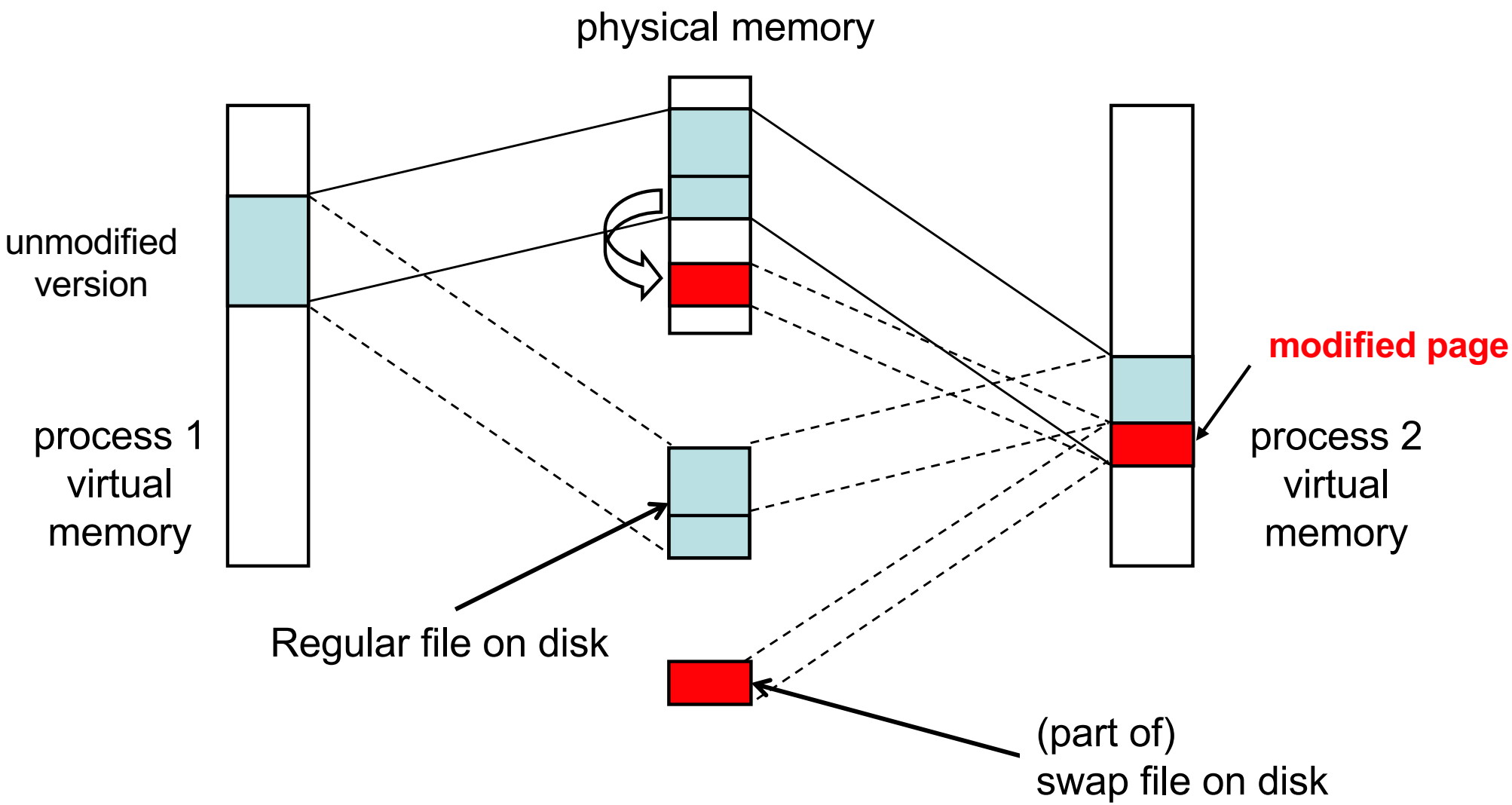
- Different levels of sharing/visibility
  - **Shared mapping**
    - Single copy in physical memory
    - Several processes can share it
    - Updates from a given process are visible by the other processes with the shared mapping
    - Updates are propagated to the backing regular file
  - **Private mapping**
    - Initially, only a single copy in memory
    - When a page is modified, a new page is allocated to store the new version
    - Updates from a given process are not visible by the other processes (with a shared or a private mapping)
    - Updates are not propagated to the backing regular file

Memory-mapped file
Shared mapping



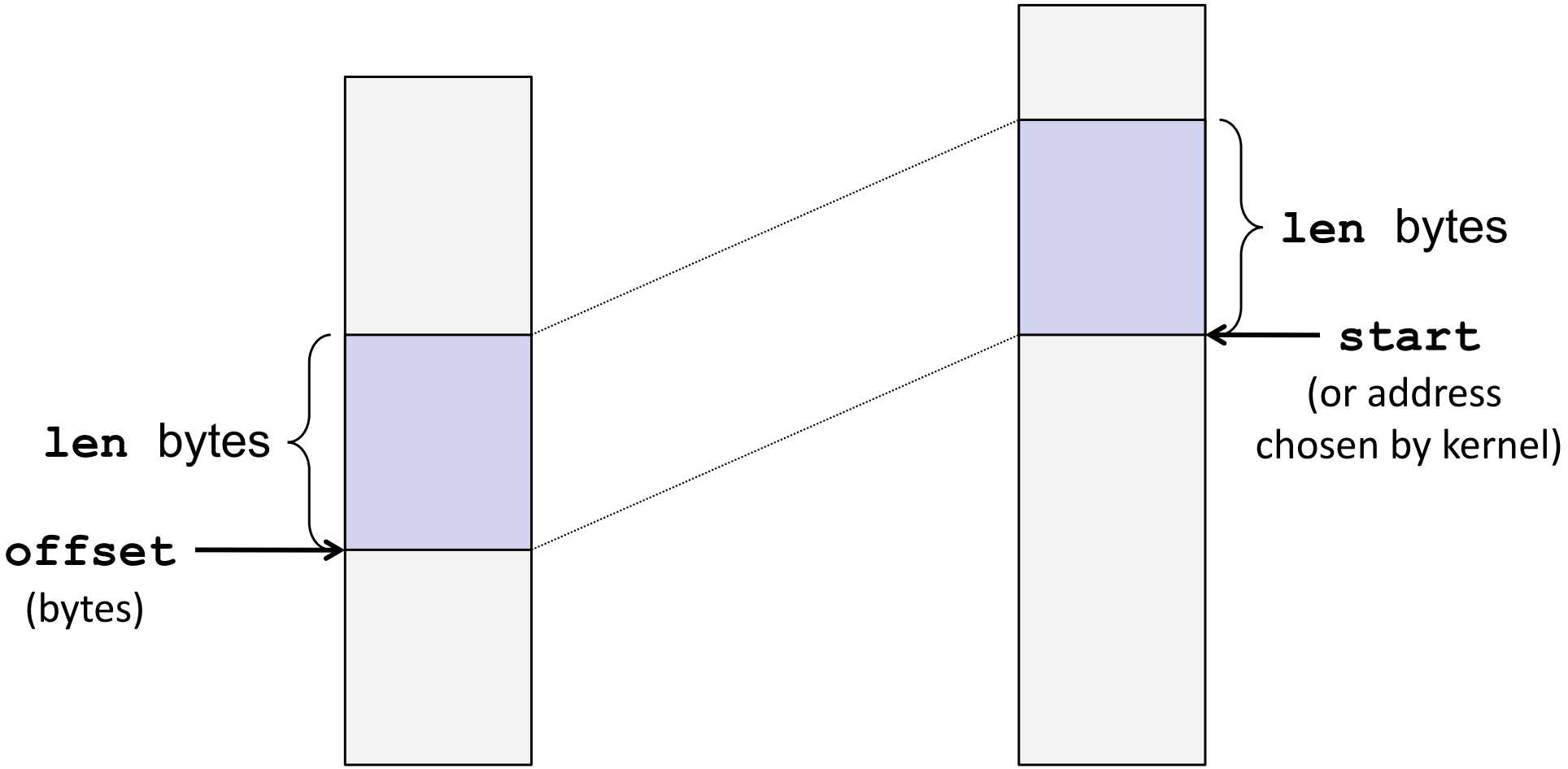
- Notice that **different processes can map the file at different addresses**

Memory-mapped file
Private mapping



The mmap system call

```
void *mmap(void *start, int len,
           int prot, int flags, int fd, int offset)
```



The mmap system call (continued)

```
void *mmap(void *start, int len, int prot, int flags,
           int fd, int offset)
```

- return value: starting address of mapping
  - or **MAP_FAILED** if error
- **fd**: open file descriptor corresponding to the file to be mapped
- **start**: hint for the starting address of the mapping
  - The kernel may choose a different address
  - Typically set to **NULL**, to let kernel choose address
- **len**: size of the mapping (in bytes)
- **offset**: offset relative to the start of the file (in bytes)
- **prot**: protection rights (for whole mapped region):
  - **PROT_READ**, **PROT_WRITE**, **PROT_EXEC**, **PROT_NONE**
  - Can combine several rights using bitwise OR (e.g., **PROT_READ | PROT_WRITE**)
- **flags**:
  - **MAP_PRIVATE**: private mapping
  - **MAP_SHARED**: shared mapping
  - **MAP_ANONYMOUS**: anonymous memory (**fd** should be -1), i.e. “demand-zero” mapping
    - Option that can be combined (bitwise OR) with either **MAP_PRIVATE** or **MAP_SHARED**

The mmap system call
Purposes of the various types of memory mappings

Visibility of modifications	*Mapping type*	
	File	**Anonymous**
Private	Initializing memory from contents of file	Memory allocation
Shared	Sharing data between processes or Memory-mapped file I/O (accessing a file without explicit **`read`**/**`write`** calls)	Sharing memory between processes (of the same family)

The mmap system call
Purposes of the various types of memory mappings (cont.)

- **Private-file**: initializing memory from contents of file
  - Example: program/library data (global static variables)
    - Modifications must not be visible from other processes (each process has its own copy)
- **Private-anonymous**
  - Used to allocate new, zero-filled memory region, with private modifications (e.g., memory heap)
- **Shared-file**
  - Memory mapped I/O: e.g., reading and (persistently) modifying a file without having to explicitly use **`read`**/**`write`**/**`fread`**/**`fwrite`** ...
  - (Persistent) shared buffer for data exchange between (arbitrary) processes
- **Shared-anonymous**
  - (Non persistent) shared buffer for data exchange between related processes (e.g., parent-child) – Note that such a mapping can only be transmitted via “family inheritance” (through **`fork`**)

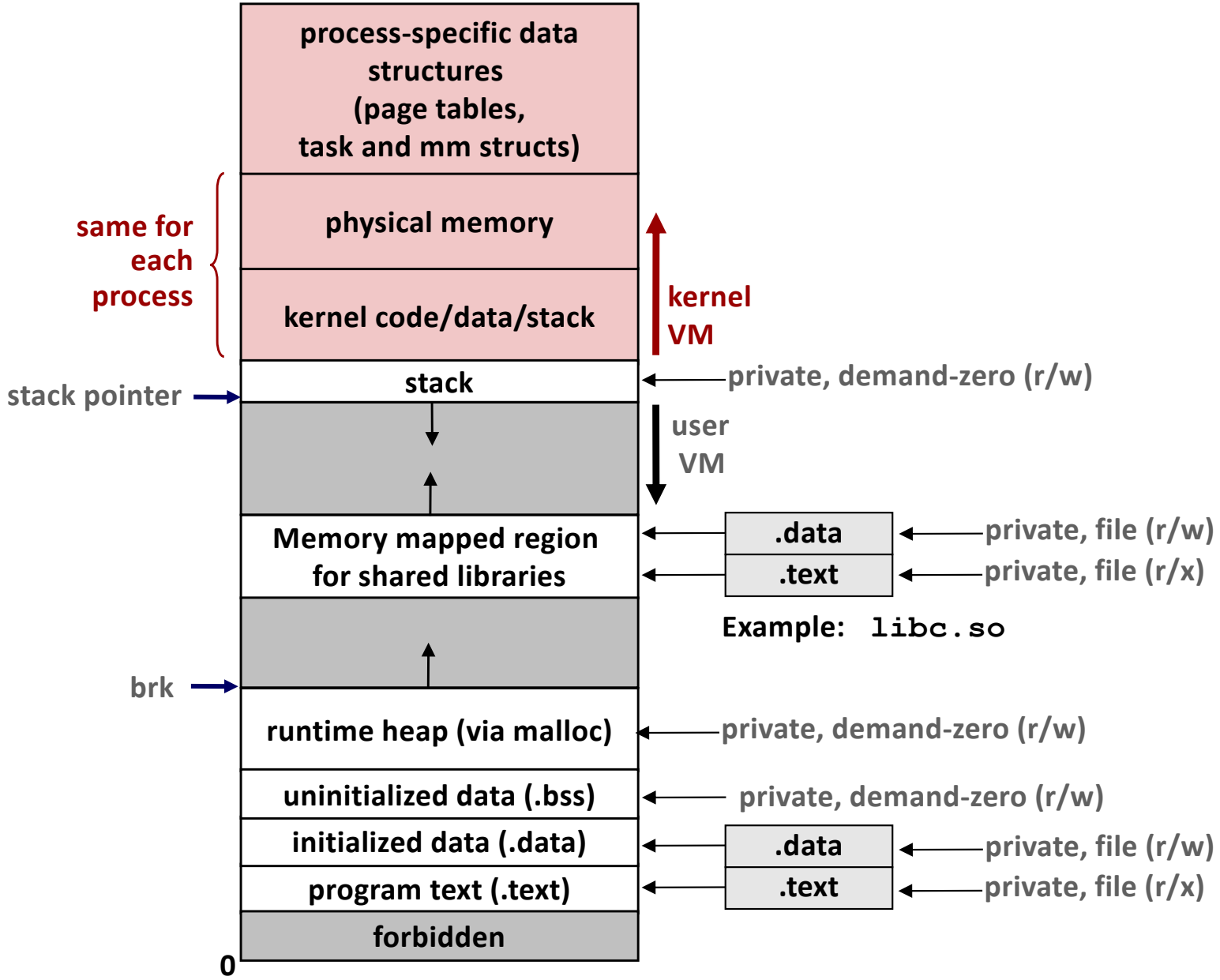
The mmap system call
Details on swapping

- **What happens when a dirty page within a memory mapped region must be swapped out (to disk)?**

- **The location on disk depends on the type of mapping**
  - **File-shared**: update the corresponding (regular) file
  - **File-private**: store the modified page in the swap file
  - **Anonymous-shared**: store the modified page in the swap file
  - **Anonymous-private**: store the modified page in the swap file

- Note:
  - The size of the swap file (on disk) + the total size of the physical memory provide an upper bound on the maximum (global) amount of virtual memory that can be allocated by the OS
  - The swap file is stored on disk (and is thus persistent) but its contents are discarded upon each reboot

Address space initialization via memory mappings



More VM system calls

- **`int msync(void *addr, size_t len, int flags);`**
  - Flushes changes of mmapped files to backing store
  - Ensures that updates are visible by other processes that access the file via **`read`**

- **`int munmap(void *addr, size_t len)`**
  - Destroys a virtual memory mapping

- **`int mprotect(void *addr, size_t len, int prot)`**
  - Changes protection on pages

- **`int mincore(void *addr, size_t len, char *vec)`**
  - Returns in **`vec`** which pages are present in RAM

Outline

- Systems calls related to virtual memory
- **Copy-on-Write**
- Hardware/OS paging extensions
- Exposing page faults to applications

Copy-on-write (CoW)

- **A technique that allows minimizing the (space) cost of maintaining two (or more) copies of a given data item**
- Used in many different contexts (memory, storage, ...) with different low-level mechanisms. Here, we focus on virtual memory.

- **Example: CoW is used to efficiently manage private memory mappings. General principle:**
  - Initially, keep a single copy of the pages of the memory-mapped region. Configure all the pages as read-only.
  - A write access to such a page will trigger a protection fault.
  - In the trap handler: notice that the trap was caused by CoW semantics, allocate a new frame, copy the original page into it and remap the corresponding page (for the process that issued the write instruction)
  - Restart the instruction that caused the write access (like in the case of a "normal" page fault)

Outline

- Systems calls related to virtual memory
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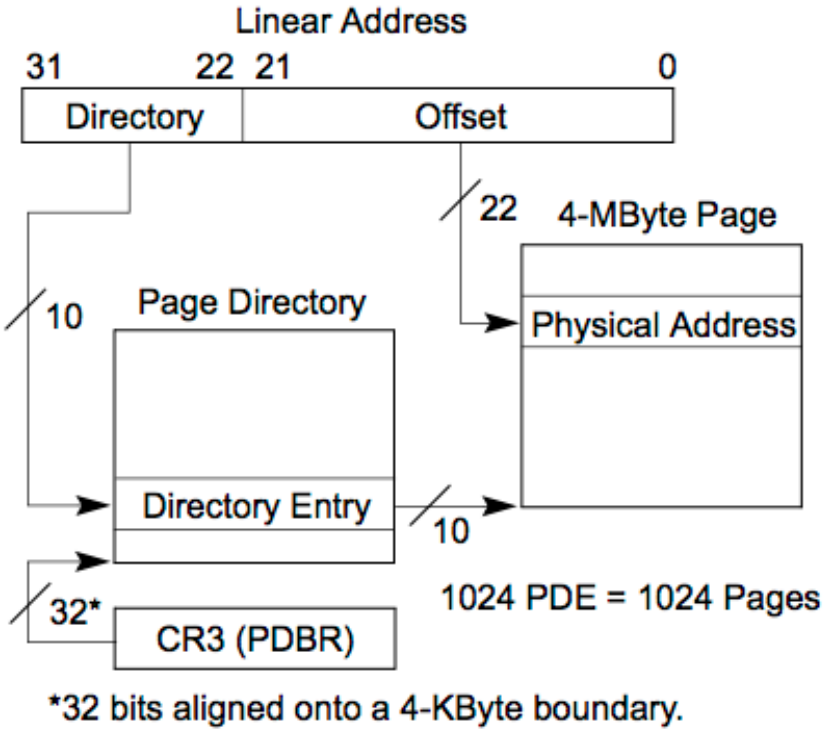
x86 paging extensions

- PSE: Page size extensions
  - Setting bit 7 in a PDE makes a 4MB translation (no page table)
  - Note that 4kB pages can coexist with 4MB pages
  - (more details later – see discussion about “superpages”)

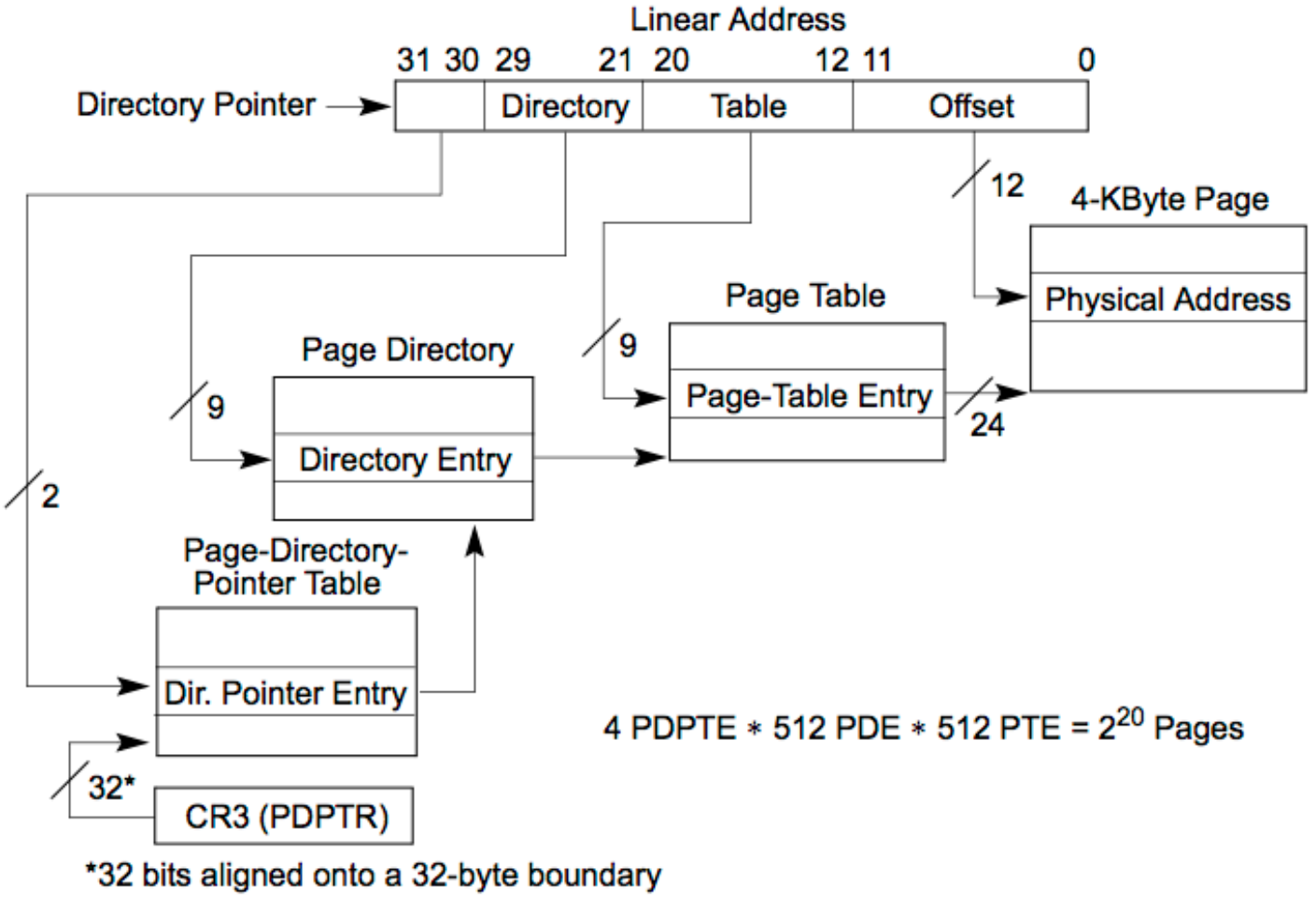


x86 paging extensions (continued)

- PAE: Physical address extensions
  - Newer 64-bit PTE format allows 36 bits of physical address
  - (But virtual addresses are still 32-bit long)
  - Page directories and page tables have only 512 entries
    - Each entry is stored on 64 bits
    - The size of a page directory or page table is still 4 kB
  - CR3 register now points to “page directory pointer table”, which contains pointers to 4 page directories
    - This allows regaining 2 lost bits
  - PDE bit 7 allows (optional) 2MB translation: same principle as PSE but with smaller page size – since there are only 21 remaining bits for the offset (compared to 22 bits with “basic PSE”)

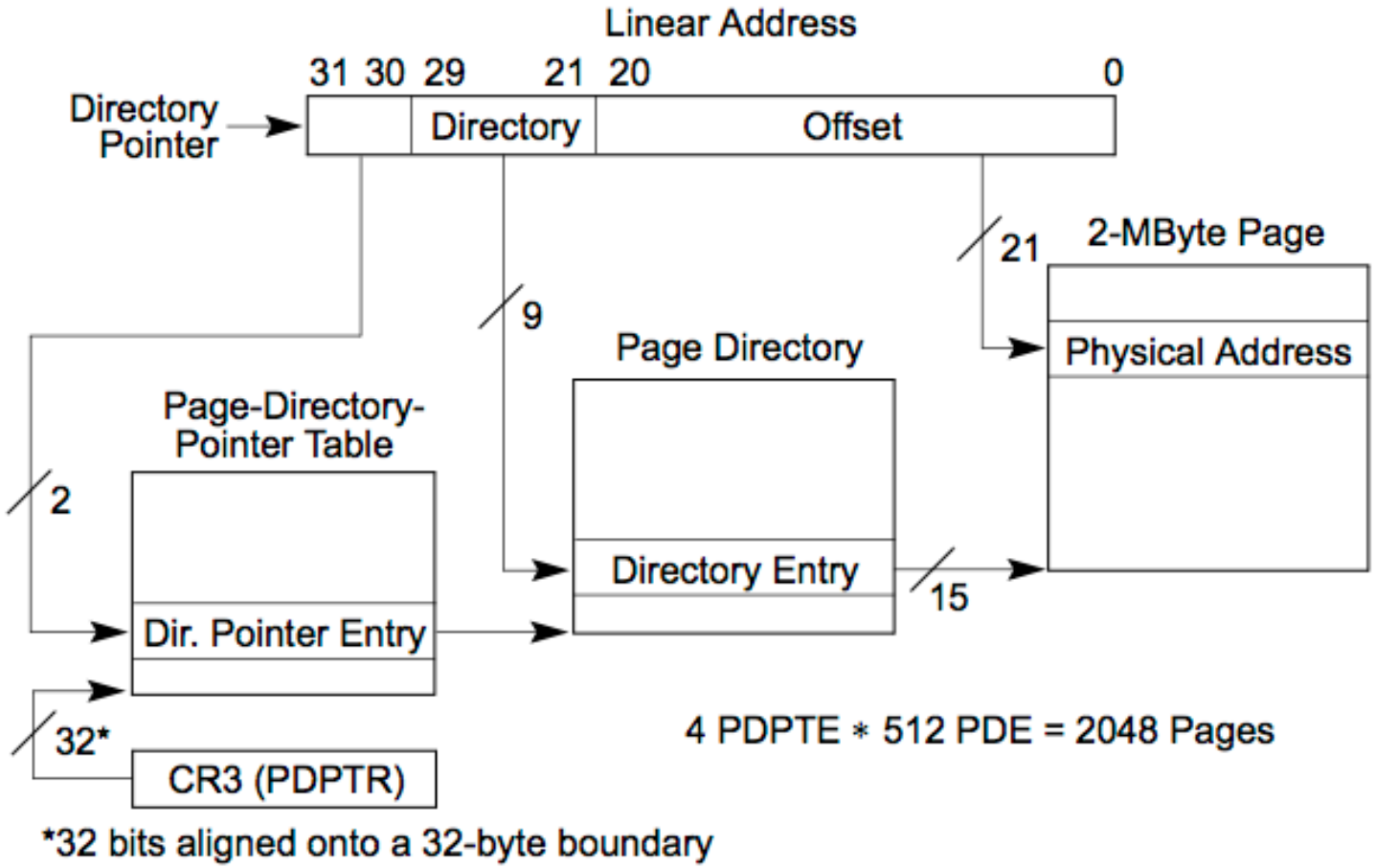
x86 paging extensions (continued)

PAE with 4-kB pages



x86 paging extensions (continued)

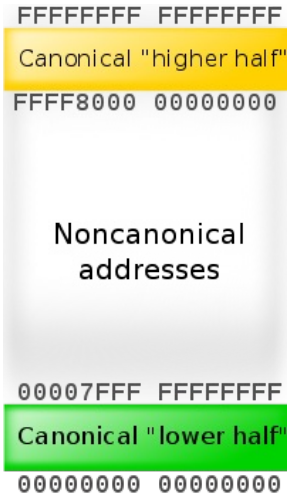
PAE with 2-MB pages



x86-64

- x86-64: **a 64-bit processor architecture** (an evolution of the x86 architecture)
  - **With 64-bit registers and a 64-bit virtual address format**
  - Here, we focus on the operating mode named *"long mode"*. (In contrast, *"legacy mode"* is for backwards compatibility with x86)

- **However, current implementations:**
  - **Do not allow** the entire address space of 2^{64} addresses to be used
  - Instead, define a mechanism for translating **48-bit virtual addresses** to **48-bit physical addresses**
    - **Only the least significant 48 bits of a virtual address are considered**
    - Bits 48 through 63 of any virtual address must be copies of bit 47



Picture from Wikipedia: https://en.wikipedia.org/wiki/X86-64

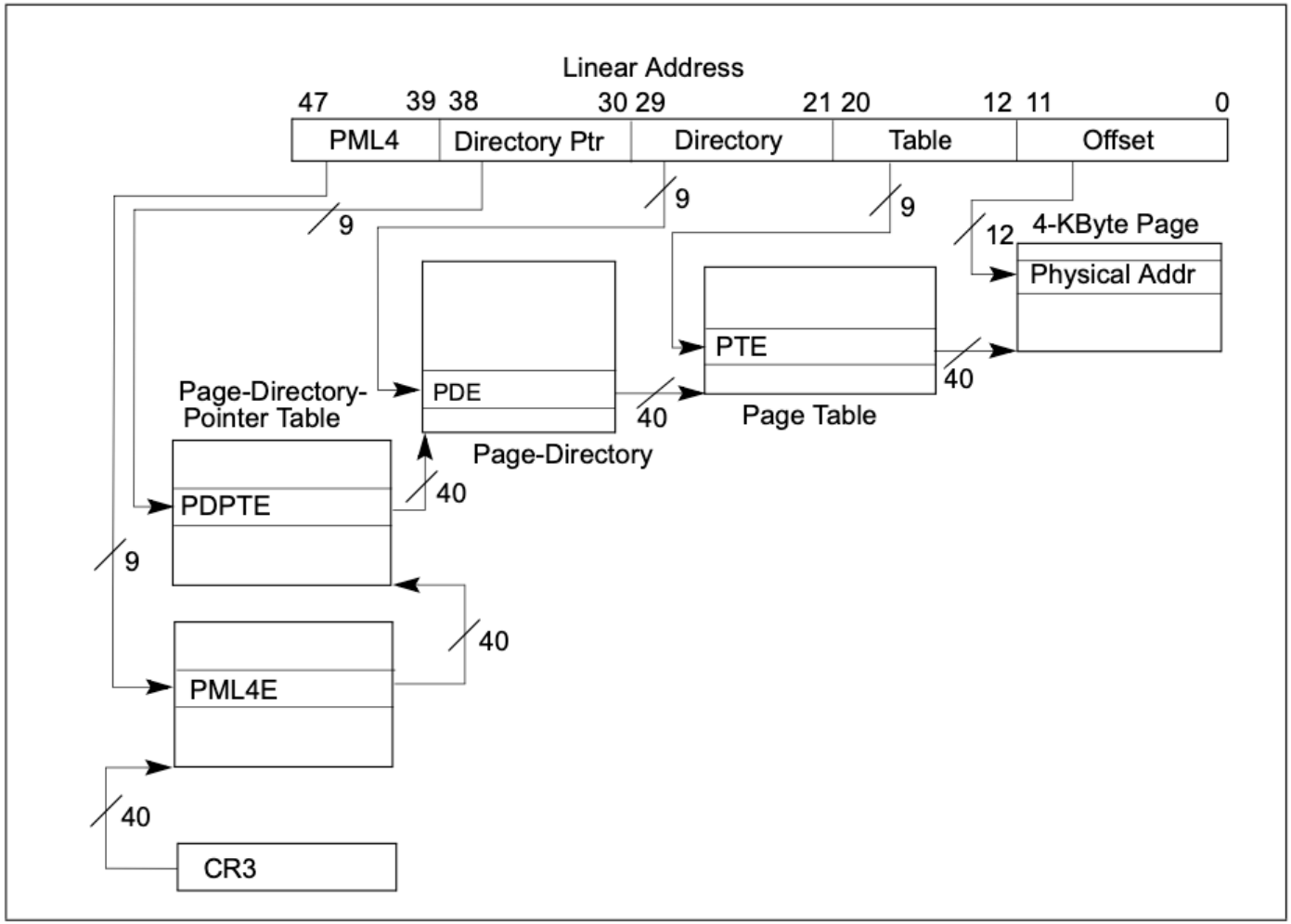
Note: Recent extensions (not studied in this lecture) support 57-bit virtual addresses

x86-64 paging

- **Long mode is a superset of x86's PAE mode**
  - Page sizes can be 4 kB, 2 MB or 1 GB
  - 4-level page table (unlike PAE, which has 3 levels)
    - Page directory pointer table is extended from 4 entries to 512
    - A new level is introduced: Page Map Level 4 (PML4)
      - Contains 512 entries in implementations with 48-bit virtual addresses

x86-64 paging (continued)

4kB page translation with 4-level paging structure



(source: Intel documentation)

Large pages

- (Also known as **“superpages”** or **“huge pages”**)
- **The MMU of a modern processor typically supports several page sizes**
  - For example, x86-64 supports page sizes of 4 kB, 2 MB and 1 GB
- **The configuration is flexible**:
  - The OS kernel can configure the hardware so that **different virtual memory regions/ranges** (possibly within the same process address space) **use different page sizes**

Large pages (continued)

- **Main advantages:**
  - Memory footprint of paging structures
  - Performance of physical memory allocation (sometimes)
  - **Performance of virtual memory translations**
    - **Increased coverage of the TLB → Increased TLB hit ratio**
      - The capacity of the TLB (number of entries) is often very limited
      - Example on a quite recent Intel processor:
        - » 1536 TLB entries
        - » TLB coverage when using 4kB pages: ~6MB
        - » TLB coverage when using 2MB pages: ~3GB
    - **Fewer levels in paging structure → Less time ”wasted” in case of TLB miss**

Large pages (continued)

- **Main weaknesses:**
  - Performance of swapping (larger data transfers)
  - Risk of fragmentation (can you explain why?)

Large pages (continued)

How to use them?

- **Explicitly:**
  - OS provides explicit interface for application programmers to request large pages in a given virtual memory region
- **Transparently:**
  - OS automatically infers that a given memory region would benefit from being "promoted" to a larger page size (no modifications needed for application-level code)
  - OS may also decide to transparently "demote" a region (switching back to smaller page size).
  - For more details, see the following paper: "A Comprehensive Analysis of Superpage Management Mechanisms and Policies"
- An OS may potentially support the two approaches

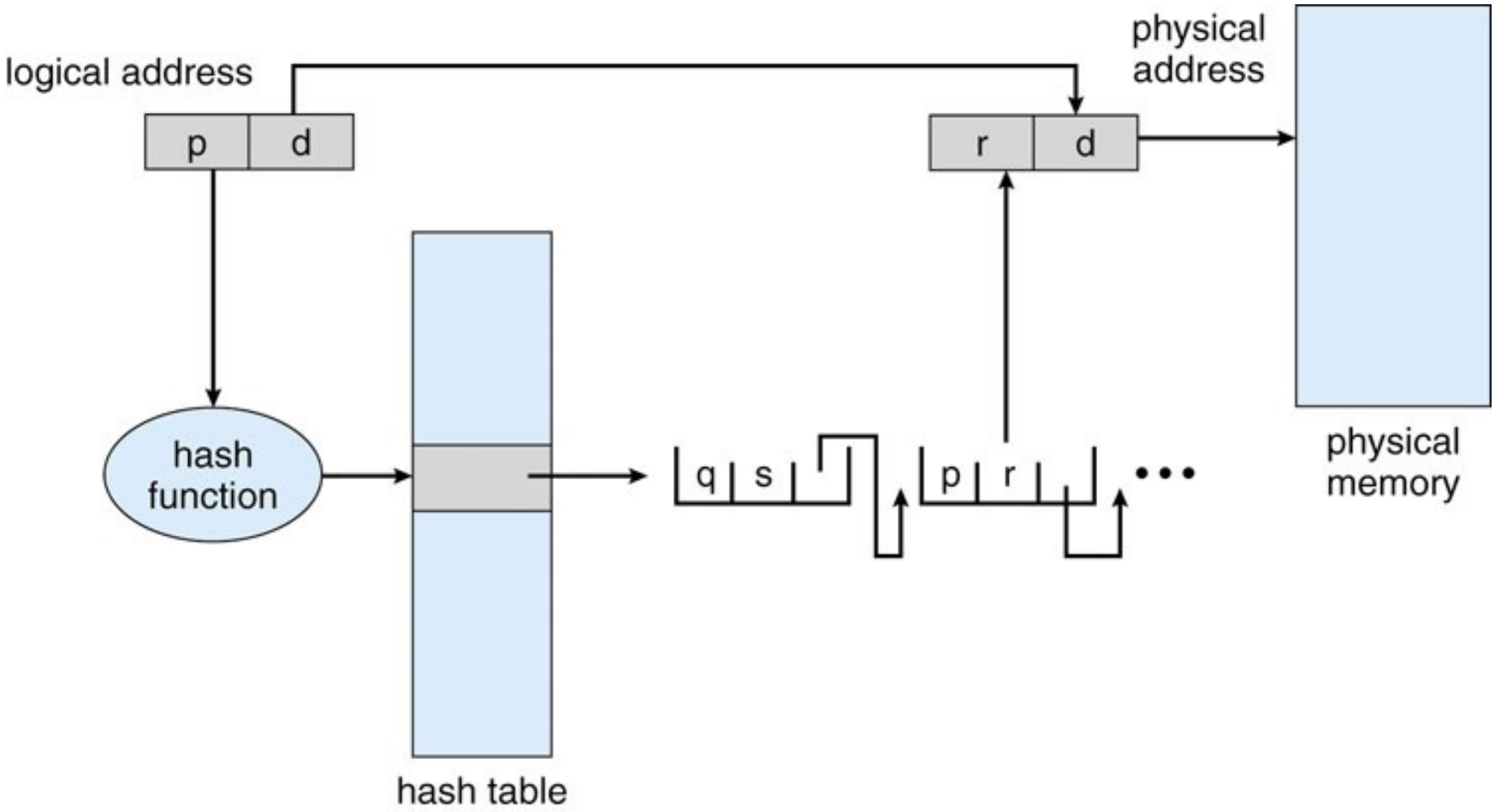
64-bit address spaces [Advanced]

- x86-64 has currently only 48-bit virtual address space
- **What if you want a 64-bit virtual address space?**
  - **Straight hierarchical page tables not efficient (esp. not space efficient)**
  - We will study two other approaches: *hashed page tables* and *inverted page tables*

- **Hashed page table**
  - Hash input value: virtual page number
  - Each entry in the hash table contains a linked list of elements that hash to the same location (to handle collisions)
  - Each element in a list contains 3 fields: (1) virtual page number, (2) physical page frame (+ details such as protection information), (3) pointer to next element in linked list
  - Variant: clustered page tables
    - Similar to hashed page table except that each element refers to several consecutive pages (e.g., 16) rather than a single page

64-bit address spaces (continued) [Advanced]

Hashed page table:



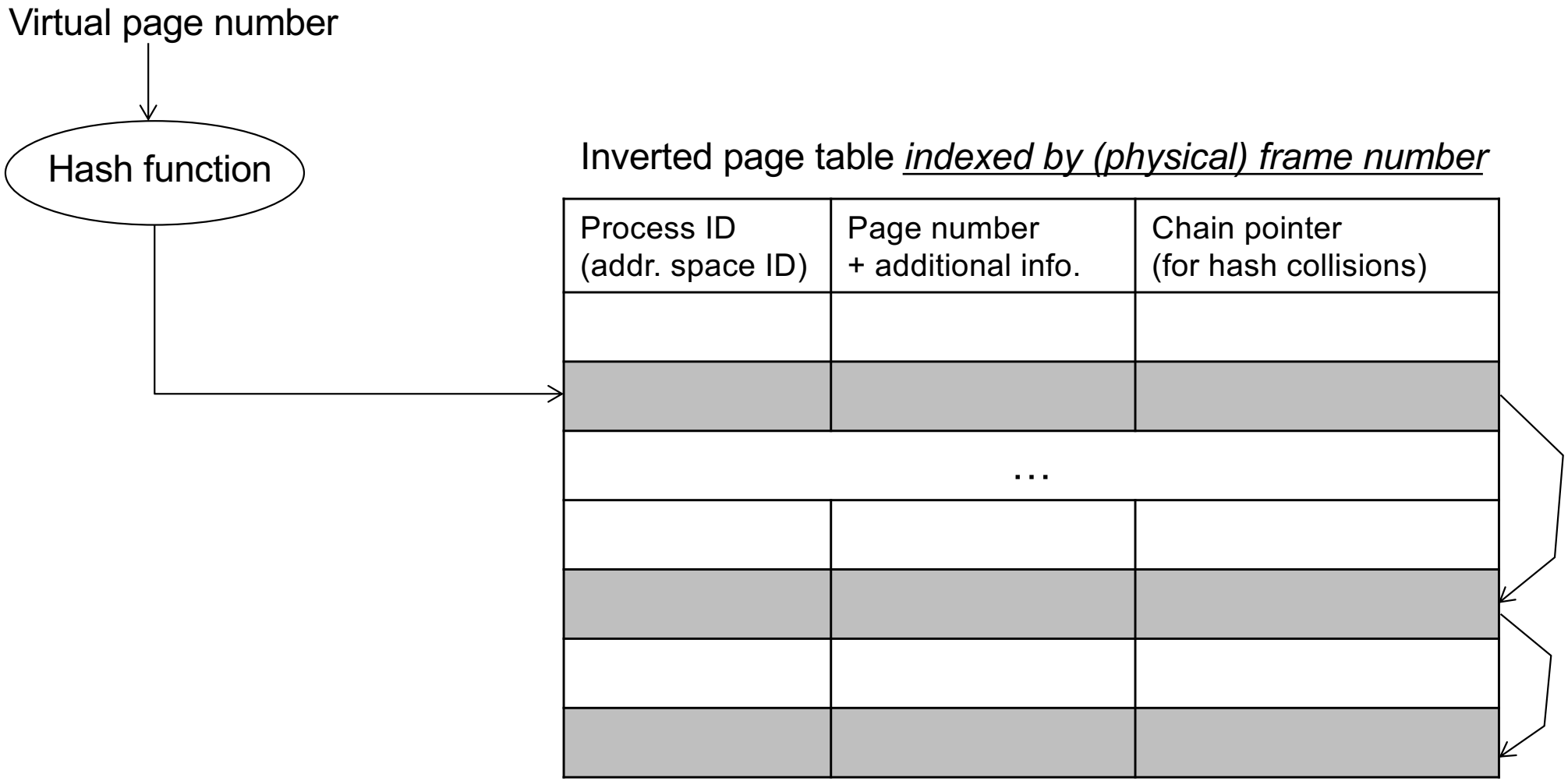
Picture from: Silberschatz et al., *Operating systems concepts* (8th edition)

64-bit address spaces (continued) [Advanced]

- **Inverted page table**
  - Examples: 64-bit UltraSPARC and PowerPC architectures
  - In the previous designs that we have studied, each process (address space) has an associated page table
  - In contrast, **an inverted page table design uses only a single page table for the whole system**
  - **One entry for each physical frame**
  - Each entry contains:
    - Corresponding virtual page number (+ details such as protection information)
    - Information about the process that owns the page
- **Issues with inverted page tables**
  - A lookup is costly (may require whole table scan) => Use a hash table (mapping a virtual page number to an index in the inverted page table)
  - Longer worst-case access time than hierarchical page tables
  - Sharing physical memory between address spaces is more difficult to implement

64-bit address spaces (continued) [Advanced]

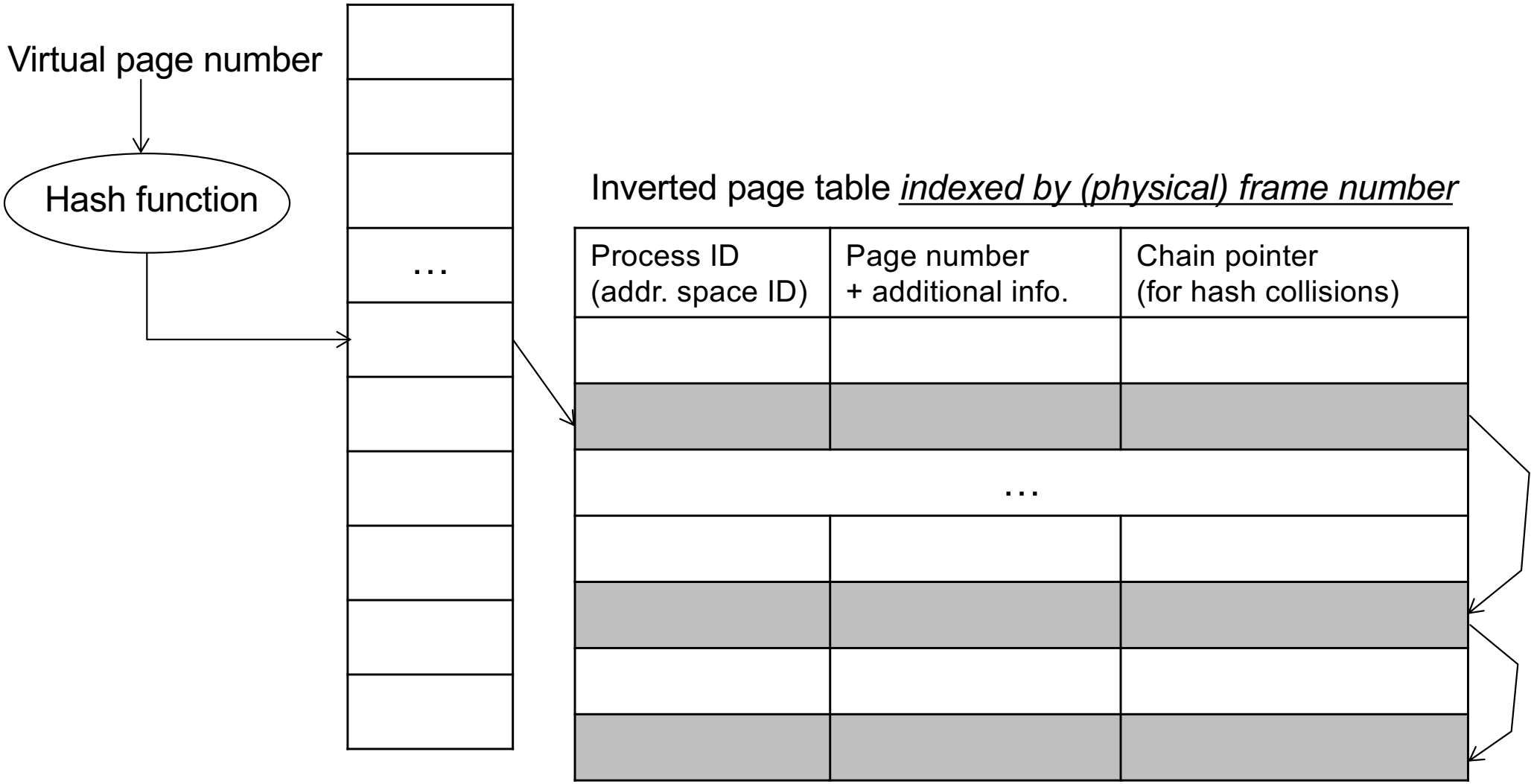
Hashed inverted page table



For more details, see:
Bruce Jacob and Trevor Mudge. Virtual memory: issues of implementation. IEEE Computer, June 1998.

64-bit address spaces (continued) [Advanced]

Hashed inverted page table with hash anchor table



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Outline

- Systems calls related to virtual memory
- Copy-on-Write
- Paging in day-to-day use
- **Exposing page faults to applications**

Exposing page faults to applications (1/2) [Advanced]

- Any invalid memory access requested by the application triggers a hardware trap
  - Any access to an invalid page (no mapping defined)
  - Write access to a read-only page
  - Attempt to execute code stored in a page defined as “non-executable”

Exposing page faults to applications (2/2) [Advanced]

- The code of the trap handler for invalid memory accesses is registered by the OS kernel
- (On a Unix system) the kernel handler sends a **`SIGSEGV`** signal to the process
- By default, the **`SIGSEGV`** handler of the application simply terminates the process (+ generates optional *"core dump"* file with debugging information)
  - When the invalid memory access is due to a bug in the application, there is usually no other choice
  - **But this mechanism can be also used by application programmers to implement advanced memory management at the application level** (see next slides for details)

Virtual-memory tricks at user level (1/3) [Advanced]

- **General idea**: allow application to detect and trigger execution of specific procedure when the application attempts to access some memory addresses

- Useful for many different purposes, such as:
  - **Application level strategies for paging to disk**
    - Example: Big object-oriented application (e.g., database)
      - Manages main memory as a cache for much larger on-disk state
      - Can make more informed page-replacement decisions than general purpose OS kernel
      - Bring in objects on-demand (and must keep track of dirty objects)
  - **Concurrent services** (running concurrently with respect to the "regular" application code)
    - Examples: concurrent garbage collector, concurrent checkpointing
    - Need to keep track of the pages that are concurrently modified by the application

Virtual-memory tricks at user level (2/3) [Advanced]

- **General approach (implementation):**
  - Application registers specific handler for **`SIGSEGV`** signal
  - Application uses specific syscall (**`mprotect`**) to restrict the accessibility of the user-level page(s) that must be monitored
    - Most common example: set R/W page to read-only
  - Next access to the page triggers invocation of the **`SIGSEGV`** handler provided by application
  - **`SIGSEGV`** handler goes through the following steps:
    - Identify faulting address
    - Perform some (application-specific and address specific) action
    - Remove accessibility restriction on the faulting page (using **`mprotect`**)
  - Completion of **`SIGSEGV`** triggers re-execution of instruction that faulted (successful this time)
  - (For unwanted faults, **`SIGSEGV`** handler still triggers termination of process)

Virtual-memory tricks at user level (3/3) [Advanced]

- **Some advanced details and links**
  - For more details (on motivation, use cases and implementation), see the paper [Appel and Li]
  - GNU libsigsegv: a library for handling page faults in user mode
  - Userfaultfd (Linux only):
    - A new facility provided by the Linux kernel allowing a thread to monitor and handle the page faults triggered by another thread (in the same process or in another process)

References

- Bruce Jacob and Trevor Mudge. **Virtual memory: issues of implementation**. IEEE Computer, June 1998.

- AMD and Intel technical documentations (cf. references from previous lectures)

- Weixi Zhu, Alan L. Cox, and Scott Rixner. **A Comprehensive Analysis of Superpage Management Mechanisms and Policies.** Proceedings of the 2020 USENIX Annual Technical Conference.
  - https://www.usenix.org/conference/atc20/presentation/zhu-weixi

- Andrew Appel and Kai Li, **Virtual memory primitives for user programs**. Proceedings of the ASPLOS conference, 1991.