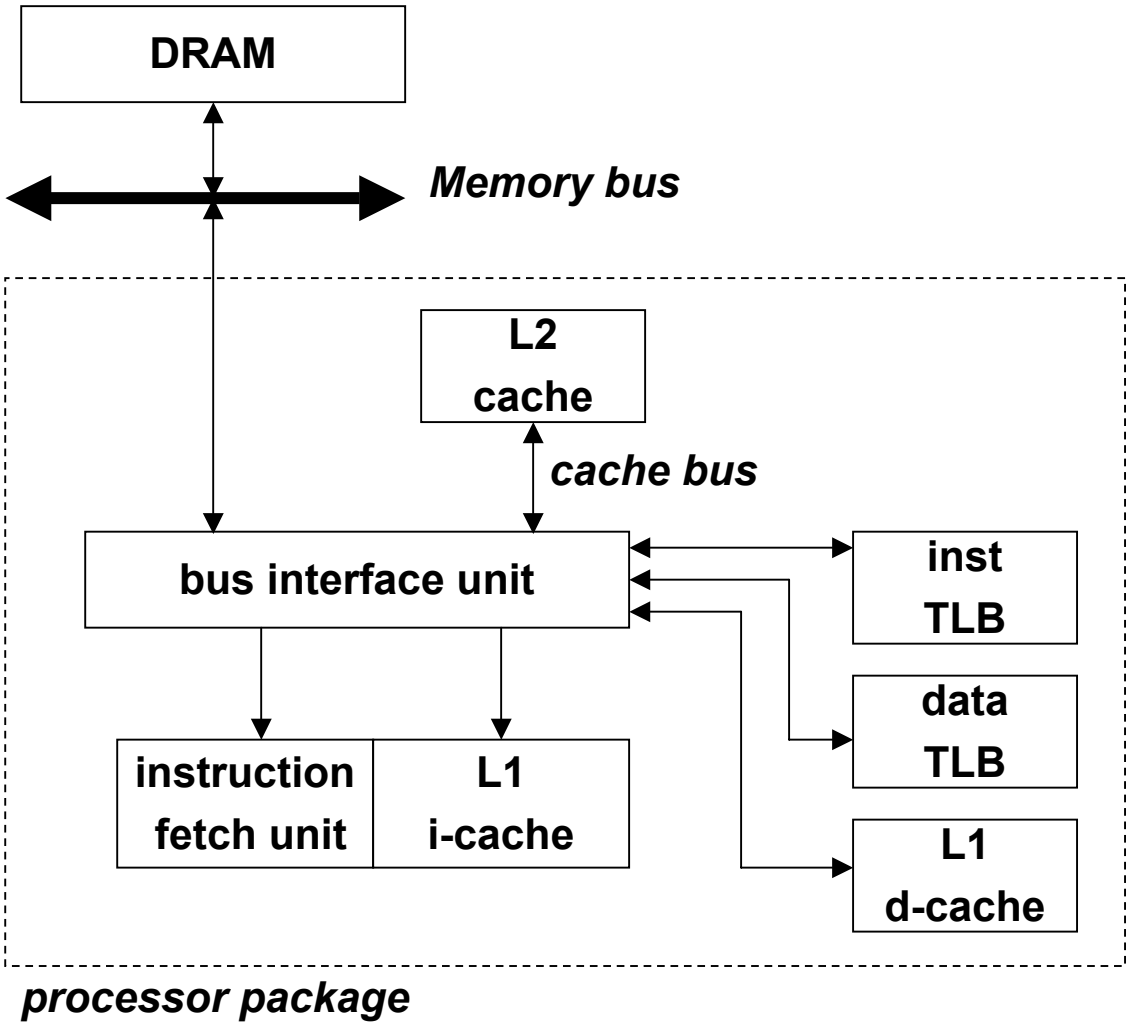
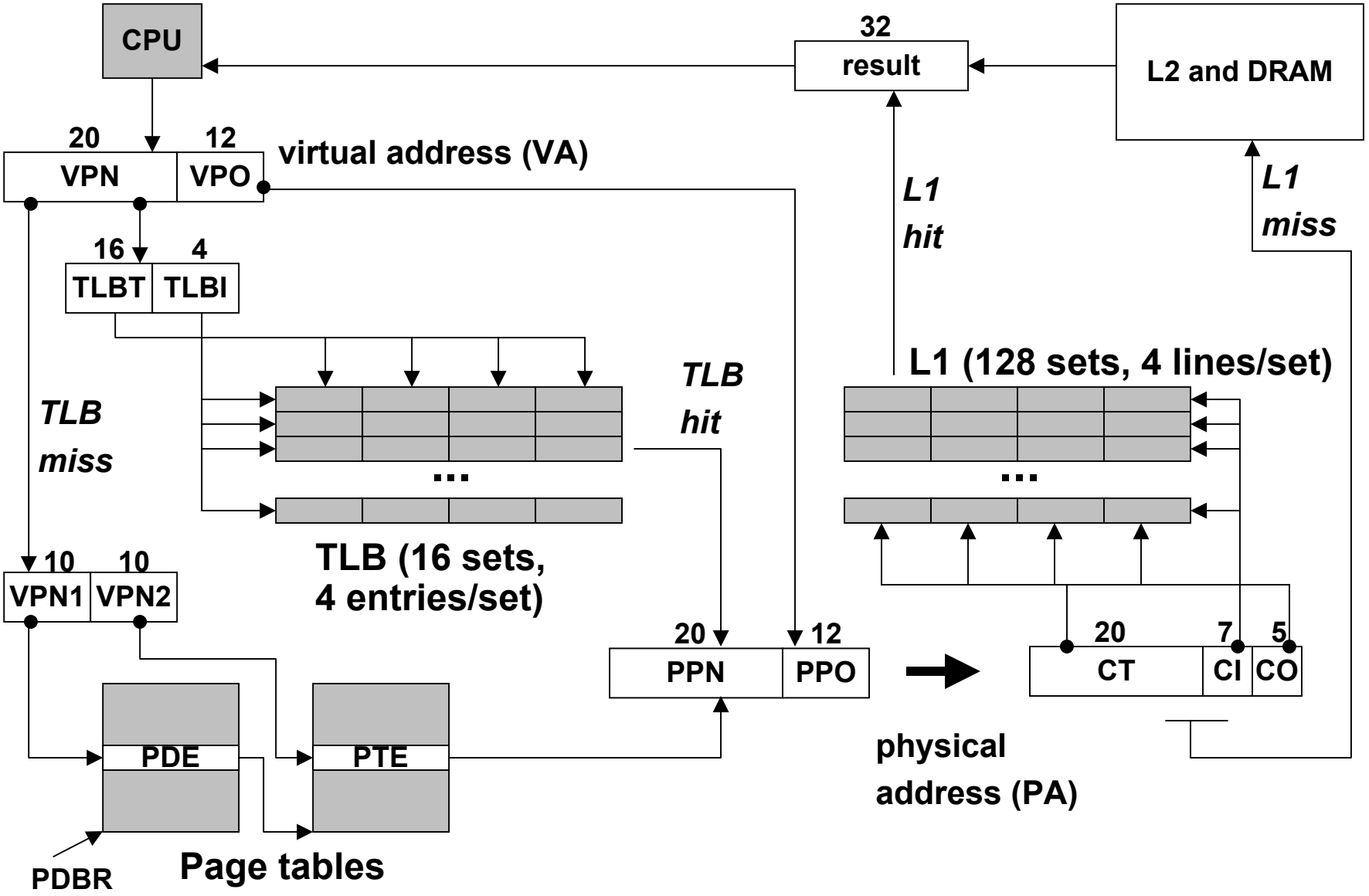
P6 (PentiumPro,II,III,Celeron) memory system



- 32 bit address space
- 4 KB page size
- L1, L2, and TLBs
  - 4-way set associative
- inst TLB
  - 32 entries
  - 8 sets
- data TLB
  - 64 entries
  - 16 sets
- L1 i-cache and d-cache
  - 16 KB
  - 32 B line size
  - 128 sets
- L2 cache
  - unified
  - 128 KB -- 2 MB

Overview of P6 memory read



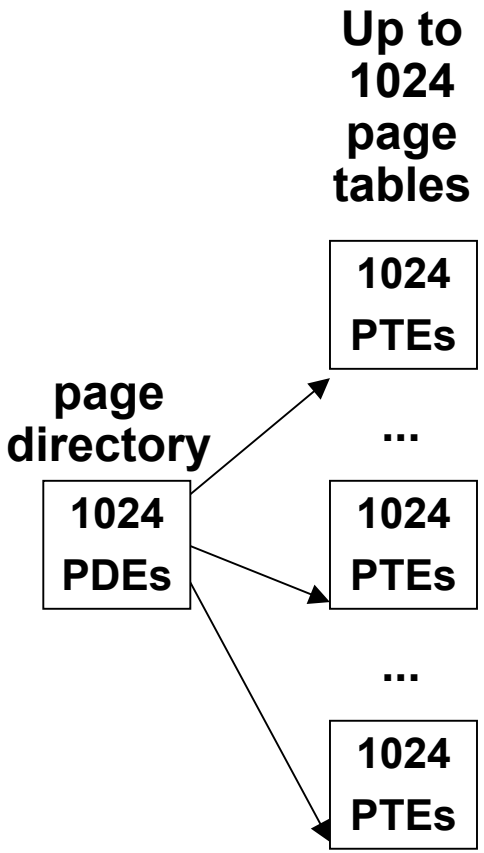
P6 2-level page table structure

Page directory

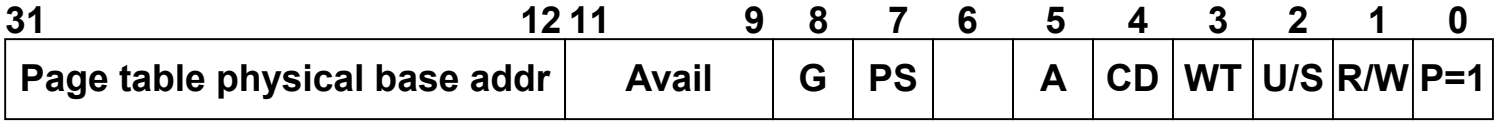
- 1024 4-byte page directory entries (PDEs) that point to page tables
- one page directory per process.
- page directory must be in memory when its process is running
- always pointed to by PDBR

Page tables:

- 1024 4-byte page table entries (PTEs) that point to pages.
- page tables can be paged in and out.



P6 page directory entry (PDE)



Page table physical base address: 20 most significant bits of physical page table address (forces page tables to be 4KB aligned)

Avail: available for system programmers

G: global page (don't evict from TLB on task switch)

PS: page size 4K (0) or 4M (1)

A: accessed (set by MMU on reads and writes, cleared by software)

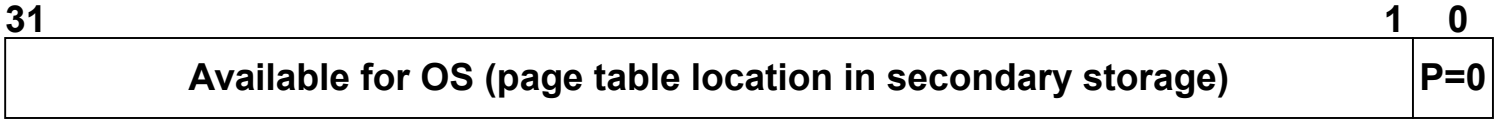
CD: cache disabled (1) or enabled (0)

WT: write-through or write-back cache policy for this page table

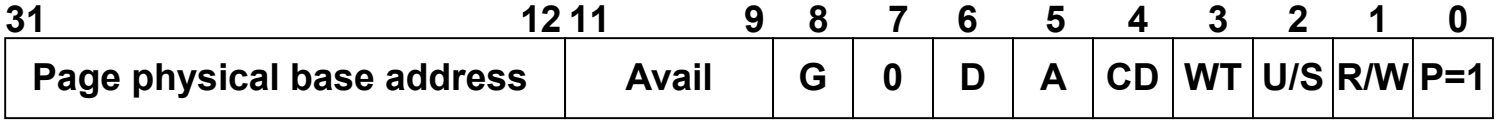
U/S: user or supervisor mode access

R/W: read-only or read-write access

P: page table is present in memory (1) or not (0)



P6 page table entry (PTE)



Page base address: 20 most significant bits of physical page address (forces pages to be 4 KB aligned)

Avail: available for system programmers

G: global page (don't evict from TLB on task switch)

D: dirty (set by MMU on writes)

A: accessed (set by MMU on reads and writes)

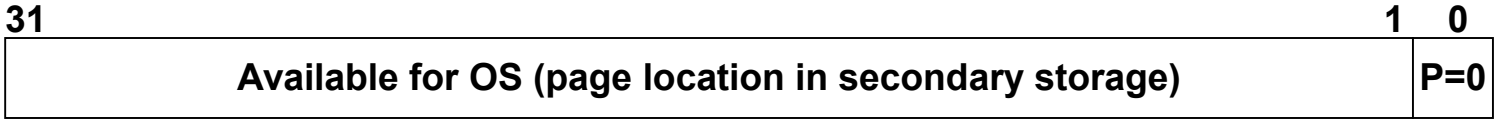
CD: cache disabled or enabled

WT: write-through or write-back cache policy for this page

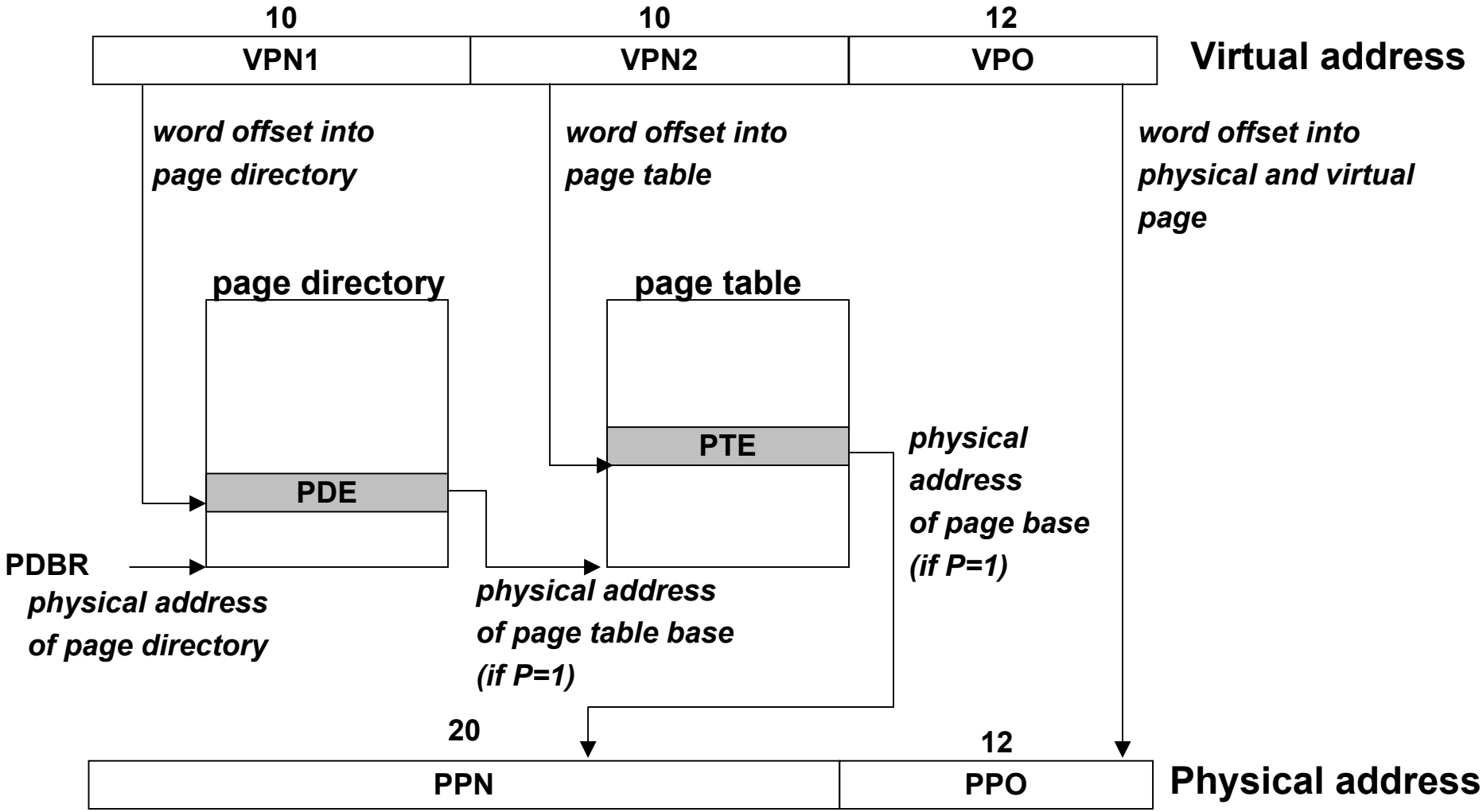
U/S: user/supervisor

R/W: read/write

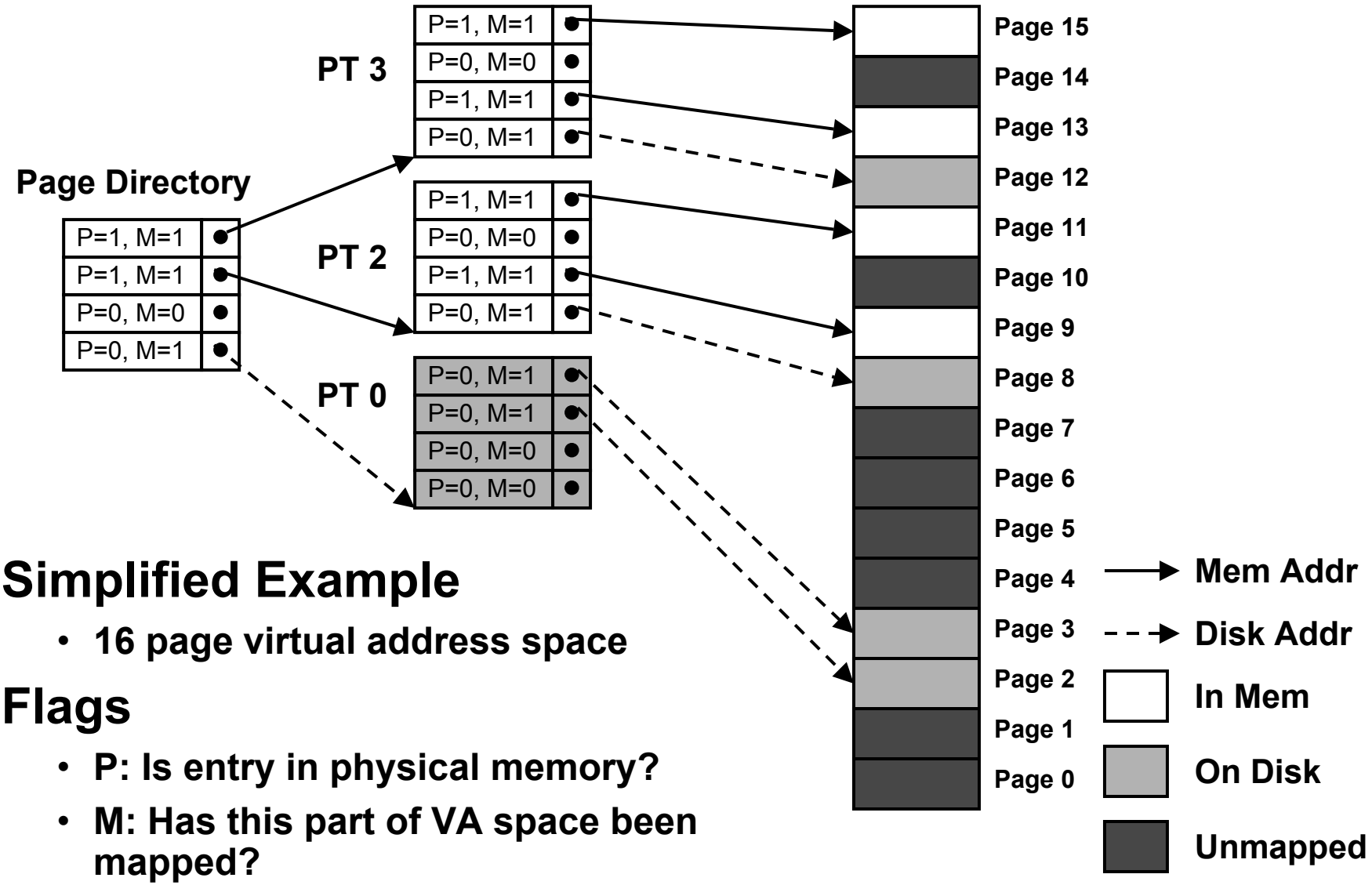
P: page is present in physical memory (1) or not (0)



How P6 page tables map virtual addresses to physical ones



Representation of Virtual Address Space



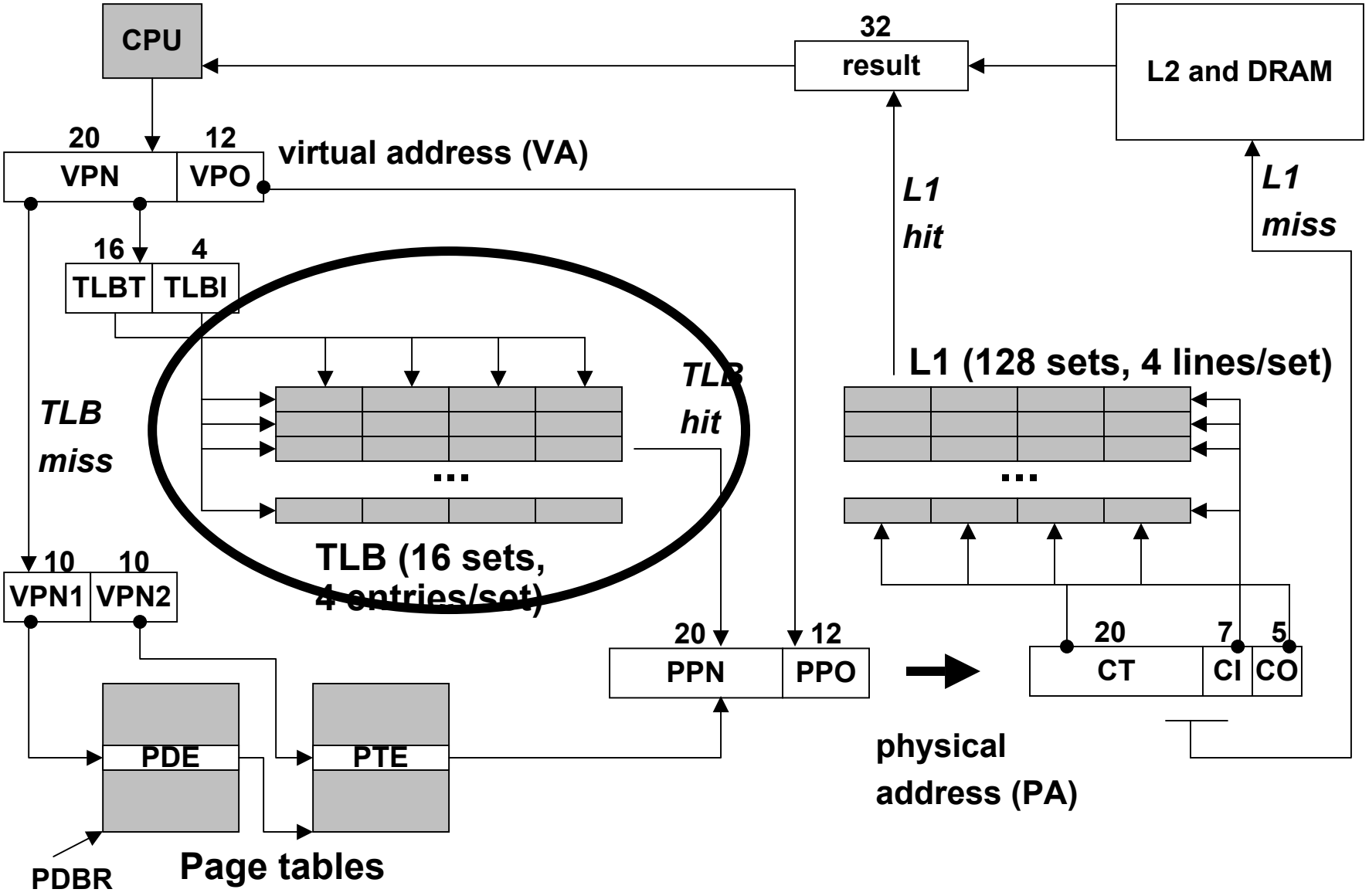
Simplified Example

- 16 page virtual address space

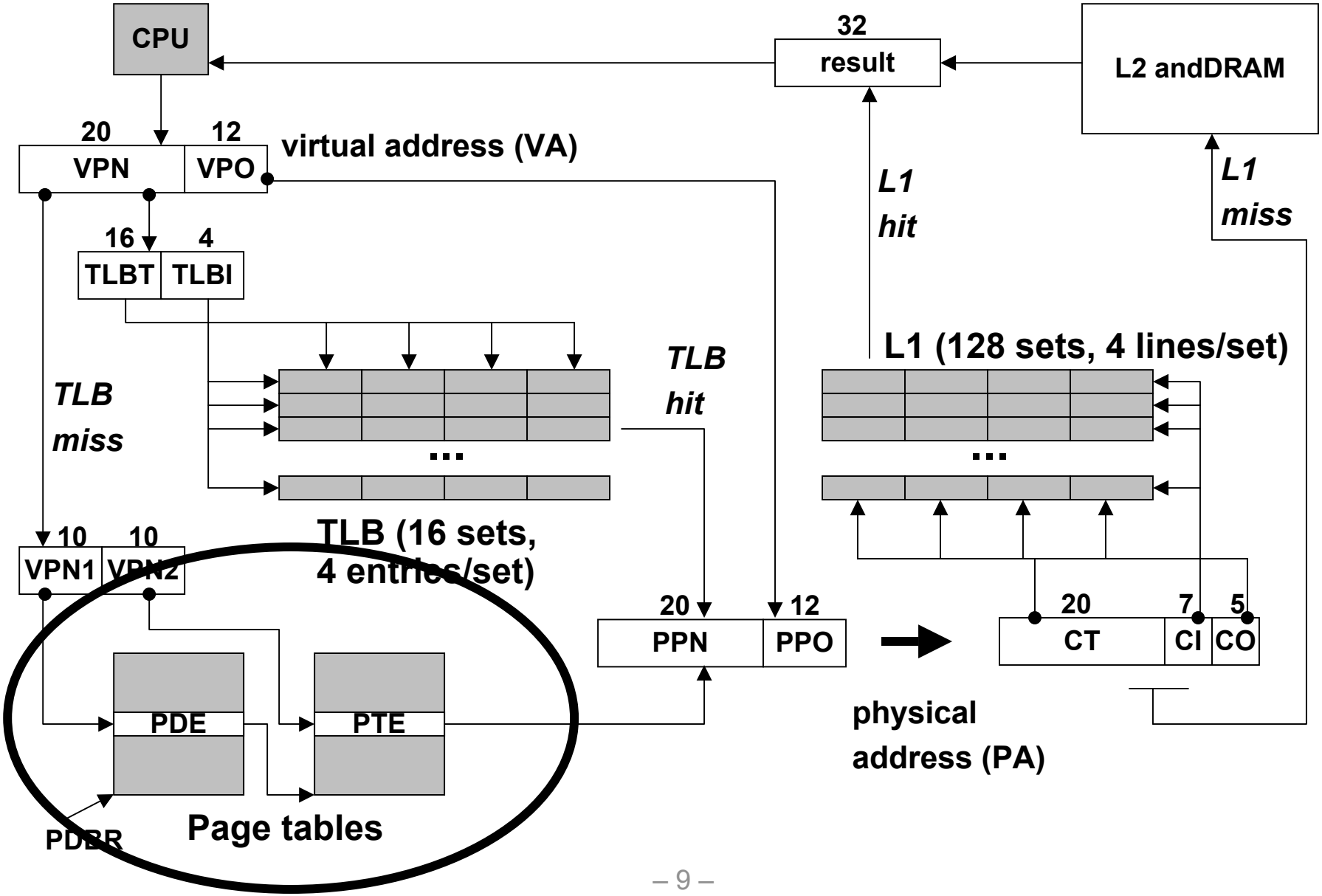
Flags

- P: Is entry in physical memory?
- M: Has this part of VA space been mapped?

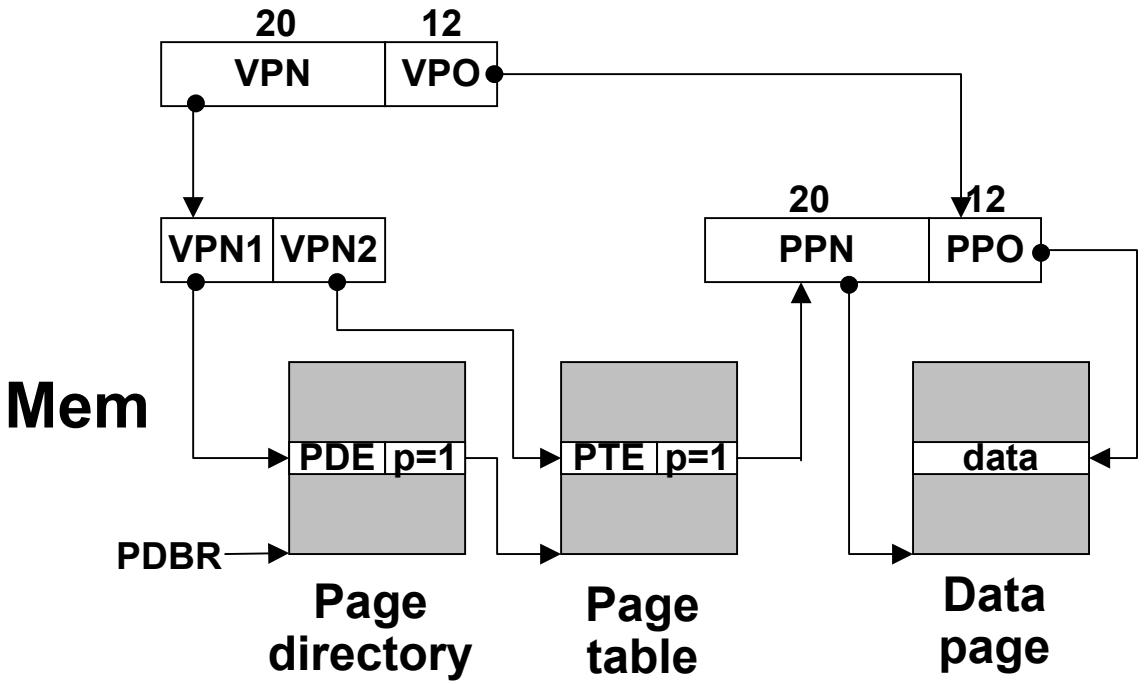
Common Case: TLB – No OS Involved



Uncommon Case: Not in TLB



Translating with the P6 page tables (case 1/1)



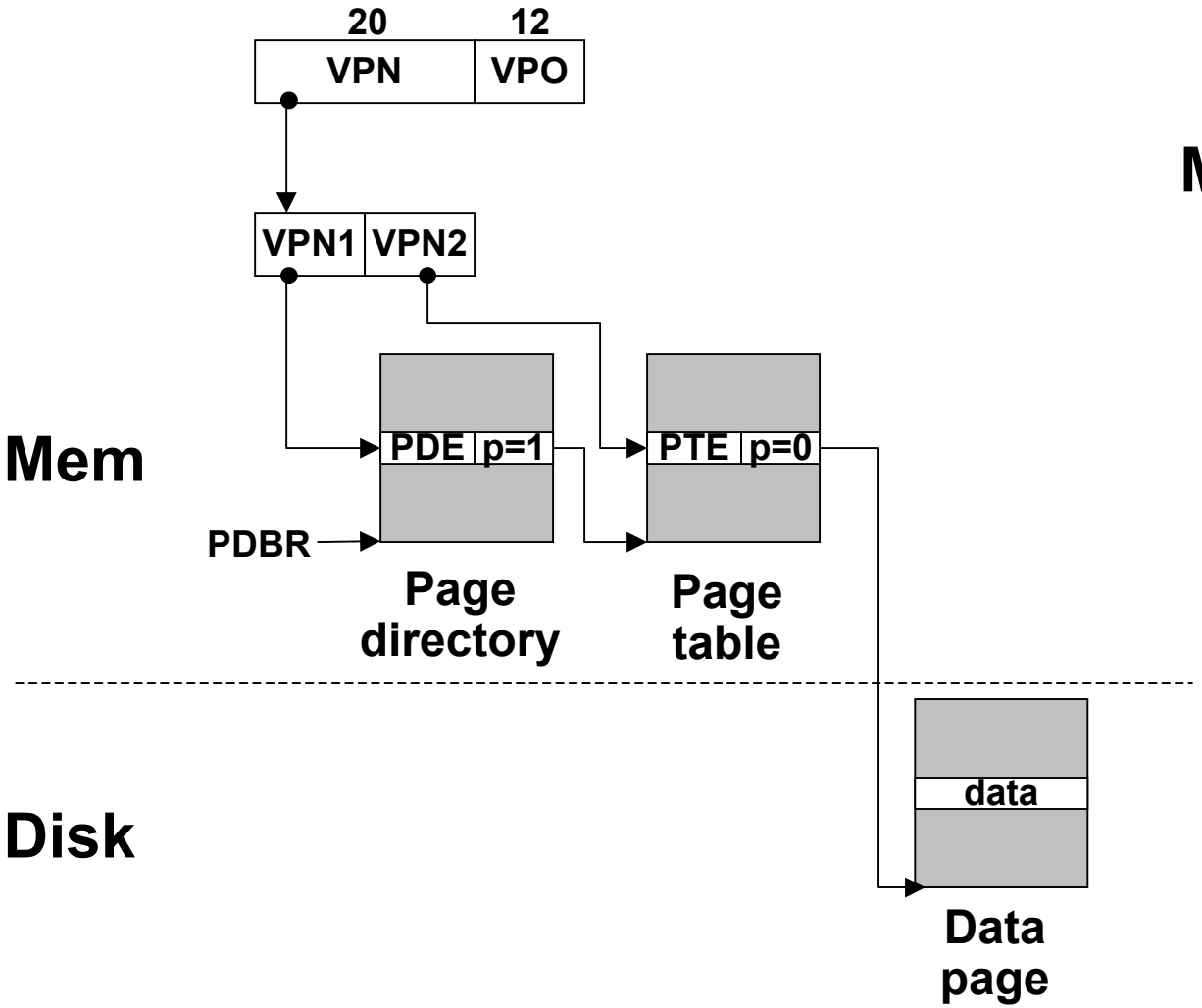
Case 1/1: page table and page present.

MMU Action:

- **MMU build physical address and fetch data word.**

- **OS action**
  - **none**

Translating with the P6 page tables (case 1/0)

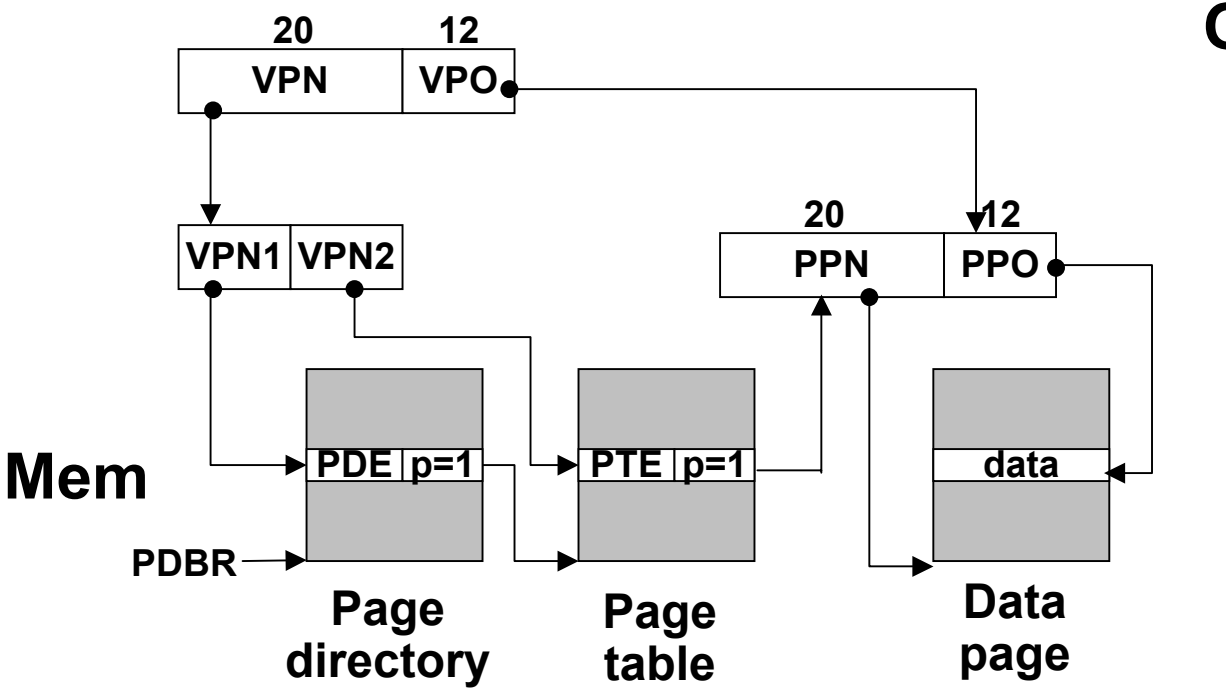


Case 1/0: page table present but page missing.

MMU Action:

- **page fault exception**
- **OS's handler receives the following args:**
  - VA that caused fault
  - fault caused by non-present page or page-level protection violation
  - read/write
  - user/supervisor

Translating with the P6 page tables (case 1/0, cont)



OS Action:

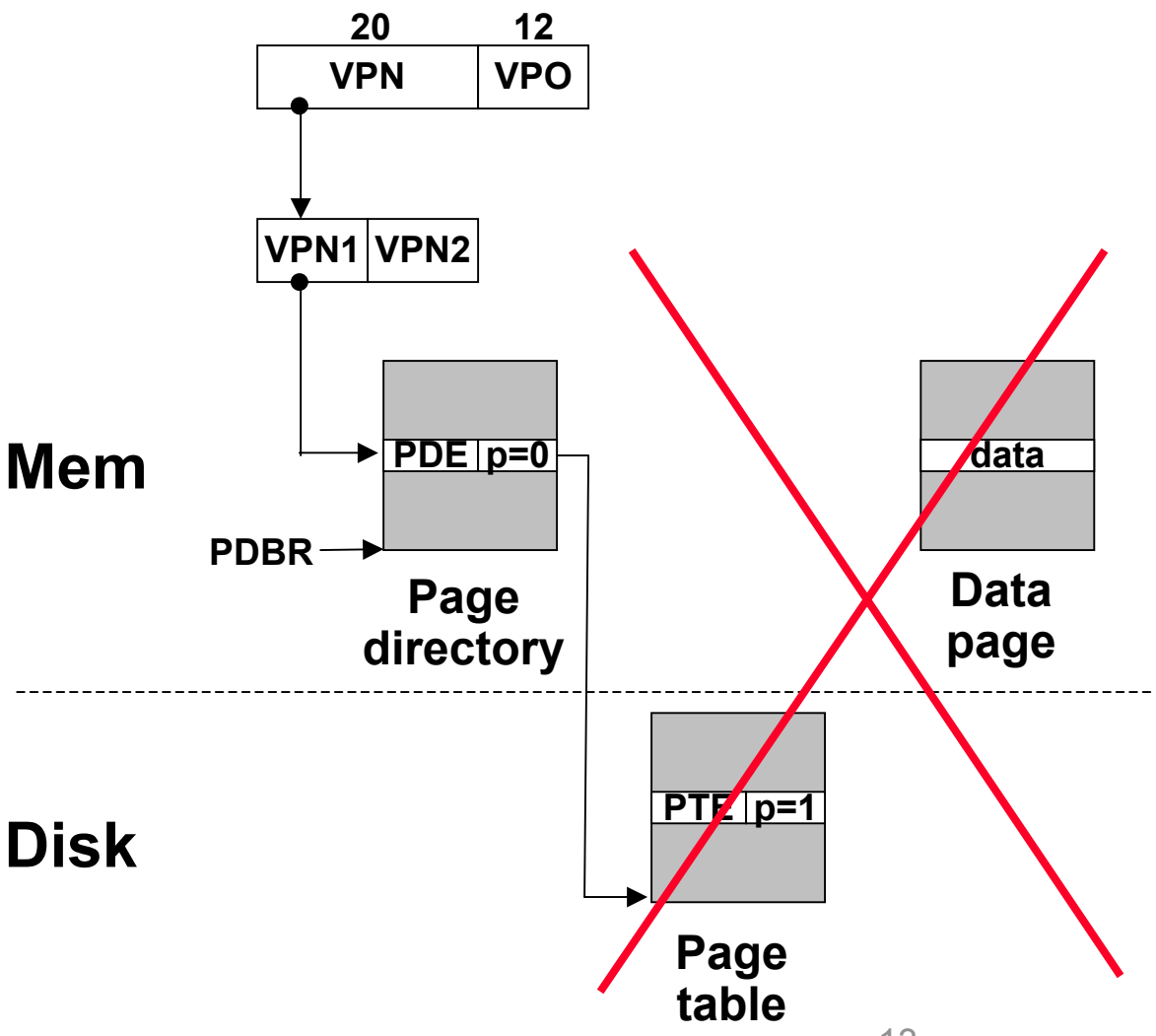
- Check for a legal virtual address.
- Read PTE through PDE.
- Find free physical page (swapping out current page if necessary)
- Read virtual page from disk and copy to virtual page
- Restart faulting instruction by returning from exception handler.

Probably Later

Lets another process run

while the disk is getting the page

Translating with the P6 page tables (case 0/1)



Case 0/1: page table missing but page present.

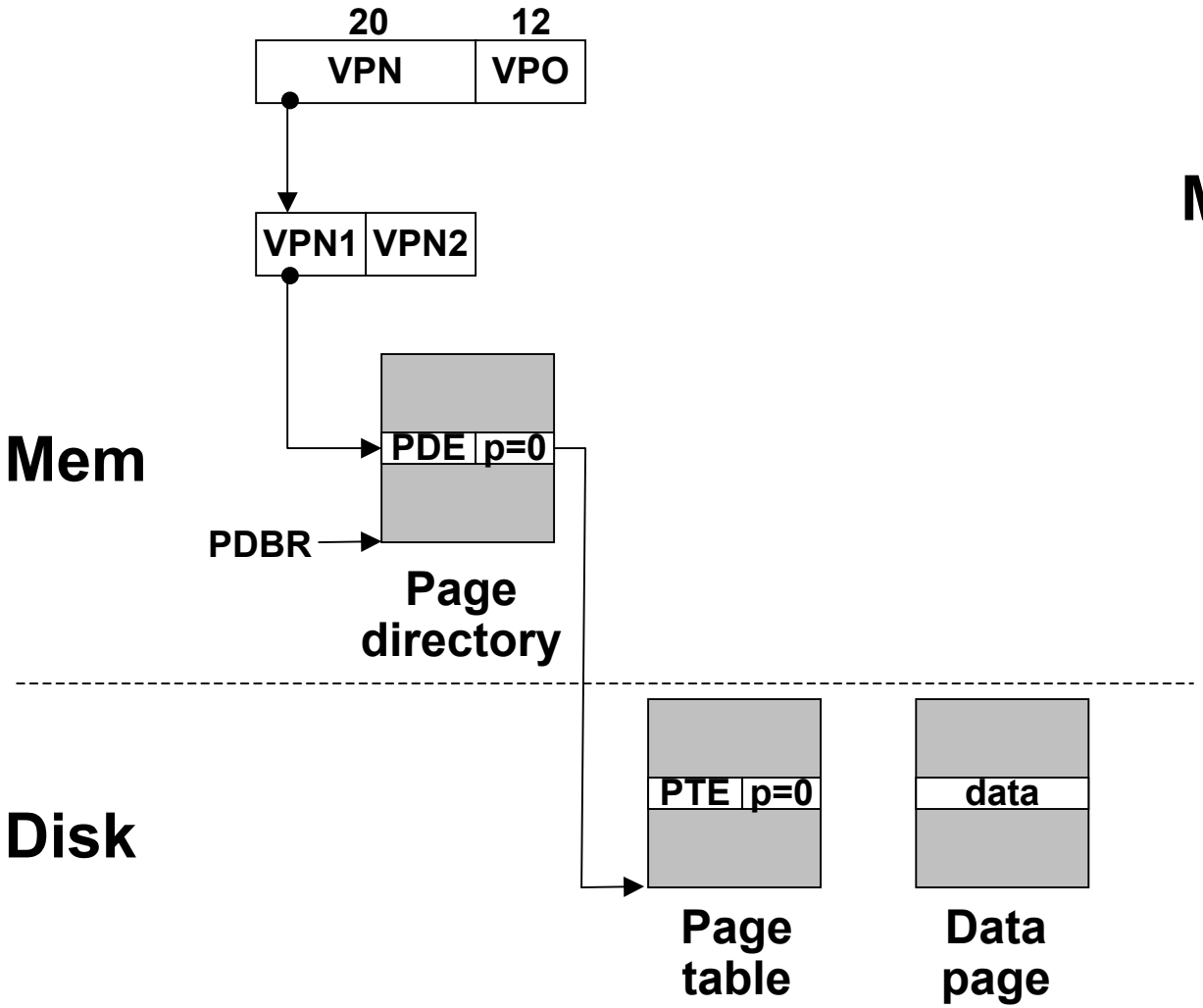
Introduces consistency issue.

- potentially every page out requires update of disk page table.

Linux disallows this

- if a page table is swapped out, then swap out its data pages too.

Translating with the P6 page tables (case 0/0)

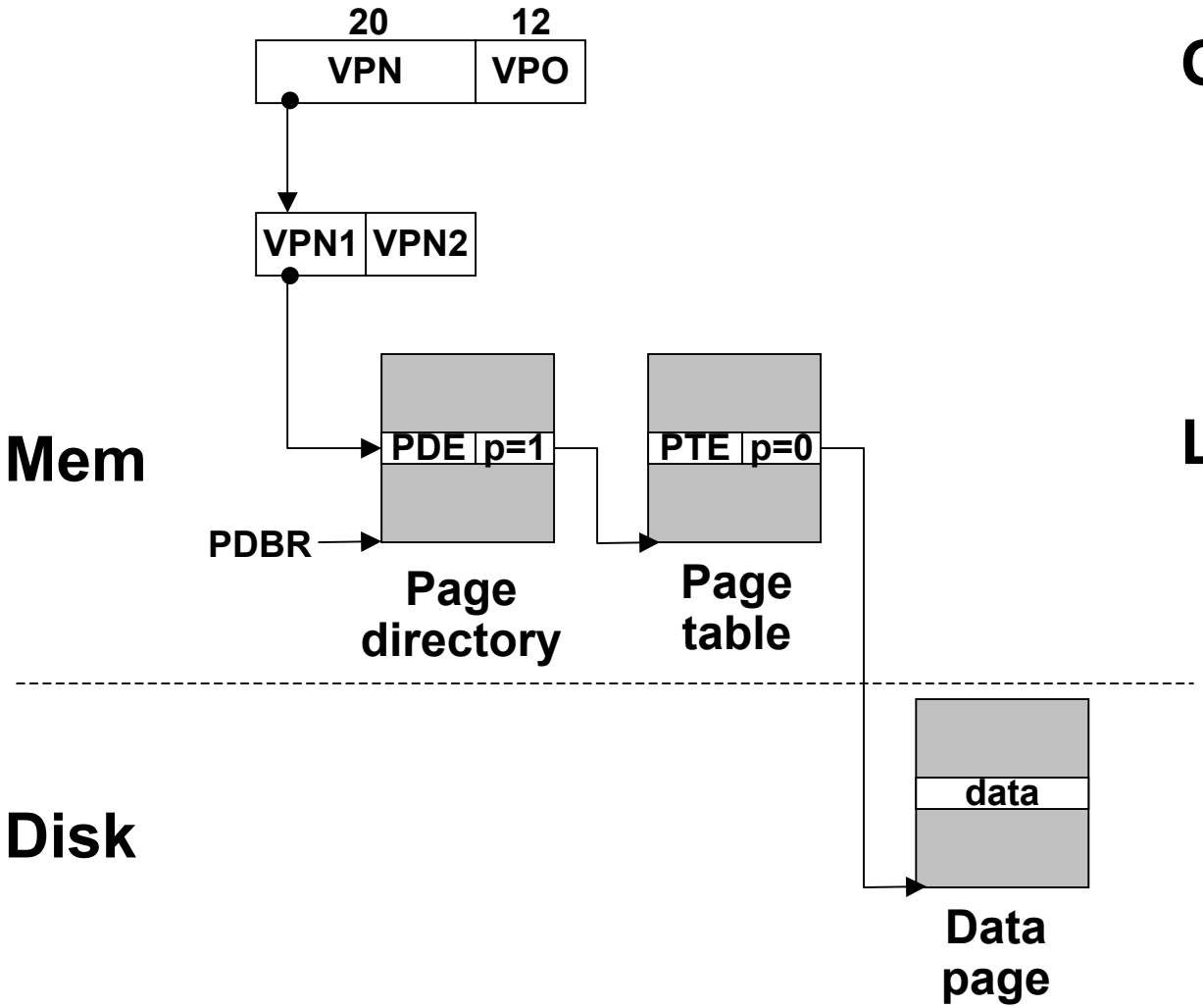


Case 0/0: page table and page missing.

MMU Action:

- **page fault exception**

Translating with the P6 page tables (case 0/0, cont)

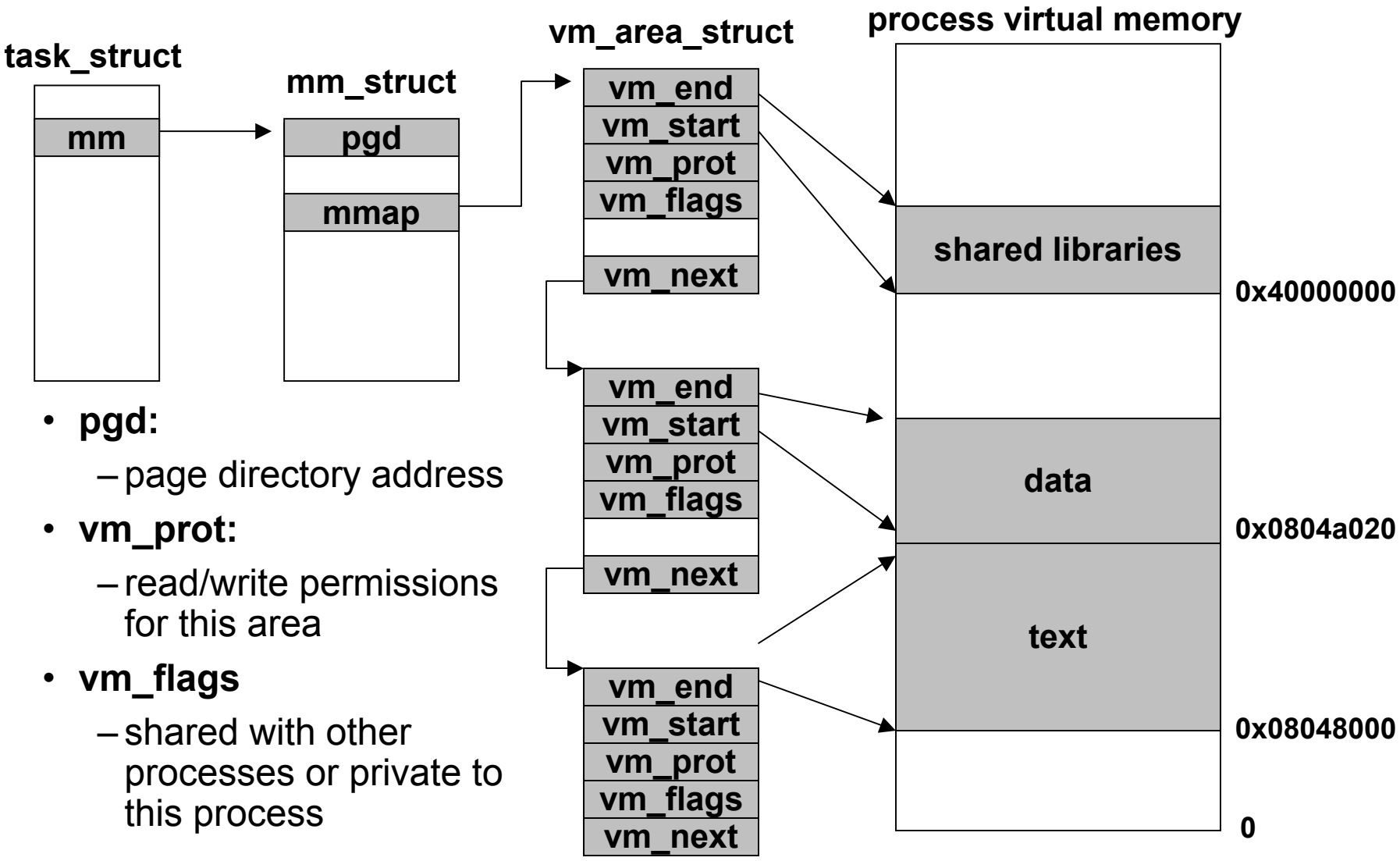


OS action:

- **swap in page table.**
- **restart faulting instruction by returning from handler.**

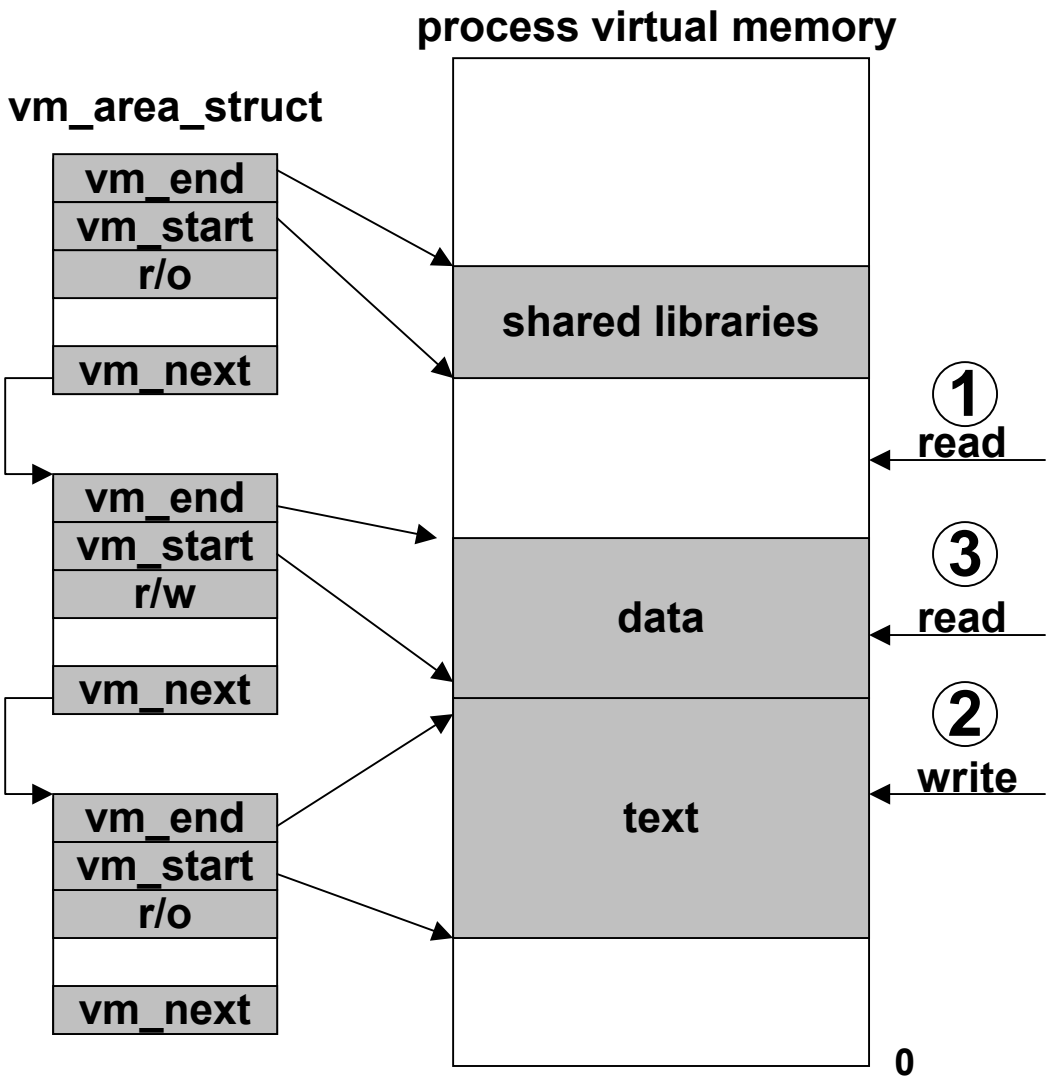
Like case 0/1 from here on.

Linux organizes VM as a collection of "areas" (Hardware Independent)



- **pgd:**
  - page directory address
- **vm_prot:**
  - read/write permissions for this area
- **vm_flags**
  - shared with other processes or private to this process

Linux page fault handling



Is the VA legal?

- i.e. is it in an area defined by a vm_area_struct?
- if not then signal segmentation violation (e.g. (1)) (or extend stack)

Is the operation legal?

- i.e., can the process read/write this area?
- if not then signal protection violation (e.g., (2))

If OK, handle fault

- e.g., (3)
- Must also update page tables

Memory mapping

Creation of new VM *area* done via "memory mapping"

- **create new vm_area_struct and page tables for area**
- **area can be backed by (i.e., get its initial values from) :**
  - regular file on disk (e.g., an executable object file)
    - » initial page bytes come from a section of a file
  - nothing (e.g., bss)
    - » initial page bytes are zeros
- **dirty pages are swapped back and forth between a special swap file.**

Key point: no virtual pages are copied into physical memory until they are referenced!

- **known as "demand paging"**
- **crucial for time and space efficiency**

User-level memory mapping

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

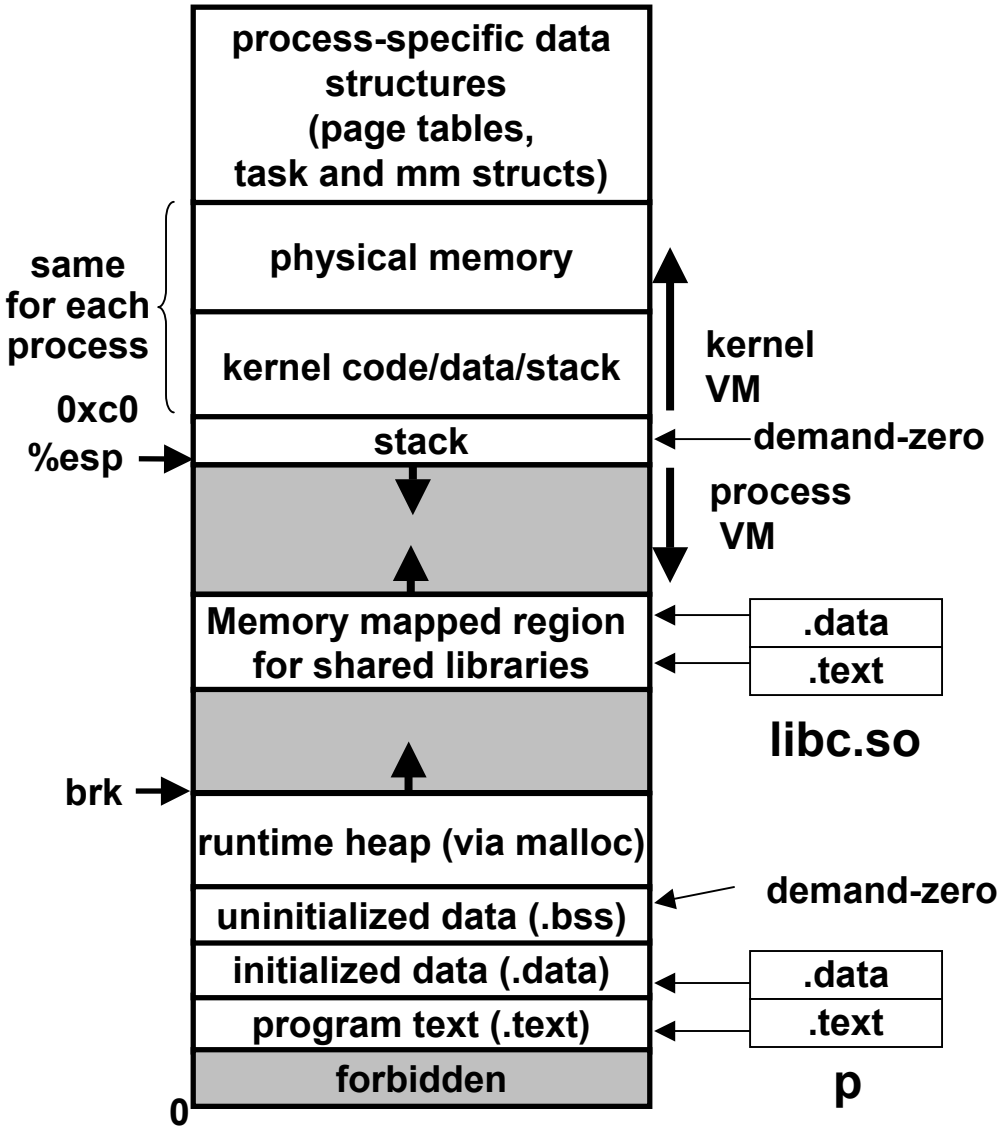
- **map `len` bytes starting at offset `offset` of the file specified by file description `fd`, preferably at address `start` (usually 0 for don't care).**
  - File can be anonymous (all zeros, not actually stored, "demand zero")
  - prot: PROT_READ, PROT_WRITE, PROT_EXEC,PROT_NONE
  - flags: MAP_PRIVATE, MAP_SHARED, MAP_ANON
- **return a pointer to the mapped area.**
- **Example: fast file copy**
  - useful for applications like Web servers that need to quickly copy files.
  - mmap allows file transfers without copying into user space.
- **`Example: Sharing`**
  - **`Map same file into multiple addresses spaces`**

mmap() example: fast file copy

```
#include <unistd.h>
#include <sys/mman.h>
#include <sys/types.h>
#include <sys/stat.h>
#include <fcntl.h>

/*
 * mmap.c - a program that uses mmap
 * to copy itself to stdout
 */
int main() {
  struct stat stat;
  int i, fd, size;
  char *bufp;

  /* open the file and get its size*/
  fd = open("./mmap.c", O_RDONLY);
  fstat(fd, &stat);
  size = stat.st_size;
```

```
/* map the file to a new VM area */
  bufp = mmap(0, size, PROT_READ,
    MAP_PRIVATE, fd, 0);

  /* write the VM area to stdout */
  write(1, bufp, size);
}
```

Exec() revisited



To run a new program p in the current process using exec():

- **free vm_area_struct's and page tables for old areas.**
- **create new vm_area_struct's and page tables for new areas.**
  - stack, bss, data, text, shared libs.
  - text and data backed by ELF executable object file.
  - bss and stack initialized to zero.
- **set PC to entry point in .text**
  - Linux will swap in code and data pages as needed.

Fork() revisted

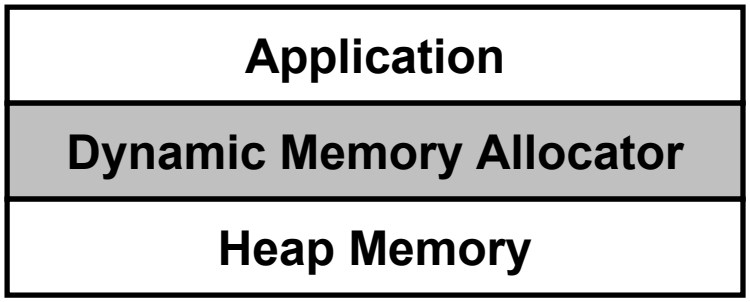
To create a new process using fork:

- **make copies of the old process's mm_struct, vm_area_struct's, and page tables.**
  - at this point the two processes are sharing all of their pages.
  - How to get separate spaces without copying all the virtual pages from one space to another?
    - » "copy on write" technique.
- **copy-on-write**
  - make pages of writeable areas read-only
  - flag vm_area_struct's for these areas as private "copy-on-write".
  - writes by either process to these pages will cause page faults.
    - » fault handler recognizes copy-on-write, makes a copy of the page, and restores write permissions.
- **Net result:**
  - copies are deferred until absolutely necessary (i.e., when one of the processes tries to modify a shared page).

Dynamic Memory Allocation – beyond the stack and globals

- **Stack**
  - **Easy to allocate (decrement esp)**
  - **Easy to deallocate (increment esp)**
  - **Automatic**
  - **Can pass values to called procedures, but not up to callers**
- **Global variables**
  - **Statically allocated**
  - **Have to decide at compile time how much space you need**
- **Allocation on the heap**
  - **Dynamically allocated**
  - **Independent of procedure calls**
  - **But must be carefully managed**
    - Automatically: garbage collection
    - Manually: malloc/free or new/delete

Dynamic Memory Allocation



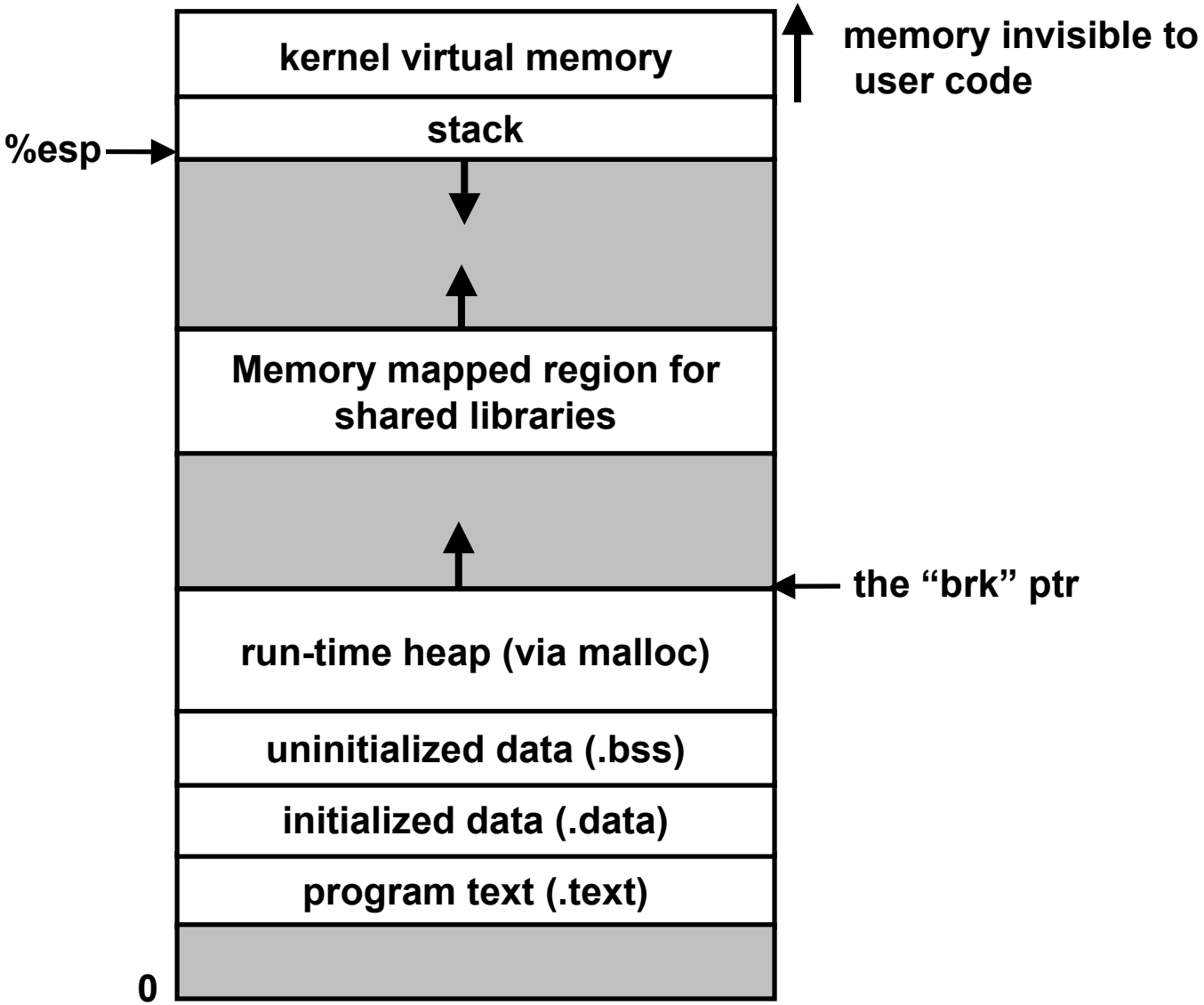
Explicit vs. Implicit Memory Allocator

- **Explicit: application allocates and frees space**
  - E.g., `malloc` and `free` in C
- **Implicit: application allocates, but does not free space**
  - E.g. garbage collection in Java, ML or Lisp

Allocation

- **In both cases the memory allocator provides an abstraction of memory as a set of blocks**
- **Doles out free memory blocks to application**

Process memory image



Allocators request additional heap memory from the operating system using the sbrk() function.

Malloc package

```
#include <stdlib.h>
void *malloc(size_t size)
```

- **if successful:**
  - returns a pointer to a memory block of at least **`size`** bytes, aligned to 8-byte boundary.
  - if `size==0`, returns NULL
- **if unsuccessful:** returns NULL

```
void free(void *p)
```

- **returns the block pointed at by p to pool of available memory**
- **p must come from a previous call to `malloc` or `realloc`.**

```
void *realloc(void *p, size_t size)
```

- **changes size of block p and returns ptr to new block.**
- **contents of new block unchanged up to min of old and new size.**

Malloc example

```
void foo(int n, int m) {
  int i, *p;

  /* allocate a block of n ints */
  if ((p = (int *) malloc(n * sizeof(int))) == NULL) {
    perror("malloc");
    exit(0);
  }
  for (i=0; i<n; i++)
    p[i] = i;

  /* add m bytes to end of p block */
  if ((p = (int *) realloc(p, (n+m) * sizeof(int))) == NULL) {
    perror("realloc");
    exit(0);
  }
  for (i=n; i < n+m; i++)
    p[i] = i;

  /* print new array */
  for (i=0; i<n+m; i++)
    printf("%d\n", p[i]);

  free(p); /* return p to available memory pool */
}
```