Virtual Memory: Systems
虚拟内存:系统

100076202： 计算机系统导论

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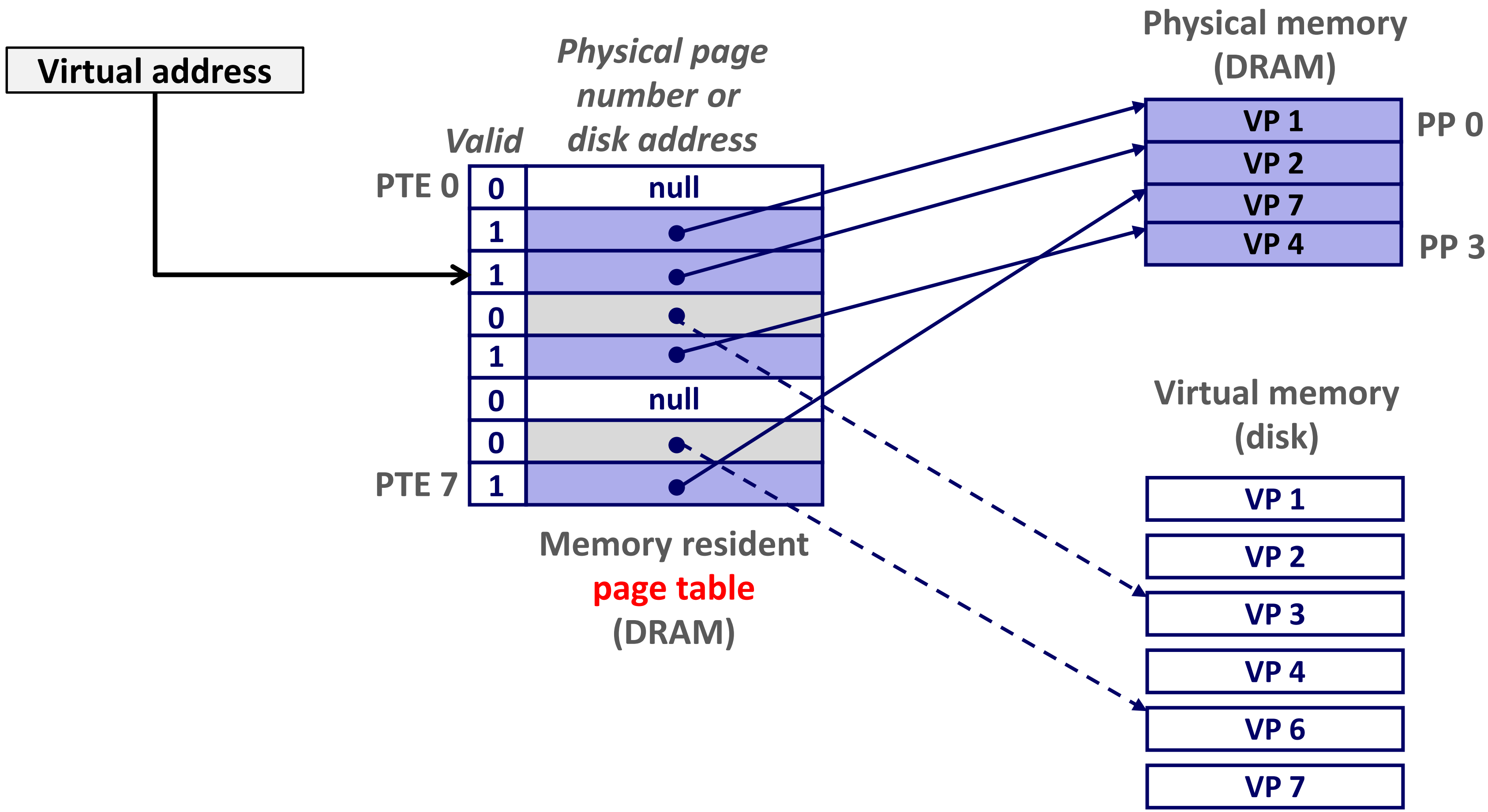
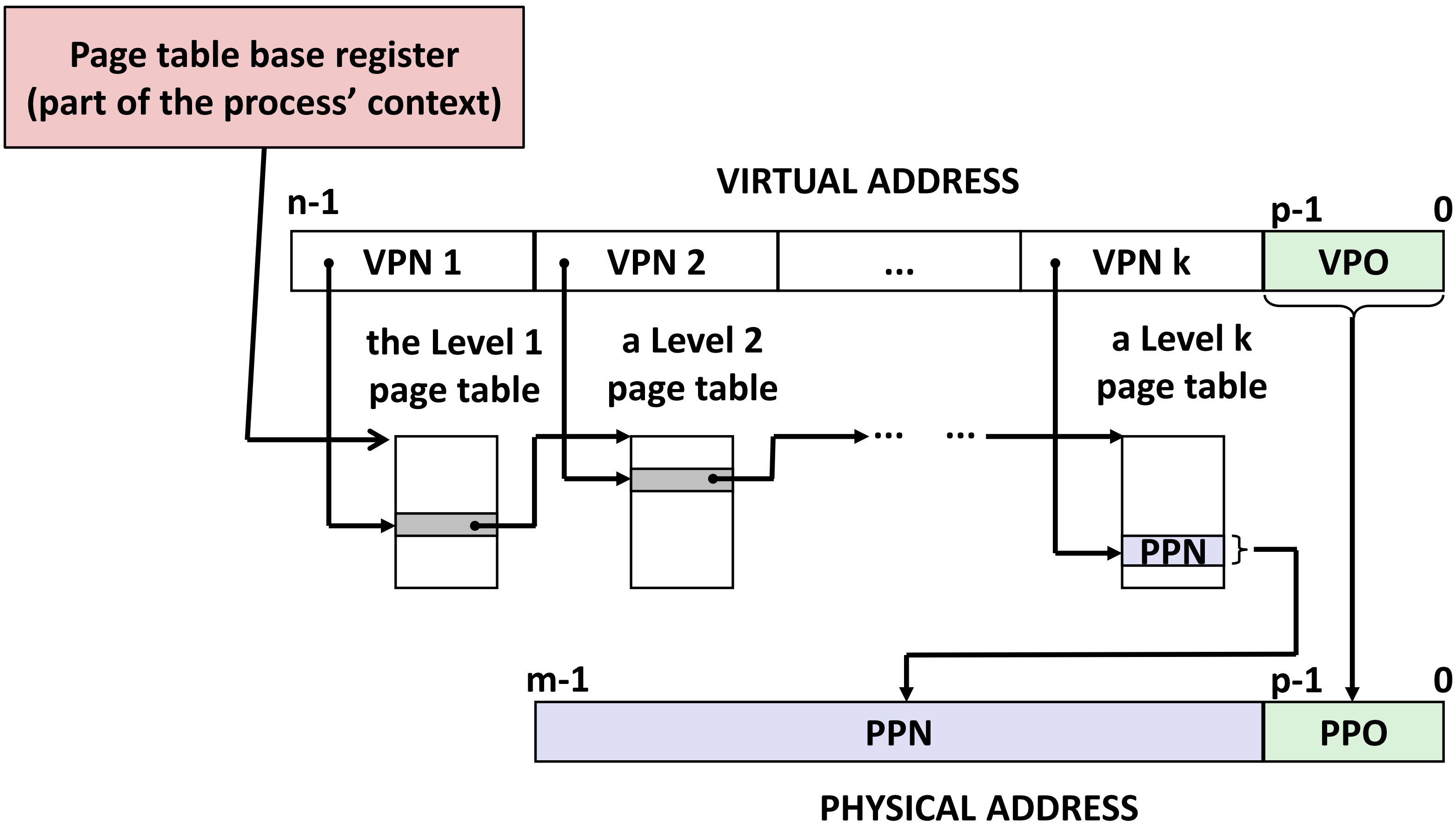
Review: Virtual Memory & Physical Memory



- A *page table* contains page table entries (PTEs) that map virtual pages to physical pages.

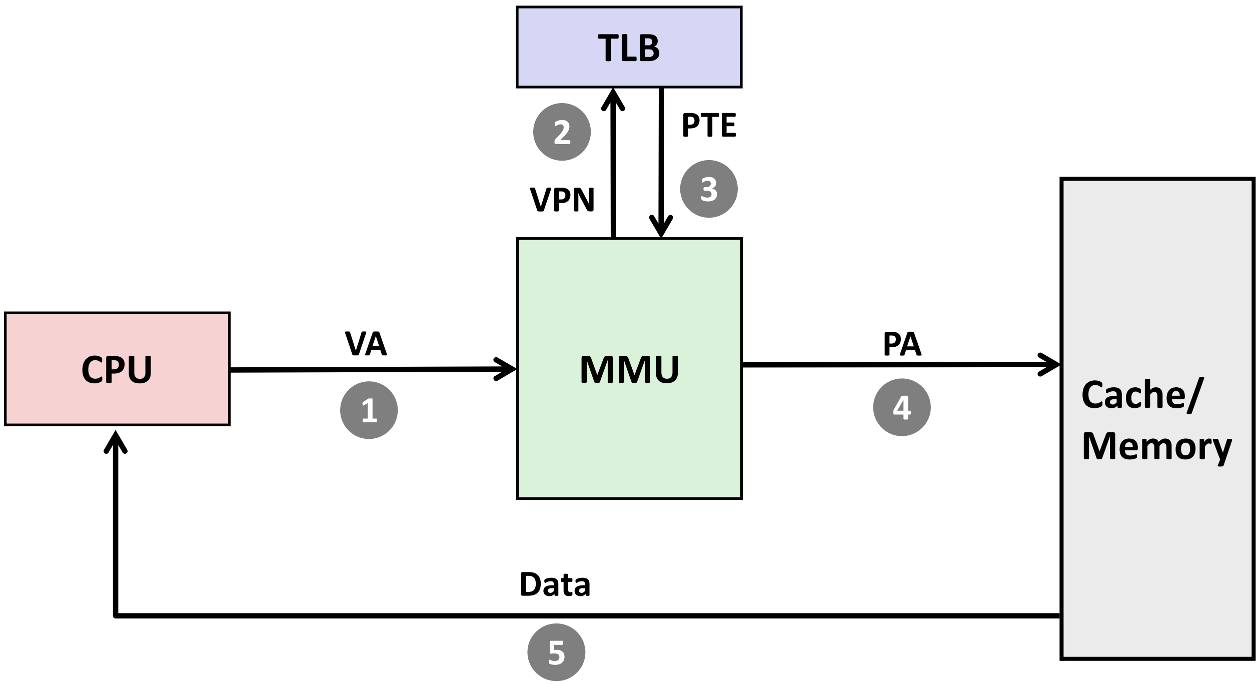
Translating with a k-level Page Table

- **Having multiple levels greatly reduces page table size**



Translation Lookaside Buffer (TLB)

- A small cache of page table entries with fast access by MMU

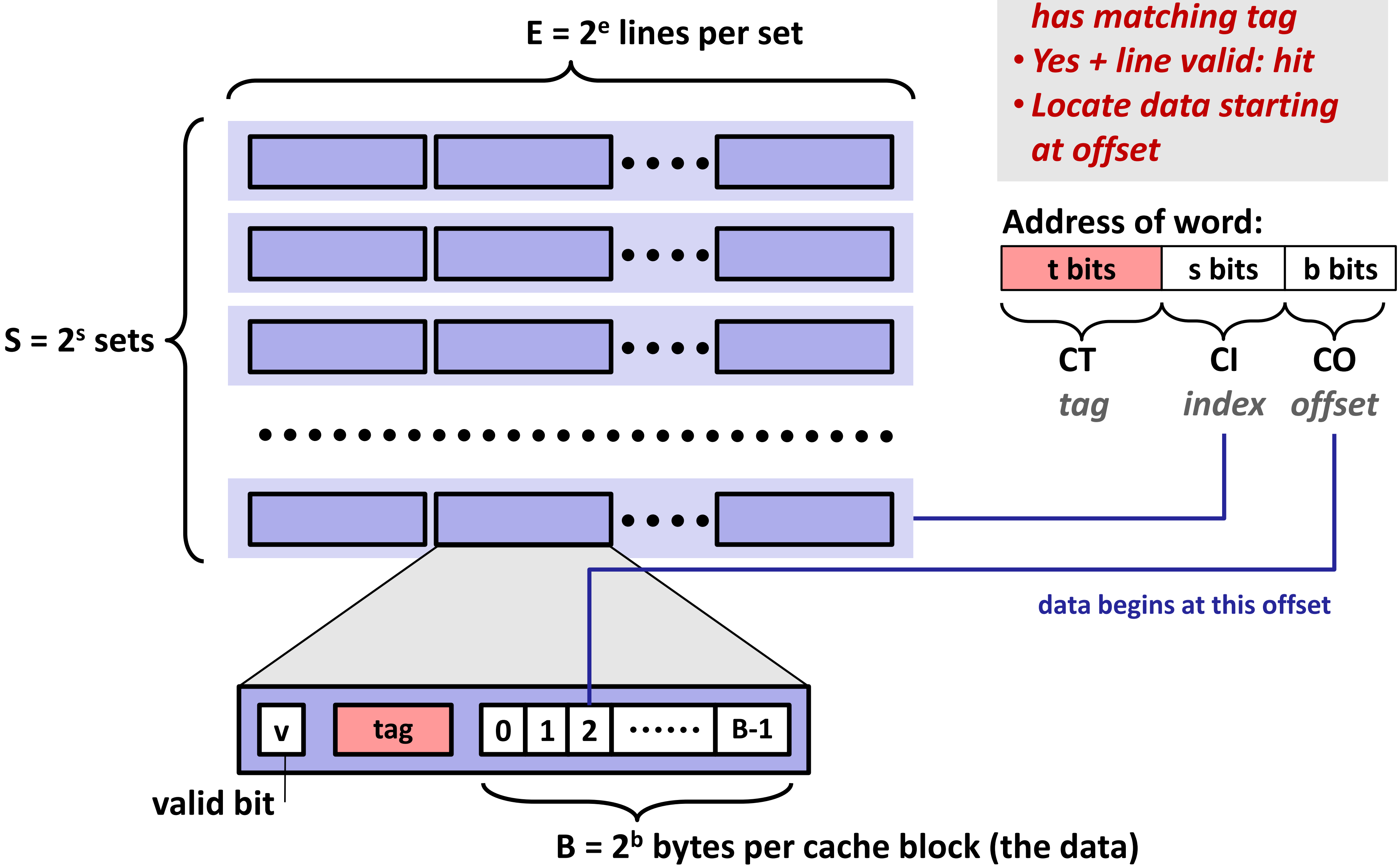


Typically, a TLB hit eliminates the k memory accesses required to do a page table lookup.

Recall: Set Associative Cache

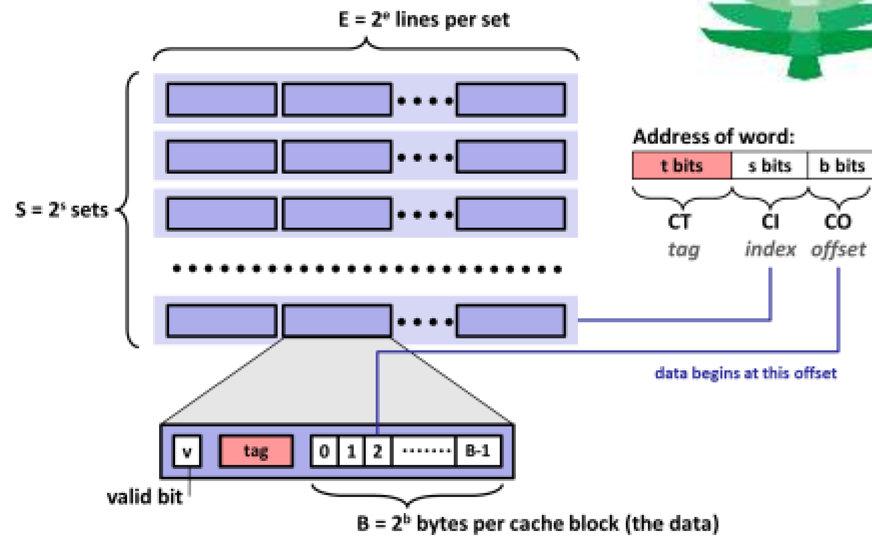
Steps for a READ:

- ***Locate set***
- ***Check if any line in set has matching tag***
- ***Yes + line valid: hit***
- ***Locate data starting at offset***

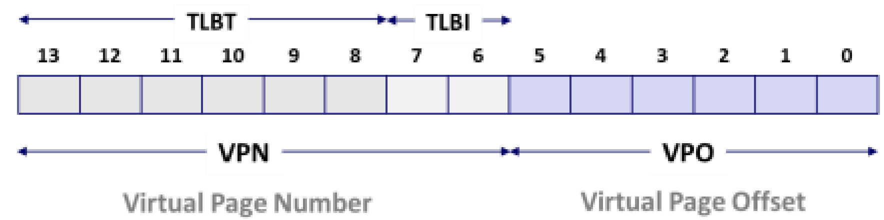


Review of Symbols

- **Basic Parameters**
  - **$N = 2^n$** : Number of addresses in virtual address space
  - **$M = 2^m$** : Number of addresses in physical address space
  - **$P = 2^p$** : Page size (bytes)

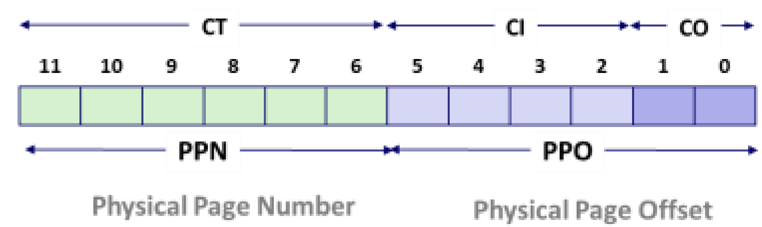


- **Components of the *virtual address* (VA)**
  - **TLBI**: TLB index
  - **TLBT**: TLB tag
  - **VPO**: Virtual page offset
  - **VPN**: Virtual page number



- **Components of the *physical address* (PA)**
  - **PPO**: Physical page offset (same as VPO)
  - **PPN:** Physical page number
  - **CO**: Byte offset within cache line
  - **CI:** Cache index
  - **CT**: Cache tag

(bits per field for our simple example)



议题 Today

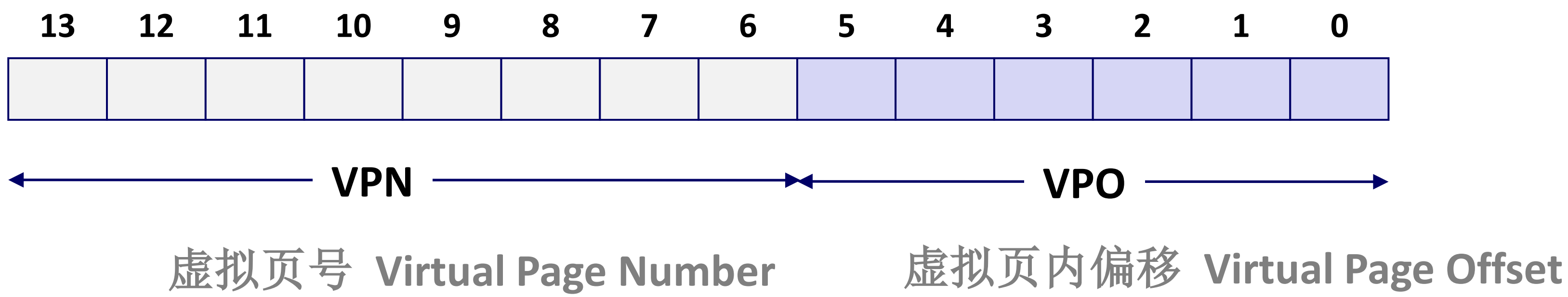
- **简单内存系统示例 Simple memory system example** CSAPP 9.6.4
- 案例研究：Core i7/Linux内存系统 Case study: Core i7/Linux memory system CSAPP 9.7
- 内存映射 Memory mapping CSAPP 9.8

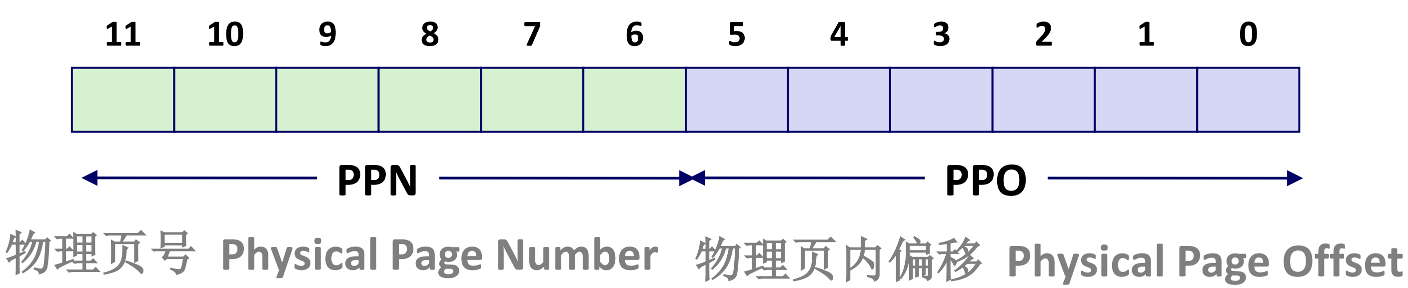
符号回顾 Review of Symbols

- 基本参数 **Basic Parameters**
  - **$N = 2^n$** : Number of addresses in virtual address space 虚拟地址空间的地址数量
  - **$M = 2^m$** : Number of addresses in physical address space 物理地址空间的地址数量
  - **$P = 2^p$** : Page size (bytes) 页大小（字节）
- 虚拟地址VA划分 **Components of the virtual address (VA)**
  - **TLBI**: TLB index TLB索引
  - **TLBT**: TLB tag TLB标记
  - **VPO**: Virtual page offset 虚拟页内偏移
  - **VPN**: Virtual page number 虚拟页号
- 物理地址PA划分 **Components of the physical address (PA)**
  - **PPO**: Physical page offset (same as VPO) 物理页内偏移（同VPO）
  - **PPN:** Physical page number 物理页号
  - **CO**: Byte offset within cache line Cache行中的偏移
  - **CI:** Cache index Cache索引
  - **CT**: Cache tag Cache标记

简单的内存系统示例
Simple Memory System Example

- **寻址 Addressing**
  - 14位虚拟地址　14-bit virtual addresses
  - 12位物理地址　12-bit physical address
  - 页大小为64字节　Page size = 64 bytes





简单内存系统TLB
Simple Memory System TLB

- 16个条目 16 entries
- 4路组相联 4-way associative

← TLBT →← TLBI →

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	0	1						

← VPN →← VPO →

VPN = 0b1101 = 0x0D

翻译后备缓冲区（TLB） Translation Lookaside Buffer (TLB)

Set	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid
0	03	–	0	09	0D	1	00	–	0	07	02	1
1	03	2D	1	02	–	0	04	–	0	0A	–	0
2	02	–	0	08	–	0	06	–	0	03	–	0
3	07	–	0	03	0D	1	0A	34	1	02	–	0

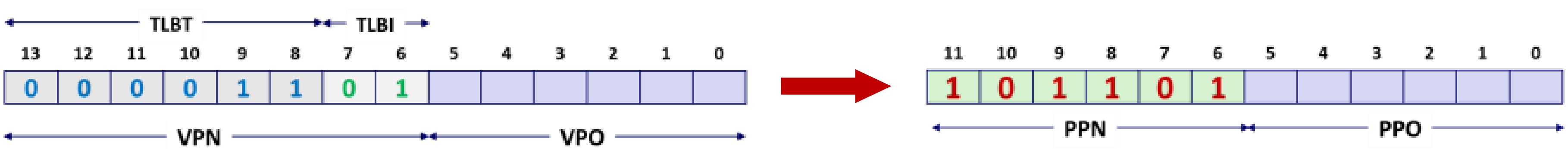
简单内存系统页表
Simple Memory System Page Table

只显示了前**16**个条目（**256**个条目） Only showing the first 16 entries (out of 256)

VPN	PPN	Valid
00	28	1
01	–	0
02	33	1
03	02	1
04	–	0
05	16	1
06	–	0
07	–	0

VPN	PPN	Valid
08	13	1
09	17	1
0A	09	1
0B	–	0
0C	–	0
0D	2D	1
0E	11	1
0F	0D	1

0x0D → 0x2D

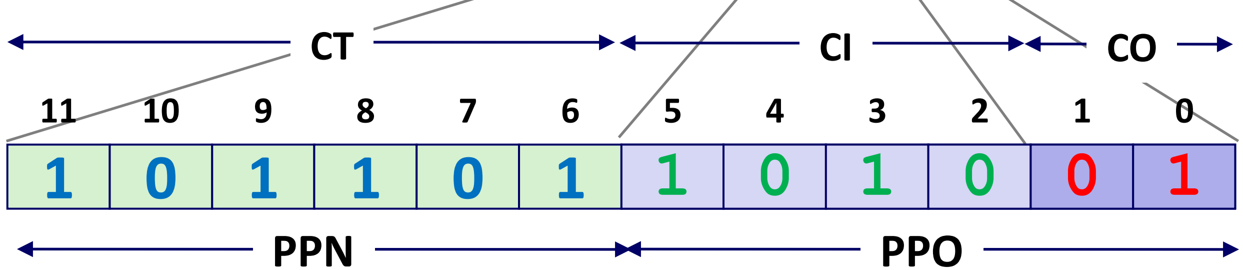


简单内存系统的Cache
Simple Memory System Cache

- 16行，4字节cache行大小 16 lines, 4-byte cache line size
- 物理地址 Physically addressed
- 直接映射 Direct mapped

V[0b00001101101001] = V[0x369]

P[0b101101101001] = P[0xB69] = 0x15



Idx	Tag	Valid	B0	B1	B2	B3
0	19	1	99	11	23	11
1	15	0	–	–	–	–
2	1B	1	00	02	04	08
3	36	0	–	–	–	–
4	32	1	43	6D	8F	09
5	0D	1	36	72	F0	1D
6	31	0	–	–	–	–
7	16	1	11	C2	DF	03

Idx	Tag	Valid	B0	B1	B2	B3
8	24	1	3A	00	51	89
9	2D	0	–	–	–	–
A	2D	1	93	15	DA	3B
B	0B	0	–	–	–	–
C	12	0	–	–	–	–
D	16	1	04	96	34	15
E	13	1	83	77	1B	D3
F	14	0	–	–	–	–

地址翻译示例 Address Translation Example

虚拟地址 Virtual Address: 0x03D4

TLBT | TLBI

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	1	1	0	1	0	1	0	0

VPN | VPO

VPN **0x0F** TLBI **0x3** TLBT **0x03** TLB Hit? **Y** Page Fault? **N** PPN: **0x0D**

TLB

Set	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid	Tag	PPN	Valid
0	03	–	0	09	0D	1	00	–	0	07	02	1
1	03	2D	1	02	–	0	04	–	0	0A	–	0
2	02	–	0	08	–	0	06	–	0	03	–	0
3	07	–	0	03	0D	1	0A	34	1	02	–	0

物理地址 Physical Address

11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	0	1	0	1	0	1	0	0

PPN | PPO

地址翻译示例 Address Translation Example

物理地址 Physical Address

	CT					CI				CO	
11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	0	1	0	1	0	1	0	0
PPN						PPO					

CO __0__ CI __0x5__ CT __0x0D__ Hit? __Y__ Byte: __0x36__

Cache

Idx	Tag	Valid	B0	B1	B2	B3
0	19	1	99	11	23	11
1	15	0	–	–	–	–
2	1B	1	00	02	04	08
3	36	0	–	–	–	–
4	32	1	43	6D	8F	09
5	0D	1	36	72	F0	1D
6	31	0	–	–	–	–
7	16	1	11	C2	DF	03

Idx	Tag	Valid	B0	B1	B2	B3
8	24	1	3A	00	51	89
9	2D	0	–	–	–	–
A	2D	1	93	15	DA	3B
B	0B	0	–	–	–	–
C	12	0	–	–	–	–
D	16	1	04	96	34	15
E	13	1	83	77	1B	D3
F	14	0	–	–	–	–

地址翻译示例：TLB/Cache不命中
Address Translation Example: TLB/Cache Miss

虚拟地址 Virtual Address: 0x0020

TLBT | TLBI

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0

VPN | VPO

VPN 0x00 TLBI 0 TLBT 0x00 TLB Hit? N Page Fault? N PPN: 0x28

物理地址 Physical Address

CT | CI | CO

11	10	9	8	7	6	5	4	3	2	1	0
1	0	1	0	0	0	1	0	0	0	0	0

PPN | PPO

CO 0 CI 0x8 CT 0x28 Hit? __ Byte: ____

Page table

VPN	*PPN*	*Valid*
00	28	1
01	–	0
02	33	1
03	02	1
04	–	0
05	16	1
06	–	0
07	–	0

地址翻译示例：TLB/Cache不命中
Address Translation Example: TLB/Cache Miss

Cache

Idx	Tag	Valid	B0	B1	B2	B3
0	19	1	99	11	23	11
1	15	0	–	–	–	–
2	1B	1	00	02	04	08
3	36	0	–	–	–	–
4	32	1	43	6D	8F	09
5	0D	1	36	72	F0	1D
6	31	0	–	–	–	–
7	16	1	11	C2	DF	03

Idx	Tag	Valid	B0	B1	B2	B3
8	24	1	3A	00	51	89
9	2D	0	–	–	–	–
A	2D	1	93	15	DA	3B
B	0B	0	–	–	–	–
C	12	0	–	–	–	–
D	16	1	04	96	34	15
E	13	1	83	77	1B	D3
F	14	0	–	–	–	–

物理地址 Physical Address

CT (bits 11–6) | CI (bits 5–2) | CO (bits 1–0)

11	10	9	8	7	6	5	4	3	2	1	0
1	0	1	0	0	0	1	0	0	0	0	0

PPN (bits 11–6) | PPO (bits 5–0)

CO 0 CI 0x8 CT 0x28 Hit? N Byte: Mem

议题 Today

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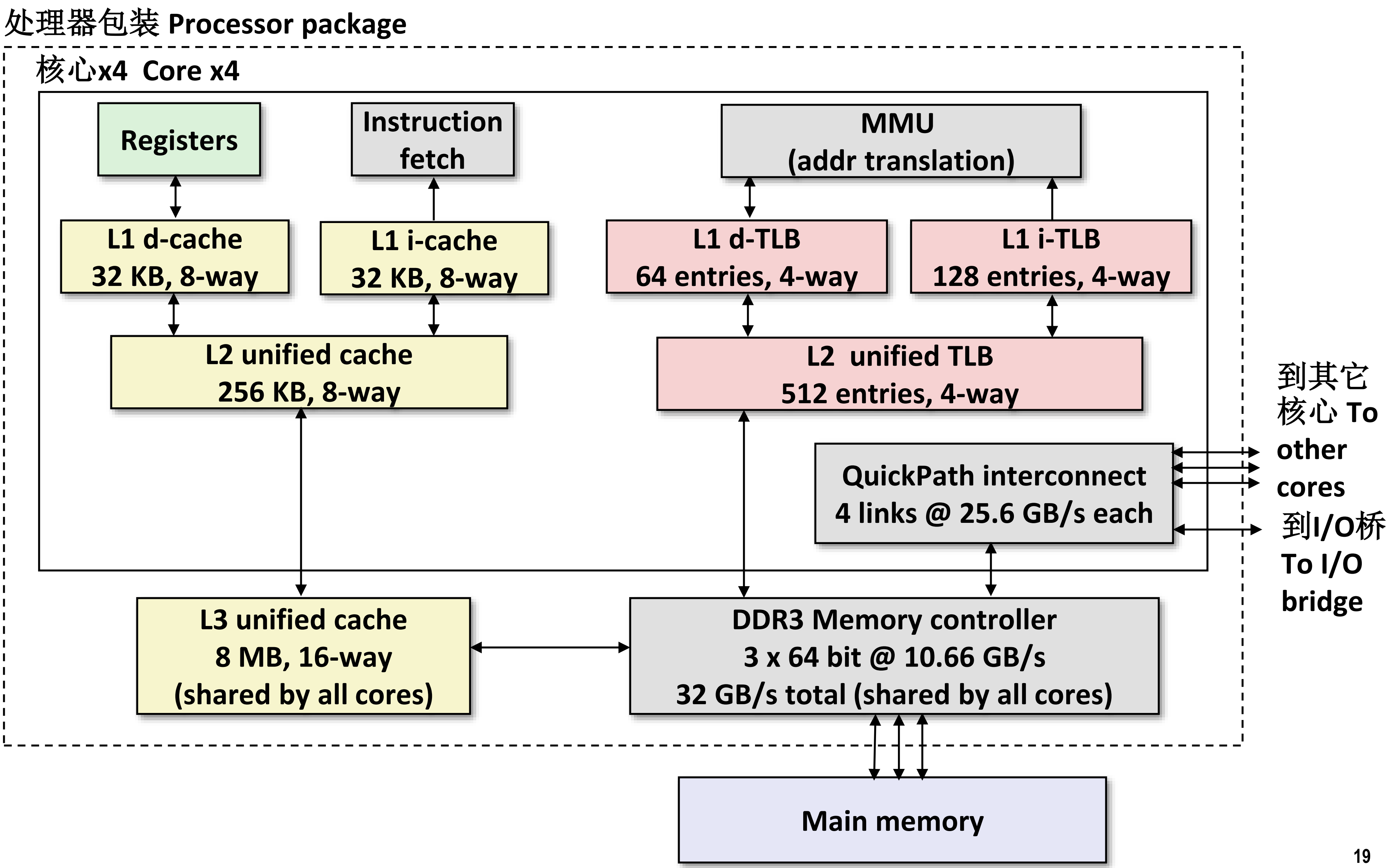
- 案例研究：Core i7/Linux内存系统 Case study: Core i7/Linux memory system
- 内存映射 Memory mapping

Intel Core i7存储系统
Intel Core i7 Memory System



符号回顾 Review of Symbols

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  - **$M = 2^m$** : Number of addresses in physical address space 物理地址空间的地址数量
  - **$P = 2^p$** : Page size (bytes)   页大小（字节）
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  - **TLBI**: TLB index   TLB索引
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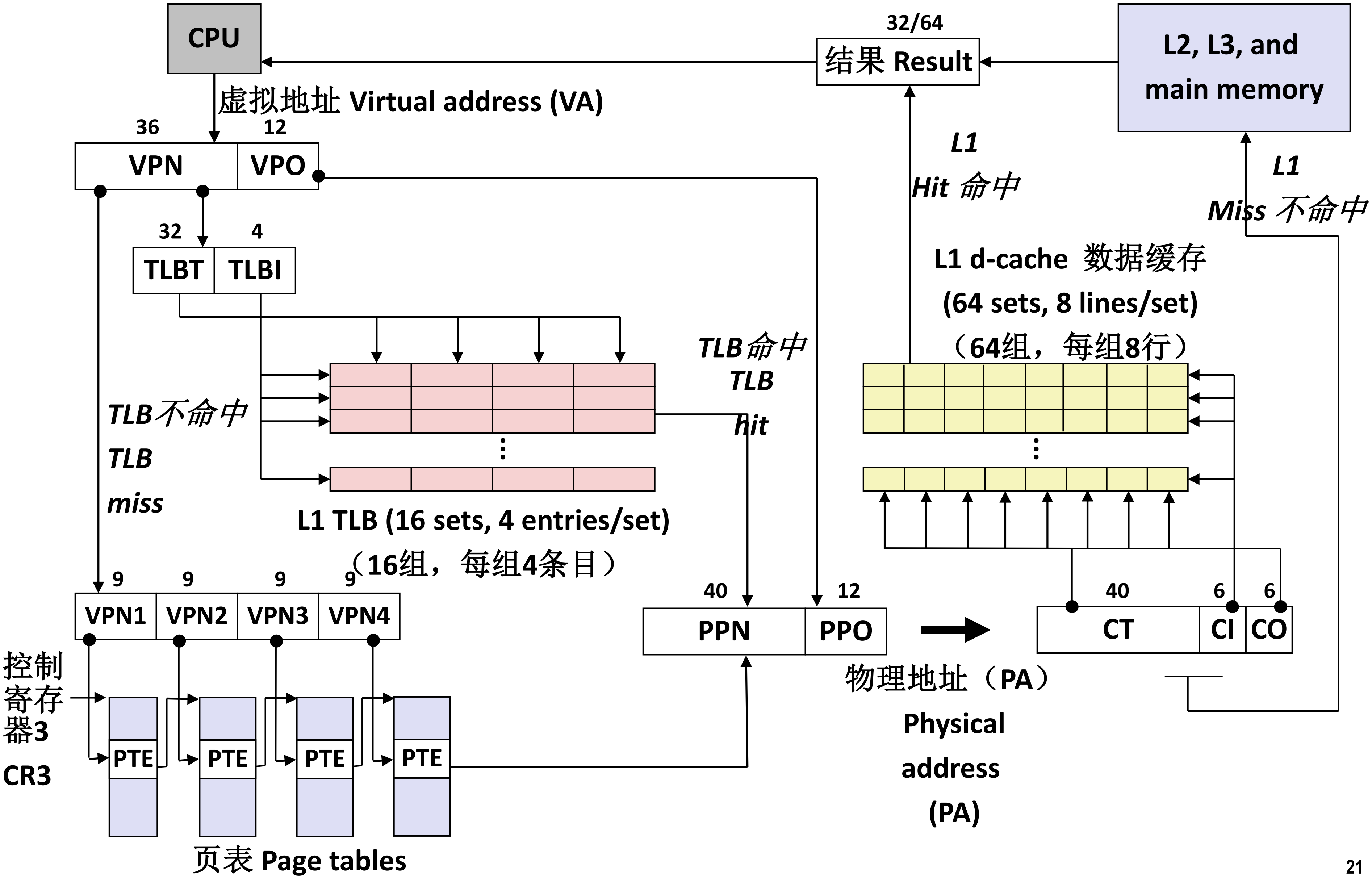
  - **VPN**: Virtual page number   虚拟页号
- 物理地址PA划分   **Components of the physical address (PA)**
  - **PPO**: Physical page offset (same as VPO)   物理页内偏移（同VPO）
  - **PPN:** Physical page number   物理页号
  - **CO**: Byte offset within cache line   Cache行中的偏移
  - **CI:** Cache index   Cache索引
  - **CT**: Cache tag   Cache标记

端到端Core i7地址翻译
End-to-end Core i7 Address Translation



Core i7 1-3级页表条目
Core i7 Level 1-3 Page Table Entries

63	62 … 52	51 … 12	11 … 9	8	7	6	5	4	3	2	1	0
XD	Unused	页表物理基地址 Page table physical base address	Unused	G	PS		A	CD	WT	U/S	R/W	P=1

操作系统可用（页表位于磁盘上）Available for OS (page table location on disk)	P=0

每个条目对应一个4k子页表，主要的字段包括： Each entry references a 4K child page table. Significant fields:

P:子页表是否在物理内存 Child page table present in physical memory (1) or not (0).

R/W: 只读或者读写权限标记位 Read-only or read-write access permission for all reachable pages.

U/S: 用户或特权（内核）模式标记位 user or supervisor (kernel) mode access permission for all reachable pages.

WT: 子页表的写直达或者写回Cache策略 Write-through or write-back cache policy for the child page table.

A: 引用标记(由MMU读写时设置，软件清除) Reference bit (set by MMU on reads and writes, cleared by software).

PS: 页面大小，4KB或者4MB(仅为1级PTE定义) Page size either 4 KB or 4 MB (defined for Level 1 PTEs only).

Page table physical base address: 物理页表地址的高40位(强制页表按照4KB对齐) 40 most significant bits of physical page table address (forces page tables to be 4KB aligned)

XD: 禁止或允许取指操作 Disable or enable instruction fetches from all pages reachable from this PTE.

Core i7 4级页表条目
Core i7 Level 4 Page Table Entries

63	62 – 52	51 – 12	11 – 9	8	7	6	5	4	3	2	1	0
XD	Unused	物理页基址/ Page physical base address	Unused	G		D	A	CD	WT	U/S	R/W	P=1

操作系统可见（内存页位于磁盘）Available for OS (page location on disk)	P=0

每个条目对应一个4k子页表，主要的字段包括： Each entry references a 4K child page. Significant fields:

P:子页表是否在物理内存 Child page table present in physical memory (1) or not (0).

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WT: 子页表的写直达或者写回Cache策略 Write-through or write-back cache policy for the child page table.

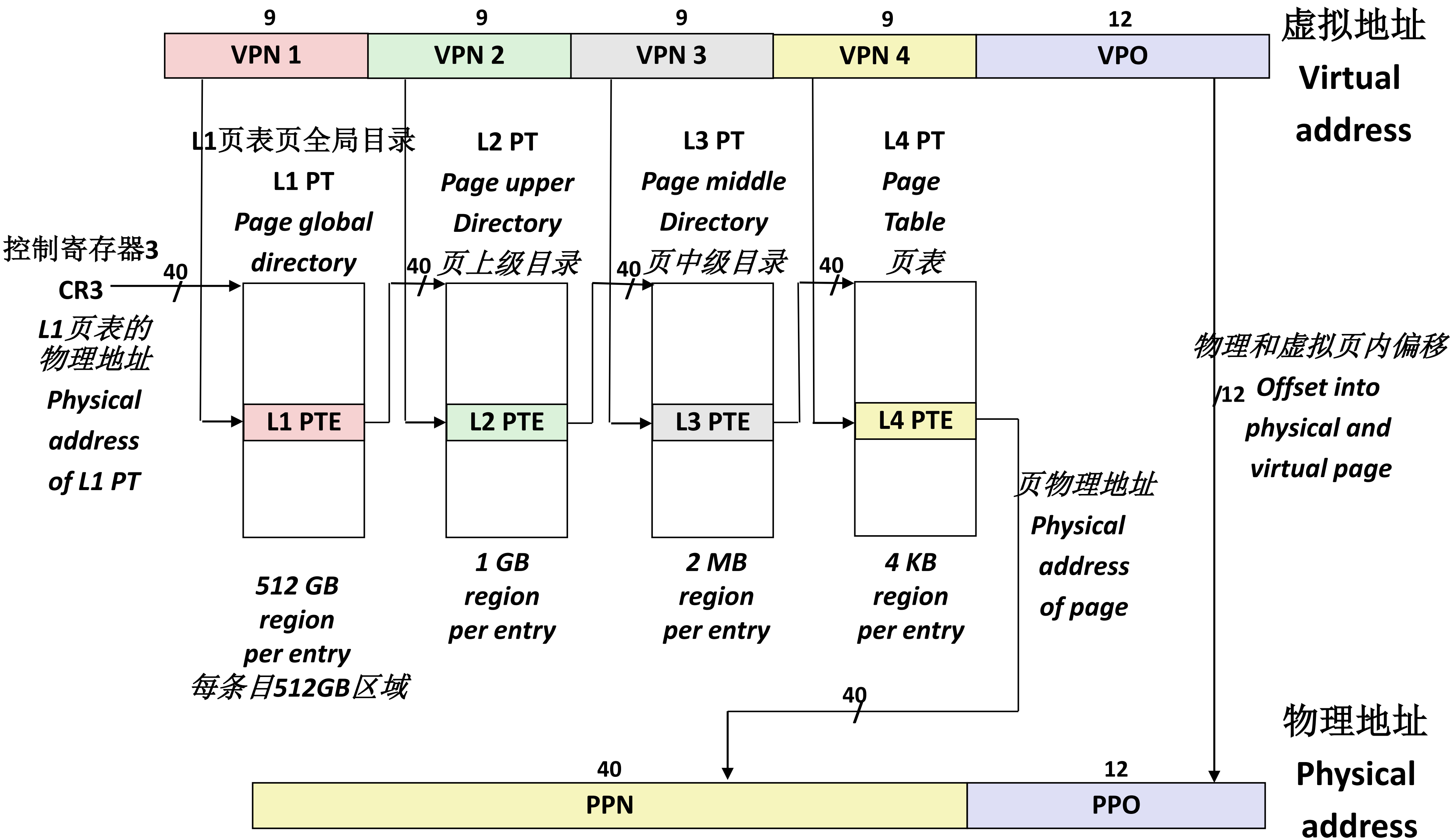
A: 引用标记(由MMU读写时设置，软件清除)/Reference bit(set by MMU on reads and writes, cleared by software).

D: 脏位(写操作时由MMU设置，软件清除) Dirty bit (set by MMU on writes, cleared by software)

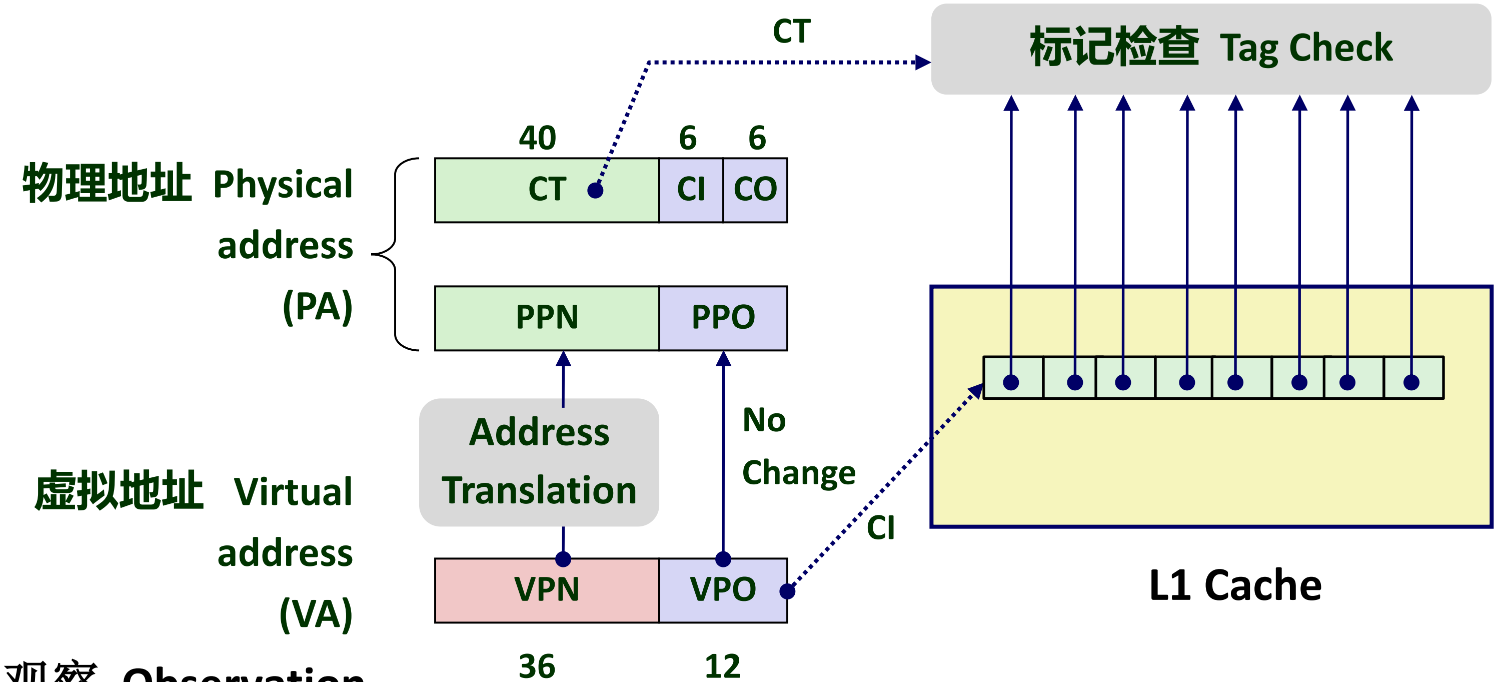
Page physical base address:物理页表地址的高40位(强制页表按照4KB对齐) 40 most significant bits of physical page address (forces pages to be 4KB aligned)

XD:禁止或允许取指操作 Disable or enable instruction fetches from this page.

Core i7页表翻译
Core i7 Page Table Translation

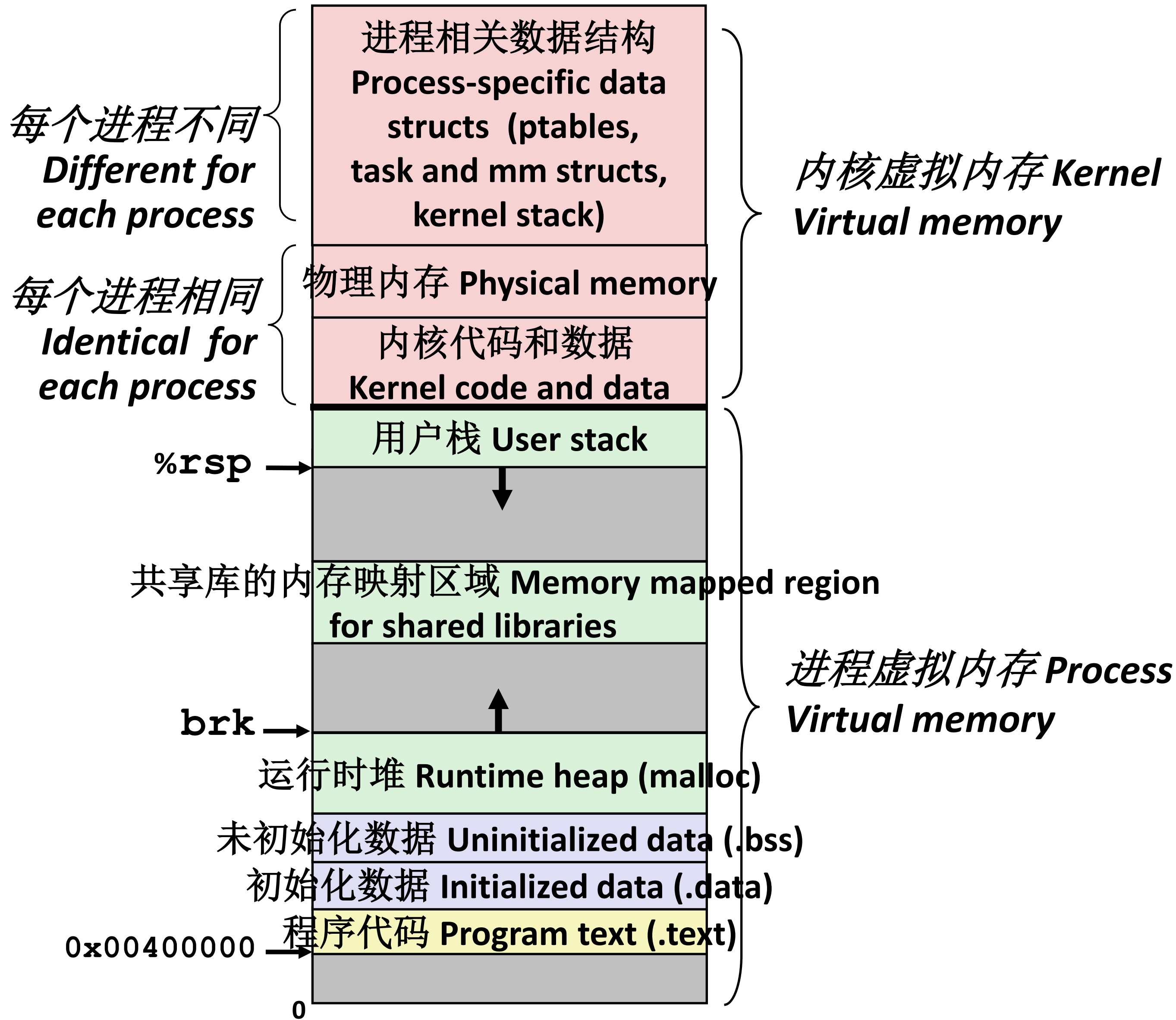


L1访问加速小技巧
Cute Trick for Speeding Up L1 Access

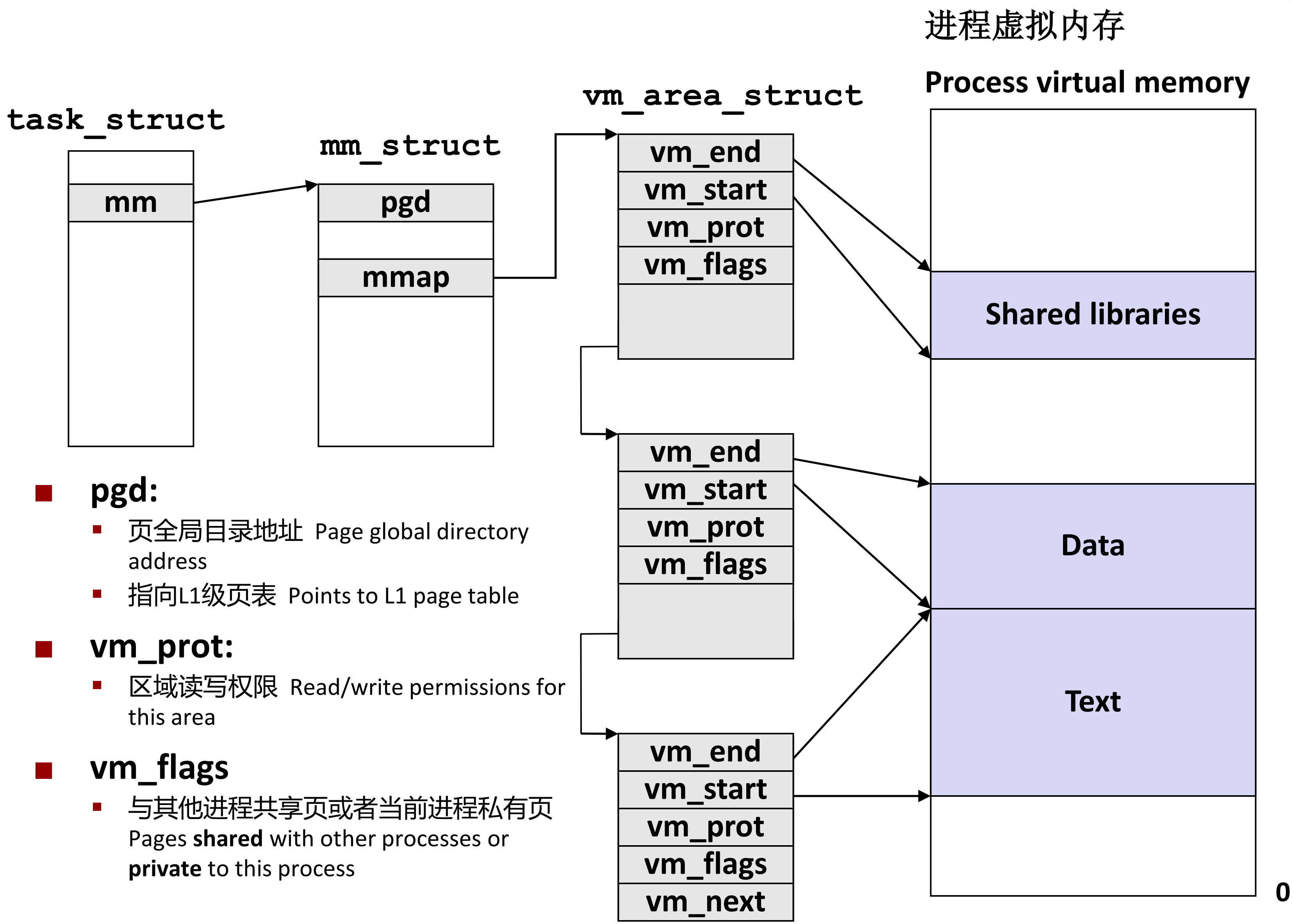


- 观察 **Observation**
  - 虚拟地址和物理地址中用于Cache索引的位是相同的 Bits that determine CI identical in virtual and physical address
  - 地址翻译的同时可以进行Cache索引 Can index into cache while address translation taking place
  - 通常情况下TLB会命中，PPN（Cache标记）接下来会可用 Generally we hit in TLB, so PPN bits (CT bits) available next
  - 虚拟索引，物理标记 “Virtually indexed, physically tagged”
  - Cache大小设计需要注意才能这样并行做 Cache carefully sized to make this possible

Linux进程的虚拟地址空间
Virtual Address Space of a Linux Process



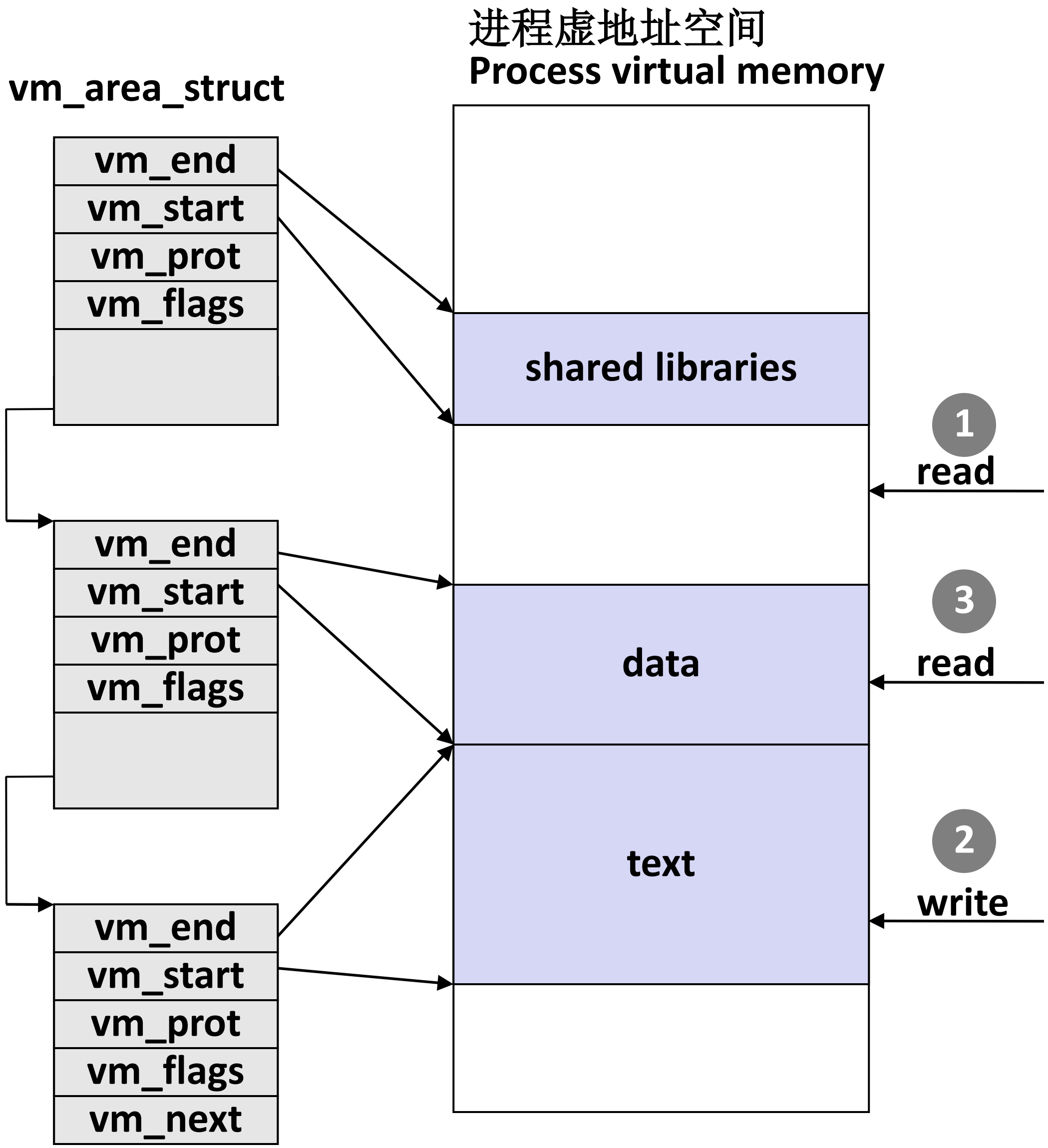
Linux将虚拟内存组织为一些区域的集合
Linux Organizes VM as Collection of “Areas”



- **pgd:**
  - 页全局目录地址 Page global directory address
  - 指向L1级页表 Points to L1 page table
- **vm_prot:**
  - 区域读写权限 Read/write permissions for this area
- **vm_flags**
  - 与其他进程共享页或者当前进程私有页 Pages **shared** with other processes or **private** to this process

每个进程有自己的task_struct等 Each process has own `task_struct`, etc

Linux中的缺页中断处理
Linux Page Fault Handling



段错误 Segmentation fault:
访问不存在的页
accessing a non-existing page

普通缺页中断
Normal page fault

保护异常 Protection exception:
例如，对只读页进行违规写操作（Linux报告为段错误） **e.g., violating permission by writing to a read-only page (Linux reports as Segmentation fault)**

议题 Today

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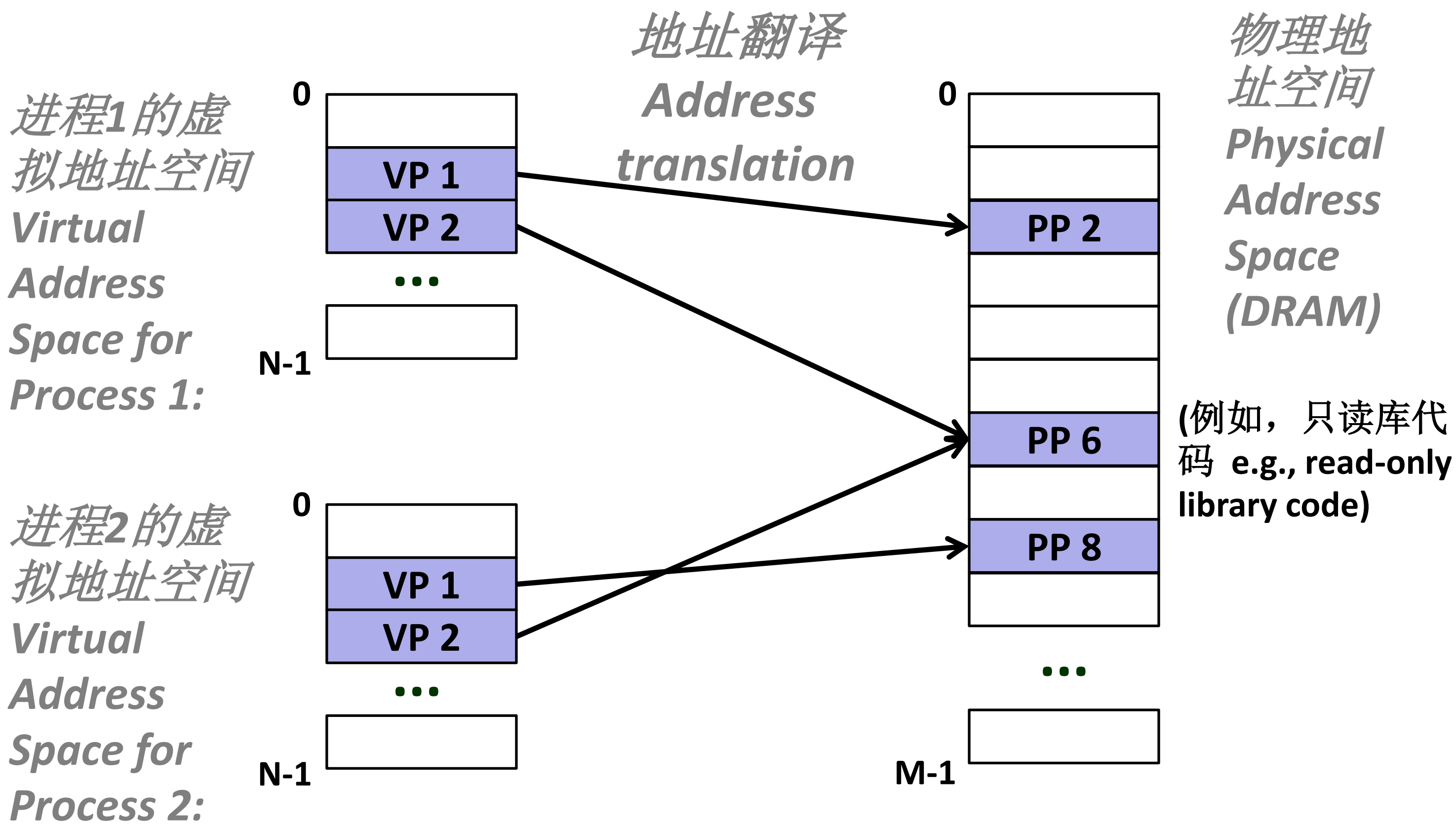
- 案例研究：Core i7/Linux内存系统 Case study: Core i7/Linux memory system
- 内存映射 Memory mapping

内存映射 Memory Mapping

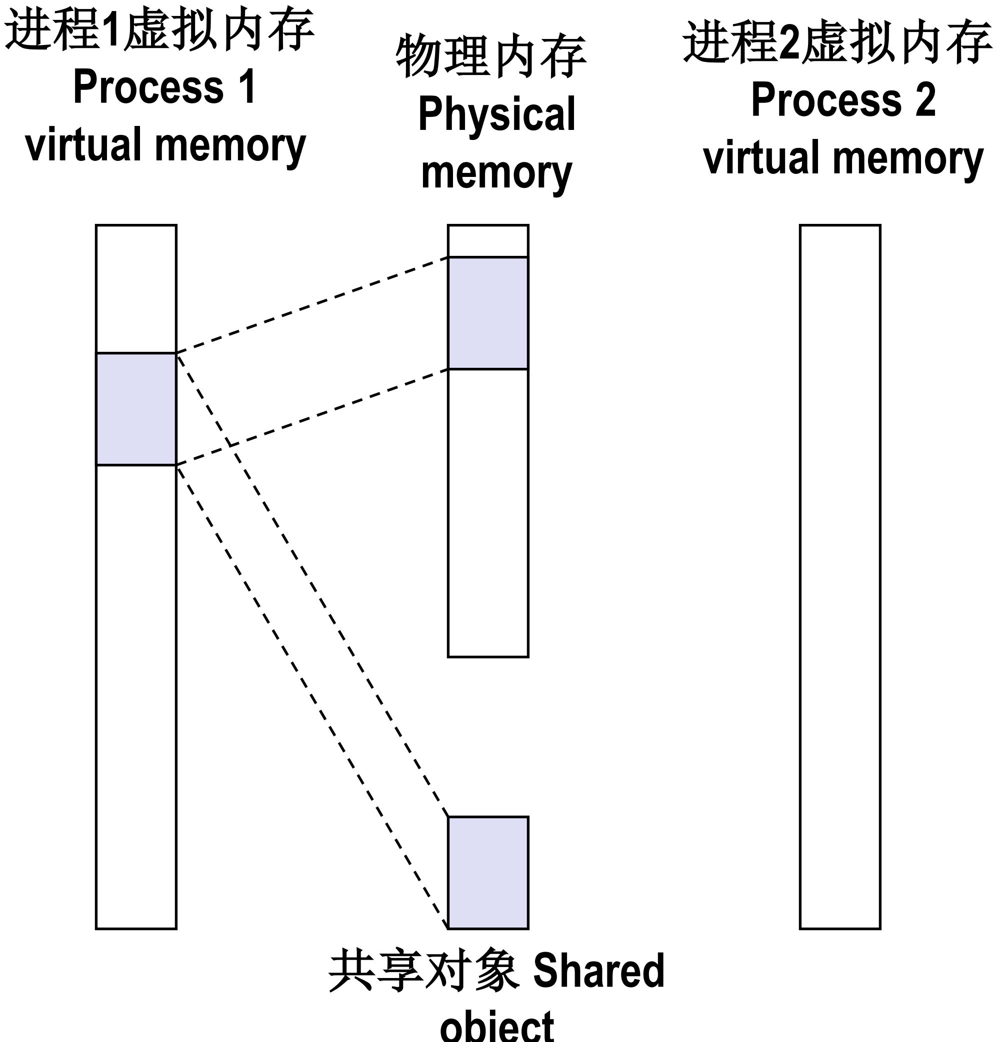
- **VM区域由与其相关联磁盘对象初始化 VM areas initialized by associating them with disk objects.**
  - 这一过程称为*内存映射* Process is known as ***memory mapping***.
- 区域可以由以下提供： **Area can be *backed by* (即从以下获得初始值 i.e., get its initial values from) :**
  - 磁盘上的***常规文件 Regular file*** on disk (例如一个可执行目标文件 e.g., an executable object file)
    - 通过文件的节初始化页中数据 Initial page bytes come from a section of a file
  - ***匿名文件 Anonymous file*** (e.g., nothing)
    - 第一次缺页时分配一个填充为0的物理页（请求二进制零的页） First fault will allocate a physical page full of 0's (***demand-zero page***)
    - 页面被写之后（脏页）就和其他页一样 Once the page is written to (***dirtied***), it is like any other page
- 脏页会在内存和一个特殊的交换文件之间来回拷贝 **Dirty pages are copied back and forth between memory and a special *swap file*.**

回顾：内存管理和保护
Review: Memory Management & Protection

- 代码和数据能够在进程之间隔离或共享 **Code and data can be isolated or shared among processes**

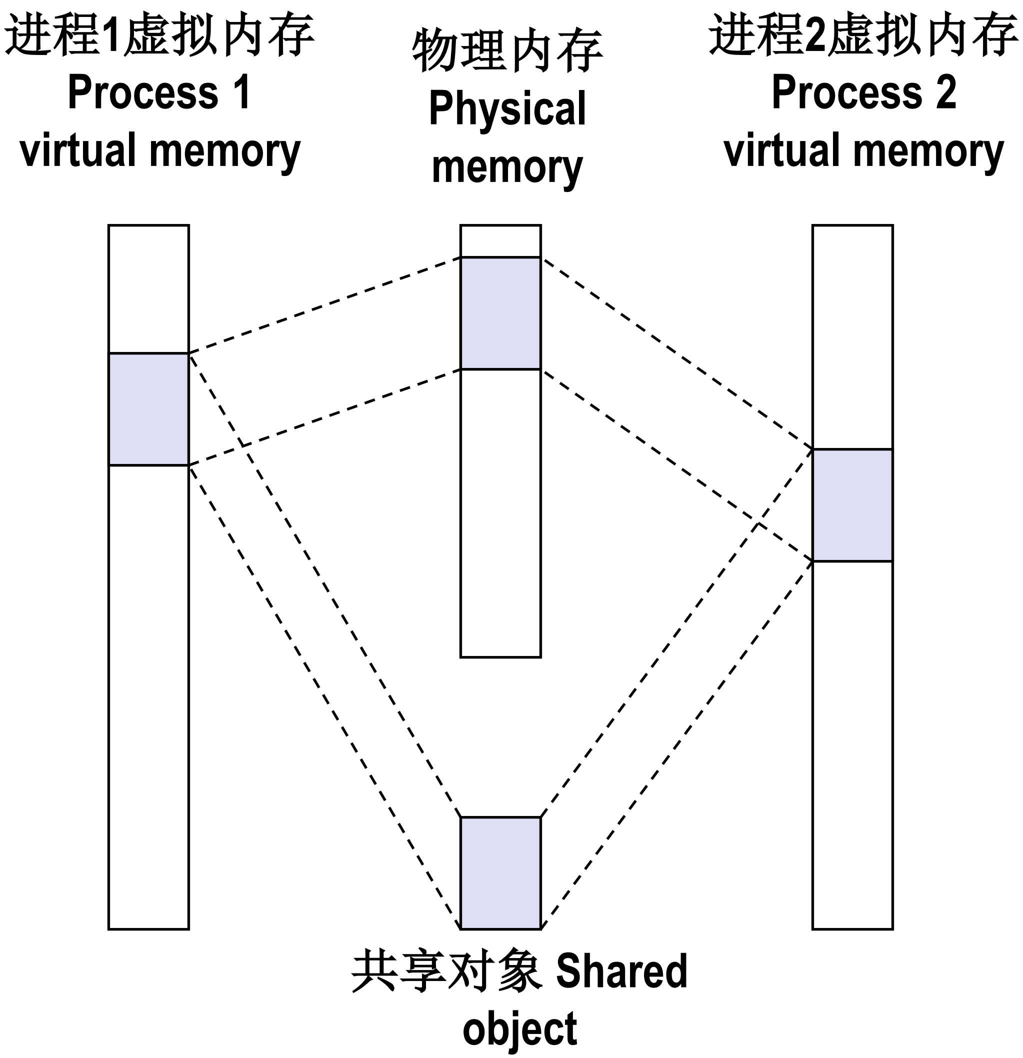


共享重回顾：共享对象
Sharing Revisited: Shared Objects



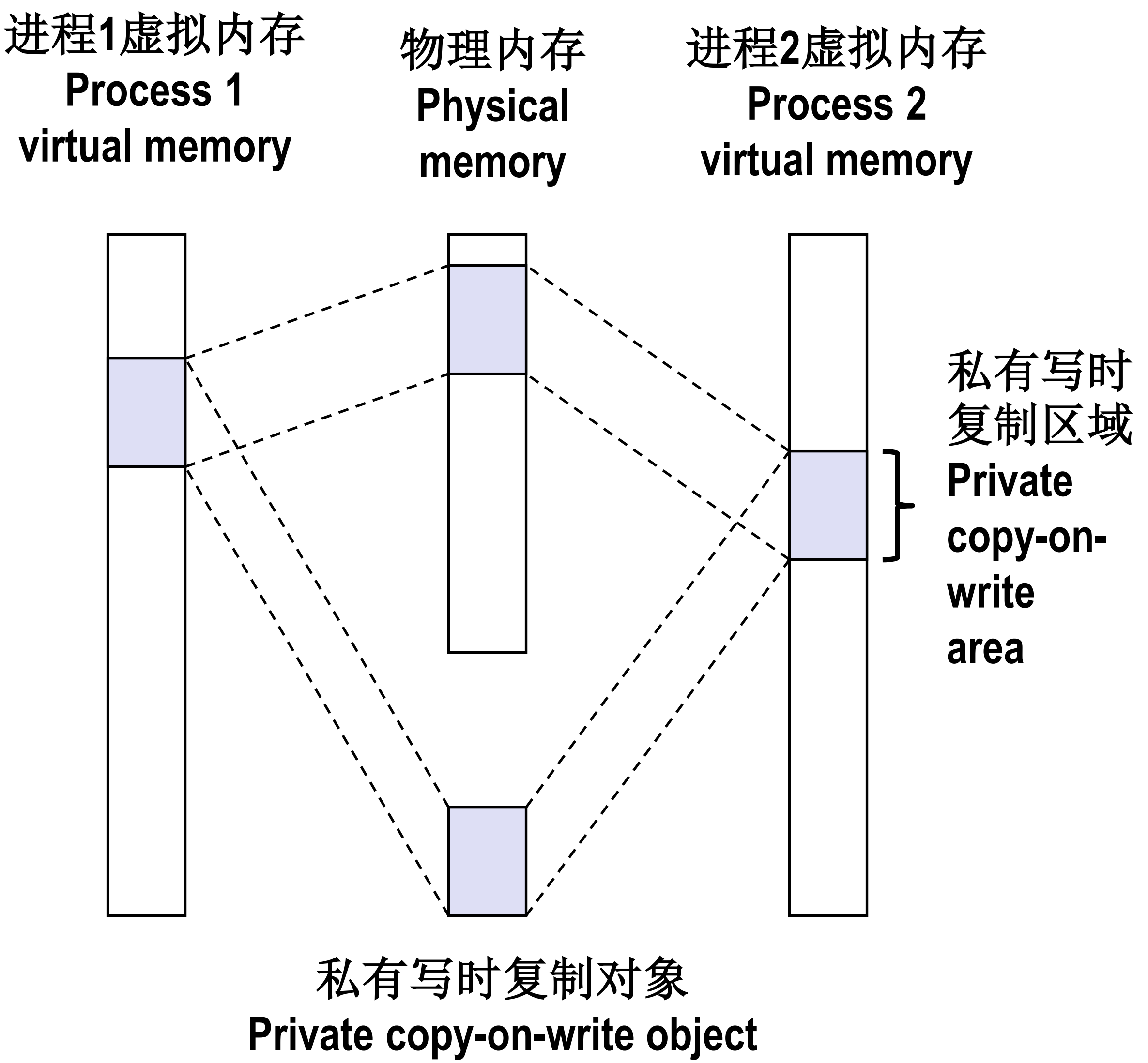
- 进程1映射共享对象 Process 1 maps the shared object.

共享重回顾：共享对象
Sharing Revisited: Shared Objects



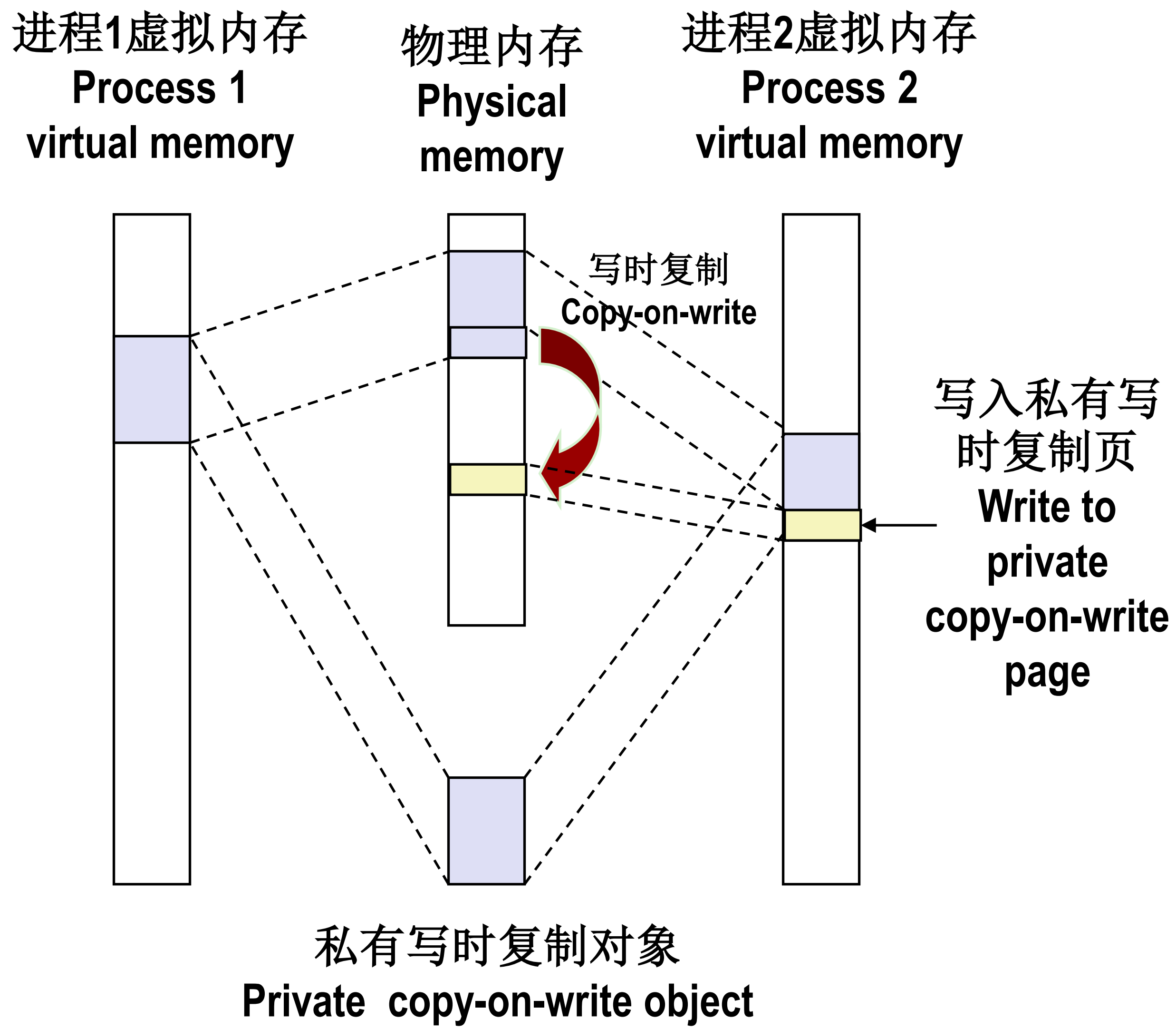
- 进程2映射共享对象 Process 2 maps the shared object.
- 注意虚拟地址如何不同 Notice how the virtual addresses can be different.
- 但是，不同必须是页大小的整倍数 But, difference must be multiple of page size.

共享重回顾:私有写时复制对象
Sharing Revisited: Private Copy-on-write (COW) Objects



- 两个进程映射了一个*私有写时复制（COW）*对象 **Two processes mapping a *private copy-on-write (COW)* object.**
- 区域被标记为私有写时复制 **Area flagged as private copy-on-write**
- 私有区域的PTE被标记为只读 **PTEs in private areas are flagged as read-only**

共享重回顾:私有写时复制对象
Sharing Revisited: Private Copy-on-write (COW) Objects

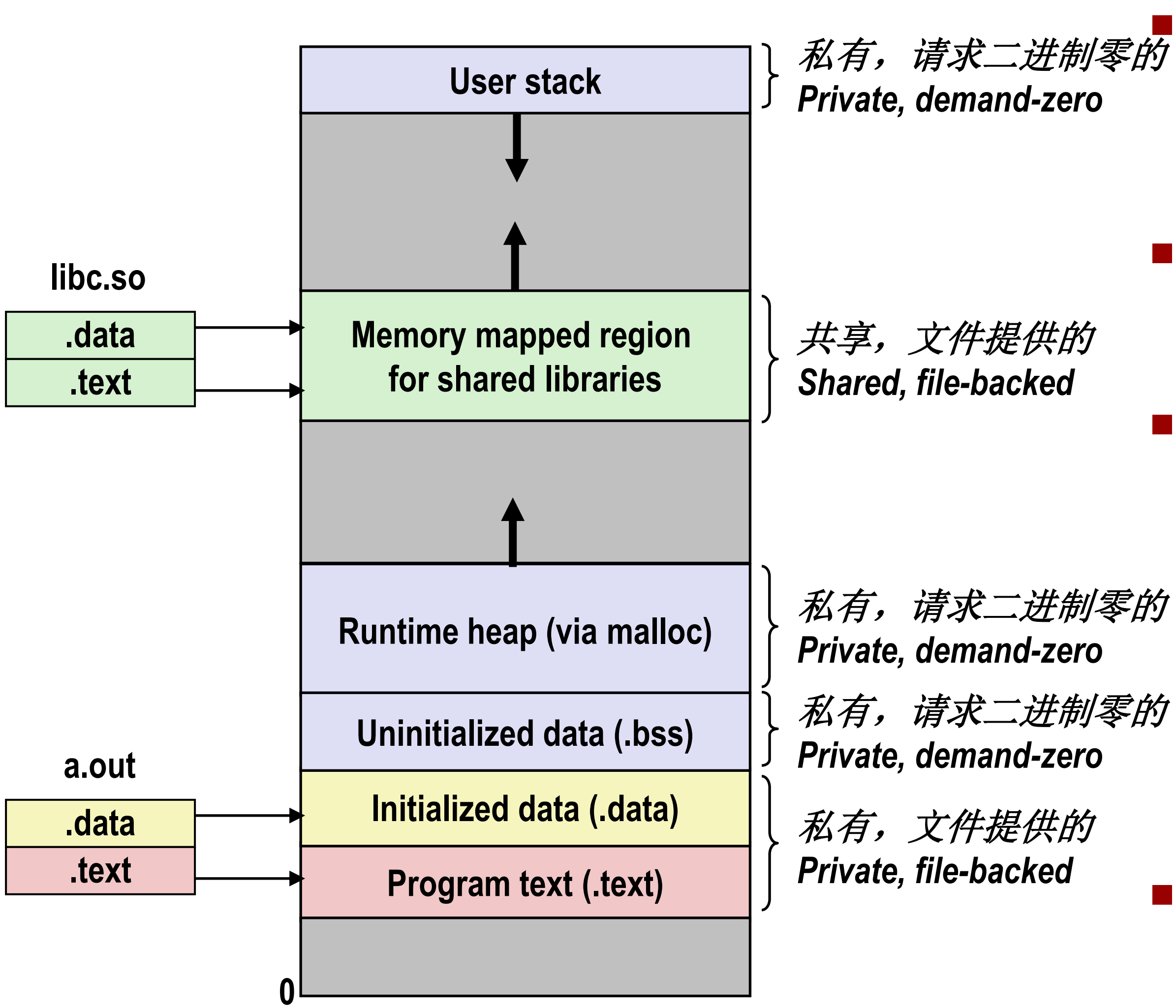


- 写私有页指令会触发保护异常 **Instruction writing to private page triggers protection fault.**
- 处理程序创建一个新的R/W页 **Handler creates new R/W page.**
- 处理程序返回后重新执行指令 **Instruction restarts upon handler return.**
- 尽可能延迟复制操作 **Copying deferred as long as possible!**

fork函数重回顾
The `fork` Function Revisited

- **VM和内存映射解释了fork如何为每个进程设置私有地址空间 VM and memory mapping explain how `fork` provides private address space for each process.**
- 为新进程创建虚拟地址 **To create virtual address for new process**
  - 创建完全与现有的完全相同的内存数据结构和页表 Create exact copies of current `mm_struct`, `vm_area_struct`, and page tables.
  - 每个进程都将其标记为只读 Flag each page in both processes as read-only
  - 在两个进程空间中的`vm_area_struct` 设置为私有`COW` Flag each `vm_area_struct` in both processes as private COW
- 返回时，每个进程有完全相同的虚拟内存 **On return, each process has exact copy of virtual memory**
- 后续写操作会因为**COW**创建新的页 **Subsequent writes create new pages using COW mechanism.**

execve重回顾
The execve Function Revisited



- 在当前进程用execve加载并运行一个新的程序a.out To load and run a new program `a.out` in the current process using `execve`:
- 释放旧区域的相关数据结构和页表 Free `vm_area_struct`'s and page tables for old areas
- 创建新区域的相关数据结构和页表 Create `vm_area_struct`'s and page tables for new areas
  - 程序和初始化过的数据由目标文件提供 Programs and initialized data backed by object files.
  - `.bss`和栈由匿名文件提供 `.bss` and stack backed by anonymous files .
- 设置PC为.text中入口点 Set PC to entry point in `.text`
  - Linux将根据需要换入代码和数据页 Linux will fault in code and data pages as needed.

发现可共享页面 Finding Shareable Pages

- **内核相同页面合并 Kernel Same-Page Merging**
  - OS扫描所有物理内存，查找重复页面 OS scans through all of physical memory, looking for duplicate pages
  - 当找到时合并成单一页面，标记为写时复制 When found, merge into single copy, marked as copy-on-write
  - 2009年在Linux内核实现 Implemented in Linux kernel in 2009
  - 仅限于标记为可能候选的页面 Limited to pages marked as likely candidates
  - 当处理器运行很多个虚拟机时特别有用 Especially useful when processor running many virtual machines

用户级内存映射 User-Level Memory Mapping

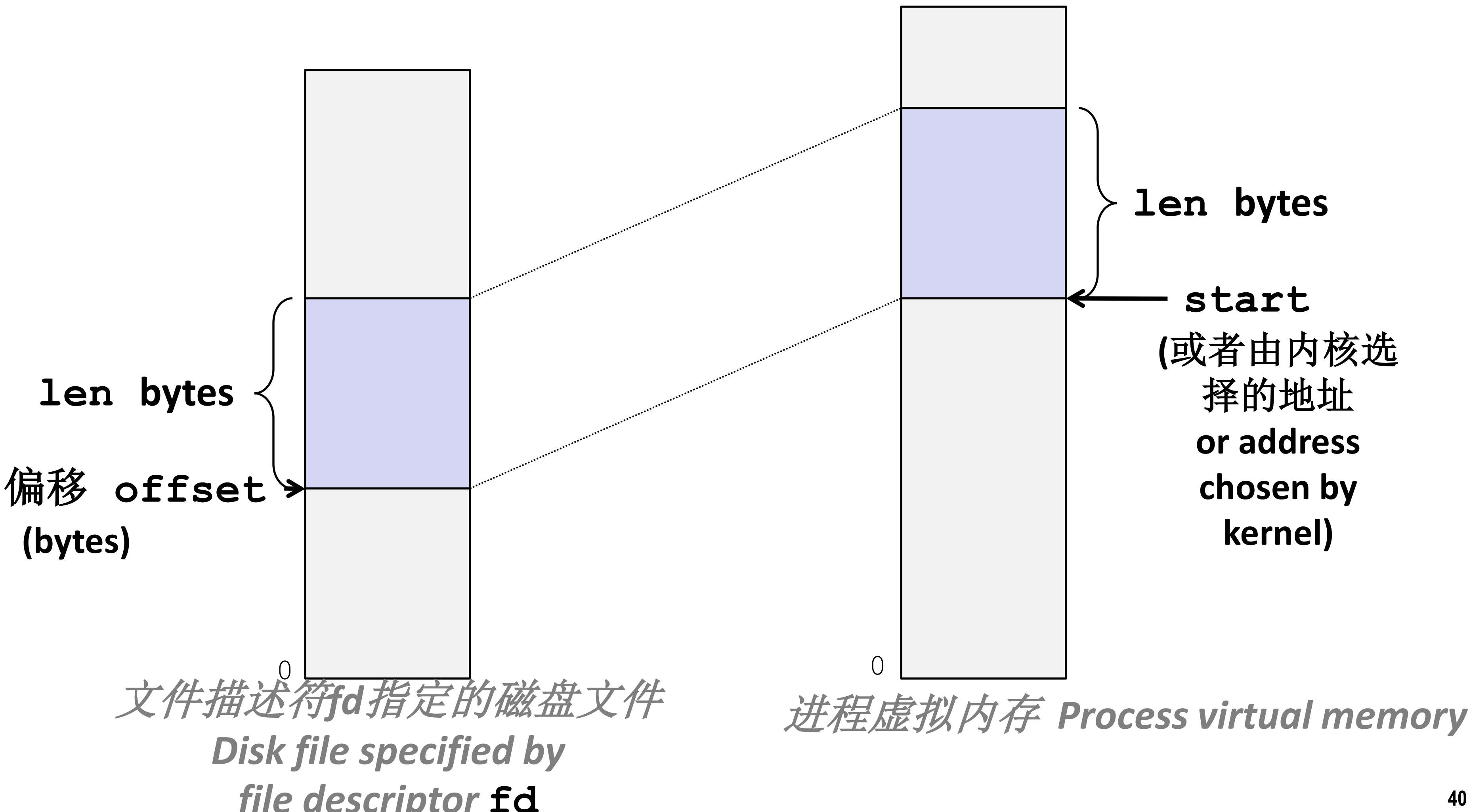
```
void *mmap(void *start, int len,
           int prot, int flags, int fd, int offset)
```

- 将文件描述符fd中偏移量`offset`开始的长度为`len`的字节映射到地址`start` **Map `len` bytes starting at offset `offset` of the file specified by file description `fd`, preferably at address `start`**
  - `start`: may be 0 for “pick an address” 有可能是0，以选取一个地址
  - `prot`: PROT_READ, PROT_WRITE, ...
  - `flags`: MAP_ANON, MAP_PRIVATE, MAP_SHARED, ...

- 返回一个映射区域的开始地址指针（有可能不是start） **Return a pointer to start of mapped area (may not be `start`)**

用户级内存映射 User-Level Memory Mapping

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



mmap的使用 Uses of mmap

- 读大文件 **Reading big files**
  - 使用页调度机制将文件调入内存 Uses paging mechanism to bring files into memory
- 共享数据结构 **Shared data structures**
  - 当用MAP_SHARE标志调用时/When call with **`MAP_SHARED`** flag
    - 多个进程访问同样的内存区域 Multiple processes have access to same region of memory
    - 有风险！ Risky!
- 基于文件的数据结构 **File-based data structures**
  - 例如数据库 E.g., database
  - 给出prot参数为：Give **`prot`** argument **`PROT_READ | PROT_WRITE`**
  - 当释放映射区域时，文件通过写回进行更新 When unmap region, file will be updated via write-back
  - 可以实现从文件加载/更新/写回到文件 Can implement load from file / update / write back to file

示例：使用mmap拷贝文件
Example: Using `mmap` to Copy Files

- 不用传输数据到用户空间来，就可以将一个文件拷贝到标准输出
  Copying a file to `stdout` without transferring data to user space .

```c
#include "csapp.h"

void mmapcopy(int fd, int size)
{

   /* Ptr to memory mapped area */
   char *bufp;

   bufp = Mmap(NULL, size,
            PROT_READ,
            MAP_PRIVATE,
            fd, 0);
   Write(1, bufp, size);
   return;
}
```

mmapcopy.c

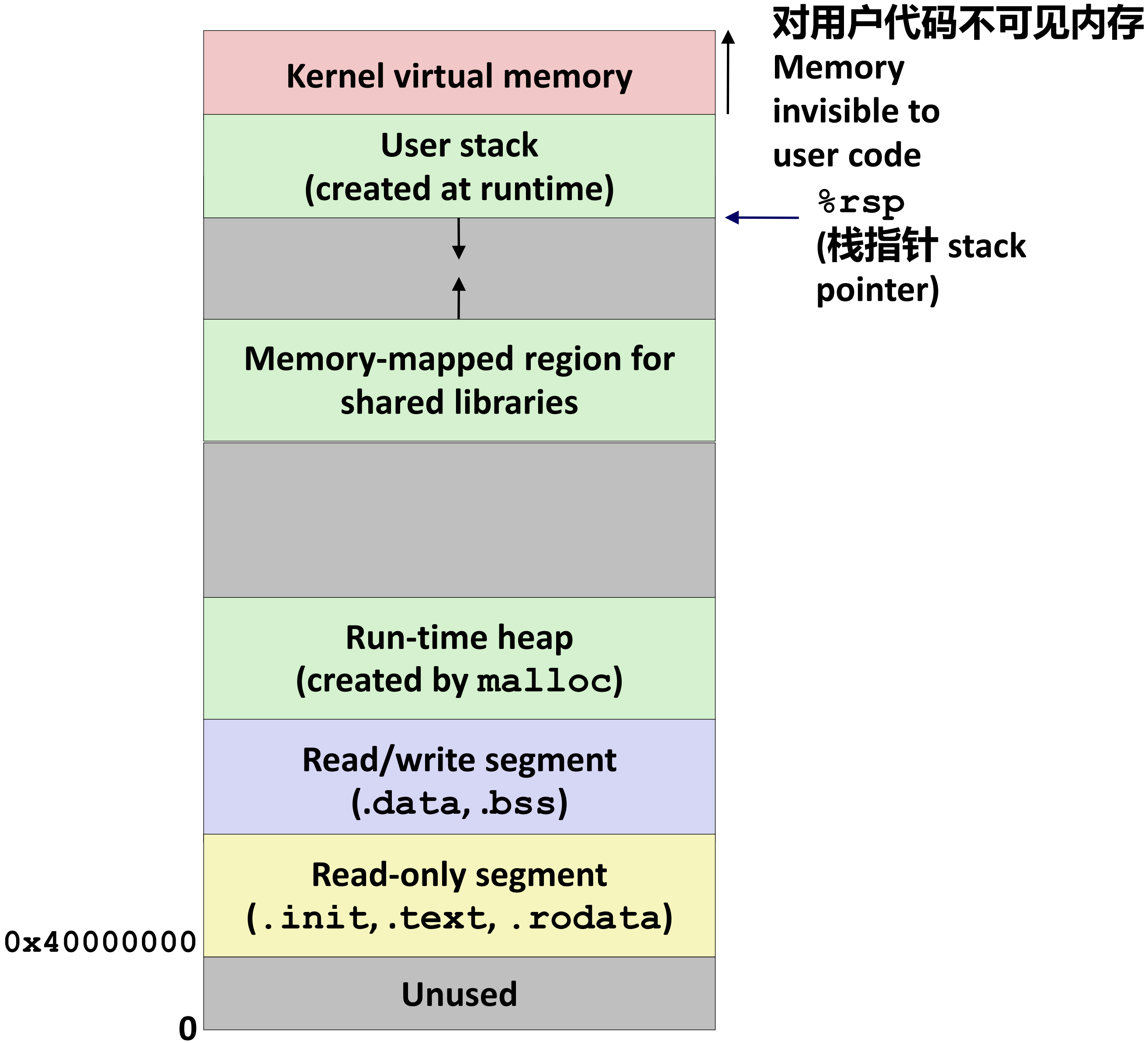
```c
/* mmapcopy driver */
int main(int argc, char **argv)
{
   struct stat stat;
   int fd;

   /* Check for required cmd line arg */
   if (argc != 2) {
      printf("usage: %s <filename>\n",
           argv[0]);
      exit(0);
   }

   /* Copy input file to stdout */
   fd = Open(argv[1], O_RDONLY, 0);
   Fstat(fd, &stat);
   mmapcopy(fd, stat.st_size);
   exit(0);
}
```

mmapcopy.c

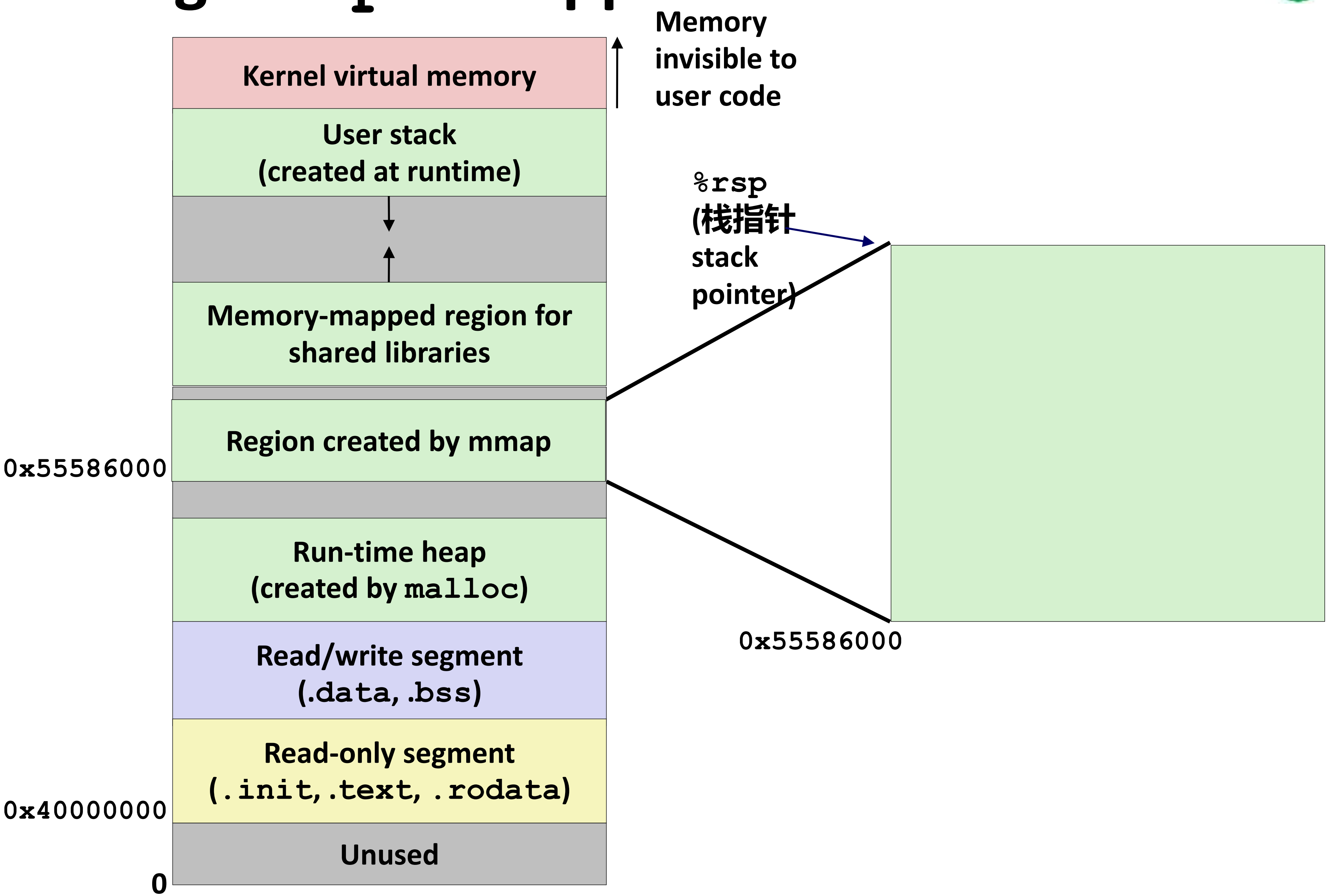
示例：使用mmap支持攻击实验
Example: Using `mmap` to Support Attack Lab

- 问题 Problem
  - 期望学生能够执行代码注入攻击 Want students to be able to perform code injection attacks
  - 我们实验机器栈不能执行代码 Shark machine stacks are not executable
- 解决方案 Solution
  - 由Sam King建议（现在在Davis）Suggested by Sam King (now at UC Davis)
  - 使用mmap分配标记为可执行的内存区域 Use `mmap` to allocate region of memory marked executable
  - 转向攻击到新的区域 Divert stack to new region
  - 执行学生的攻击代码 Execute student attack code
  - 恢复回原始栈 Restore back to original stack
  - 删除映射的区域 Remove mapped region

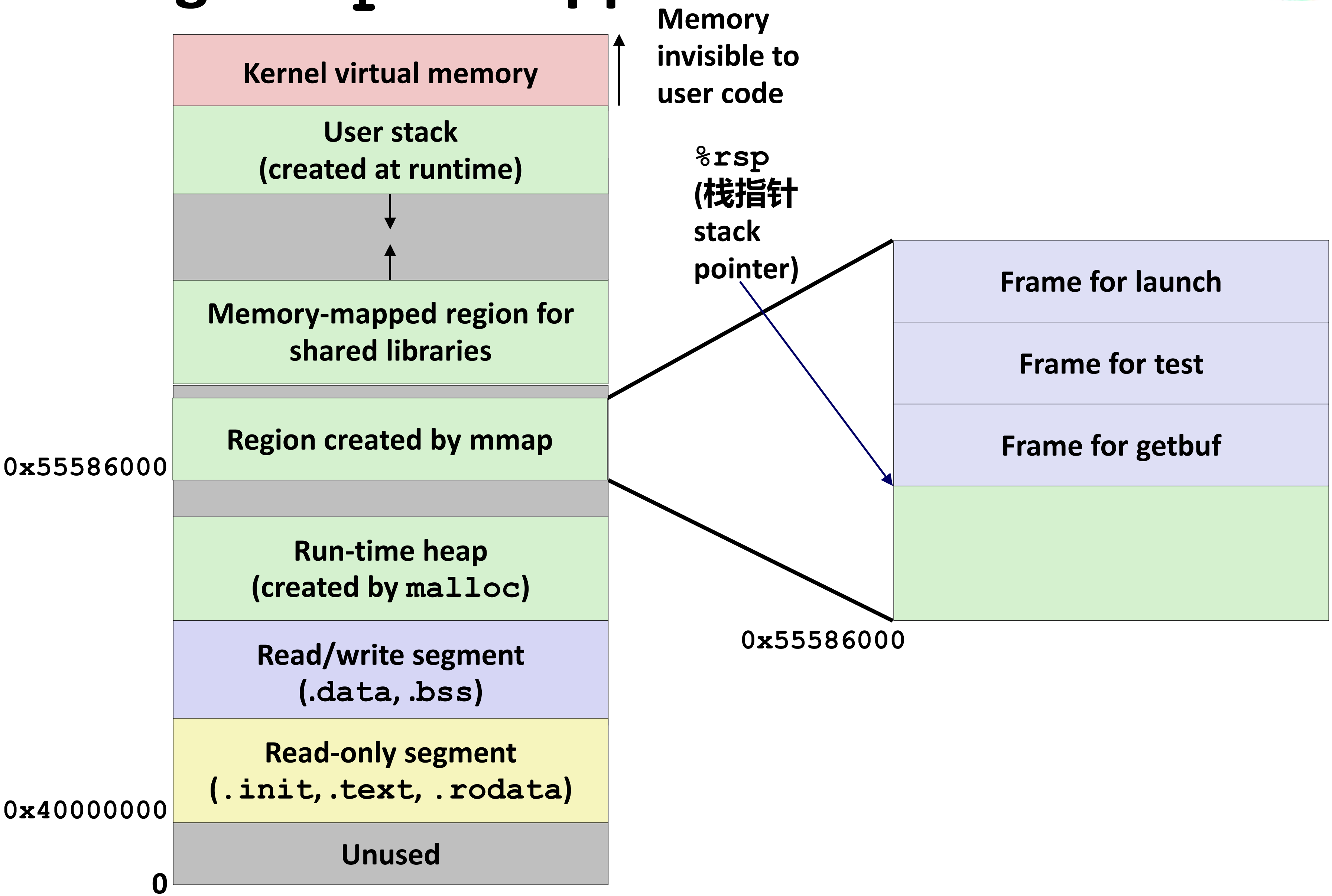
使用mmap支持攻击实验
Using mmap to Support Attack Lab



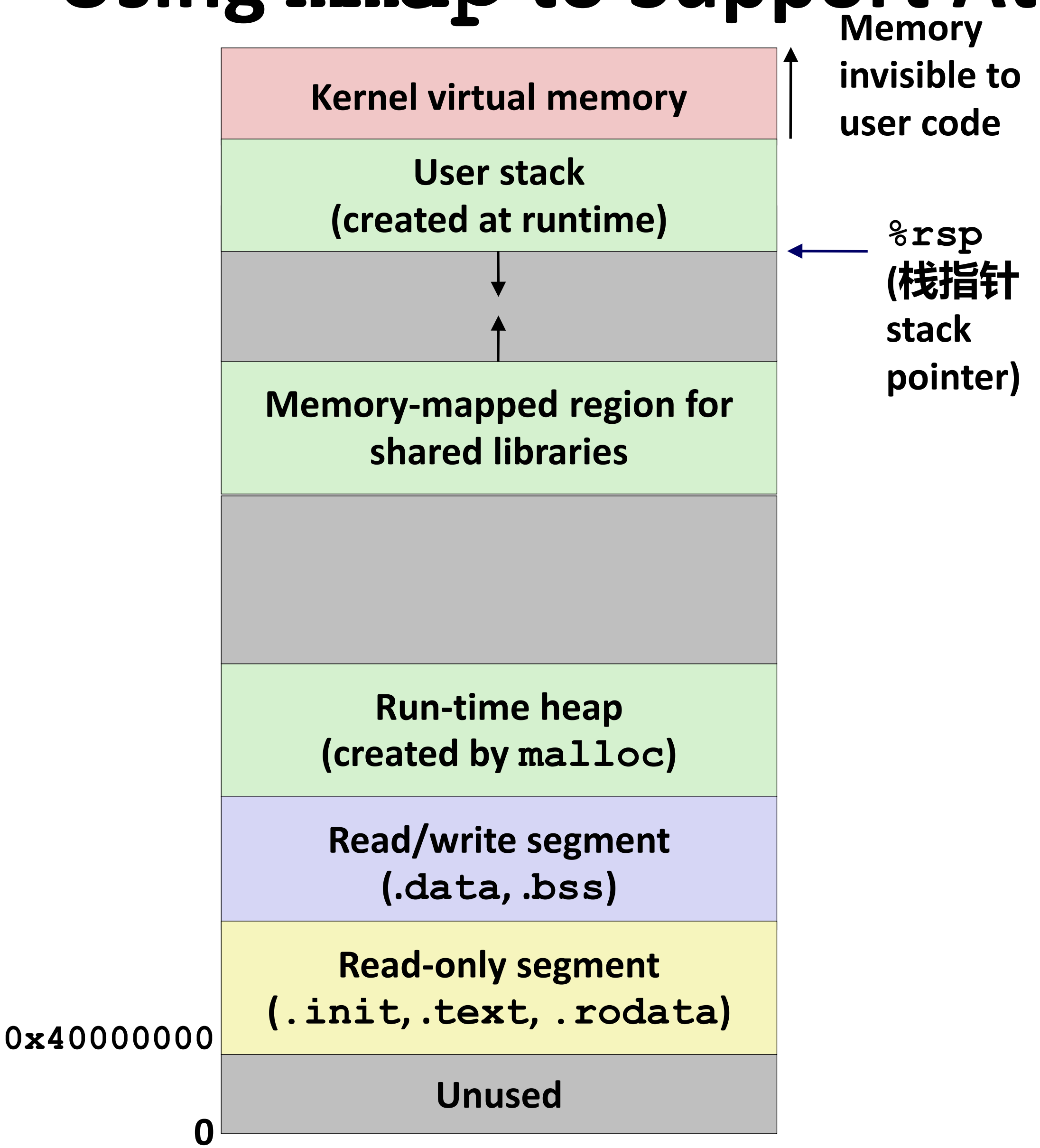
使用mmap支持攻击实验
Using mmap to Support Attack Lab



使用mmap支持攻击实验
Using mmap to Support Attack Lab



使用mmap支持攻击实验
Using mmap to Support Attack Lab



总结 Summary

- **虚拟内存需要硬件支持 VM requires hardware support**
  - 异常处理机制 Exception handling mechanism
  - TLB
  - 各种控制寄存器 Various control registers
- **虚拟内存需要操作系统支持 VM requires OS support**
  - 管理页表 Managing page tables
  - 实现页替换策略 Implementing page replacement policies
  - 管理文件系统 Managing file system
- **虚拟内存使能许多能力 VM enables many capabilities**
  - 从内存加载程序 Loading programs from memory
  - 提供内存保护 Providing memory protection

使用mmap支持攻击实验
Using mmap to Support Attack Lab

分配新的区域 Allocate new region

```
void *new_stack = mmap(START_ADDR, STACK_SIZE, PROT_EXEC|PROT_READ|PROT_WRITE,
                MAP_PRIVATE | MAP_GROWSDOWN | MAP_ANONYMOUS | MAP_FIXED,
                0, 0);
if (new_stack != START_ADDR) {
    munmap(new_stack, STACK_SIZE);
    exit(1);
}
```

转向栈到新区域并执行攻击代码
Divert stack to new region & execute attack code

```
stack_top = new_stack + STACK_SIZE - 8;
asm("movq %%rsp,%%rax ; movq %1,%%rsp ;
movq %%rax,%0"
    : "=r" (global_save_stack) // %0
    : "r"  (stack_top)         // %1
);

launch(global_offset);
```

恢复栈并删除区域
Restore stack and remove region

```
asm("movq %0,%%rsp"
    :
    : "r" (global_save_stack) // %0
);

munmap(new_stack, STACK_SIZE);
```