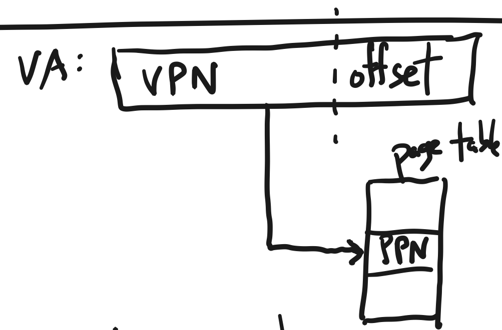
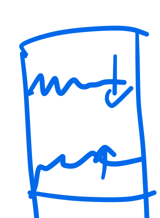
- [x] 1. Last time
- [x] 2. x86-64: addresses
- [x] 3. x86-64: page table structures
- [x] 4. TLBs
- [ ] 5. where does the OS live? ←



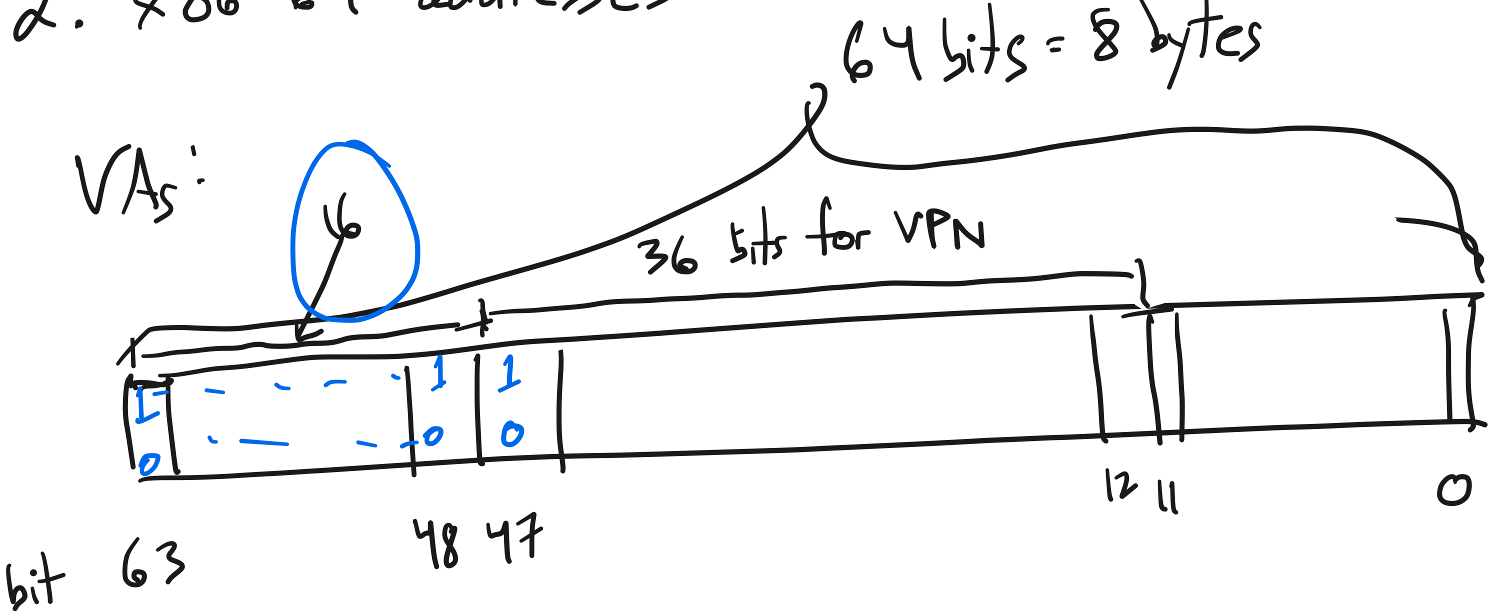
1. Last time

- purpose of VM (virtual mem)
- central mechanism: page table
- idealized page table: VPN is an index into a giant table, PPN is the contents of the table at the index
- thus, pg table implements a map from VPN → PPN
- in reality, it's a map from VPN → PPN ∪ {∅}, because a VPN might not have a valid mapping in the table.
- NOTE: VPN + PPN do not necessarily have the same # of bits.

· Because the table would be gigantic, it's not materialized as a linear table. Instead, the architecture specifies multilevel page tables



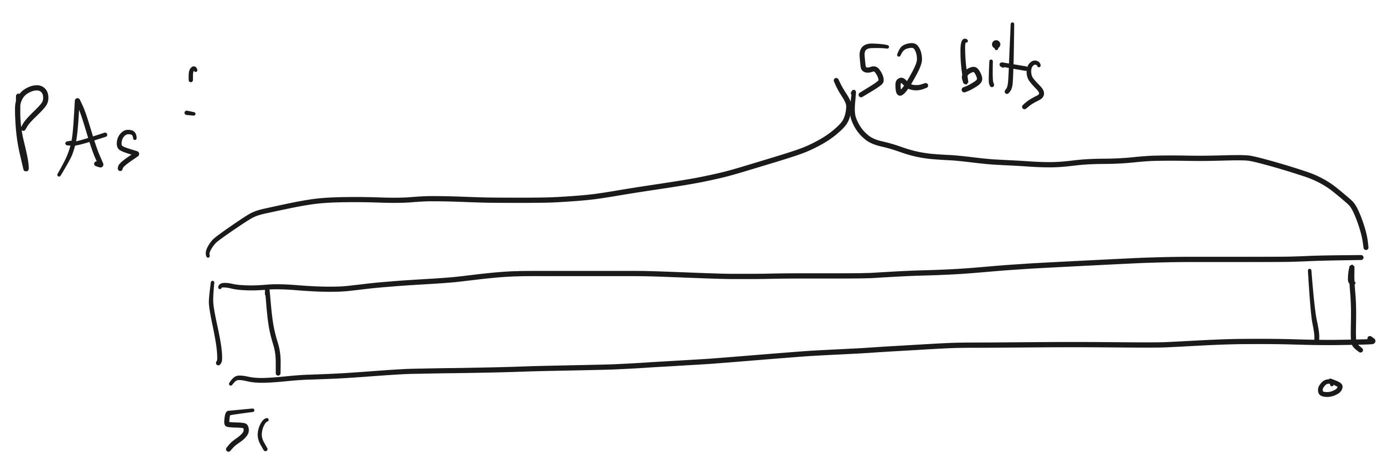
2. x86-64: addresses



$$[-2^{47}, 2^{47}-1]$$

Address space has 48 usable bits, 2^{48} possible addresses (each addresses a byte).

Thus, 256 TB.



Physical memory can be addressed w/ up to 52 bits.

How much physical memory can thus be supported?

$2^{52} = 4$ PB

Mapping: going from 48-bit number (VA) to 52-bit number (PA) at the granularity of ranges of 2^{12}.

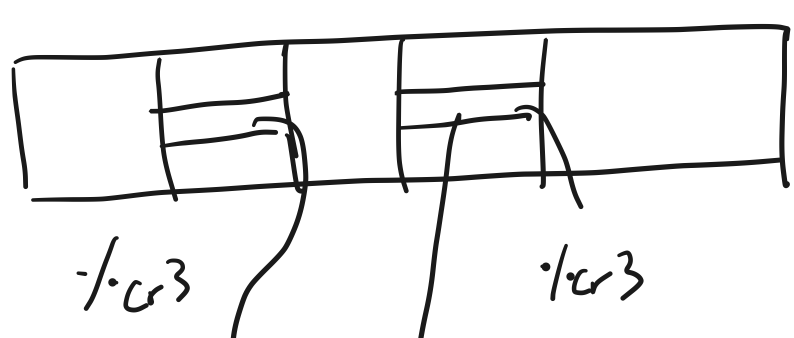
So it's really a mapping from 36-bit numbers to 40-bit numbers.

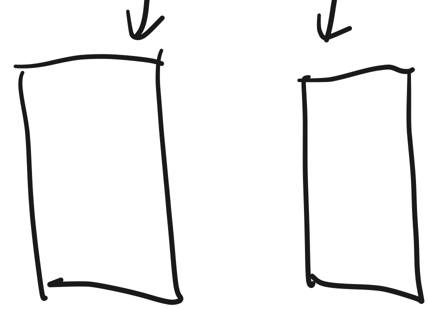
---

3. Page table structures

[see handout]

proc table





Exercise: OS wants to map

VA 0x0202~~000~~ to

PA 0x3~~000~~

VPN: 0x202

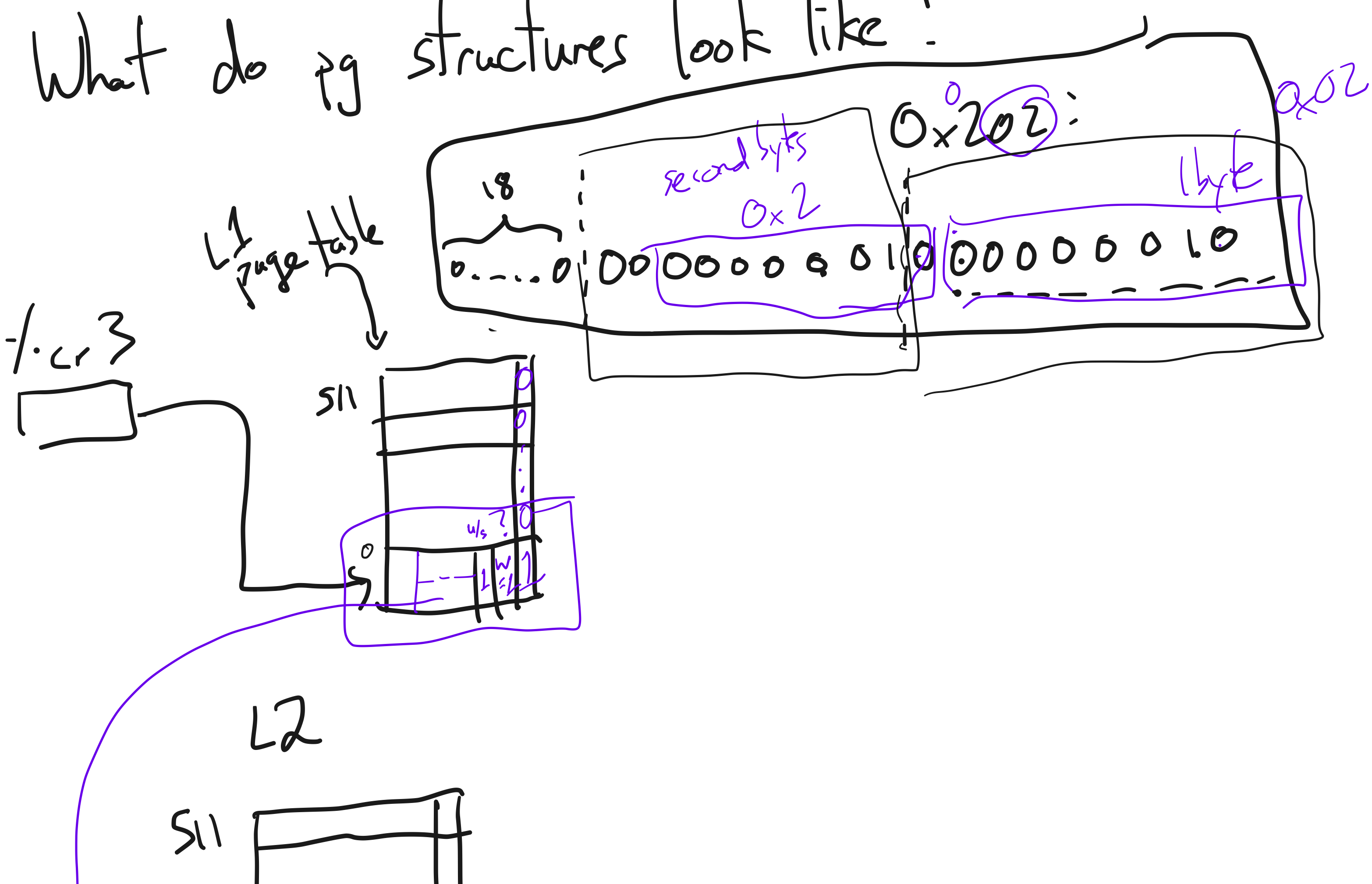
PPN 0x3

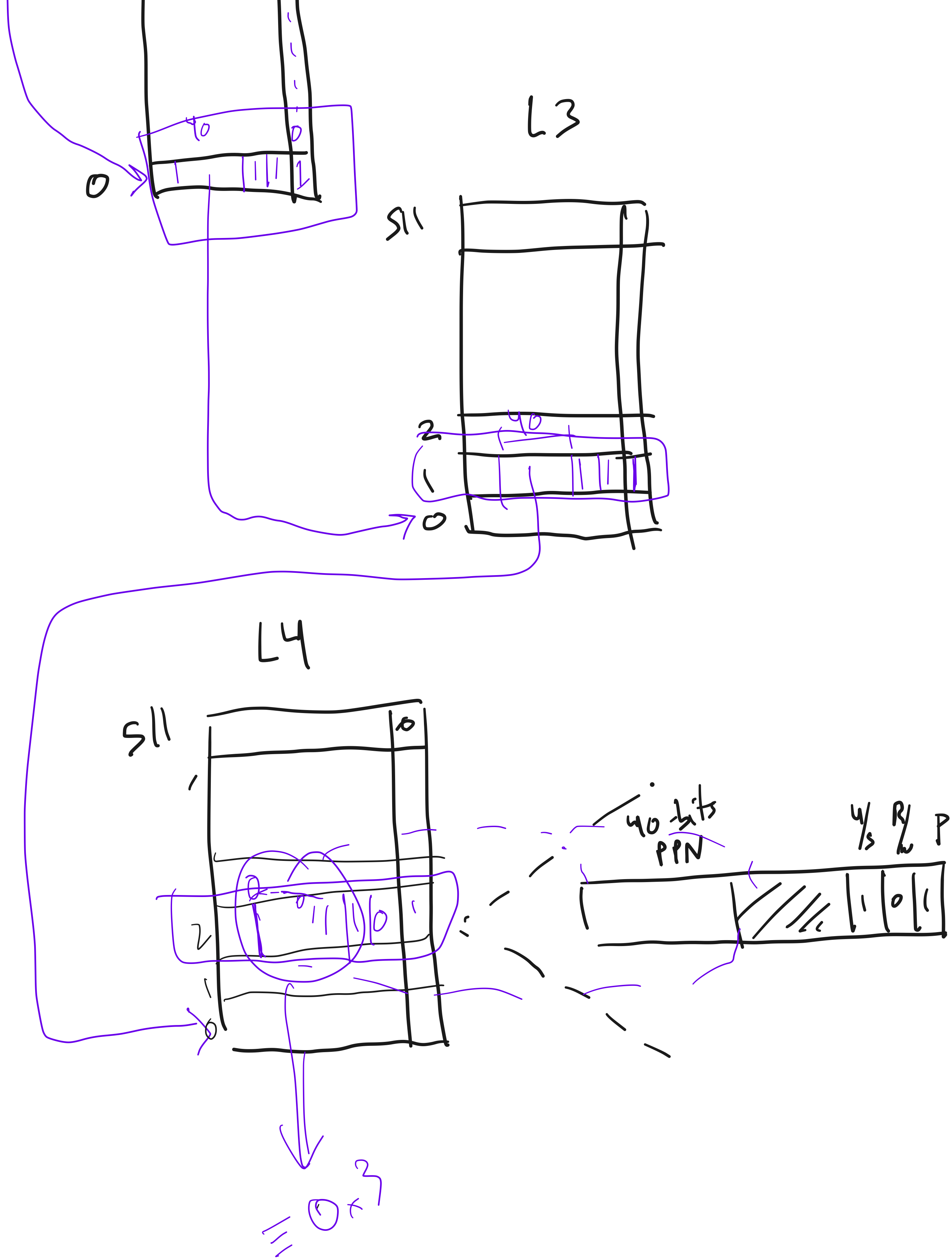
4 bits

12 bits

and make it accessible to user-level but read-only.

What do pg structures look like?





L3
511
2
1
0
L4
511
2
1
0
40 bits
PPN
U/S
R/W
P
= 0x3

---

4. TLB

< VPN, (PPN, perms) >

PTE

R/W = 0

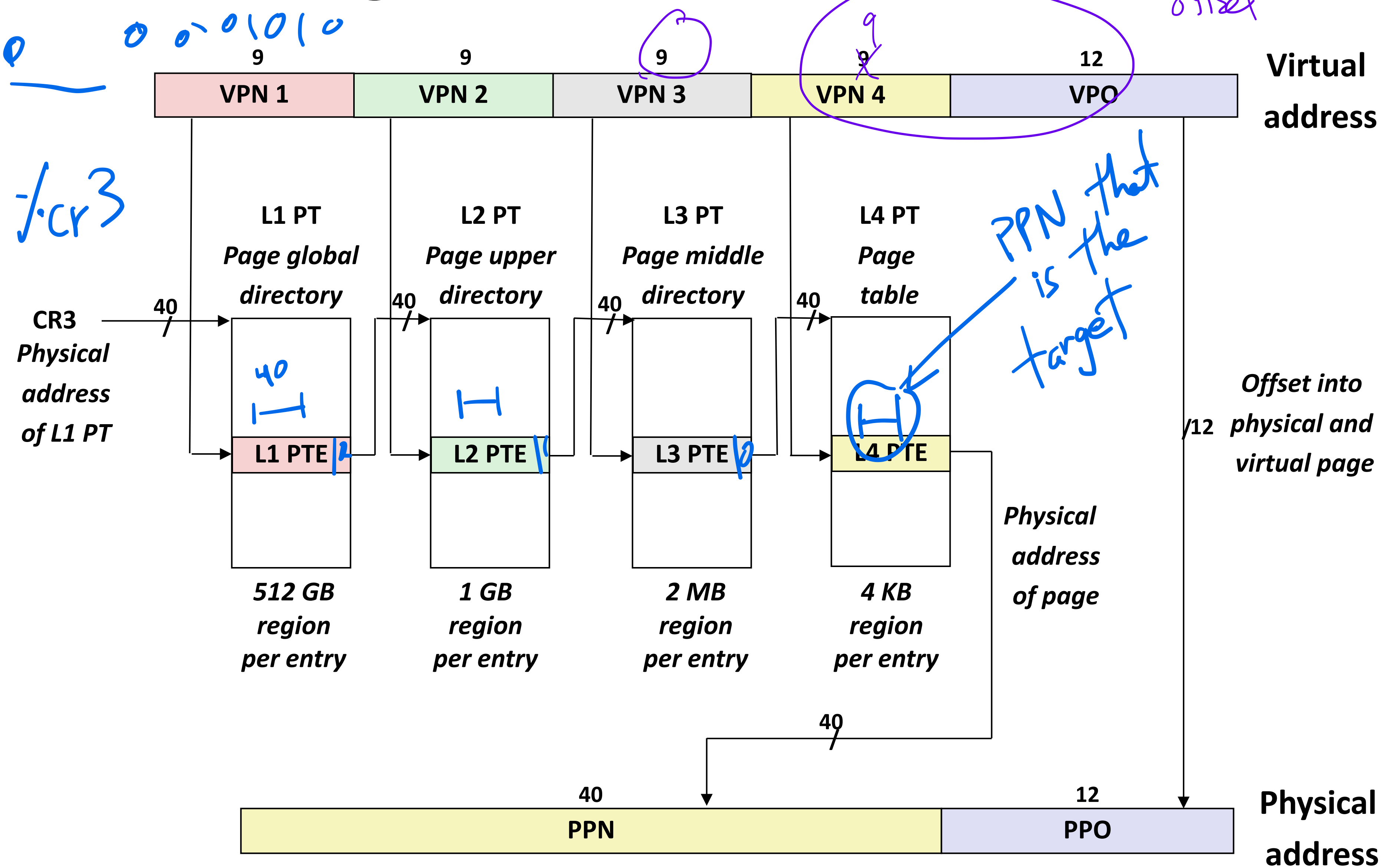
H/W managed: x86, ARM

S/W managed: MIPS

TLB miss $\xrightarrow{?}$ pg fault (No!)

pg fault $\xrightarrow{?}$ TLB miss (No!) illegal mem op.

Core i7 Page Table Translation



const char * _ _

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

movq $0x1, 0x20000

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	Page table physical base address	Unused	G	PS		A	CD	WT	U/S	R/W	P=1

Available for OS	P=0

Each entry references a 4K child page table. Significant fields:

P: Child page table present in physical memory (1) or not (0).

R/W: Read-only or read-write access access permission for all reachable pages.

U/S: user or supervisor (kernel) mode access permission for all reachable pages.

WT: Write-through or write-back cache policy for the child page table.

A: Reference bit (set by MMU on reads and writes, cleared by software).

PS: Page size: if bit set, we have 2 MB or 1 GB pages (bit can be set in Level 2 and 3 PTEs only).

Page table physical base address: 40 most significant bits of physical page table address (forces page tables to be 4KB aligned)

XD: Disable or enable instruction fetches from all pages reachable from this PTE.

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	Page physical base address	Unused	G		D	A	CD	WT	U/S	R/W	P=1

Available for OS (for example, if page location on disk)	P=0

Each entry references a 4K child page. Significant fields:

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

R/W: Read-only or read-write access permission for this page

U/S: User or supervisor mode access

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

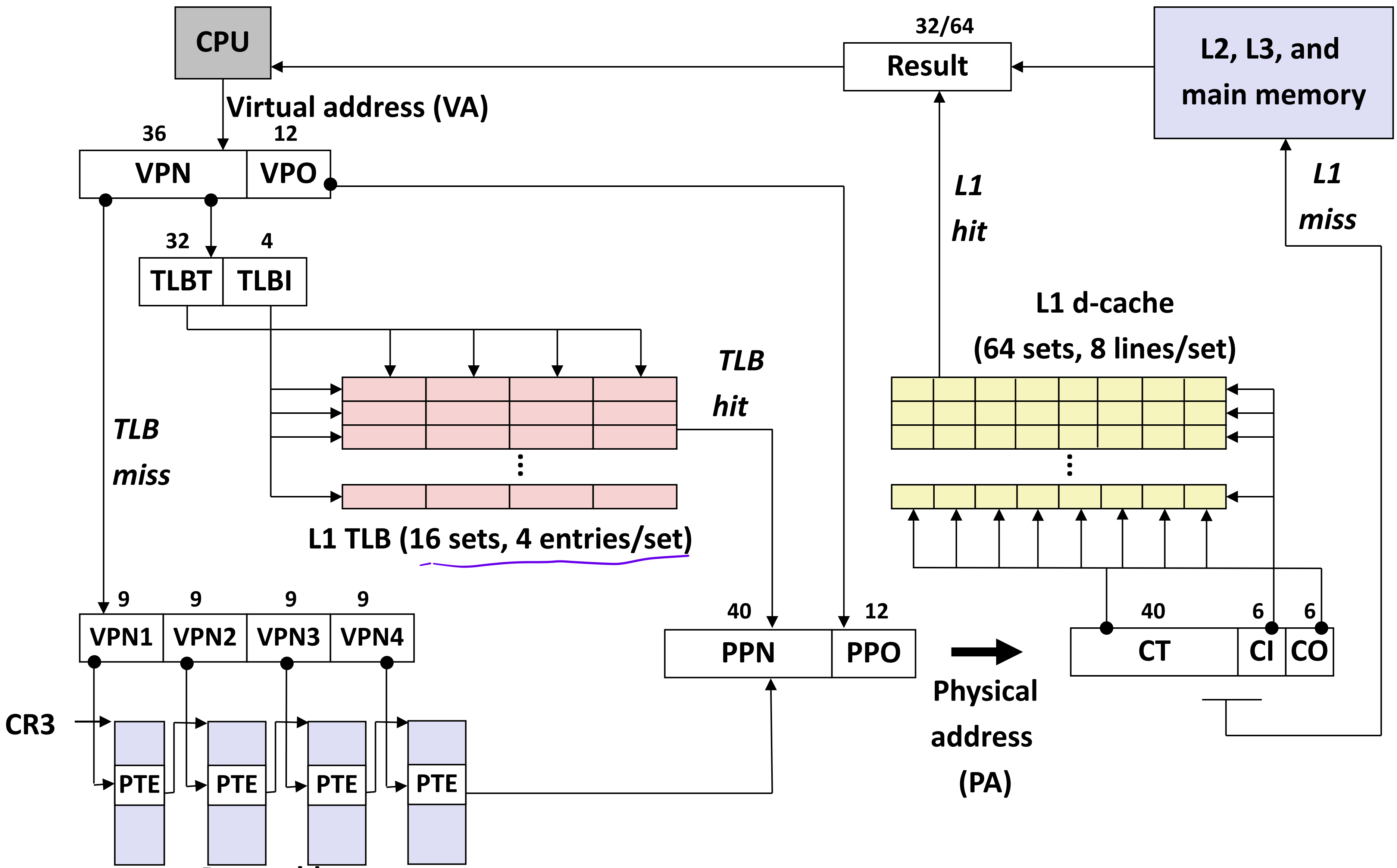
A: Reference bit (set by MMU on reads and writes, cleared by software)

D: Dirty bit (set by MMU on writes, cleared by software)

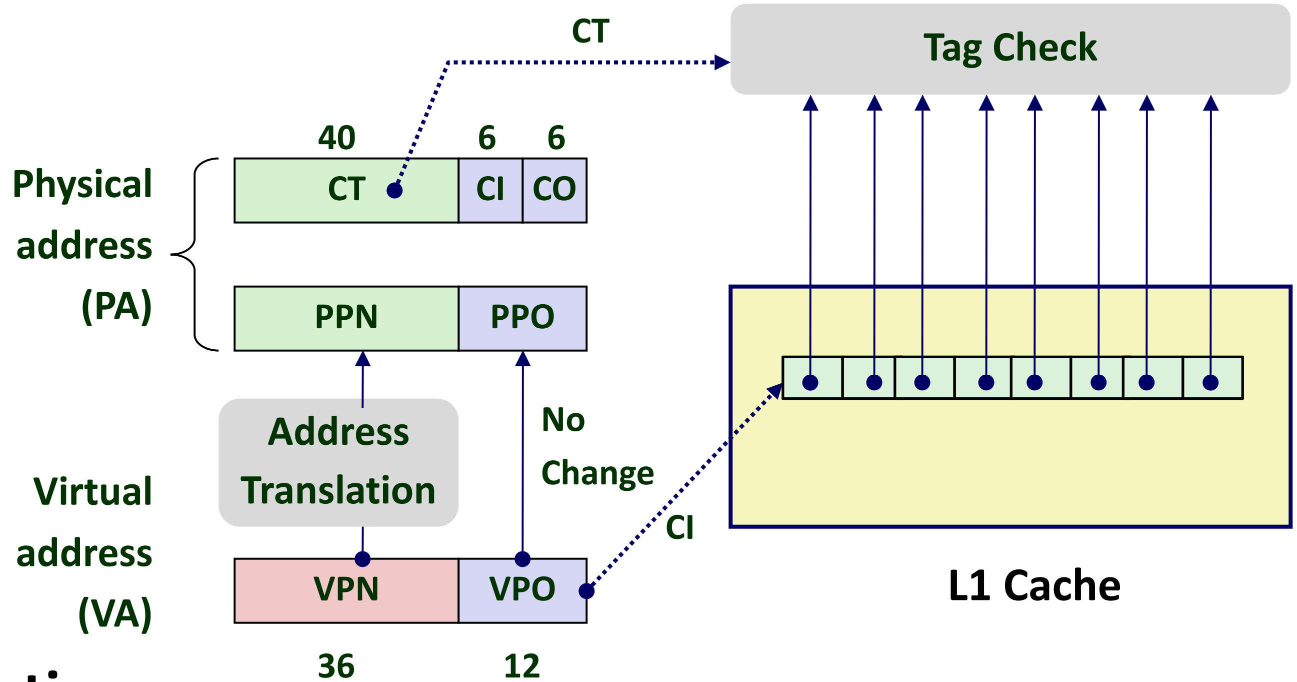
Page physical base address: 40 most significant bits of physical page address
(forces pages to be 4KB aligned)

XD: Disable or enable instruction fetches from this page.

End-to-end Core i7 Address Translation

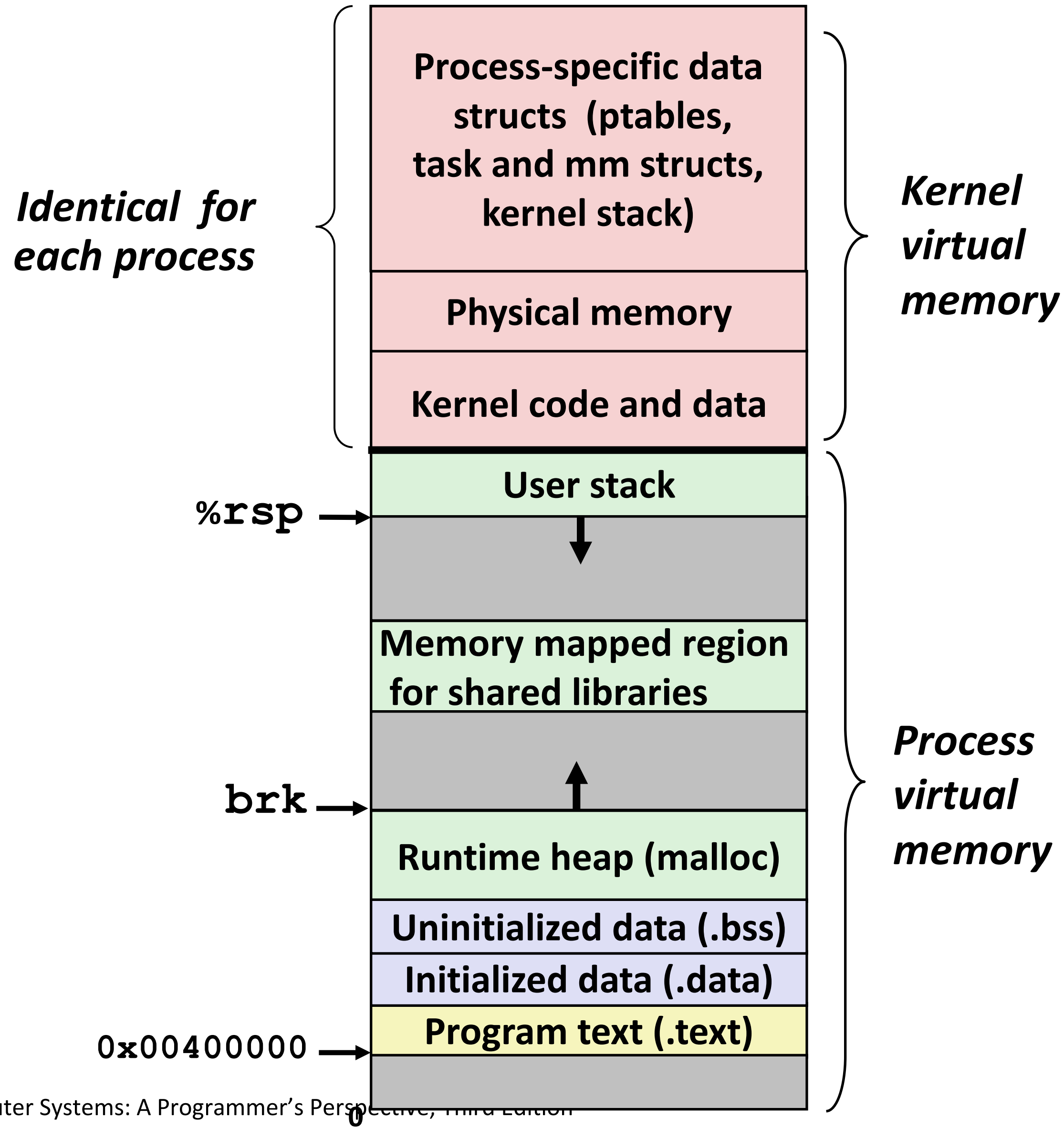


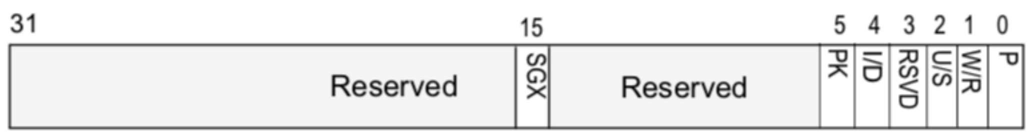
Cute Trick for Speeding Up L1 Access



- **Observation**
  - Bits that determine CI identical in virtual and physical address
  - Can index into cache while address translation taking place
  - Cache carefully sized to make this possible: 64 sets, 64-byte cache blocks
  - Means 6 bits for cache index, 6 for *cache* offset
  - That's 12 bits; matches *VPO, PPO* → One reason pages are 2^{12} bits = 4 KB

Virtual Address Space of a Linux Process





P	0	The fault was caused by a non-present page.
	1	The fault was caused by a page-level protection violation.
W/R	0	The access causing the fault was a read.
	1	The access causing the fault was a write.
U/S	0	A supervisor-mode access caused the fault.
	1	A user-mode access caused the fault.
RSVD	0	The fault was not caused by reserved bit violation.
	1	The fault was caused by a reserved bit set to 1 in some paging-structure entry.
I/D	0	The fault was not caused by an instruction fetch.
	1	The fault was caused by an instruction fetch.
PK	0	The fault was not caused by protection keys.
	1	There was a protection-key violation.
SGX	0	The fault is not related to SGX.
	1	The fault resulted from violation of SGX-specific access-control requirements.

Figure 4-12. Page-Fault Error Code