CS 105

"Tour of the Black Holes of Computing!"

Virtual Memory: Systems

Topics

- Simple memory system example
- Case study: Core i7
- Linux memory management
- Memory mapping

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

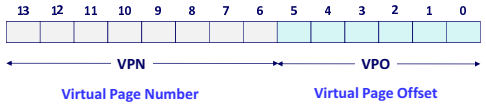
Components of the physical address (PA)

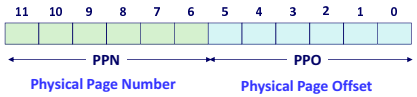
- PPO: Physical page offset (same as VPO)
- PPN: Physical page number
- CO: Byte offset within cache line
- CI: Cache index
- CT: Cache tag

Simple Memory System Example

Addressing

- 14-bit virtual addresses
- 12-bit physical address
- Page size = 64 bytes

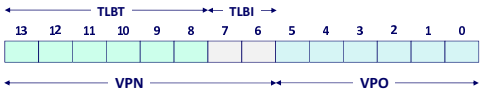




1. Simple Memory System TLB

16 entries

4-way associative



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

2. Simple Memory System Page Table

Only show 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

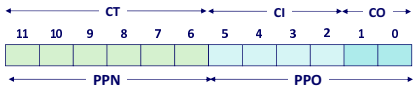
VPN	PPN	Valid
08	13	1
09	17	1
0A	09	1
0B	–	0
0C	–	0
0D	2D	1
0E	11	1
0F	0D	1

3. Simple Memory System Cache

16 lines, 4-byte block size

Physically addressed

Direct mapped

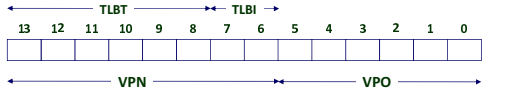


Idx	Tag	Valid	B0	B1	B2	B3
0	19	1	99	11	23	11
1	15	0	–	–	–	–
2	1B	1	00	02	04	08
3	36	0	–	–	–	–
4	32	1	43	6D	8F	09
5	0D	1	36	72	F0	1D
6	31	0	–	–	–	–
7	16	1	11	C2	DF	03

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	–	–	–	–

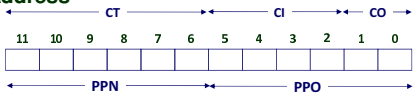
Address Translation Example #1

Virtual Address: `0x03D4`



VPN ____ TLBI ___ TLBT ____ TLB Hit? __ Page Fault? __ PPN: ____

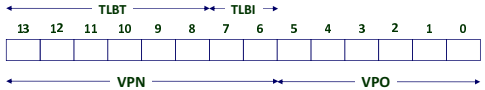
Physical Address



CO ___ CI___ CT ____ Hit? __ Byte: ____

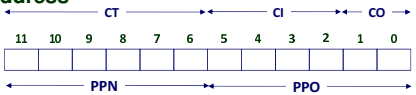
Address Translation Example #2

Virtual Address: `0x0020`



VPN ____ TLBI ___ TLBT ____ TLB Hit? __ Page Fault? __ PPN: ____

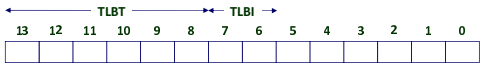
Physical Address



CO___ CI___ CT ____ Hit? __ Byte: ____

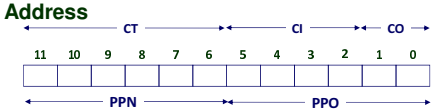
Address Translation Example #3

Virtual Address: 0x0316

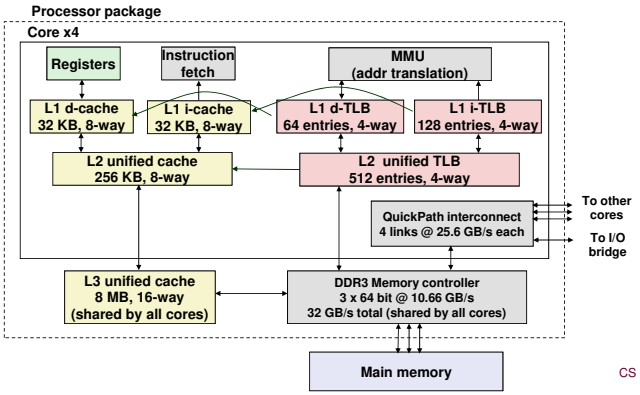


VPN ____ TLBI ___ TLBT ____ TLB Hit? __ Page Fault? __ PPN: ____

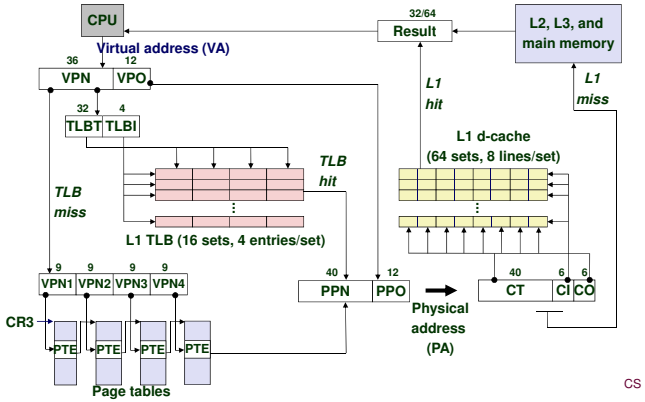
Physical Address



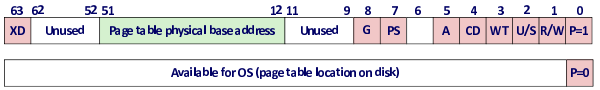
Intel Core i7 Memory System



End-to-End Core i7 Address Translation



Core i7 Level 1-3 Page Table Entries



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.

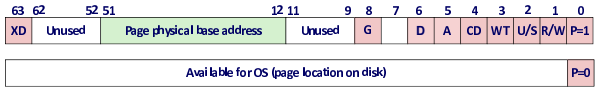
A: Reference bit (set by MMU on reads and writes, cleared by software).

PS: Page size either 4 KB or 4 MB (defined for Level 1 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



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 child page

U/S: User or supervisor mode access

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

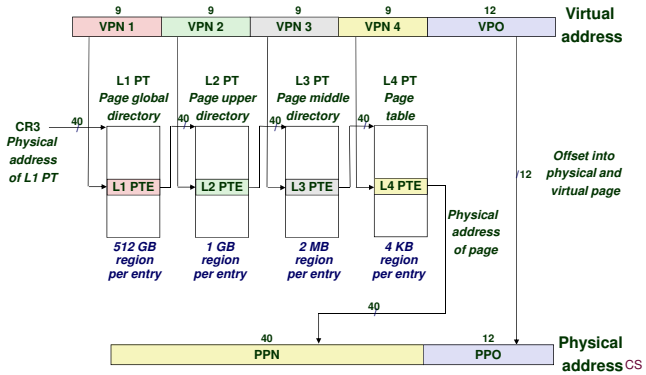
A: Reference bit (set by MMU on reads and writes, cleared by software)

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

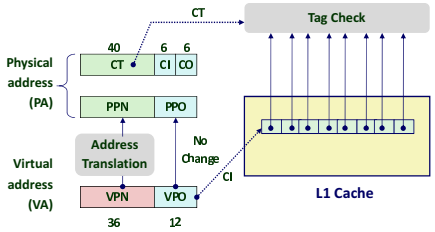
Page physical base address: 40 most significant bits of physical page address (forces pages to be 4KB aligned)

XD: Disable or enable instruction fetches from this page.

Core i7 Page Table Translation



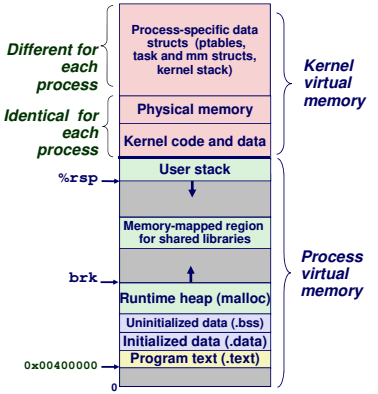
Cute Trick for Speeding Up L1 Access



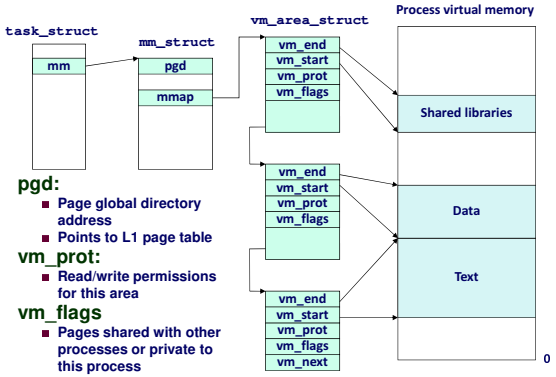
Observation

- Bits that determine CI are identical in virtual and physical address
- Can index into cache while address translation taking place
- Generally we hit in TLB, so PPN bits (CT bits) available next
- "Virtually indexed, physically tagged"
- Cache carefully sized to make this possible

Virtual Address Space of a Linux Process



Linux Organizes VM As Collection of "Areas"

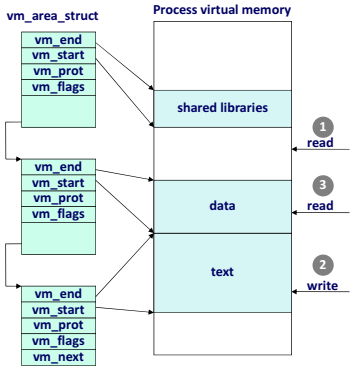


pgd:
- Page global directory address
- Points to L1 page table

vm_prot:
- Read/write permissions for this area

vm_flags
- Pages shared with other processes or private to this process

Linux Page-Fault Handling



Segmentation fault:
accessing a nonexistent page

Normal page fault

Protection exception:
e.g., violating permission by writing to a read-only page (Linux reports as Segmentation fault)

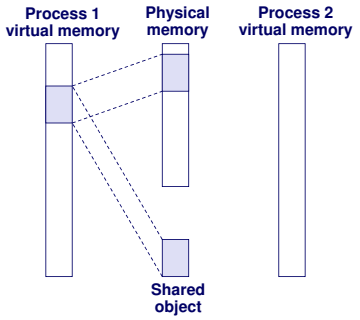
Memory Mapping

VM areas initialized by associating them with disk objects.
- Process is known as *memory mapping*.

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
- *Anonymous file* (e.g., nothing)
  - First fault will allocate physical page full of 0's (*demand-zero page*)
  - Once the page is written to (*dirtied*), it is like any other page

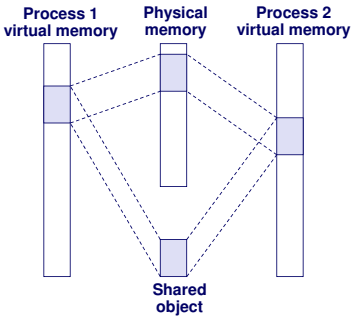
Dirty pages are copied back and forth between memory and a special *swap file*.

Sharing Revisited: Shared Objects



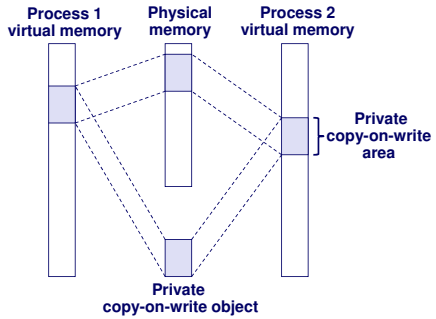
- Process 1 maps the shared object

Sharing Revisited: Shared Objects



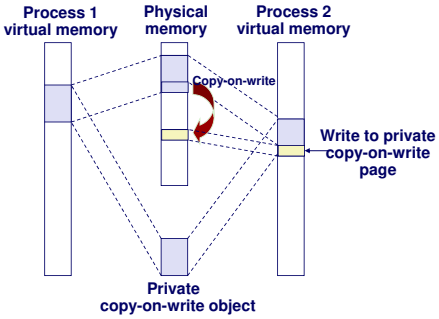
- Process 2 maps the shared object
- Notice how the virtual addresses can be different.

Sharing Revisited: Private Copy-on-Write (COW) Objects



- Two processes mapping a *private copy-on-write (COW)* object.
- Area flagged as private copy-on-write
- PTEs in private areas are flagged as read-only

Sharing Revisited: Private Copy-on-write (COW) Objects



- Instruction writing to private page triggers protection fault
- Handler creates new R/W page
- Instruction restarts upon handler return
- Copying deferred as long as possible!

The `fork` Function Revisited

VM and memory mapping explain how `fork` provides private address space for each process

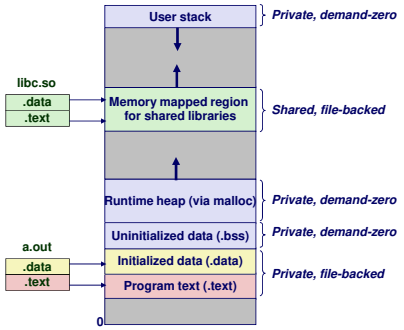
To create virtual address for new new process

- Create exact copies of current `mm_struct`, `vm_area_struct`, and page tables.
- Flag each page in both processes as read-only
- Flag each `vm_area_struct` in both processes as private COW

On return, each process has exact copy of virtual memory

Subsequent writes create new pages using COW mechanism.

The `execve` Function Revisited



- To load and run a new program `a.out` in the current process using `execve`:
- Free `vm_area_struct`'s and page tables for old areas
- Create `vm_area_struct`'s and page tables for new areas
  - Programs and initialized data backed by object files
  - `.bss` and stack backed by anonymous files
- Set PC to entry point in `.text`
  - Linux will fault in code and data pages as needed

User-Level Memory Mapping

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

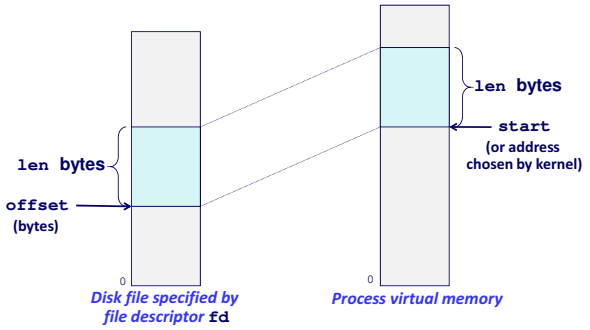
Map `len` bytes starting at offset `offset` of the file specified by file description `fd`, preferably at address `start`

- `start`: may be 0 for "pick an address"
- `prot`: PROT_READ, PROT_WRITE, ...
- `flags`: MAP_ANON, MAP_PRIVATE, MAP_SHARED, ...

Return pointer to start of mapped area (might not be `start`)

User-Level Memory Mapping

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



Example: Using `mmap` to Copy Files

- 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) {
        fprintf(stderr, "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