

CENG 3420

Computer Organization & Design



Lecture 09: Virtual Memory

Bei Yu

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Overview



Introduction

Virtual Memory

VA \rightarrow PA

TLB

Performance Issues

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TLB

Performance Issues



Physical memory may not be as large as “possible address space” spanned by a processor, e.g.

- ▶ A processor can address 4G bytes with 32-bit address
- ▶ But installed main memory may only be 1GB

How if we want to simultaneously run many programs which require a total memory consumption **greater** than the installed main memory capacity?

Terminology:

- ▶ A running program is called a process or a **thread**
- ▶ Operating System (**OS**) controls the processes

Virtual Memory



- ▶ Use main memory as a “**cache**” for secondary memory
- ▶ Each program is compiled into its own **virtual** address space
- ▶ What makes it work? [Principle of Locality](#)



- ▶ Use main memory as a “**cache**” for secondary memory
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Why virtual memory?

- ▶ During run-time, virtual address is translated to a **physical** address
- ▶ Efficient & safe sharing memory among multiple programs
- ▶ Ability to run programs larger than the size of physical memory
- ▶ Code relocation: code can be loaded anywhere in main memory

Bottom of the Memory Hierarchy



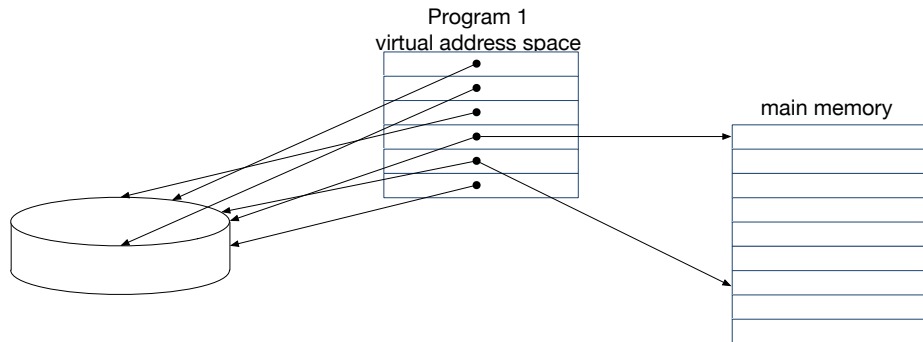
Consider the following example:

- ▶ Suppose we hit the limit of 1GB in the example, and we suddenly need some more memory on the fly.
- ▶ We move some main memory chunks to the harddisk, say, 100MB.
- ▶ So, we have 100MB of “free” main memory for use.
- ▶ What if later on, those instructions / data in the saved 100MB chunk are needed again?
- ▶ We have to “free” some other main memory chunks in order to move the instructions / data back from the harddisk.

Two Programs Sharing Physical Memory



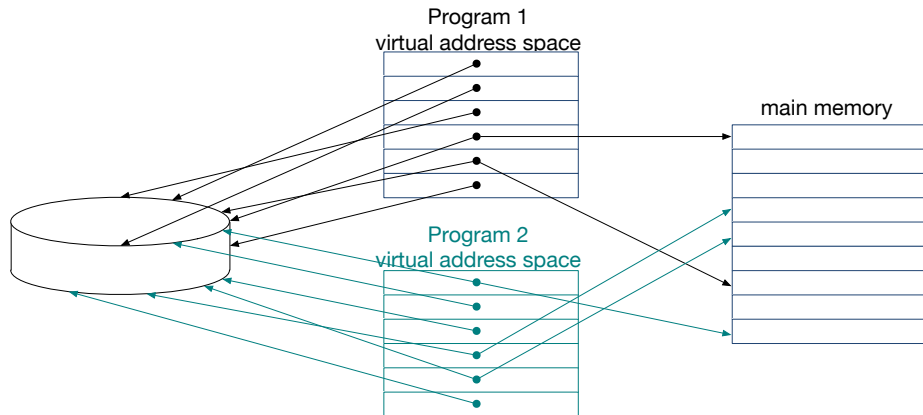
- ▶ A program's address space is divided into **pages** (fixed size) or **segments** (variable sizes)



Two Programs Sharing Physical Memory



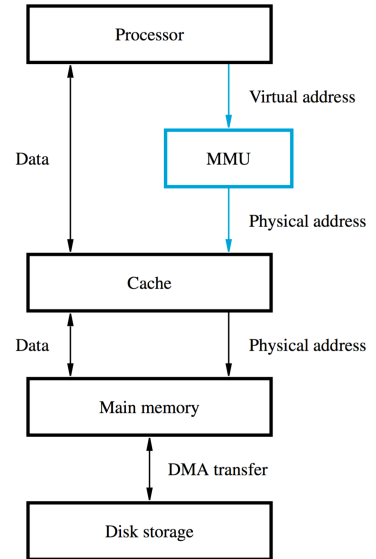
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Virtual Memory Organization



- ▶ Part of process(es) are stored temporarily on harddisk and brought into main memory as needed
- ▶ This is done automatically by the OS, application program does not need to be aware of the existence of virtual memory (VM)
- ▶ Memory management unit (MMU) translates virtual addresses to physical addresses



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- ▶ Memory divided into **pages** of size ranging from 2KB to 16KB
 - ▶ Page too small: too much time spent getting pages from disk
 - ▶ Page too large: a large portion of the page may not be used
 - ▶ This is similar to cache block size issue (discussed earlier)
- ▶ For harddisk, it takes a considerable amount of time to locate a data on the disk but once located, the data can be transferred at a rate of several MB per second.
- ▶ If pages are too large, it is possible that a substantial portion of a page is not used but it will occupy valuable space in the main memory.

Address Translation

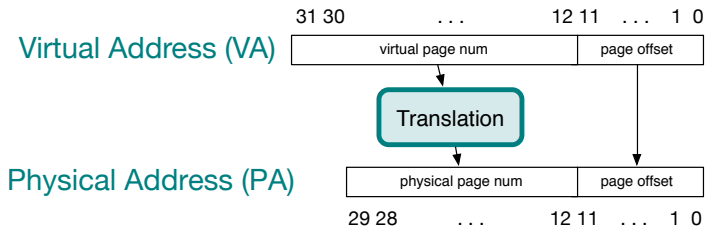


- ▶ An area in the main memory that can hold one page is called a **page frame**.
- ▶ Processor generates virtual addresses
 - ▶ MS (**high** order) bits are the **virtual page number**
 - ▶ LS (**low** order) bits are the **offset**
- ▶ Information about where each page is stored is maintained in a data structure in the main memory called the **page table**
 - ▶ Starting address of the page table is stored in a page table base register
 - ▶ Address in physical memory is obtained by indexing the virtual page number from the page table base register

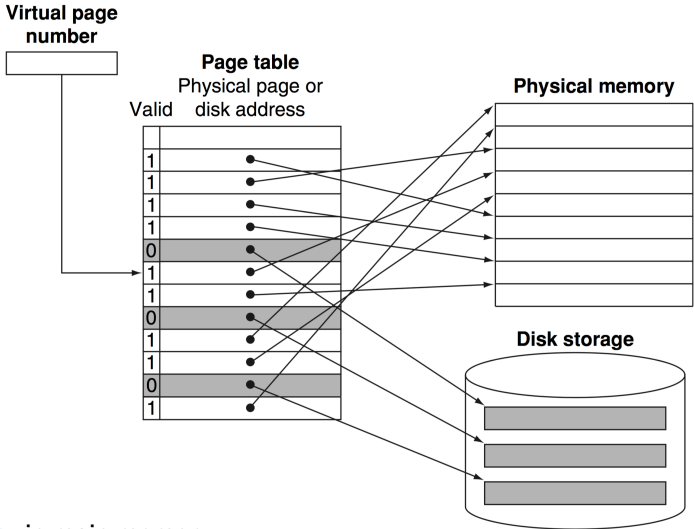
Address Translation



- ▶ Virtual address → physical address by combination of HW/SW
- ▶ Each memory request needs first an address translation
- ▶ Page Fault: a virtual memory miss



Address Translation Mechanisms



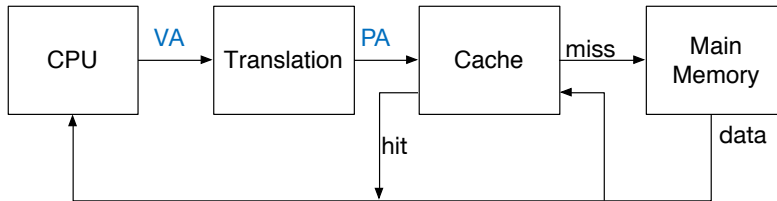
- ▶ **Page Table:** in main memory
- ▶ **Process:** page table + program counter + registers

Virtual Addressing with a Cache



Disadvantage of virtual addressing:

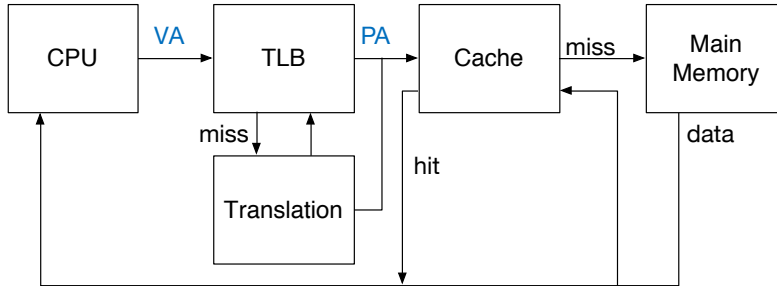
- ▶ One **extra** memory access to translate a VA to a PA
- ▶ memory (cache) access very expensive...



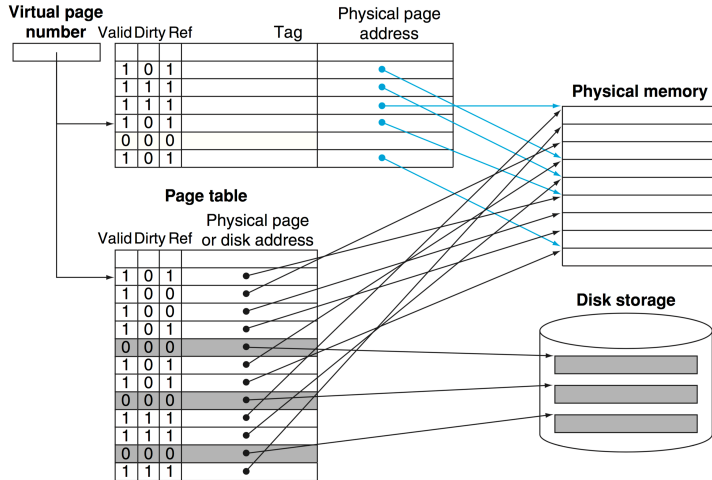
Translation Look-aside Buffer (TLB)



- ▶ A small **cache**: keeps track of recently used address mappings
- ▶ Avoid page table lookup



Translation Look-aside Buffer (TLB)



▶ Dirty bit:

▶ Ref bit:

More about TLB



Organization:

- ▶ Just like any other cache, can be fully associative, set associative, or direct mapped.

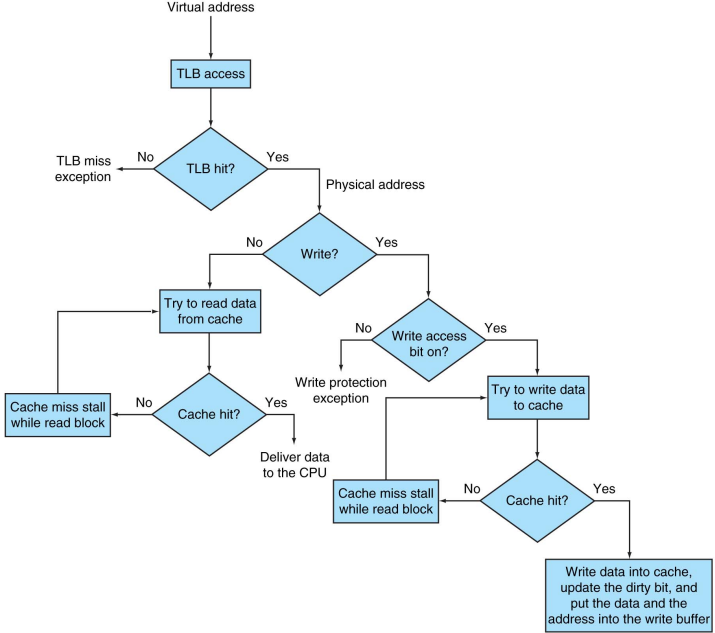
Access time:

- ▶ **Faster** than cache: due to smaller size
- ▶ Typically not more than 512 entries even on high end machines

A TLB miss:

- ▶ If the page is in main memory: miss can be handled; load translation info from page table to TLB
- ▶ If the page is NOT in main memory: **page fault**

Cooperation of TLB & Cache



TLB Event Combinations



- ▶ TLB / Cache miss: page / block not in “cache”
- ▶ Page Table miss: page NOT in memory

TLB	Page Table	Cache	Possible? Under what circumstances?
Hit	Hit	Hit	
Hit	Hit	Miss	
Miss	Hit	Hit	
Miss	Hit	Miss	
Miss	Miss	Miss	
Hit	Miss	Miss / Hit	
Miss	Miss	Hit	

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Hit	Hit	Hit	Yes – what we want!
Hit	Hit	Miss	Yes – although page table is not checked if TLB hits
Miss	Hit	Hit	Yes – TLB miss, PA in page table
Miss	Hit	Miss	Yes – TLB miss, PA in page table but data not in cache
Miss	Miss	Miss	Yes – page fault
Hit	Miss	Miss / Hit	
Miss	Miss	Hit	

TLB Event Combinations



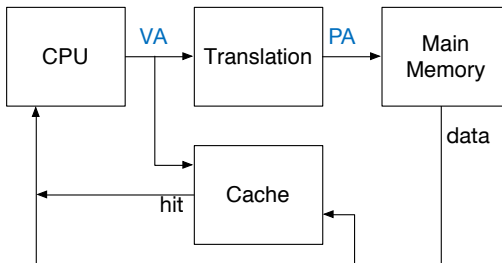
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Miss	Miss	Miss	Yes – page fault
Hit	Miss	Miss / Hit	Impossible – TLB translation not possible if page is not in memory
Miss	Miss	Hit	Impossible – data not allowed in cache if page is not in memory

QUESTION: Why Not a Virtually Addressed Cache?



- ▶ Access Cache using virtual address (VA)
- ▶ Only address translation when cache misses

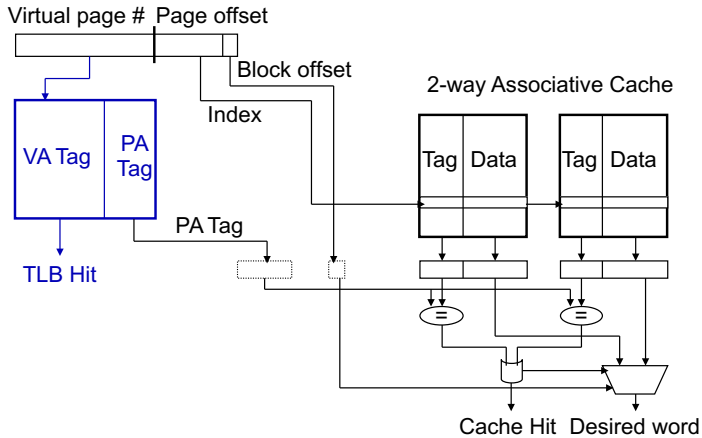


Answer:

Overlap Cache & TLB Accesses



- ▶ High order bits of VA are used to access TLB
- ▶ Low order bits of VA are used as index into cache



The Hardware / Software Boundary



Which part of address translation is done by hardware?

- ▶ TLB that caches recent translations:
 - ▶ TLB access time is part of cache hit time
 - ▶ May allot extra stage in pipeline
- ▶ Page Table storage, fault detection and updating
 - ▶ Dirty & Reference bits
 - ▶ Page faults result in interrupts
- ▶ Disk Placement:

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- ▶ Disk Placement: (Software)

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Q1: Where A Block Be Placed in Upper Level?

Scheme name	# of sets	Blocks per set
Direct mapped	# of blocks	1
Set associative	$\frac{\text{\# of blocks}}{\text{Associativity}}$	Associativity
Fully associative	1	# of blocks



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Q2: How Is Entry Be Found?

Scheme name	Location method	# of comparisons
Direct mapped	Index	1
Set associative	Index the set; compare set's tags	Degree of associativity
Fully associative	Compare all tags	# of blocks



Q3: Which Entry Should Be Replaced on a Miss?

- ▶ **Direct mapped**: only one choice
- ▶ **Set associative** or **fully associative**:
 - ▶ Random
 - ▶ LRU (Least Recently Used)

Note that:

- ▶ For a 2-way set associative, random replacement has a miss rate $1.1\times$ than LRU
- ▶ For high level associativity (4-way), LRU is too **costly**



Q4: What Happen On A Write?

▶ Write-Through:

- ▶ The information is written in both the block in cache & the block in lower level of memory
- ▶ Combined with **write buffer**, so write waits can be eliminated
- ▶ ⊕:
- ▶ ⊕:

▶ Write-Back:

- ▶ The information is written only to the block in cache
- ▶ The modification is written to lower level, only when the block is replaced
- ▶ Need dirty bit: tracks whether the block is clean or not
- ▶ **Virtual memory** always use write-back
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- ▶ ⊕: write with speed of cache
- ▶ ⊕: repeated writes require only one write to lower level



Performance

How **fast** machine instructions can be brought into the processor and how **fast** they can be executed.

- ▶ Two key factors are **performance** and **cost**, i.e., **price/performance ratio**.
- ▶ For a hierarchical memory system with cache, the processor is able to access instructions and data more quickly when the data wanted are in the cache.
- ▶ Therefore, the impact of a cache on performance is dependent on the **hit and miss rates**.

Cache Hit Rate and Miss Penalty



- ▶ High hit rates over 0.9 are essential for **high-performance** computers.
- ▶ A penalty is incurred because extra time is needed to bring a block of data from a slower unit to a faster one in the hierarchy.
- ▶ During that time, the processor is **stalled**.
- ▶ The waiting time depends on the details of the cache operation.

Miss Penalty

Total access time seen by the processor when a **miss** occurs.



Example: Consider a computer with the following parameters:

Access times to the cache and the main memory are t and $10t$ respectively. When a cache miss occurs, a block of 8 words will be transferred from the MM to the cache. It takes $10t$ to transfer the first word of the block and the remaining 7 words are transferred at a rate of one word per t seconds.

- ▶ Miss penalty = $t + 10t + 7 \times t + t$
- ▶ First t : Initial cache access that results in a miss.
- ▶ Last t : Move data from the cache to the processor.



Average Memory Access Time

$$h \times C + (1 - h) \times M$$

- ▶ h : hit rate
 - ▶ M : miss penalty
 - ▶ C : cache access time
-
- ▶ High cache hit rates ($> 90\%$) are essential
 - ▶ Miss penalty must also be reduced



Question: Memory Access Time Example

- ▶ Assume **8** cycles to read a single memory word;
- ▶ **15** cycles to load a 8-word block from main memory (previous example);
- ▶ cache access time = 1 cycle
- ▶ For every **100** instructions, statistically **30** instructions are data read/ write
- ▶ Instruction fetch: 100 memory access: assume hit rate = 0.95
- ▶ Data read/ write: 30 memory access: assume hit rate = 0.90

Calculate: (1) Execution cycles without cache; (2) Execution cycles with cache.

Caches on Processor Chips



- ▶ In high-performance processors, two levels of caches are normally used, L1 and L2.
- ▶ L1 must be very fast as they determine the memory access time seen by the processor.
- ▶ L2 cache can be slower, but it should be much larger than the L1 cache to ensure a high hit rate. Its speed is less critical because it only affects the miss penalty of the L1 cache.
- ▶ Average access time on such a system:

$$h_1 \cdot C_1 + (1 - h_1) \cdot [h_2 \cdot C_2 + (1 - h_2) \cdot M]$$

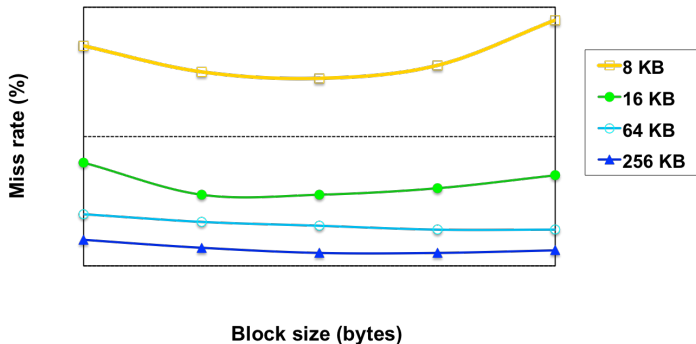
- ▶ h_1 (h_2): the L1 (L2) hit rate
- ▶ C_1 the access time of L1 cache,
- ▶ C_2 the miss penalty to transfer data from L2 cache to L1
- ▶ M : the miss penalty to transfer data from MM to L2 and then to L1.

Larger Block Size



- ▶ Take advantage of spatial locality.
- ▶ 😊 If all items in a larger block are needed in a computation, it is better to load these items into the cache in a single miss.
- ▶ 😞 Larger blocks are effective only up to a certain size, beyond which too many items will remain unused before the block is replaced.
- ▶ 😞 Larger blocks take longer time to transfer and thus increase the miss penalty.
- ▶ Block sizes of 16 to 128 bytes are most popular.

Miss Rate v.s. Block Size v.s. Cache Size



Miss rate goes up if the block size becomes a significant fraction of the cache size because the number of blocks that can be held in the same size cache is smaller (increasing **capacity** misses)



Write buffer:

- ▶ Read request is served first.
- ▶ Write request stored in write buffer first and sent to memory whenever there is no read request.
- ▶ The addresses of a read request should be compared with the addresses of the write buffer.

Prefetch:

- ▶ Prefetch data into the cache before they are needed, while the processor is busy executing instructions that do not result in a read miss.
- ▶ Prefetch instructions can be inserted by the programmer or the compiler.

Load-through Approach

- ▶ Instead of waiting the whole block to be transferred, the processor resumes execution as soon as the required word is loaded in the cache.