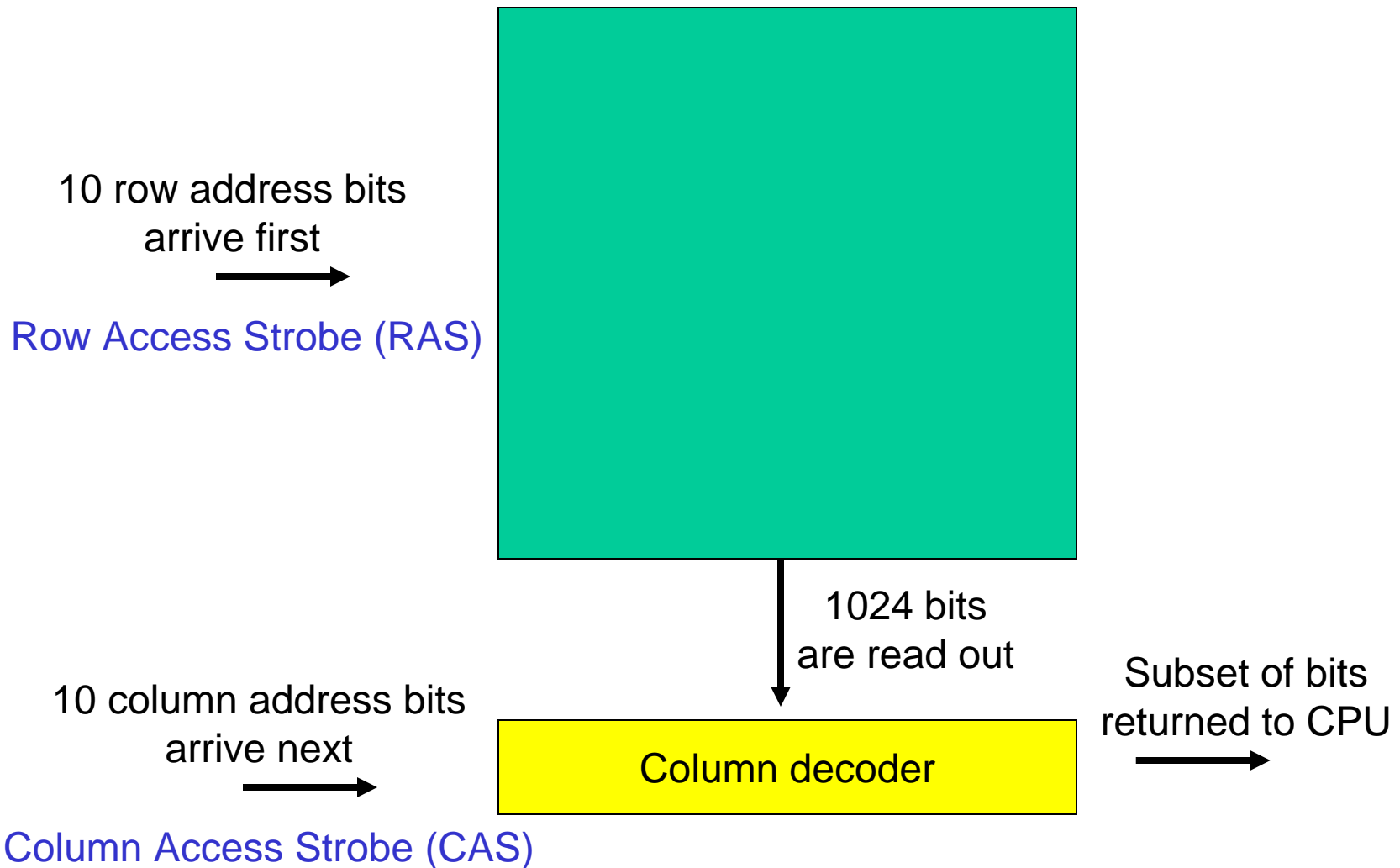


Lecture 13: Memory Design

- Topics: virtual memory, DRAMs
(Sections 5.3, Appendix C.4-C.5)

DRAM Access

1M DRAM = 1024 x 1024 array of bits



DRAM Properties

- The RAS and CAS bits share the same pins on the chip
- Each bit loses its value after a while – hence, each bit has to be refreshed periodically – this is done by reading each row and writing the value back (hence, *dynamic* random access memory) – causes variability in memory access time
- Dual Inline Memory Modules (DIMMs) contain 4-16 DRAM chips and usually feed eight bytes to the processor

Technology Trends

- Improvements in technology (smaller devices) → DRAM capacities double every two years
- Time to read data out of the array improves by only 5% every year → high memory latency (the memory wall!)
- Time to read data out of the column decoder improves by 10% every year → influences bandwidth

Increasing Bandwidth

- The column decoder has access to many bits of data – many sequential bits can be forwarded to the CPU without additional row accesses (fast page mode)
- Each word is sent asynchronously to the CPU – every transfer entails overhead to synchronize with the controller – by introducing a clock, more than one word can be sent without increasing the overhead – synchronous DRAM

Increasing Bandwidth

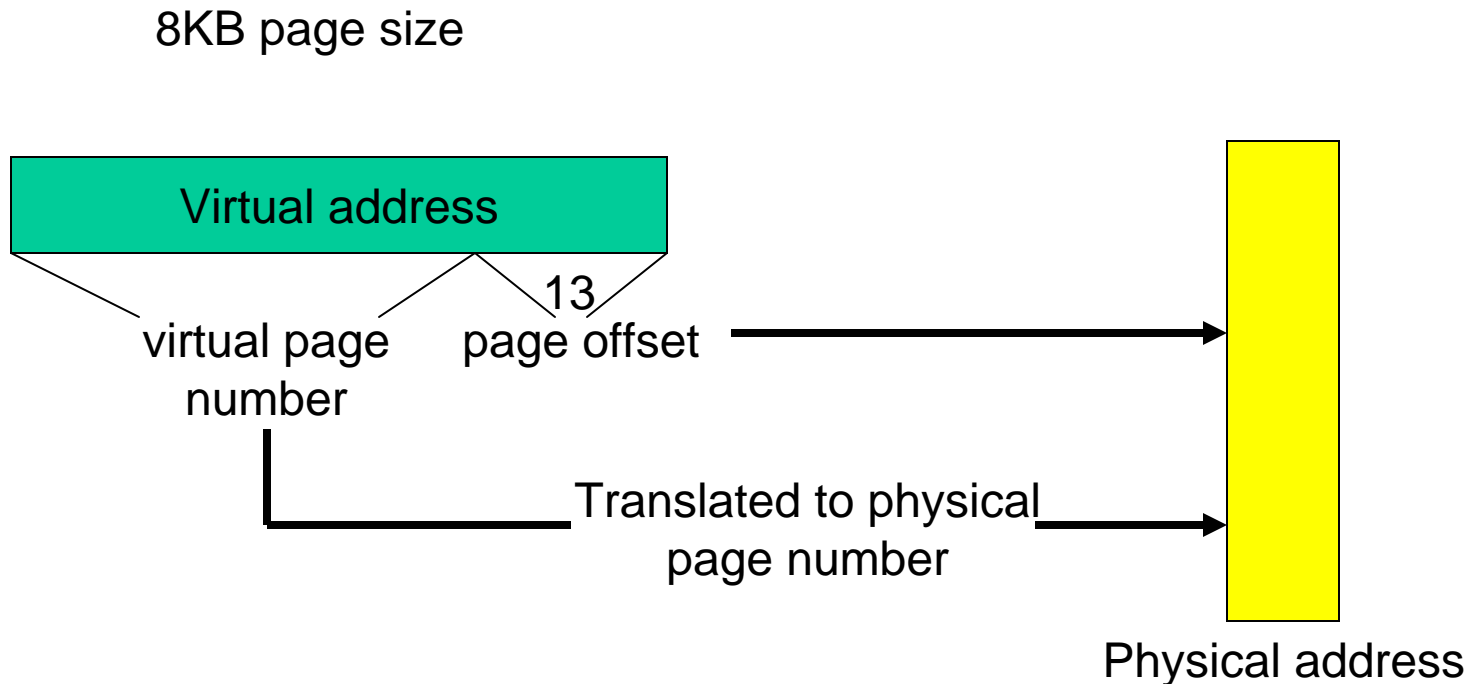
- By increasing the memory width (number of memory chips and the connecting bus), more bytes can be transferred together – increases cost
- Interleaved memory – since the memory is composed of many chips, multiple operations can happen at the same time – a single address is fed to multiple chips, allowing us to read sequential words in parallel

Virtual Memory

- Processes deal with virtual memory – they have the illusion that a very large address space is available to them
- There is only a limited amount of physical memory that is shared by all processes – a process places part of its virtual memory in this physical memory and the rest is stored on disk
- Thanks to locality, disk access is likely to be uncommon
- The hardware ensures that one process cannot access the memory of a different process

Address Translation

- The virtual and physical memory are broken up into pages



Memory Hierarchy Properties

- A virtual memory page can be placed anywhere in physical memory (fully-associative)
- Replacement is usually LRU (since the miss penalty is huge, we can invest some effort to minimize misses)
- A page table (indexed by virtual page number) is used for translating virtual to physical page number
- The memory-disk hierarchy can be either inclusive or exclusive and the write policy is writeback

TLB

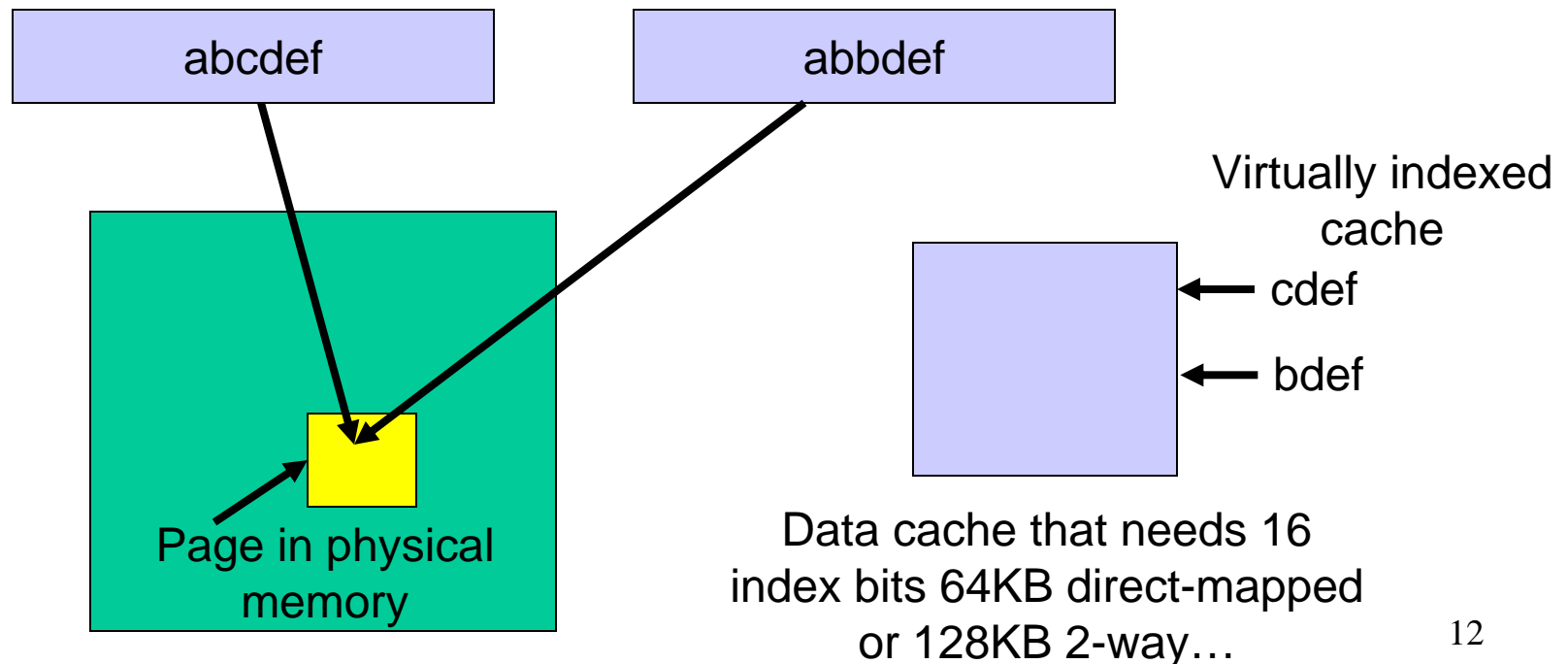
- Since the number of pages is very high, the page table capacity is too large to fit on chip
- A translation lookaside buffer (TLB) caches the virtual to physical page number translation for recent accesses
- A TLB miss requires us to access the page table, which may not even be found in the cache – two expensive memory look-ups to access one word of data!
- A large page size can increase the coverage of the TLB and reduce the capacity of the page table, but also increases memory wastage

TLB and Cache

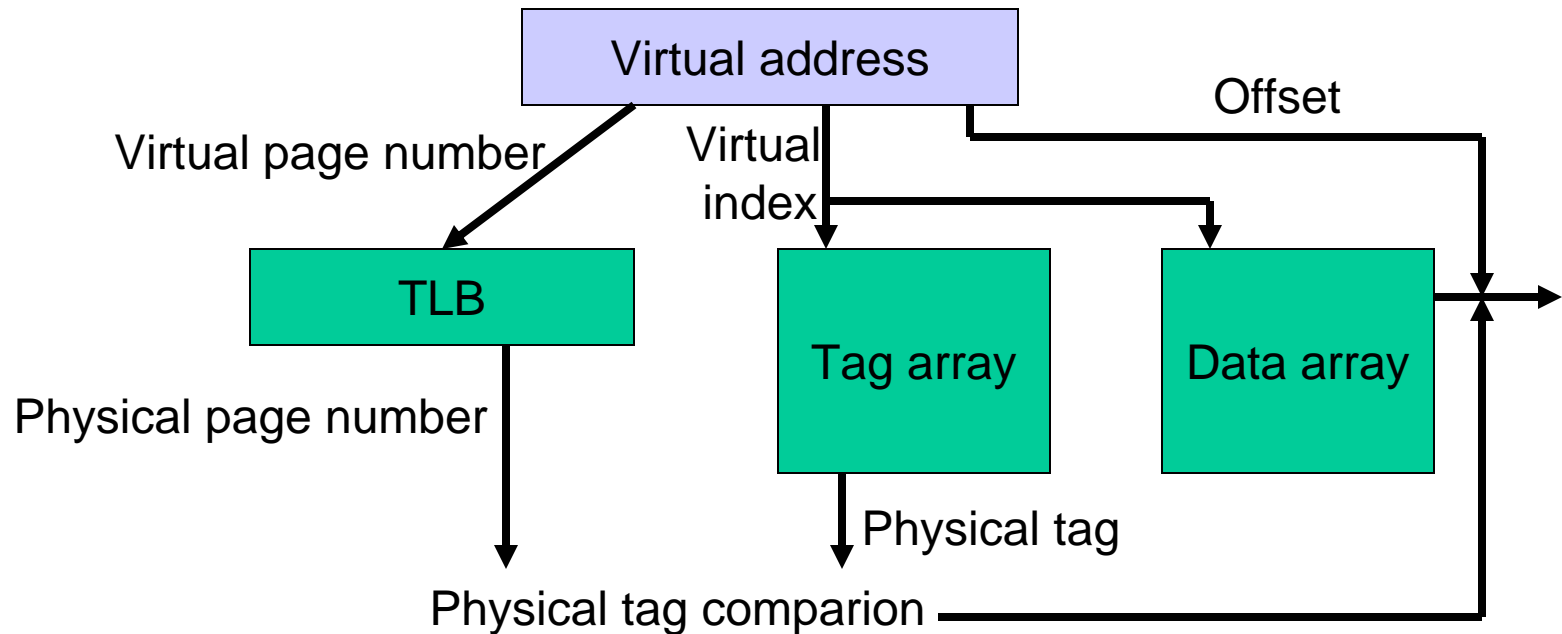
- Is the cache indexed with virtual or physical address?
 - To index with a physical address, we will have to first look up the TLB, then the cache → longer access time
 - Multiple virtual addresses can map to the same physical address – can we ensure that these different virtual addresses will map to the same location in cache? Else, there will be two different copies of the same physical memory word
- Does the tag array store virtual or physical addresses?
 - Since multiple virtual addresses can map to the same physical address, a virtual tag comparison can flag a miss even if the correct physical memory word is present

Virtually Indexed Caches

- 24-bit virtual address, 4KB page size → 12 bits offset and 12 bits virtual page number
- To handle the example below, the cache must be designed to use only 12 index bits – for example, make the 64KB cache 16-way
- Page coloring can ensure that some bits of virtual and physical address match



Cache and TLB Pipeline



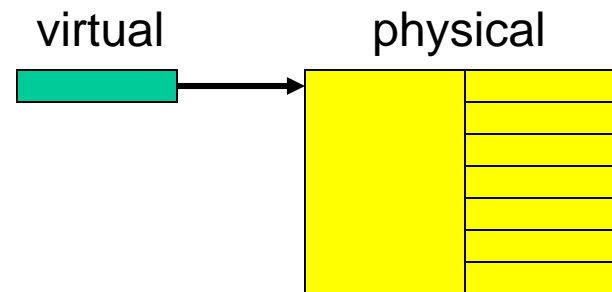
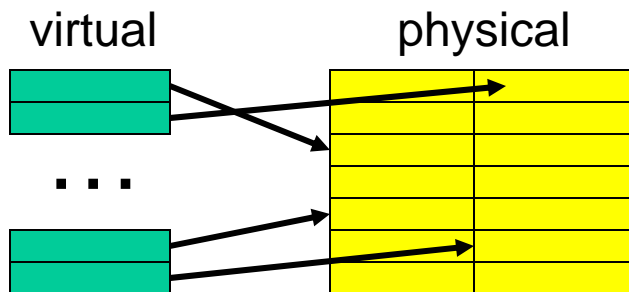
Virtually Indexed; Physically Tagged Cache

Superpages

- If a program's working set size is 16 MB and page size is 8KB, there are 2K frequently accessed pages – a 128-entry TLB will not suffice
- By increasing page size to 128KB, TLB misses will be eliminated – disadvantage: memory wastage, increase in page fault penalty
- Can we change page size at run-time?
- Note that a single page has to be contiguous in physical memory

Superpages Implementation

- At run-time, build superpages if you find that contiguous virtual pages are being accessed at the same time
- For example, virtual pages 64-79 may be frequently accessed – coalesce these pages into a single superpage of size 128KB that has a single entry in the TLB
- The physical superpage has to be in contiguous physical memory – the 16 physical pages have to be moved so they are contiguous



Ski Rental Problem

- Promoting a series of contiguous virtual pages into a superpage reduces TLB misses, but has a cost: copying physical memory into contiguous locations
- Page usage statistics can determine if pages are good candidates for superpage promotion, but if cost of a TLB miss is x and cost of copying pages is Nx , when do you decide to form a superpage?
- If ski rentals cost \$20 and new skis cost \$200, when do I decide to buy new skis?
 - If I rent 10 times and then buy skis, I'm guaranteed to not spend more than twice the optimal amount

Protection

- The hardware and operating system must co-operate to ensure that different processes do not modify each other's memory
- The hardware provides special registers that can be read in user mode, but only modified by instrs in supervisor mode
- A simple solution: the physical memory is divided between processes in contiguous chunks by the OS and the bounds are stored in special registers – the hardware checks every program access to ensure it is within bounds

Protection with Virtual Memory

- Virtual memory allows protection without the requirement that pages be pre-allocated in contiguous chunks
- Physical pages are allocated based on program needs and physical pages belonging to different processes may be adjacent – efficient use of memory
- Each page has certain read/write properties for user/kernel that is checked on every access
 - a program's executable can not be modified
 - part of kernel data cannot be modified/read by user
 - page tables can be modified by kernel and read by user

Title

- Bullet