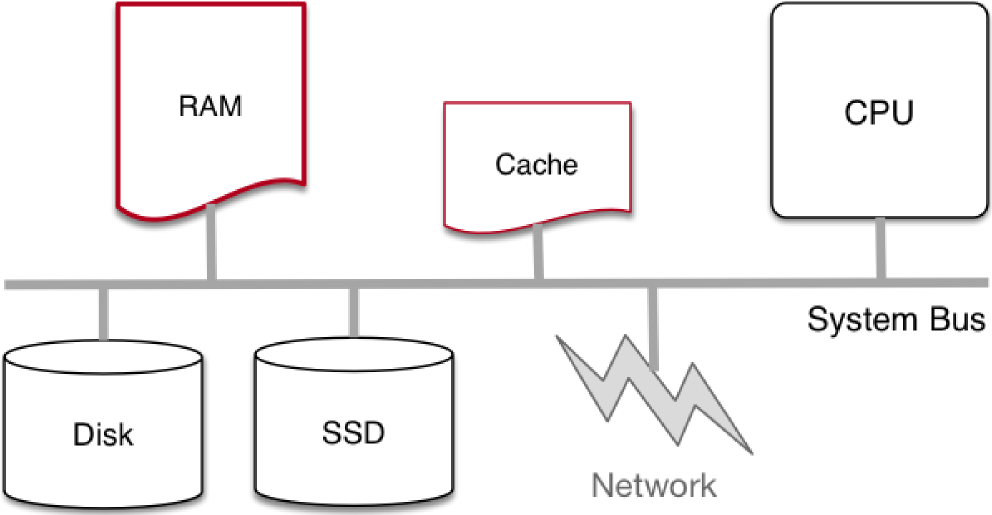
Memory

Systems typically contain 4-16GB of volatile RAM



Single Process Resident in RAM without Operating System

- Many small embedded system run without operating system.
- Single program running, probably written in C.
- Devices (sensors, switches, ...) often wired at particular address.
- E.g can set motor speed by storing byte at 0x100400.
- Program accesses (any) RAM directly.
- Development and debugging tricky.
- Widely used for simple micro-controllers.
- Parallelism and exploiting multiple-core CPUs problematic

Single Process Resident in RAM with Operating System

- Operating system need (simple) hardware support.
- Part of RAM (kernel space) must be accessible only in a privileged mode.
- System call enables privileged mode and passes execution to operating system code in kernel space.
- Privileged mode disabled when system call returns.
- Privileged mode could be implemented by a bit in a special register
- If only one process resident in RAM at any time - switching between processes is slow .
- Operating system must write out all memory of old process to disk and read all memory of new process from disk.
- OK for some uses, but inefficient in general.
- Little used in modern computing.

Multi Processes Resident in RAM without Virtual Memory

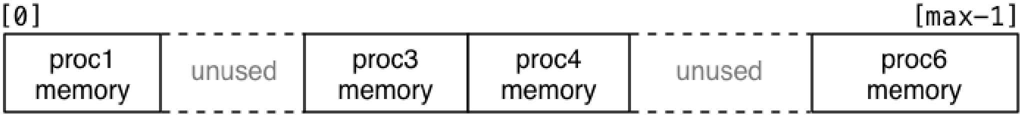
- If multiple processes to be resident in RAM O/S can swap execution between them quickly.
- RAM belonging to other processes & kernel must be protected
- Hardware support can limit process accesses to particular **segment** (region) of RAM.
- BUT program may be loaded anywhere in RAM to run
- Breaks instructions which use absolute addresses, e.g.: **`lw`**, **`sw`**, **`jr`**
- Either programs can't use absolute memory addresses (relocatable code)
- Or code has to be modified (relocated) before it is run - not possible for all code!
- Major limitation - much better if programs can assume always have same address space
- Little used in modern computing.

Virtual Memory

- Big idea - disconnect address processes use from actual RAM address.
- Operating system translates (virtual) address a process uses to an physical (actual) RAM address.
- Convenient for programming/compilers - each process has same virtual view of RAM.
- Can have multiple processes be in RAM, allowing fast switching
- Can load part of processes into RAM on demand.
- Provides a mechanism to share memory betwen processes.
- Address to fetch every instruction to be executed must be translated.
- Address for load/store instructions (e.g. **`lw`**, **`sw`**) must be translated .
- Translation needs to be really fast so largely implemented in hardware (silicon).

Virtual Memory with One Memory Segment Per Process

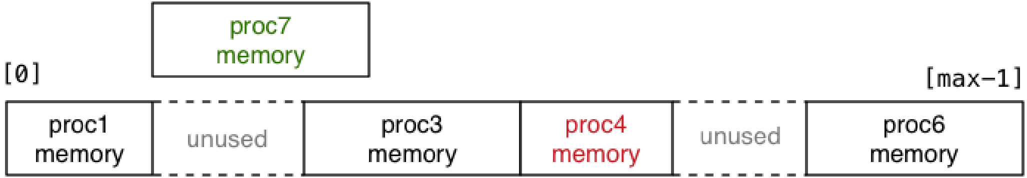
Consider a scenario with multiple processes loaded in memory:



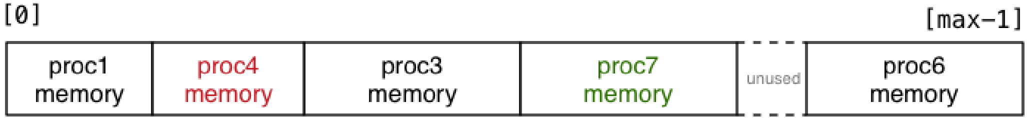
- Every process is in a contiguous section of RAM, starting at address **base** finishing at address **limit**.
- Each process sees its own address space as [0 .. size - 1]
- Process can be loaded anywhere in memory without change.
- Process accessing memory address **a** is translated to **a + base**
- and checked that **a + base** is **< limit** to ensure process only access its memory
- Easy to implement in hardware.

Virtual Memory with One Memory Segment Per Process

Consider the same scenario, but now we want to add a new process



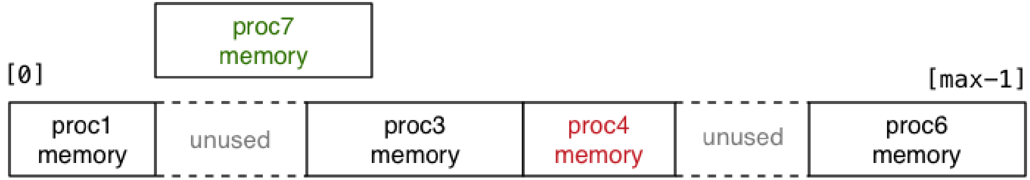
- The new process doesn't fit in any of the unused slots (fragmentation).
- Could move some process to make a single large slot



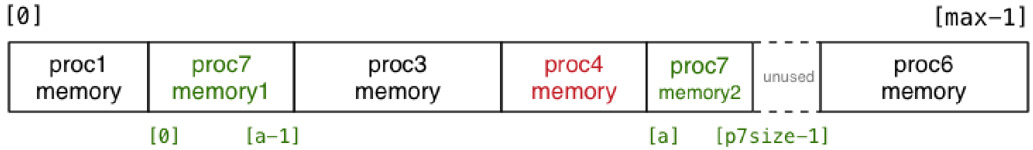
- Slow if RAM heavily used.
- Does not allow sharing or loading on demand.
- Limits process address space to size of RAM.

Virtual Memory with Multiple Memory Segments Per Process

Idea: split process memory over multiple parts of physical memory.



becomes



Virtual Memory with Multiple Memory Segments Per Process

With arbitrary sized memory segments, translating virtual to physical address is complicated making hardware support difficult:

```c
// translate virtual_address to physical RAM address
uint32_t translate(uint32_t process_id, uint32_t virtual_addr) {
  uint32_t n_segments;
  Segment *segments = get_segments(process_id, &n_segments);
  for (int i = 0; i < n_segments; i++) {
    Segment *c = &segments[i];
    if (virtual_addr >= c->base &&
        virtual_addr <  c->base + c->size) {
      uint32_t offset = virtual_addr - c->base;
      return c->mem + offset;
    }
  }
  // handle illegal memory access
}
```

Virtual Memory with Pages

Address mapping would be simpler if all segments were same size

- call each segment of address space a ***page***
- make all pages the same size ***P***
- page ***I*** holds addresses: ***I*P ... (I+1)*P***
- translation of addresses can be implemented with an array
- each process has an array called the ***page table***
- each array element contains the physical address in RAM of that page
- for virtual address ***V***, ***page_table[V / P]*** contains physical address of page
- the address will at be at offset ***V % P*** in both pages
- so physical address for ***V*** is: ***page_table[V / P] + V % P***

Virtual Memory with Pages

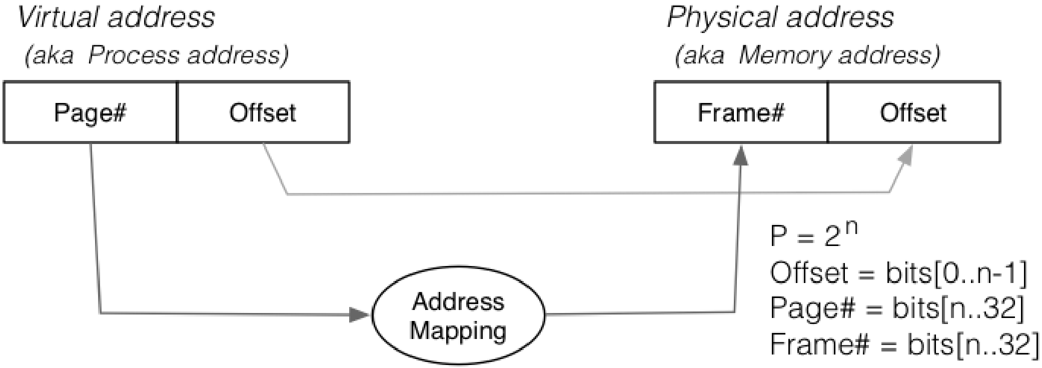
With pages, translating virtual to physical address is simpler making hardware support difficult:

```c
// translate virtual_address to physical RAM address
uint32_t translate(uint32_t process_id, uint32_t virtual_addr) {
  uint32_t pt_size;
  PageInfo *page_table = get_page_table(process_id, &pt_size);
  page_number = virtual_addr / PAGE_SIZE;
  if (page_number < pt_size) {
      uint32_t offset = virtual_addr % PAGE_SIZE;
      return PAGE_SIZE * page_table[page_number].frame + offset;
  }
  // handle illegal memory access
}
```

- Calculation of *page_number* and *offset* can be faster/simpler bit operations if *PAGE_SIZE* $== 2^n$, e.g. 4096, 8192, 16384
- Note **PageInfo** entries will have more information about the page ...

Address Mapping

If $P == 2^n$, then address mapping becomes



Virtual Memory with pages - Lazy Loading

A side-effect of this type of virtual $\longrightarrow$ physical address mapping

- don't need to load all of process's pages up-front
- start with a small memory "footprint" (e.g. `main` + stack top)
- load new process address pages into memory *as needed*
- grow up to the size of the (available) physical memory

The strategy of ...

- dividing process memory space into fixed-size pages
- on-demand loading of process pages into physical memory

is what is generally meant by *virtual memory*

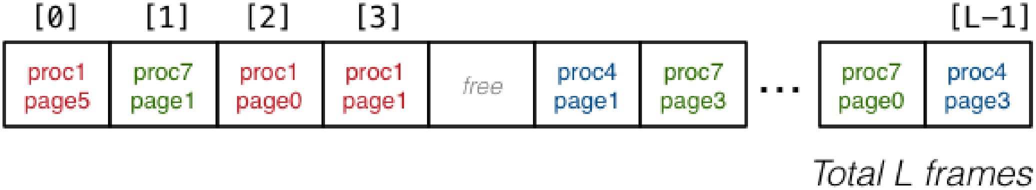
Virtual Memory

Pages/frames are typically 4KB .. 256KB in size

With 4GB memory, would have $\approx$ 1 million $\times$ 4KB frames

Each frame can hold one page of process address space

Leads to a memory layout like this (with L total pages of physical memory):



When a process completes, all of its frames are released for re-use

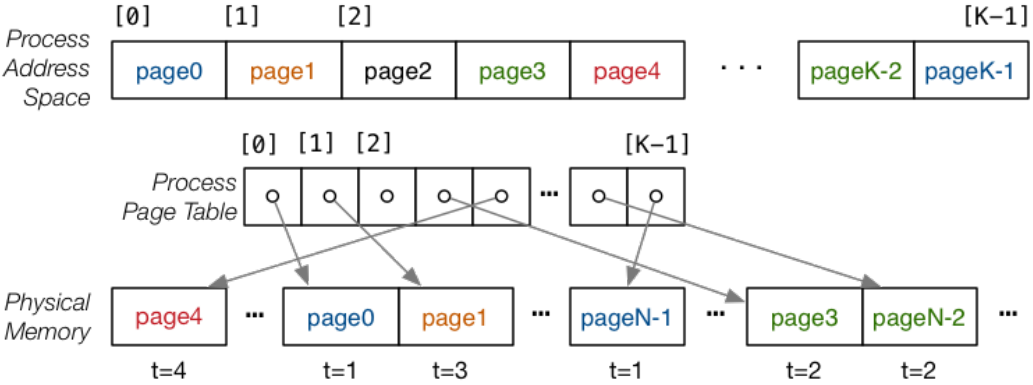
Page Tables

Consider a possible per-process page table, e.g.

- each page table entry (PTE) might contain
  - page status ... *not_loaded*, *loaded*, *modified*
  - frame number of page (if *loaded*)
  - ... maybe others ... (e.g. last accessed time)
- we need $\lceil ProcSize/PageSize \rceil$ entries in this table

Example Page Table

Example of page table for one process:



Timestamps show when page was loaded.

Virtual Memory - Loading Pages

```c
typedef struct {int status, int frame, ...} PageInfo;

uint32_t translate(uint32_t process_id, uint32_t virtual_addr) {
  uint32_t pt_size;
  PageInfo *page_table = get_page_table(process_id, &pt_size);
  page_number = virtual_addr / PAGE_SIZE;
  if (page_number < pt_size) {
      if (page_table[page_number].status != LOADED) {
          // page fault - need to load page into free frame
          page_table[page_number].frame = ???
          page_table[page_number].status = LOADED;
      }
      uint32_t offset = virtual_addr % PAGE_SIZE;
      return PAGE_SIZE * page_table[page_number].frame + offset;
  }
  // handle illegal memory access
}
```

Virtual Memory - Loading Pages

Consider a new process commencing execution ...

- initially has zero pages loaded
- load page containing code for `main()`
- load page for `main()`'s stack frame
- load other pages when process references address within page

Do we ever need to load all process pages at once?

Virtual Memory - Working Sets

From observations of running programs ...

- in any given window of time, process typically access only a small subset of their pages
- often called *locality of reference*
- subset of pages called the *working set*

Implications:

- if each process has a relatively small working set,
  can hold pages for many active processes in memory at same time
- if only need to hold some of process's pages in memory,
  process address space can be larger than physical memory

Virtual Memory - Loading Pages

We say that we ”load” pages into physical memory

But where are they loaded from?

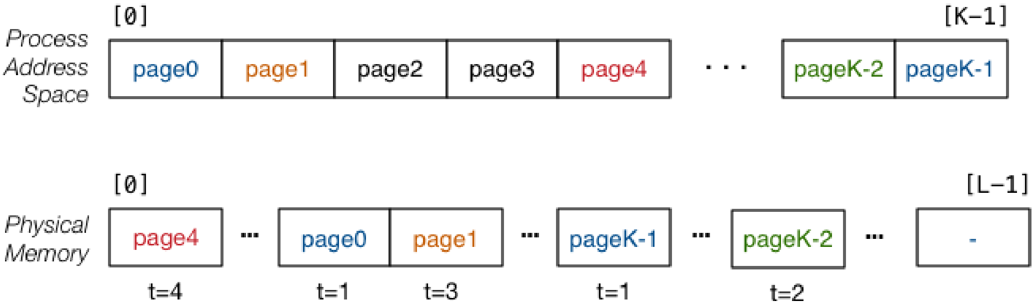
- code is loaded from the executable file stored on disk into read-only pages
- some data (e.g. C strings) also loaded into read-only pages
- initialised data (C global/static variables) also loaded from executable file
- pages for uninitialised data (heap, stack) are zero-ed
    - prevents information leaking from other processes
    - results in uninitialised local (stack) variables often containing 0

Consider a process whose address space exceeds physical memory

Virtual Memory - Loading Pages

We can imagine that a process's address space ...

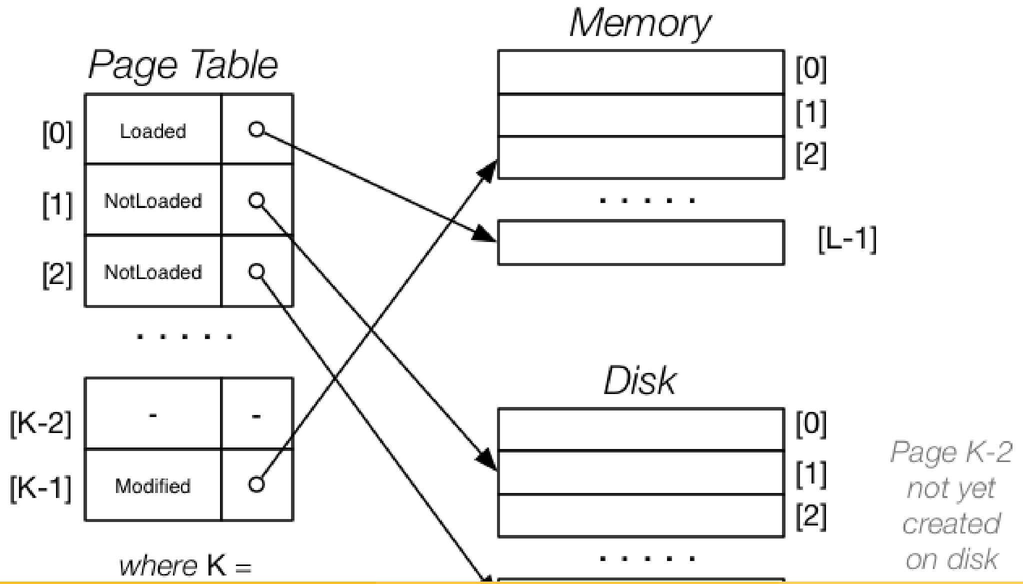
- exists on disk for the duration of the process's execution
- and only some parts of it are in memory at any given time



Transferring pages between disk↔memory is **very** expensive

- need to ensure minimal reading from / writing to disk

Page table with some pages not loaded



Virtual Memory - Handling Page Faults

An access to a page which is not-loaded in RAM is called a ***page fault***.

Where do we load it in RAM?

First need to check for a free frame

- need a way of quickly identifying free frames
- commonly handled via a free list

What if there are currently no free page frames, possibilities:

- *suspend* the requesting process until a page is freed
- *replace* one of the currently loaded/used pages

Suspending requires the operating system to

- mark the process as unable to run until page available
- switch to running another process
- mark the process as able to run when page available

Page Replacement

If no free pages we need to choose a page to evict:

- best page is one that won't be used again by its process
- prefer pages that are read-only (no need to write to disk)
- prefer pages that are unmodified (no need to write to disk)
- prefer pages that are used by only one process (see later)

OS can't predict whether a page will be required again by its process

But we do know whether it has been used recently (if we record this)

One good heuristic - replace Least Recently Ued (LRU) page.

- page not used recently probably not needed again soon

Exercise: Page Replacement

Show how the page frames and page tables change when

- there are 4 page frames in memory
- the process has 6 pages in its virtual address space
- a LRU page replacement strategy is used

For each of the following sequences of virtual page accesses

```
0, 5, 0, 0, 5, 1, 5, 1, 2, 4, 3, 3, 4, 2, 5, 3, 2
```

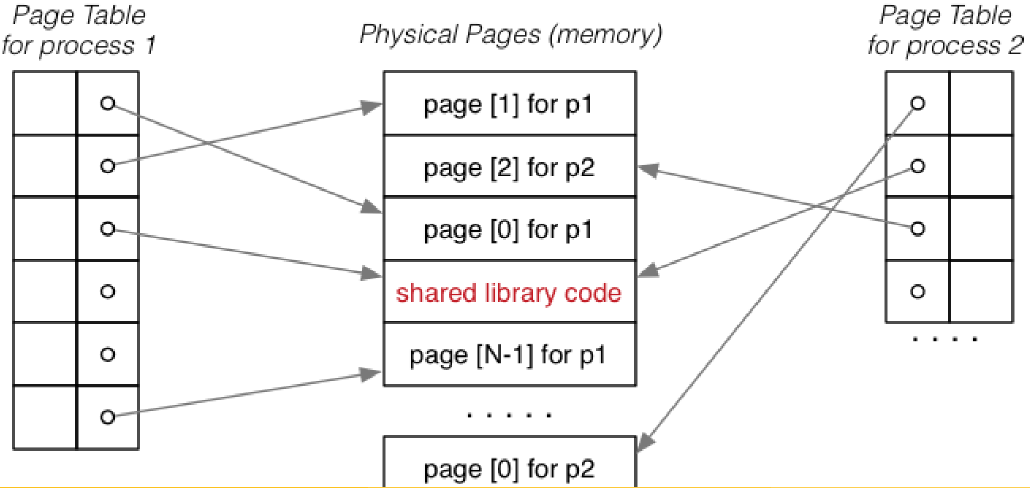
```
5, 0, 0, 0, 5, 1, 1, 5, 1, 5, 2, 2, 3, 0, 0, 5
```

Assume that all PTEs and frames are initially empty/unused

Virtual Memory - Read-only Pages

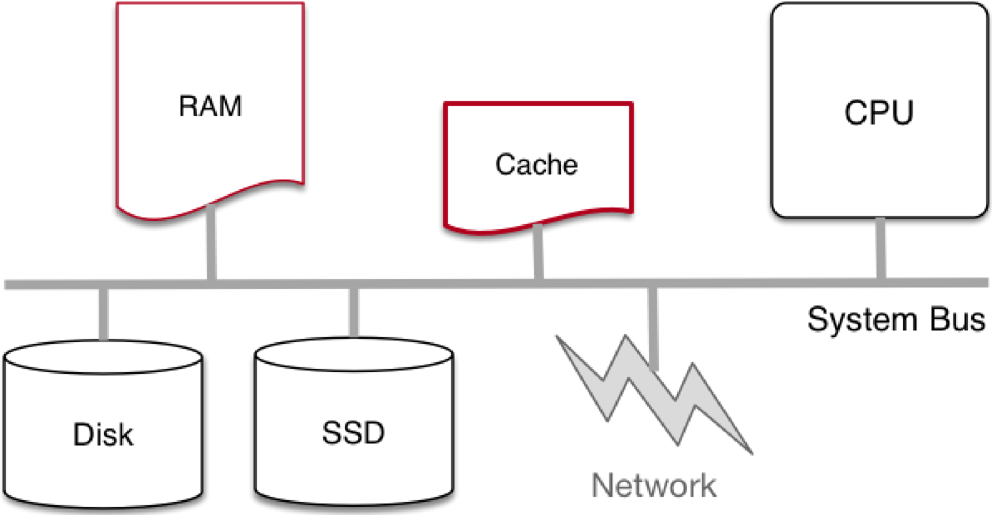
Virtual memory allows sharing of read-only pages (e.g. library code)

- several processes include same frame in virtual address space



Cache Memory

Cache memory = small*, fast memory* close to CPU



Cache Memory

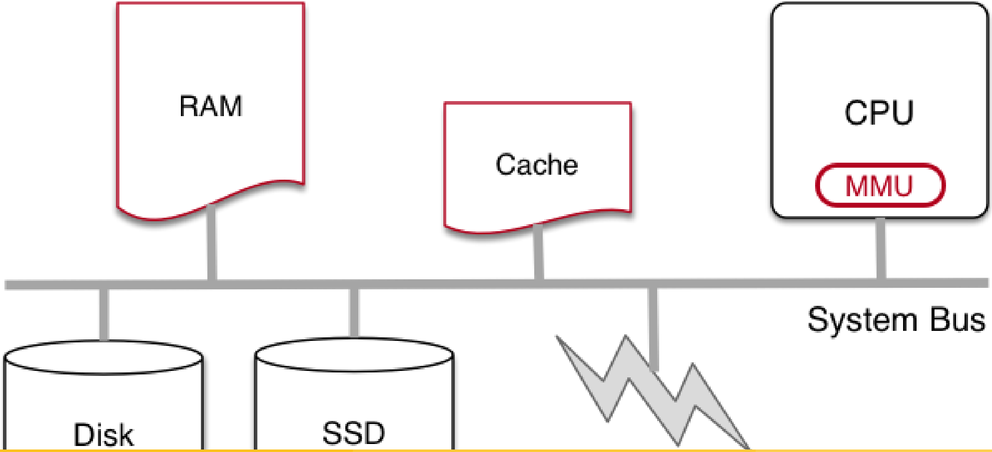
Cache memory

- holds parts of RAM that are (hopefully) heavily used
- transfers data to/from RAM in blocks (*cache blocks*)
- memory reference hardware first looks in cache
  - if required address is there, use its contents
  - if not, get it from RAM and put in cache
  - possibly replacing an existing cache block
- replacement strategies have similar issues to virtual memory

Memory Management Hardware

Address translation is very important/frequent

- provide specialised hardware (MMU) to do it efficiently
- sometimes located on CPU chip, sometimes separate



Memory Management Hardware

TLB = translation lookaside buffer

- lookup table containing (virtual,physical) address pairs