COMP1521 23T3 — Virtual Memory

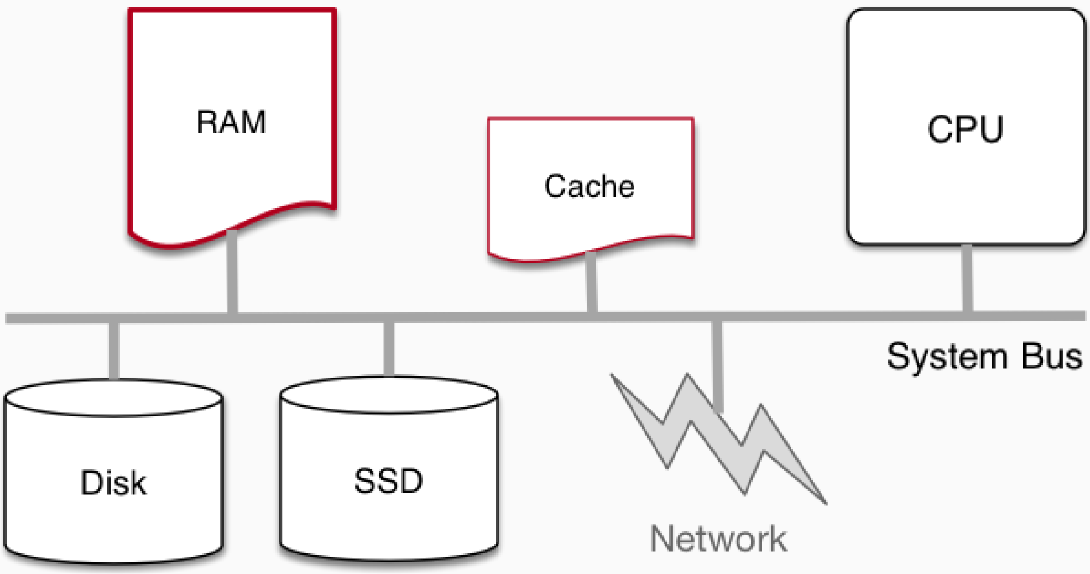
https://www.cse.unsw.edu.au/~cs1521/23T3/

Introduction to Virtual Memory and Caching

- Short introduction to virtual memory and caching.

Memory

General purpose computers typically contain 4-128GB of volatile Random Access Memory (RAM)



Single Process Resident in RAM without Operating System

- Many small embedded systems run without operating system.
- Single program running, typically written in C, perhaps with some assembler.
- Devices (sensors, switches, ...) often wired at particular address.
- E.g motor speed can be set by storing byte at 0x100400.
- Program accesses (any) RAM directly.
- Development and debugging tricky.
  - might be done by sending ascii values bit by bit on a single wire
- Widely used for simple micro-controllers.
- Parallelism and exploiting multiple-core CPUs problematic

Single Process Resident in RAM with Operating System

- Operating systems 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 RAM used by old process to disk (or flash) 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

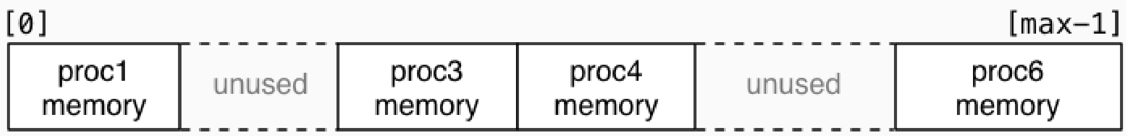
- If multiple processes to be resident in RAM operating system can swap execution between them quickly.
- RAM belonging to other processes & operating system operating system must be protected
- Hardware support can limit process accesses to particular **segment** (region) of RAM.
- BUT program may be 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 - needs to be largely implemented in hardware (silicon).

Virtual Memory with One Memory Segment Per Process

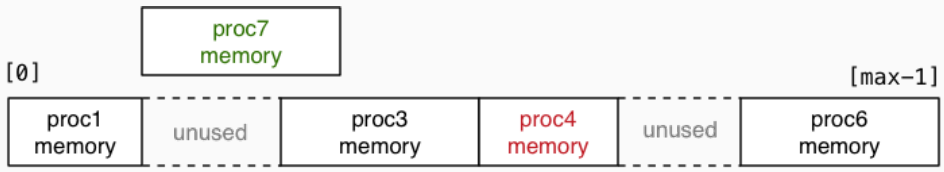
Consider a scenario with multiple processes loaded in memory:



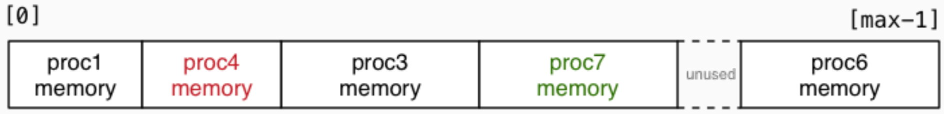
- Every process is in a contiguous section of RAM, starting at address **base** finishing at address **limit**.
- Each process sees its own address space as [0 .. size - 1]
- Process can be loaded anywhere in memory without change.
- Process accessing memory address **a** is translated to **a** + **base**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



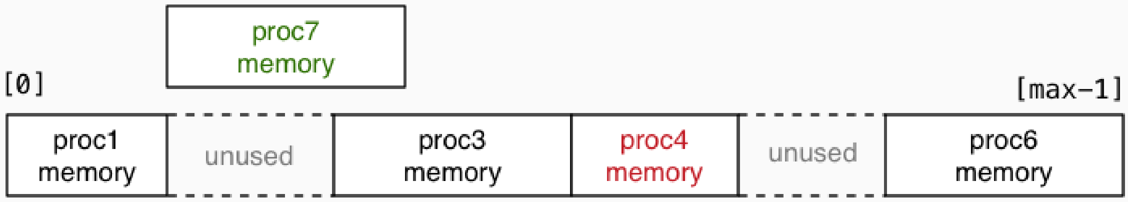
- The new process doesn't fit in any of the unused slots (fragmentation).
  - Need to move other processes to make a single large slot



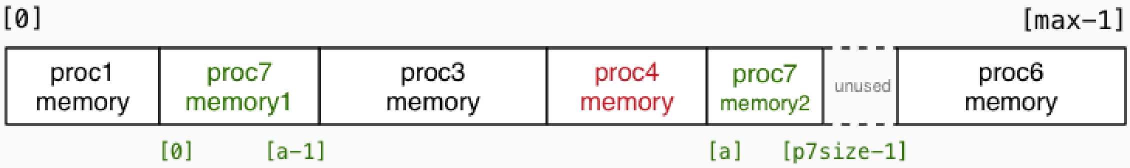
- Slow if RAM heavily used.
- Does not allow sharing or loading on demand.
- Limits process address space to size of RAM.
- Little used in modern computing.

Virtual Memory with Multiple Memory Segments Per Process

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



becomes



Virtual Memory with Arbitrary-Sized Multiple Memory Segments Per Process

Implications for splitting process memory across physical memory

- each chunk of process address space has its own *base*
- each chunk of process address space has its own *size*
- each chunk of process address space has its own *memory* location

Need a table of process/address information to manage this

With arbitrary sized memory segments hardware support is difficult

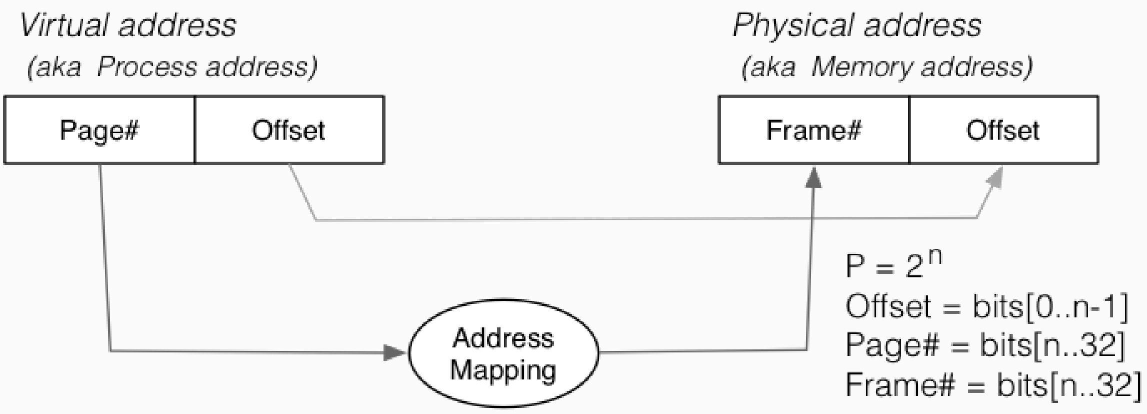
Virtual Memory with Pages

Big idea: make all segments same size, and make size power of 2

- call each segment of address space a ***page*** and make all pages the same size *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
- physical pages called **frames**
- the address will at be at offset *V % P* in both
- so physical address for *V* is: *page_table[V / P] + V % P*
- calculation can be faster/simpler bit operations if $P == 2^n$, e.g. 4096, 8192, 16384
- this is simple enough to implement in hardware (silicon)

Address Mapping

If $P == 2^n$, then some bits (*offset*) are the same in virtual and physical address



Virtual Memory with pages - Lazy Loading

A side-effect of this type of virtual → 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

4096 bytes is a common pages/frame size, but sizes 512 to 262144 bytes used

With 4GB memory, would have ≈ 1 million × 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

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

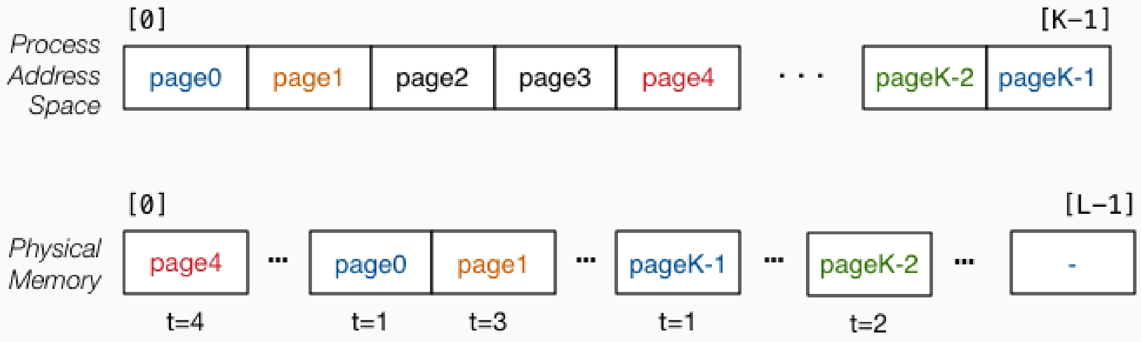
But where are they loaded from?

- 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

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

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

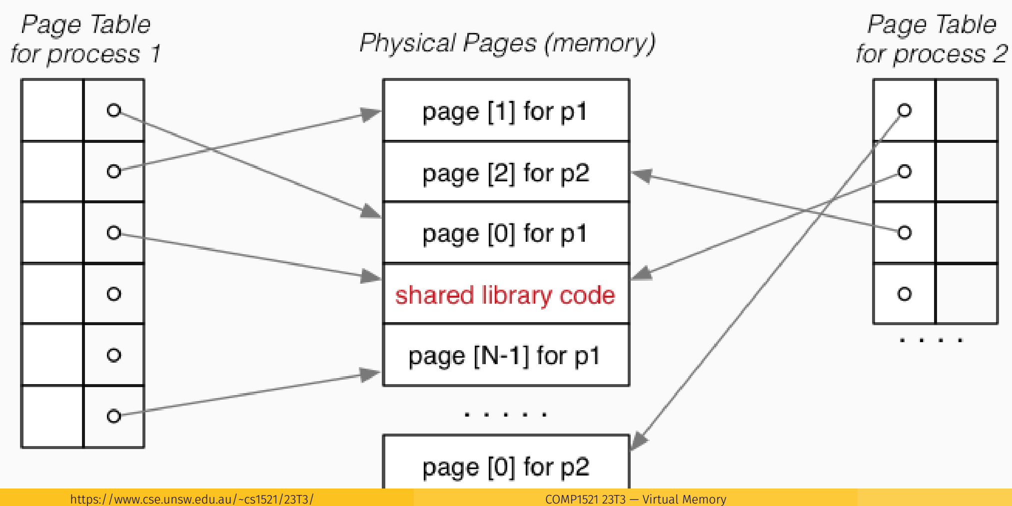
Suspending requires the operating system to

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

Virtual Memory - Read-only Pages

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

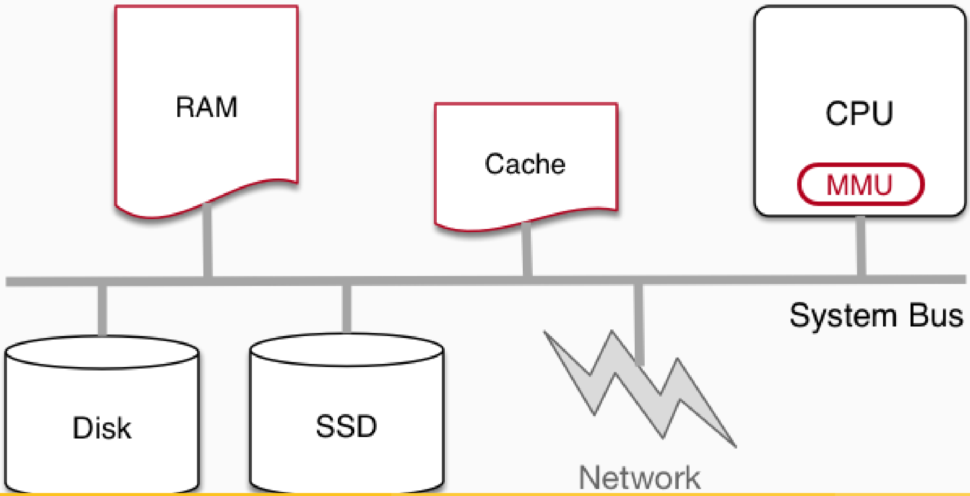
- several processes include same frame in virtual address space
- allows all running programs to use same pages for e.g. C library code (printf)



Memory Management Hardware

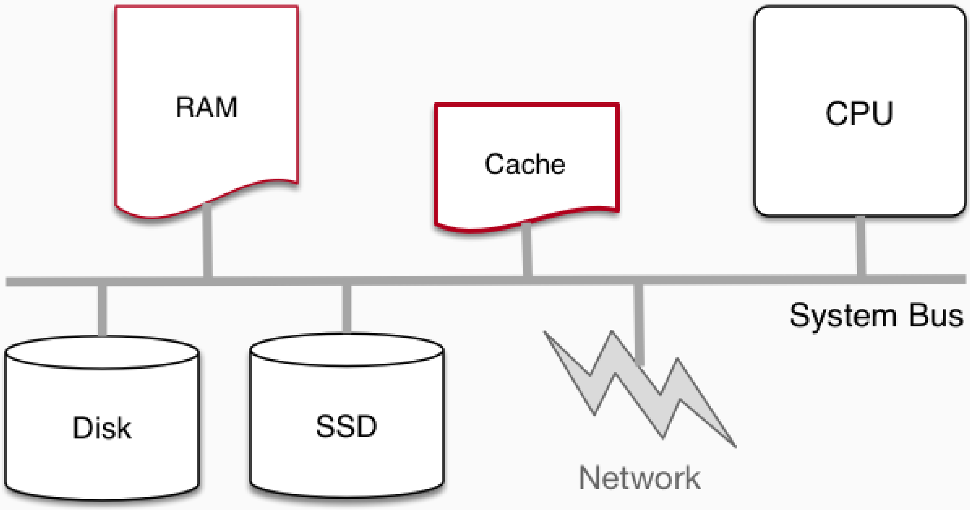
Address translation is very important/frequent

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



Cache Memory

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



Small = MB, Fast = $5 \times RAM$

Cache Memory

- cache memory makes memory accesses (e.g. **lw**, **sw**) faster
- cache memory implemented entirely in silicon typically on same chip as CPU
- independent of virtual memory (works with physical address)
- holds small blocks of RAM that are have been recently used
  - cache blocks also called cache lines
- typical size of cache blocks (line) 64 bytes
- CPU hardware (silicon) when loading or storing adddress first looks in cache
  - if block containing address is there, cache is used
    - for load operations value in cache is used
    - for store operations value in cache is changed
    - in both cases, much faster than access RAM
  - if not, block containing address is fetched from RAM into cache
  - possibly evicting an existing cache block
    - which may require writing (flushing) its contents to RAM
- cache replacement strategies have similar issues to virtual memory
- modern CPU may have multiple (3+) levels of caching