Virtual memory

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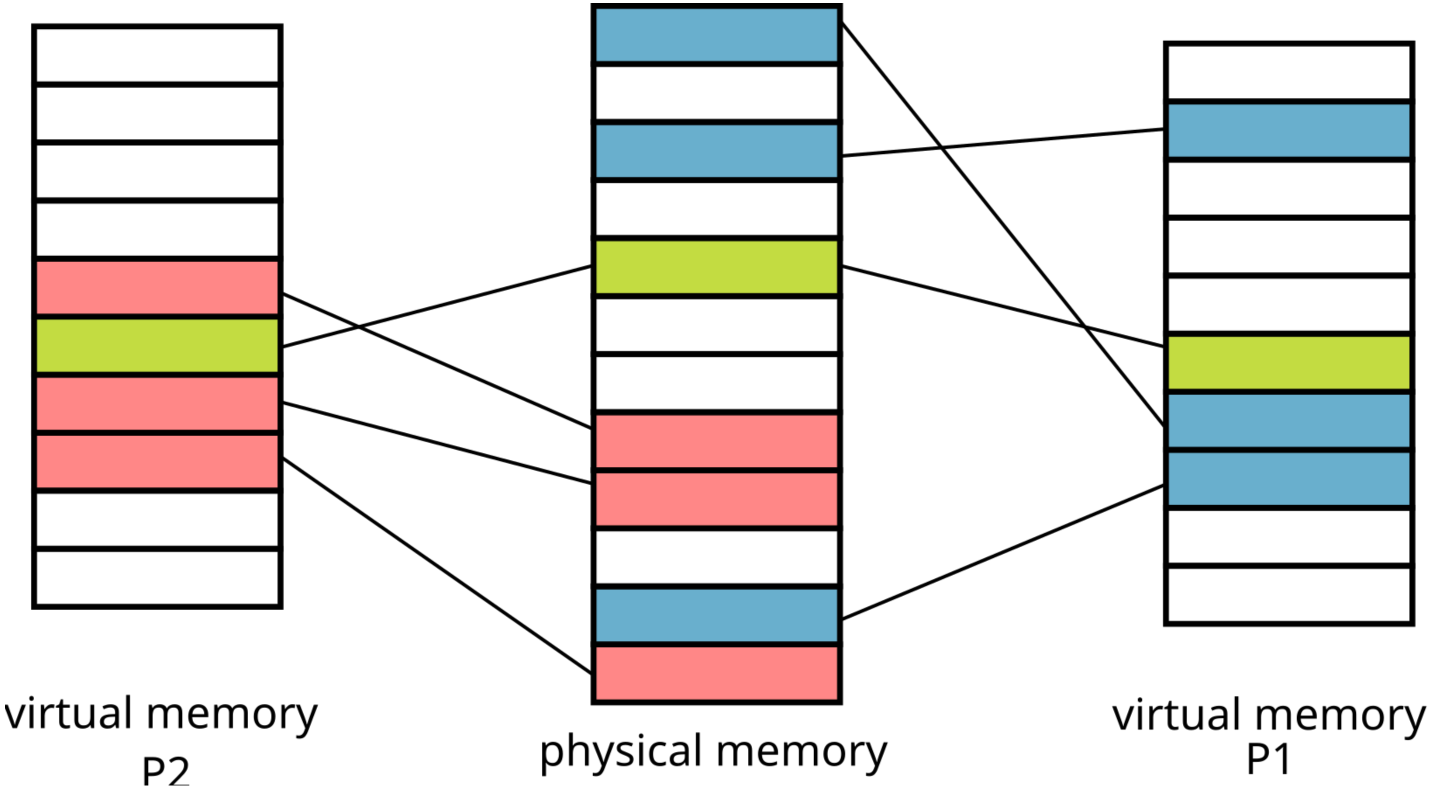
Introduction

- A process needs to be present in main memory to run
- Central memory divided into two parts
  - The space reserved for the operating system
  - The space allocated to processes
- Memory management concerns the process space
- Memory capacities are increasing, but so are the requirements → Need for multiple memory levels
  - Fast memory (cache)
  - Central memory (RAM)
  - Auxiliary memory (disk)
- Principle of inclusion to limit updates between different levels

Paging

Overview



- The address space of each program is split into **pages**
- Physical memory divided into **page frames**
- Matching between some **pages** and **page frames**

Status of memory pages

- The memory pages of a process can be
  - In main memory / in RAM (active pages)
  - Non-existent in memory (inactive pages never written)
  - In secondary memory / in the Swap (inactive pages that have already been written)

  → each process has a contiguous memory space to store its data
- The paging mecanism
  - Translates virtual addresses to/from physical addresses
  - Loads the necessary pages (in case of page faults)
  - (Optionally) move active pages to secondary memory

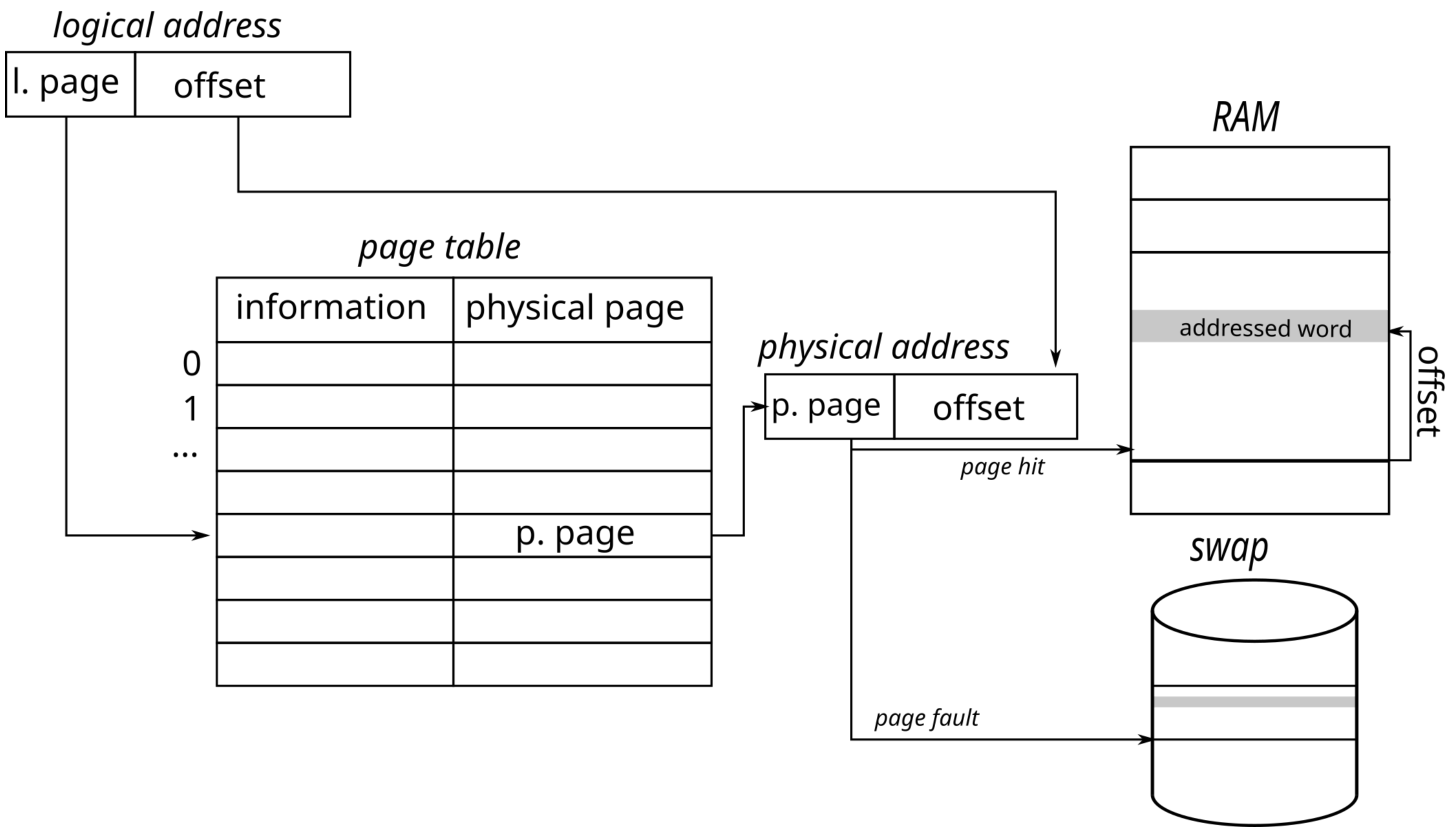
Logical (or virtual) address

- Address space is divided using the most significant bits
  - Logical address on `k` bits:
    - Page number: `p` bits
    - Offset in the page: `d = (k - p)` bits

  → 2^p pages and each page contains 2^{k-p} bytes
- Page size
  - Usually 4 KiB (k-p = 12 bits, so p = 52 bits)
  - *Huge pages*: 2 MiB, 1 GiB, 512 GiB, or 256 TiB pages
- Choice = compromise between various opposing criteria
  - Last page is half wasted
  - Small capacity memory : small pages
  - Scalability of the page management system

Page table

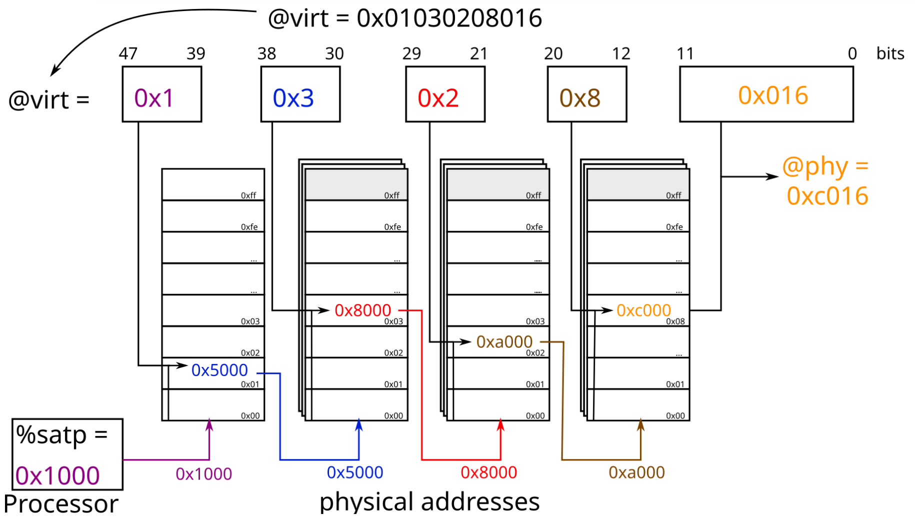
- The correspondence between logical address and address physical is done with a page table that contains
  - Page frame number
  - Information bits (presence, permissions, upload timestamp …)



Implementation of a page table

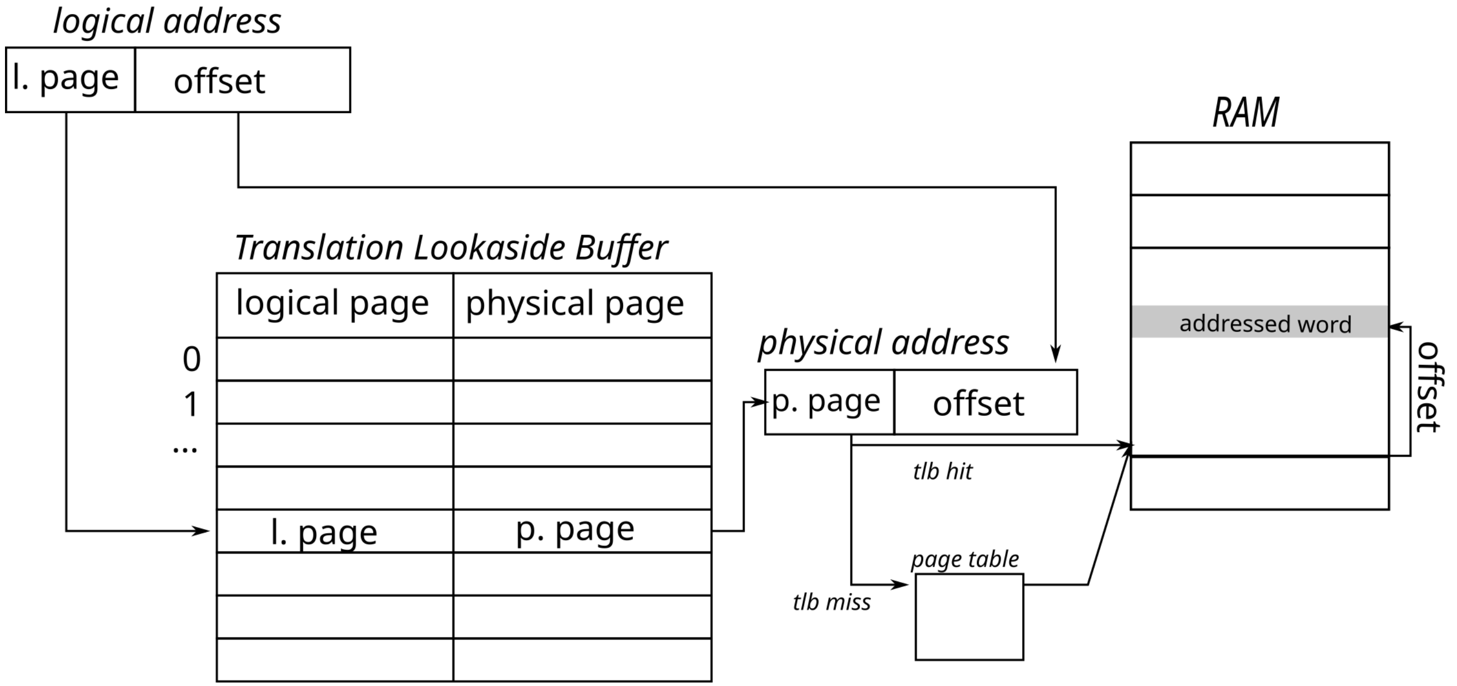
- On `x86_64` or `RISC-V`, a page table = 4-levels tree
  - The physical address of a 512-entry root table is stored in the `satp` register (`cr3` on `x86` architectures)
  - Each entry in a table gives the address of the following table
  - virtual address decomposed into 4 indexes (`n[0..3]`) + 1 *offset*, then translated using:

```
uint64_t cur = %satp3;             // cur = root table physical address
for(int i=0; i<3; i++)
  cur = ((uint64_t*)cur)[n[i]]; // physical memory access, next entry
return cur + offset;              // add the offset
```



Translation Lookaside Buffer (TLB)

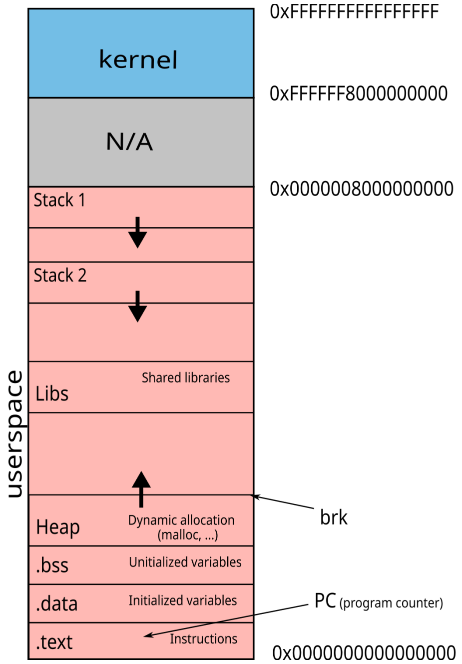
- Problem: any access to information requires several memory accesses
- Solution: use associative memories (fast access registers)
- Principle
  - A number of registers are available
  - Logical page number N_p compared to the content of each register
  - if found → gives the corresponding frame number N_c
  - Otherwise use the page table



User point of view

Memory space of a process

- Composed of:
  - kernel space
  - the different sections of the executed ELF file (`.text`, `.data`, etc.)
  - the heap
  - the stack (one per thread)
  - shared libraries



Memory mapping

- How to populate the memory space of a process?
  - For each ELF file to be loaded:
    - open the file with `open`
    - each ELF section is *mapped* in memory (with `mmap`) with the appropriate permissions
    - Results are visible in `/proc/<pid>/maps`

```
$ cat /proc/self/maps
5572f3023000-5572f3025000 r--p 00000000 08:01 21495815   /bin/cat
5572f3025000-5572f302a000 r-xp 00002000 08:01 21495815   /bin/cat
5572f302e000-5572f302f000 rw-p 0000a000 08:01 21495815   /bin/cat
5572f4266000-5572f4287000 rw-p 00000000 00:00 0          [heap]
7f33305b4000-7f3330899000 r--p 00000000 08:01 22283564   /usr/lib/locale/locale-archive
7f3330899000-7f33308bb000 r--p 00000000 08:01 29885233   /lib/x86_64-linux-gnu/libc-2.28.so
7f33308bb000-7f3330a03000 r-xp 00022000 08:01 29885233   /lib/x86_64-linux-gnu/libc-2.28.so
[...]
7f3330ab9000-7f3330aba000 rw-p 00000000 00:00 0
7ffe4190f000-7ffe41930000 rw-p 00000000 00:00 0          [stack]
7ffe419ca000-7ffe419cd000 r--p 00000000 00:00 0          [vvar]
7ffe419cd000-7ffe419cf000 r-xp 00000000 00:00 0          [vdso]
```

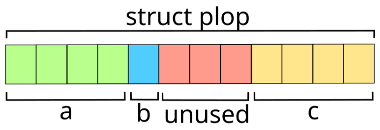
Memory allocation

- `void* malloc(size_t size)`
  - Returns a pointer to an buffer of `size bytes`
- `void* realloc(void* ptr, size_t size)`
  - Changes the size of a buffer previously allocated by `malloc`
- `void* calloc(size_t nmemb, size_t size)`
  - Same as `malloc`, but memory is initialized to 0
- `void *aligned_alloc( size_t alignment, size_t size )`
  - Same as `malloc`. The returned address is a multiple of `alignment`
- `void free(void* ptr)`
  - Free an allocated buffer

Memory alignment

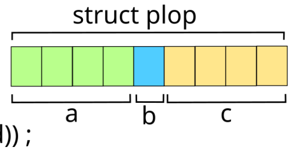
- Memory alignment depends on the type of data
  - `char` (1-byte), `short` (2-bytes), `int` (4-bytes), …
- A data structure may be larger than its content

```
struct plop {
   int a;
   char b;
   int c;
};
```



- A data structure can be packed with `__attribute__((packed))`

```
struct plop {
   int a;
   char b;
   int c;
}__attribute__((packed)) ;
```



The libc point of view

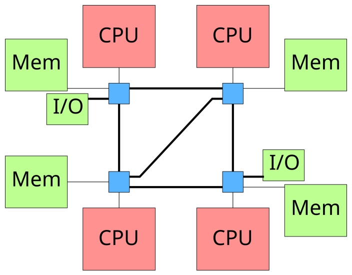
- How to request memory from the OS
  - `void *sbrk(intptr_t increment)`
    - increase the heap size by `increment` bytes
  - `void *mmap(void *addr, size_t length, int prot, int flags, int fd, off_t offset)`
    - map a file in memory
    - if `flags` contains `MAP_ANON`, does not map any file, but allocates an area filled with 0s

Memory allocation strategies

Non-Uniform Memory Access

- Several interconnected memory controllers
- Memory consistency between processors
- Privileged access to the local *memory bank*
- Possible access (with an additional cost) to distant *memory banks*

→ *Non-Uniform Memory Access* → On which memory bank to allocate data?



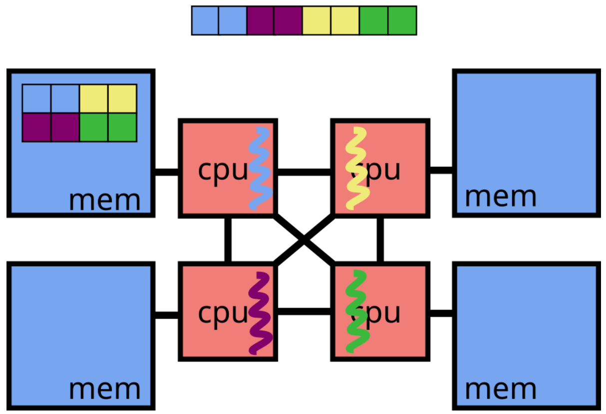
First touch allocation strategy

- Linux default lazy allocation strategy
- Allocation of a memory page on the local node when first accessed
- Assumption: the first thread to use a page will probably will use it in the future

```c
double *array = malloc(sizeof(double)*N);

for(int i=0; i<N; i++) {
  array[i] = something(i);
}

#pragma omp parallel for
for(int i=0; i<N; i++) {
  double value = array[i];
  /* ... */
}
```



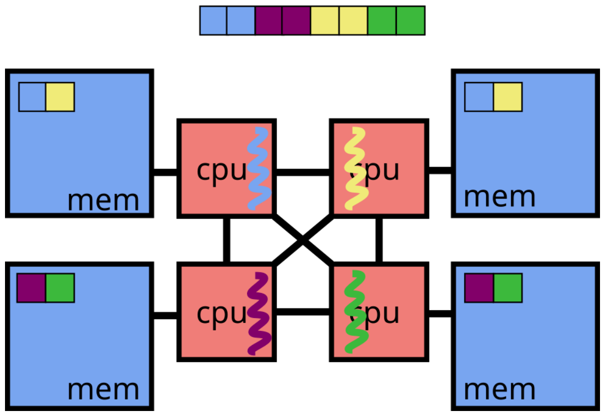
Interleaved allocation strategy

- Pages are allocated on the different nodes in a *round-robin* fashion
- Allows load balancing between NUMA nodes
- `void *numa_alloc_interleaved(size_t size)`

```
double *array =
  numa_alloc_interleaved(sizeof(double)*N);

for(int i=0; i<N; i++) {
  array[i] = something(i);
}

#pragma omp parallel for
for(int i=0; i<N; i++) {
  double value = array[i];
  /* ... */
}
```



mbind

- `long mbind(void *addr, unsigned long len, int mode, const unsigned long *nodemask, unsigned long maxnode, unsigned flags)`
- Place a set of memory pages on a (set of) NUMA node → allows manual placement of memory pages

```
double *array = malloc(sizeof(double)*N);
mbind(&array[0], N/4*sizeof(double),
MPOL_BIND, &nodemask, maxnode,
MPOL_MF_MOVE);

#pragma omp parallel for
for(int i=0; i<N; i++) {
  double value = array[i];
  /* ... */
}
```