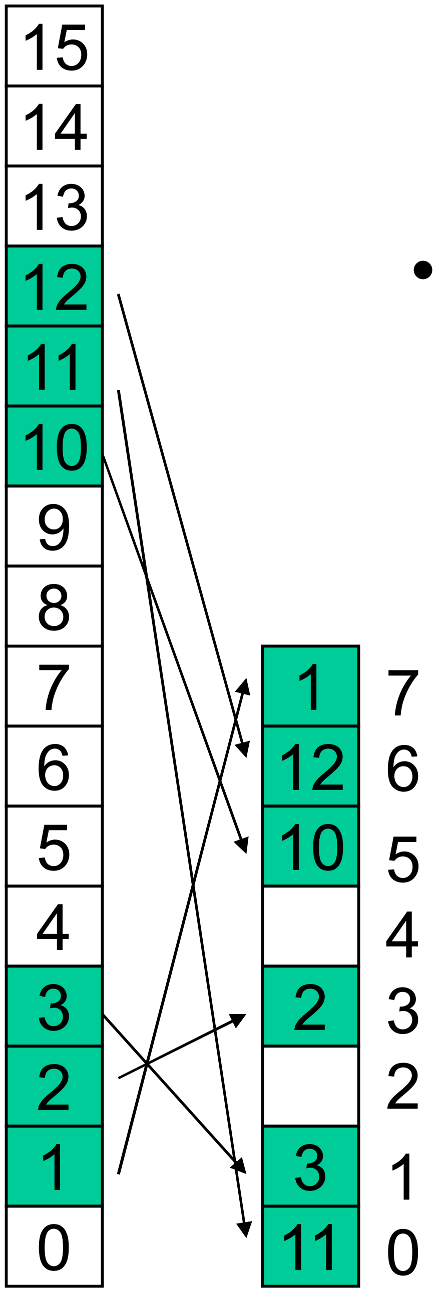
- Consult today at 4pm, k17, 203
- I am away next week
  - Herbert Bos
  - lectures as usual
  - extended lectures cancelled
- Assignment due next week

# Virtual Memory

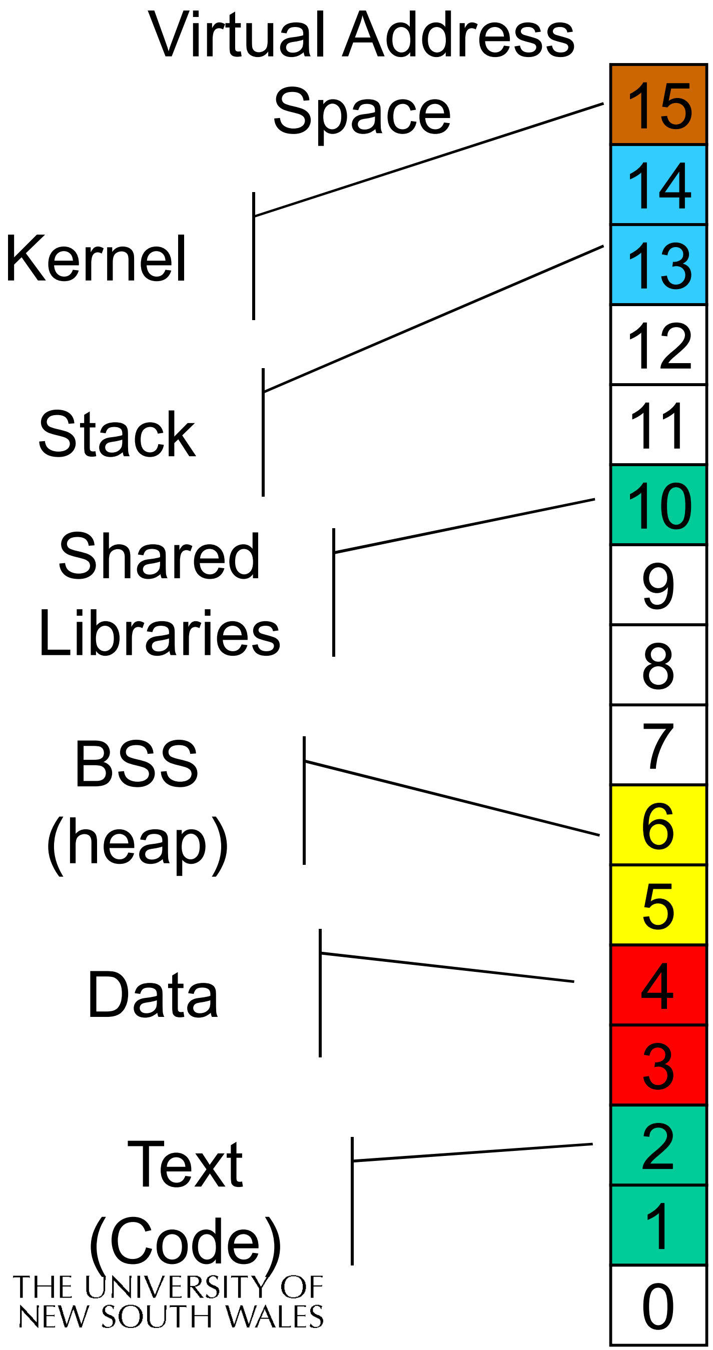
# Paging

- Virtual Memory
  - Divided into equal-sized *pages*
  - A *mapping* is a translation between
    - A page and a frame
    - A page and null
  - Mappings defined at runtime
    - They can change
  - Address space can have holes
  - Process does not have to be contiguous in physical memory

- Physical Memory
  - Divided into equal-sized *frames*

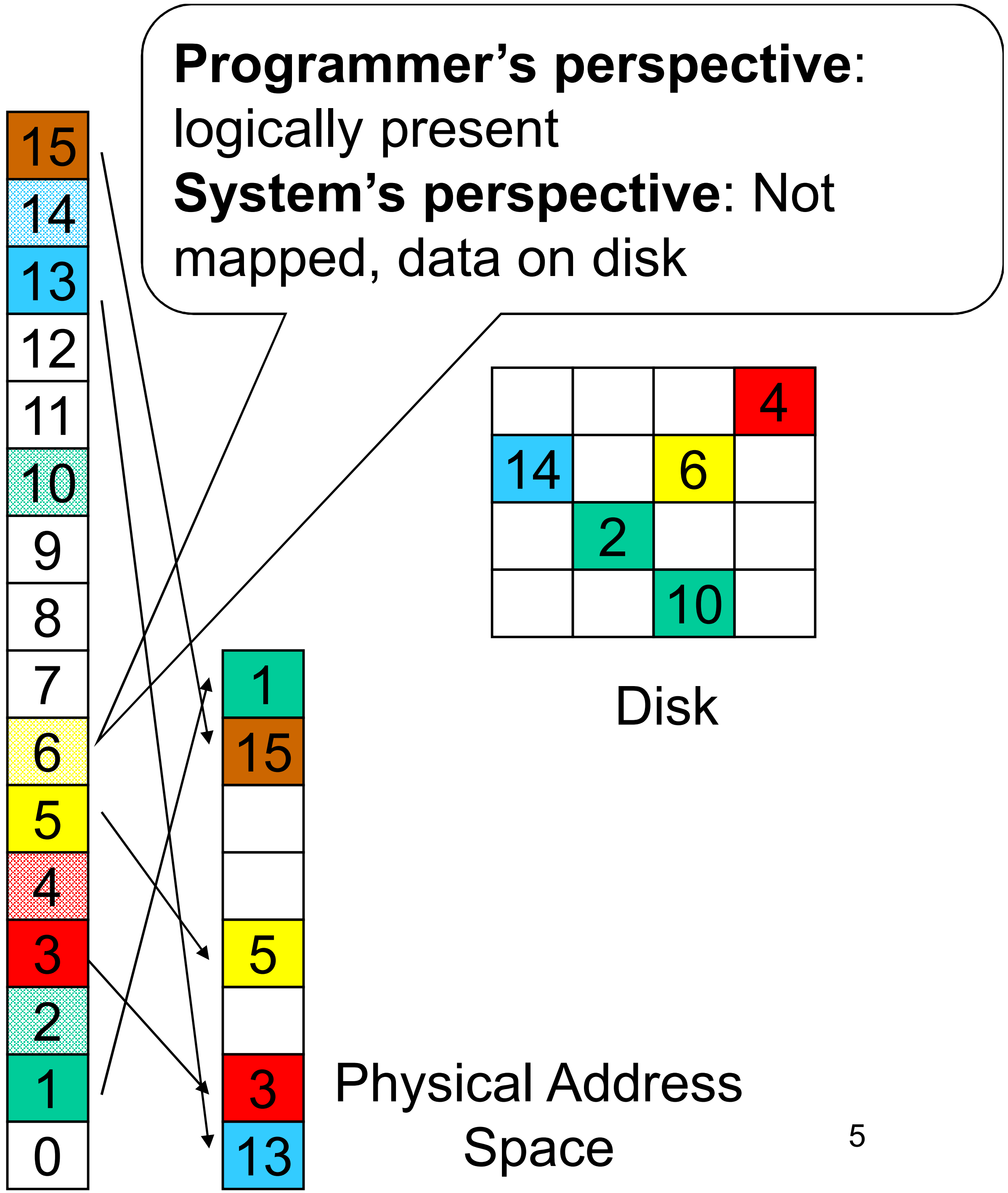


# Typical Address Space Layout



- Stack region is at top, and can grow down
- Heap has free space to grow up
- Text is typically read-only
- Kernel is in a reserved, protected, shared region
- 0-th page typically not used, why?

- A process may be only partially resident
  - Allows OS to store individual pages on disk
  - Saves memory for infrequently used data & code
- What happens if we access non-resident memory?

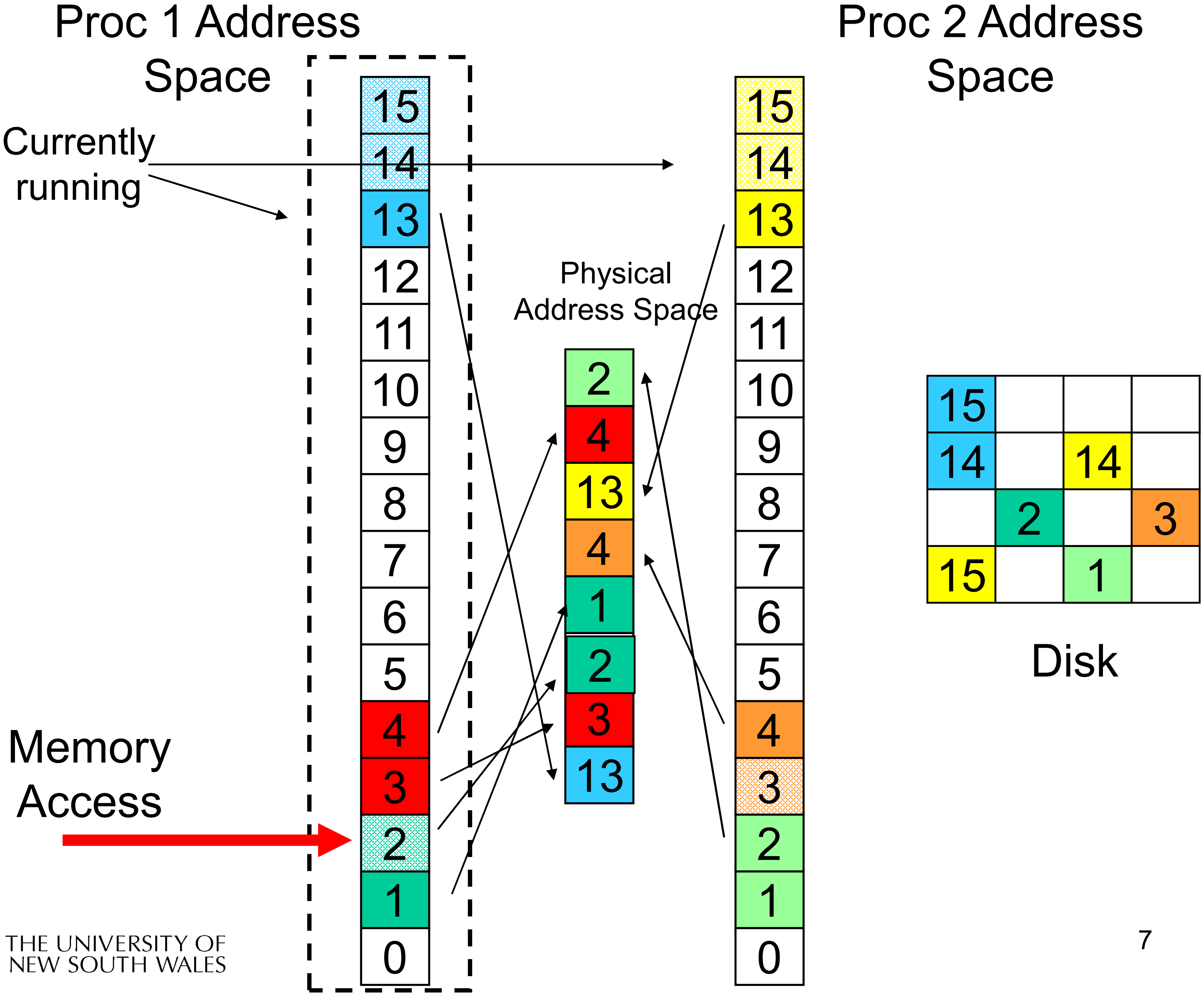


**Programmer’s perspective**: logically present
**System’s perspective**: Not mapped, data on disk

Virtual Address Space

# Page Faults

- Referencing an invalid page triggers a page fault
    - An exception handled by the OS
- Broadly, two standard page fault types
    - Illegal Address (protection error)
        - Signal or kill the process
    - Page not resident
        - Get an empty frame
        - Load page from disk
        - Update page (translation) table (enter frame #, set valid bit, etc.)
        - Restart the faulting instruction
- Note: Some implementations store disk block numbers of non-resident pages in the page table (with valid bit ***Unset***)



Proc 1 Address Space

Currently running

Memory Access

Physical Address Space

Proc 2 Address Space

Disk

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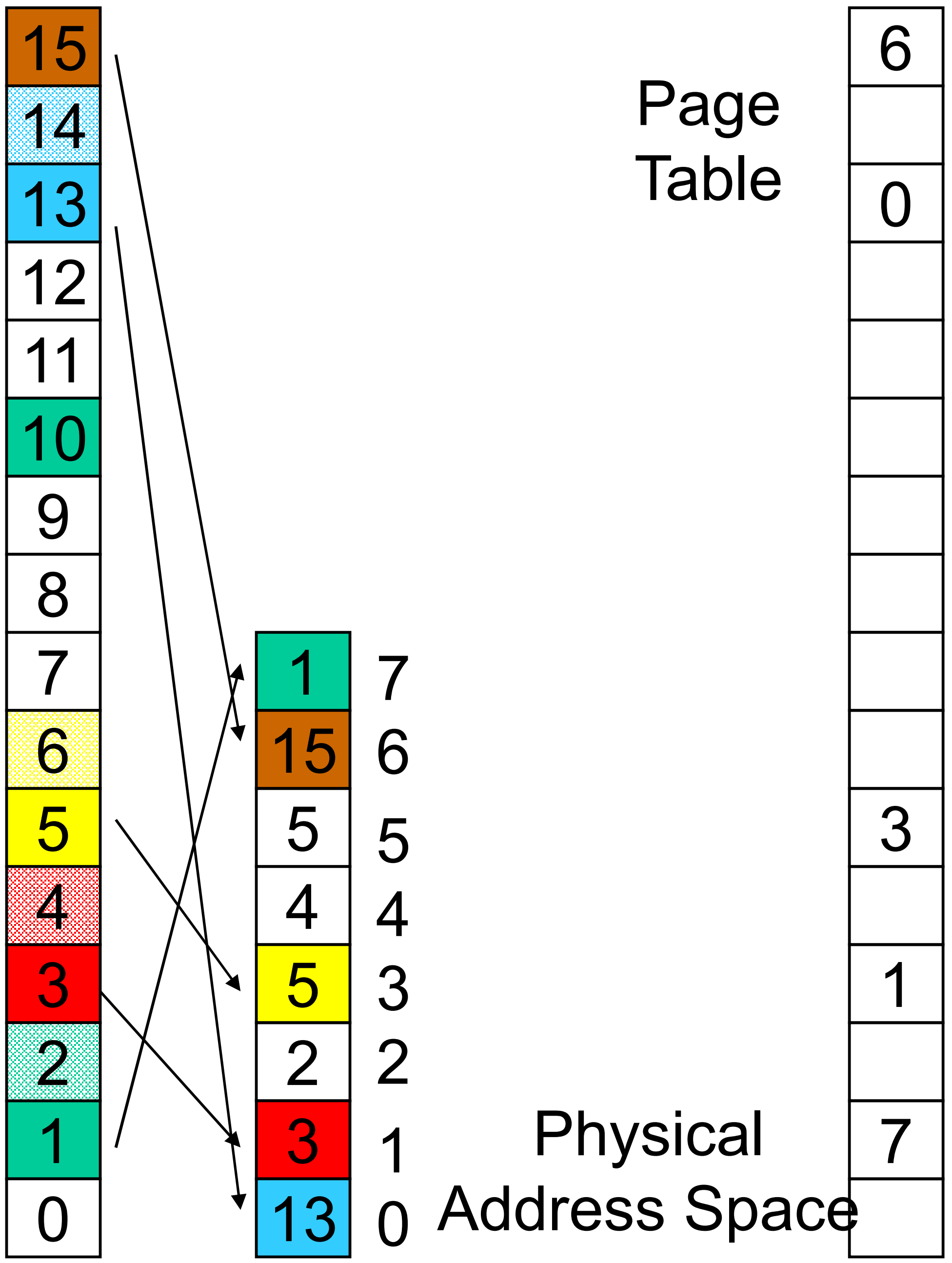
- Page table for resident part of address space

Virtual Address Space



Page Table

Physical Address Space

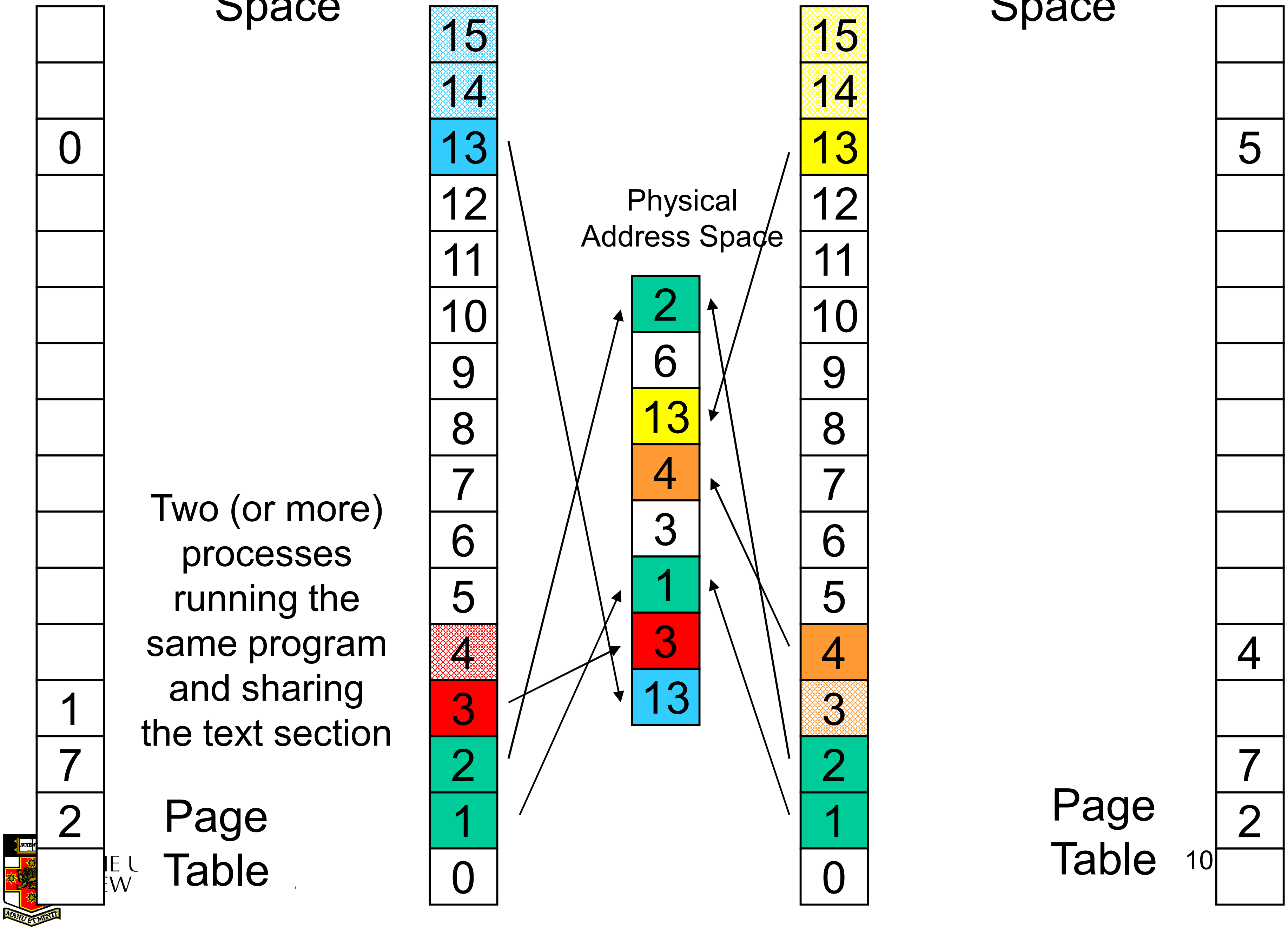
# Shared Pages

- Private code and data
  - Each process has own copy of code and data
  - Code and data can appear anywhere in the address space

- Shared code
  - Single copy of code shared between all processes executing it
  - Code must not be self modifying
  - Code must appear at same address in all processes

Proc 1 Address Space

Proc 2 Address Space



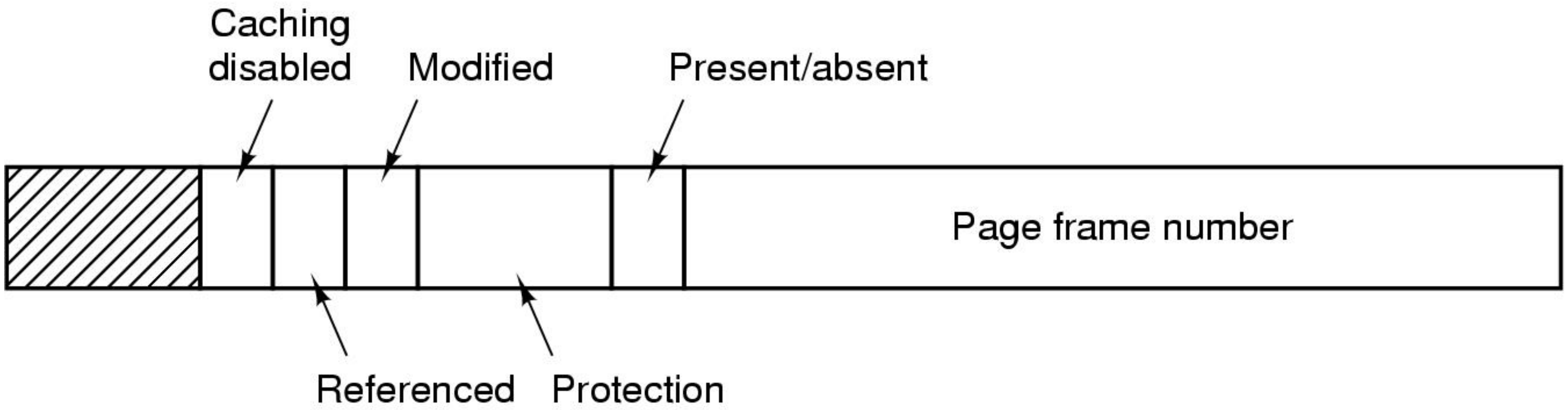
Two (or more) processes running the same program and sharing the text section

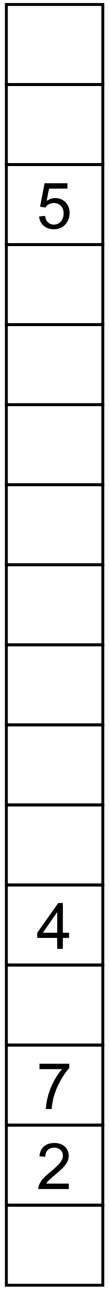
Page Table

Page Table

# Page Table Structure

- Page table is (logically) an array of frame numbers
  - Index by page number
- Each page-table entry (PTE) also has other bits





Page Table

# PTE bits

- Present/Absent bit
  - Also called *valid bit,* it indicates a valid mapping for the page
- Modified bit
  - Also called *dirty bit,* it indicates the page may have been modified in memory
- Reference bit
  - Indicates the page has been accessed
- Protection bits
  - Read permission, Write permission, Execute permission
  - Or combinations of the above
- Caching bit
  - Use to indicate processor should bypass the cache when accessing memory
    - Example: to access device registers or memory

# Address Translation

- Every (virtual) memory address issued by the CPU must be translated to physical memory
  - Every *load* and every *store* instruction
  - Every instruction fetch
- Need Translation Hardware
- In paging system, translation involves replace page number with a frame number

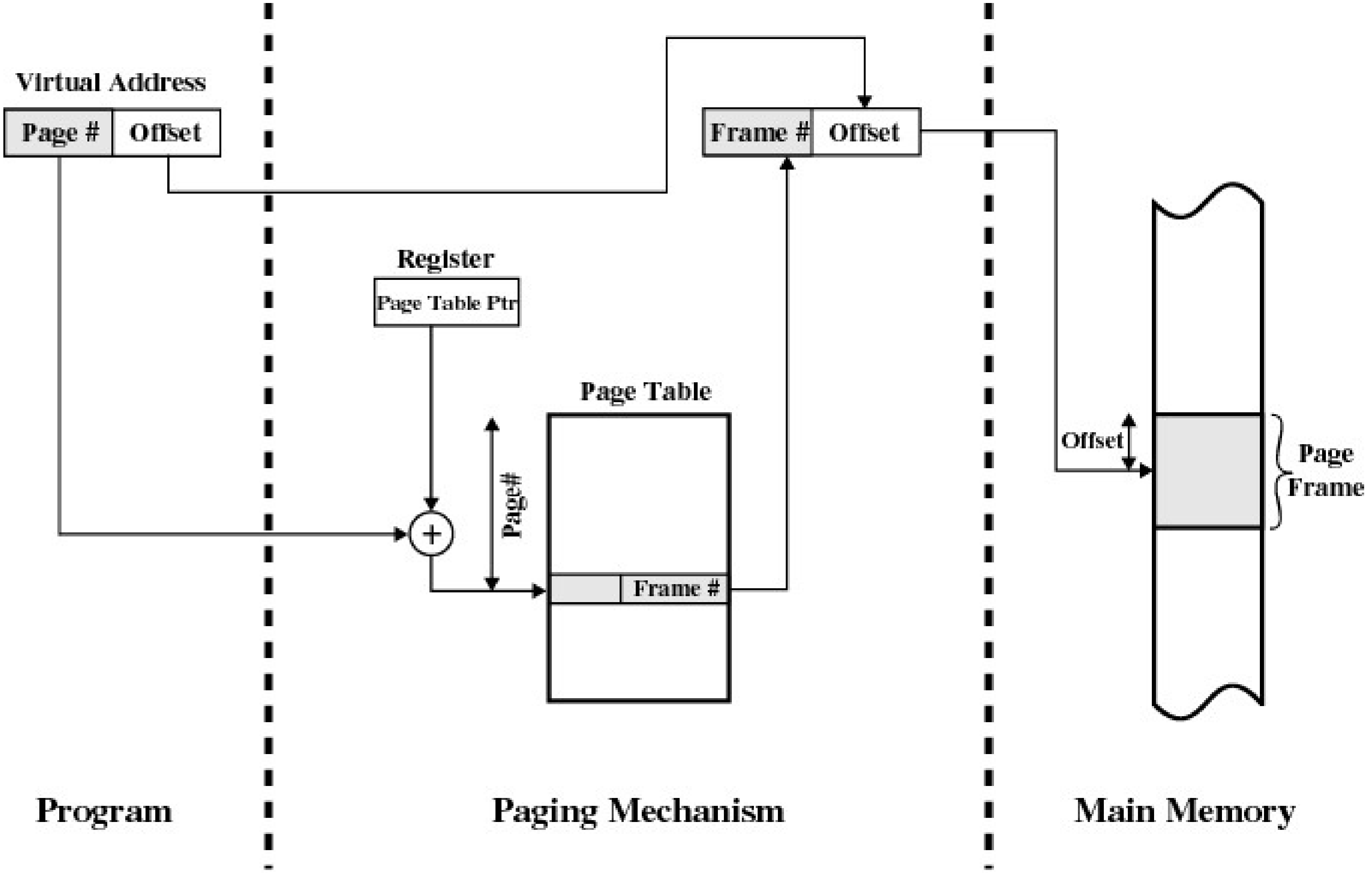


Figure 8.3 Address Translation in a Paging System

# Page tables (recap)

# virtual memory

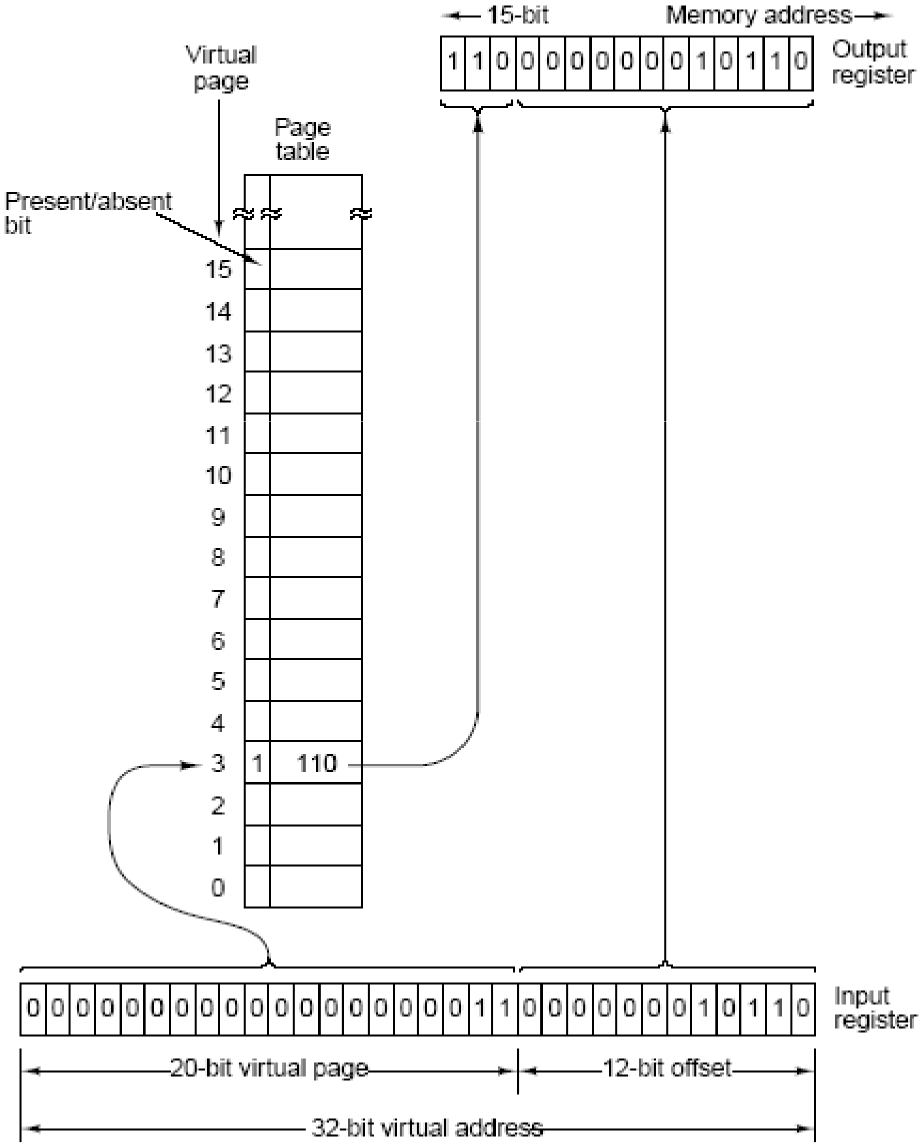
## virtual and physical mem chopped up in pages

- **programs use virtual addresses**
- **virtual to physical mapping by MMU**

  **-first check if page present (present/absent bit)**

  **-if yes: address in page table form MSBs in physical address**

  **-if no: bring in the page from disk ➔ page fault**



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# Page Tables

- Assume we have
  - 32-bit virtual address (4 Gbyte address space)
  - 4 KByte page size
  - How many page table entries do we need for one process?

# Page Tables

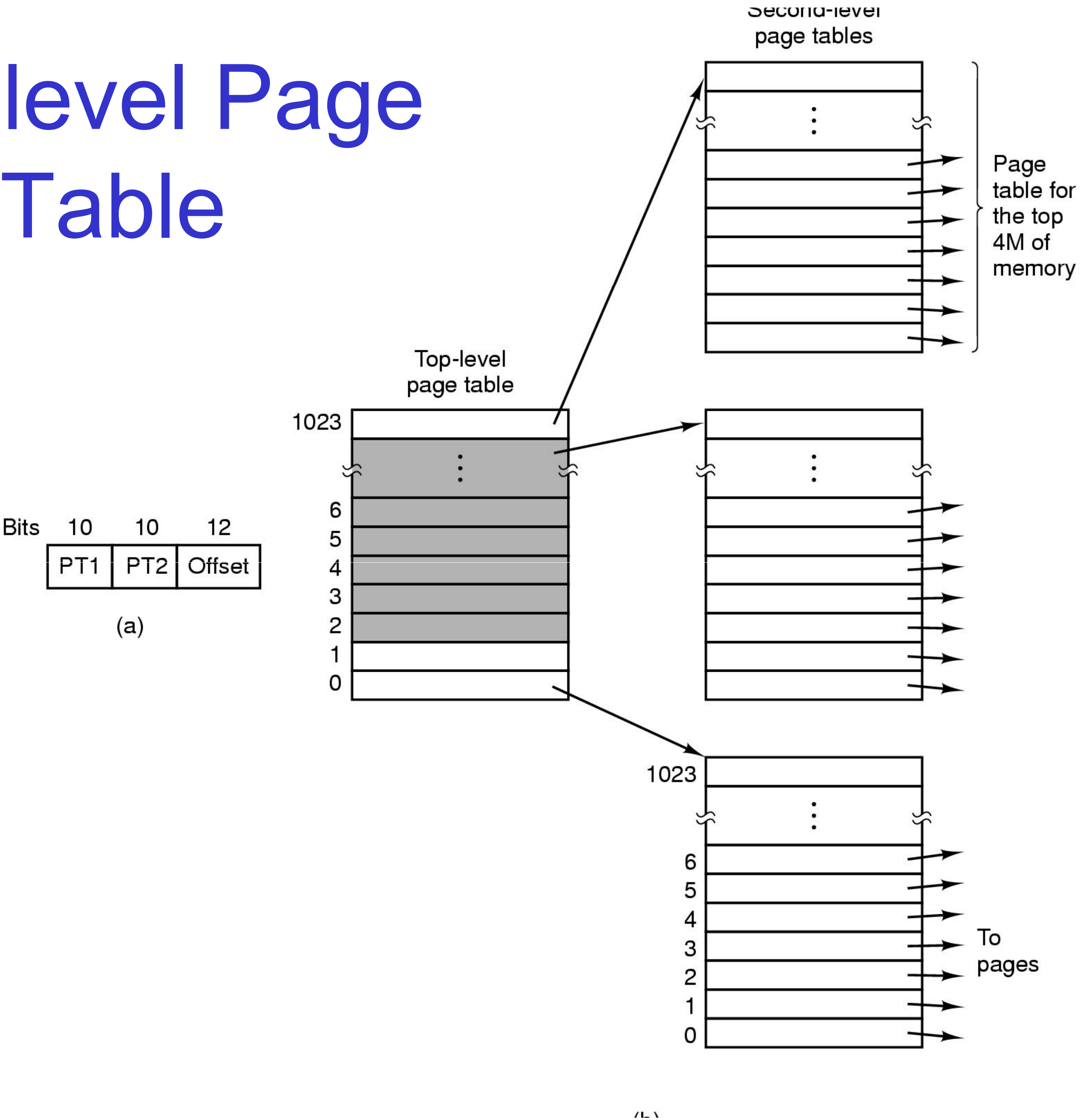
- Assume we have
  - 64-bit virtual address (humungous address space)
  - 4 KByte page size
  - How many page table entries do we need for one process?
- Problem:
  - Page table is very large
  - Access has to be fast, lookup for every memory reference
  - Where do we store the page table?
    - Registers?
    - Main memory?

# Page Tables

- Page tables are implemented as data structures in main memory
- Most processes do not use the full 4GB address space
  - e.g., 0.1 – 1 MB text, 0.1 – 10 MB data, 0.1 MB stack
- We need a compact representation that does not waste space
  - But is still very fast to search
- Three basic schemes
  - Use data structures that adapt to sparsity
  - Use data structures which only represent resident pages
  - Use VM techniques for page tables (details left to extended OS)

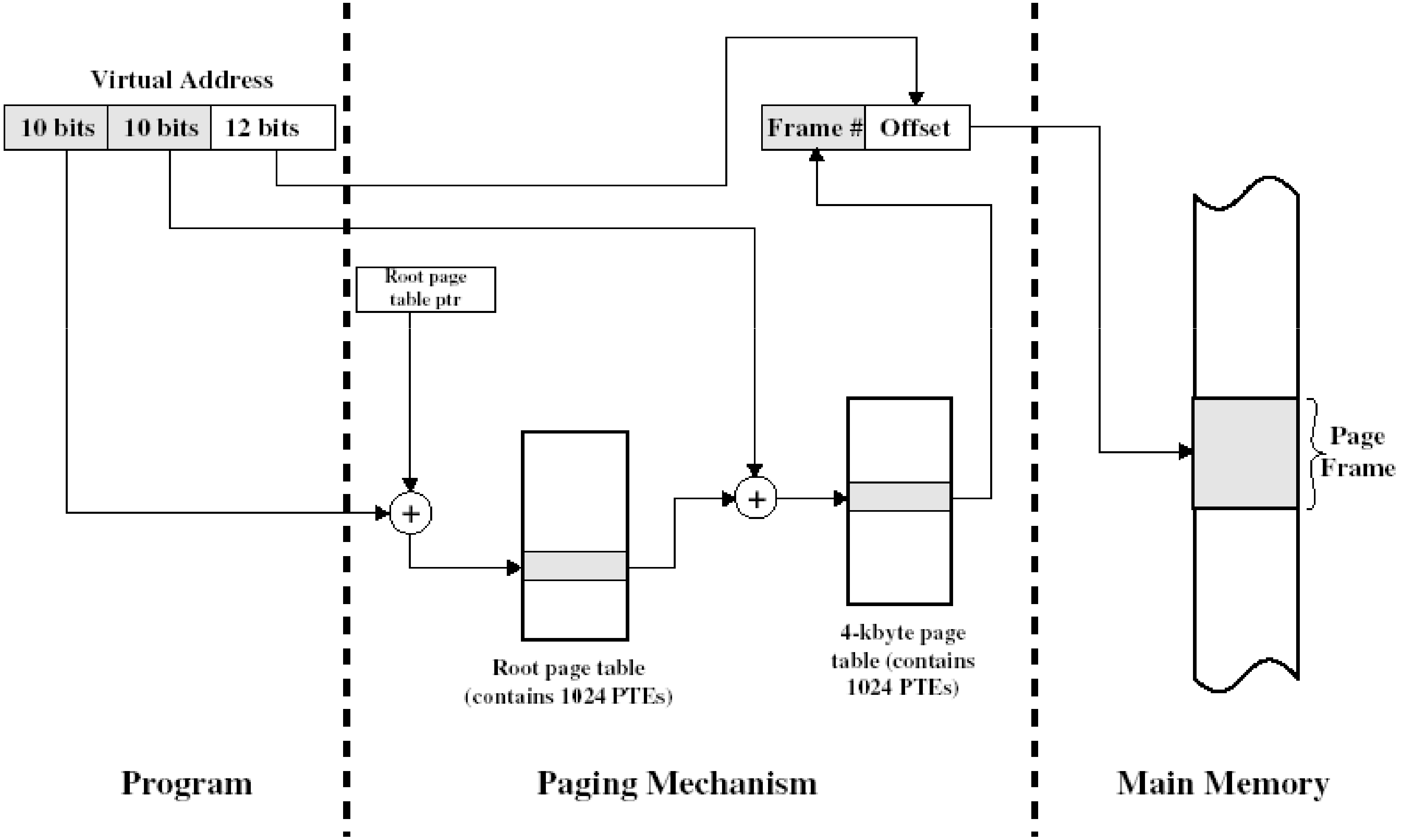
# Two-level Page Table

- 2nd –level page tables representing unmapped pages are not allocated
  - Null in the top-level page table

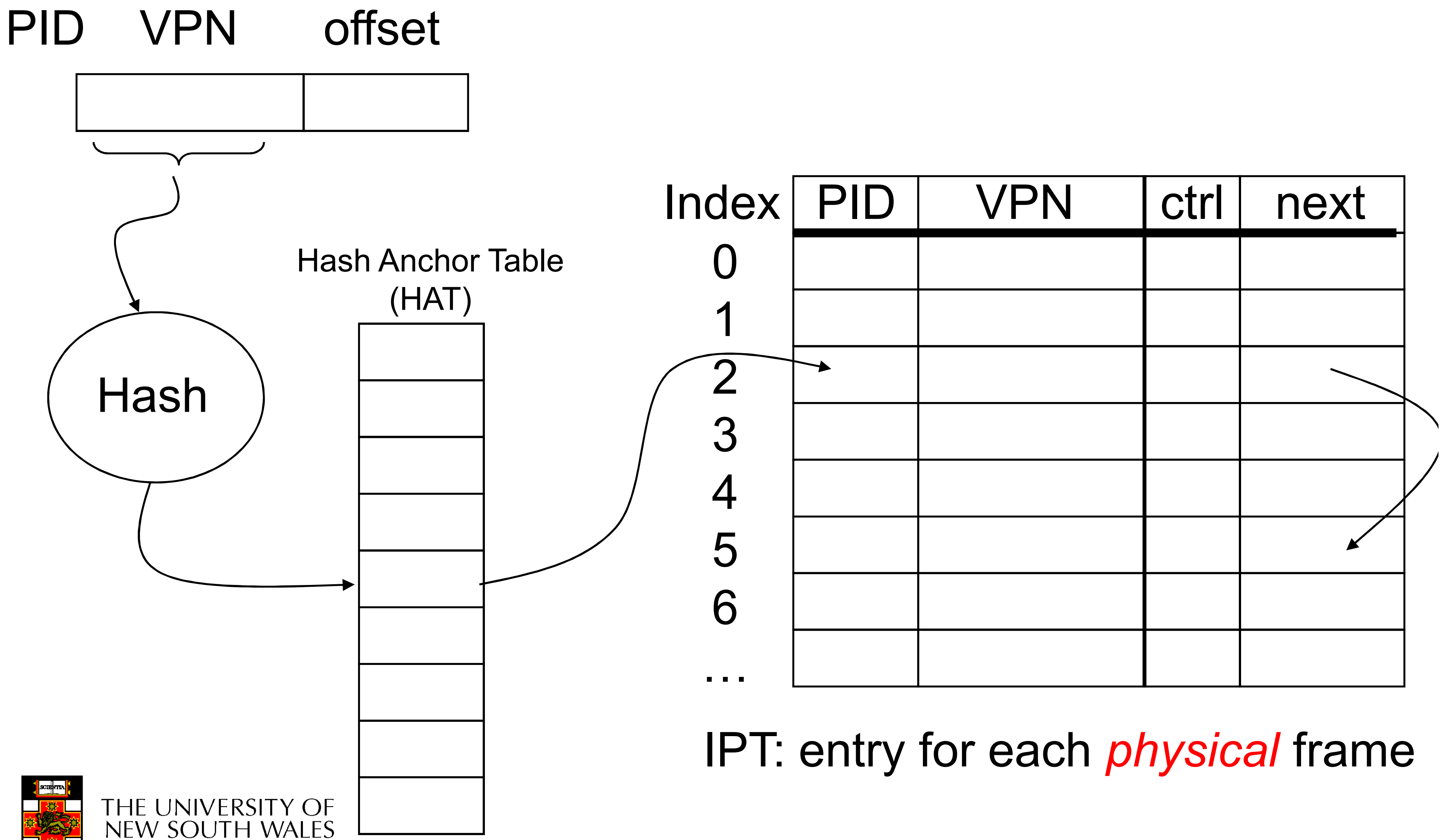


(a)

# Two-level Translation



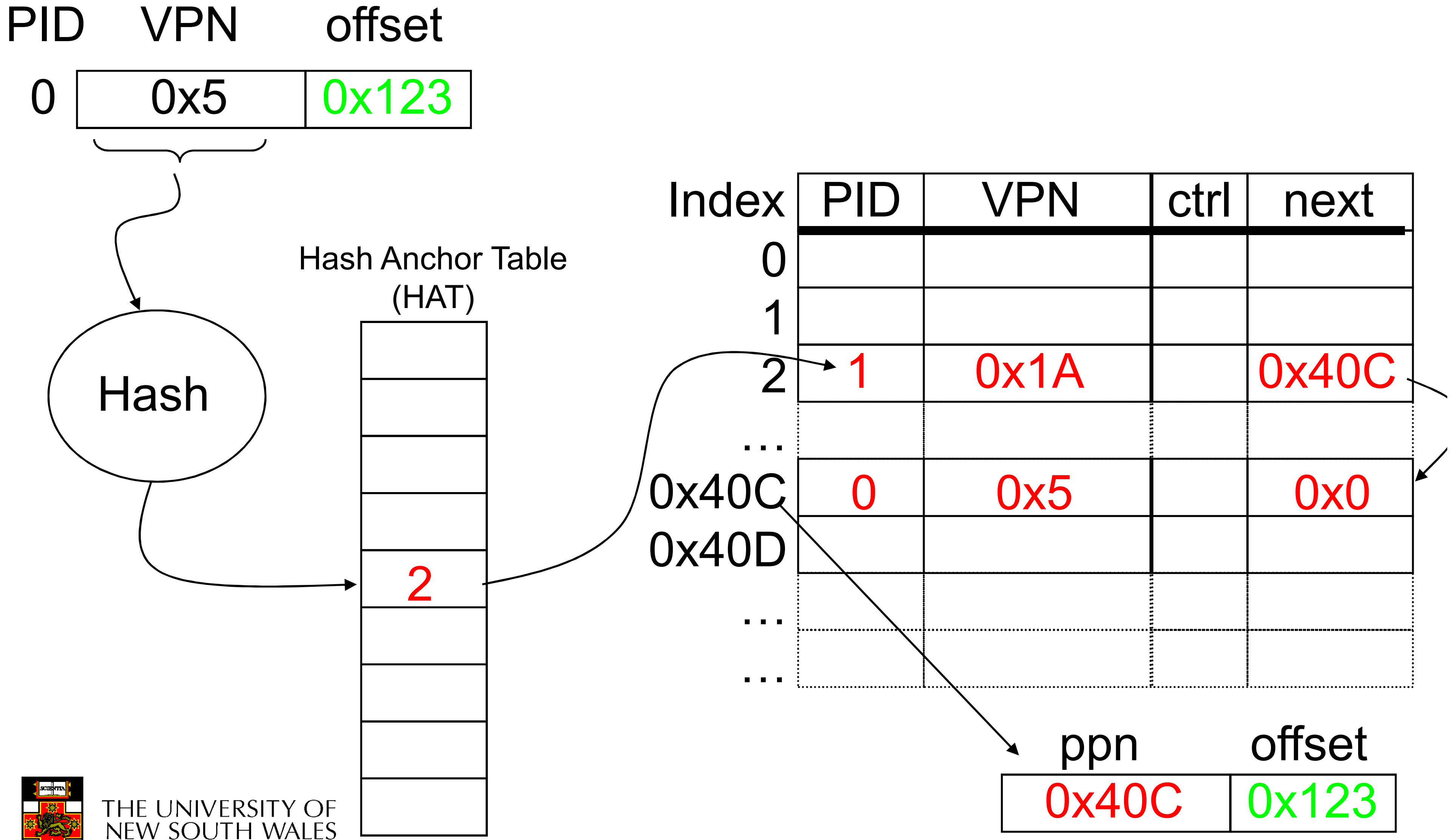
# Alternative: Inverted Page Table



| Index | PID | VPN | ctrl | next |
|---|---|---|---|---|
| 0 | | | | |
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| … | | | | |

IPT: entry for each *physical* frame

# Alternative: Inverted Page Table



| Index | PID | VPN | ctrl | next |
|---|---|---|---|---|
| 0 | | | | |
| 1 | | | | |
| 2 | 1 | 0x1A | | 0x40C |
| … | | | | |
| 0x40C | 0 | 0x5 | | 0x0 |
| 0x40D | | | | |
| … | | | | |
| … | | | | |

# Inverted Page Table (IPT)

- “Inverted page table” is an array of page numbers sorted (indexed) by frame number (it’s a frame table).
- Algorithm
  - Compute hash of page number
  - Extract index from hash table
  - Use this to index into inverted page table
  - Match the page number in the IPT entry
  - If match, use the index value as frame # for translation
  - If no match, get next candidate IPT entry from chain field
  - If NULL chain entry ⇒ page fault

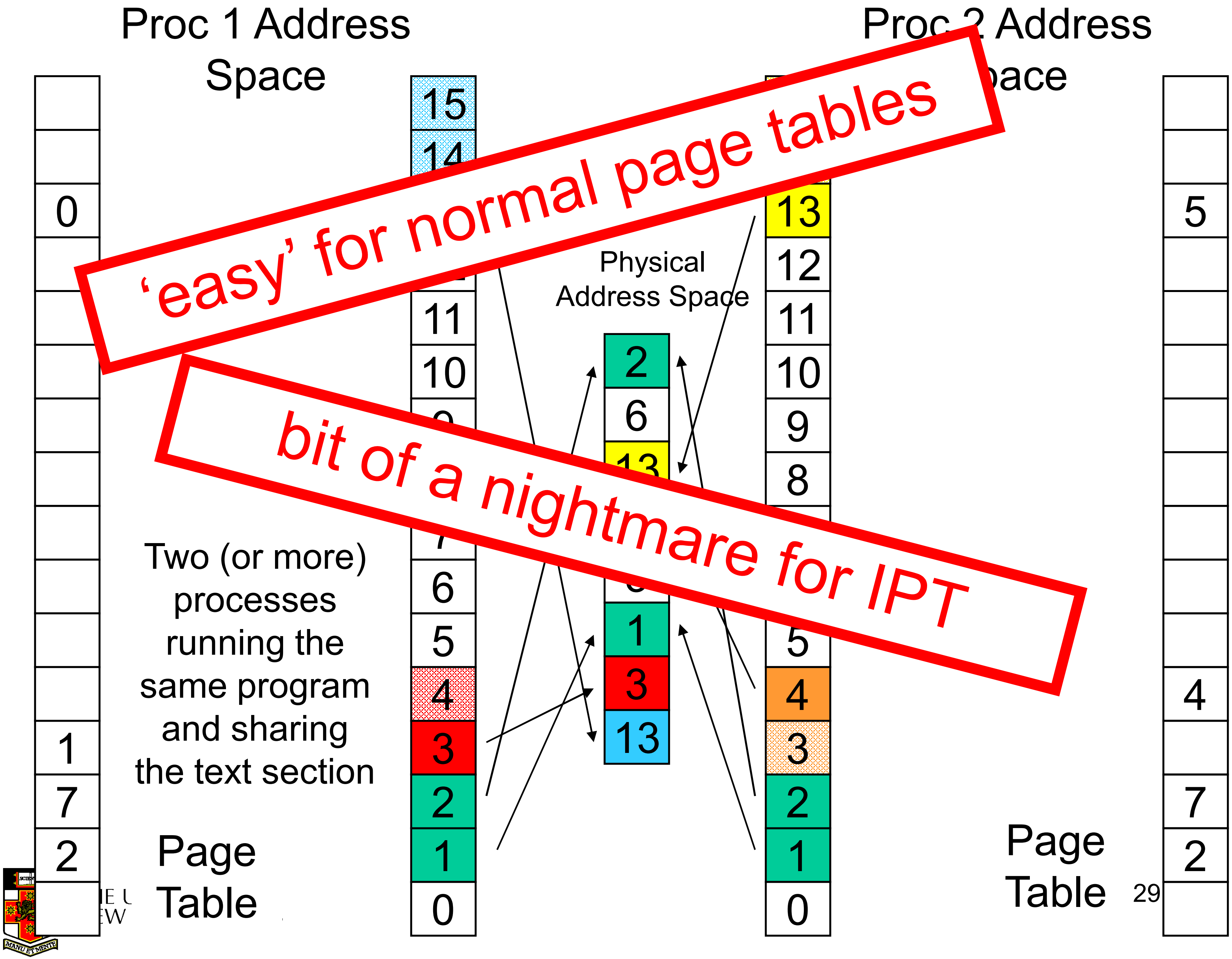
# Properties of IPTs

- IPT grows with size of RAM, NOT virtual address space
- Frame table is needed anyway (for page replacement, more later)
- Need a separate data structure for non-resident pages
- Saves a vast amount of space (especially on 64-bit systems)
- Used in some IBM and HP workstations

# Given *n* processes

- how many page tables will the system have for
  - ‘normal’ page tables
  - inverted page tables?

# Another look at sharing…



Two (or more) processes running the same program and sharing the text section

‘easy’ for normal page tables

bit of a nightmare for IPT

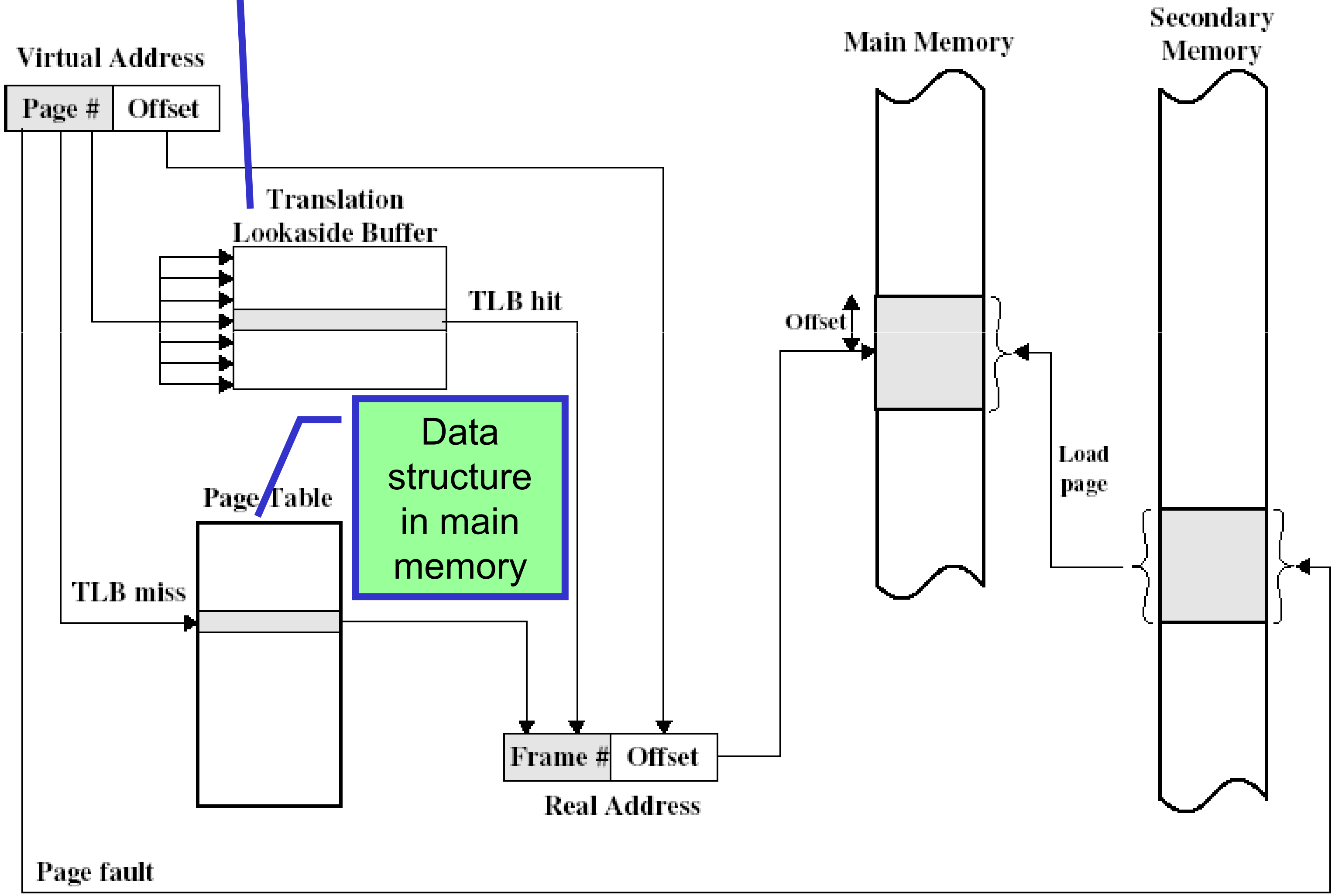
# VM Implementation Issue

- Problem:
  - Each virtual memory reference can cause two physical memory accesses
    - One to fetch the page table entry
    - One to fetch/store the data

    ⇒Intolerable performance impact!!
- Solution:
  - High-speed cache for page table entries (PTEs)
    - Called a *translation look-aside buffer* (TLB)
    - Contains recently used page table entries
    - Associative, high-speed memory, similar to cache memory
    - May be under OS control (unlike memory cache)

# TLB operation

On-CPU hardware device!!!



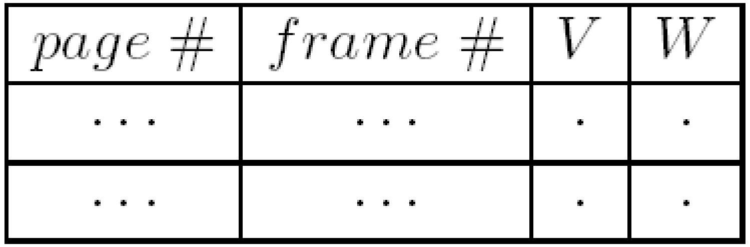
Data structure in main memory

# Translation Lookaside Buffer

- Given a virtual address, processor examines the TLB
- If matching PTE found (*TLB hit*), the address is translated
- Otherwise (*TLB miss*), the page number is used to index the process's page table
  - If PT contains a valid entry, reload TLB and restart
  - Otherwise, (page fault) check if page is on disk
    - If on disk, swap it in
    - Otherwise, allocate a new page or raise an exception

# TLB properties

- Page table is (logically) an array of frame numbers
- TLB holds a (recently used) subset of PT entries
  - Each TLB entry must be identified (tagged) with the page # it translates
  - Access is by associative lookup:
    - All TLB entries' tags are concurrently compared to the page #
    - TLB is associative (or content-addressable) memory



| *page #* | *frame #* | *V* | *W* |
|---|---|---|---|
| $\cdots$ | $\cdots$ | $\cdot$ | $\cdot$ |
| $\cdots$ | $\cdots$ | $\cdot$ | $\cdot$ |

# TLB properties

- TLB may or may not be under direct OS control
  - Hardware-loaded TLB
    - On miss, hardware performs PT lookup and reloads TLB
    - Example: Pentium
  - Software-loaded TLB
    - On miss, hardware generates a TLB miss exception, and exception handler reloads TLB
    - Example: MIPS
- TLB size: typically 64-128 entries
- Can have separate TLBs for instruction fetch and data access
- TLBs can also be used with inverted page tables (and others)

# TLB and context switching

- TLB is a shared piece of hardware
- Page tables are per-process (address space)
- TLB entries are *process-specific*
  - On context switch need to *flush* the TLB (invalidate all entries)
    - high context-switching overhead (Intel x86)
  - **or** tag entries with *address-space ID* (ASID)
    - called a *tagged TLB*
    - used (in some form) on all modern architectures
    - TLB entry: ASID, page #, frame #, valid and write-protect bits

# TLB effect

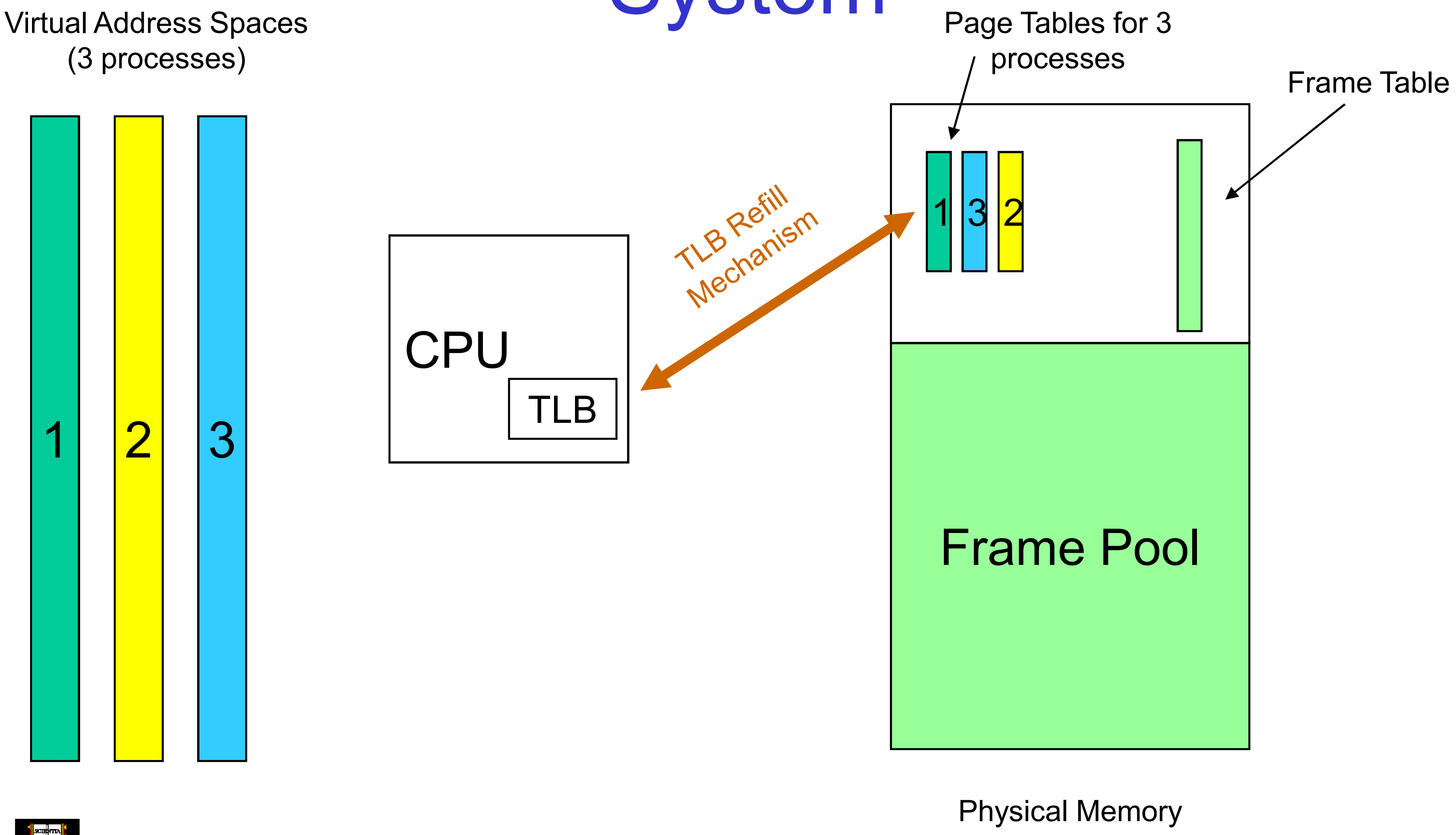
- Without TLB
  - Average number of physical memory references per virtual reference

    = 2
- With TLB (assume 99% hit ratio)
  - Average number of physical memory references per virtual reference

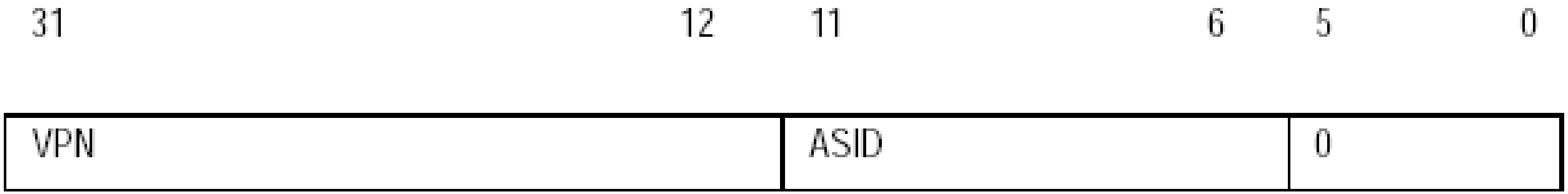
    = .99 * 1 + 0.01 * 2

    = 1.01

# Simplified Components of VM System

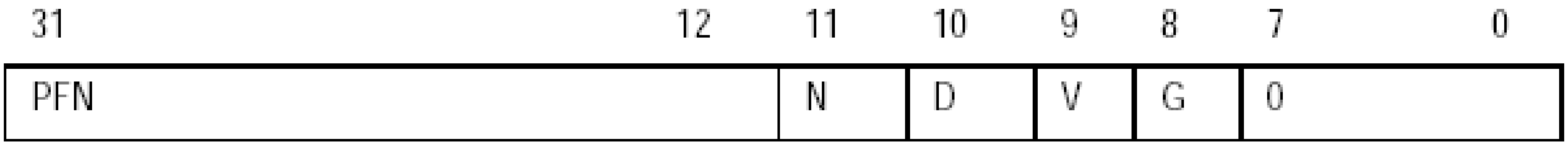


# MIPS R3000 TLB



| 31 12 | 11 6 | 5 0 |
|---|---|---|
| VPN | ASID | 0 |

EntryHi Register (TLB key fields)



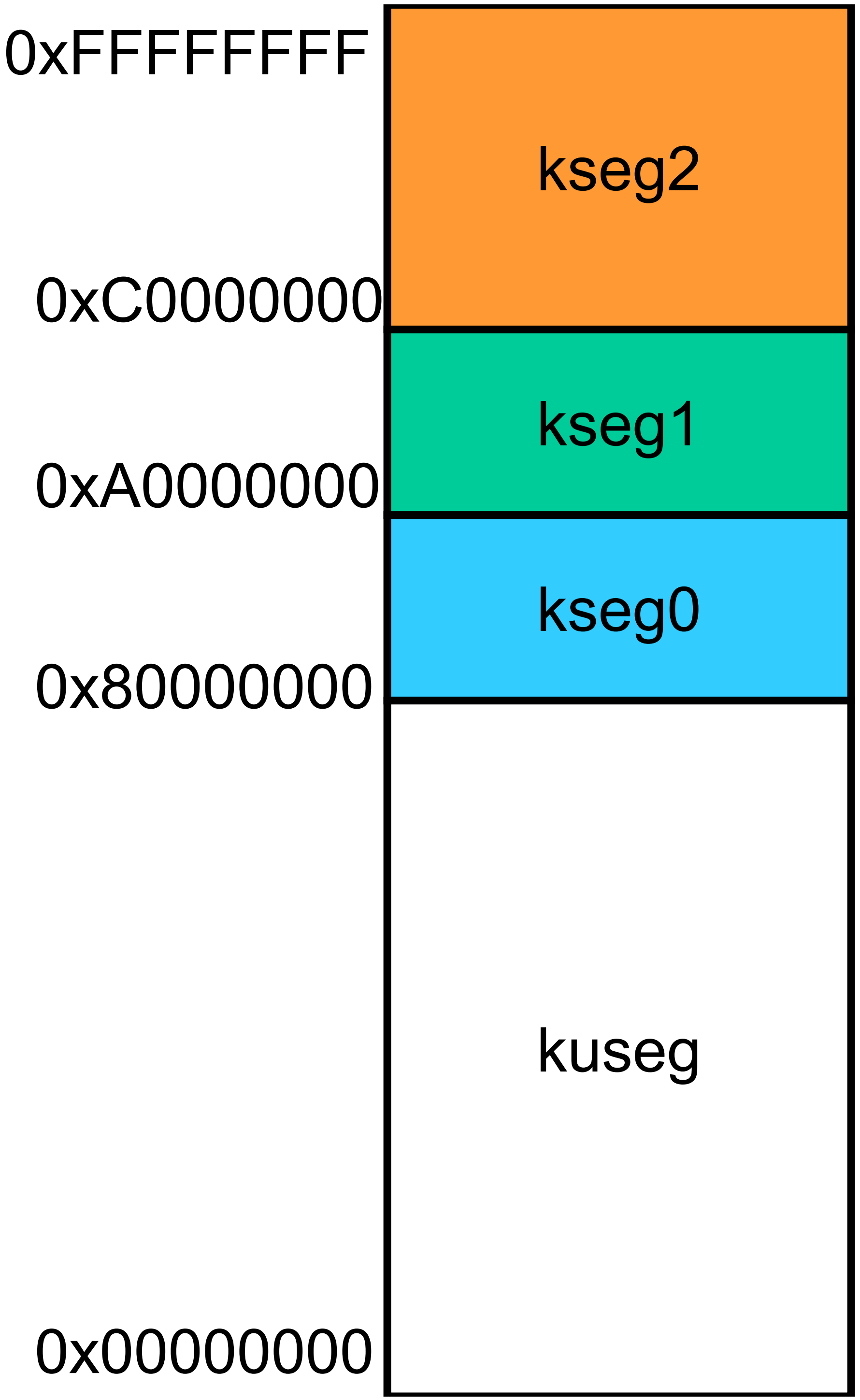
| 31 12 | 11 | 10 | 9 | 8 | 7 0 |
|---|---|---|---|---|---|
| PFN | N | D | V | G | 0 |

EntryLo Register (TLB data fields)

- N = Not cacheable
- D = Dirty = Write protect
- G = Global (ignore ASID in lookup)
- V = valid bit
- 64 TLB entries
- Accessed via software through Cooproprocessor 0 registers
  - EntryHi and EntryLo

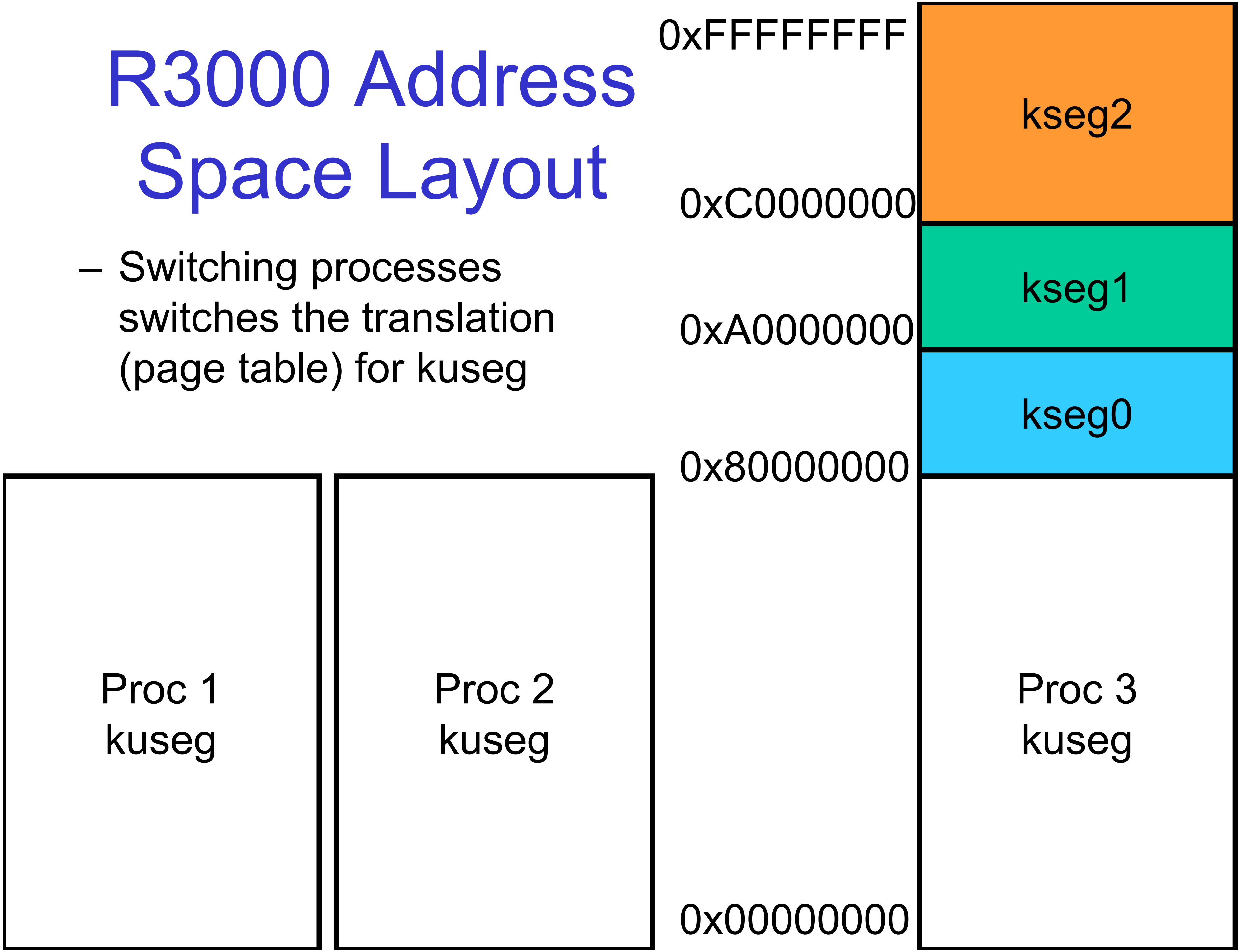
# R3000 Address Space Layout

- kuseg:
  - 2 gigabytes
  - TLB translated (mapped)
  - Cacheable (depending on ‘N’ bit)
  - user-mode and kernel mode accessible
  - Page size is 4K



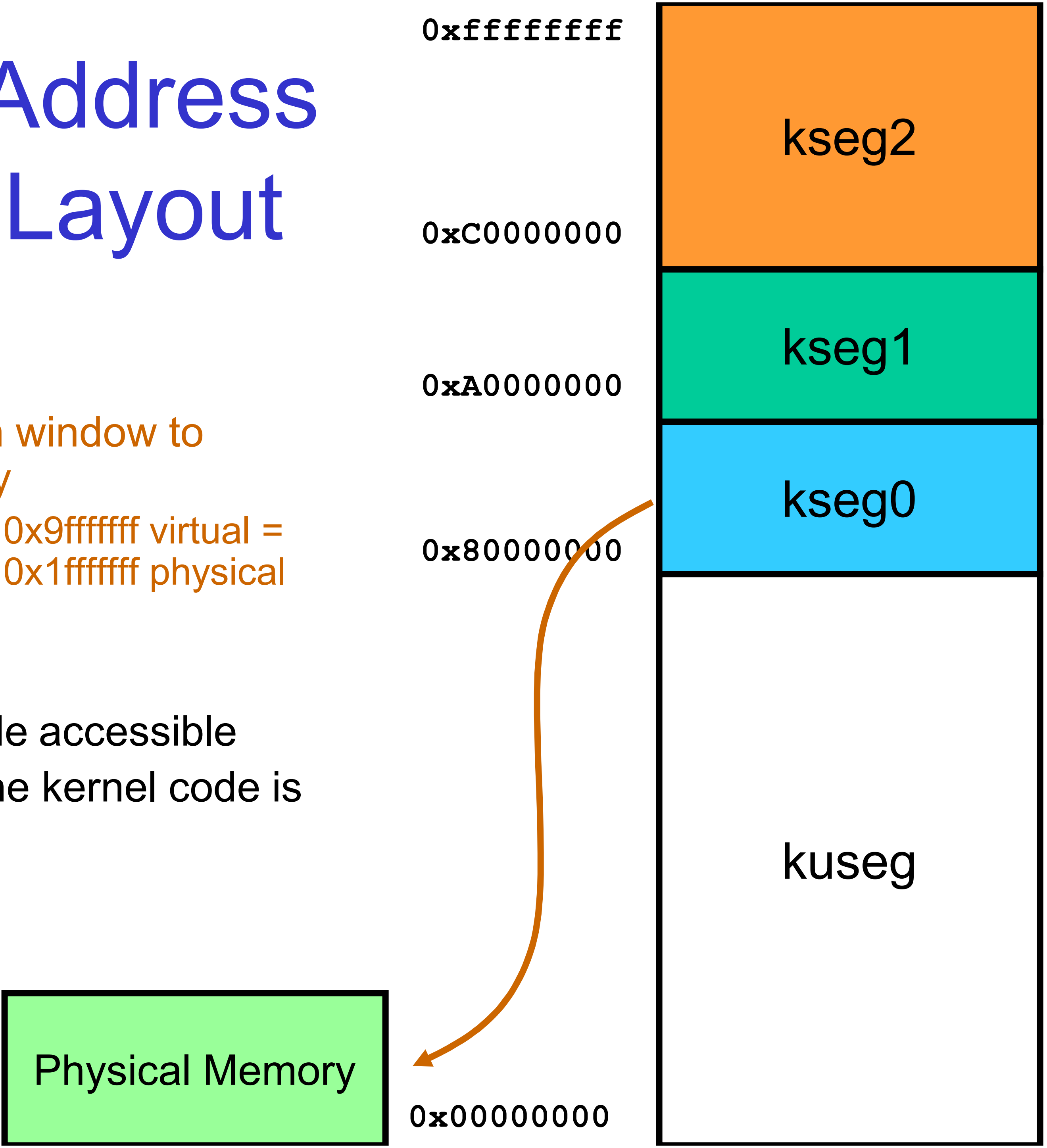
# R3000 Address Space Layout

– Switching processes switches the translation (page table) for kuseg



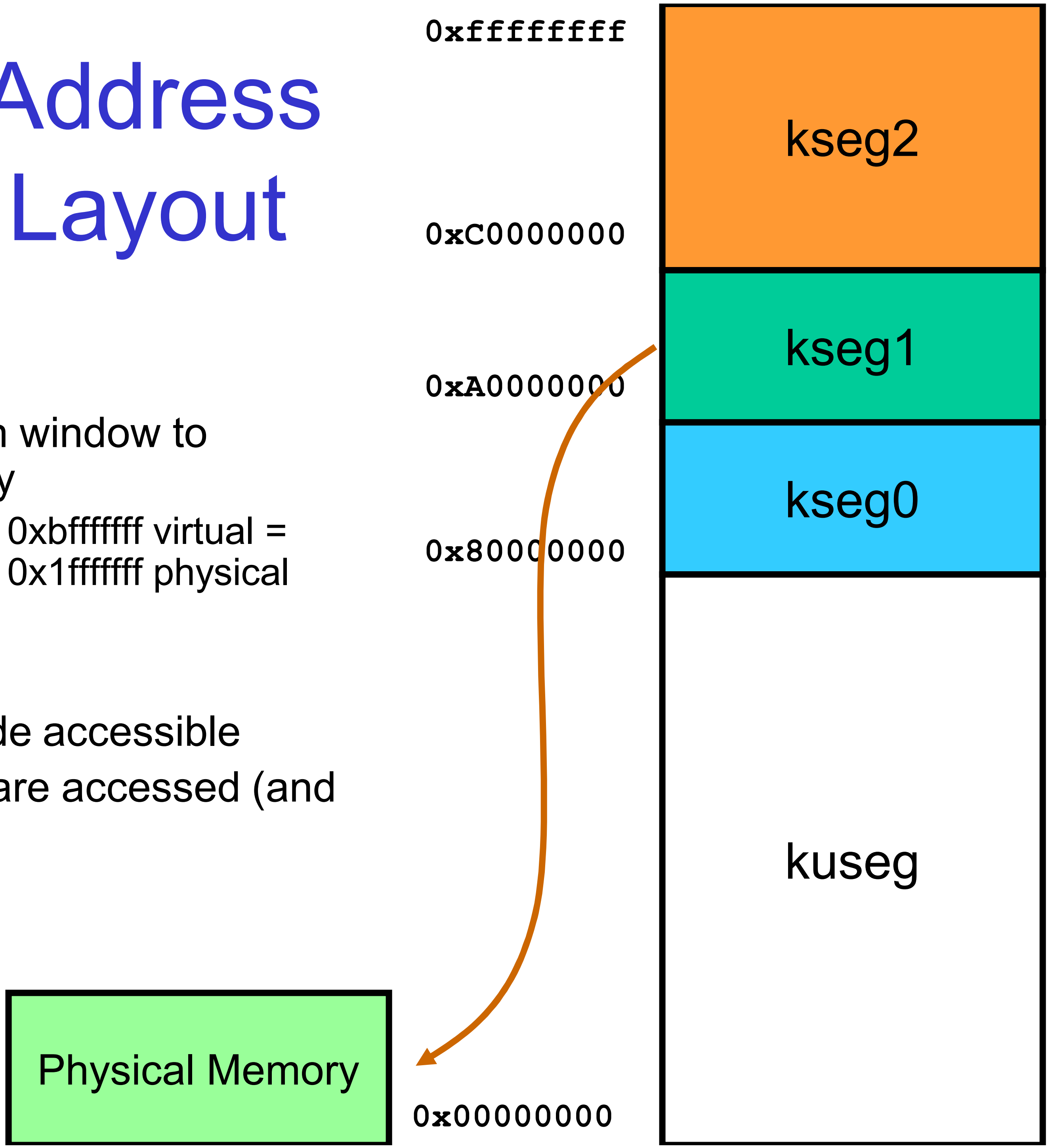
# R3000 Address Space Layout

- kseg0:
  - 512 megabytes
  - Fixed translation window to physical memory
    - 0x80000000 - 0x9fffffff virtual = 0x00000000 - 0x1fffffff physical
    - TLB not used
  - Cacheable
  - Only kernel-mode accessible
  - Usually where the kernel code is placed



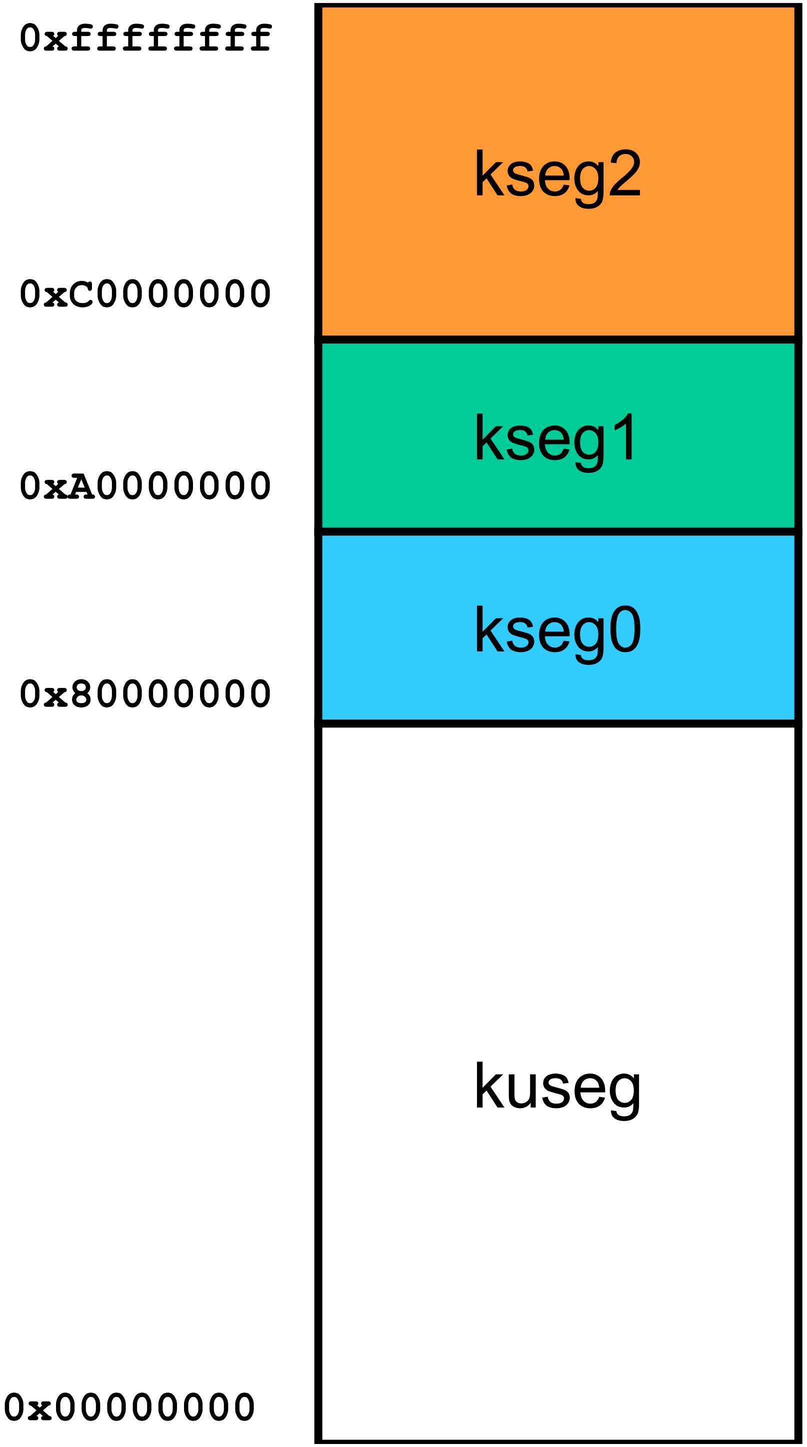
# R3000 Address Space Layout

- kseg1:
  - 512 megabytes
  - Fixed translation window to physical memory
    - 0xa0000000 - 0xbfffffff virtual = 0x00000000 - 0x1fffffff physical
    - TLB not used
  - **NOT** cacheable
  - Only kernel-mode accessible
  - Where devices are accessed (and boot ROM)



# R3000 Address Space Layout

- kseg2:
  - 1024 megabytes
  - TLB translated (mapped)
  - Cacheable
    - Depending on the ‘N’-bit
  - Only kernel-mode accessible
  - Can be used to store the virtual linear array page table


0xffffffff
kseg2
0xC0000000
kseg1
0xA0000000
kseg0
0x80000000
kuseg
0x00000000