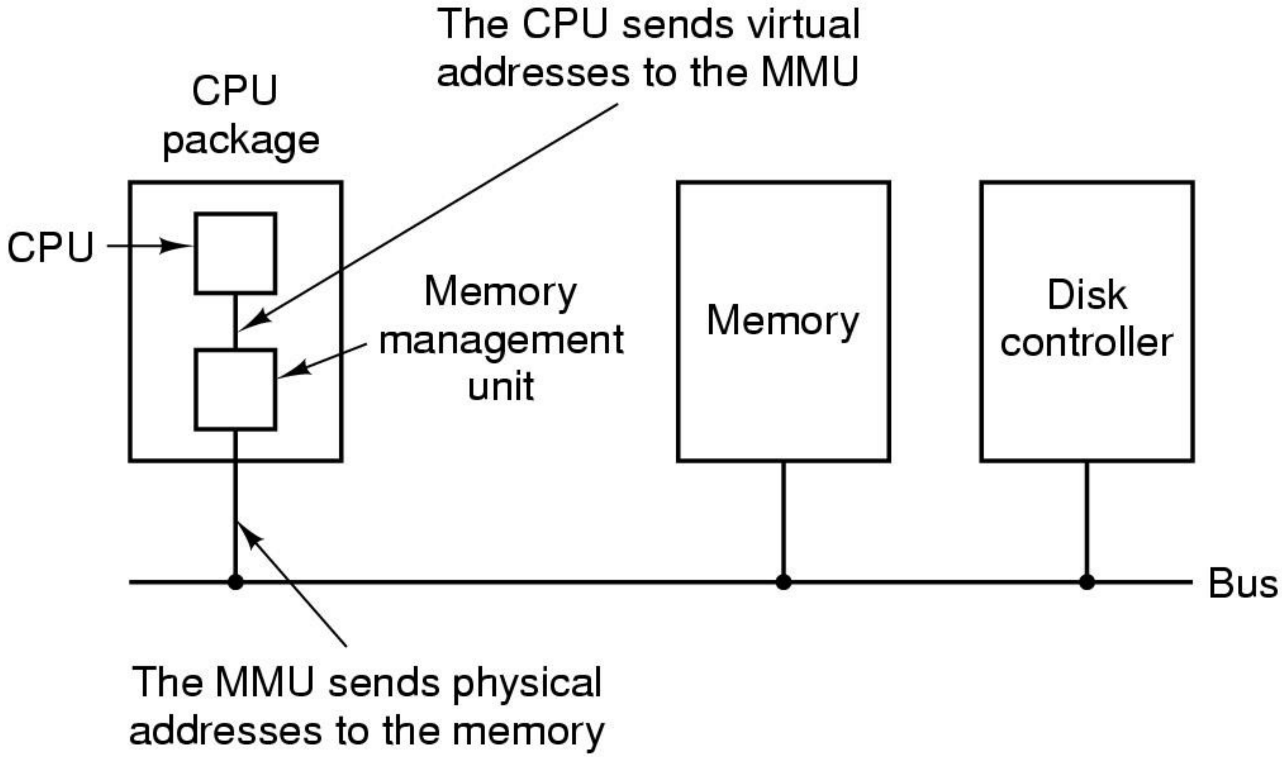
Virtual Memory

Learning Outcomes

- An understanding of page-based virtual memory in depth.
  - Including the R3000's support for virtual memory.

Memory Management Unit (or TLB)

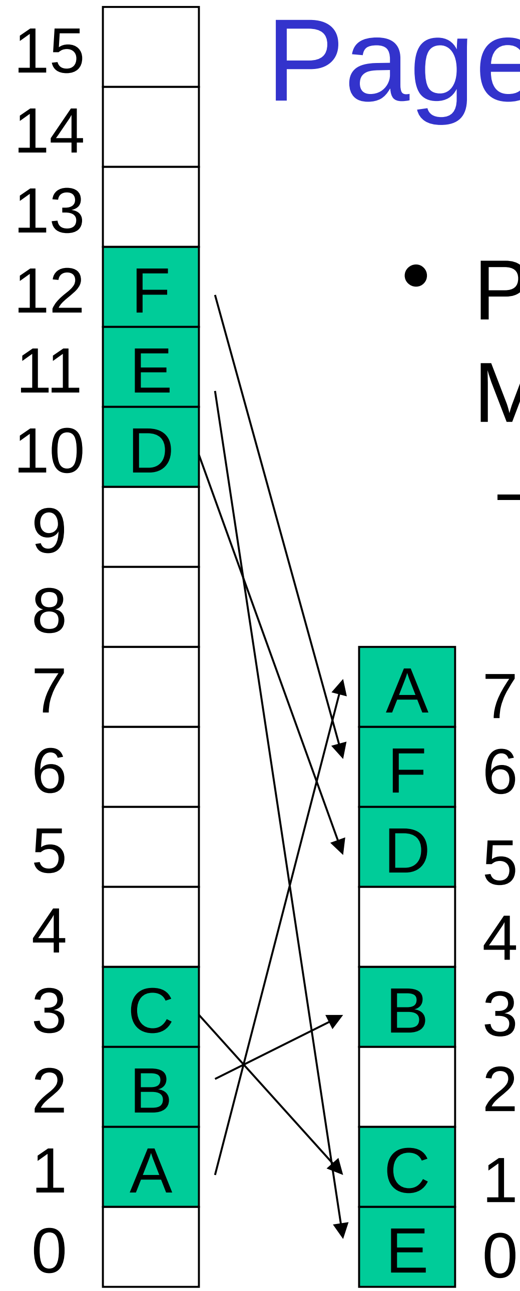


The position and function of the MMU

Page-based VM

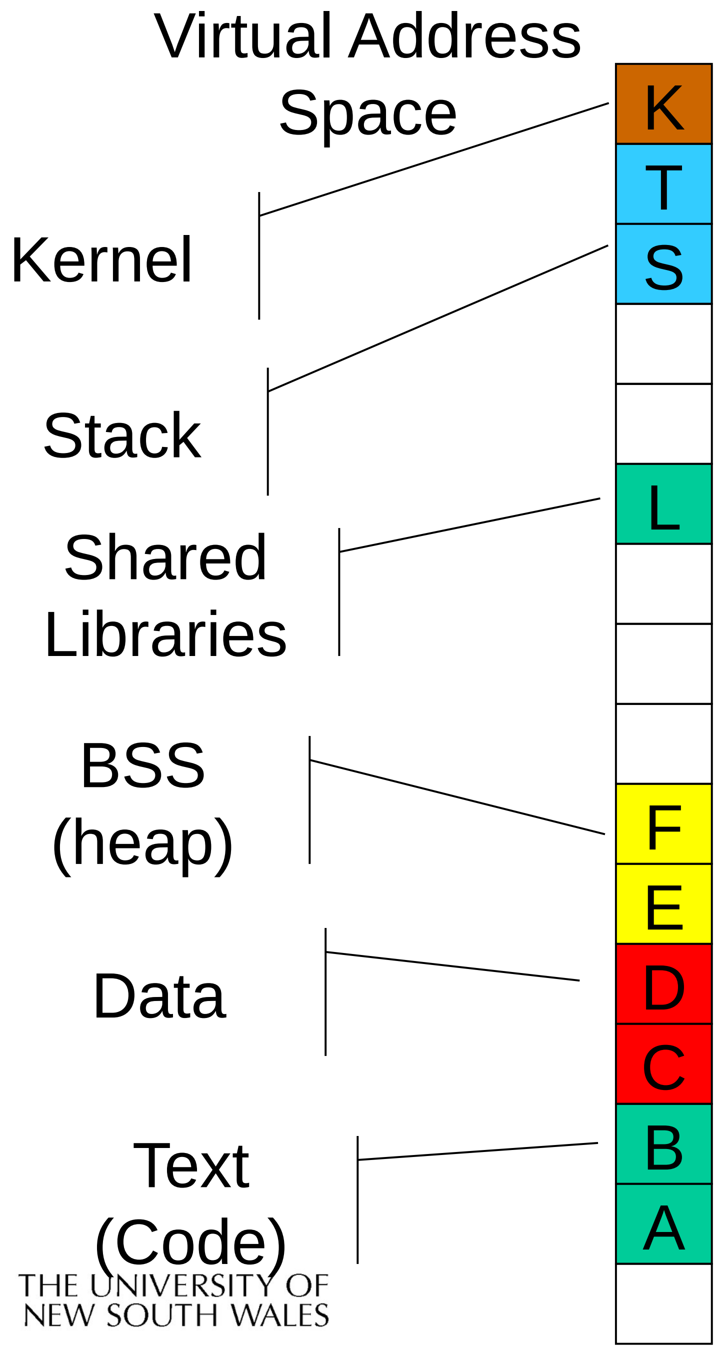
Virtual Address Space

- Virtual Memory
  - Divided into equal-sized *pages*
  - A *mapping* is a translation between
    - A page and a frame
    - A page and *invalid*
  - 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*

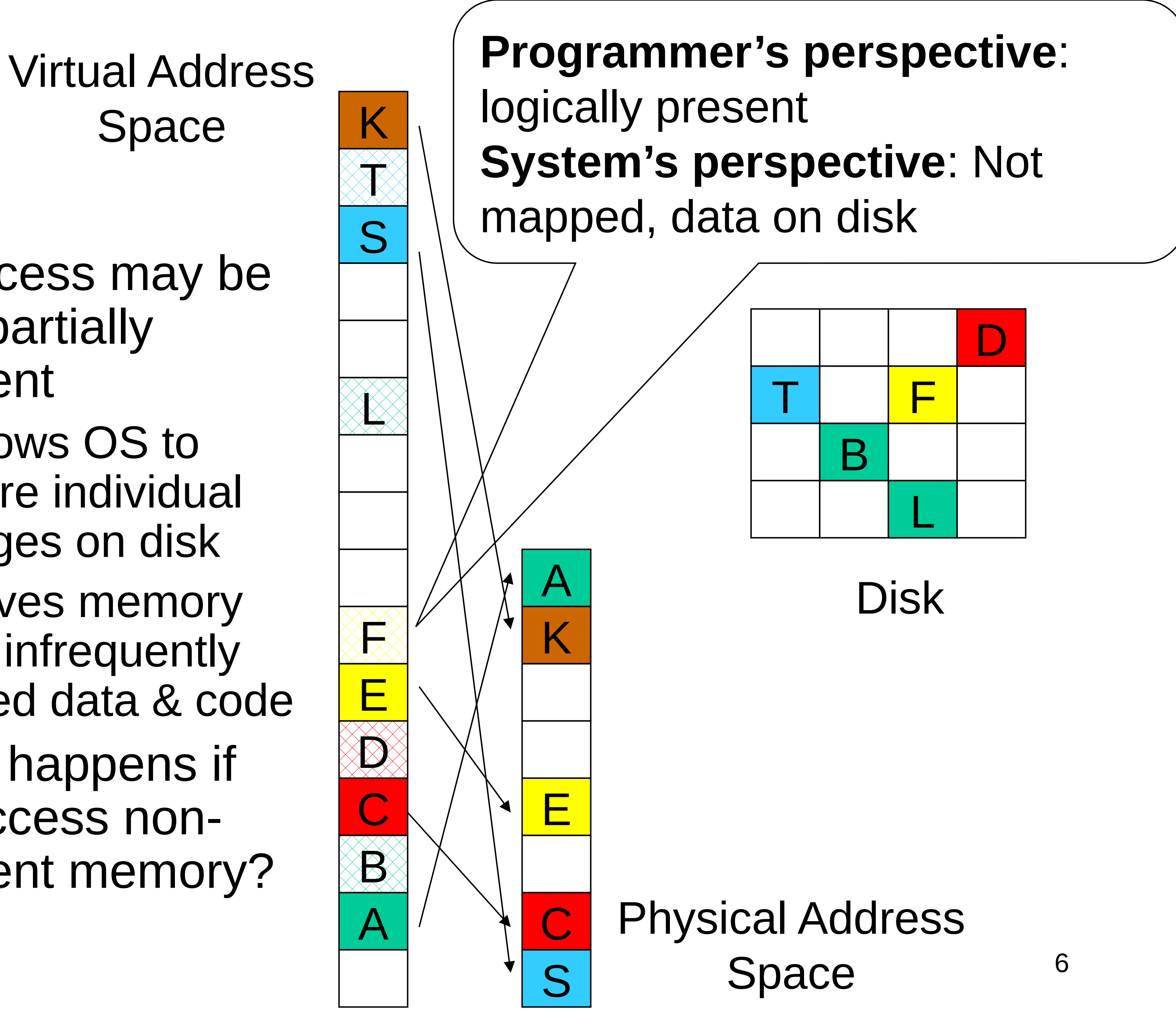
Physical Address Space

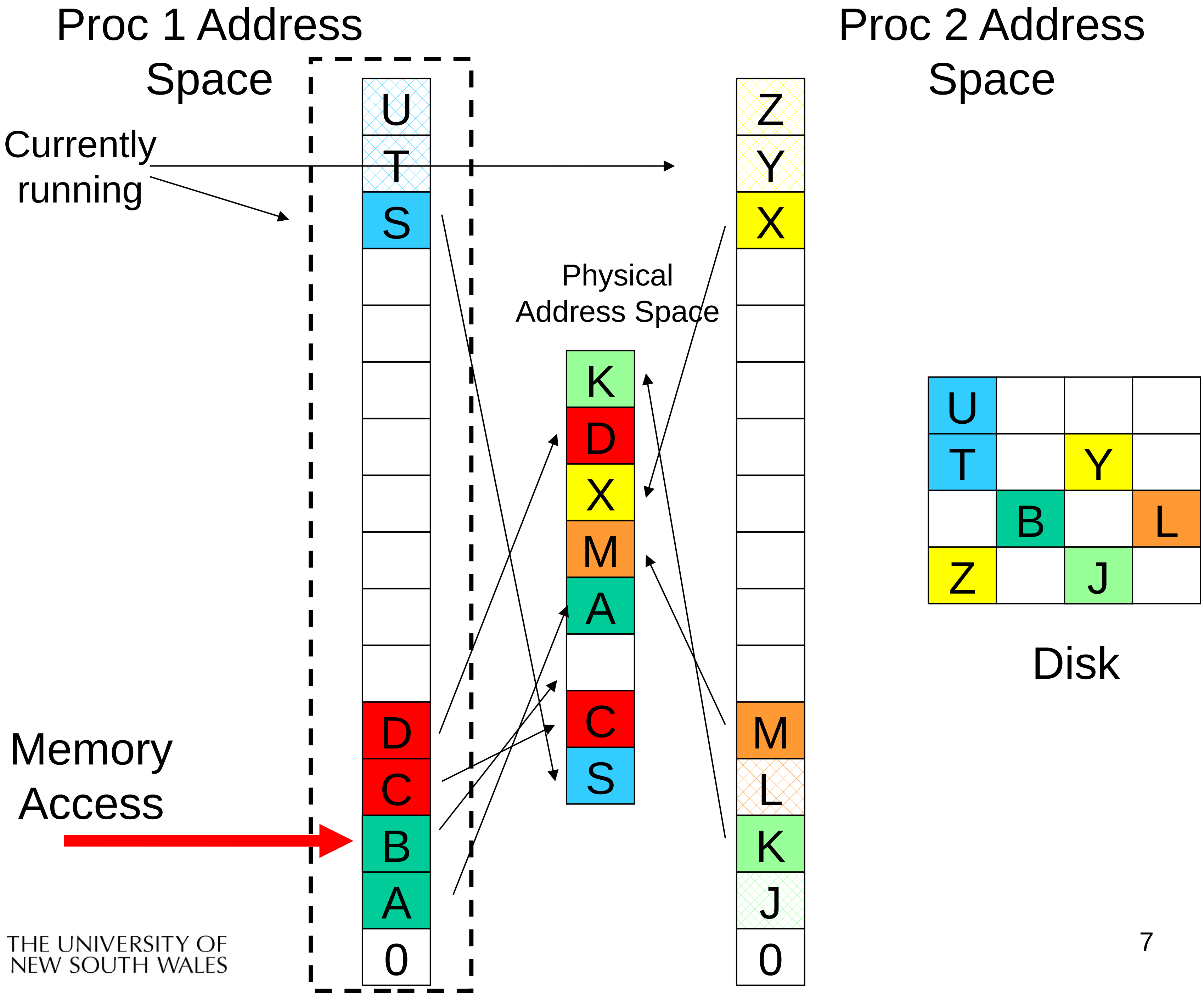


Typical Address Space Layout

- 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?

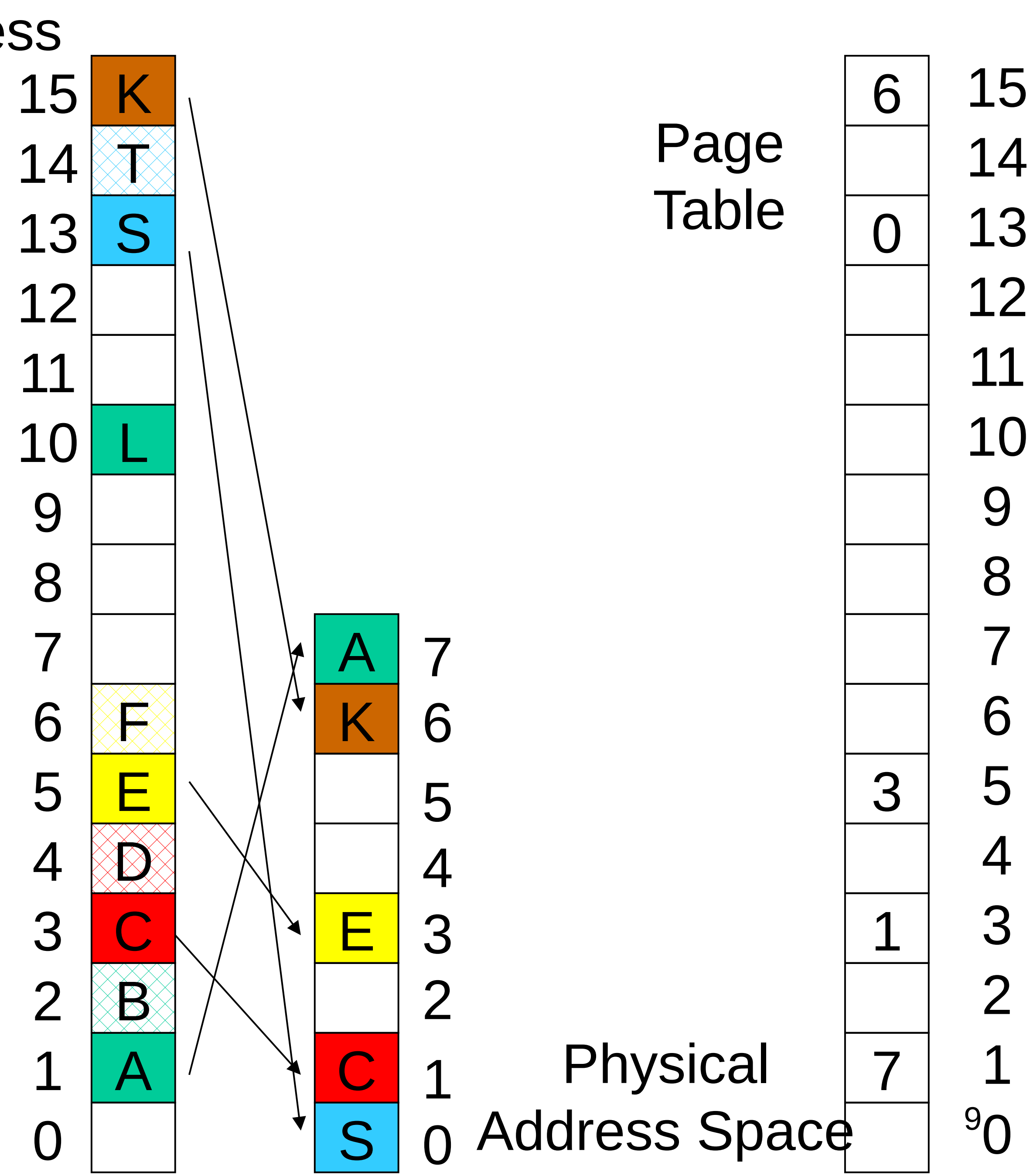



Proc 1 Address Space
Currently running
Memory Access
U
T
S
D
C
B
A
0
Physical Address Space
K
D
X
M
A
C
S
Proc 2 Address Space
Z
Y
X
M
L
K
J
0
U
T
Y
B
L
Z
J
Disk

Page Faults

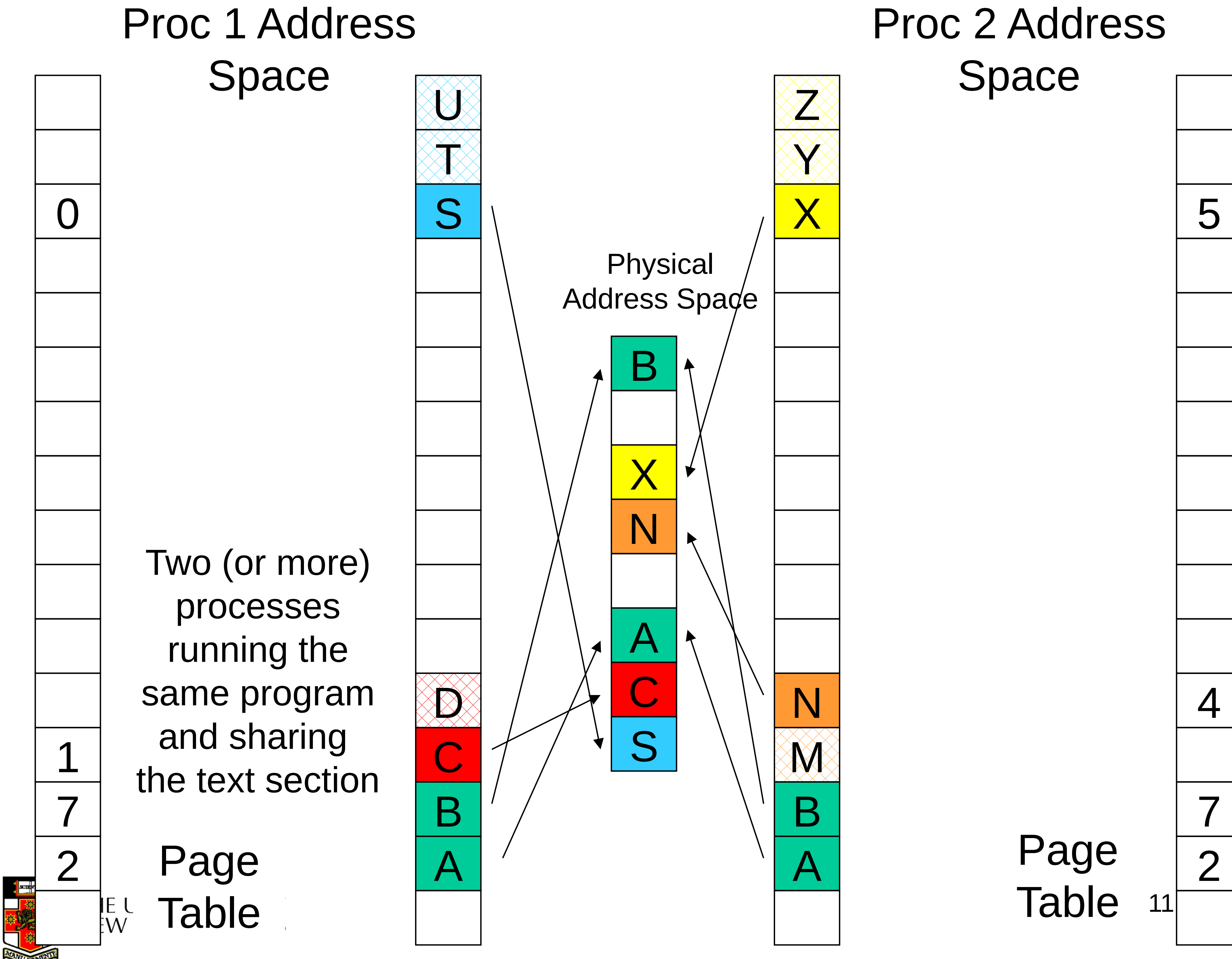
- Referencing an invalid page triggers a page fault
    - An exception handled by the OS
- Broadly, two standard page fault types
  - Illegal Address (protection error)
    - Signal or kill the process
  - Page not resident
    - Find an unused memory frame
    - Load page from disk
    - Update page (translation) table (enter frame #, set valid bit, etc.)
    - Restart the faulting instruction

- Page table for resident part of 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
Physical Address Space
U
T
S
D
C
B
A
Z
Y
X
N
M
B
A
B
X
N
A
C
S
0
1
7
2
5
4
7
2
Two (or more) processes running the same program and sharing the text section
Page Table
Page Table

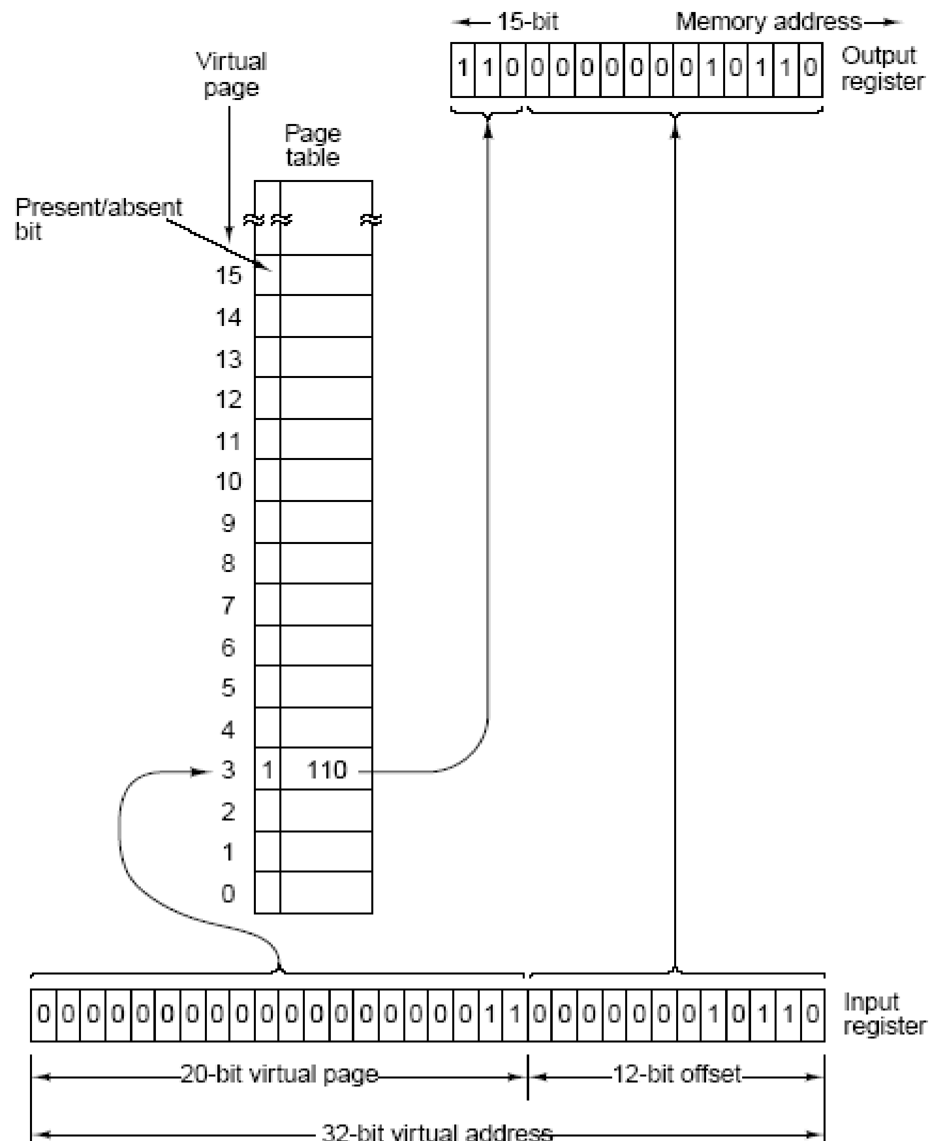
Address Translation

- Every (virtual) memory address issued by the CPU must be translated to physical memory
  - Every *load* and every *store* instruction
  - Every instruction fetch
- Needs translation hardware
- In a page-based system, translation involves replacing the page number with a frame number

Virtual Memory Summary

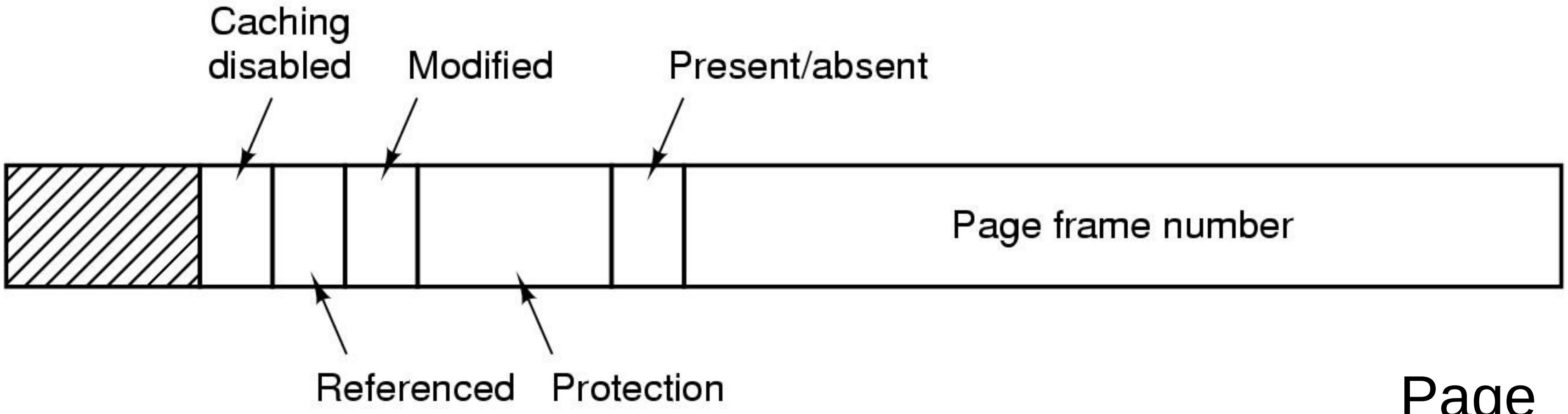
virtual and physical mem chopped up in pages/frames

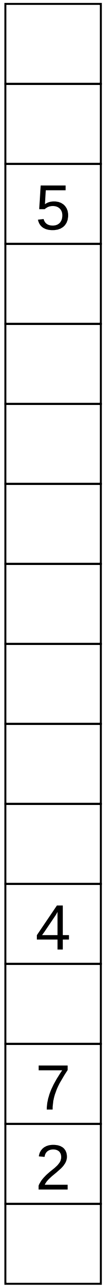
- **programs use virtual addresses**
- **virtual to physical mapping by MMU**
- **split virtual address**
  - **page number & offset**
- **look up frame number**
  - **if found, create physical address**
  - **if not found, fault**



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 Attributes (bits)

- Present/Absent bit
  - Also called *valid* bit, it indicates a valid mapping for the page
- 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
- Modified bit
  - Also called *dirty* bit, it indicates the page may have been modified in memory
- Reference bit
  - Indicates the page has been accessed
- Specific translation hardware may support only some combinations

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

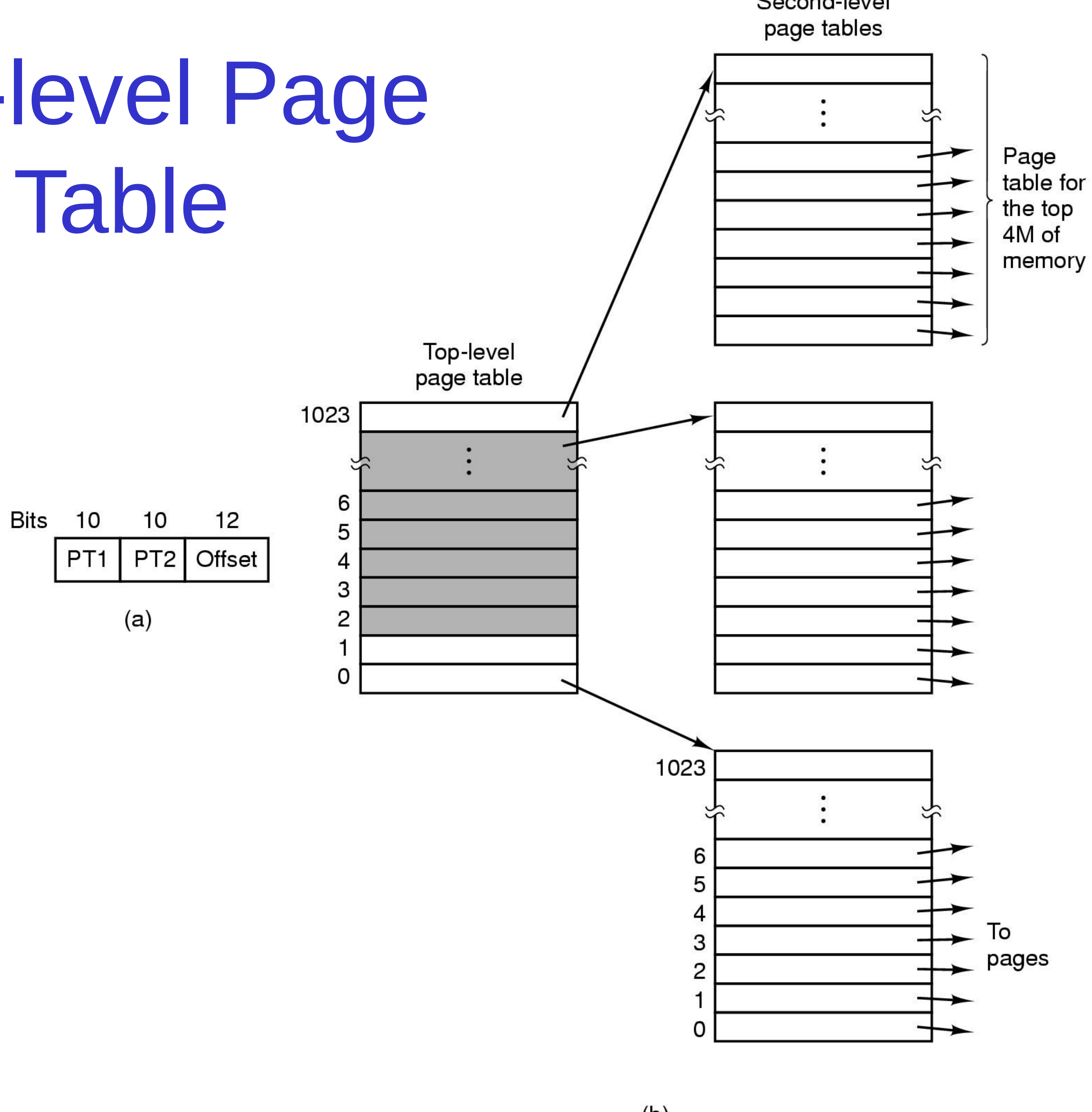
- Assume we have
  - 64-bit virtual address (giant address space)
  - 4 KByte page size
  - How many page table entries do we need for one process?
- Problem:
  - Page table is very large
  - Access has to be fast, lookup for every memory reference
  - Where do we store the page table?
    - Registers?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

Page Tables

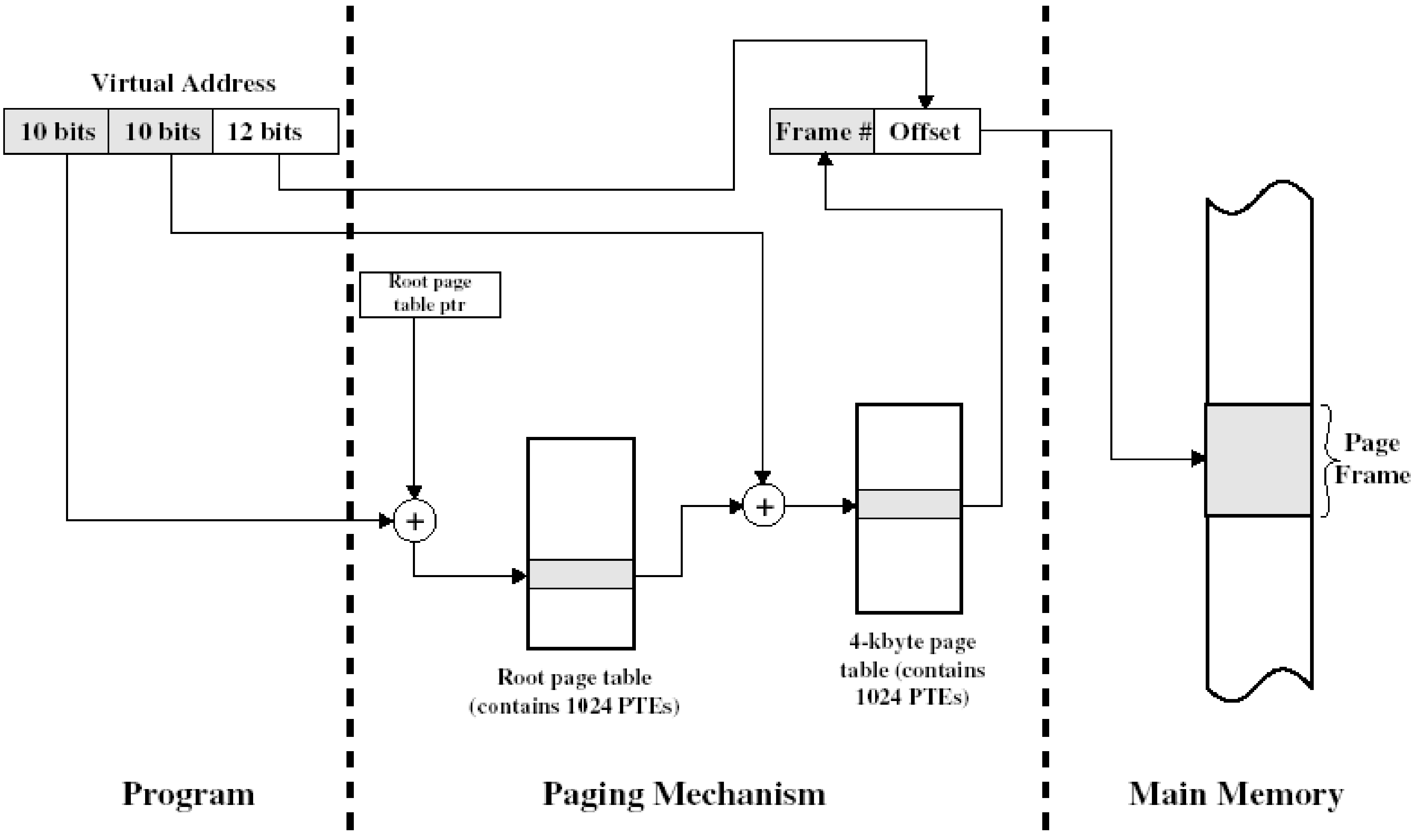
- Page tables are implemented as data structures in main memory
- Most processes do not use the full 4GB address space
  - e.g., 0.1 – 1 MB text, 0.1 – 10 MB data, 0.1 MB stack
- We need a compact representation that does not waste space
  - But is still very fast to search
- Three basic schemes
  - 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

- Another kind of prefix tree
- 2nd –level page tables representing unmapped pages are not allocated
  - Null in the top-level page table



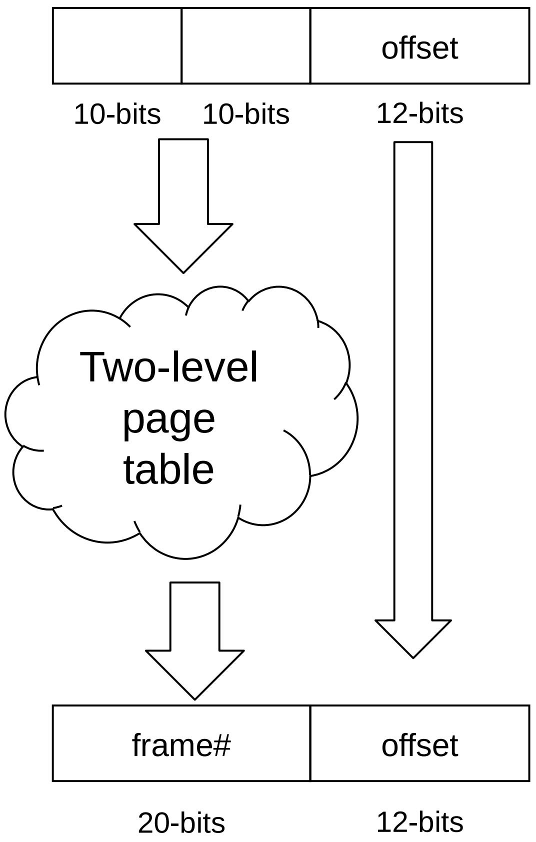
Two-level Translation



Example Translations

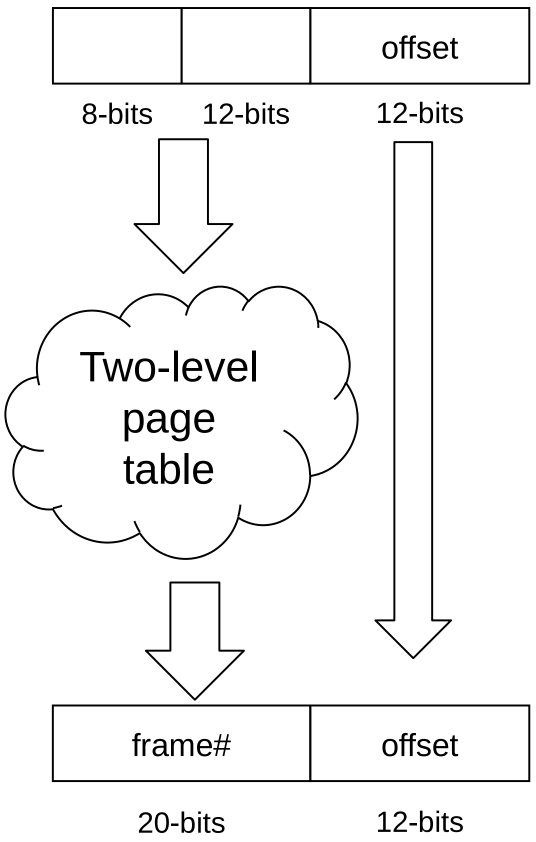
Summarising Two-level Page Tables

- Translating a 32-bit virtual address into a 32-bit physical
- Recall:
  - the level 1 page table node has 2^{10} entries
    - $2^{10} * 4 = 4$ KiB node
  - the level 2 page table node have 2^{10} entries
    - $2^{10} * 4 = 4$ KiB node



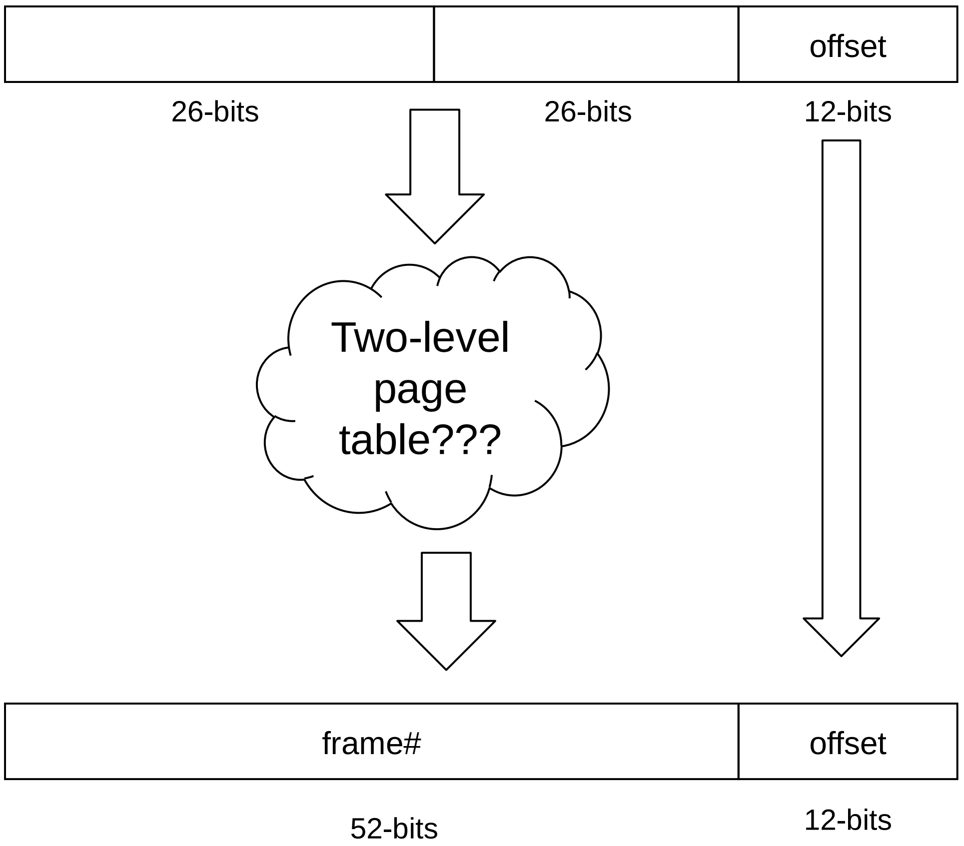
Index bits determine node sizes

- Translating a 32-bit virtual address into a 32-bit physical
- Changing the indexing:
  - the level 1 page table node has 2^8 entries
    - $2^8 * 4 = 1$ KiB node
  - the level 2 page table node have 2^{12} entries
    - $2^{12} * 4 = 16$ KiB node



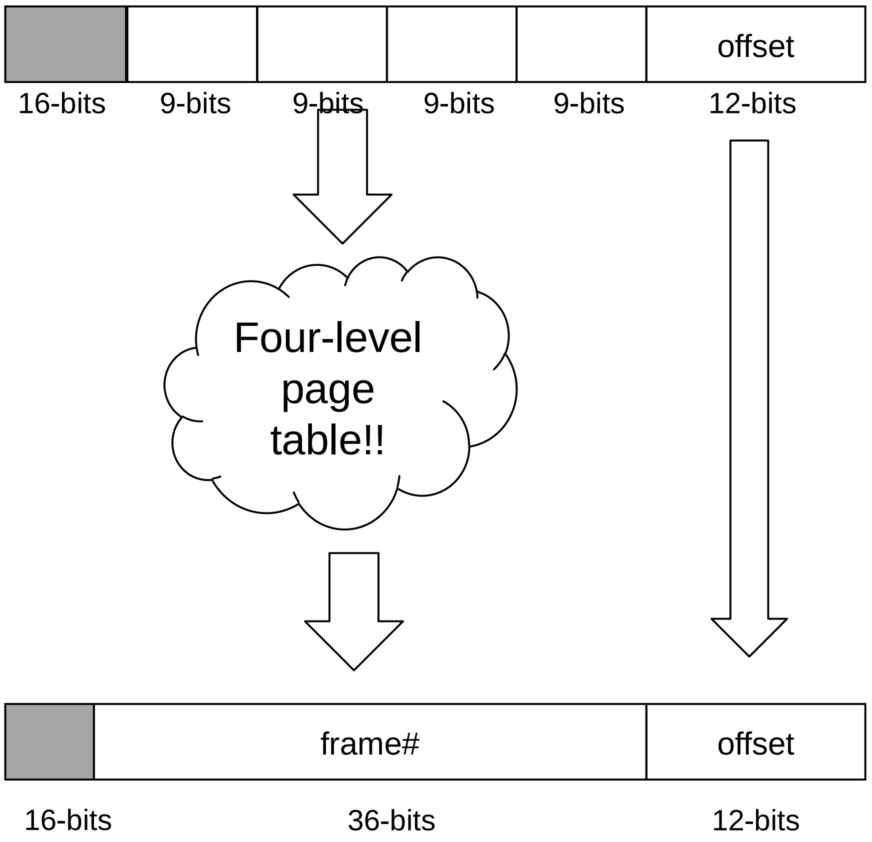
Supporting 64-bit Virtual to Physical Translation

- Translating a 64-bit virtual address into a 64-bit physical???
- Support 64-bits?:
  - the level 1 page table node has 2^{26} entries
    - $2^{26} * 8 = 512$ MiB node
  - the level 2 page table node have 2^{12} entries
    - $2^{26} * 8 = 512$ MiB node



Multi-level Page Tables

- Translating a 64-bit virtual address into a 64-bit physical (Intel/AMD pre-Ice Lake)
  - Only support 48-bit addresses
    - Top 16-bits unused
  - the level 1 page table node has 2^9 entries
    - $2^9 * 8 = 4$ KiB node
  - the level 2 page table node have 2^9 entries
    - $2^9 * 8 = 4$ KiB node
  - the level 3 page table node have 2^9 entries
    - $2^9 * 8 = 4$ KiB node
  - the level 4 page table node have 2^9 entries
    - $2^9 * 8 = 4$ KiB node



Intel 4-Level Page Tables

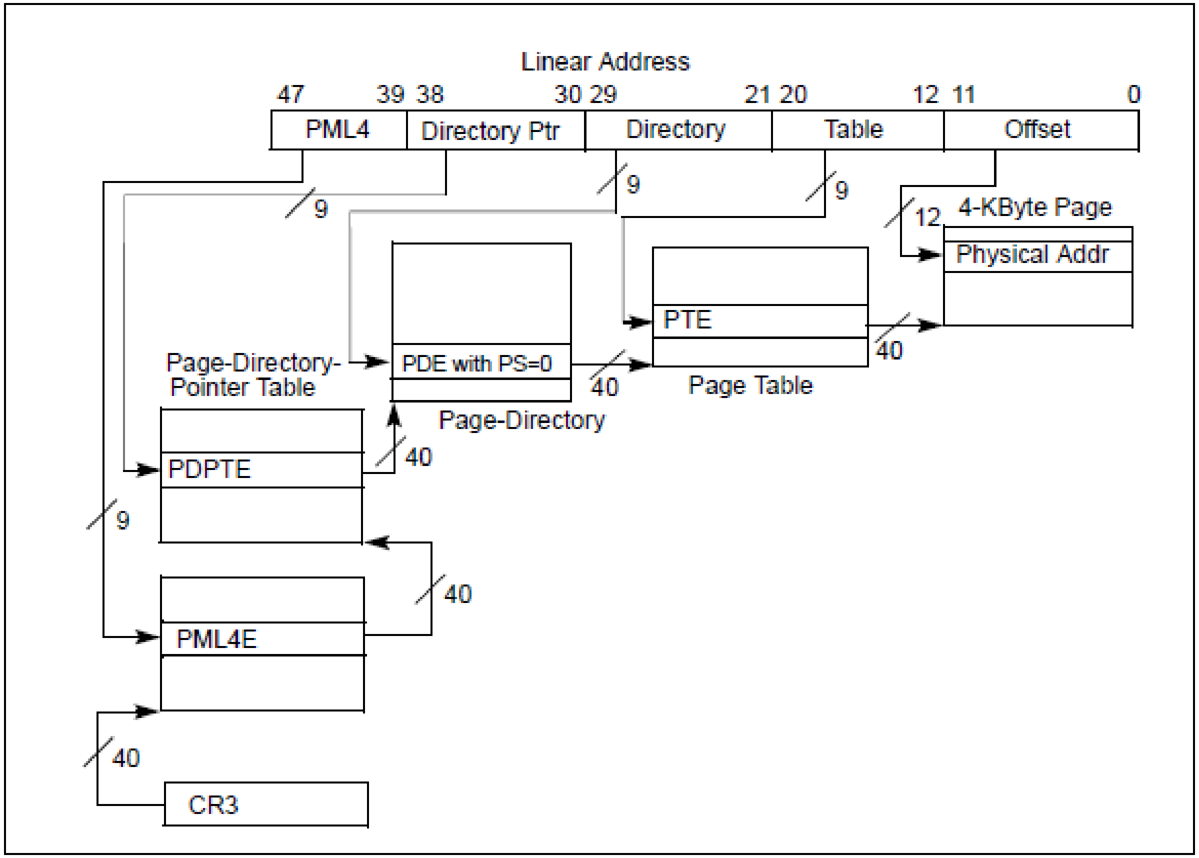


Figure 4-8. Linear-Address Translation to a 4-KByte Page using 4-Level Paging

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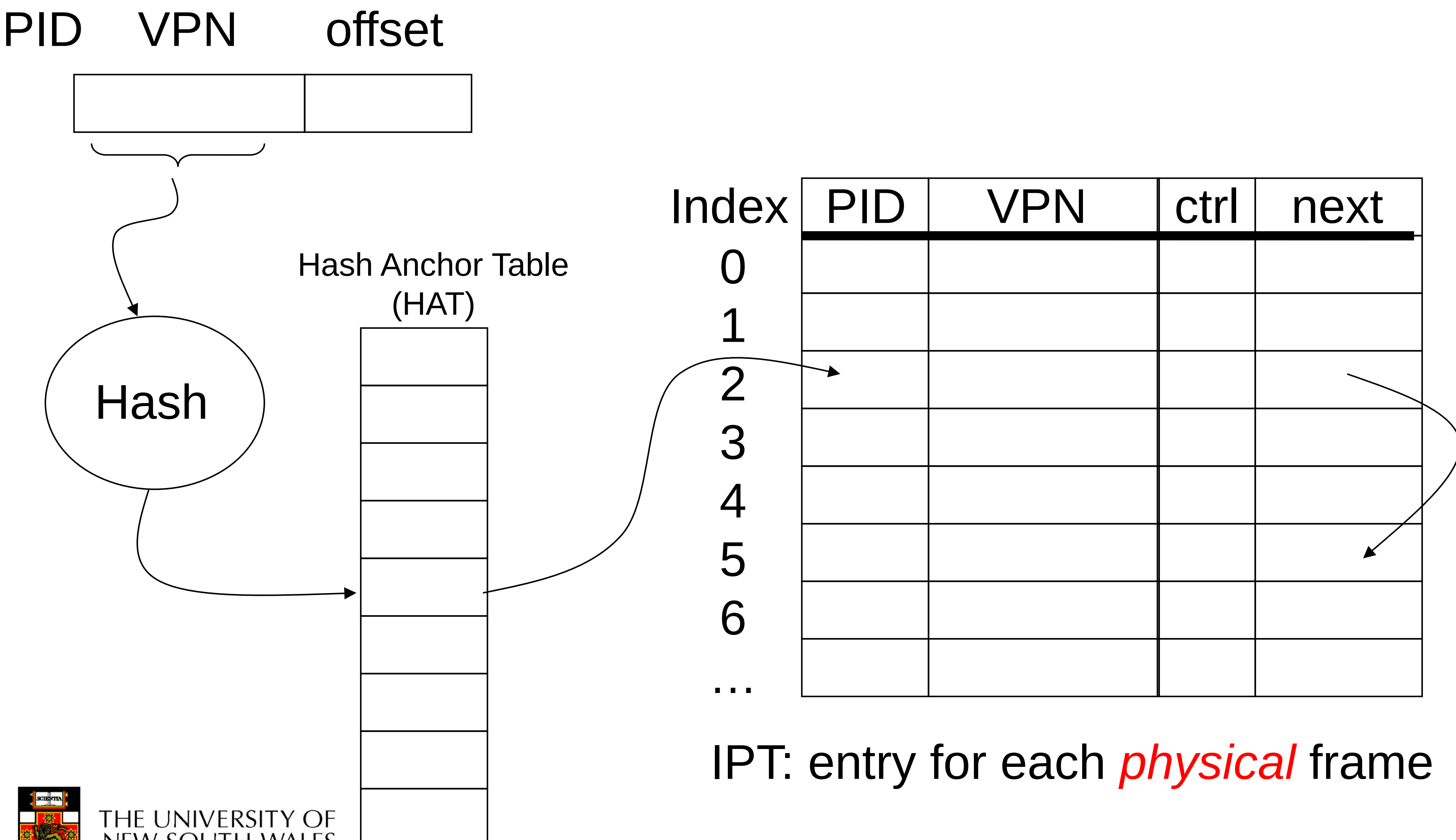
Observation

An observation:

- Virtual memory is usually much larger than available physical memory.
- This is especially true for a 64-bit address space.
- A table of all frames is much smaller than a table of all (possible) pages.

Alternative: Inverted Page Table



IPT: entry for each *physical* frame

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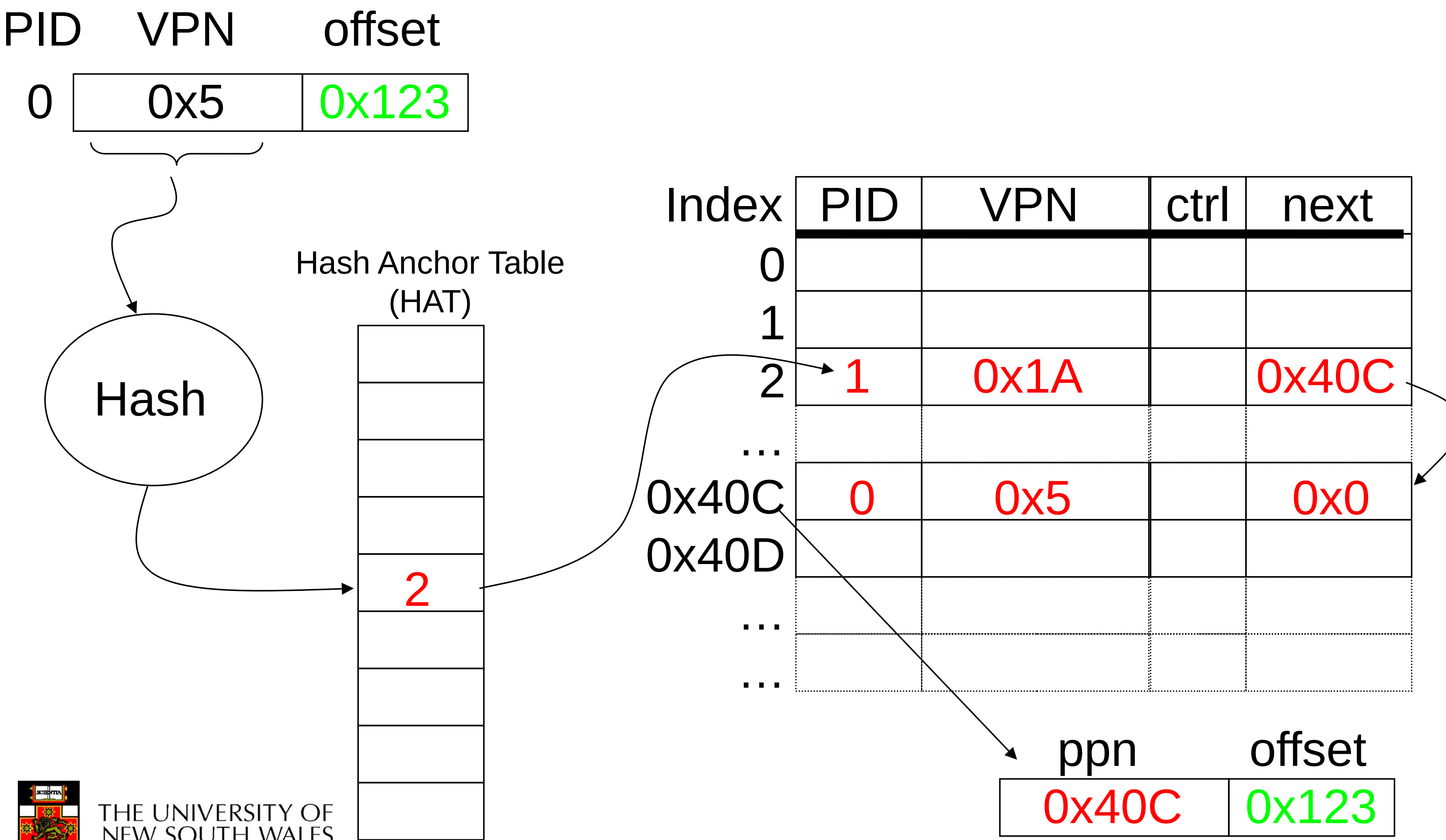
Alternative: Inverted Page Table



Inverted Page Table (IPT)

- "Inverted page table" is an array of page numbers sorted (indexed) by frame number.
  - A mapping from frame $\rightarrow$ page, or frame table.
- Algorithm
  - Compute hash of page number
  - Extract index from hash table
  - Use this to index into inverted page table
  - Match the PID and 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 $\Rightarrow$ page fault

Properties of IPTs

- IPT grows with size of RAM, NOT virtual address space.
- Frame table may be needed anyway (for page replacement, which we will explain later).
- Need a separate data structure for non-resident pages.
- Saves a vast amount of space (especially in the early days of 64-bit systems).
- Used in some IBM and HP workstations.

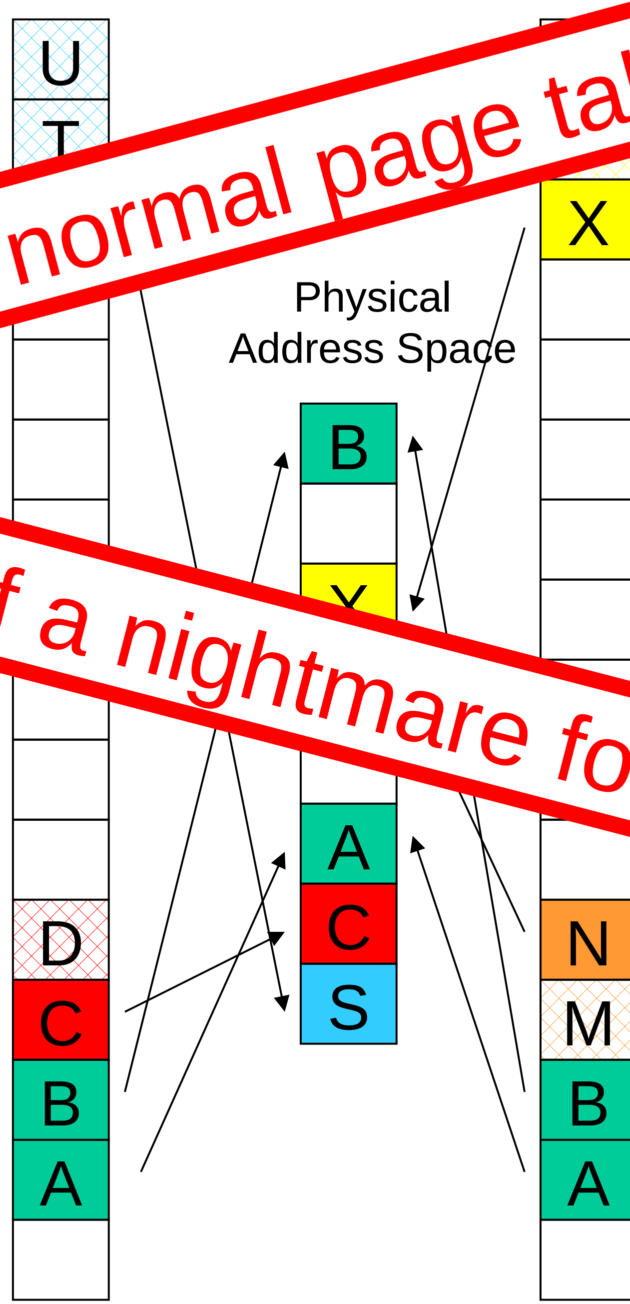
Given *n* processes

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

Another look at sharing…

Proc 1 Address Space

Proc 2 Address Space



‘easy’ for normal page tables

bit of a nightmare for IPT

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

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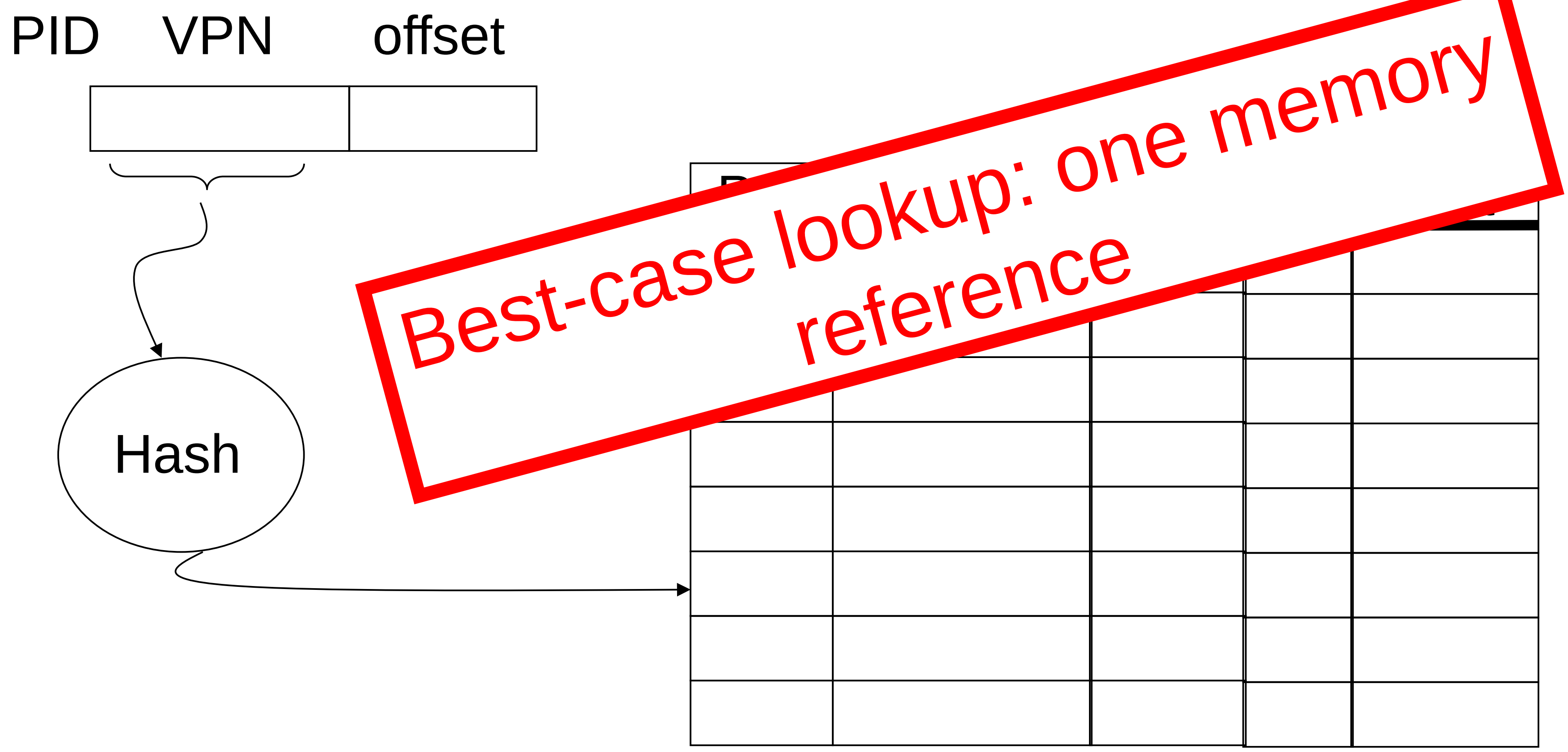
Improving the IPT: Hashed Page Table

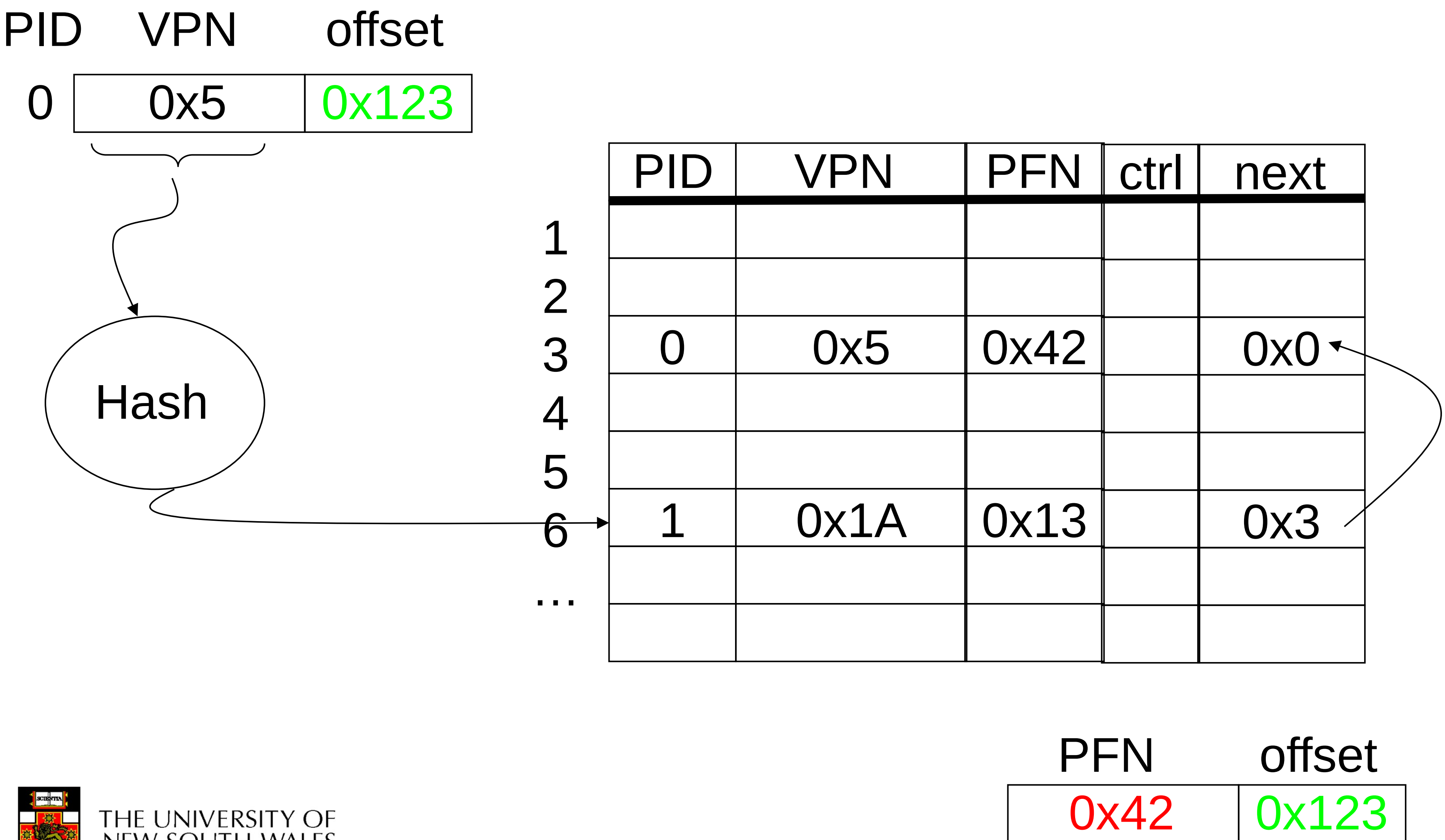
- Retain fast lookup of IPT
  - A single memory reference in best case
- Page table size now proportional to physical memory
  - As opposed to IPT exactly one-per-frame
  - Still scales with physical memory, not virtual
  - Enable efficient frame sharing
  - Support more than one mapping for same frame
- Key addition: adding frame number to HPT entry

Hashed Page Table

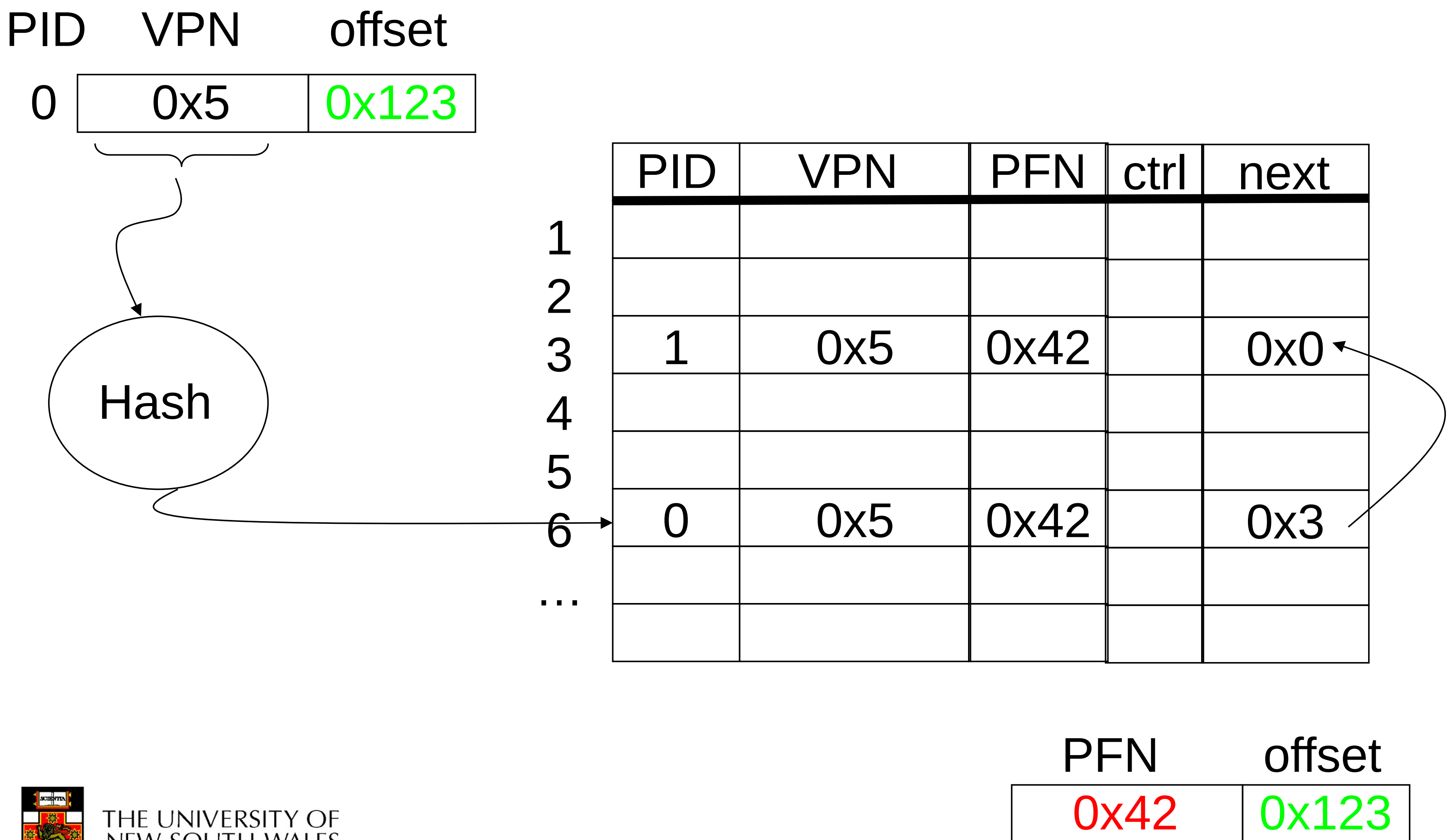


HPT: Frame number stored in table

Hashed Page Table



Sharing Example



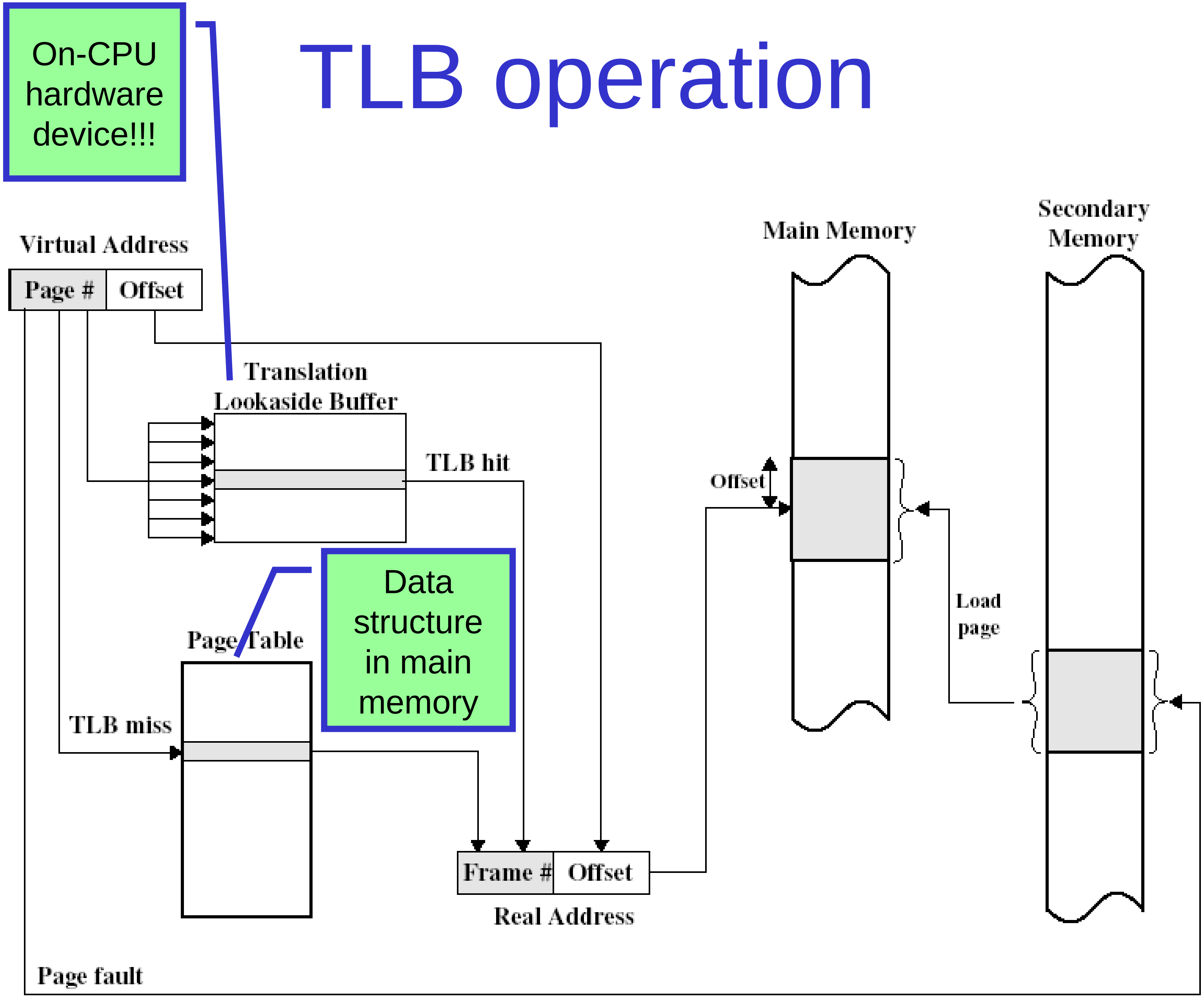
Sizing the Hashed Page Table

- HPT sized based on physical memory size
- With sharing
  - Each frame can have more than one PTE
  - More sharing increases number of slots used
    - Increases collision likelihood
- However, we can tune HPT size based on:
    - Physical memory size
    - Expected sharing
    - Hash collision avoidance.
  - HPT a power of 2 multiple of number of physical memory frame

VM Implementation Issue

- Performance?
  - Each virtual memory reference can cause multiple physical memory accesses
    - At least 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



Translation Lookaside Buffer

- Given a virtual address, CPU looks in the TLB
- If a matching entry is 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: x86, ARM
  - Software-loaded TLB
    - On miss, hardware generates a TLB miss exception, and exception handler reloads TLB
    - Example: MIPS, Itanium (optionally)
- TLB size: typically 64-128 entries
- May be separate TLBs for instructions and data
- TLBs can also be used with inverted page tables and other designs.

TLB and Context Switching

- TLB is a shared piece of hardware
- Normal 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
  - This is a crucial part of the job of the OS.

TLB effect

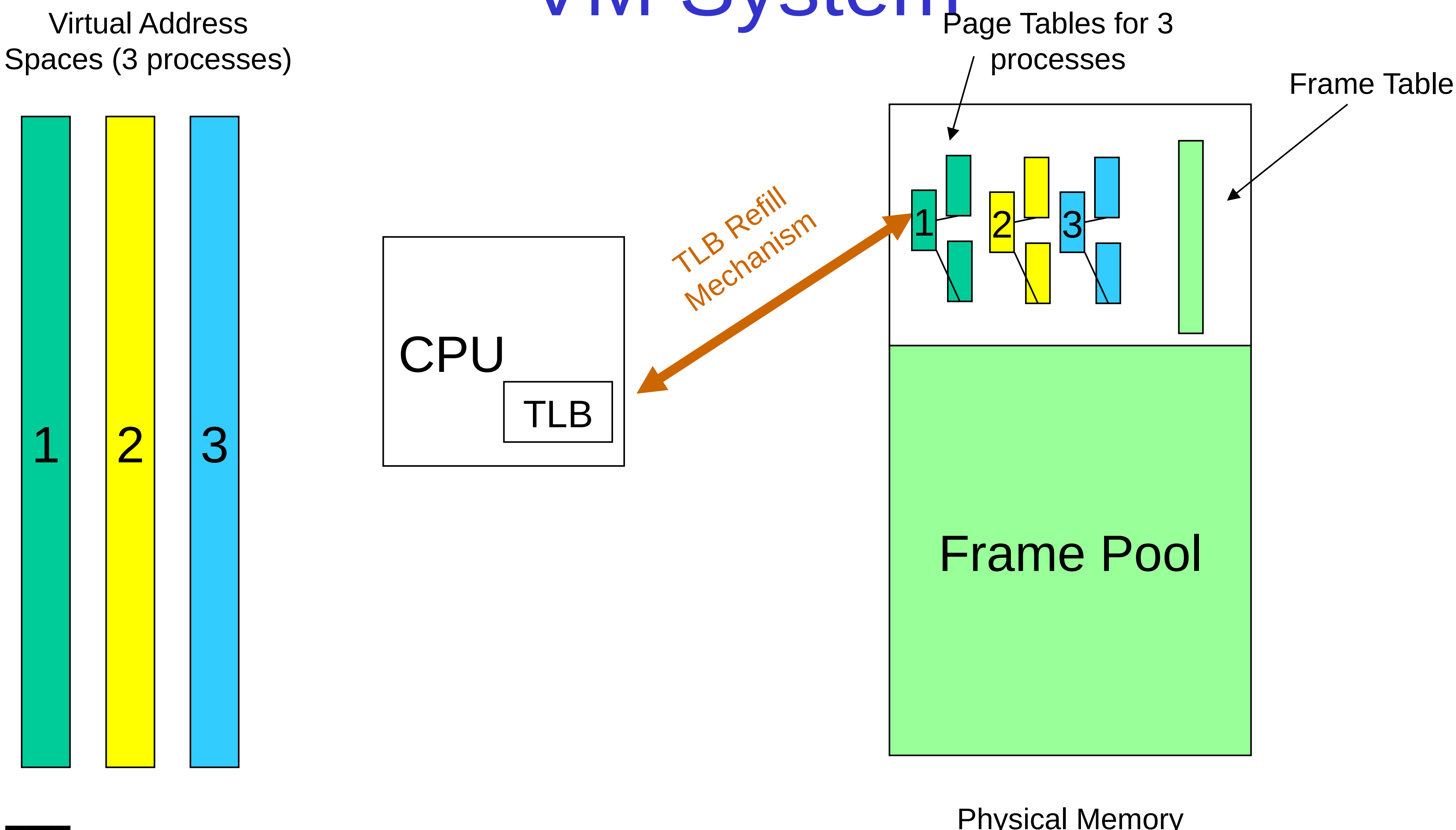
- Without TLB
  - Average number of physical memory references per virtual reference

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

    = .99 * 1 + 0.01 * 2

    = 1.01

Recap - Simplified Components of VM System



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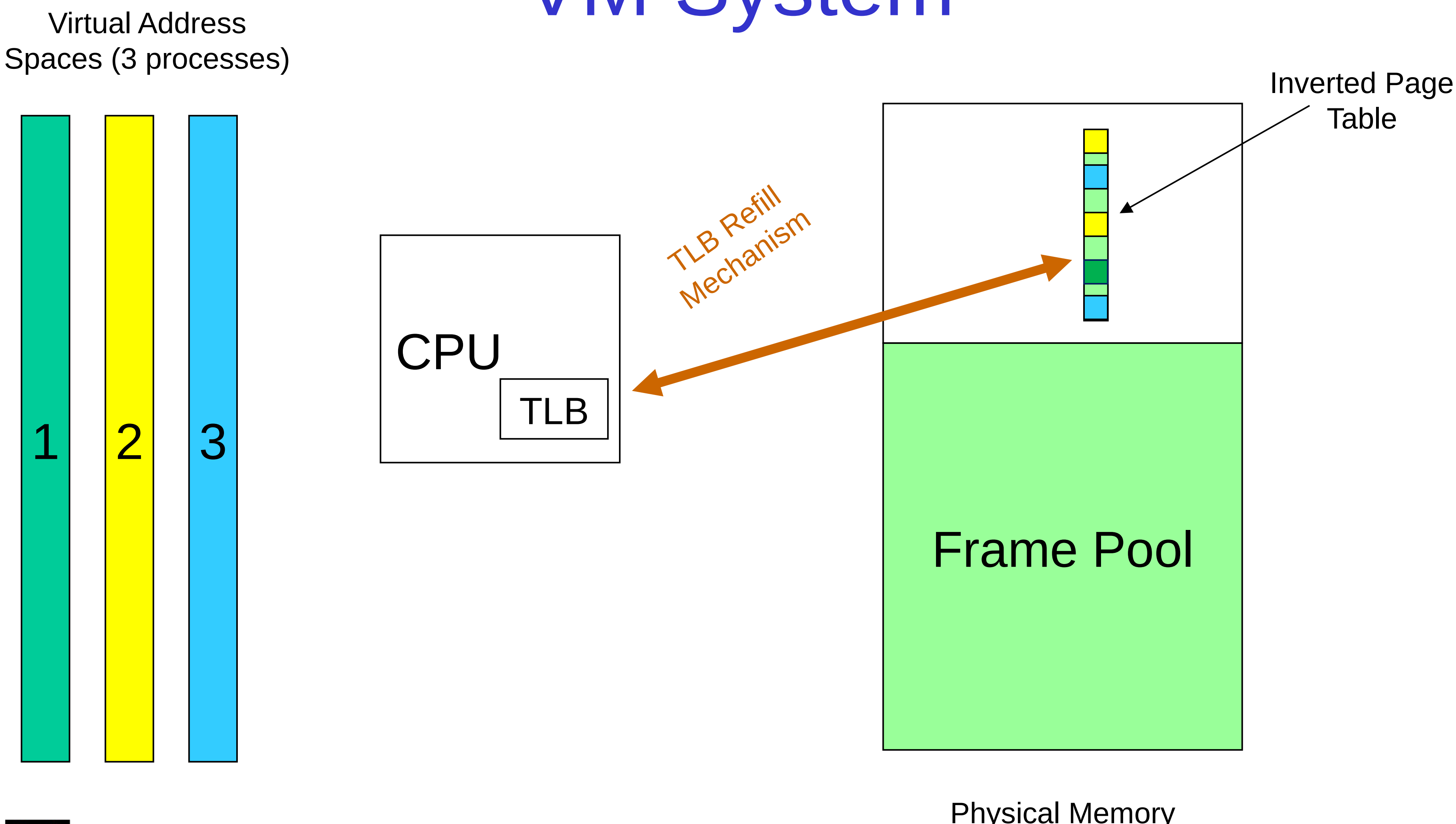

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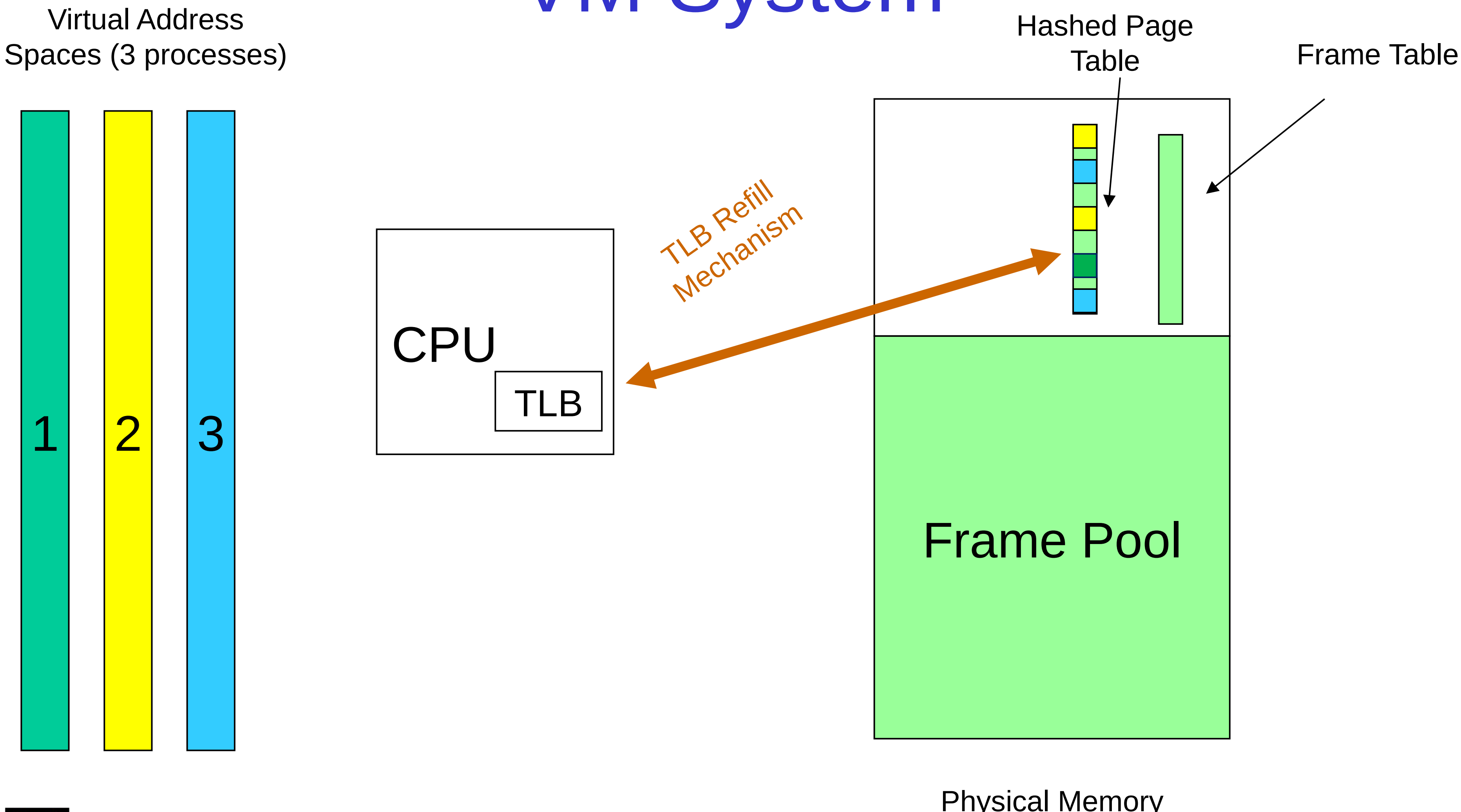
Recap - Simplified Components of VM System



MIPS R3000 TLB

31 ... 12	11 ... 6	5 ... 0
VPN	ASID	0

EntryHi Register (TLB key fields)

Figure 6.1. EntryHi and EntryLo register fields

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

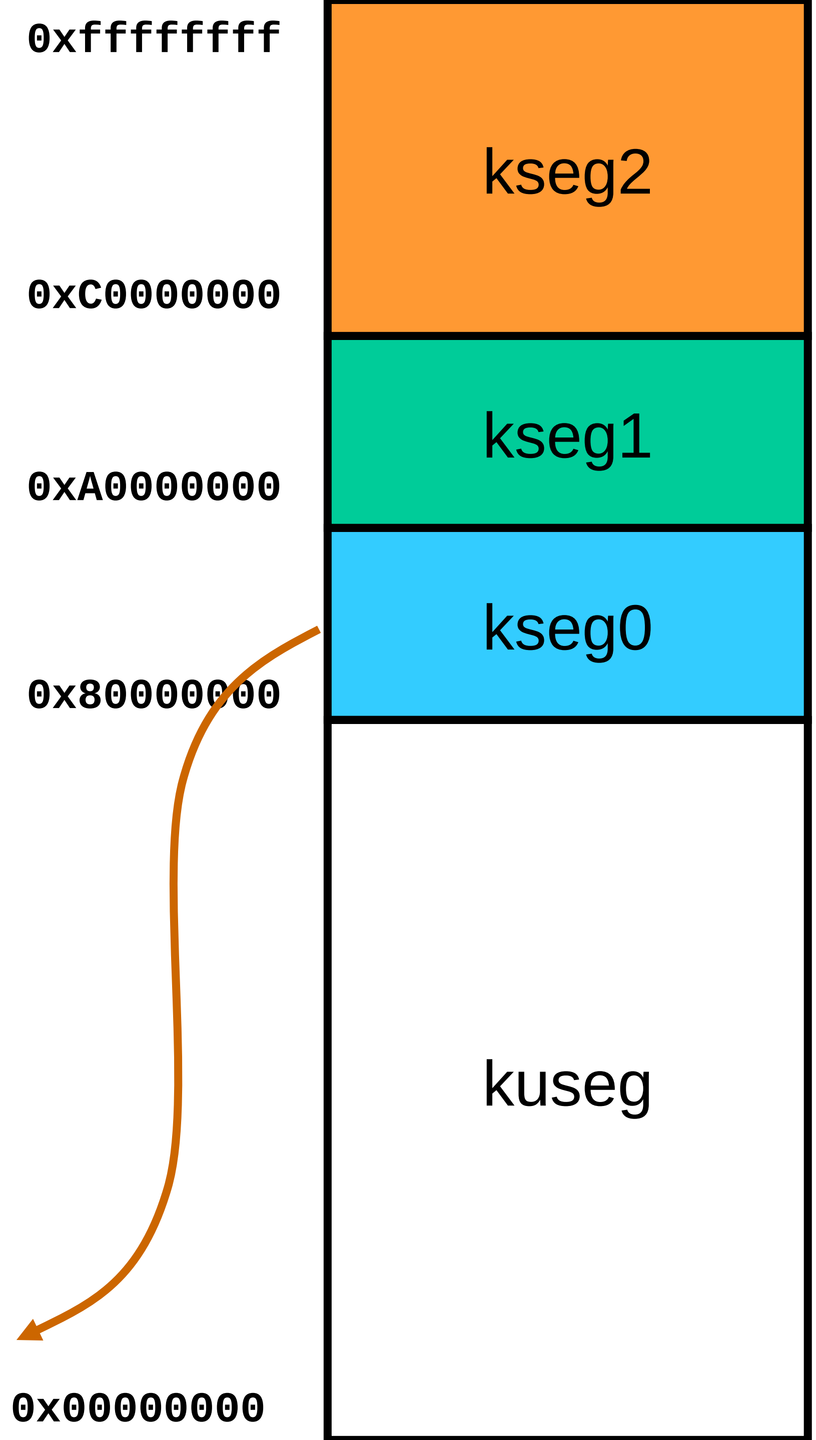
EntryLo Register (TLB data fields)

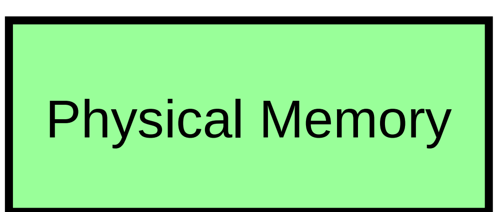
Figure 6.2. EntryHi and EntryLo register fields

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

R3000 Address Space Layout

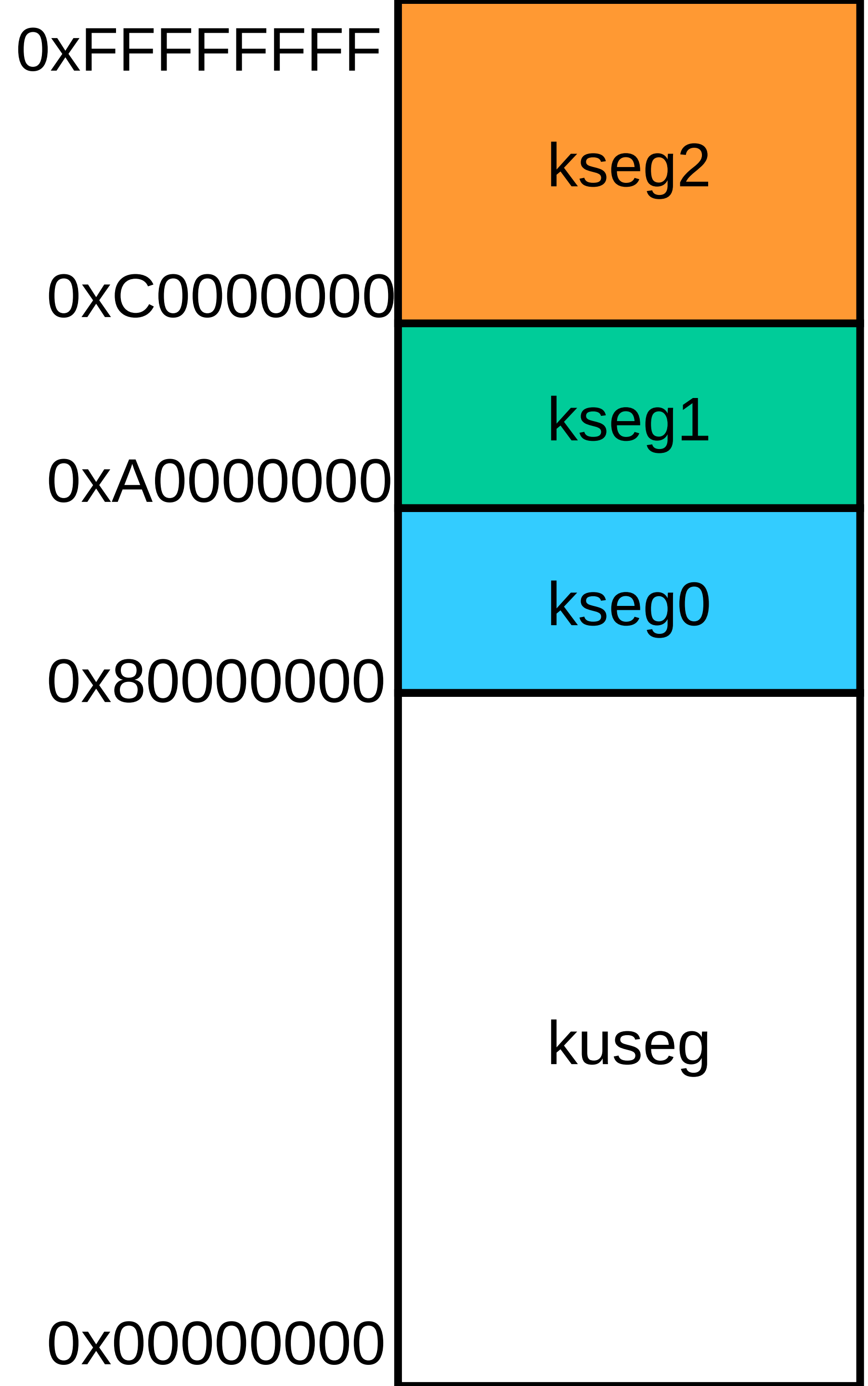
- kseg0:
  - 512 megabytes
  - Fixed translation window to physical memory
    - 0x80000000 - 0x9fffffff virtual = 0x00000000 - 0x1fffffff physical
    - TLB not used
  - Cacheable
  - Only privileged-mode accessible
  - Usually where the kernel code and data is accessed





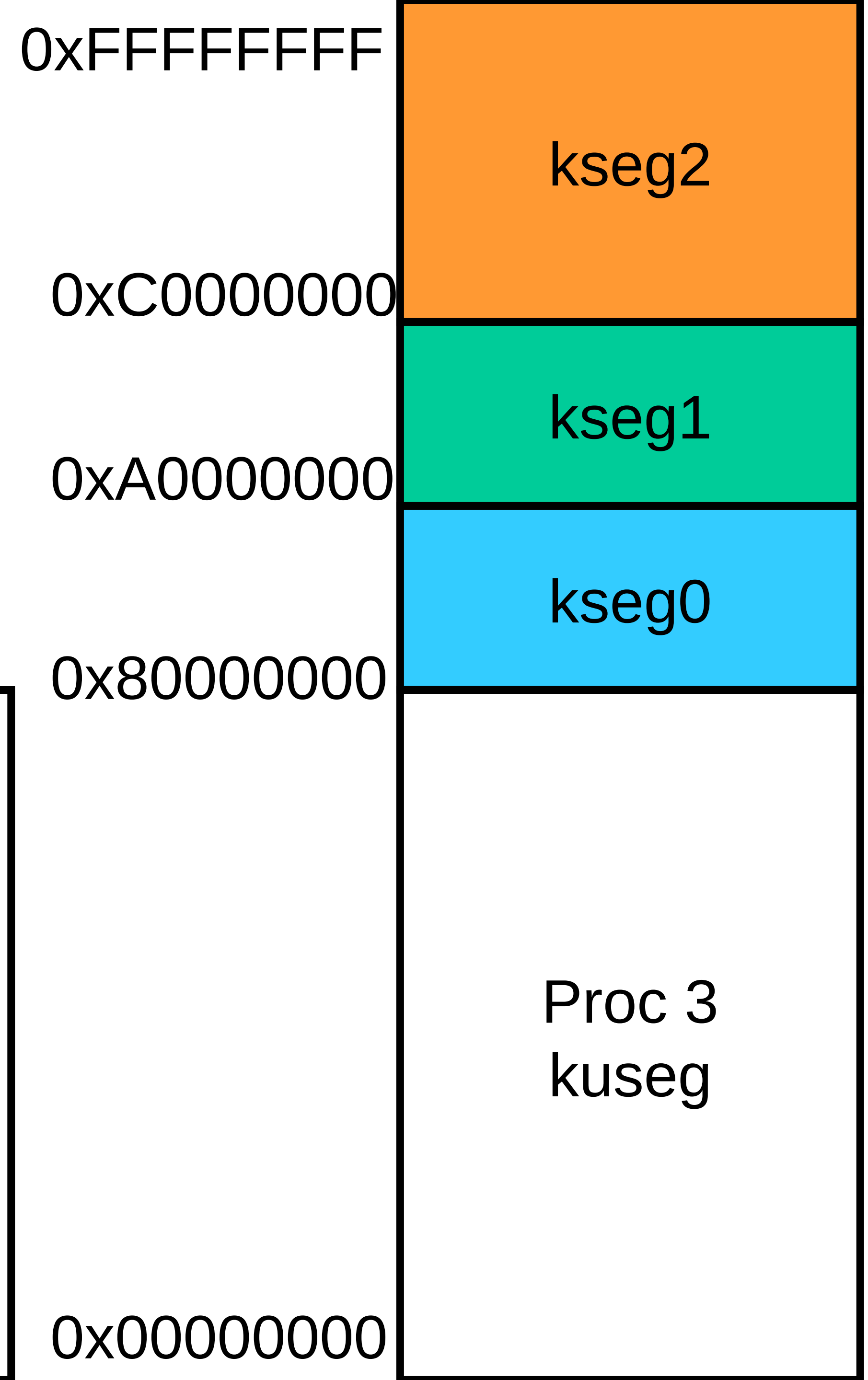
R3000 Address Space Layout

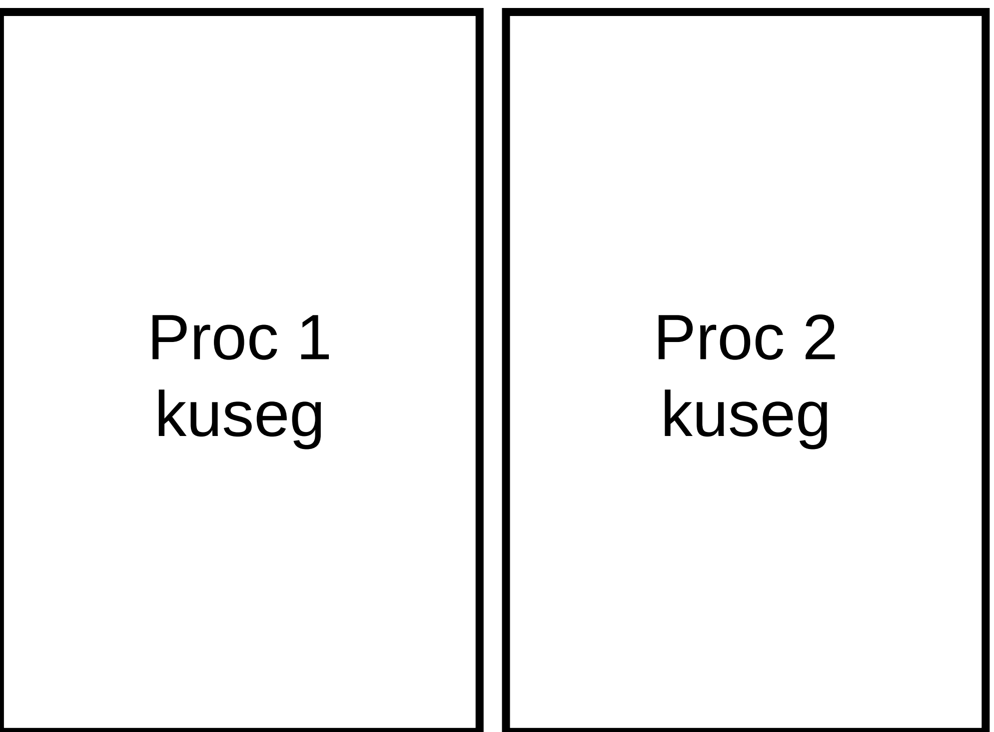
- kuseg:
  - 2 gigabytes
  - TLB translated (mapped)
  - Cacheable (depending on ‘N’ bit)
  - Both user-mode and kernel mode accessible
  - Page size is 4K



R3000 Address Space Layout

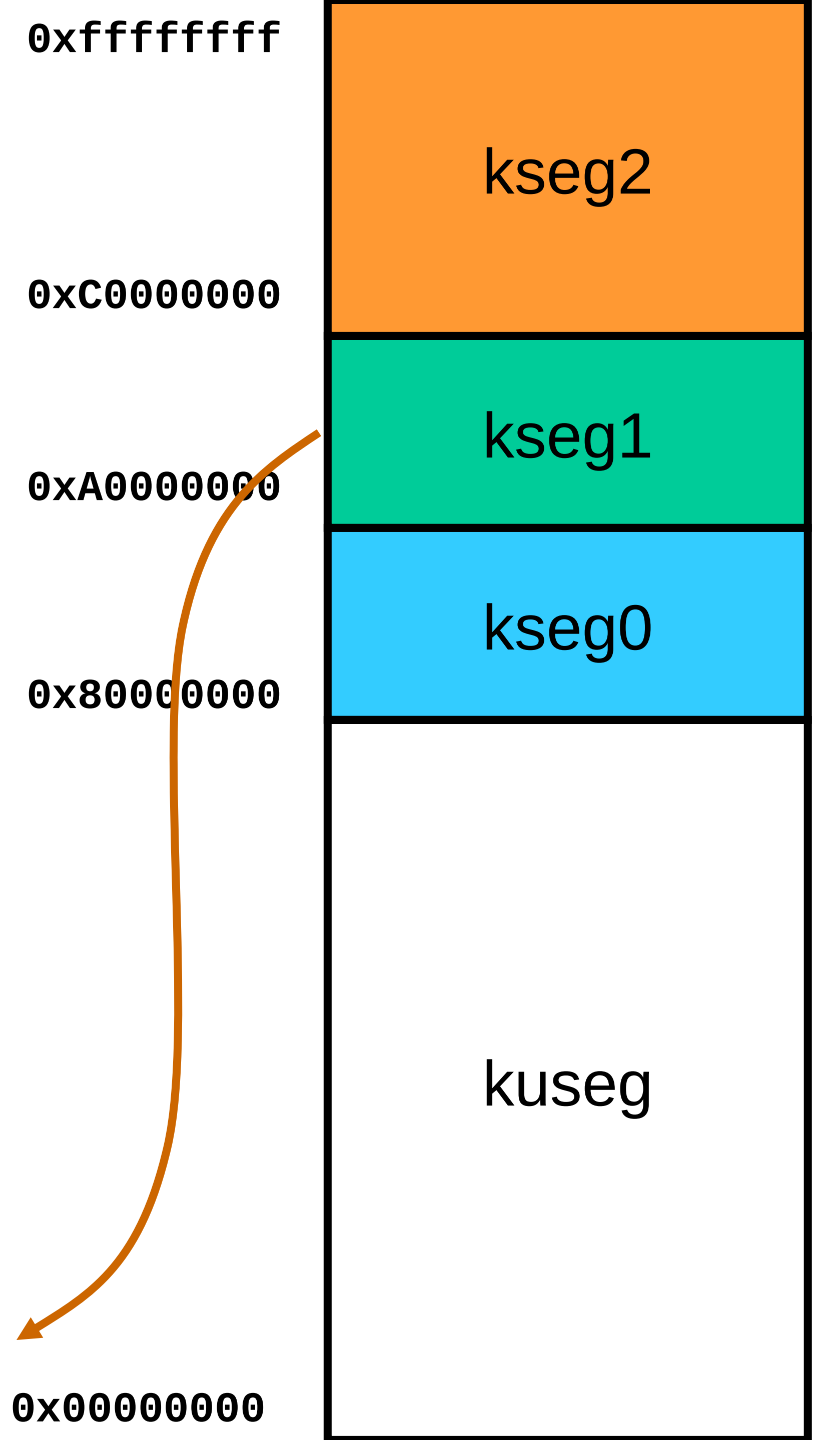
- Switching processes switches the translation (page table) for kuseg

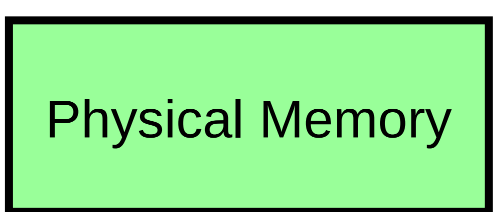




R3000 Address Space Layout

- 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)





This Lecture

- Page-based VM apparatus
- Additional uses of paging
  - Swapping
  - Sharing
- Page tables
  - Two-level and multi-level
  - Inverted and Hash PTs
- The TLB
- MIPS R3000 Address-Space Layout