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Memory Management

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Basic Concepts
- Memory Allocation
- Swapping

Virtual Memory

Paging & Segmentation
- Demand Paging
- Page replacement algorithms
- Working set model

Linux Memory Management

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Memory Hierarchy

Hardware: CPU registers and main memory

- Register access in one CPU clock cycle (or less)
- Main memory can take many cycles
- Caches sit between main memory and CPU registers

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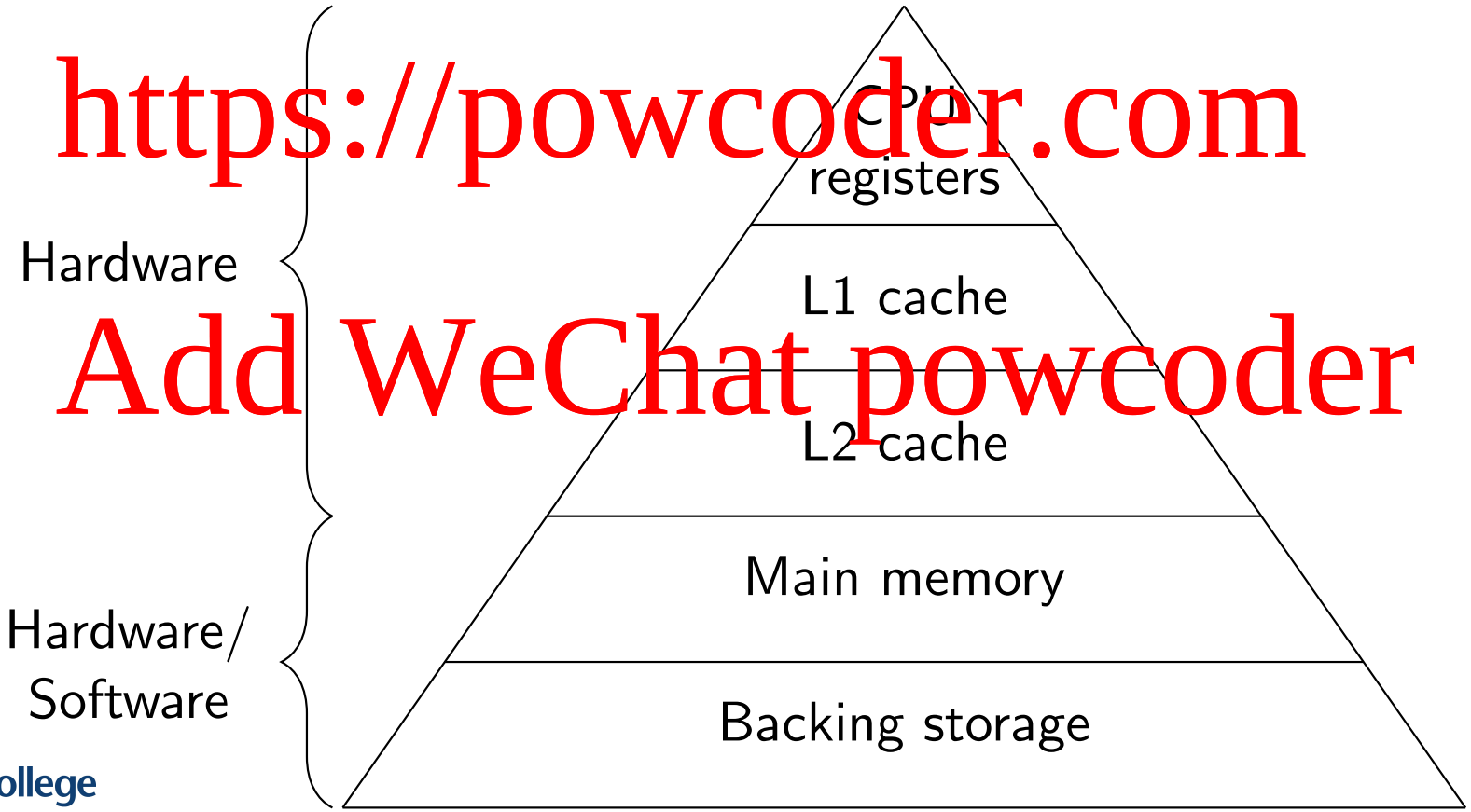

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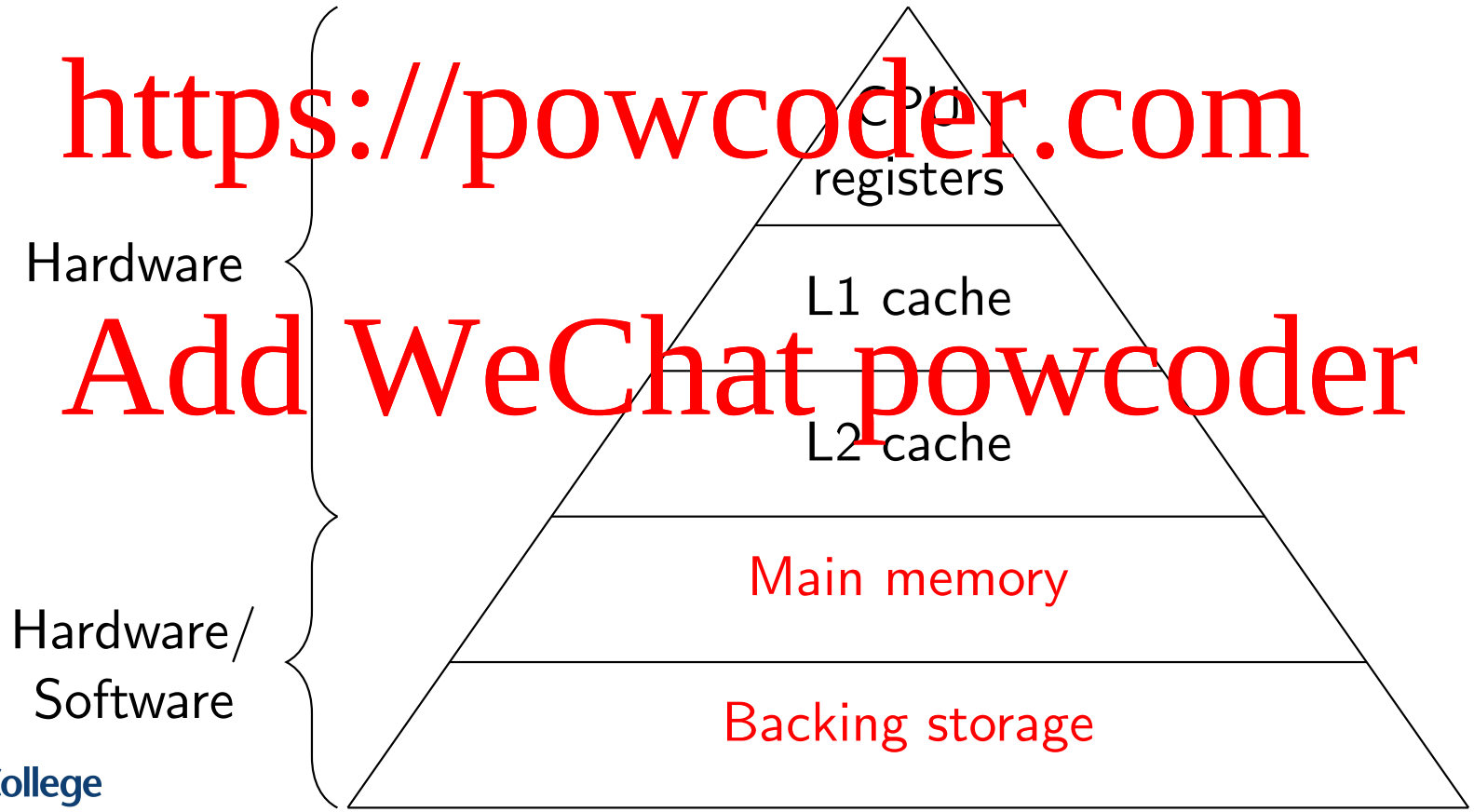

Memory Management

Memory is a key component of the computer

- e.g. every instruction cycle involves memory access ⇒ process has to be loaded into memory before it can execute

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Memory management needs to provide

- Memory allocation
- Memory protection

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Characteristics

- No knowledge of how memory addresses are generated
  - e.g. instruction counter, indexing, indirection, ...
- No knowledge what memory addresses are used for
  - e.g. instructions or data
- True for simple case but may want protection with respect to read, write, execute, etc.

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Logical vs. Physical Address Space

Memory management binds logical address space to physical address space

Logical address

- Generated by the CPU
- Address space seen by the process

Physical address

- Address seen by the memory unit
- Refers to physical system memory

Logical and physical addresses

- Same in compile- and load-time address-binding schemes
- Different in execution-time address-binding schemes

How do you achieve this mapping?

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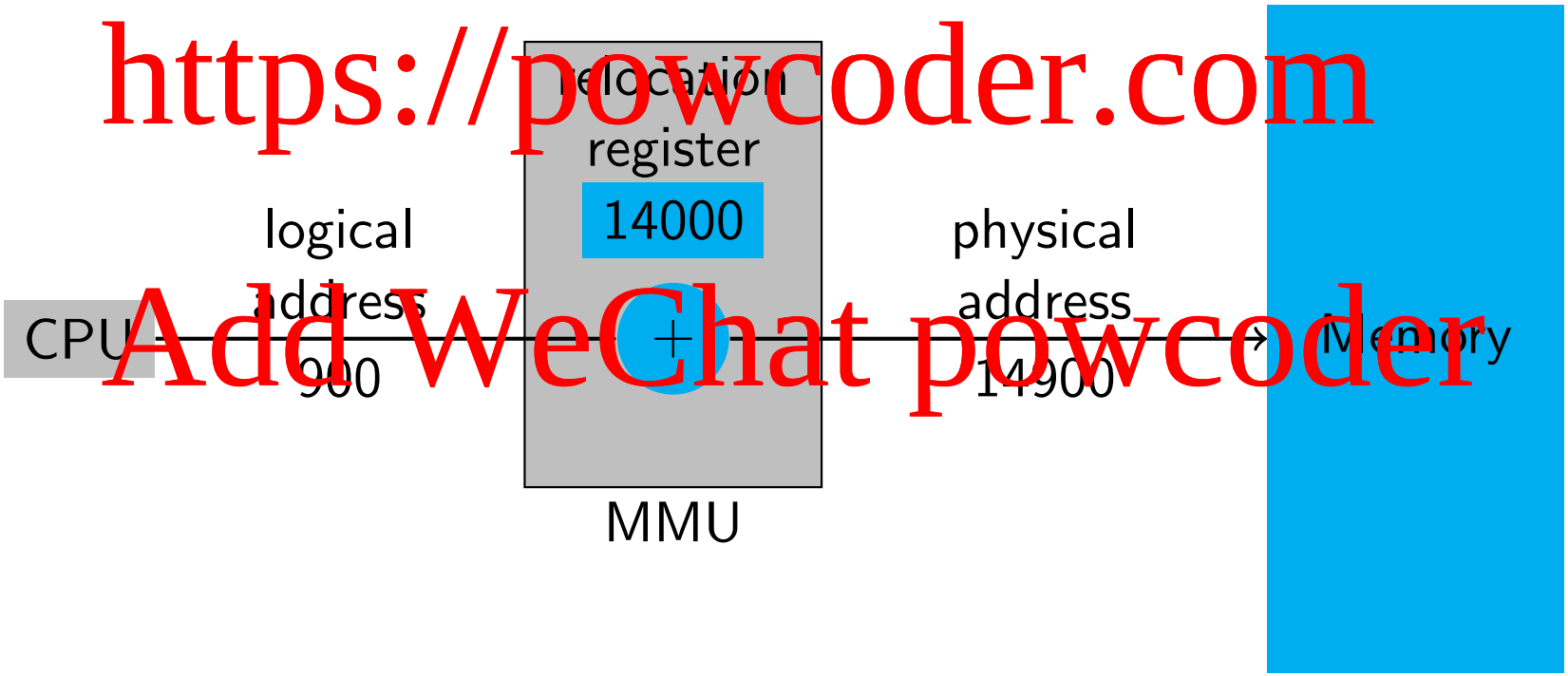
Memory-Management Unit (MMU)

Hardware device for mapping logical to physical addresses

- e.g. add value in relocation register to every address generated by process when sent to memory
- User process deals with logical addresses only
- Has to be fast → implemented in hardware



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Memory Allocation

Main memory is usually split into two partitions:

- Resident operating system (**kernel**)
  - Usually held in low memory with interrupt vector
- User processes (**user**)
  - Held in high memory

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How do you decide where to load a new process?

Need to figure out the strategy for process to be loaded into the correct location

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Contiguous Memory Allocation I

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Contiguous allocation with relocation registers

- base register contains physical start address for process
- limit register contains maximum logical address for process
- MMU maps logical address dynamically
  - Physical address = logical address + base
  - If logical address > limit then error

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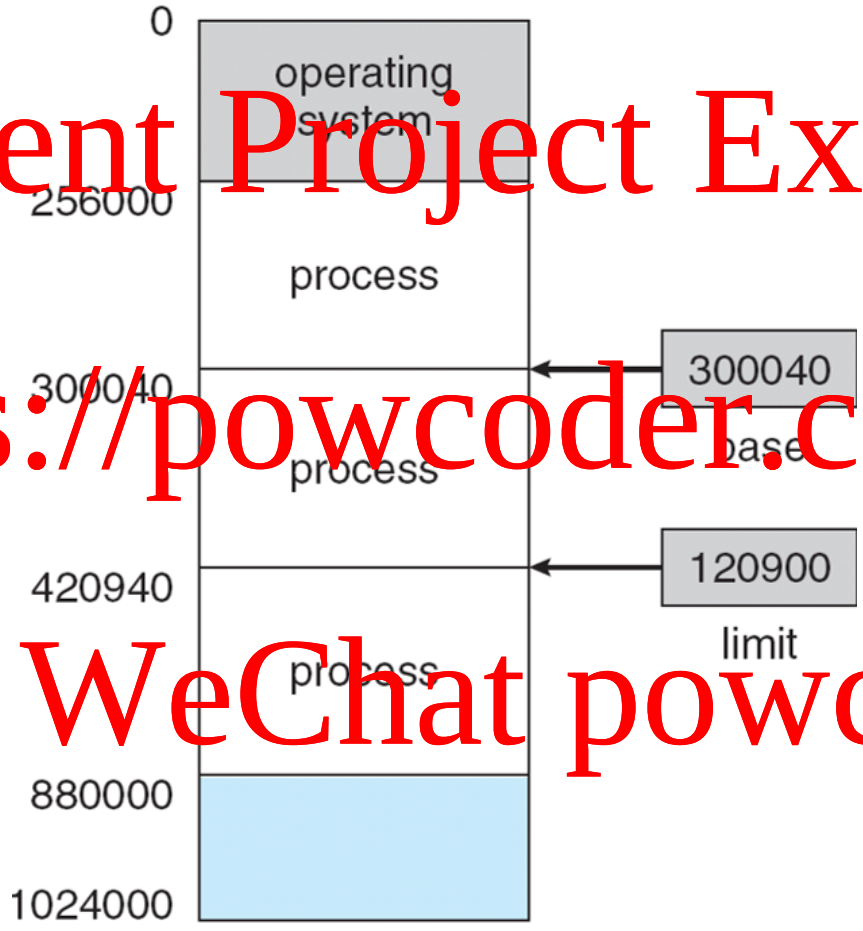
Contiguous Memory Allocation II

base and limit register define logical address space



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e.g jmp 100 in program would go to physical location 300140

Multiple-Partition Allocation

Hole

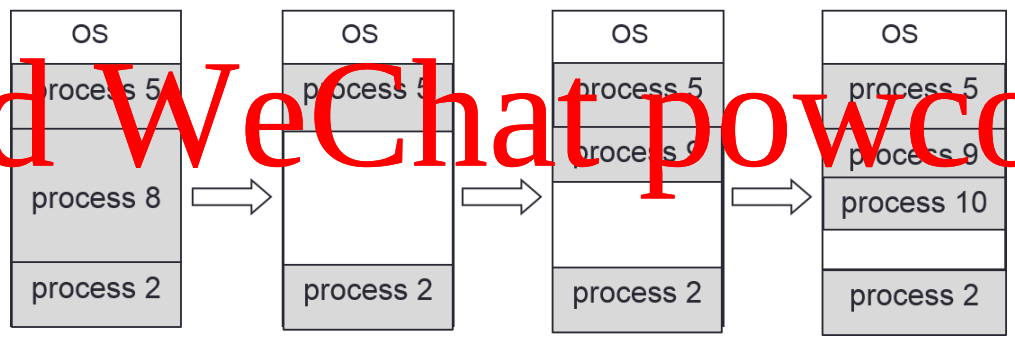
- Block of available memory
- Holes of various size scattered throughout memory

When new process arrives:

- allocate memory from hole large enough

OS maintains information about:

- Allocated partitions
- Free partitions (holes)



What is the best algorithm for allocation?

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Dynamic Memory Allocation

First-fit → Allocate first hole that is big enough

Best-fit → Allocate smallest hole that is big enough

- Must search entire list, unless ordered by size
- Produces smallest leftover hole

Worst-fit → Allocate largest hole

- Must also search entire list
- Produces largest leftover hole

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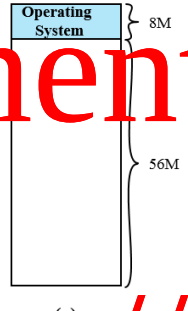
Why best-fit or worst-fit?

First-fit and best-fit better than worst-fit in terms of speed and storage utilisation

Fragmentation

External fragmentation → memory exists to satisfy request, but not contiguous



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Reduce external fragmentation by compaction

- Shuffle memory contents to place all free memory together in one large block → leads to I/O bottlenecks

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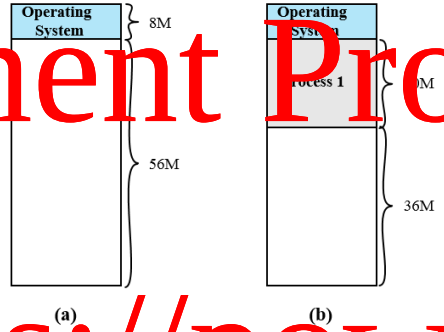

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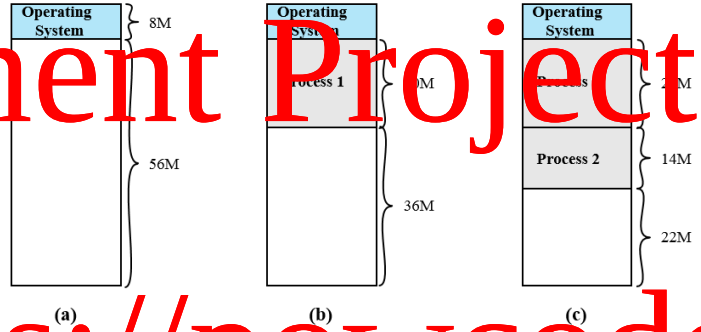

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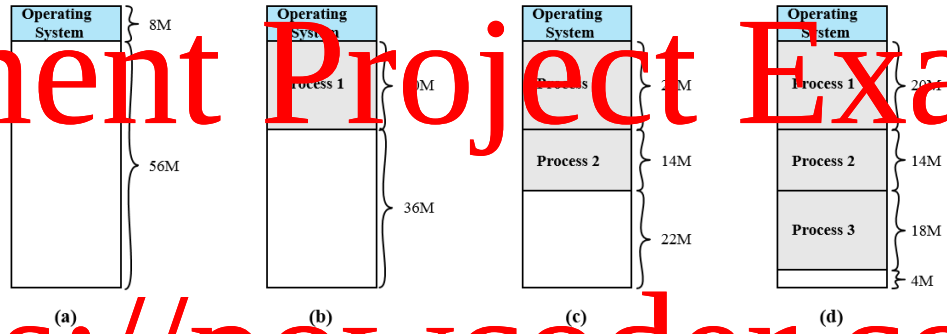

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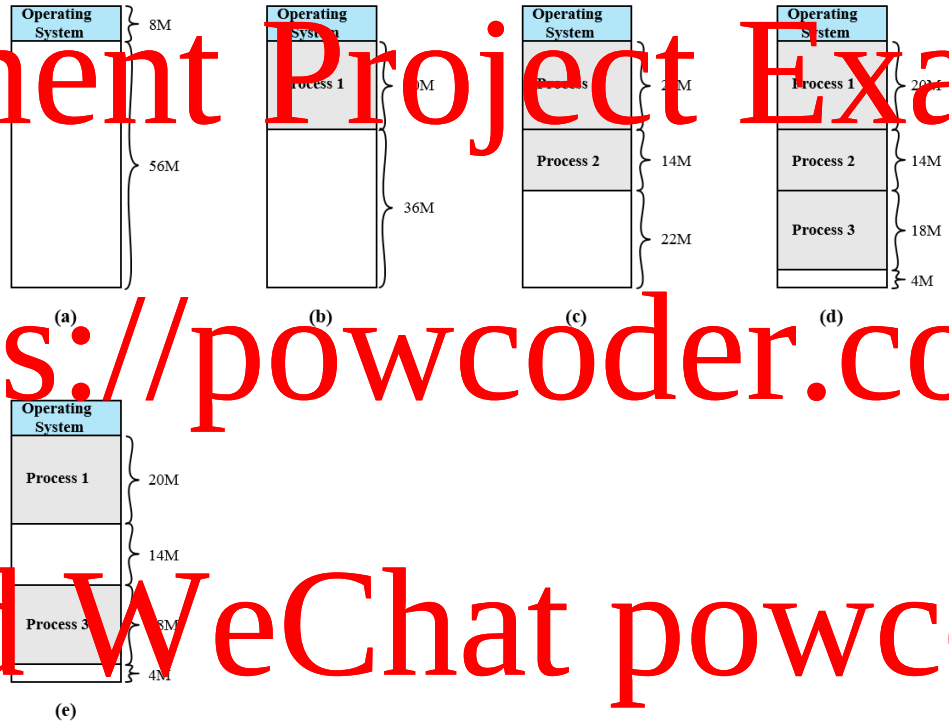

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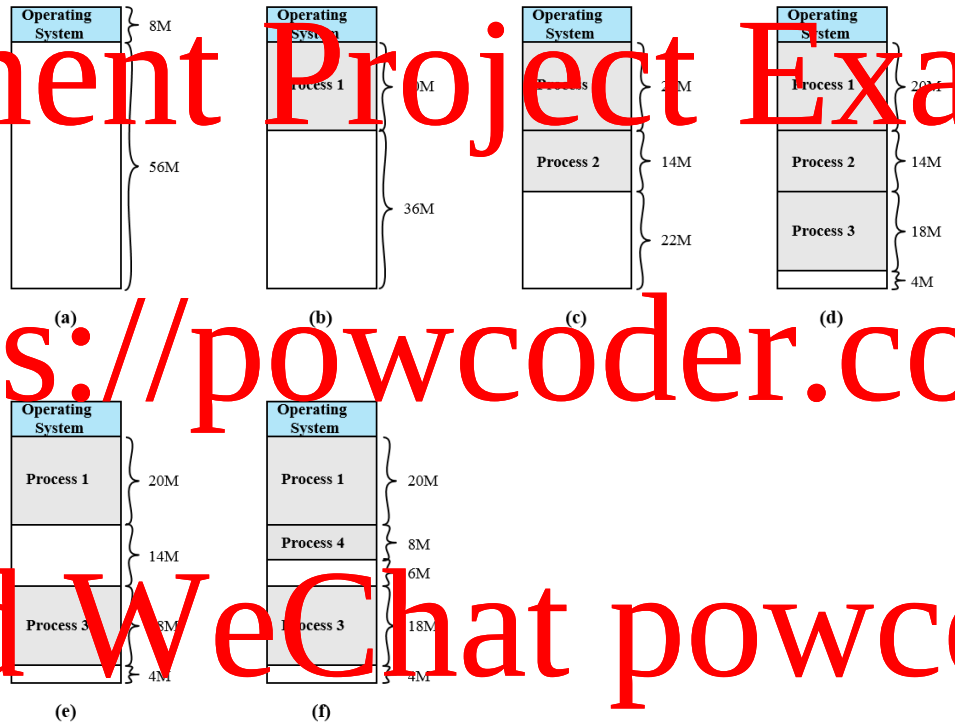

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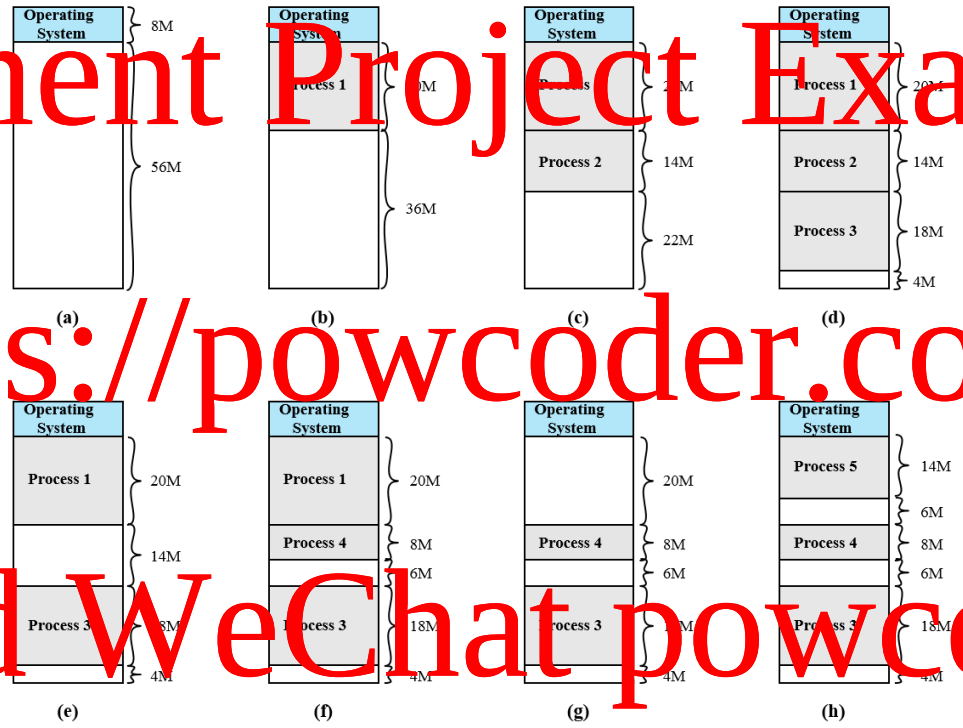

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Reduce external fragmentation by compaction

- Shuffle memory contents to place all free memory together in one large block → leads to I/O bottlenecks

Swapping

Problem: Number of processes limited by amount of available memory

- But ... only running processes need to be in memory

Solution:

- **Swap** processes temporarily out of memory to backing store
- Bring back into memory for continued execution
- Requires swap space → can be file or dedicated partition on disk
- Transfer time is major part of swap time

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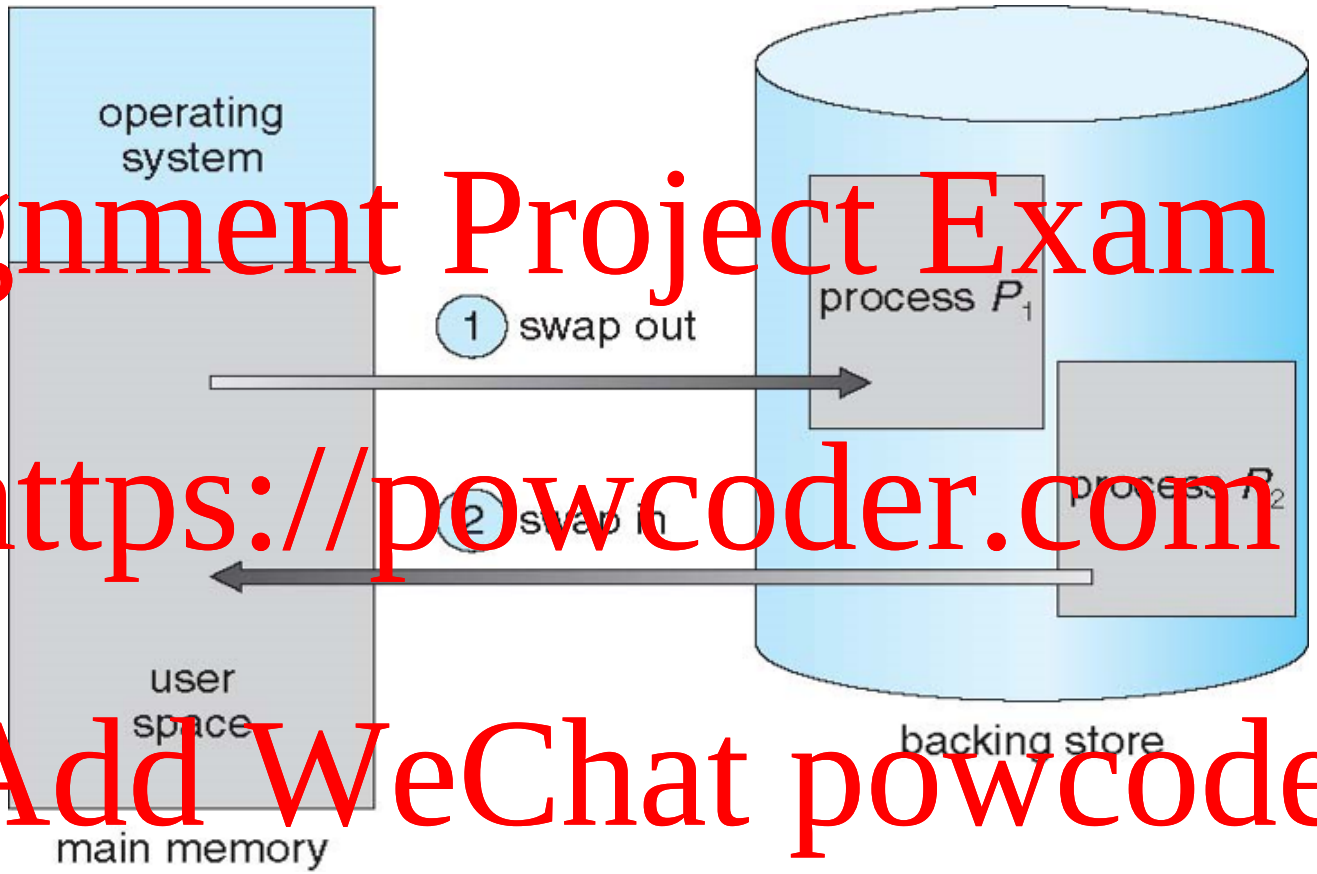
Swapping



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What if a process is "too large" to fit into memory ⇒ can only part of a process exist in memory?

Virtual Memory

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- Separation of user logical memory from physical memory
  - Only part of process needs to be in memory for execution
  - Logical address space can be much larger than physical address space
  - Address spaces can be shared by several processes
  - Allows for more efficient process creation

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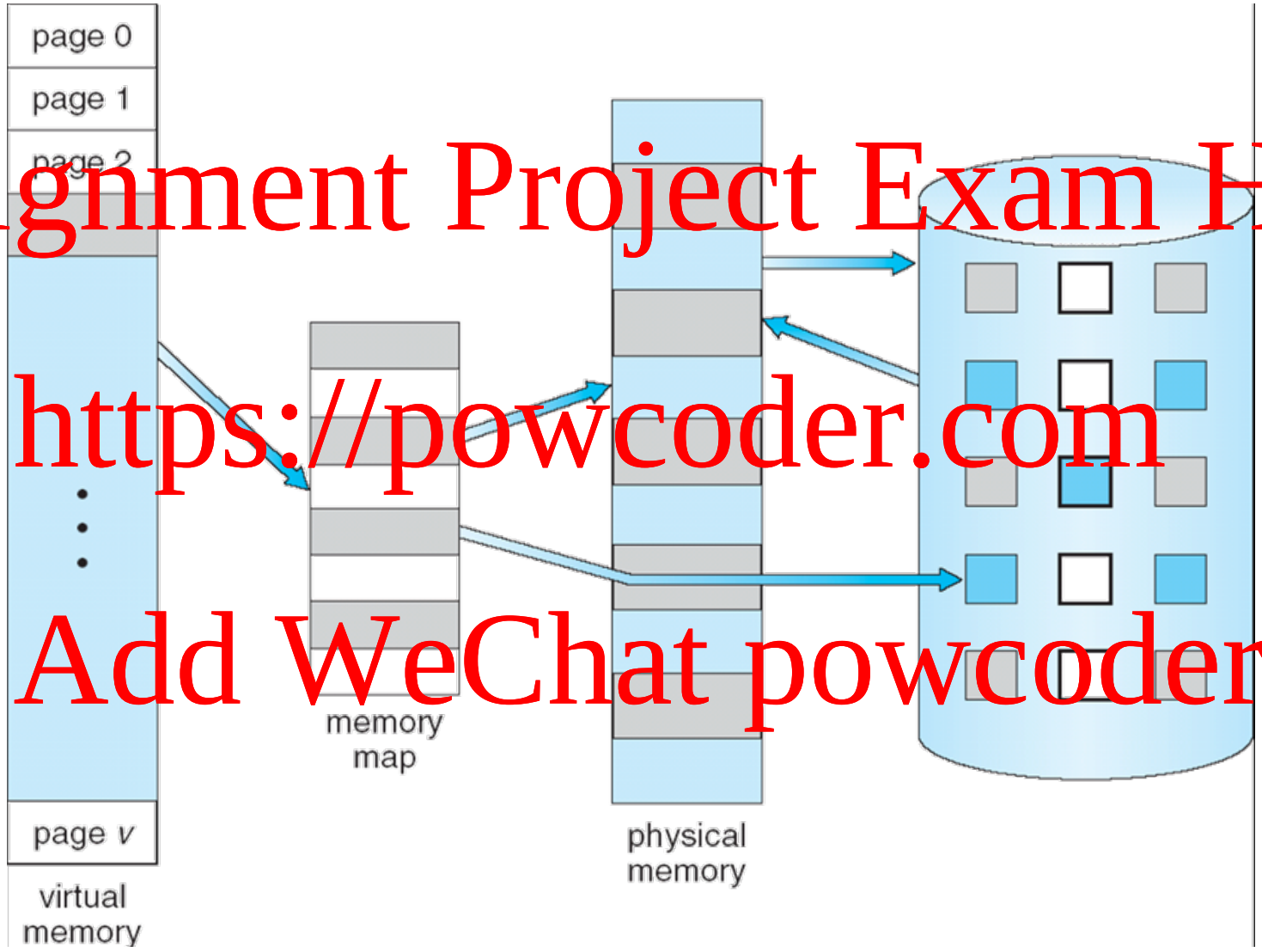
Virtual Memory



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Virtual memory can be implemented via

- Paging
- Segmentation

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Paging

Physical address space of process can be noncontiguous

- Process allocated physical memory when available
  - Avoid external fragmentation
  - Avoid problems of variable sized memory chunks

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Frames

- Fixed-sized blocks of physical memory
- Keep track of all free frames

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Pages

- Block of same size (as frame) of logical memory

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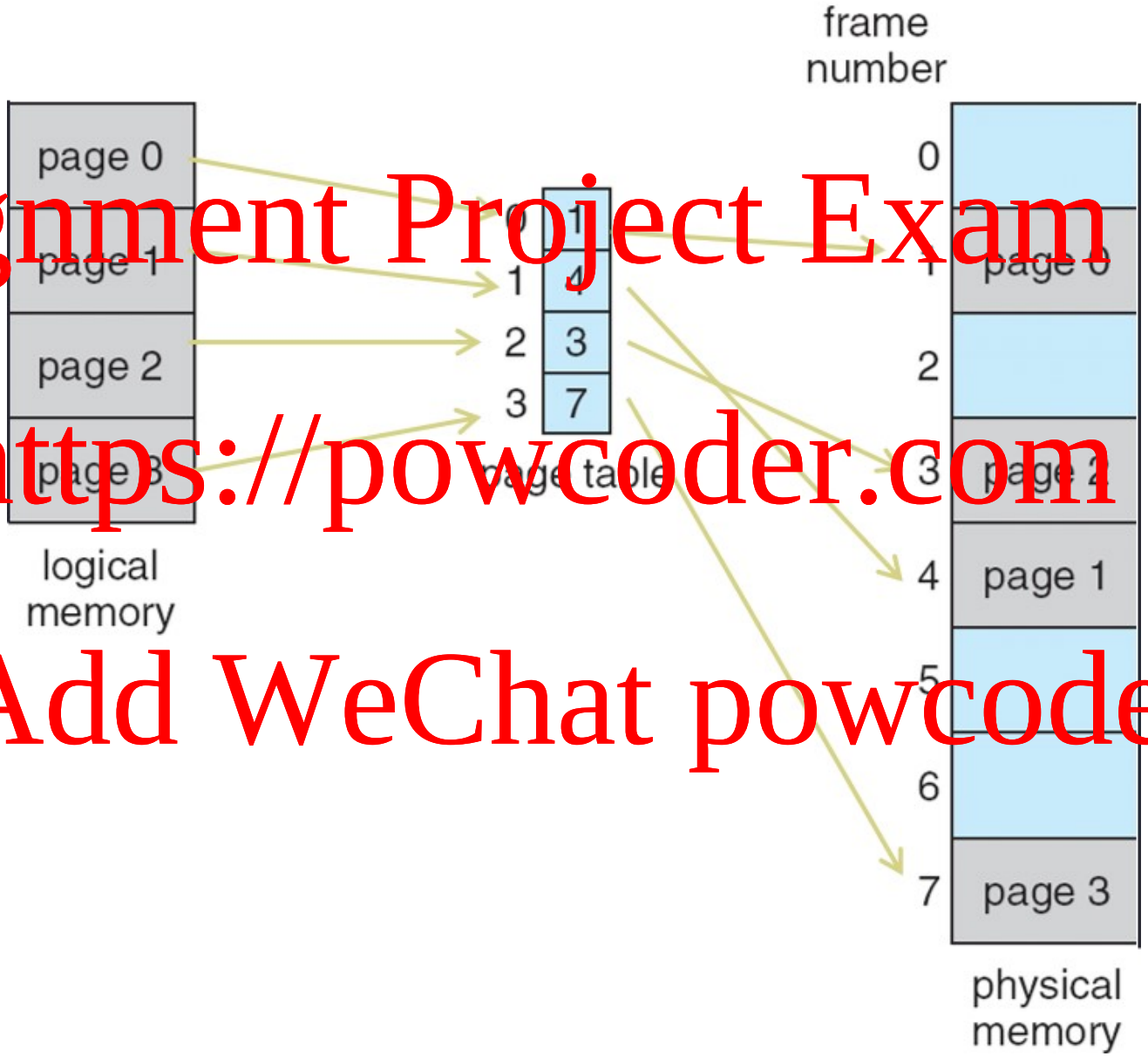
To run program of size *n* pages

- Find *n* free frames and load program
- Set up **page table** to translate logical into physical addresses

Page Table Example



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Address Translation I

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How does logical address translate to physical address?

Hint: pages and frames are the same size $\Rightarrow$ address offset in the page will be the **same** as that in the frame

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Address now consists of two parts: **page number** and **page offset**

- only need to translate page number into its corresponding frame address

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Address Translation II

How do you calculate the page number?

Depends on address size and page/frame size

e.g. Consider a page/frame size of 64 bytes

- 64 bytes can be addressed $\Rightarrow$ total of 64 addresses
- Number of bits required for 64 addresses = 6 ($2^6 = 64$)

For a 10-bit **virtual** address we have:

- page offset requires 6 bits (based on above)
- page number has 4 bits (remaining bits) $\Rightarrow$ between 0 ... 15

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Address Translation III

Page number (p)

- Used as an index into page table
- Page table has base address of pages in physical memory

Page offset (d)

- Defines physical memory address sent to the memory unit
- Combined with base address

For given address size of m-bits and page size of 2^n

page number	page offset
p	d
(m – n) bits	n bits

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Paging Hardware

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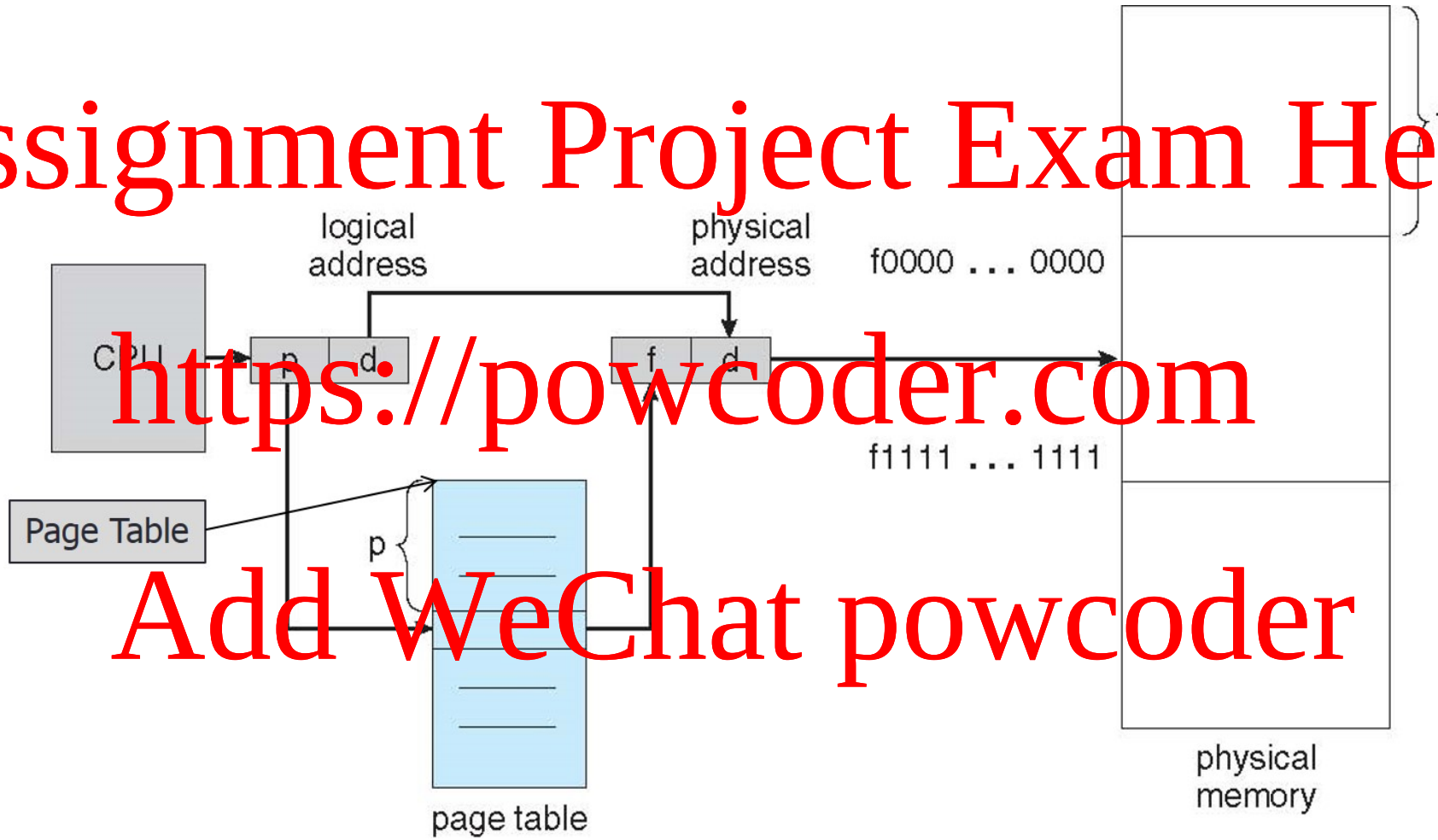
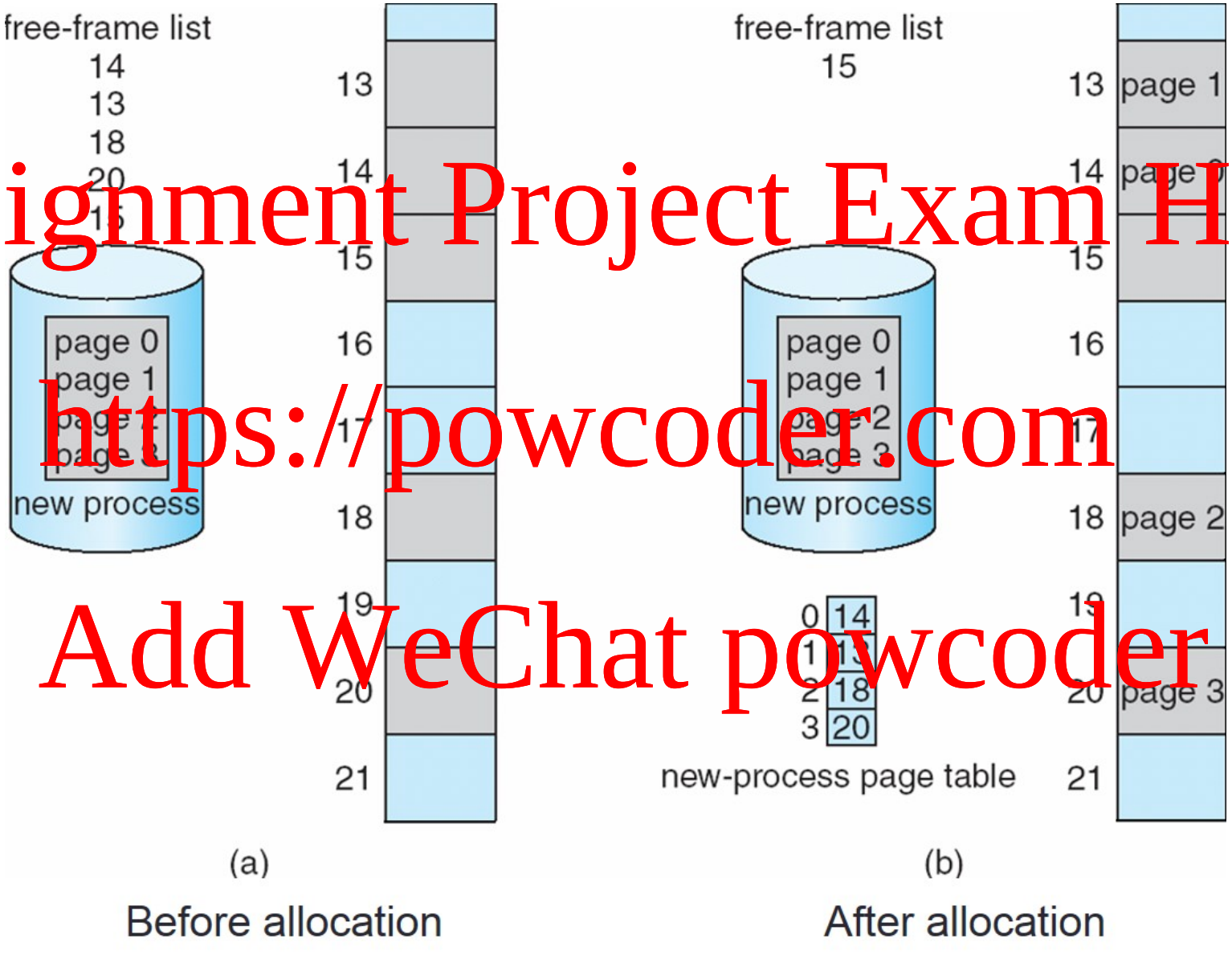


Free Frames



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Example Problem

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Address Translation

Consider a 32-bit virtual memory address and a page size of 1 KB.
How many pages can a process potentially have?

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Example Problem

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Address Translation

Consider a 32-bit virtual memory address and a page size of 1 KB. How many pages can a process potentially have?

1 KB page size = 1024 bytes $\Rightarrow$ total of 1024 addresses
Number of bits needed for 1024 address = 10 ($2^{10} = 1024$)

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Example Problem

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1 KB page size = 1024 bytes $\Rightarrow$ total of 1024 addresses
Number of bits needed for 1024 address = 10 ($2^{10} = 1024$)

For a 32-bit address you have:

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- page offset requires 10 bits
- page number has 22 bits $\Rightarrow 2^{22}$ (4194304) potential pages

Fragmentation

Internal fragmentation → Allocated memory is larger than requested memory, but size difference internal to partition

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Example - Calculating Internal Fragmentation

Page size = 2048 bytes; Process size = 72,766 bytes

Number of pages = $\frac{72766}{2048} = 35$

Bytes left-over = 72766 % 2048 = 1086

Internal fragmentation = 2048 – 1086 = 962 bytes

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Worst-case fragmentation ⇒ 1 frame = 1 byte

Average-case fragmentation ⇒ $\frac{1}{2}$ frame size

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Are small frames desirable?

- Each page table entry takes memory to track
- Page size growing over time → typically 4 KB but some architectures support variable page sizes up to 256 MB

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Page Table Implementation

Page table kept in main memory

- Page-table base register (PTBR) points to page table
  - Context switch requires update of PTBR for new process page table (if necessary)
- Page-table length register (PTLR) indicates size

Problem

- Inefficient as every data/instruction access requires two memory accesses → one for page table and one for data/instruction

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Associative Memory

Solution: use special fast-lookup hardware cache as associative memory

Associative memory → supports parallel search

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- Called **Translation Look-aside Buffer (TLB)**

Page #	Frame #
1	4
3	74
9	50
7	7

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- Address translation (p, d)
  - If p in associative register, get frame # out
  - Otherwise, get frame # from page table in memory

Translation Look-aside Buffers (TLBs) I

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- TLBs usually needs to be flushed after context switch
  - Can lead to substantial overhead
  - What about kernel pages for system calls?

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Some TLBs store address-space ids (ASIDs) in entries

- Uniquely identifies each process to provide address-space protection for that process

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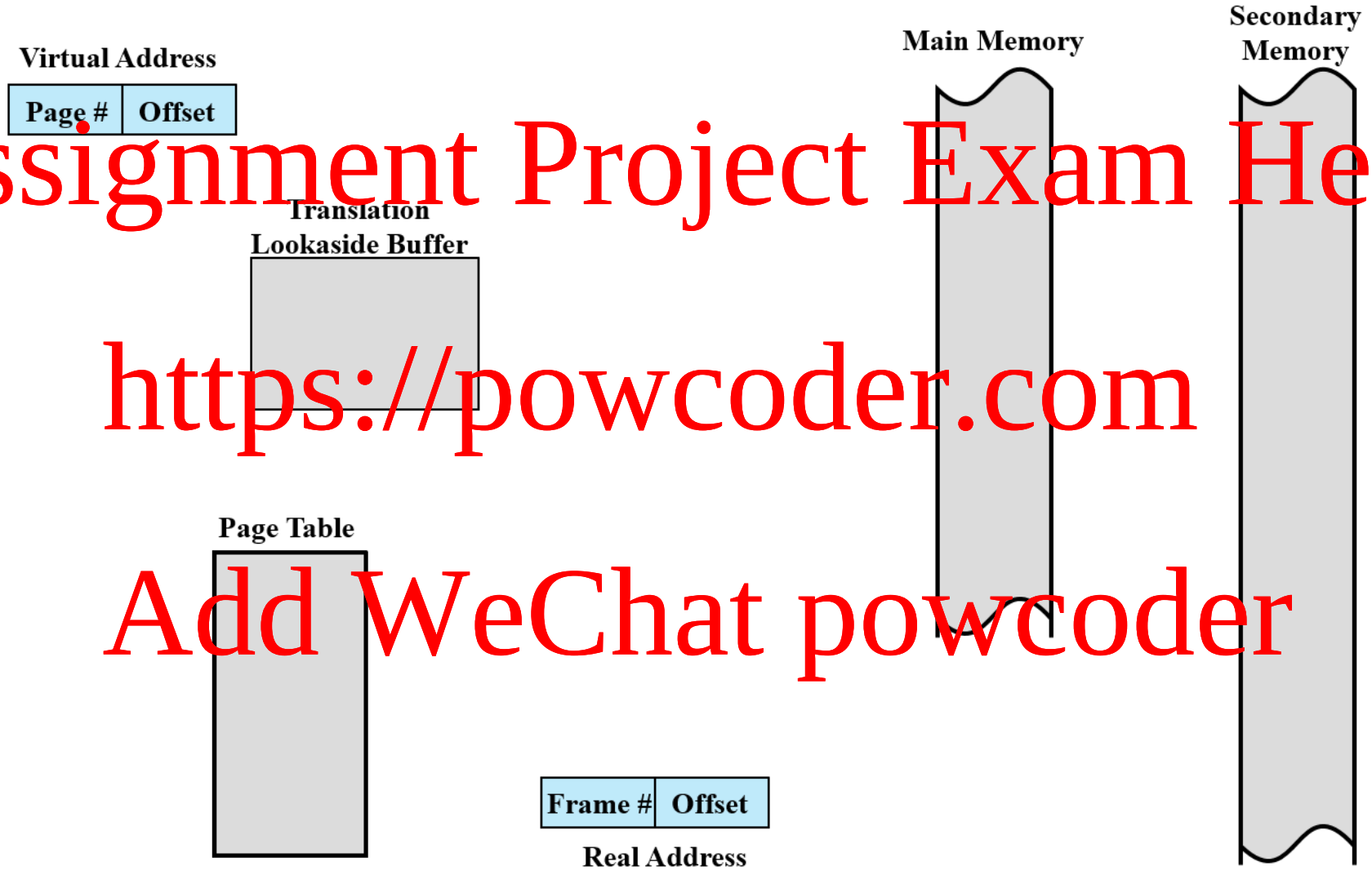
Translation Look-aside Buffers (TLBs) II



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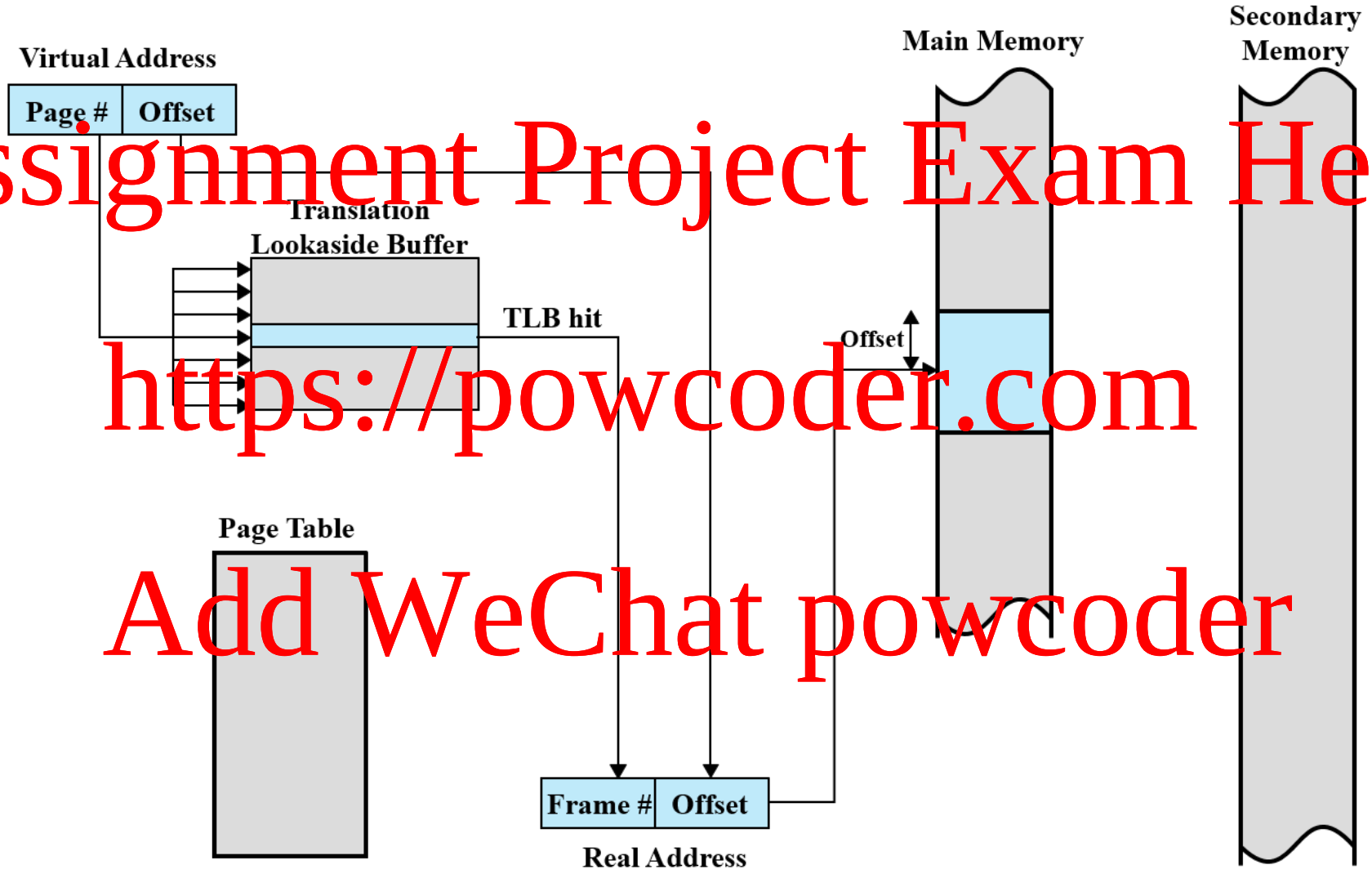

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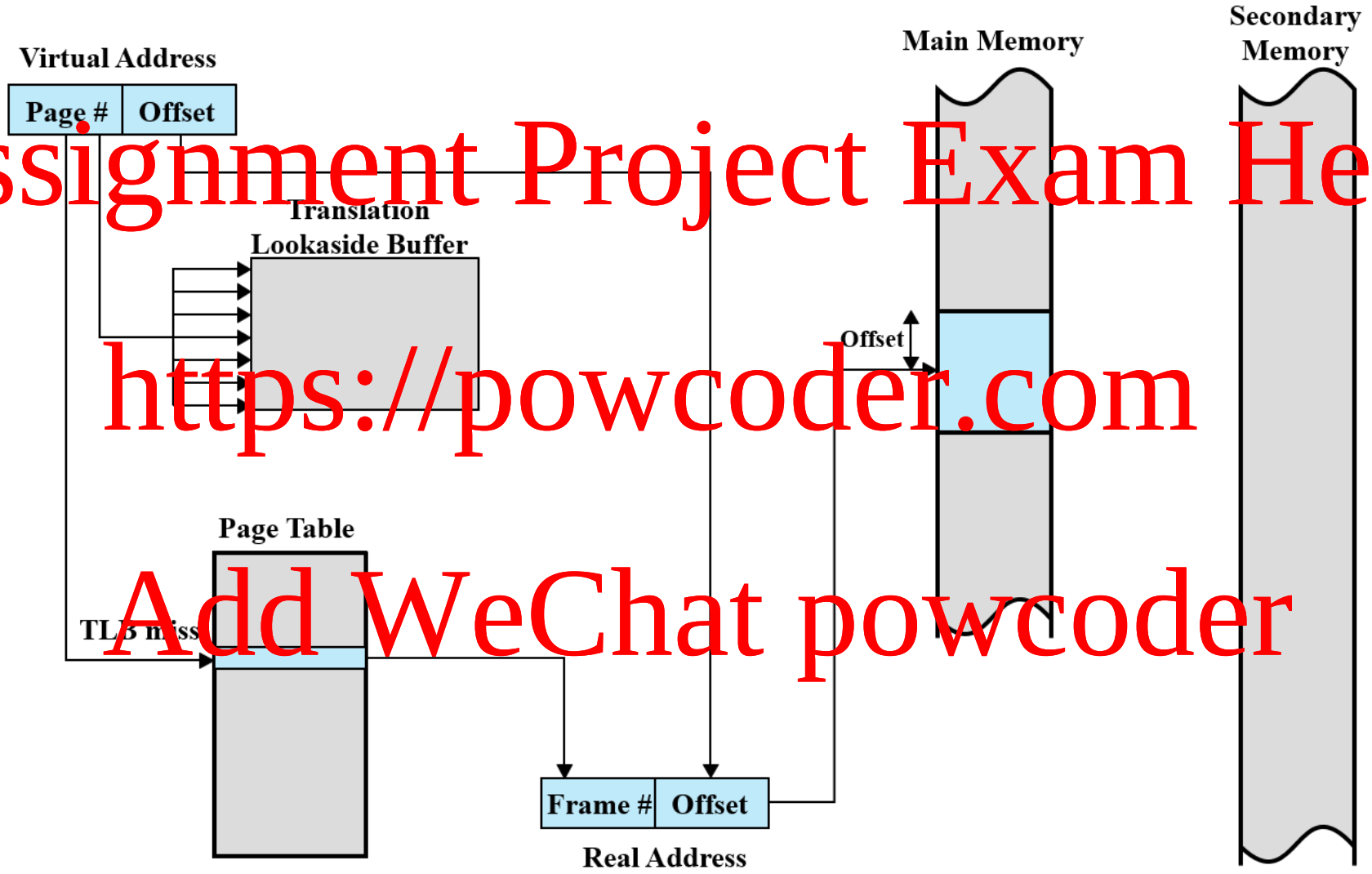

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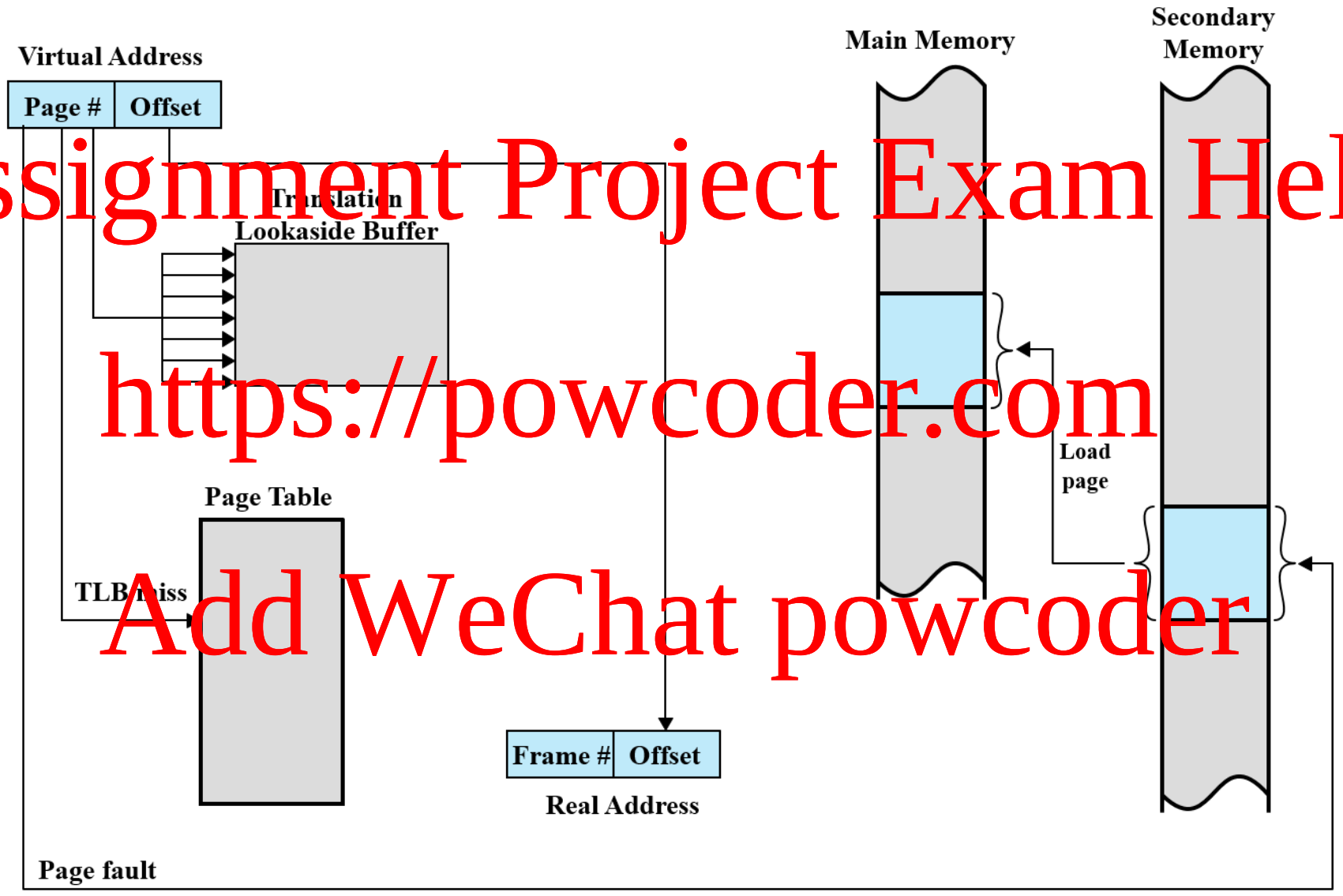

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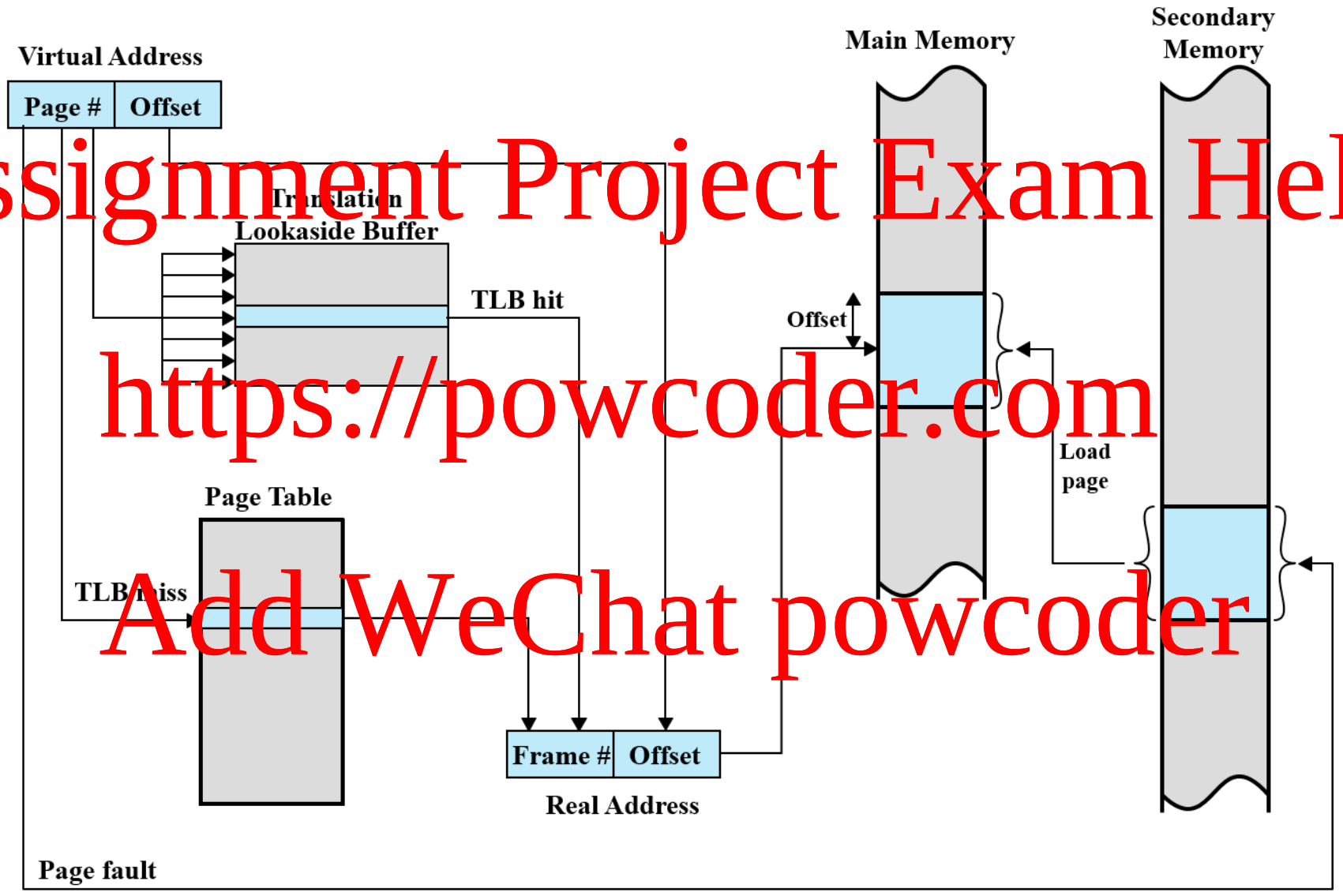

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Example Problem

Effective Access Time

TLB Lookup = ϵ (can be $<$ 10% of memory access time m)

Hit Ratio = α

- Fraction of times that page is found in associative registers
- Ratio related to number of associative registers

Effective Access Time (EAT) = $(\epsilon + m)\alpha + (\epsilon + 2m)(1 - \alpha)$
$= 2m + \epsilon - m\alpha$

Consider $\alpha = 80\%$, $\epsilon = 10$ *ns* for TLB search, $m = 100$ *ns* for memory access

- EAT = 110 x 0.80 + 210 x 0.20 = 130 *ns*

A more realistic hit ratio might be 99%

- EAT = 110 x 0.99 + 210 x 0.01 = 111 *ns*

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Page Table Size

Why do we need need to worry?

Page table can grow to be very large in size

On a 32-bit machine with a 4 KB page size:

- Number of page table entries $= \frac{2^{32}}{2^{12}} = 2^{20}$
- Size of each page table entry = 32 bits
- Size of page table = 2^{20} x 32 bits = 4 MB

On 64-bit machine with 4 KB pages $\rightarrow$ page table needs 2^{52} entries

- with 8 bytes per entry, that's 30 million GB ...
- lot of memory to be allocated ☹

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Page Table Types

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Hierarchical page table

Hashed page table

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Inverted page table

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Hierarchical Page Table I

Idea: Let the page-table be broken-up and paged if it is too large

Simple technique → **two-level page table** for a machine with 32-bit addresses and a 4 KB page size

- page offset needs 12 bits
- page table size = 4 MB

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How do you break the page table up?

Each part of the page table that is being paged must fit on a page

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- Recall: page size = 4 KB
- Number of entries on one page = $\frac{Page\ size}{Address\ size} = \frac{4\ KB}{32\ bits} = 2^{10}$
- No of bits required for 2^{10} entries = 10
- Address bits left for top-level page table = 32 – 10 – 12 = 10

Hierarchical Page Table II

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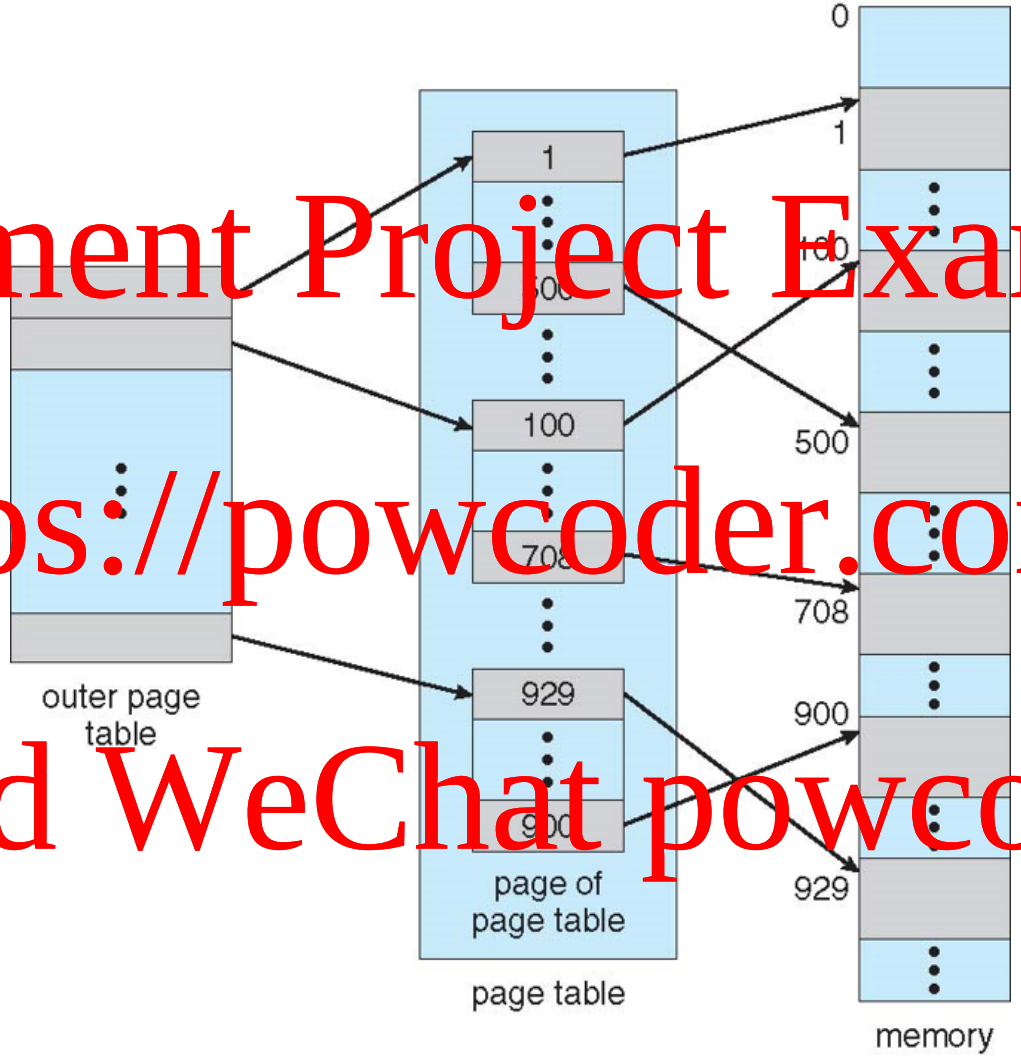


Fix outer page table in memory

Two-Level Paging I

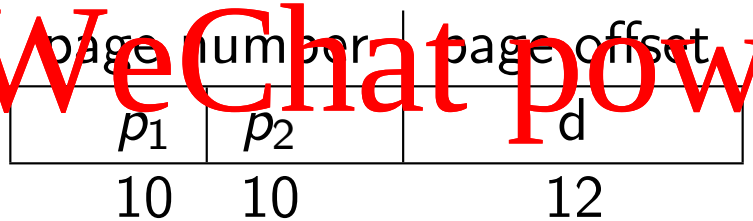
Logical address divided

- Page number consisting of 20 bits
- Page offset consisting of 12 bits

Since page table paged, page number further divided

- 10 bit page number
- 10 bit page offset within 2^{nd} level page table

Thus, logical addresses as follows



$p_1 \rightarrow$ index into the outer page table

$p_2 \rightarrow$ displacement within page pointed to by outer page table

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Two-Level Paging II

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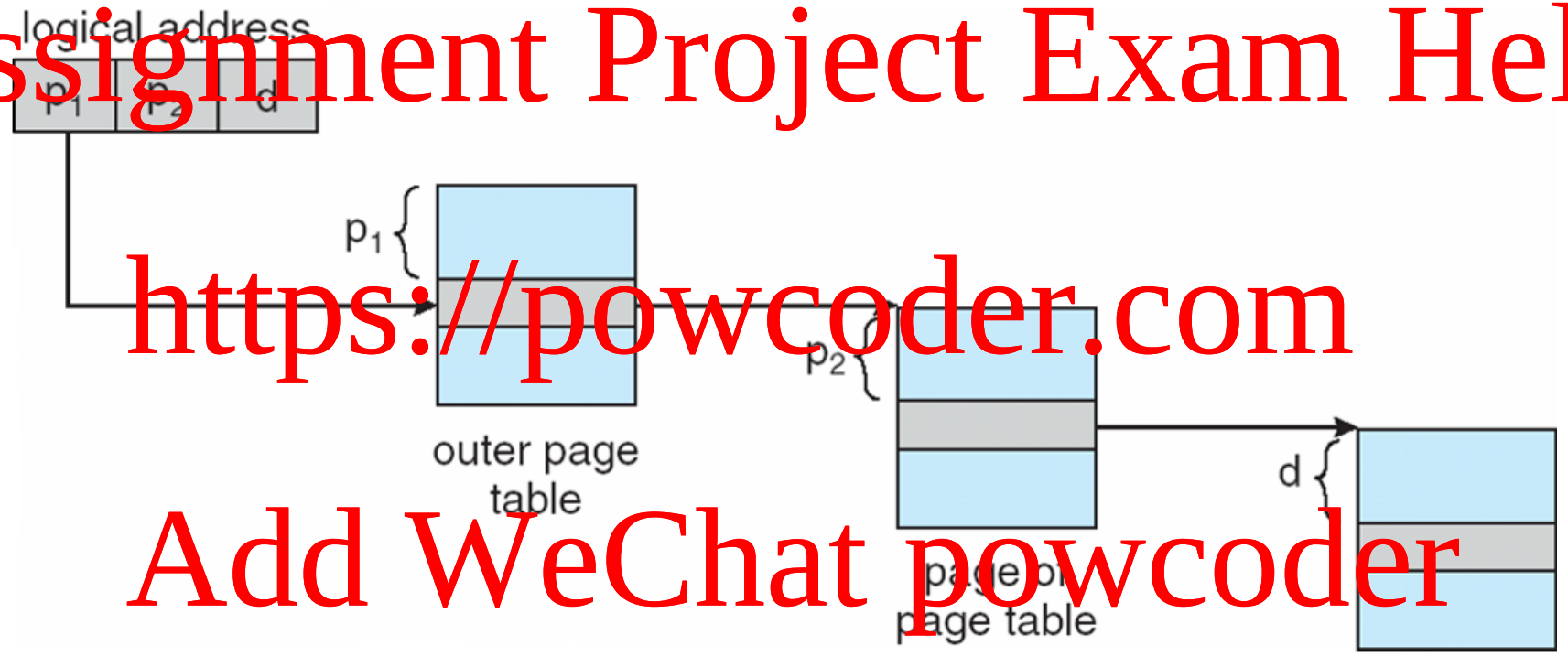

Example Problem

Page Table Addressing

Consider a paging system that uses a three-level page table. Virtual addresses are composed into four fields (a, b, c, d) with d being the offset. What is the maximum number of pages in a virtual address space?

Answer: 2^{a+b+c}, since there are a total of $2^{a+b+c+d}$ addresses in the address space and each page has 2^d addresses

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Page Table: Another Idea

Don't store entry per page but per frame

- **Hashed page table**
- **Inverted page table**

Hashed Page Table

Hash virtual page number into page table

- Page table contains chain of elements hashing to same location
- Search for match of virtual page number in chain
- Extract corresponding physical frame if match found

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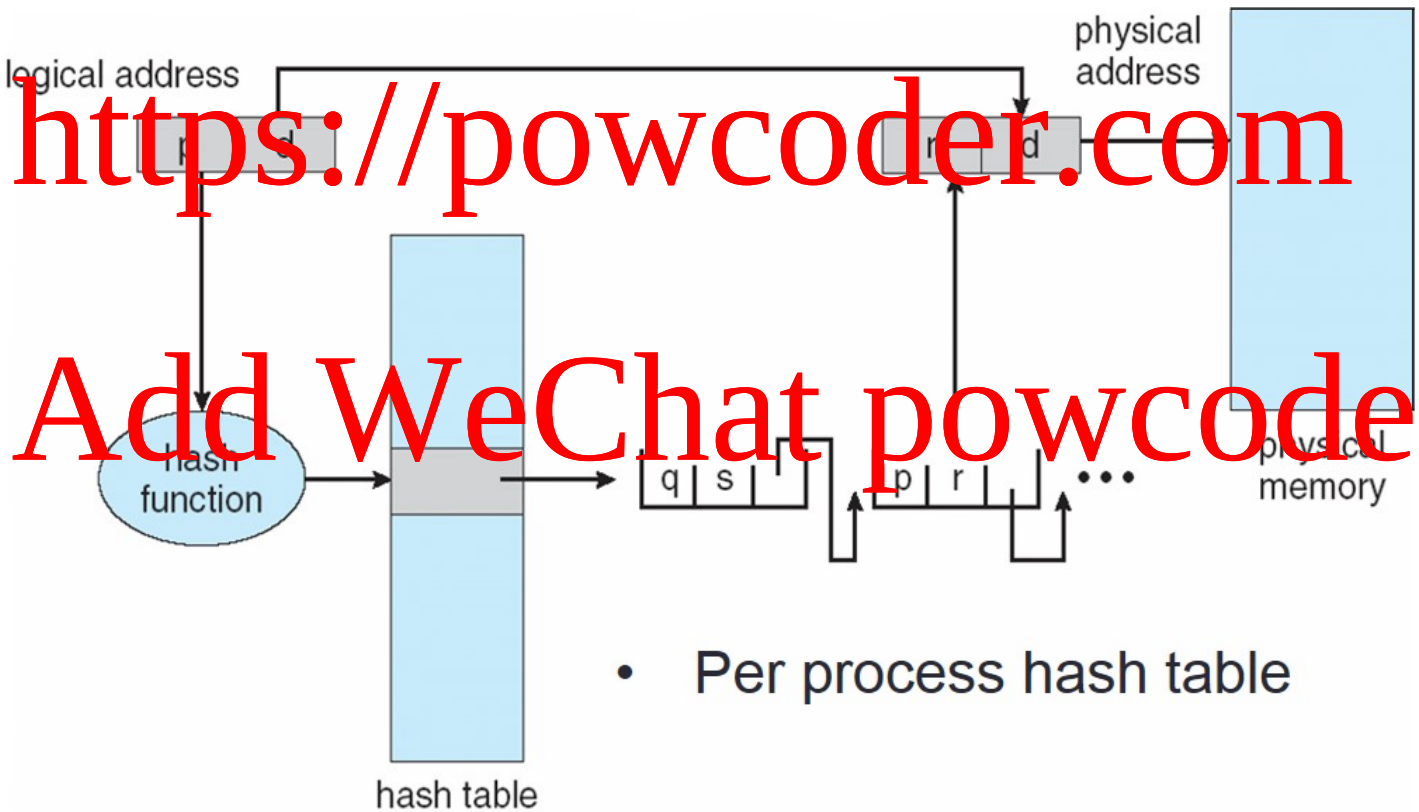

Inverted Page Table

One entry per physical frame

Decreases memory needed to store page table

- But increases time to search table when page reference occurs

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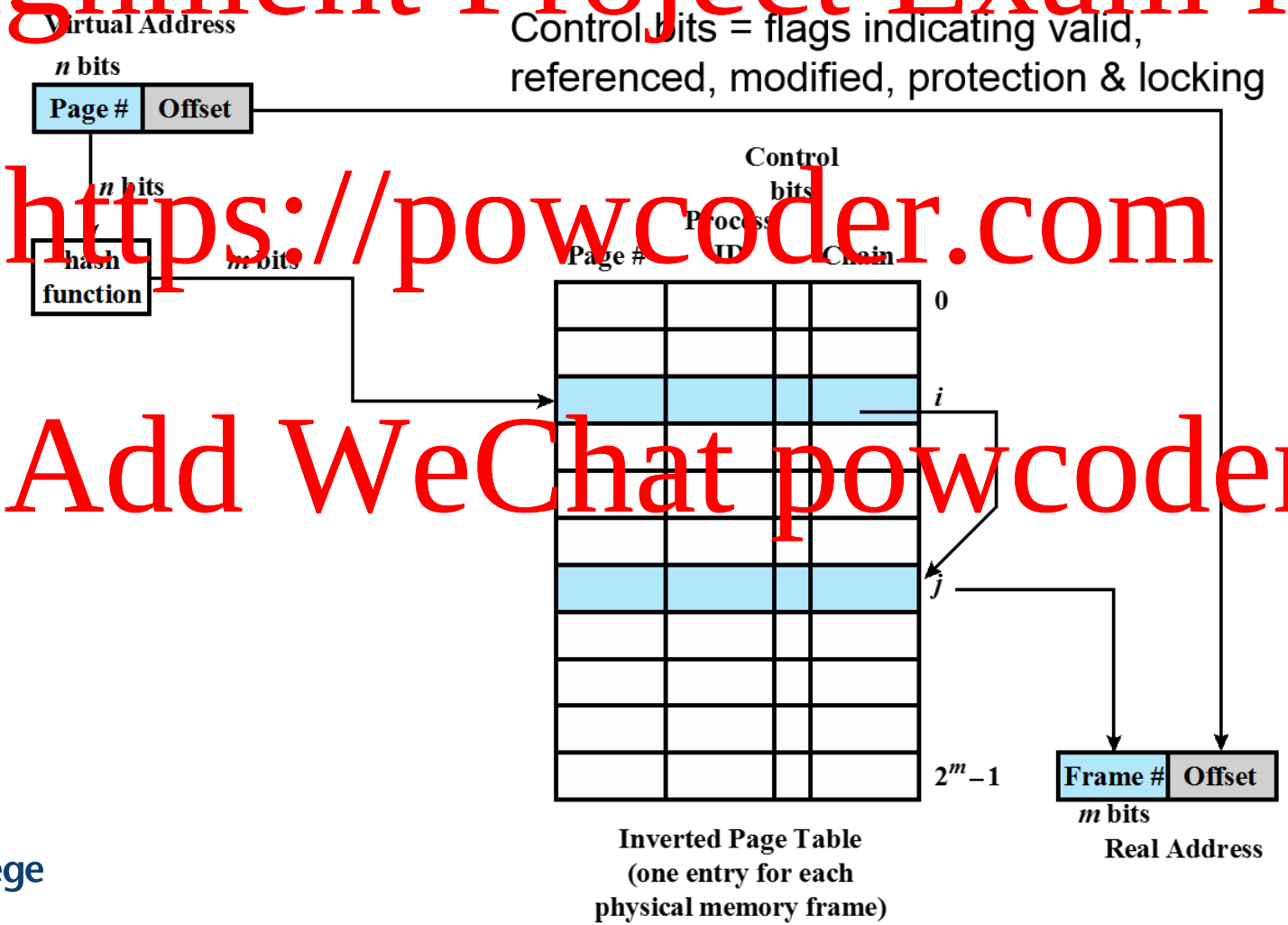

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Segmentation

Paging gives one-dimensional virtual address space → what about separate address spaces for code, data, stack?

Segment

- Independent address space from 0 to some maximum
- Can grow/shrink independently
- Support different kinds of protection (read/write/execute)
- Unlike pages, programmers are aware of segments
- Segment corresponds to program, procedure, stack, object, array, etc.

Memory allocation harder due to variable size

- May need to move segment which grows
- May suffer from external fragmentation
- But good for shared libraries

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Logical View of Segmentation

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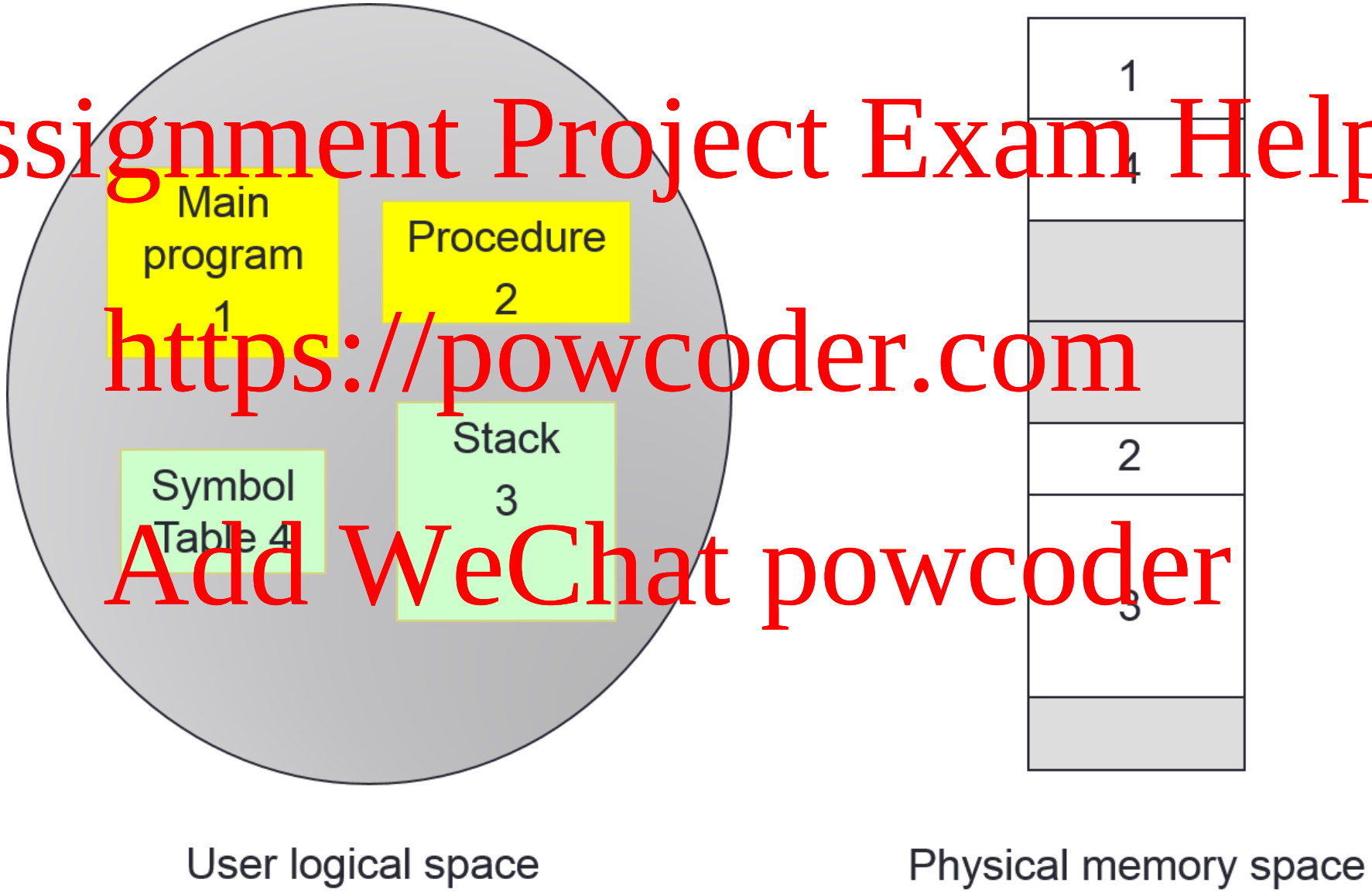

Segmentation Address Translation

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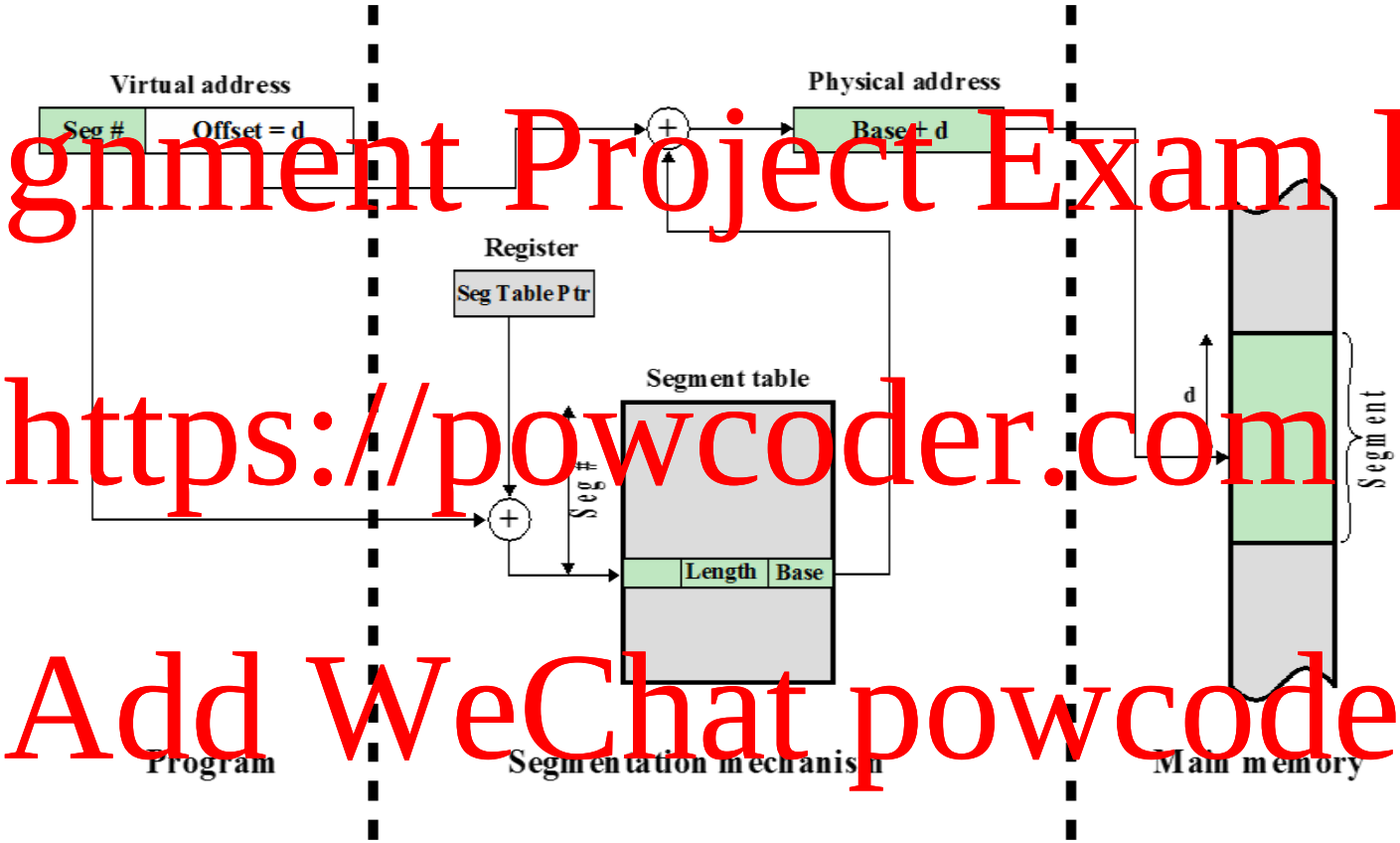
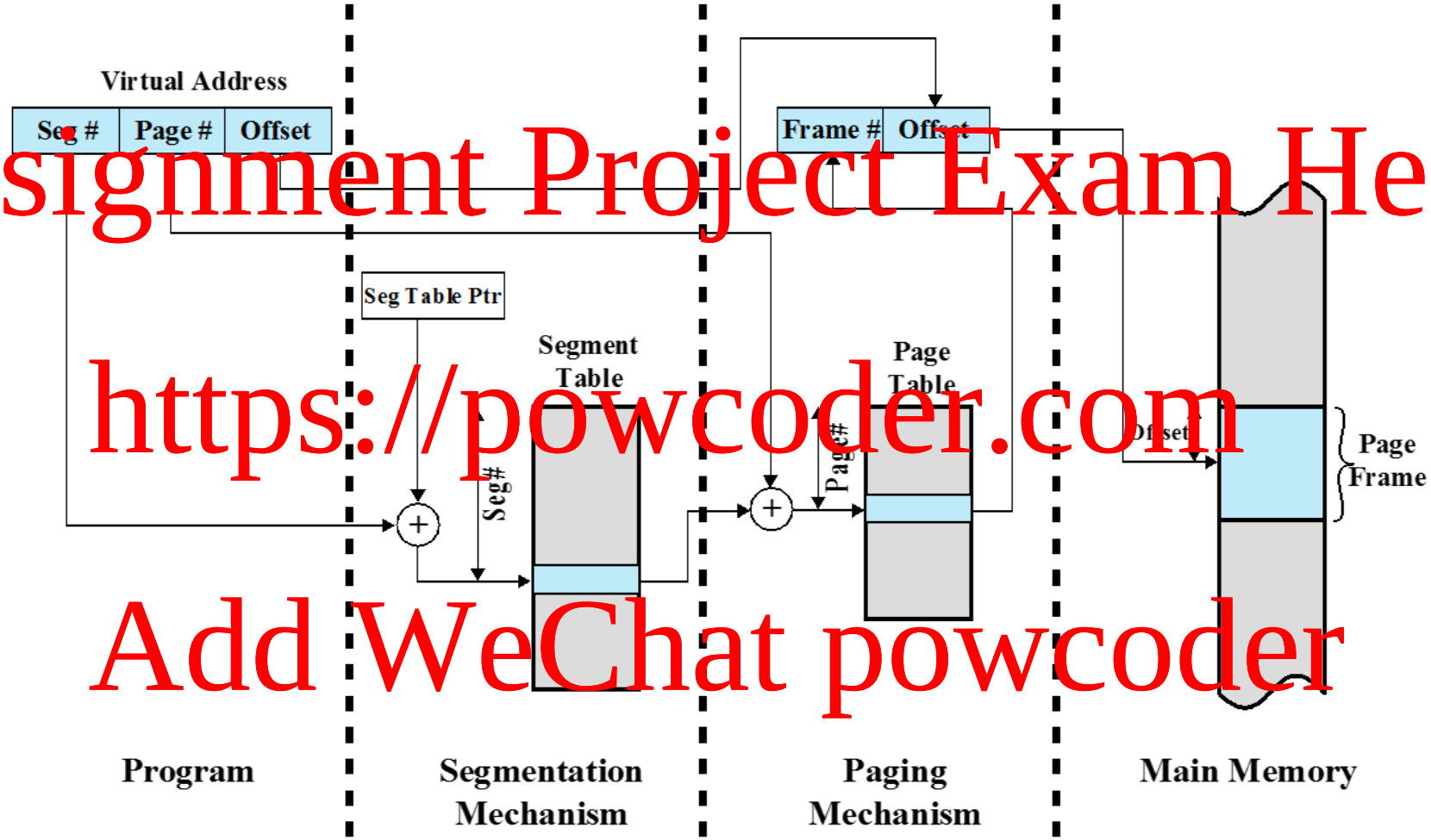


- One bit in table indicates whether segment is in memory
- Another bit indicates whether segment is modified

Hybrid Segmentation/Paging



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Most OSs use only paging

Memory Control Bits

Protection bits → associated with a frame indicate read-only, read-write, execute-only

Valid-invalid bit

- **Valid** → page present in physical memory
- **Invalid** → page missing in physical memory
  - Page fault is generated ⇒ kernel trap to bring in page from backing store

Page replacement bits → to indicate if page was been modified or referenced (used later). Also, lock bit to prevent page from being transferred out

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Memory Validity

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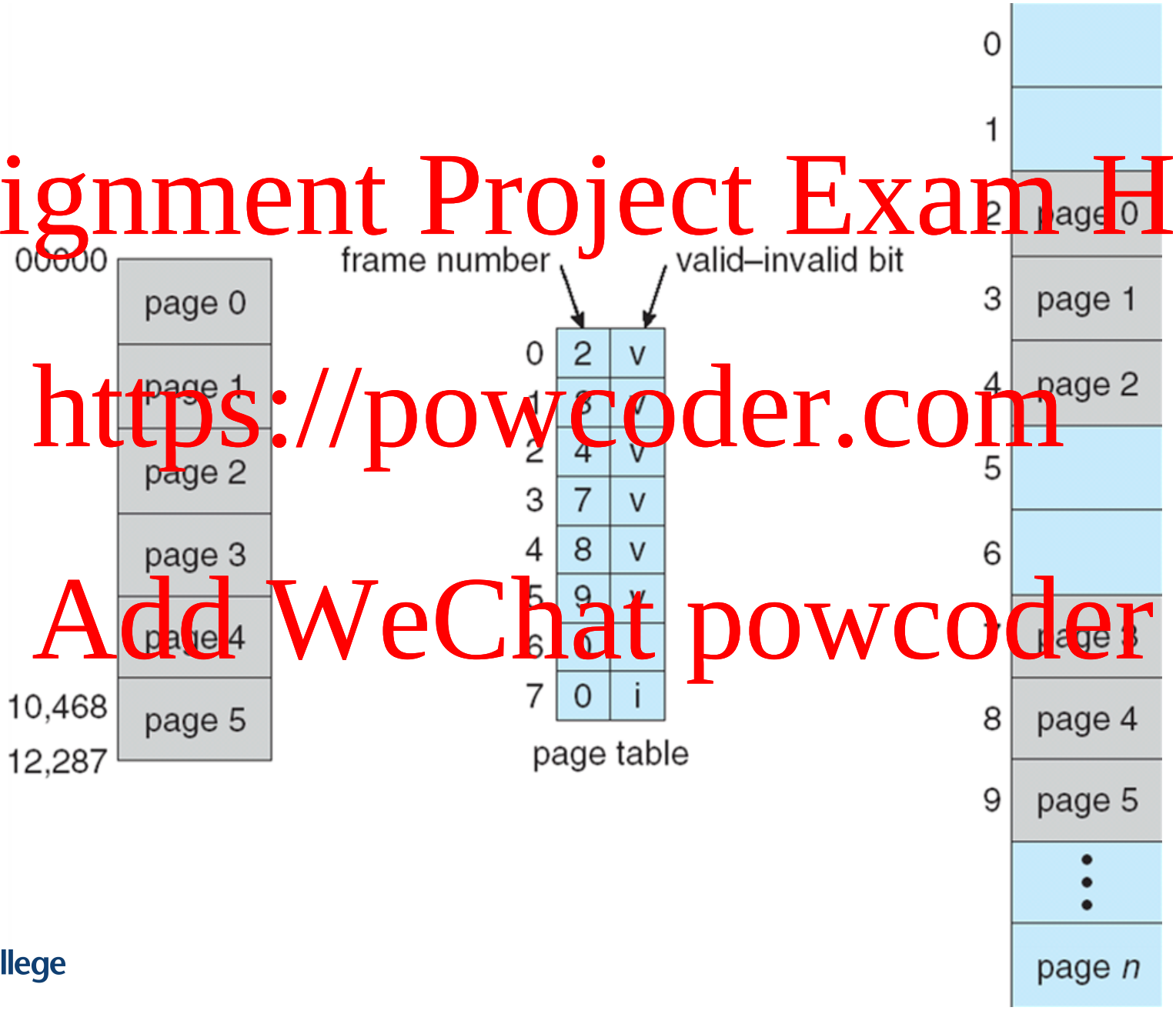

Demand Paging I

When do you bring the page into memory?

Bring page into memory only when needed

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- Lower I/O load
- Less memory needed
- Faster response time
- Support for more users

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Page needed → reference it

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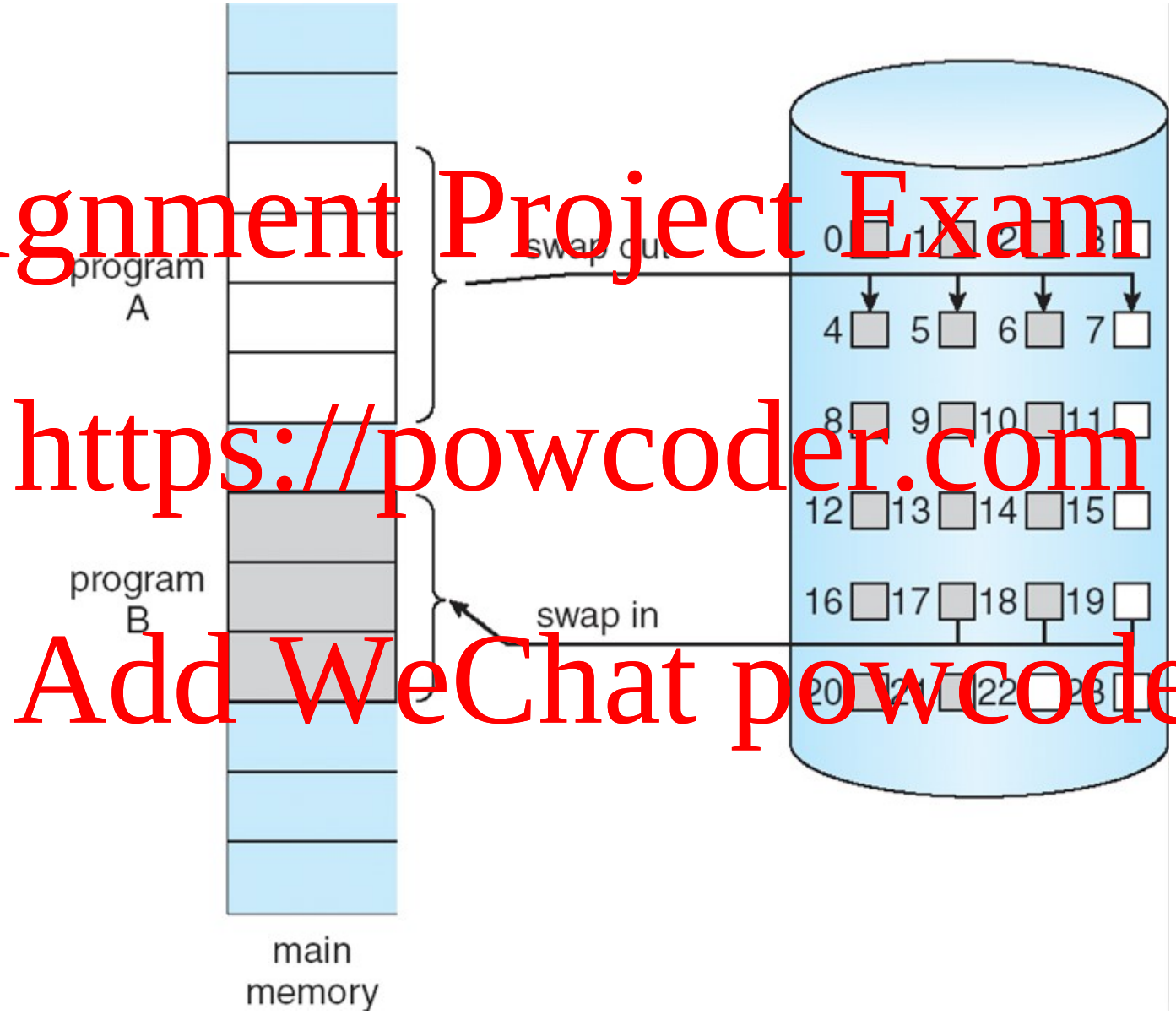
- Invalid reference → abort
- Not-in-memory → bring into memory

Many page faults when process first starts

Eventually required pages are in memory so page fault rate drops

Demand Paging II



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Demand Paging III

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Use **valid-invalid** bit to check memory validity

- 1 → in memory
- 0 → not in memory
  - Initially set to 0 on all entries
  - If 0 during address translation → page fault

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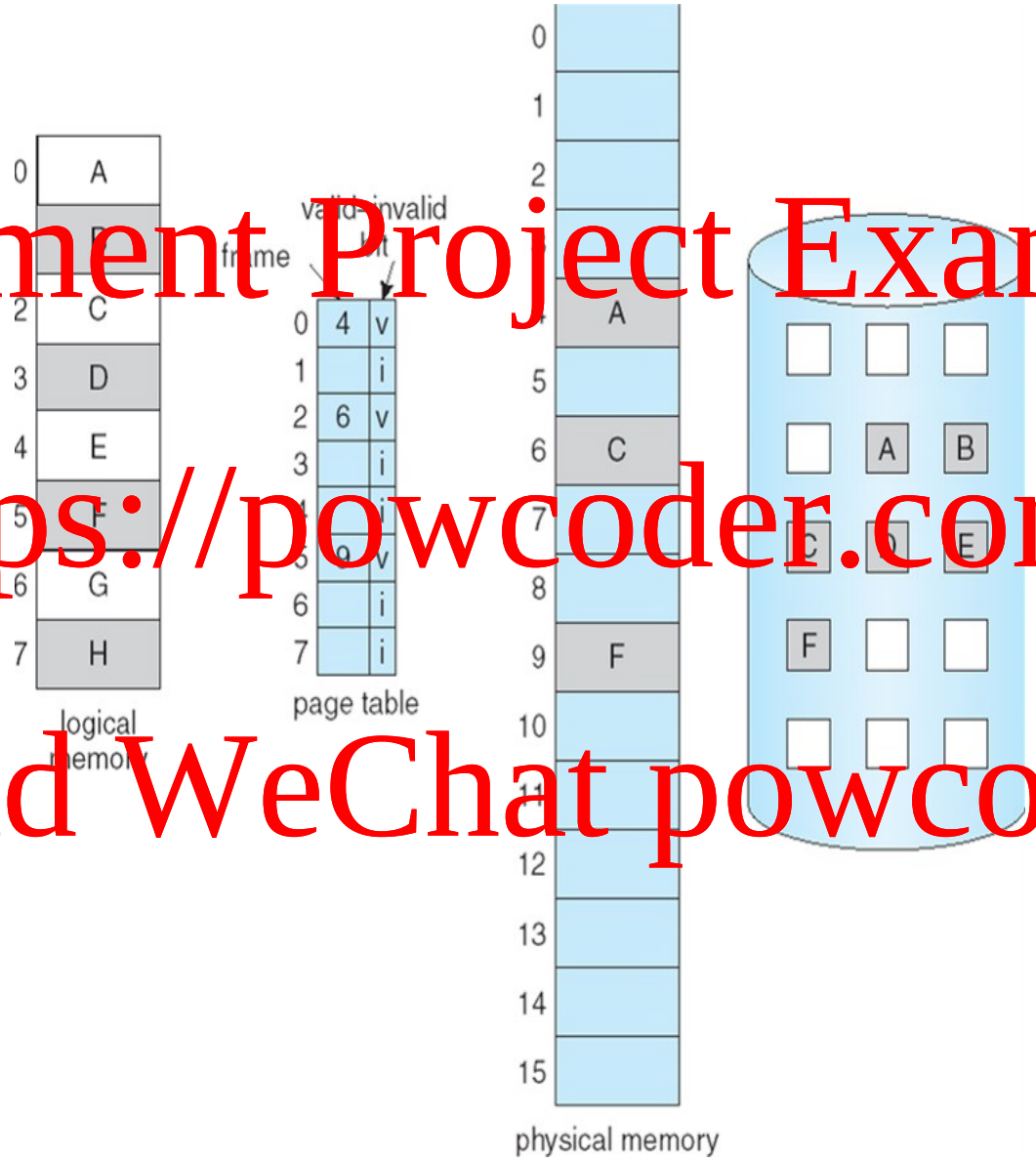
Demand Paging IV



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Page Faults I

First reference, trap to OS → page fault

OS looks at another table to decide:

- Invalid reference → abort
- Valid reference but just not in memory → handle request

To handle valid request:

- Get empty frame
- Swap page into frame
- Reset tables, validation bit = 1
- Restart last instruction

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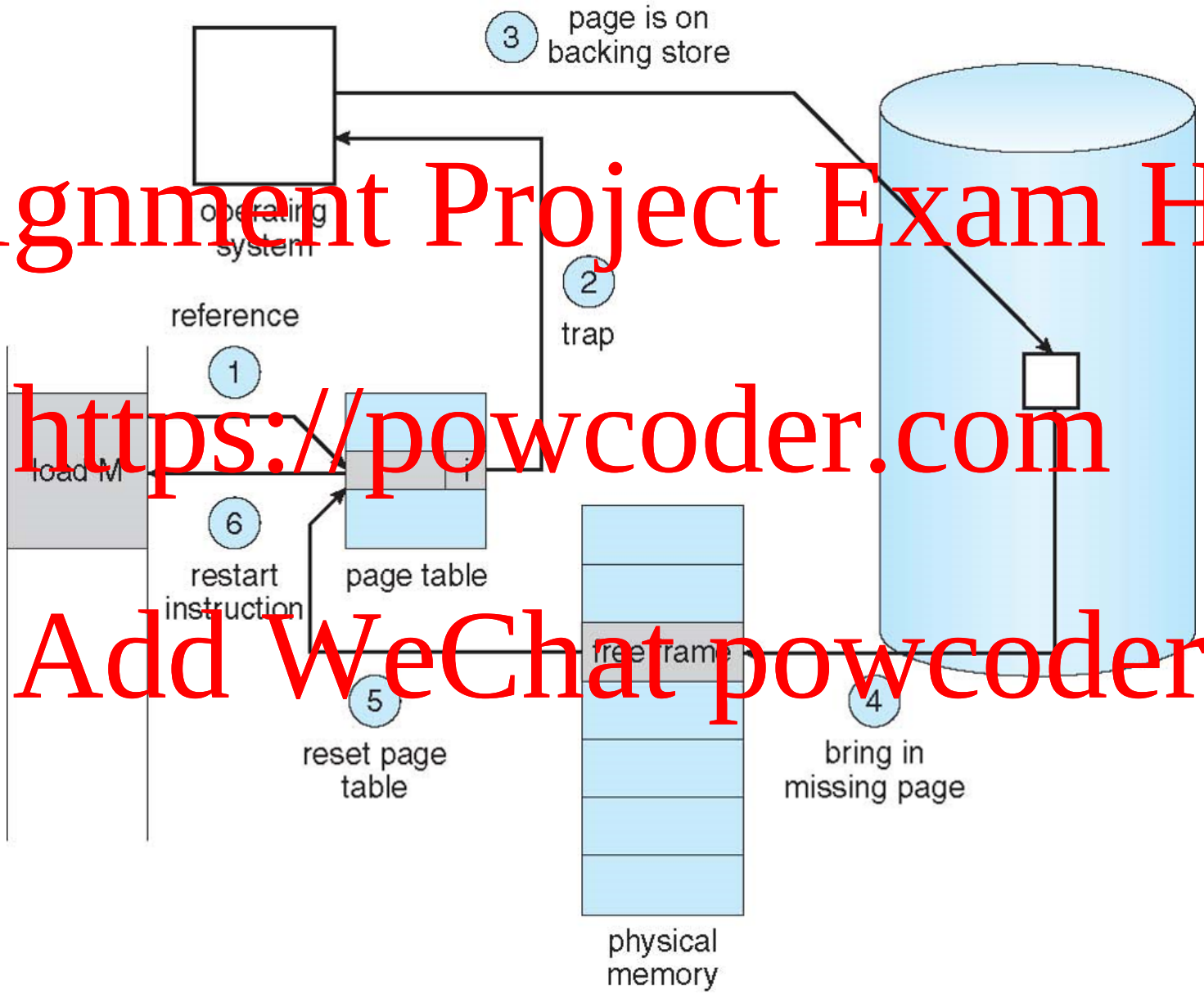
Page Faults II



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Performance: Demand Paging

Page Fault Rate (p), $0 \leq p \leq 1.0$

- If p = 0, no page faults
- If p = 1, every reference causes a page fault

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Effective Access Time (EAT) = (1 − p) x memory access + p
x (page fault overhead
+ [swap page out]
+ swap page in
+ restart overhead)

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Note: no need to swap page out if not modified

Virtual Memory Tricks

Copy-on-Write (COW)

- Allows parent and child processes to initially share same pages in memory → if either process modifies shared page, then copy page
- Efficient process creation: copy only modified pages
- Free pages allocated from pool of zeroed-out pages

Memory-mapped files

- Map file into virtual address space using paging
- Simplifies programming model for I/O

I/O Interlock

- Pages must sometimes be locked into memory
  - Pages used for DMA from disk

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Example Problem

Demand Paging

Memory access time = 200 *ns*

Average page-fault service time = 8 *ms*

$$\begin{aligned} EAT &= (1 - p) \times 200 + p \times (8\ ms) \\ &= (1 - p) \times 200 + p \times 8{,}000{,}000 \\ &= 200 + p \times 7{,}999{,}800 \end{aligned}$$

If one access out of 1,000 causes a page fault, then EAT = 8.2 *ms* $\rightarrow$ slowdown by a factor of 40!

If we want performance degradation $< 10\%$

$$\begin{aligned} EAT &< EAT + 10\% \text{ of } EAT \\ 200 + 7{,}999{,}800 \times p &< 220 \\ 7{,}999{,}800 \times p &< 20 \\ p &< 0.0000025 \end{aligned}$$

Less than one page fault in every 400,000 memory accesses

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Page Replacement

No free frame? Replace page

How do you decide which page to replace?

Find some unused page in memory to swap out $\Rightarrow$ need strategy for page replacement

Minimise number of page faults

- Avoid bringing same page into memory several times

Prevent over-allocation of memory

- Page-fault service routine should include page replacement

Use modify (dirty) bit to reduce overhead of page transfers

- Only modified pages written to disk

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Basic Page Replacement I

1. Find location of desired page on disk
2. Find free frame
3. Frame found?
   - Yes? $\Rightarrow$ use it
   - No? $\Rightarrow$ use replacement algorithm to select **victim** frame
4. Load desired page into (newly) freed frame
5. Update page and frame tables
6. Restart process

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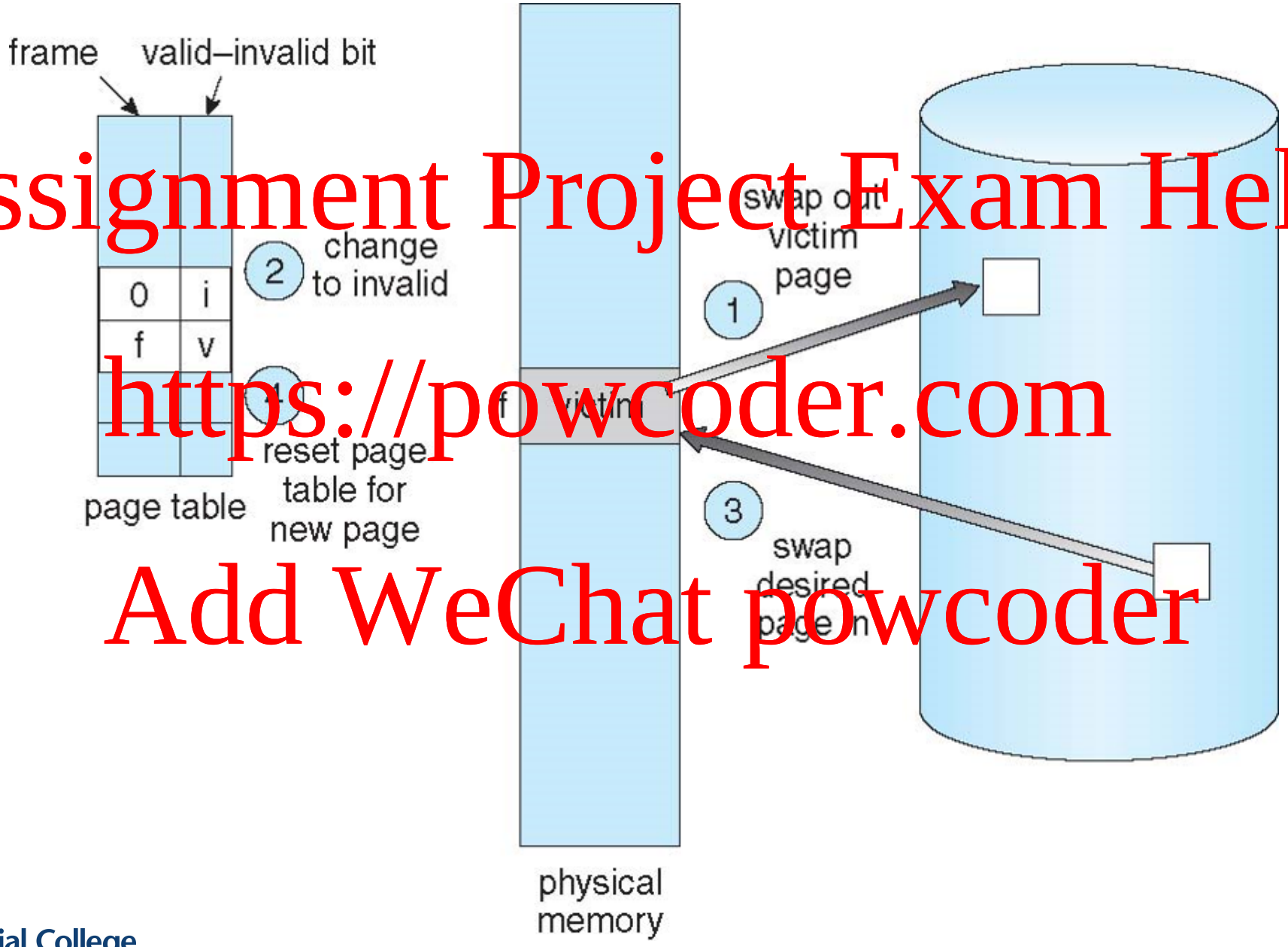
Basic Page Replacement II



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Aim: Lowest page-fault rate

How do we compare page replacement algorithms?

Use a Reference String → particular string of memory references and calculate number of page faults for each algorithm

E.g. 1, 2, 3, 3, 2, 4, 1, 4, 5, 5, 7, 2, 3, 1

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Optimal Algorithm

Replace page that will not be used for the longest period of time

- Unimplementable, as knowledge of future references needed
- Useful for measuring how well other algorithms perform

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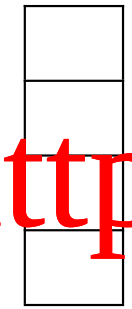

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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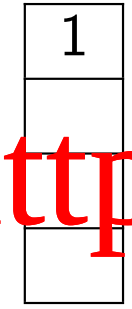

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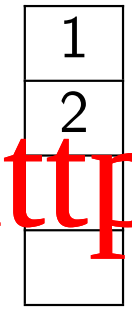

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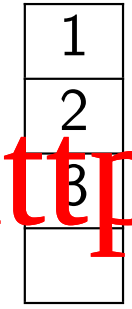

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1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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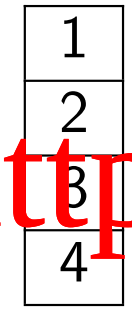

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1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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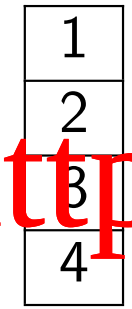

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1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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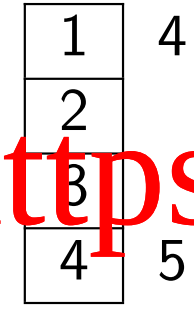

4
5

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1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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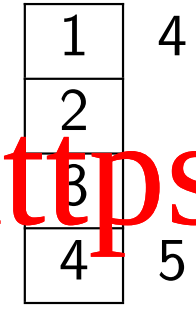

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

6 page faults

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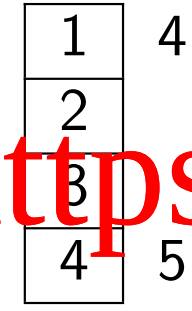

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

6 page faults

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Reference string

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7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
7	7	7	2		2		2			2			2				7		
	0	0	0		0		4			0			0				0		
		1	1		3		3			3			1				1		

Total of 9 page faults

First-In-First-Out (FIFO) Algorithm

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- Replace oldest page
  - May replace heavily used page

Reference string

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7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
7	7	7	2		2	2	4	4	4	0			0	0			7	7	7
	0	0	0		3	3	3	2	2	2			1	1			1	0	0
		1	1		1	0	0	0	3	3			3	2			2	2	1

Total of 15 page faults

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Heavily used pages, 0, 2, 3 are being swapped in and out

Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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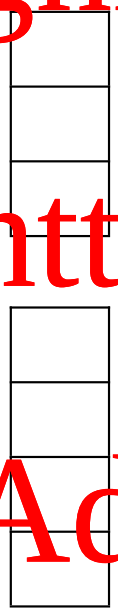
Assume 3 frames



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Assume 4 frames

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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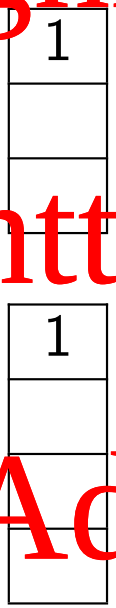

Assume 3 frames

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Assume 4 frames

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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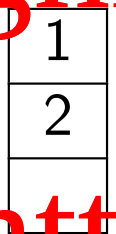

Assume 3 frames

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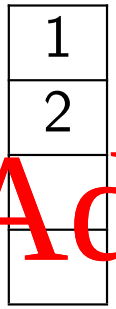

Assume 4 frames

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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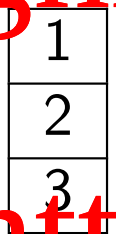

Assume 3 frames

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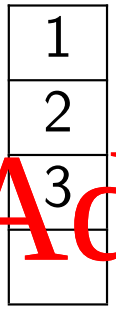

Assume 4 frames

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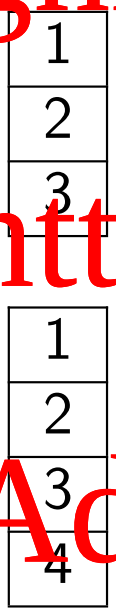

Assume 3 frames

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Assume 4 frames

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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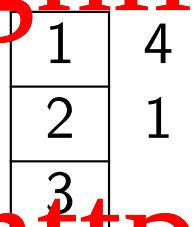

Assume 3 frames

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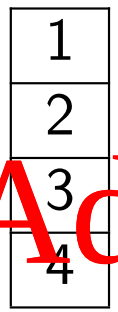

Assume 4 frames

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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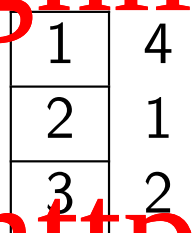

Assume 3 frames

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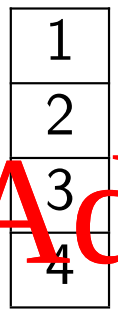

Assume 4 frames

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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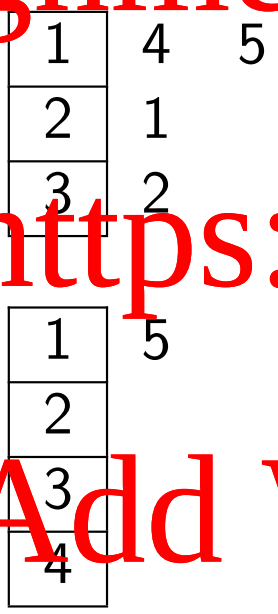

Assume 3 frames

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Assume 4 frames

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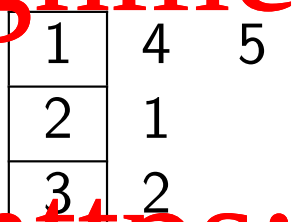

Assume 3 frames

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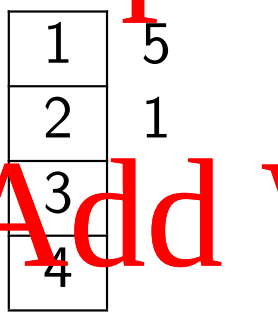

Assume 4 frames

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Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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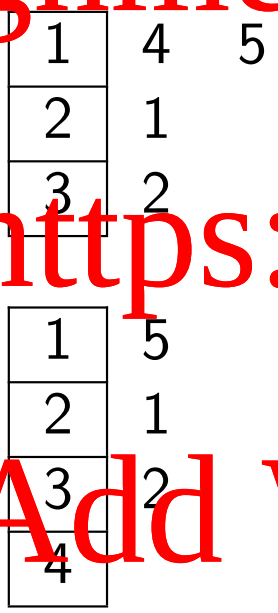

Assume 3 frames

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Assume 4 frames

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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1	4	5	
2	1	3	Assume 3 frames
3	2		

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1	5	
2	1	Assume 4 frames
3	2	
4	3	

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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1	4	5	
2	1	3	Assume 3 frames
3	2	4	

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1	5	4	
2	1		Assume 4 frames
3	2		
4	3		

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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1	4	5	
2	1	3	Assume 3 frames
3	2	4	9 page faults

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1	5	4	
2	1	5	Assume 4 frames
3	2		10 page faults
4	3		

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Belady's Anomaly

Reference string: 1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5 (FIFO replacement)

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1	4	5	
2	1	3	Assume 3 frames
3	2	4	9 page faults

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1	5	4	
2	1	5	Assume 4 frames
3	2		10 page faults
4	3		

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Belady's Anomaly: More frames $\Rightarrow$ more page faults

Least Recently Used (LRU) Algorithm

Each page entry has a counter

- When page referenced, copy clock into counter
- When page needs to be replaced, choose lowest counter

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Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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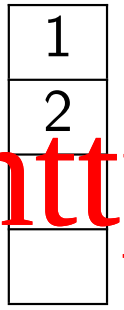

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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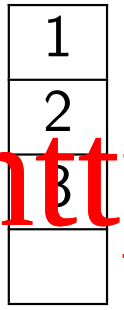

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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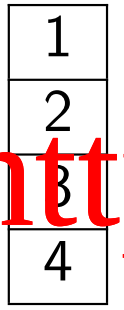

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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Least Recently Used (LRU) Algorithm

Each page entry has a counter

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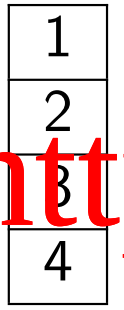

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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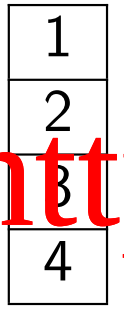

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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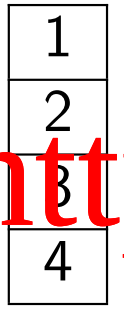

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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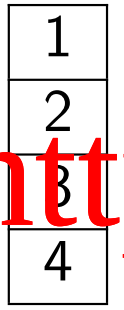

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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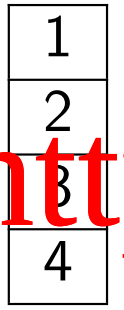

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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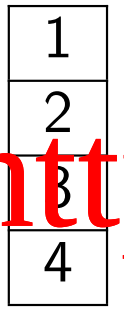

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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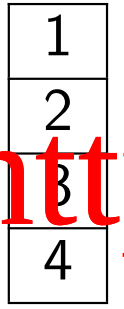

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

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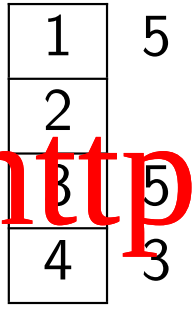

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

8 page faults

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Least Recently Used (LRU) Algorithm

Each page entry has a counter

- When page referenced, copy clock into counter
- When page needs to be replaced, choose lowest counter

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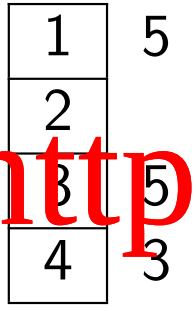

Assume 4 frames

1, 2, 3, 4, 1, 2, 5, 1, 2, 3, 4, 5

8 page faults

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Reference string

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7	0	1	2	0	3	0	4	2	3	0	3	2	1	2	0	1	7	0	1
7	7	7	2		2		4	4	4	0			1		1		1		
	0	0	0		0		0	0	3	3			3		0		0		
		1	1		3		3	2	2	2			2		2		7		

Total of 12 page faults

LRU Approximation Algorithms

Proper LRU is expensive → use approximations instead

Reference bit

- With each page associate reference bit r, initially r = 0
  - When page referenced, set r = 1
  - Replace page with r = 0 (if one exists)
- Periodically reset reference bits
- Does not provide proper order for LRU

Clock Replacement Policy

- Needs reference bit r and uses clock replacement
- If page to be replaced (in clock order) has r = 1 then
  - Set r = 0 and leave page in memory
  - Continue till you find r = 0, and replace that page
  - If all r = 1, replace starting page

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Clock Page Replacement

When page fault occurs, the page being pointed to is inspected

- If r = 0, evict page
- If r = 1, clear r, and advance pointer

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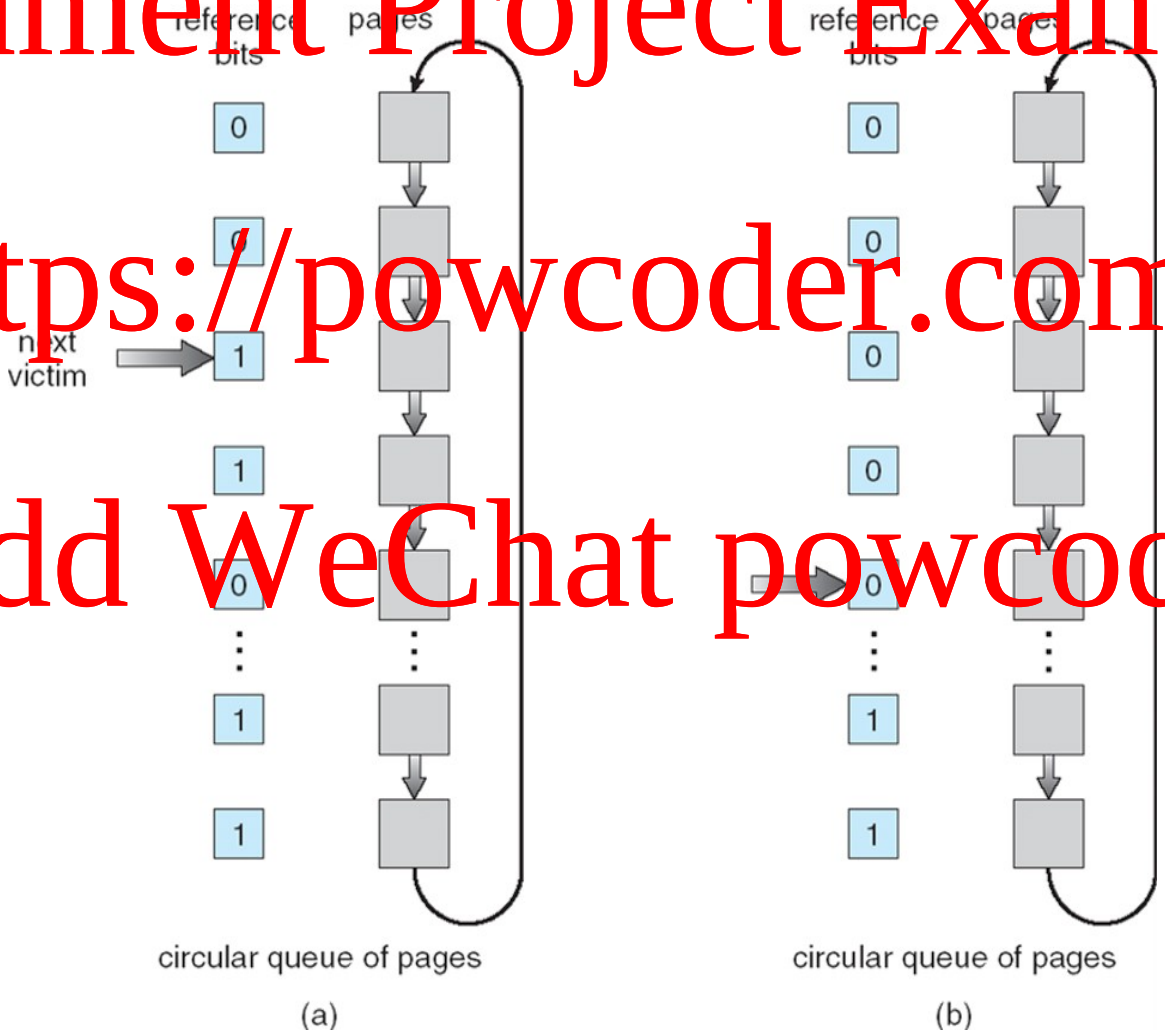

Counting Algorithms

Keep counter of number of references made to each page

LFU (least frequently used) algorithm

- Replace page with smallest count
- May replace page just brought into memory
- Page with heavy usage in past will have high count
  - Reset counters or use **aging**

MFU (most frequently used) algorithm

- Replace page with largest count
- Page with smallest count probably just brought in and yet to be used

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Example Problem

Page Replacement

Reference string: 1, 2, 1, 3, 2, 1, 4, 3, 1, 1, 2, 4, 1, 5, 6, 2, 1.

Assuming number of frames is 3, calculate the number of page faults for LRU and Clock page replacement algorithms.

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Using LRU:

1	2	1	3	2	1	4	3	1	1	2	4	1	5	6	2	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
	2	2	2	2	2	2	3	3	3	3	4	4	4	6	6	6
			3	3	3	4	4	4	4	2	2	2	5	5	5	1
Y	Y	N	Y	N	N	Y	Y	N	N	Y	Y	N	Y	Y	Y	Y

Total of 11 page faults

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Using Clock:

1	2	1	3	2	1	4	3	1	1	2	4	1	5	6	2	1
1	1	1	1	1	1	4	4	4	4	4	4	4	5	5	5	5
	2	2	2	2	2	2	2	1	1	1	1	1	1	6	6	6
			3	3	3	3	3	3	3	2	2	2	2	2	2	1
Y	Y	N	Y	N	N	Y	N	Y	N	Y	N	N	Y	Y	N	Y

Total of 9 page faults

Locality of Reference I

For program to run efficiently

- System must maintain program's favoured subset of pages in main memory

Otherwise thrashing

- Excessive paging activity causing low processor utilisation
- Program repeatedly requests pages from secondary storage

Locality of Reference

- Programs tend to request same pages in space and time

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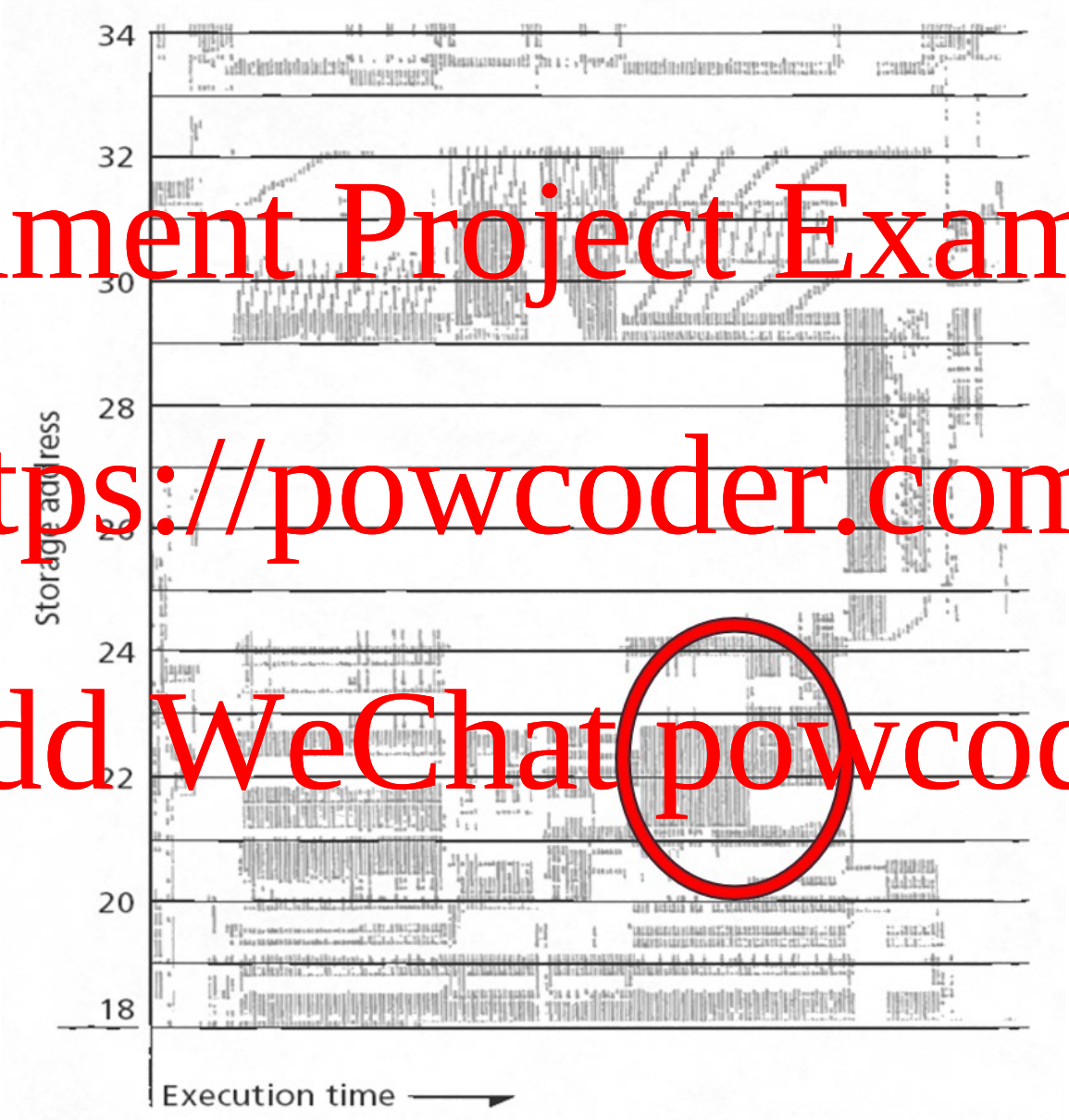
Locality of Reference II



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Working Set Model

Working set of pages → W (t, w)

- Set of pages referenced by process during process-time interval (t – w) to t

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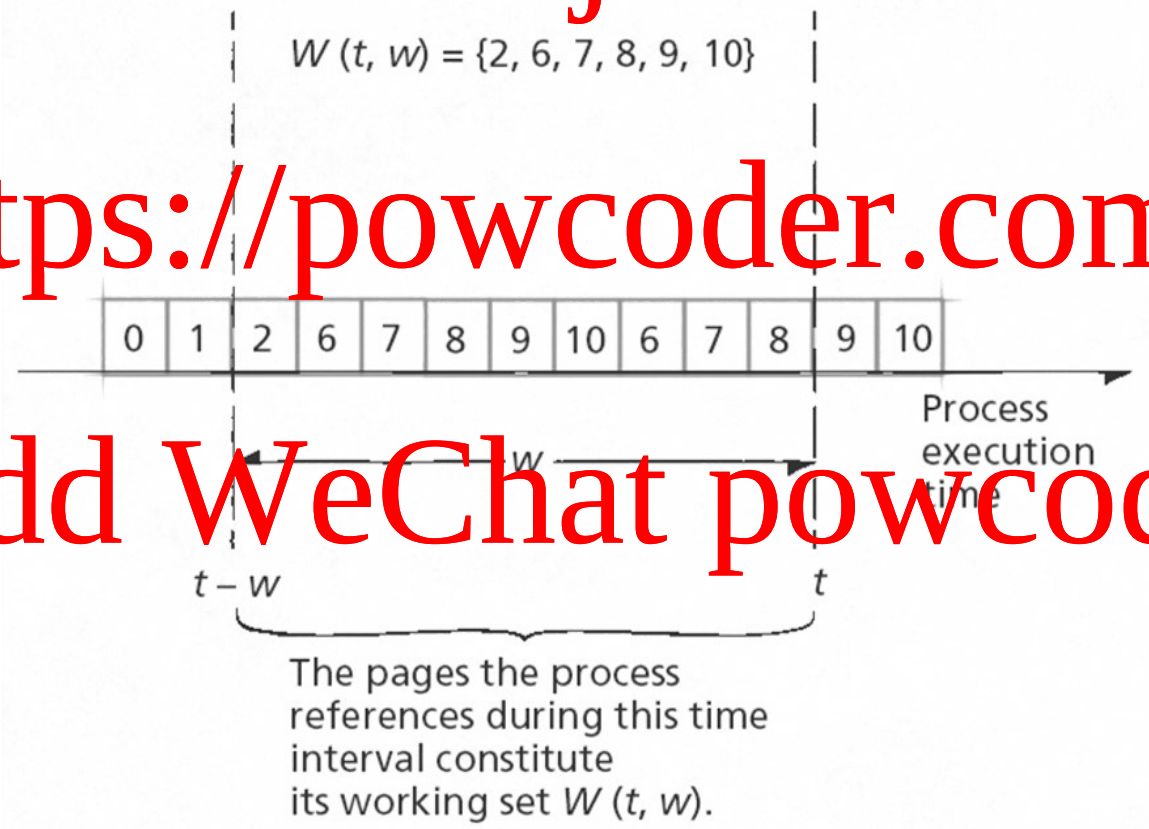

Working Set Clock Algorithm

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Idea: Add "time of last use" to Clock Replacement algorithm

- Keeps track if page in working set

At each page fault, examine page pointed to

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- If $r = 1$, then set $r = 0$ and move to next page
- If $r = 0$, calculate age
  - If age $<$ working set age w, continue (page in working set)
  - If age $>$ working set age w

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    - If page is clean, replace
    - Otherwise trigger write-back, continue to next page

Working Set Size

Processes transition between working sets

- OS temporarily maintains in memory, pages outside of current working set
- Goal of memory management is to reduce mis-allocation

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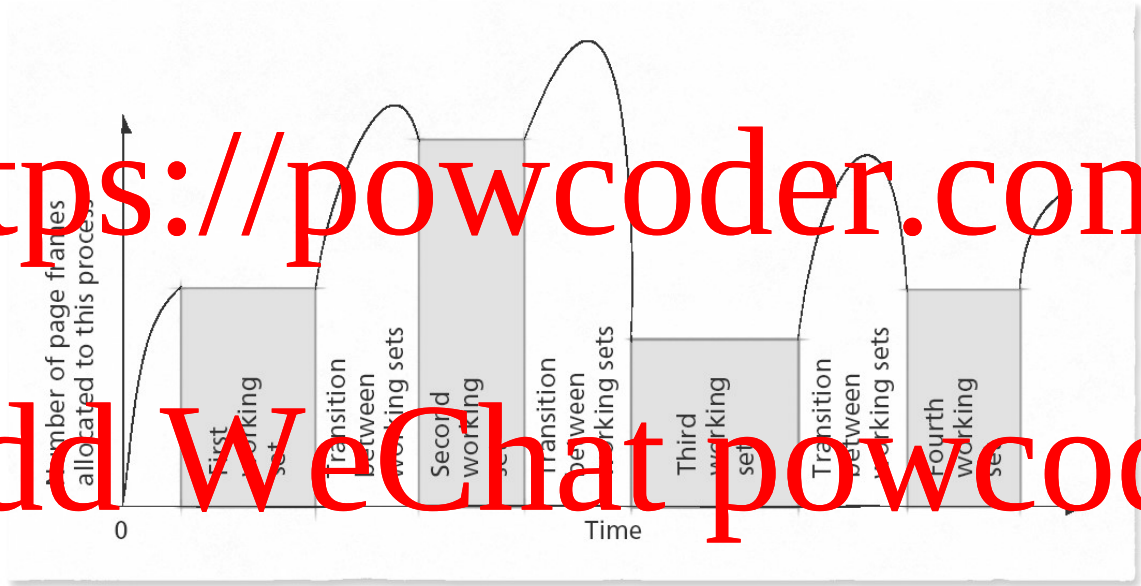

What about page fault frequency?

If many faults ⇒ allocate more page frames

Global vs. Local Page Replacement

Local strategy

- Each process gets fixed allocation of physical memory
- Need to pick up changes in working set size

Global strategy

- Dynamically share memory between runnable processes
- Initially allocate memory proportional to process size
- Consider page fault frequency (PFF) to tune allocation
  - Measure page faults/per sec and increase/decrease allocation

No universally agreed solution

- Linux: global page replacement
- Windows: local page replacement
- Depends on scheduling strategy (i.e. round-robin, ...)

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Linux Memory Management

Mapping and Sharing Memory

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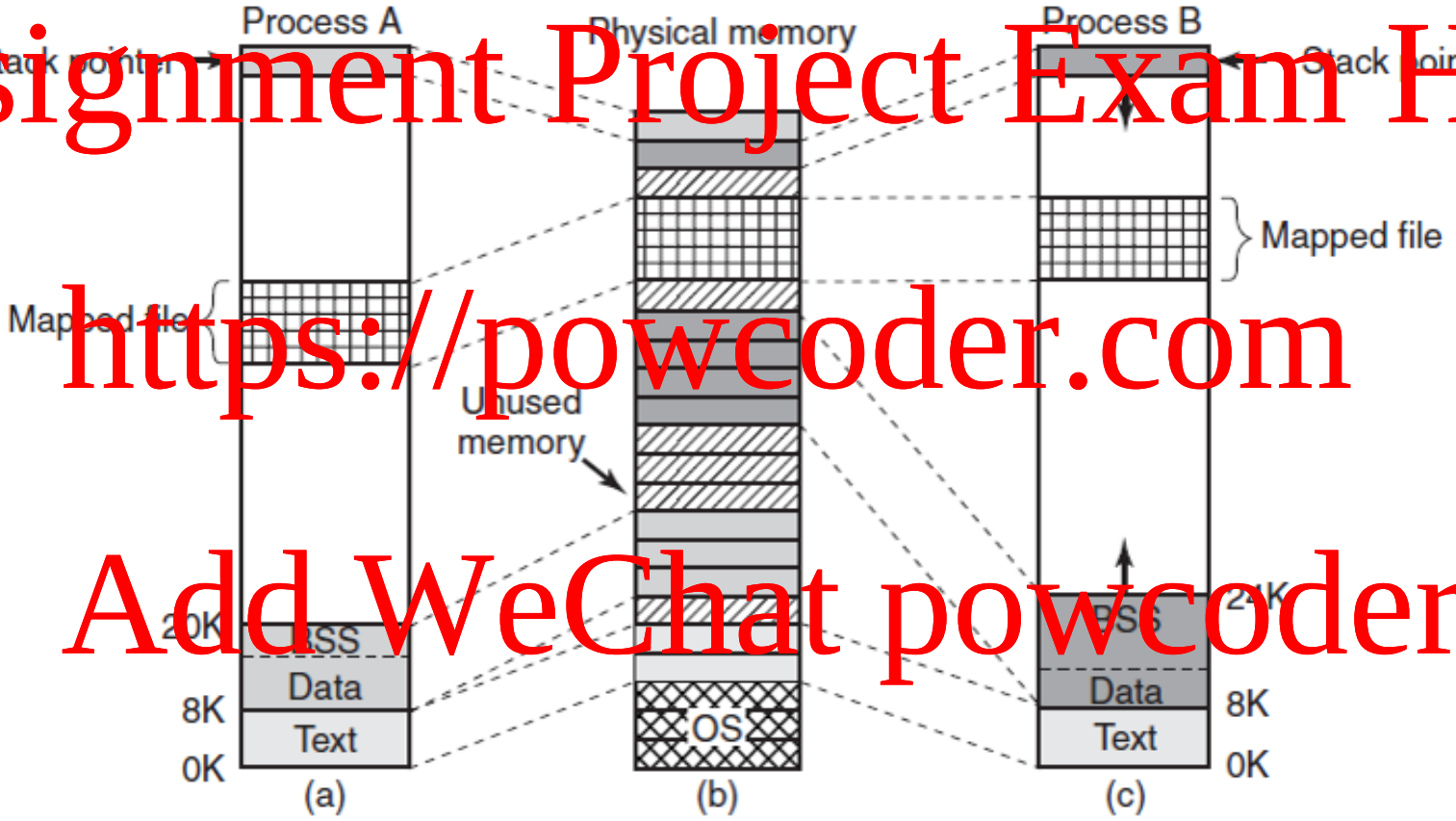

Memory Management System Calls

System call	Description
`s = brk(addr)`	Change data segment size
`a = mmap (addr,len,prot,flags,fd,offset)`	Map a file/device into memory
`s = munmap (addr,len)`	Unmap a file/device from memory

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Return code `s` is -1 if error

`a` and `addr` are memory addresses

`len` is a length

`prot` controls protection

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`flags` are miscellaneous bits

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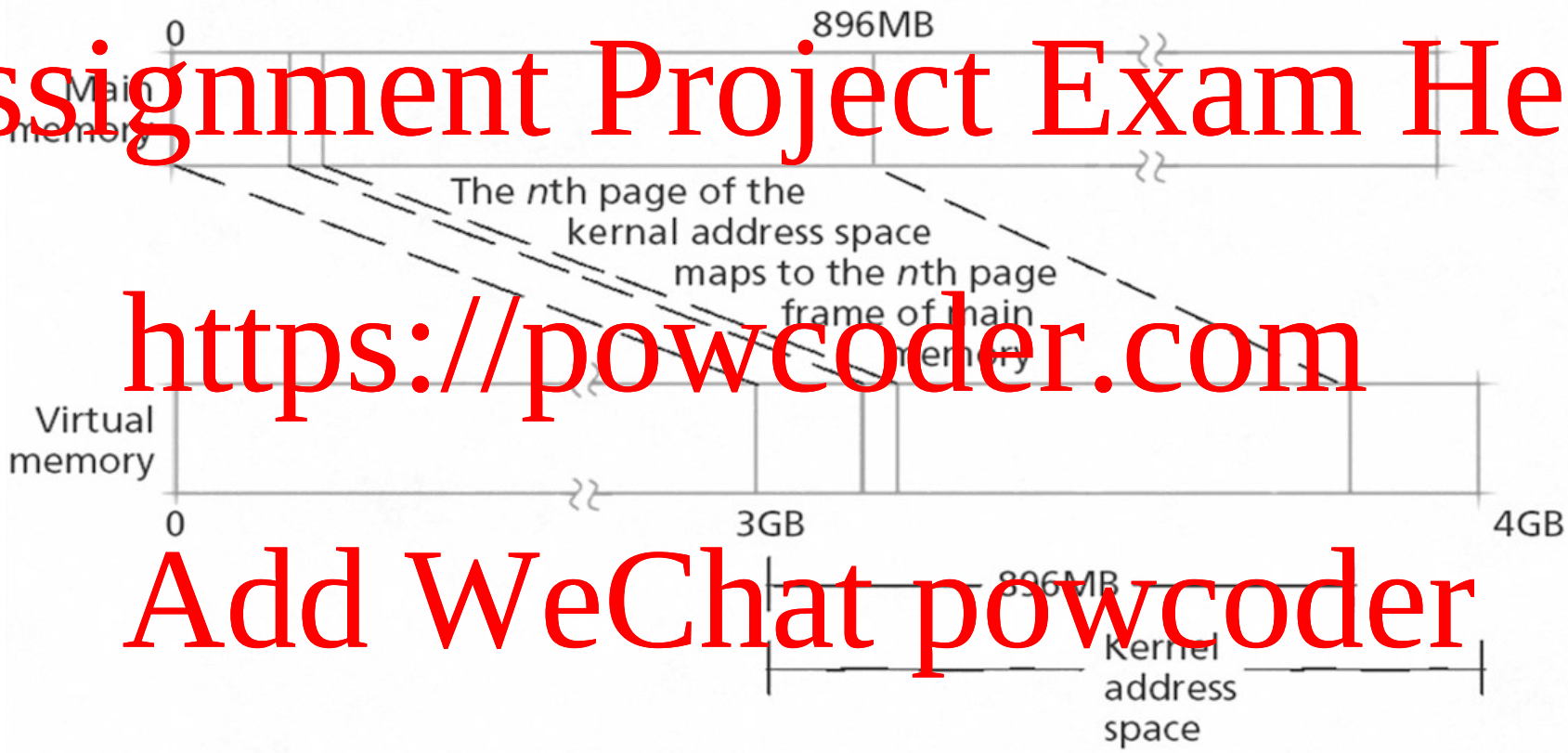
`fd` is a file descriptor

`offset` is a file offset

Virtual Memory Layout I



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Virtual Memory Layout II

On a 32-bit machine, process has 4 GB of space

Top 1 GB used for Kernel memory

- User processes can make system calls without TLB flush
- Kernel space not visible in user mode
- Kernel typically resides in 0 – 1 GB of physical memory

Kernel maps lower 896 MB of physical memory to its virtual address space

- All memory access must be virtual but need efficient access to user memory + DMA in low memory
- Create temporary mappings for $>$ 896 MB of physical memory in remaining 128 MB of virtual memory

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Physical Memory Management

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Linux memory zones

- ZONE_DMA and ZONE_DMA32: pages used for DMA
- ZONE_NORMAL: normal regularly mapped pages
- ZONE_HIGHMEM ($>$ 896 MB): pages with high memory addresses – not permanently mapped

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Kernel and memory map are pinned, i.e. never paged out

Paging

	Usually on IA-32	On x86-64
Page size	4 KB	Larger page sizes (e.g. 4 MB)
Virtual address space	4 GB	128 TB
Page-table	Two-level (or three levels with Physical Address Extension (PAE))	Up to four-level page table

Offset bits contain page status: dirty, read-only, ...

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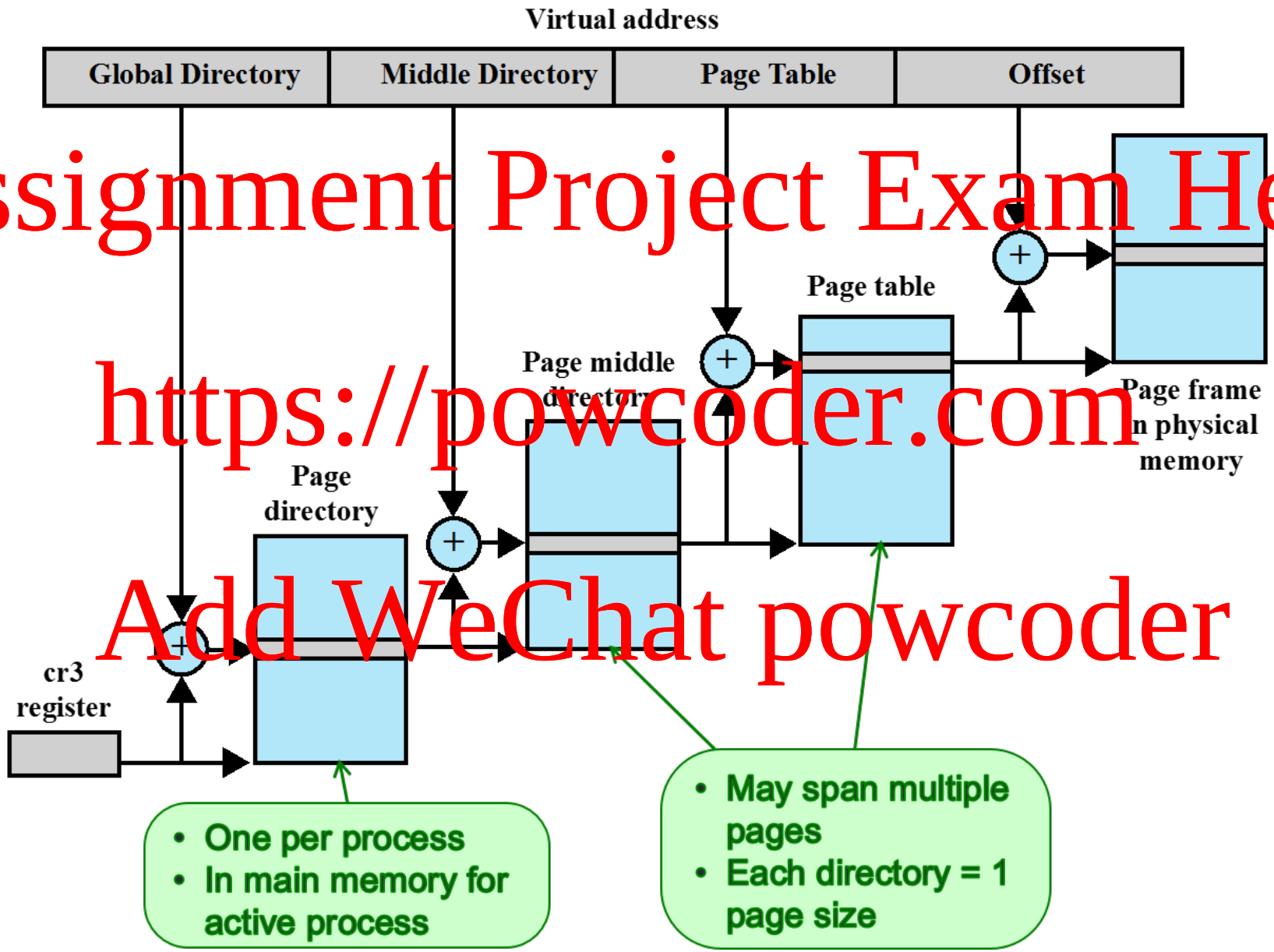
3-level Paging



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Buddy Memory Allocation

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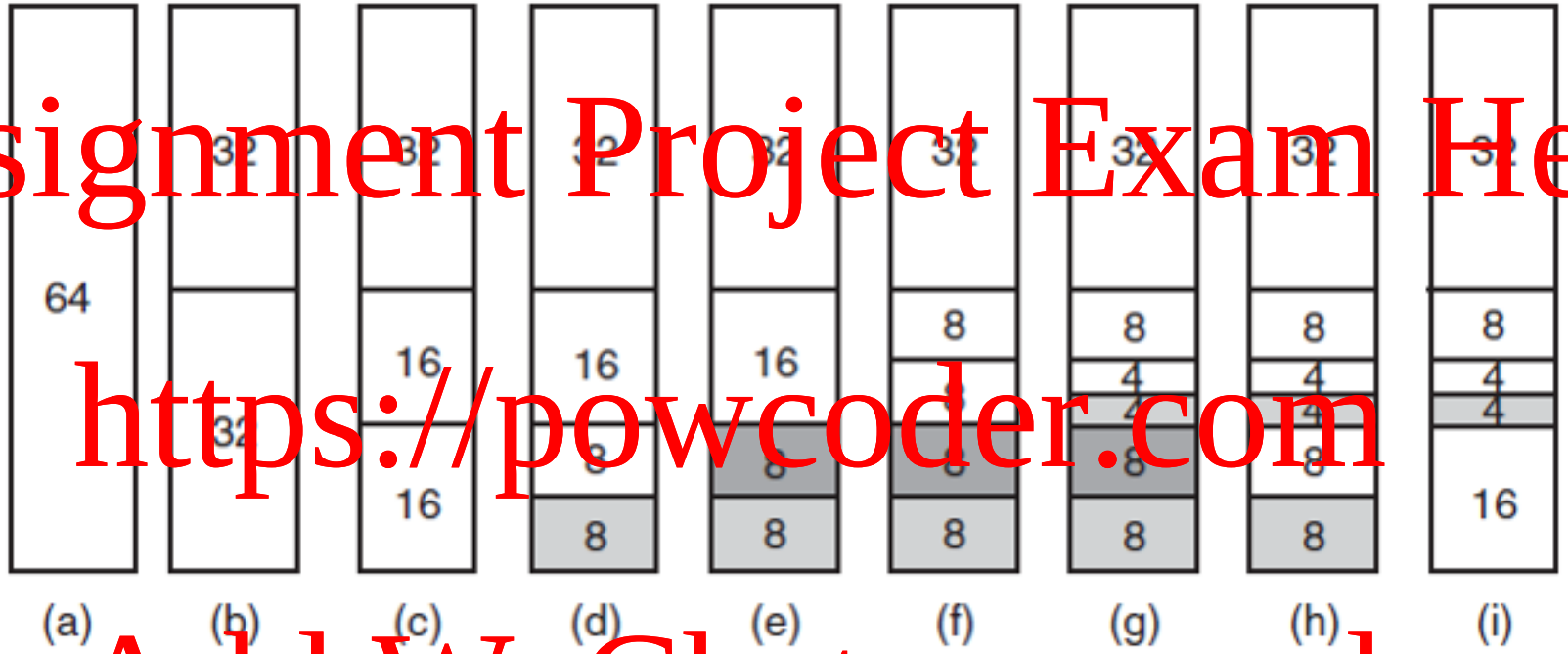

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- Tries to map contiguous pages to contiguous frames to optimise transfers
- Split and merge frames as required

Page Replacement I

Linux uses variation of clock algorithm to approximate LRU page-replacement strategy

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Memory manager uses two linked lists (and reference bits)

- **Active list**
  - Contains active pages
  - Most-recently used pages near head of active list
- **Inactive list**
  - Contains inactive pages
  - Least-recently used pages near tail of inactive list
- Only replace pages in inactive list

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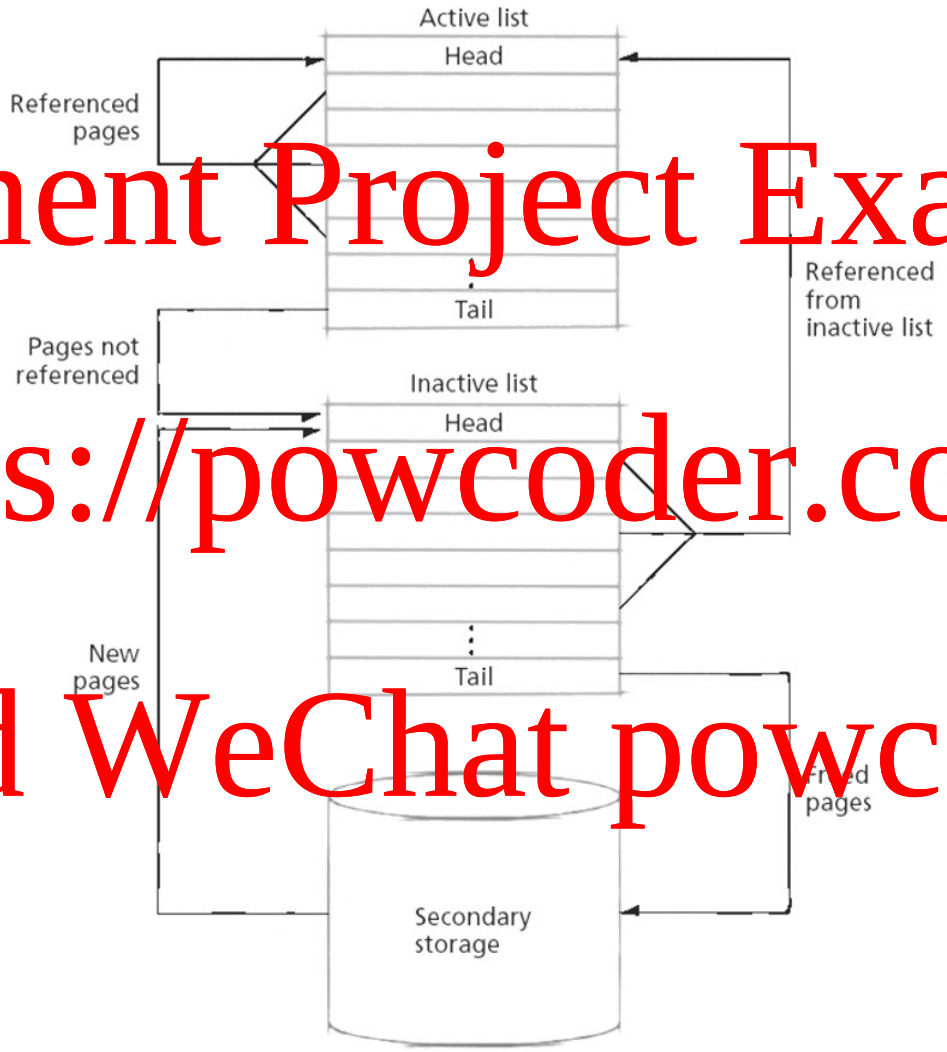
Page Replacement II



Assignment Project Exam Help
https://powcoder.com
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Page Replacement III

Assignment Project Exam Help

kswapd (swap daemon)

- Pages in inactive list reclaimed when memory low
- Uses dedicated swap partition or file
- Must handle locked and shared pages

https://powcoder.com

pdflush kernel thread

- Periodically flushes dirty pages to disk

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