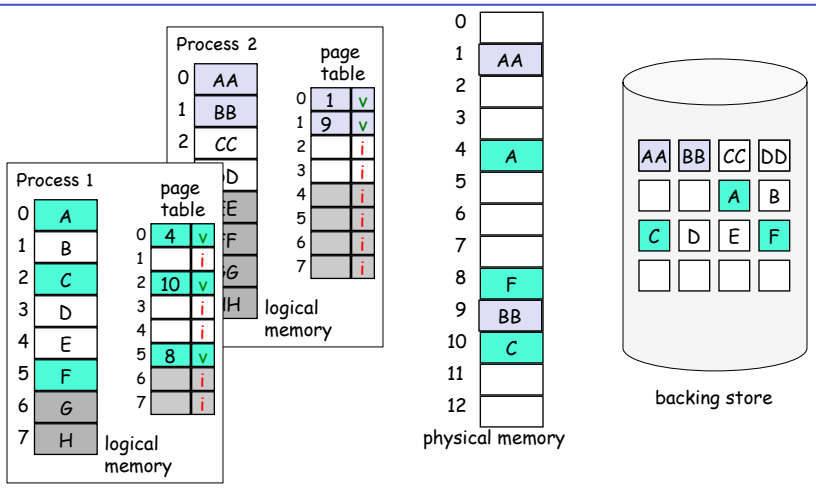
Virtual Memory

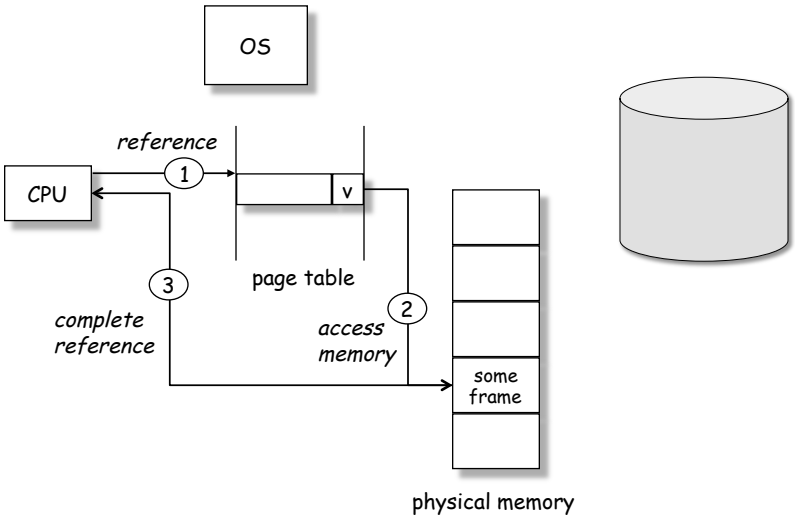
- Overview / Motivation
- Locality of Reference
- Demand Paging
- Policies
  - Placement
  - Replacement
  - Allocation

Demand Paging

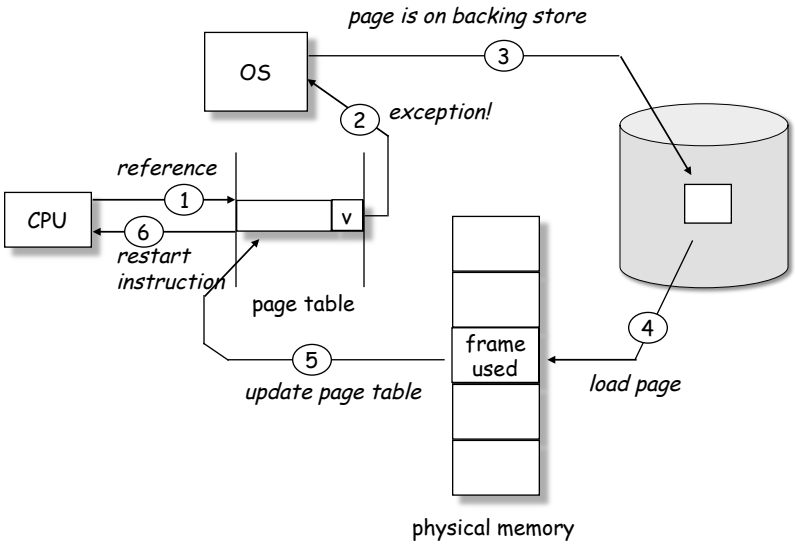


- "Lazy Swapper": only swap in pages that are needed.
- Whenever CPU tries to access a page that is not swapped in, a **page fault** occurs.

Mechanics of a Memory Reference



Mechanics of a Page Fault

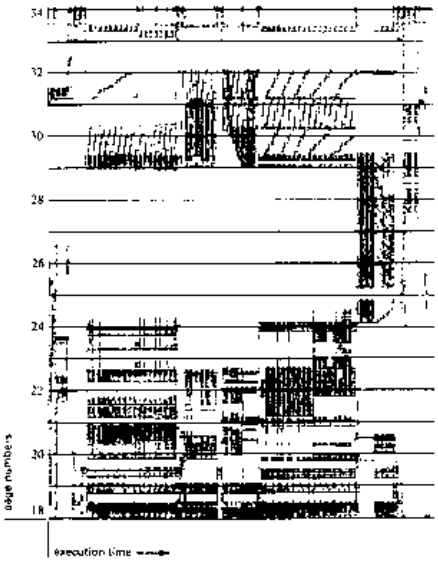


Locality of Reference

- Page faults are expensive!
- **Thrashing**: Process spends most of the time paging in and out instead of executing code.
- Most programs display a pattern of behavior called the **principle of locality of reference**.

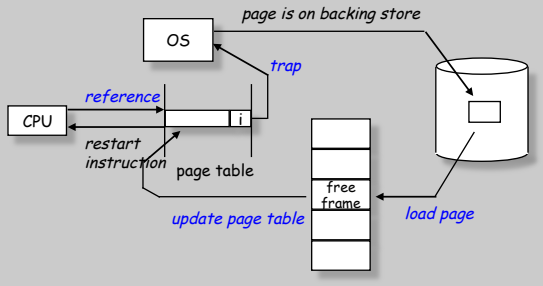
Locality of Reference: A program that references a location *n* at some point in time is likely to reference the same location *n* and locations in the immediate vicinity of *n* in the near future.

Memory Access Trace: Example



Performance of Demand Paging

Operations during Page Fault:



1. service page fault interrupt
2. swap in page
3. restart process

Effective Memory Access Time ema:

*ema = (1-p) * ma + p * "page fault time"*

where

- *p* = probability of a page fault
- *ma* = memory access time

Interlude: Architectural Considerations

- Must be able to restart any instruction after a page fault, *e.g.*,

  `ADD A,B TO C`

- What about operations that modify several locations in memory?
  - e.g. block copy operations?
- What about operations with side effects?
  - e.g. PDP-11, 80x86 auto-decrement, auto-increment operations?
  - Add mechanism for OS to "undo" instructions.

OS Policies for Virtual Memory

- **Fetch Policy**
  - How/when to get pages into physical memory.
  - demand paging *vs.* pre-paging.
- **Placement Policy**
  - Where in physical memory to put pages.
  - Only relevant in NUMA machines.
- **Replacement Policy**
  - Physical memory is full. Which frame to page out?
- **Resident Set Management Policy**
  - How many frames to allocate to process?
  - Replace someone else's frame?
- **Cleaning Policy**
  - When to write a modified page to disk.
- **Load Control**

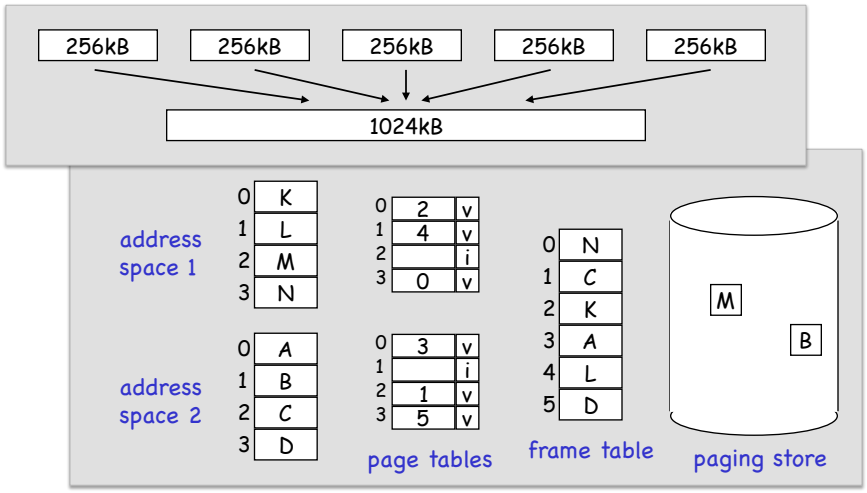
Configuring the Windows Memory Manager

- Registry Values that Affect the Memory Manager:

```
ClearPageFileAtShutdown
DisablePagingExecutive
IoPageLockLimit
LargePageMinimum
LargeSystemCache
NonPagedPoolQuota
NonPagedPoolSize
PagedPoolQuota
PagedPoolSize
SystemPages
```

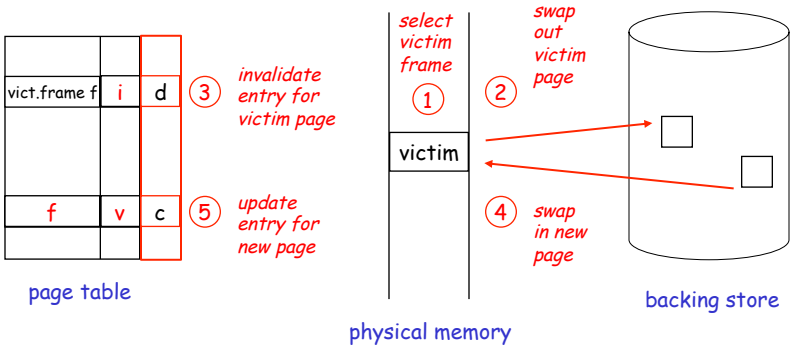
Page Replacement

- Virtual memory allows higher degrees of multiprogramming by over-allocating memory.



Mechanics of Page Replacement

Invoked whenever no free frame can be found.



Problem: Need two page transfers

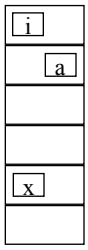
Solution: **Dirty bit**.

Page Replacement Algorithms

- Objective: Minimize page fault rate.
- Why bother?

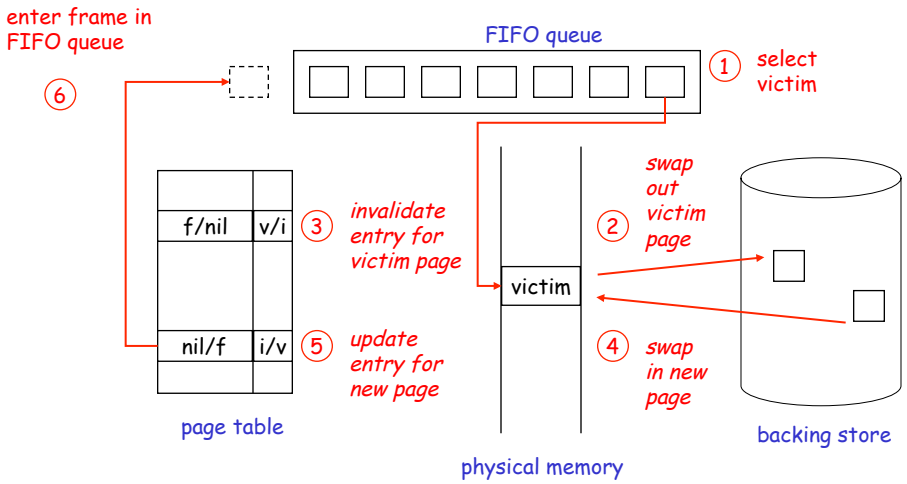
- Example

```
for(int i=0; i<10; i++) {
  a = x * a;
}
```



- Evaluation: Sequence of memory references: **reference string**.

FIFO Page Replacement



FIFO Page Replacement (cont.)

- Example:

time	1	2	3	4	5	6	7	8	9	10
reference string	c	a	d	b	e	b	a	b	c	d
frames	a	a	a	a	a	e	e	e	e	e	d
	b	b	b	b	b	b	b	a	a	a	a
	c	c	c	c	c	c	c	c	b	b	b
	d	d	d	d	d	d	d	d	d	c	c
						!		!	!	!	!

- Advantage: simplicity
- Disadvantage: Assumes that pages residing the longest in memory are the least likely to be referenced in the future (does not exploit *principle of locality*).

Optimal Replacement Algorithm

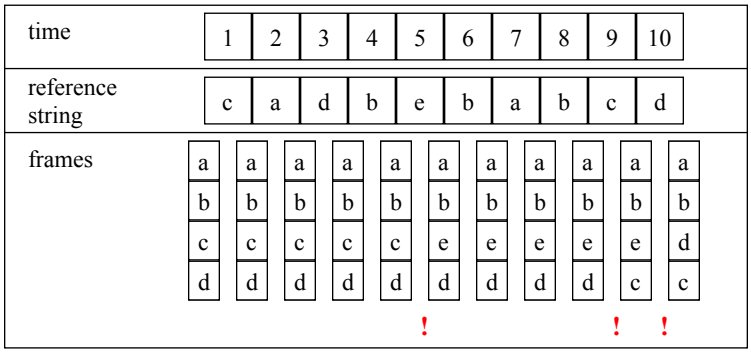
Algorithm with provably lowest page fault rate of all algorithms:

Replace that page which will not be used for the longest period of time (in the future).

time	1	2	3	4	5	6	7	8	9	10
reference string	c	a	d	b	e	b	a	b	c	d
frames	a	a	a	a	a	a	a	a	a	a	d
	b	b	b	b	b	b	b	b	b	b	b
	c	c	c	c	c	c	c	c	c	c	c
	d	d	d	d	d	e	e	e	e	e	e
						!				!	

Approximation to Optimal: LRU

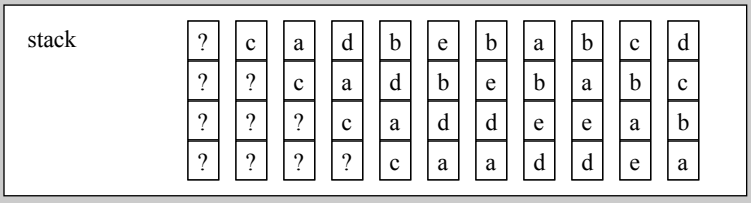
Least Recently Used: replace the page that has not been accessed for longest period of time (in the past).



LRU: Implementation

Problem: We need to keep chronological history of page references; need to be reordered upon each reference.

- **Stack:**



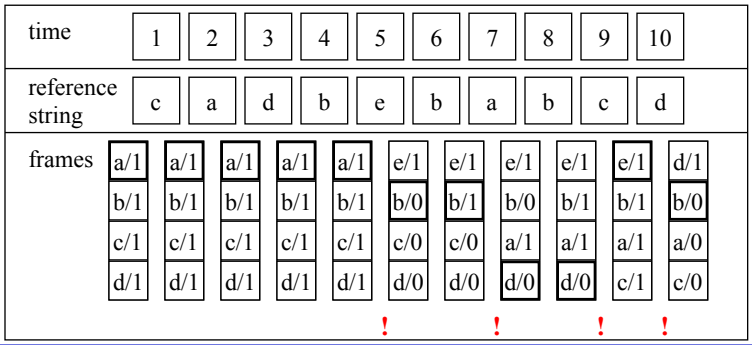
- **Capacitors:** Associate a capacitor with each memory frame. Capacitor is charged with every reference to the frame. The subsequent exponential decay of the charge can be directly converted into a time interval.

- **Aging registers:** Associate aging register of n bits (R_{n-1}, ..., R_0) with each frame in memory. Set R_{n-1} to 1 for each reference. Periodically shift registers to the right.

Approximation to LRU: Clock Algorithm

Associate a *use_bit* with every frame in memory.

- Upon each reference, set *use_bit* to 1.
- Keep a pointer to first "victim candidate" page.
- To select victim: If current frame's *use_bit* is 0, select frame and increment pointer. Otherwise delete *use_bit* and increment pointer.



Improvement on Clock Algorithm (Second Chance Algorithm)

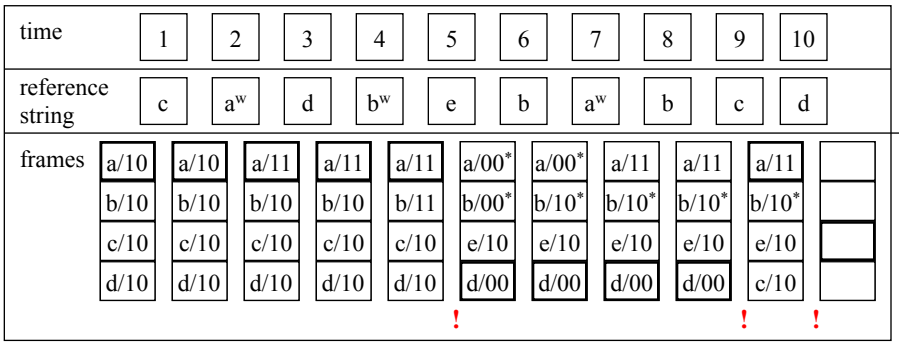
- Consider read/write activity of page: *dirty_bit* (or *modify_bit*)
- Algorithm same as clock algorithm, except that we scan for frame with both *use_bit* and *dirty_bit* equal to 0.
- Each time the pointer advances, the *use_bit* and *dirty_bit* are updated as follows:

	ud	ud	ud	ud
before	11	10	01	00
after	01	00	00*	(select)

- Called *Second Chance* because a frame that has been written to is not removed until <u>two</u> full scans of the list later.
- <u>Note</u>: Other authors (e.g., Stallings) describe a slightly different algorithm!

Improved Clock (cont)

- Example:

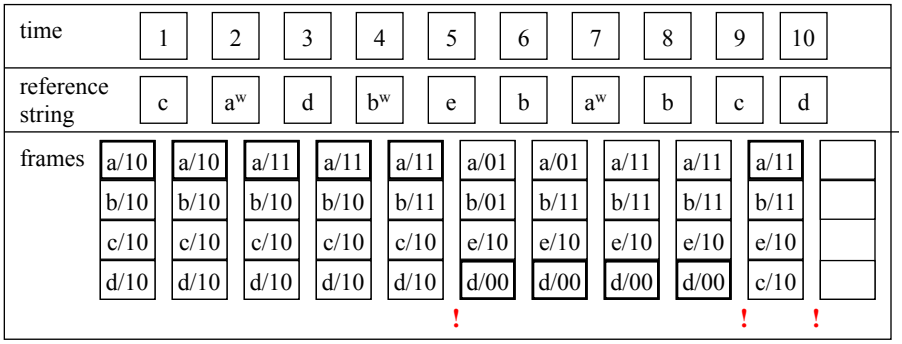


The Macintosh VM Scheme (see Stallings)

- Uses **use_bit** and **modify_bit**.
- **Step 1:** Scan the frame buffer. Select first frame with **use_bit** and **modify_bit** cleared.
- **Step 2:** If Step 1 fails, scan frame buffer for frame with **use_bit** cleared and **modify_bit** set. During scan, clear **use_bit** on each bypassed frame.
- Now all **use_bit**'s are cleared. Repeat Step 1 and, if necessary, Step 2.

The Macintosh Scheme (cont)

- Example:



Resident Set Management

- Local vs. Global replacement policy:
  - Local: The page to be replaced is selected from the resident set of pages of the faulting process.
  - Global: The page to be replaced may belong to any of the processes in memory.
- Each program requires a certain minimum set of pages to be resident in memory to run efficiently.
- The size of this set changes dynamically as a program executes.
- This leads to algorithms that attempt to maintain an optimal resident set for each active program. (Page replacement with variable number of frames.)

The Working Set Model

Working Set $W(t,\Delta)$: Set of pages referenced by process during time interval $(t-\Delta, t)$.

$$\|W(t,1)\| = 1 \qquad 1 \leq \|W(t,\Delta)\| \leq min(\Delta, N)$$

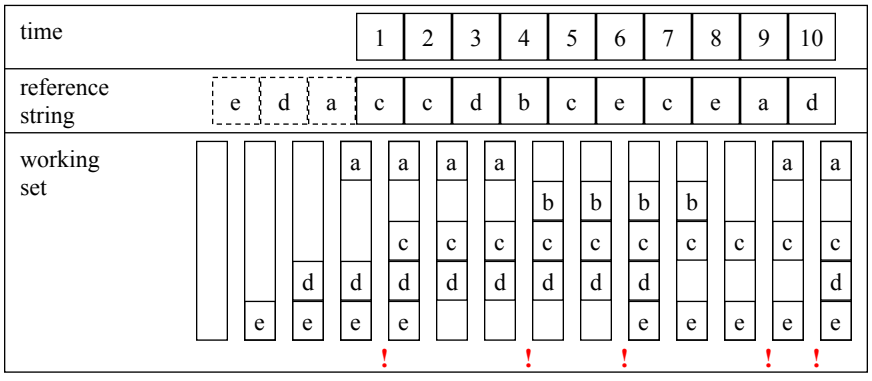
The storage management strategy follows two rules:

- Rule 1: At each reference, the current working set is determined and only those pages belonging to the working set are retained in memory.
- Rule 2: A program may run only if its entire current working set is in memory.

Underlying Assumption: Size of working set remains constant over small time intervals.

Working Set Model (cont.)

- Example: (Δ = 4)



Problems:

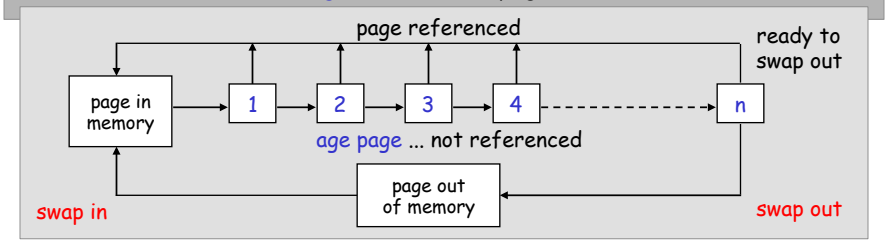
- Difficulty in keeping track of working set.
- Estimation of appropriate window size Δ.

Improve Paging Performance: Page Buffering

- Victim frames are not overwritten directly, but are removed from page table of process, and put into:
  - free frame list (clean frames)
  - modified frame list (modified frames)
- Victims are picked from the free frame list in FIFO order.
- If referenced page is in free or modified list, simply reclaim it.
- Periodically (or when running out of free frames) write modified frame list to disk.

Page Buffering and Page Stealer

- Kernel process (e.g., `pageout` in Solaris) swaps out memory frames that are no longer part of a working set of a process, using reference bits.
- Periodically increments age field in valid pages.

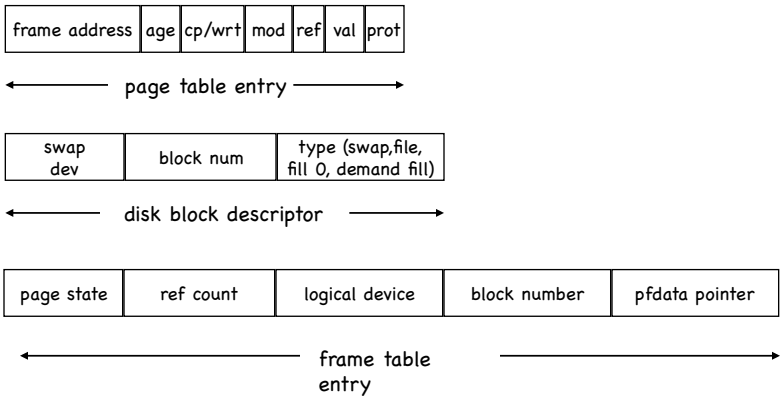


- Page stealer wakes up when available free memory is below *low-water mark*. Swaps out frames until available free memory exceeds *high-water mark*.
- Page stealer collects frames to swap and swaps them out in a single run. Until then, frames still available for reference.

`fork()` System Call in Paging Systems

- Naive: `fork()` makes a physical copy of parent address space. However, `fork()` mostly followed by an `exec()` call, which overwrites the address space.
- Lazy Copy: Use `copy_on_write` bit:
  - During `fork()` system call, only page table is copied. All `copy_on_write` bits of pages are set. If either process writes to the page, incurs protection fault, and, in handling the fault, kernel makes a new copy of the page for the faulting process.
- In practice, this is a bit trickier…

Implementation of Demand Paging in UNIX SVR4



Linux Frame Table

- Every page is represented by:

```
struct page {
    ulong   flags;              // dirty, locked, etc.
    atomic_t  count;            // reference counter
    struct list_head  list;
    struct AS  *mapping;        // address space associated with page
    ulong  index;
    struct list_head lru;
    (pte)
    (private)
    void * virtual;             // virtual address (could be null)
    /* … etc. */
}
```

Demand Paging on Less-Sophisticated Hardware

- Demand paging most efficient if hardware sets the *reference* and *dirty* bits and causes a protection fault when a process writes a page whose *copy_on_write* bit is set.
- Can duplicate *valid* bit by a *software-valid* bit and have the kernel turn off the *valid* bit. The other bits can then be simulated in software.

Example: **Reference Bit:**

- If process references a page, it incurs a page fault because *valid* bit is off. Page fault handler then checks *software-valid* bit.
- If set, kernel knows that page is really valid and can set *software-reference* bit.

Hardware Valid	Software Valid	Software Reference
Off	On	Off

before referencing page

Hardware Valid	Software Valid	Software Reference
On	On	On

after referencing page

Exercise: Implement Copy-on-Write

Given:
- valid bit
- read-only bit

Implement:
- copy-on-write bit