Linux memory management (with focus on page allocations/reclaim)

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Documentation and other sources

- Documentation/mm
  - Still ad-hoc, ongoing but rather glacial effort to systematize and fill the gaps
- Books (of the past and the future)
  - Understanding The Linux Virtual Manager (Mel Gorman)
    - Very good and systematic coverage but too old – from 2.4 era (with *What's new in 2.6* sections)
    - Still very useful to understand core design principles
    - https://www.kernel.org/doc/gorman/
  - The Linux Memory Manager (Lorenzo Stoakes)
    - "The target release date is late 2024" and "the book will target Linux 6.0"
    - "I have written 1,291 pages of the book, the first draft of which is nearly complete!"
    - https://linuxmemory.org/
- LWN - https://lwn.net/
  - Many very good articles (not limited to kernel), LSF/MM/BPF conference coverage…
- Various company-branded or personal blog posts

Linux MM – APIs for kernel

- bootmem/memblock allocator – early initialization
- page allocator – page order (2^N physically contiguous pages)
- slab allocator – sub page granularity, internal fragmentation management
  - SLUB – the remaining implementation – aimed for better scalability at the expense of more memory, much better debugging capabilities than the original SLAB had
- vmalloc – virtually contiguous memory allocator – via page tables
- mempool allocator – a layer on top of page or slab allocator
  - guarantee for a forward progress – mostly for IO paths
- page cache management for filesystems
- userspace memory handling and accounting – process management
- page table management
  - `get_user_pages()` – virtual→struct page translation
  - generic page table walkers

MM – APIs for userspace

- Syscalls to manage memory
  - mmap, munmap, mprotect, brk, mlock – POSIX
  - madvise – hints from userspace e.g. MADV_DONTNEED, MADV_FREE etc...
  - userfaultfd – page fault handling from userspace
  - SystemV shared memory – IPC, shmget, shmat, shmdt
  - memfd_create – anonymous memory referenced by a file descriptor – for IPC
- Memory backed filesystems
  - ramdisk – fixed sized memory backed block device
  - ramfs – simple memory backed filesystem
  - tmpfs – more advanced memory backed filesystem, support for swapout, ACL, extended attributes
- Memory cgroups controller – more fine grained partitioning of the system memory
  - Mostly for user space consumption limiting, kernel allocations are opt-in
  - Support for hard limit, soft/low limit, swap configuration, userspace OOM killer
- Access to huge pages (traditionally 2MB, 1GB)
  - hugetlbfs – filesystem backed by preallocated huge pages
  - THP – transparent huge pages for anonymous private or tmpfs memory
  - mTHP – allows sizes with more granularity than page table levels (i.e. between 4kB and 2MB on x86_64)
- NUMA allocation policies
  - mbind, set_mempolicy, get_mempolicy

Physical memory representation

- Managed in page size granularity – arch specific, mostly 4kB
- Each order-0 page is represented by `struct page`
  - Higher-order pages typically “compound pages”, first struct page “head”, the rest “tail” with a link to head, the tail pages might be used to store additional information, e.g. the order is stored in the first tail page
- Heavily packed – 64B on 64bit systems (~1.5% with 4kB pages)
  - Unions to distinguish different usage, or distinct types reinterpreting whole struct page (e.g. `struct slab`)
  - Special tricks to save space – set bottom bits in pointers etc…
  - Page flags for various page states, including page lock (bit lock)
- Statically allocated during boot/memory hotplug – memmap
  - Typically “sparsemem vmemmap” – virtually contiguous, `0xffffea`… on x86_64 (modulo KASLR)
  - Pages belong to different NUMA nodes and zones within nodes, node/zone ids are part of page flags word
- Reference counted to control lifetime and allow sharing and ad-hoc access
  - `get_page()`, `put_page()`, `get_page_unless_zero()`
  - memory is returned to the page allocator when refcount drops to 0
- `pfn_valid()`, `pfn_to_page()`, `page_to_pfn()` – physical page frame number to struct page translation
- `struct folio` – a new type to better abstract both order-0 and compound head page (cannot be a tail page), layout matches `struct page`, gradually introduced throughout the kernel

Page allocator

- `alloc_pages(gfp_t gfp_mask, unsigned int order)` to get a `struct page` (and the associated physical memory)
  - `alloc_pages_node(int nid, ...)` to indicate the preferred numa node
- `order` – size of the allocation will be 2^{order} contiguous naturally aligned pages
- `gfp_mask` – bitmask for the allocation mode
  - Restrict to/*allow* specific zones – `__GFP_DMA, __GFP_DMA32,` *`__GFP_HIGHMEM, __GFP_MOVABLE`*
  - Define allocation context wrt possibility of doing memory reclaim if free memory not available anymore
    - `__GFP_KSWAPD_RECLAIM, __GFP_DIRECT_RECLAIM, __GFP_IO, __GFP_FS`
  - Define allocation context wrt how hard to try succeed vs availability to fallback
    - Reserves access: `__GFP_HIGH, __GFP_MEMALLOC, __GFP_NOMEMALLOC`
    - Urgency: `__GFP_NORETRY, __GFP_RETRY_MAYFAIL, __GFP_NOFAIL`
  - Page mobility hints to help anti-fragmentation mechanisms
    - `__GFP_MOVABLE, __GFP_RECLAIMABLE`
  - Standard combinations defined for most typical contexts:
    - `GFP_KERNEL`: `__GFP_RECLAIM | __GFP_IO | __GFP_FS` – unmovable allocation, can reclaim both by kswapd and directly
    - `GFP_HIGHUSER_MOVABLE`: `GFP_KERNEL | __GFP_HIGHMEM | __GFP_MOVABLE` – can reclaim, can use highmem and movable zones, pages are going to be movable
    - `GFP_NOWAIT`: `__GFP_KSWAPD_RECLAIM` – unmovable kernel allocation, cannot direct reclaim
    - `GFP_ATOMIC`: `__GFP_KSWAPD_RECLAIM | __GFP_HIGH` – like `GFP_NOWAIT` but higher priority, can dip into reserves

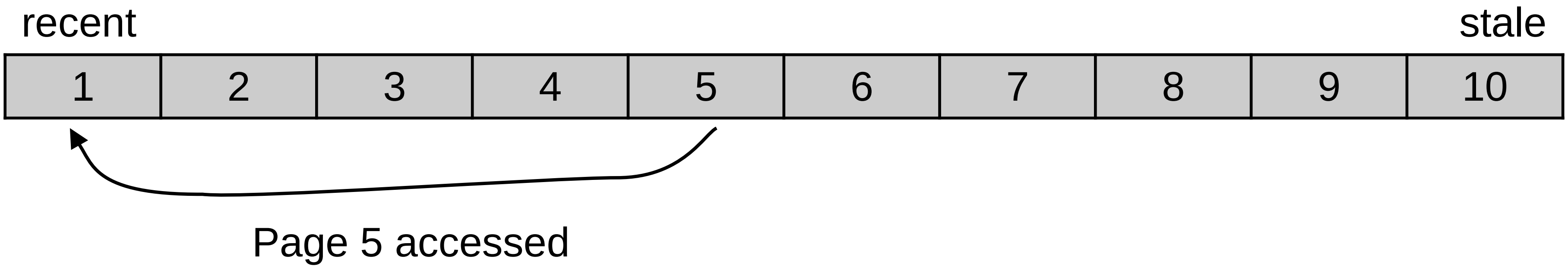
Page allocator – memory reclaim

- Eventually memory will become (nearly) all used due to caching file contents (page cache) as well as kernel objects, for faster access
- Each zone has watermarks (scaled to its size) `min < low < high`, free pages checked during page allocation
  - Below low watermark: wake up kswapd kthread to reclaim up to high watermark
  - Below min watermark: the allocation itself has to reclaim up to min watermark
- Reclaim will try to evict a mix of userspace pages and kernel objects
  - Anonymous pages (from `mmap(MAP_PRIVATE)`) must be swapped out first
  - Page cache must be written back when dirty, or simply discarded when clean
  - Kernel objects: each type of reclaimable objects registers shrinker callbacks with specific implementation of both tracking of hot/coldness, and actual freeing
- To minimize disk I/O and latency, we want to reclaim cold pages
  - Struct pages are linked on a LRU list sorted from most recent (head) to least recent (tail)

LRU list – ideal model

recent									stale
1	2	3	4	5	6	7	8	9	10

LRU list – ideal model



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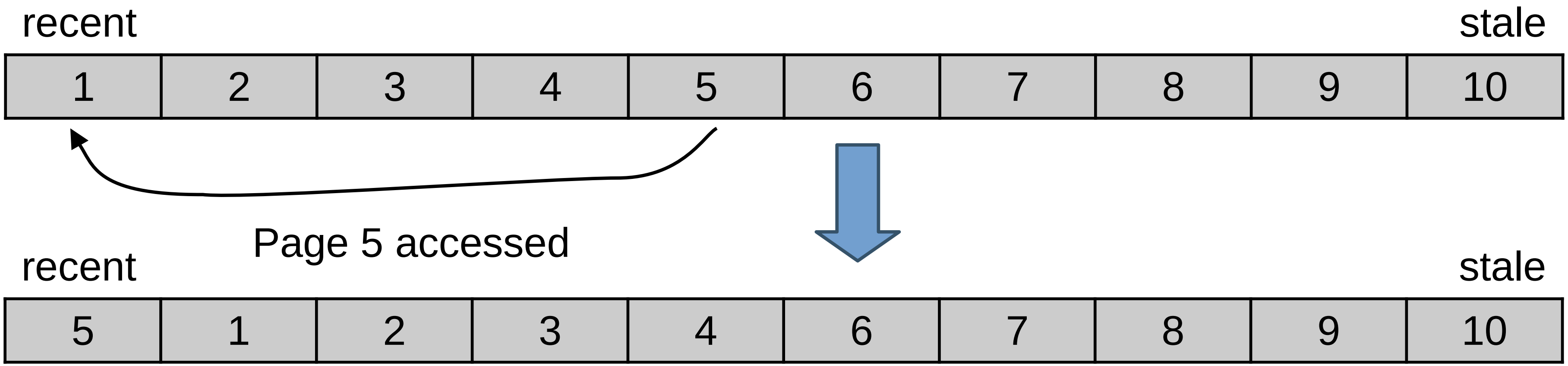

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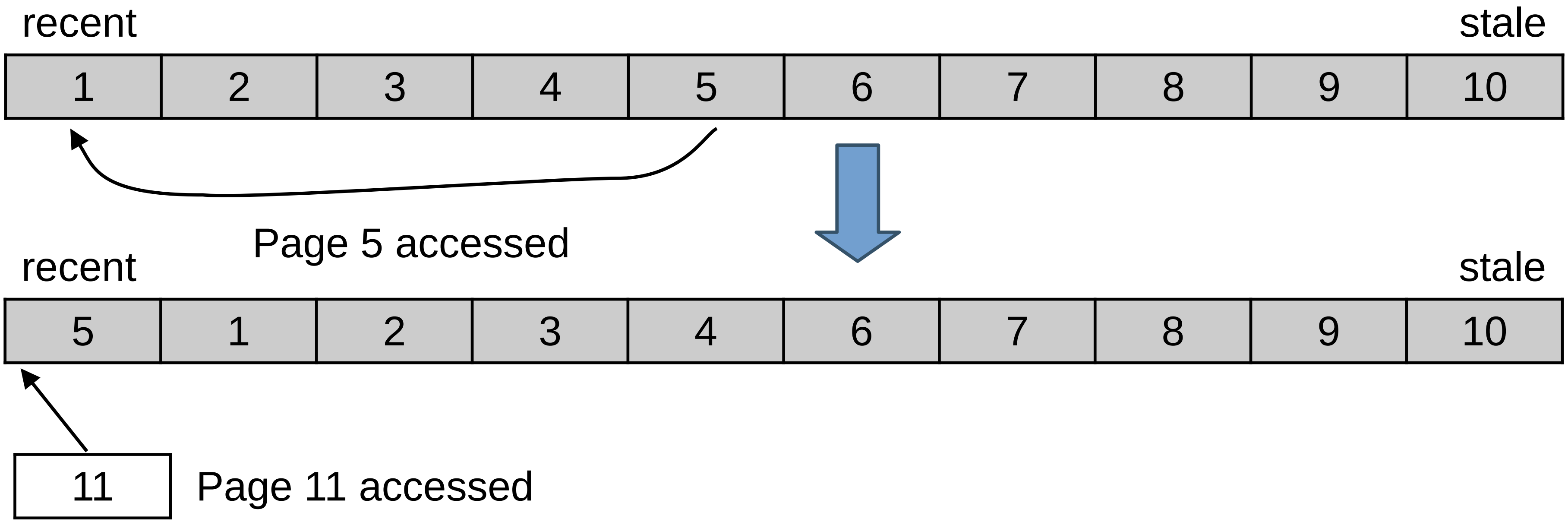

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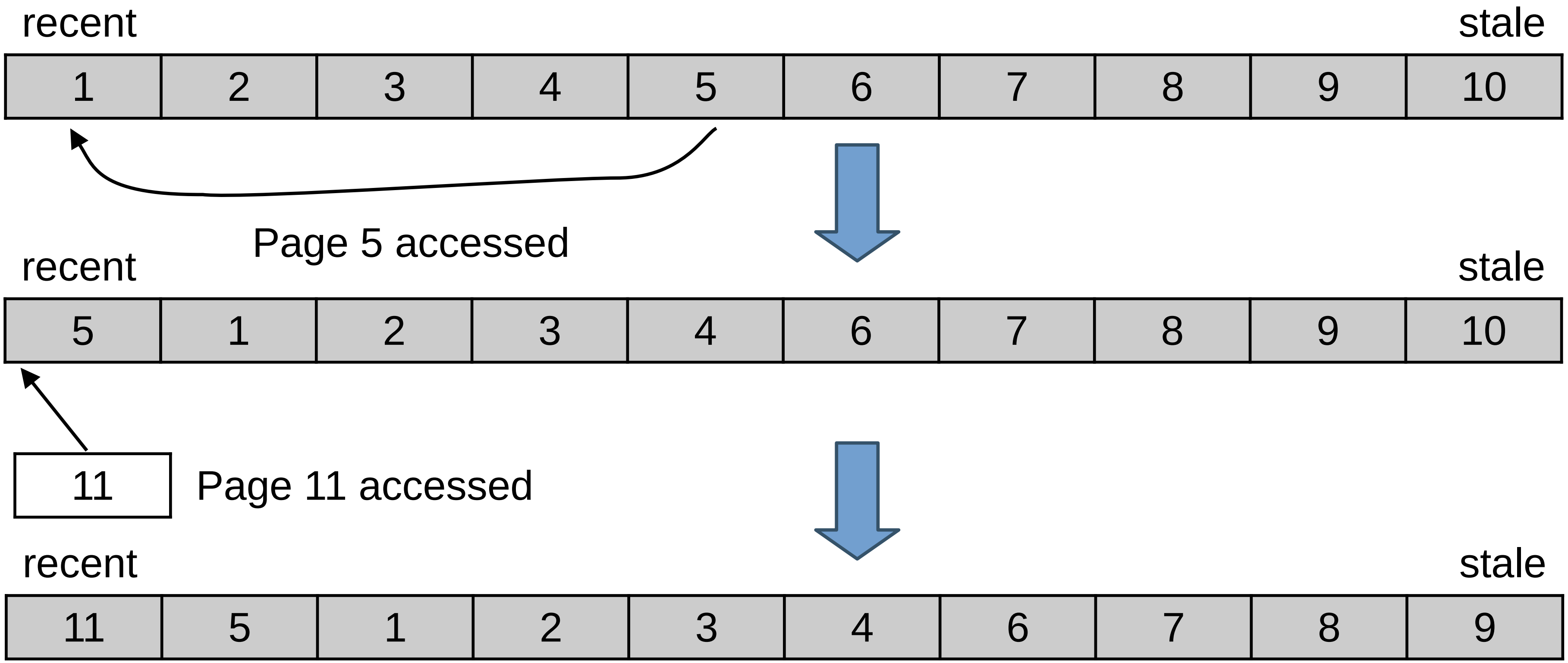

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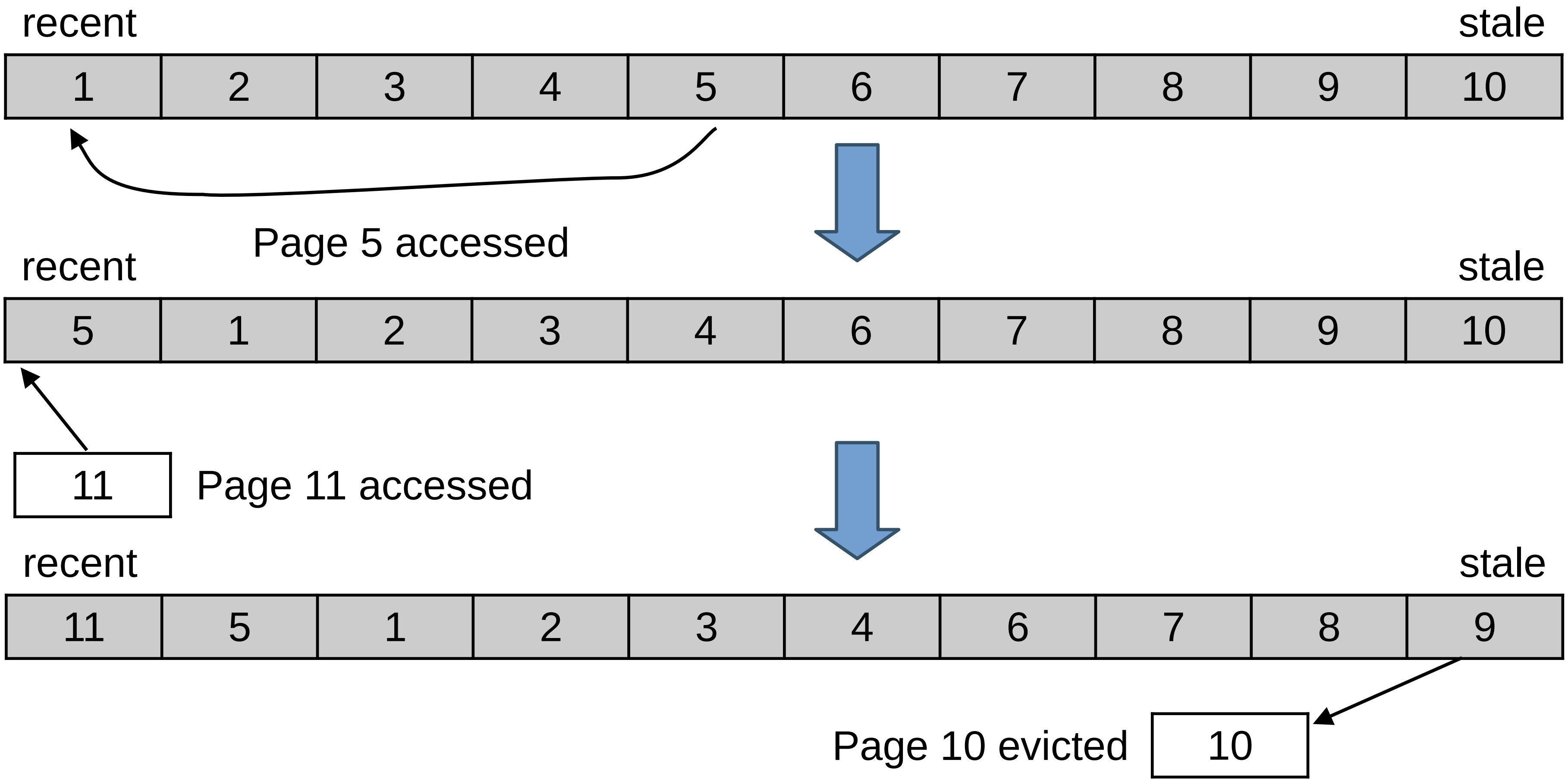

LRU – anonymous/file split

- Anonymous and file pages have distinct properties
  - Clean file pages can be just evicted, anonymous have to be swapped out at least once...
  - Historically, reclaim has been biased towards file pages more than anonymous
- Single list would be ineffective when reclaiming just one type
- Hence separate anon and file LRU lists
  - But now we **have** to choose which one (or both) to reclaim, and balance their sizes

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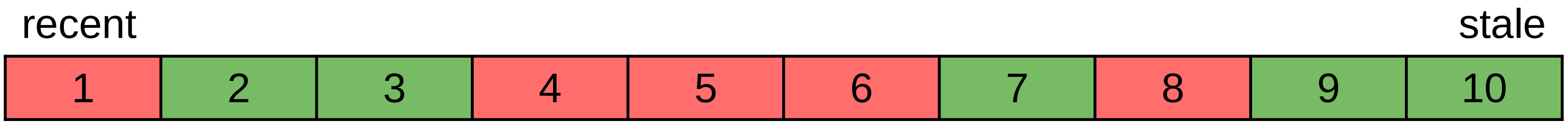

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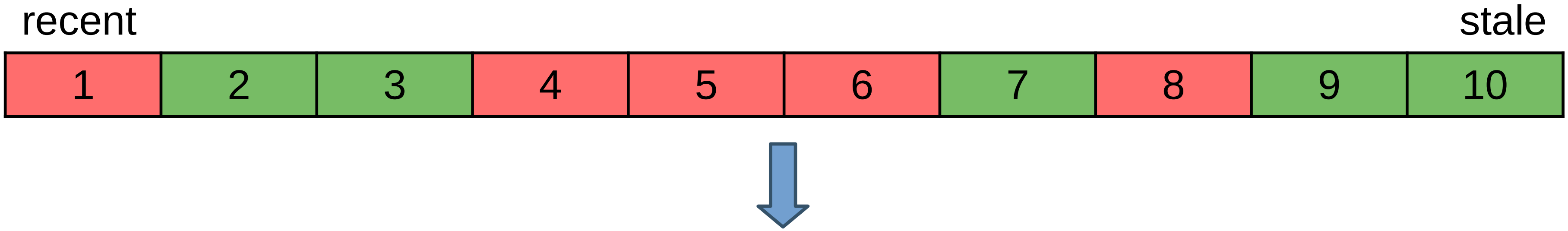

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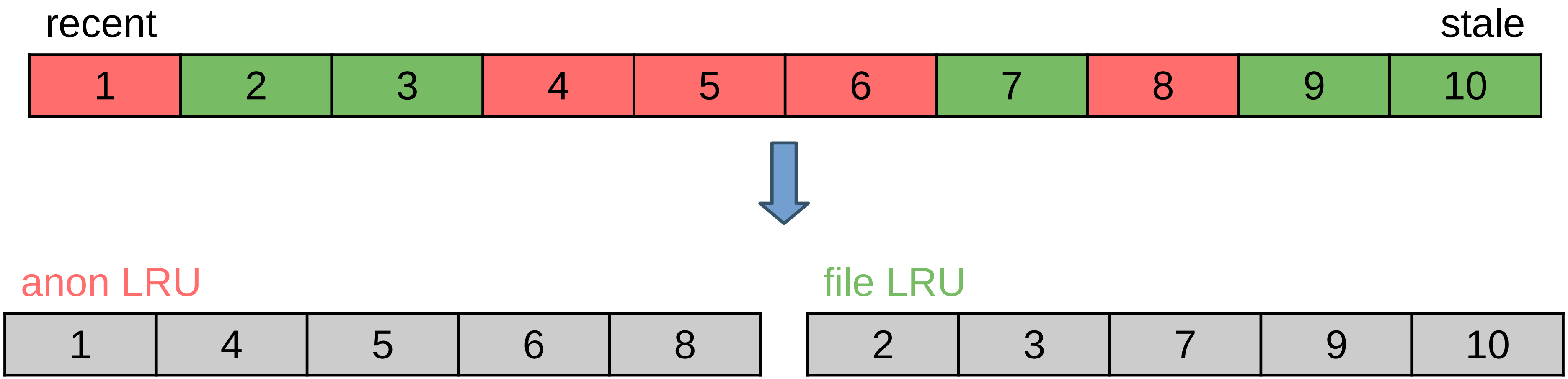

LRU – active/inactive split

- Ideal LRU model not achievable in practice
  - Capturing each memory access for precise tracking would be prohibitively slow
  - Approximated by detecting if page has been accessed since last check
  - More effective if we track hotter and colder pages separately
- Hence separate active and inactive LRU lists for each type
  - Also virtual fifth list for unevictable pages – not relevant to reclaim, not linking any pages today
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anon LRU

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file LRU

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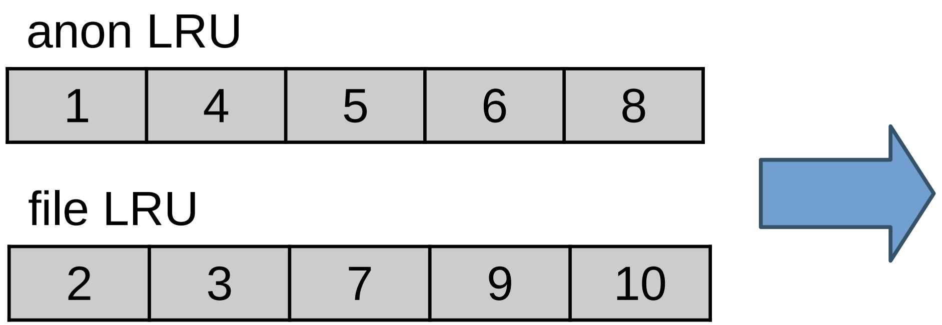

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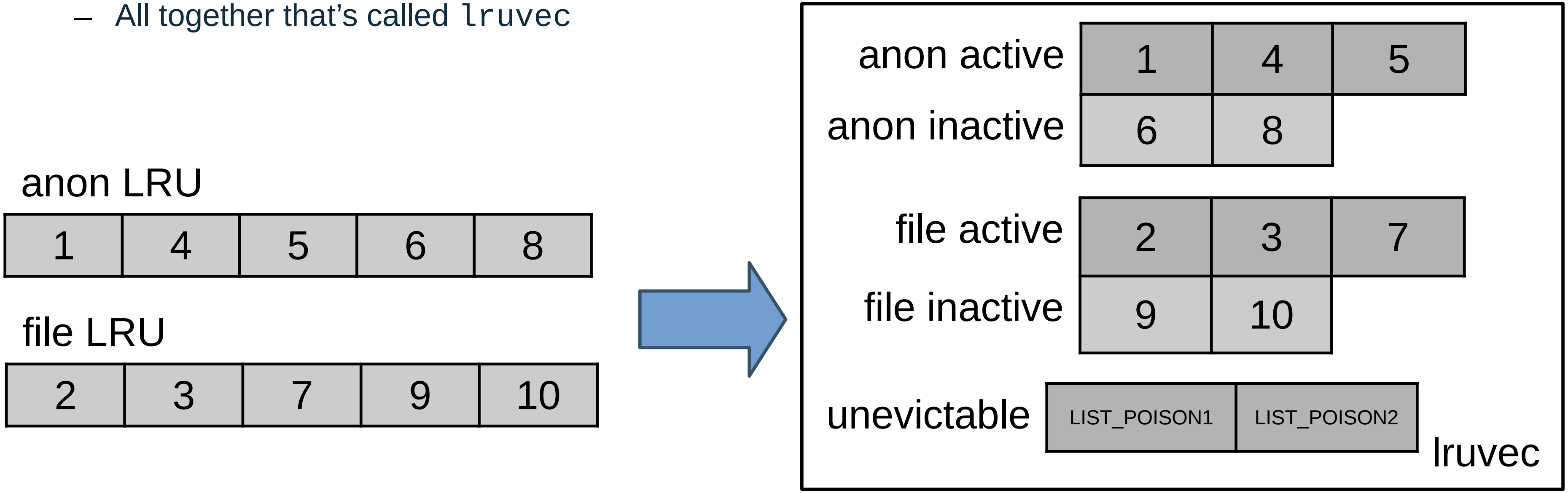

LRU – node/memcg lruvecs

- Four reclaimable LRU lists per lruvec
  - Large part of reclaim heuristics is to decide how many pages to scan and try to reclaim in each one (*shrink* the list)
    - Pages are taken from the tail of each list, can be moved to the head of another list (activated/deactivated), back to head of the same list (kept), or evicted entirely (reclaimed)

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- In practice, there are many lruvecs
  - Different memory cgroups have distinct lruvecs, for memcg reclaim
    - Global memory reclaim has to iterate over all memcgs
  - Different NUMA nodes have distinct lruvecs, as nodes are reclaimed separately
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	Root memcg	Memcg1	Memcg2	Memcg3	Memcg4	Memcg5
Node 0	lruvec	lruvec	lruvec	lruvec	lruvec	lruvec
Node 1	lruvec	lruvec	lruvec	lruvec	lruvec	lruvec

Page states relevant to reclaim selection

- Determined by page flags, mainly the following:
  - LRU – page is on any LRU list, Active – page is on active list
  - Referenced – inactive page has been accessed “recently”
  - Workingset – page is considered part of active userspace’s workingset
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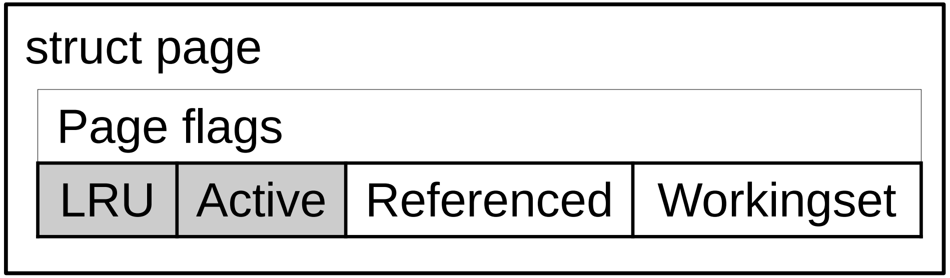

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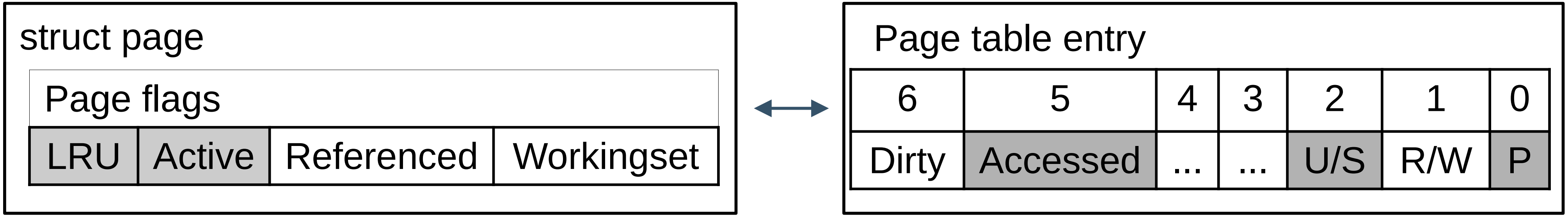

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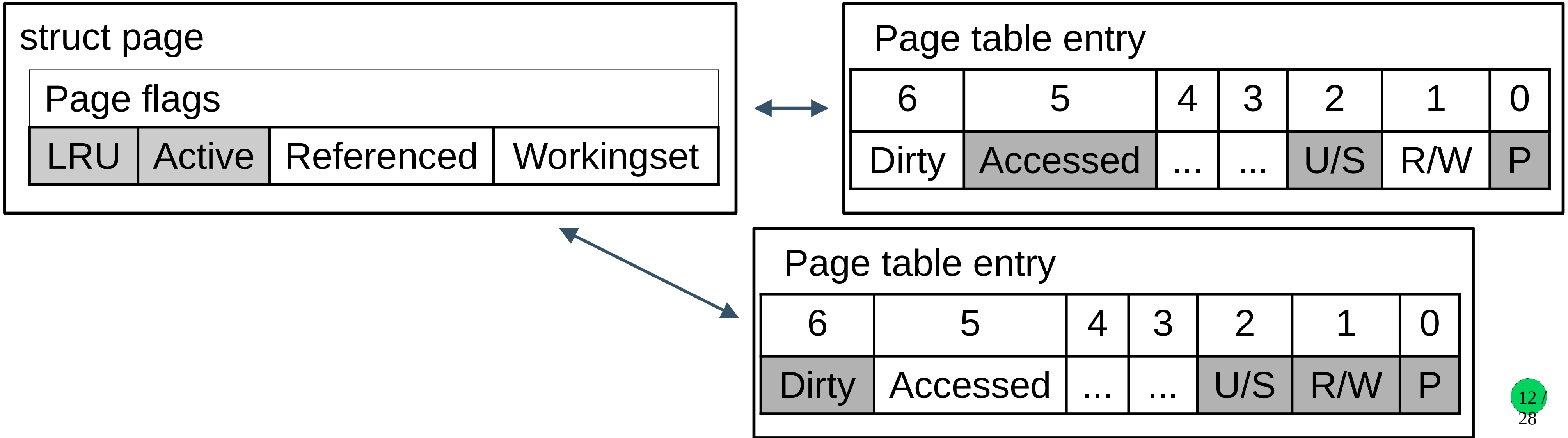

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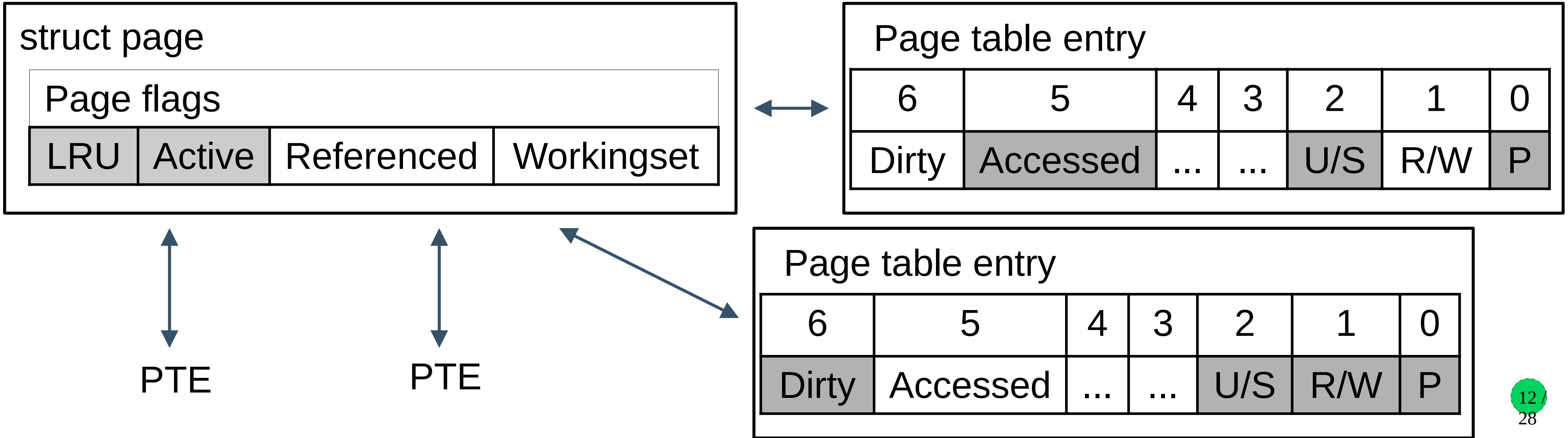
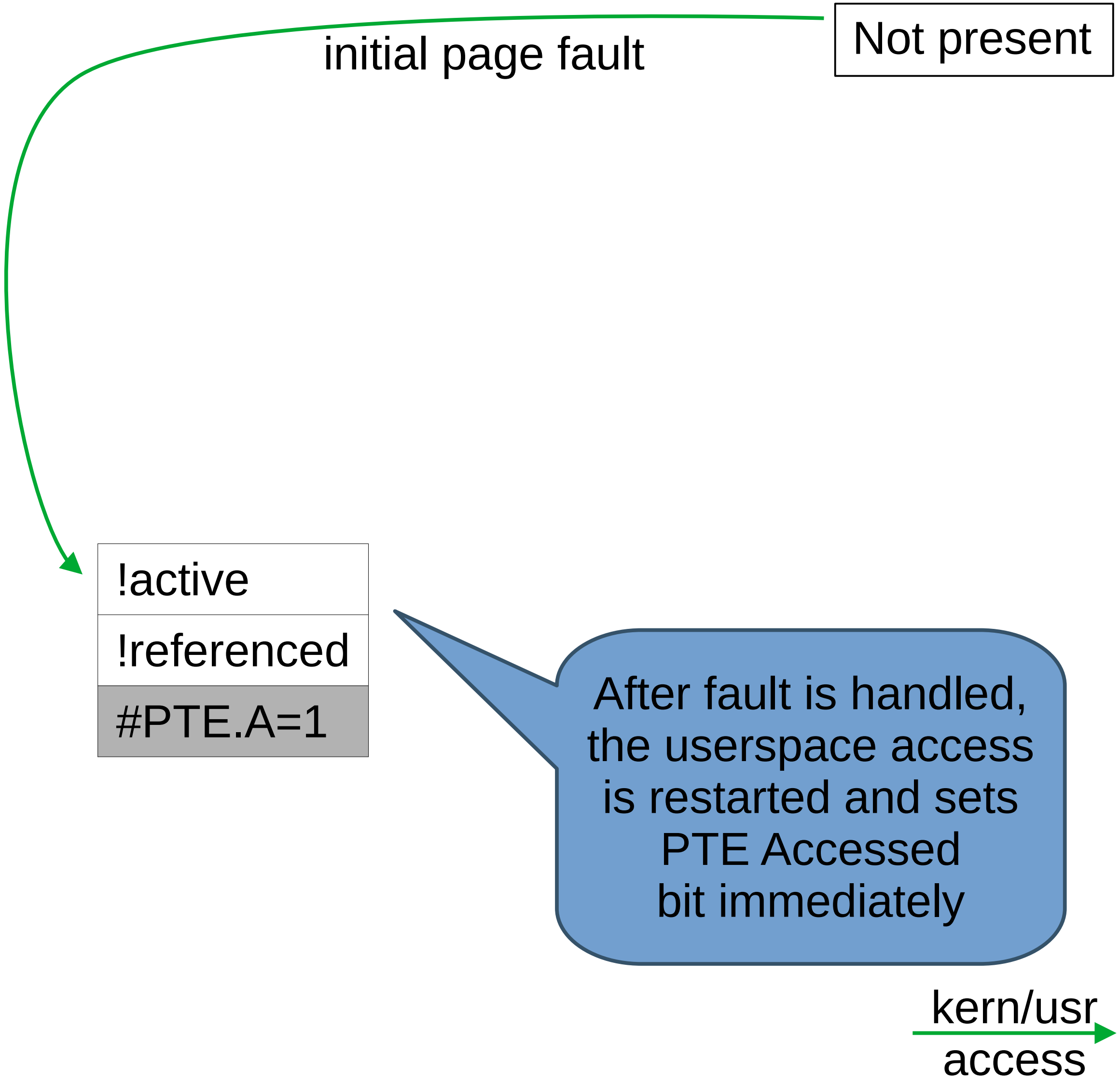
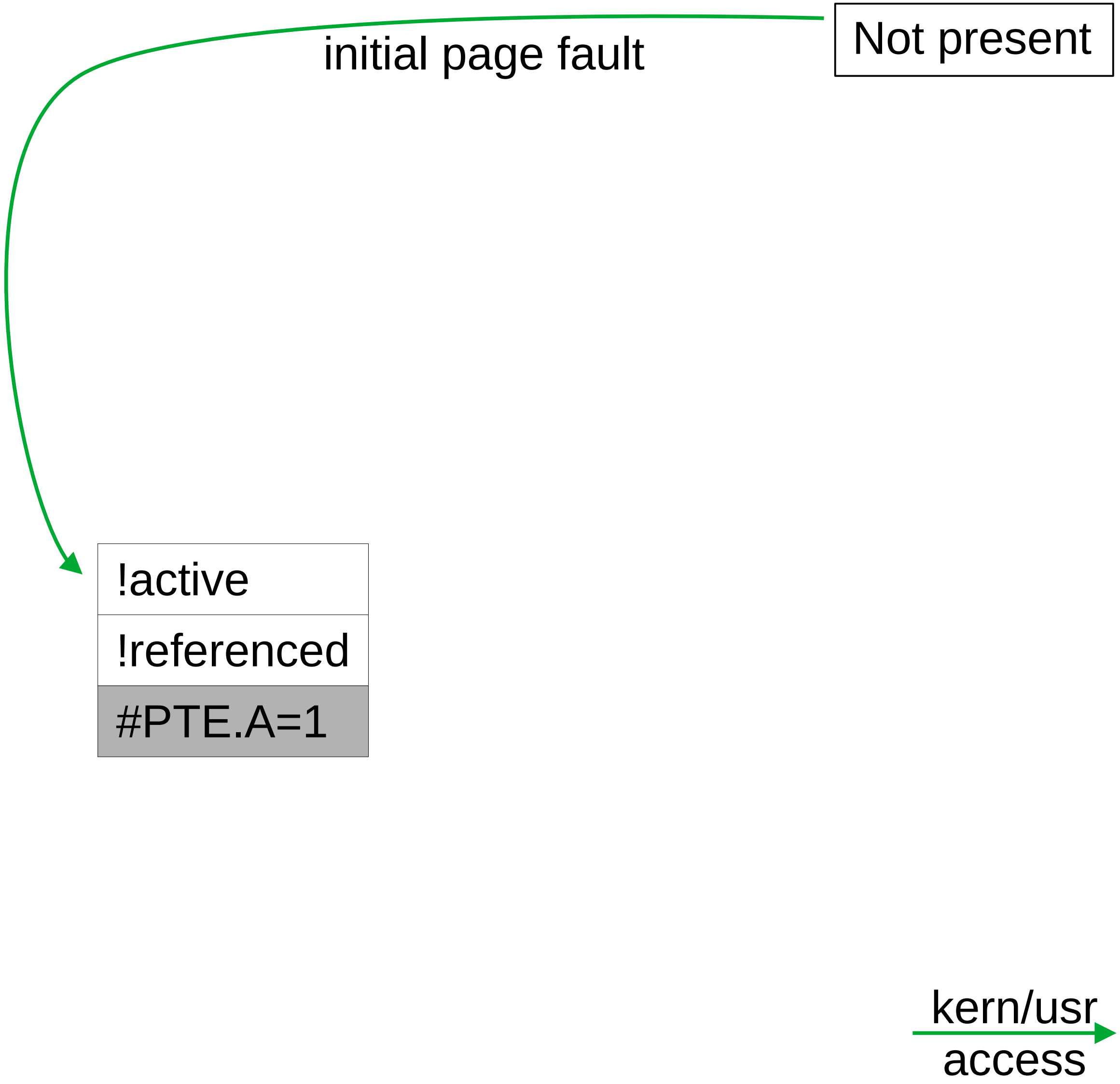


Not present


Not present
initial page fault
!active
!referenced
#PTE.A=1
After fault is handled, the userspace access is restarted and sets PTE Accessed bit immediately
kern/usr access


Not present
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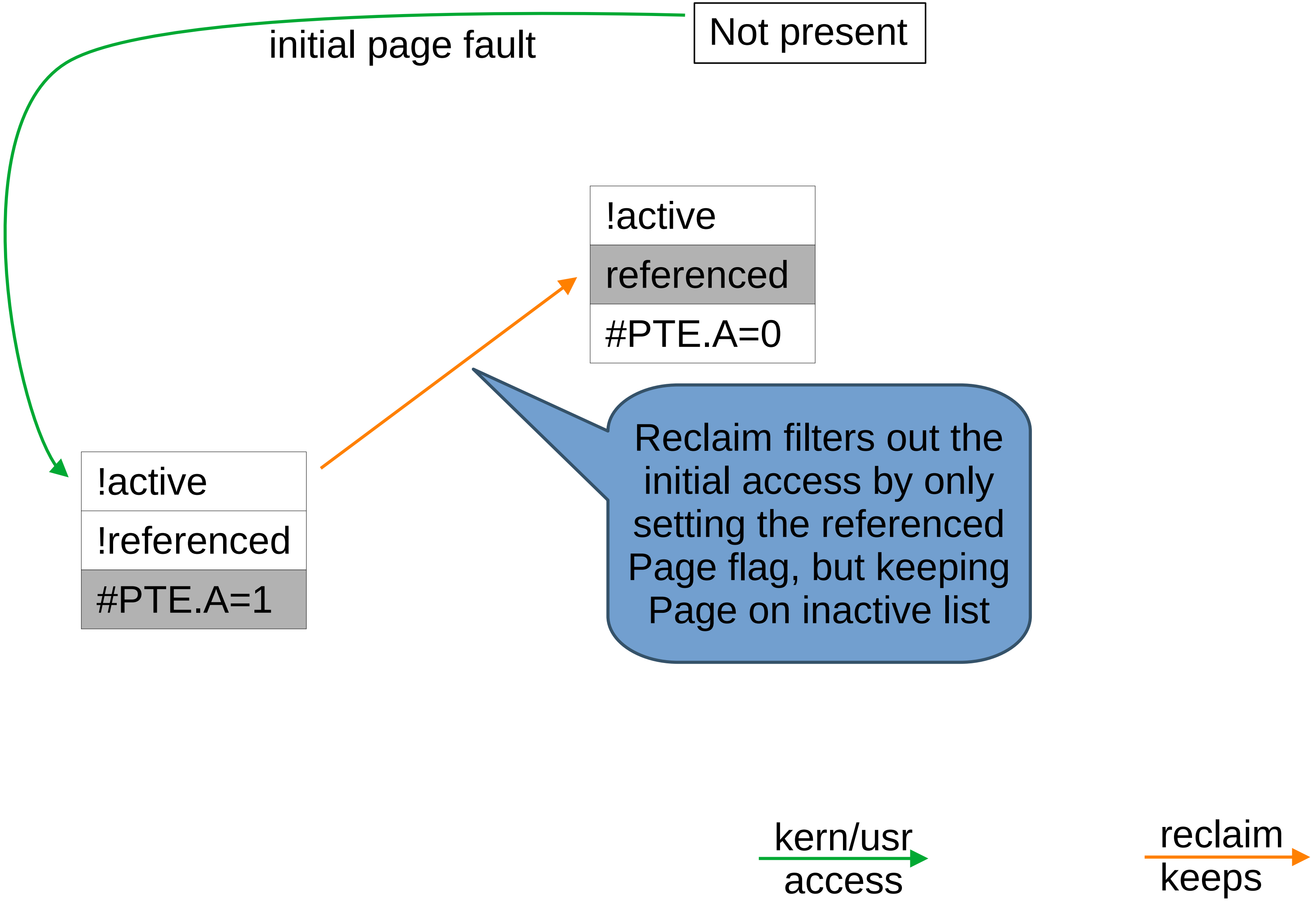
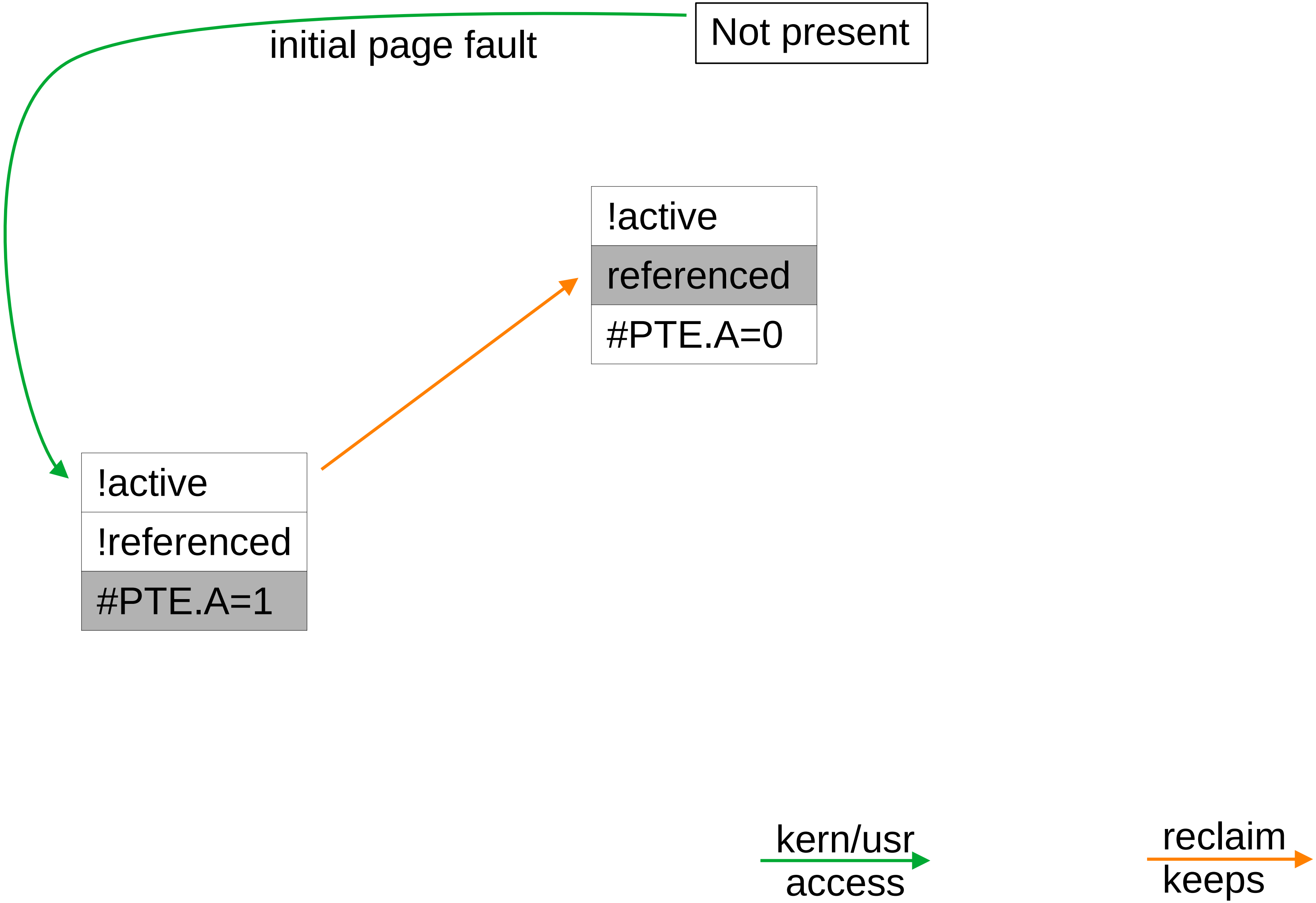
kern/usr
access


Not present
initial page fault
!active
referenced
#PTE.A=0
!active
!referenced
#PTE.A=1
Reclaim filters out the initial access by only setting the referenced Page flag, but keeping Page on inactive list
kern/usr access
reclaim keeps


Not present
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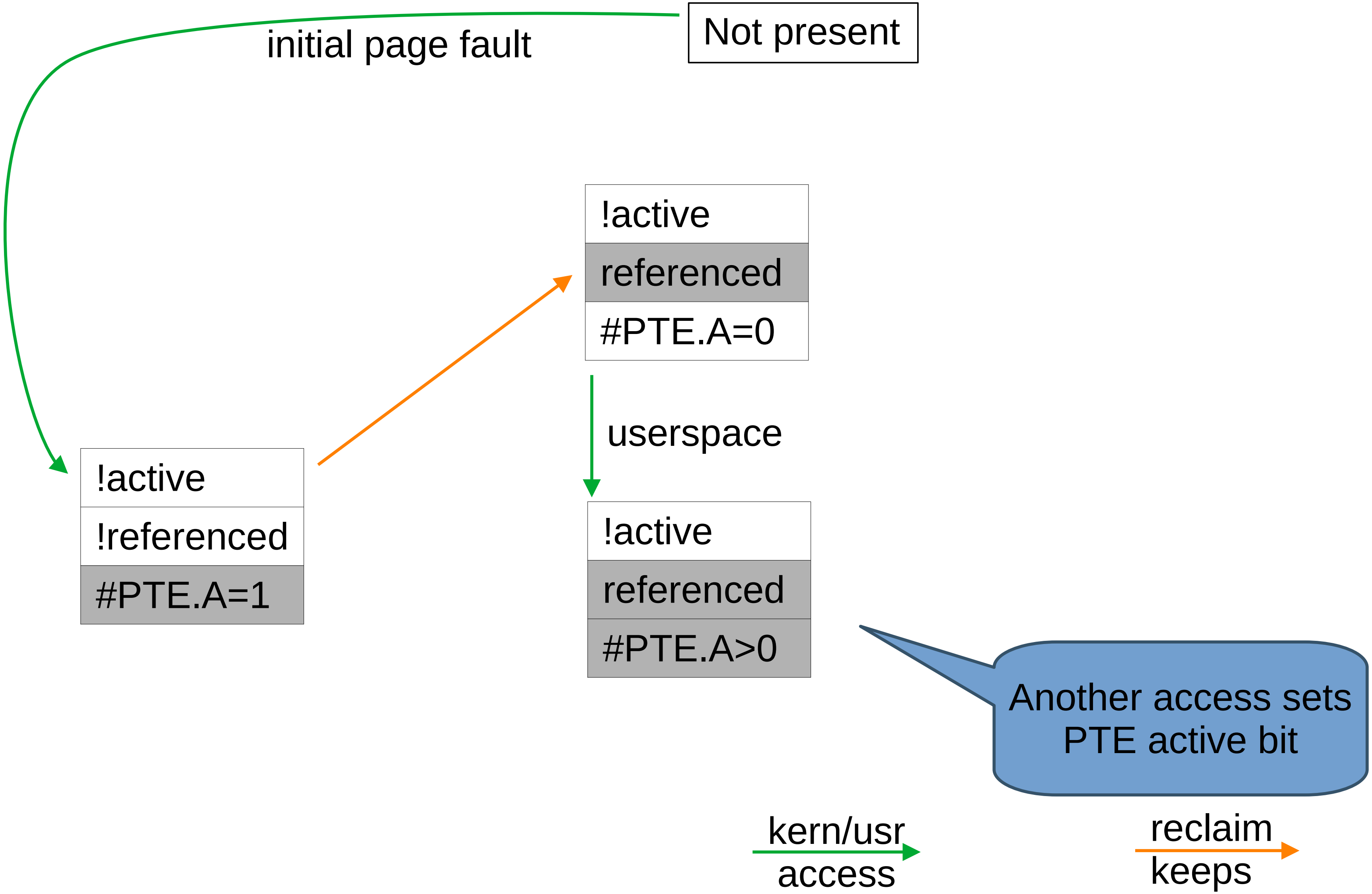
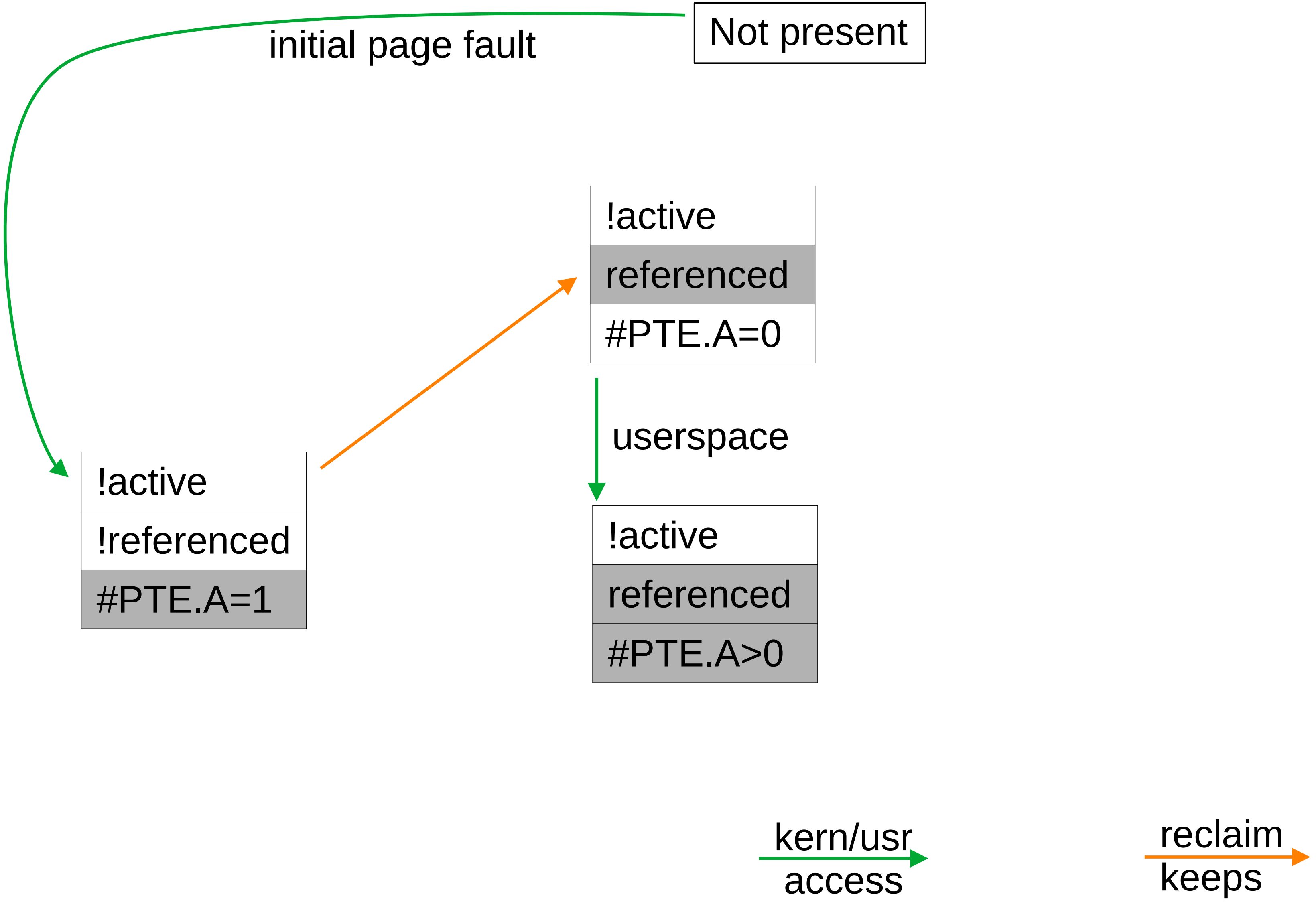
kern/usr
access
reclaim
keeps


Not present
initial page fault
!active
referenced
#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A>0
Another access sets PTE active bit
kern/usr access
reclaim keeps


Not present
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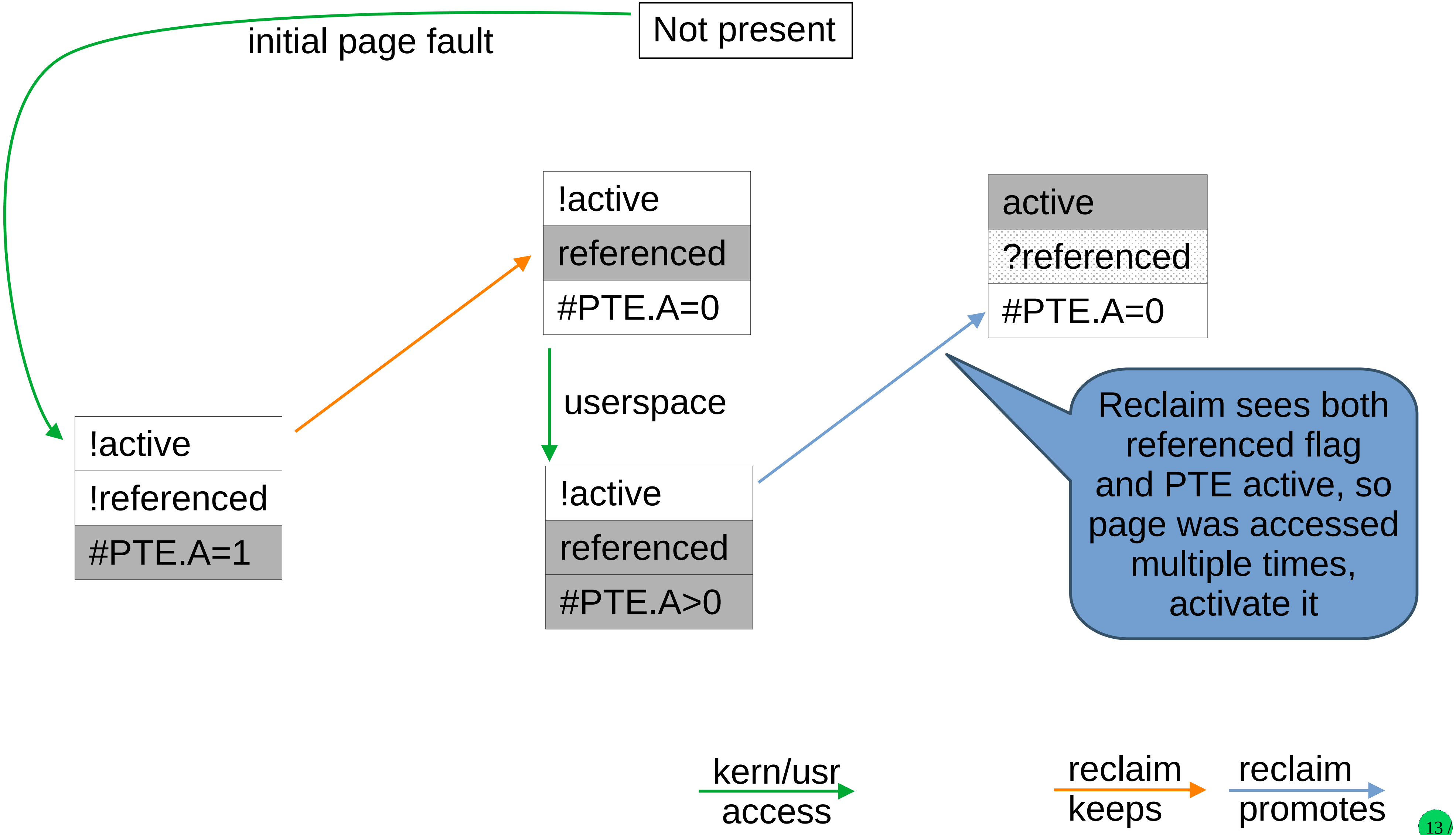
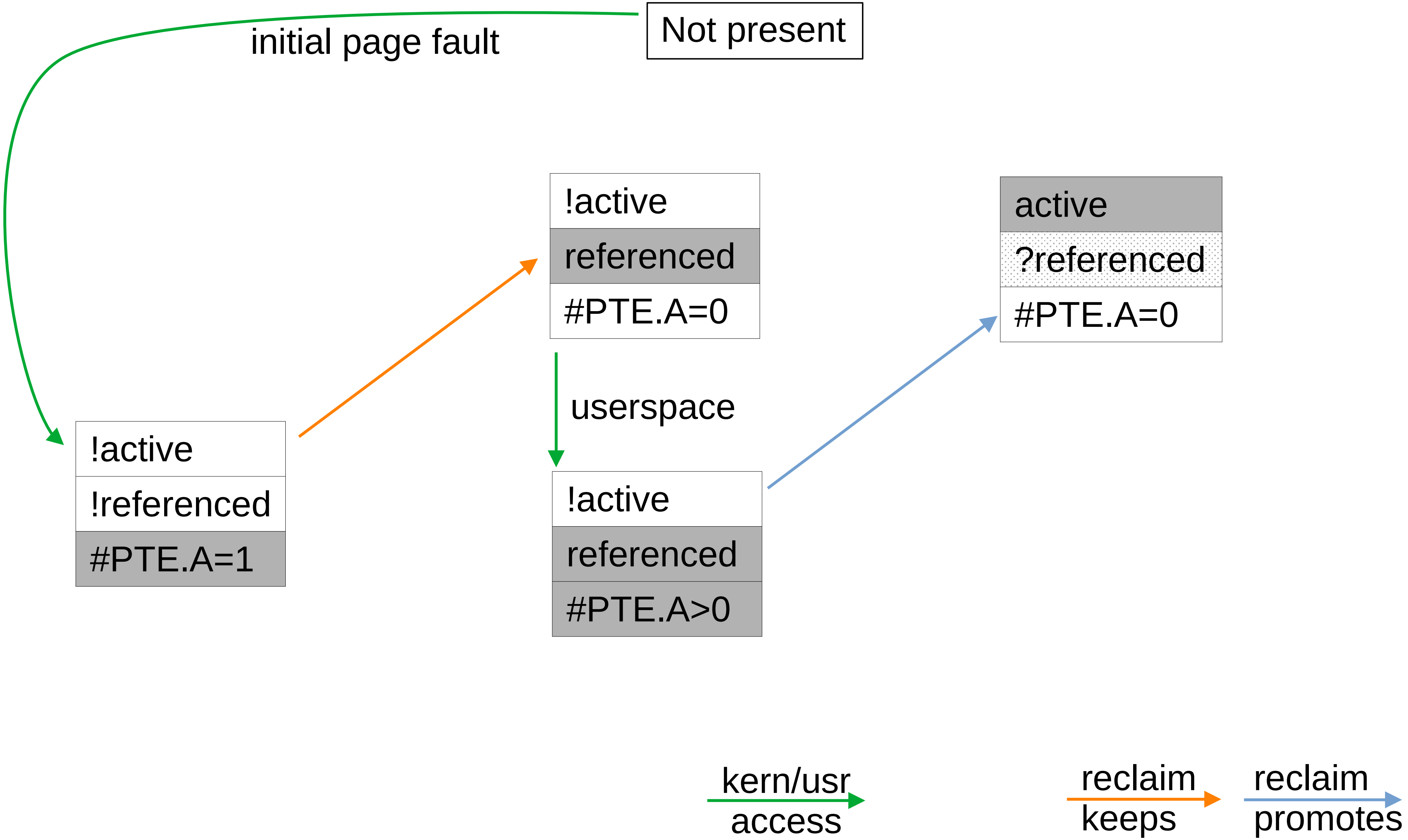

Not present
initial page fault
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
active
?referenced
#PTE.A=0
Reclaim sees both referenced flag and PTE active, so page was accessed multiple times, activate it
kern/usr access
reclaim keeps
reclaim promotes



Not present
initial page fault
!active
referenced
#PTE.A=0
active
?referenced
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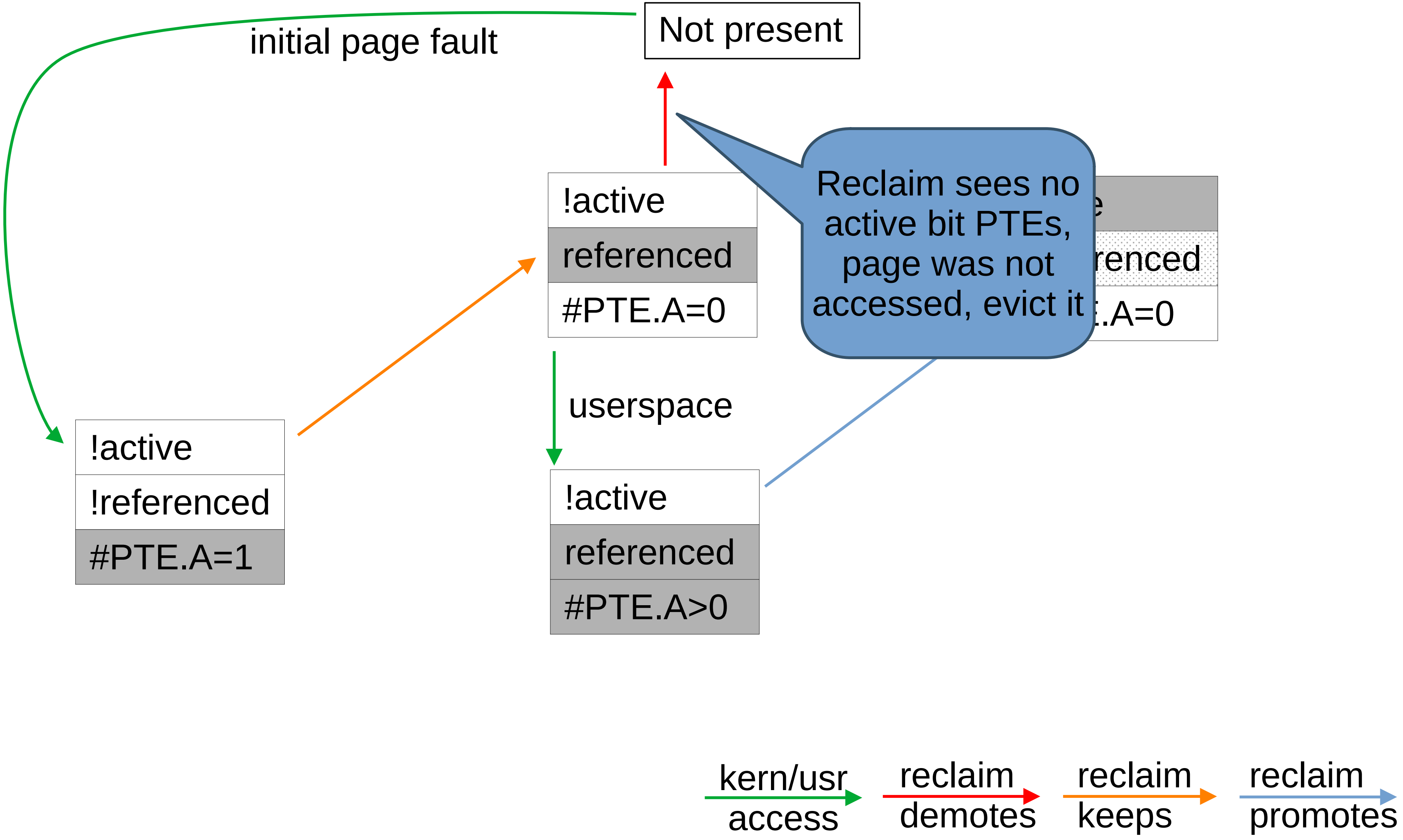
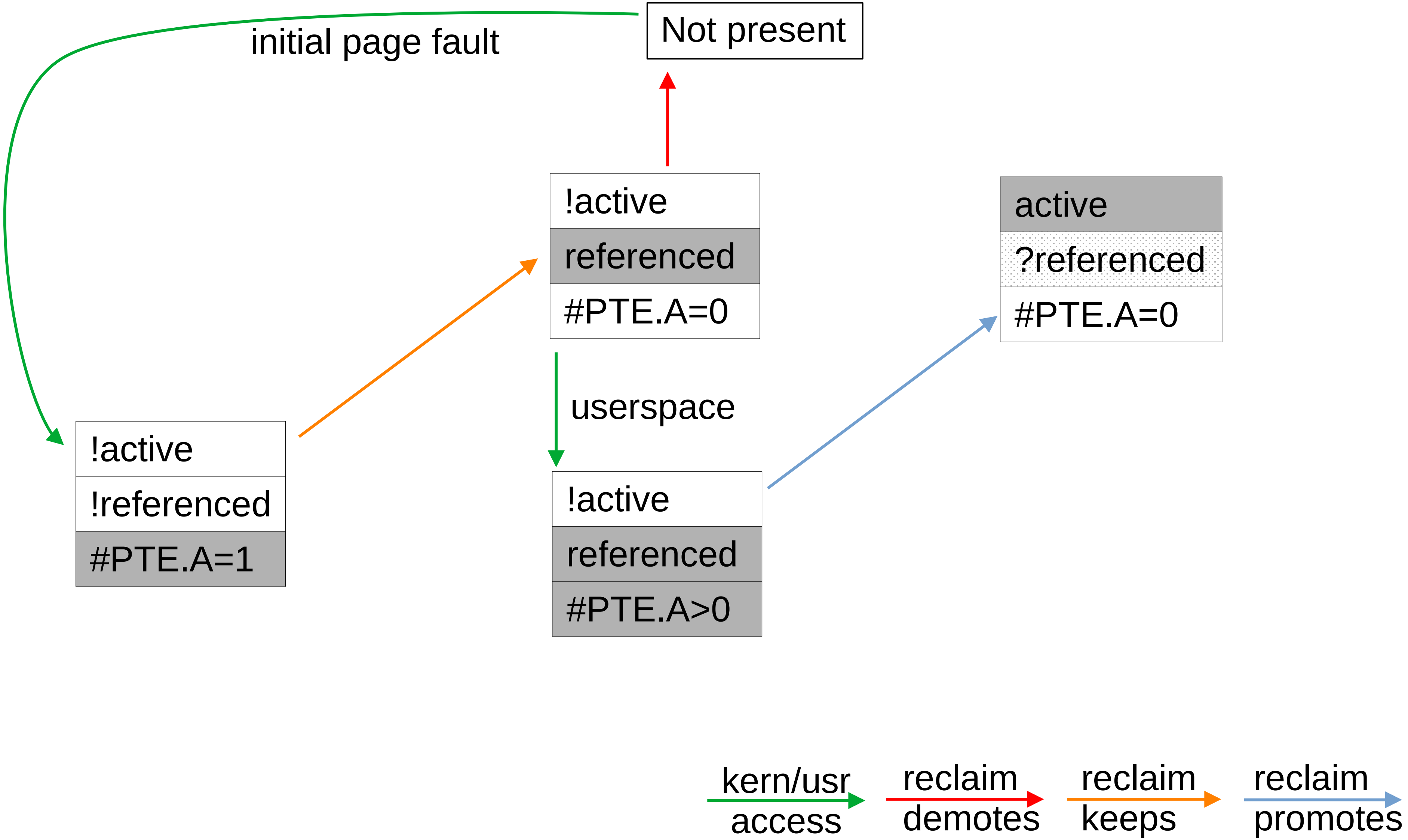

Not present
initial page fault
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
Reclaim sees no active bit PTEs, page was not accessed, evict it
kern/usr access
reclaim demotes
reclaim keeps
reclaim promotes



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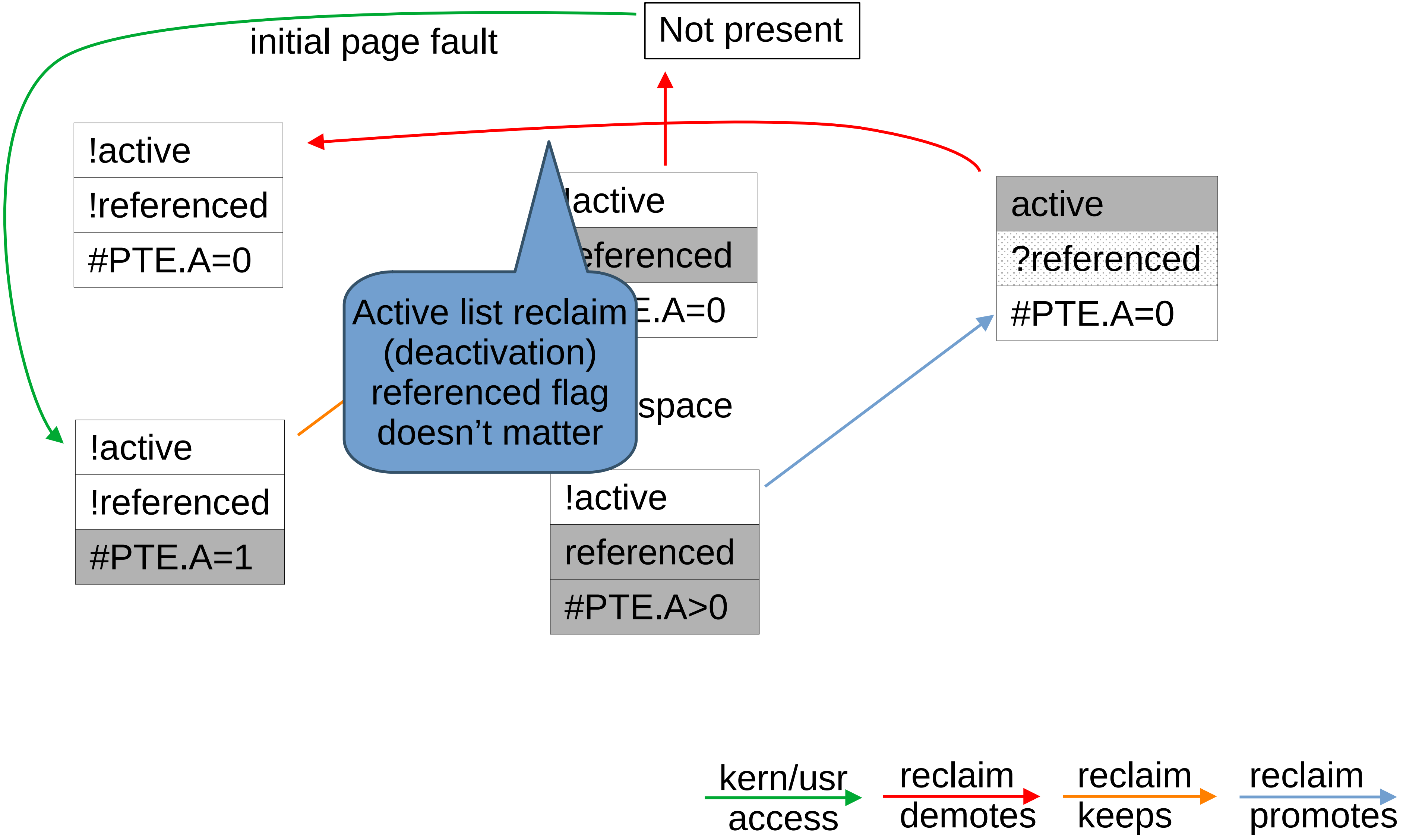
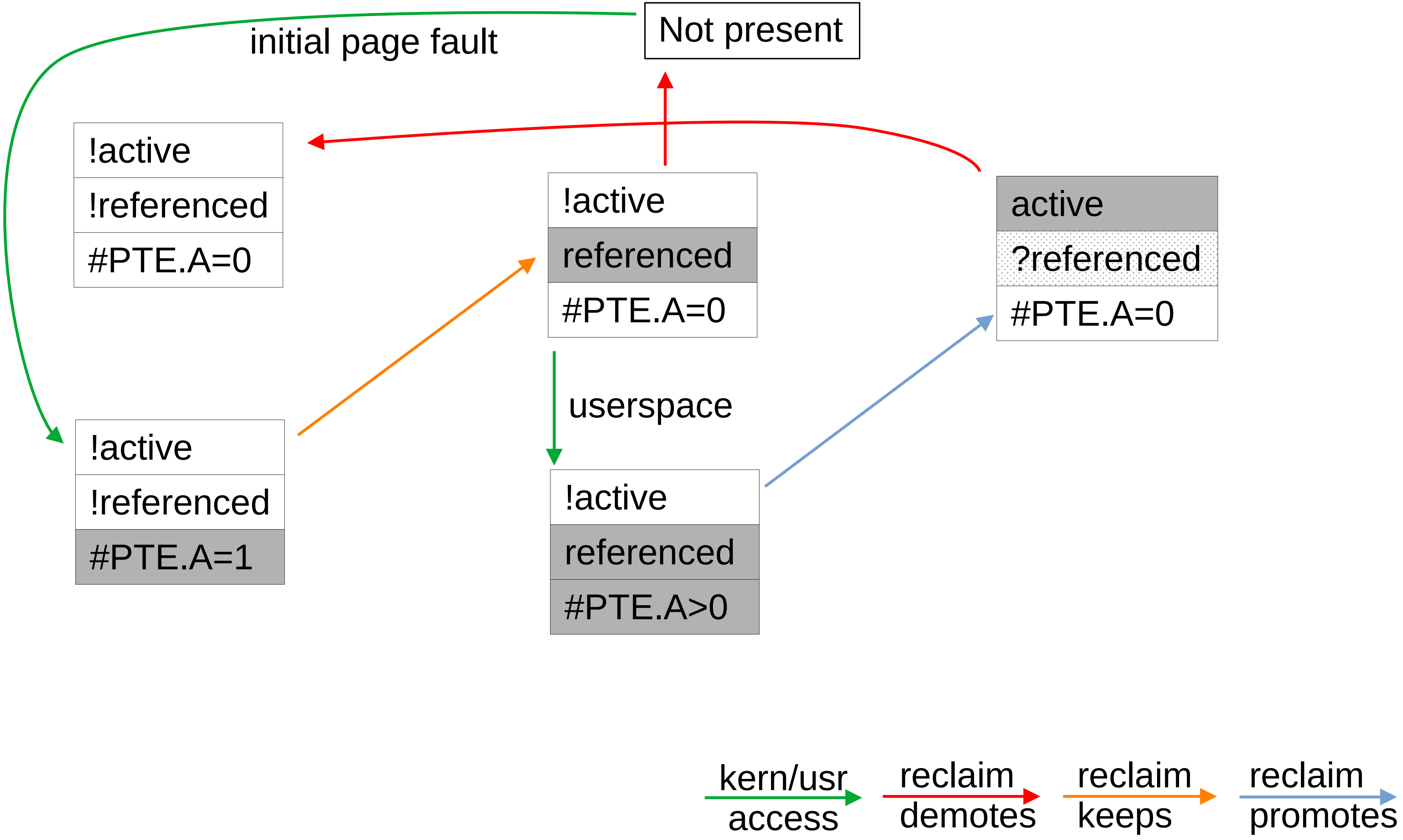
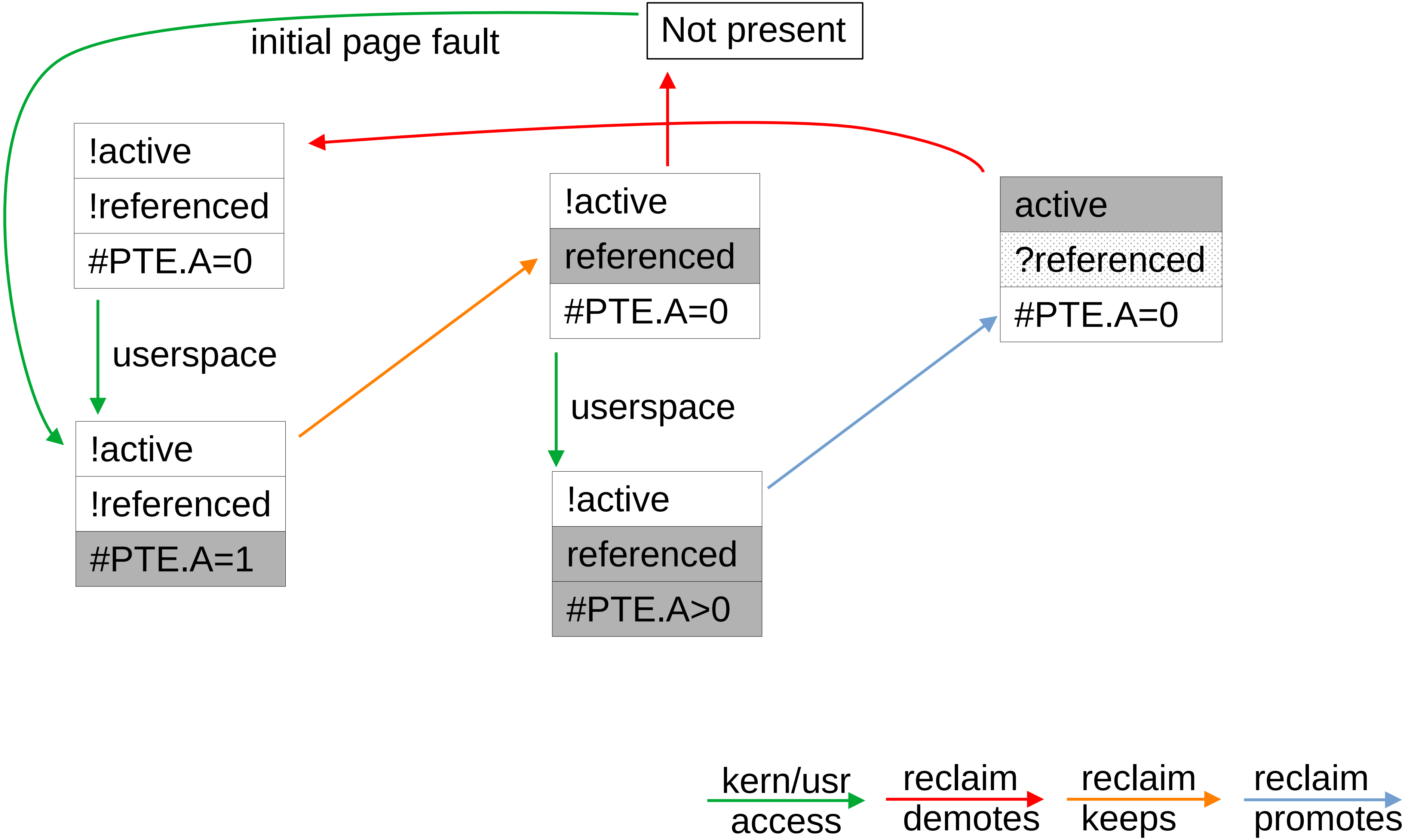

Not present
initial page fault
!active
!referenced
#PTE.A=0
!active
active
?referenced
#PTE.A=0
Active list reclaim
(deactivation)
referenced flag
doesn't matter
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A>0
kern/usr
access
reclaim
demotes
reclaim
keeps
reclaim
promotes



Not present
initial page fault
!active
!referenced
#PTE.A=0
!active
referenced
#PTE.A=0
active
?referenced
#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A>0
kern/usr access
reclaim demotes
reclaim keeps
reclaim promotes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!active
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#PTE.A=0
userspace
!active
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#PTE.A=1
!active
referenced
#PTE.A=0
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referenced
#PTE.A>0
active
?referenced
#PTE.A=0
kern/usr access
reclaim demotes
reclaim keeps
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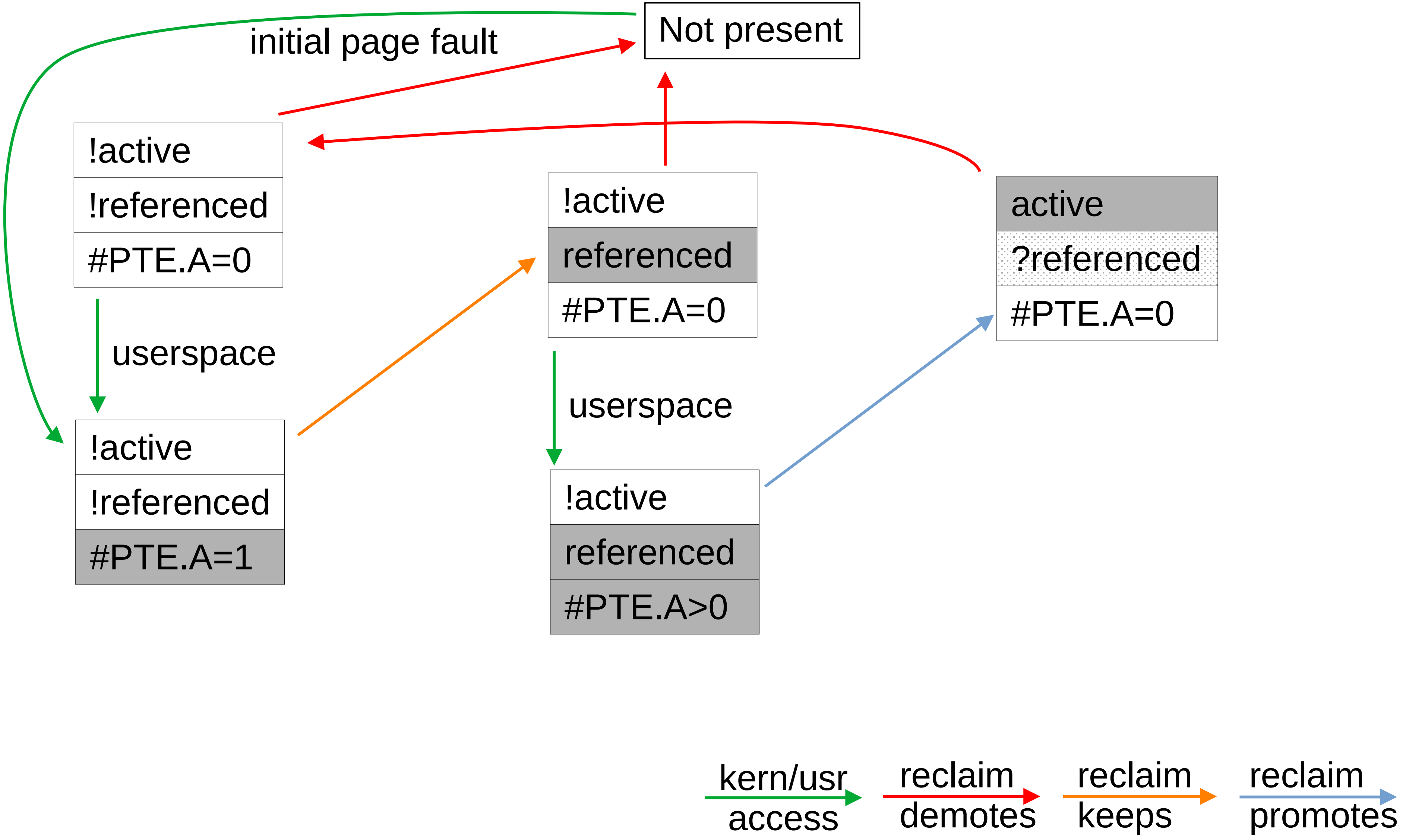
Not present
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#PTE.A=0
userspace
!active
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#PTE.A=1
!active
referenced
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
active
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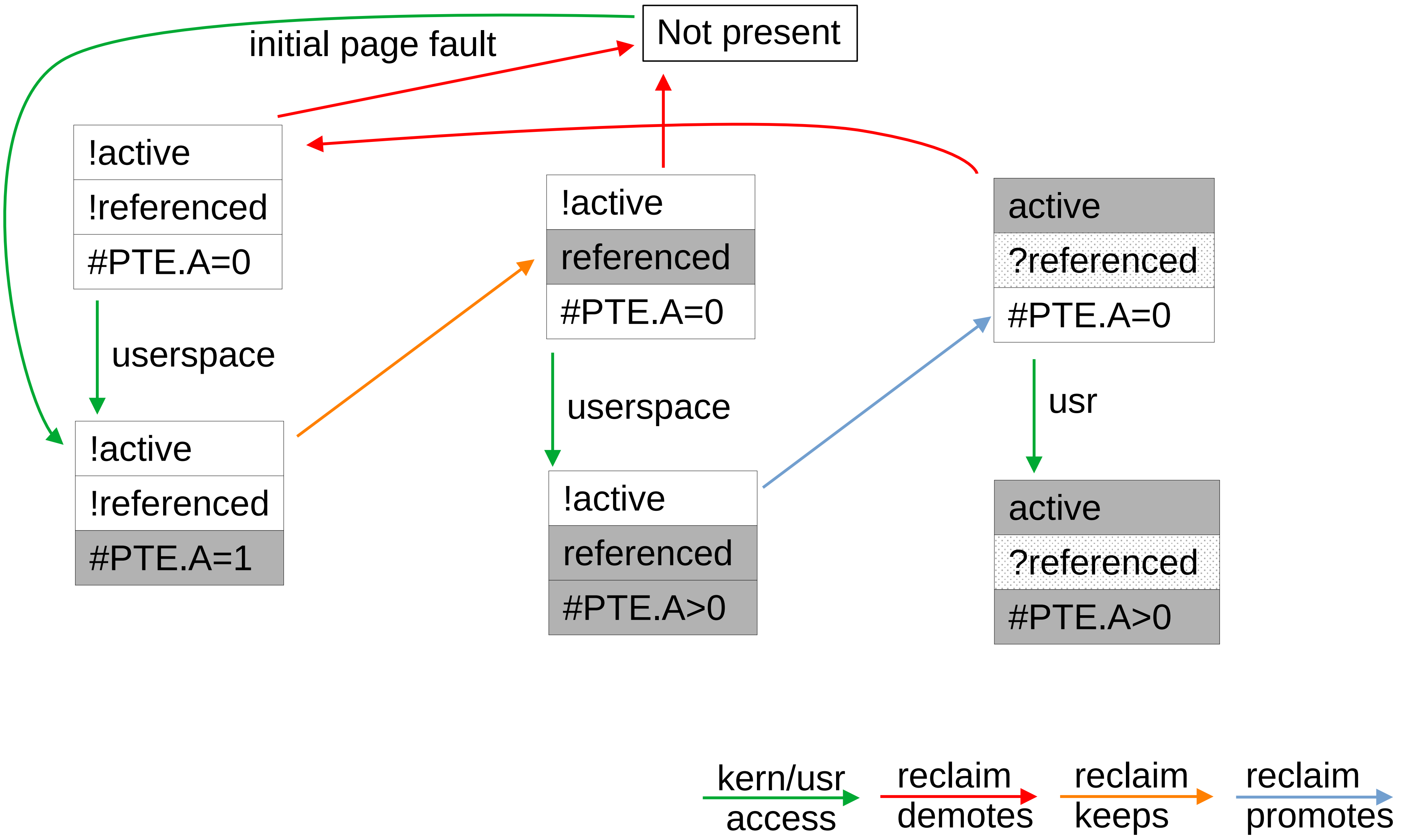
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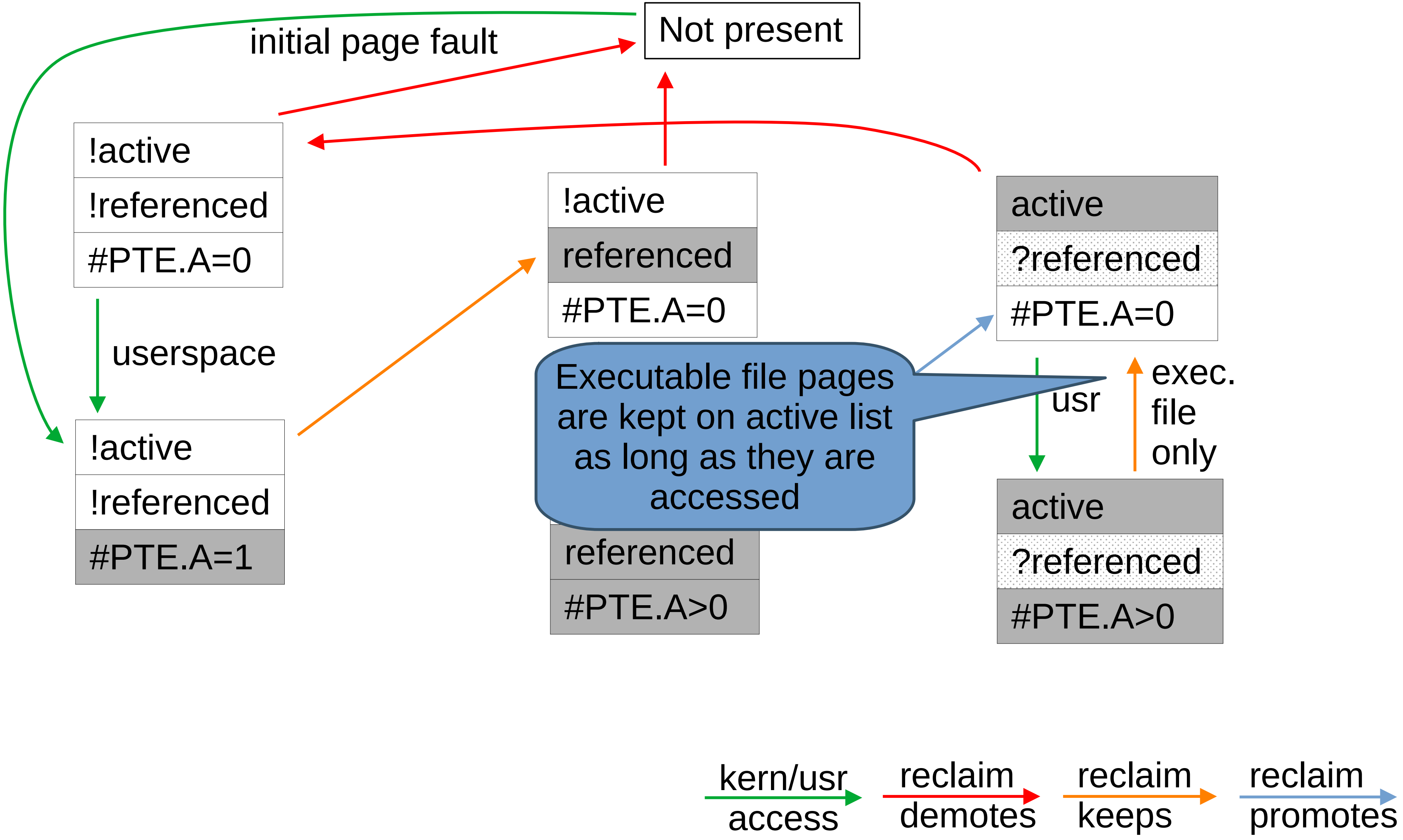
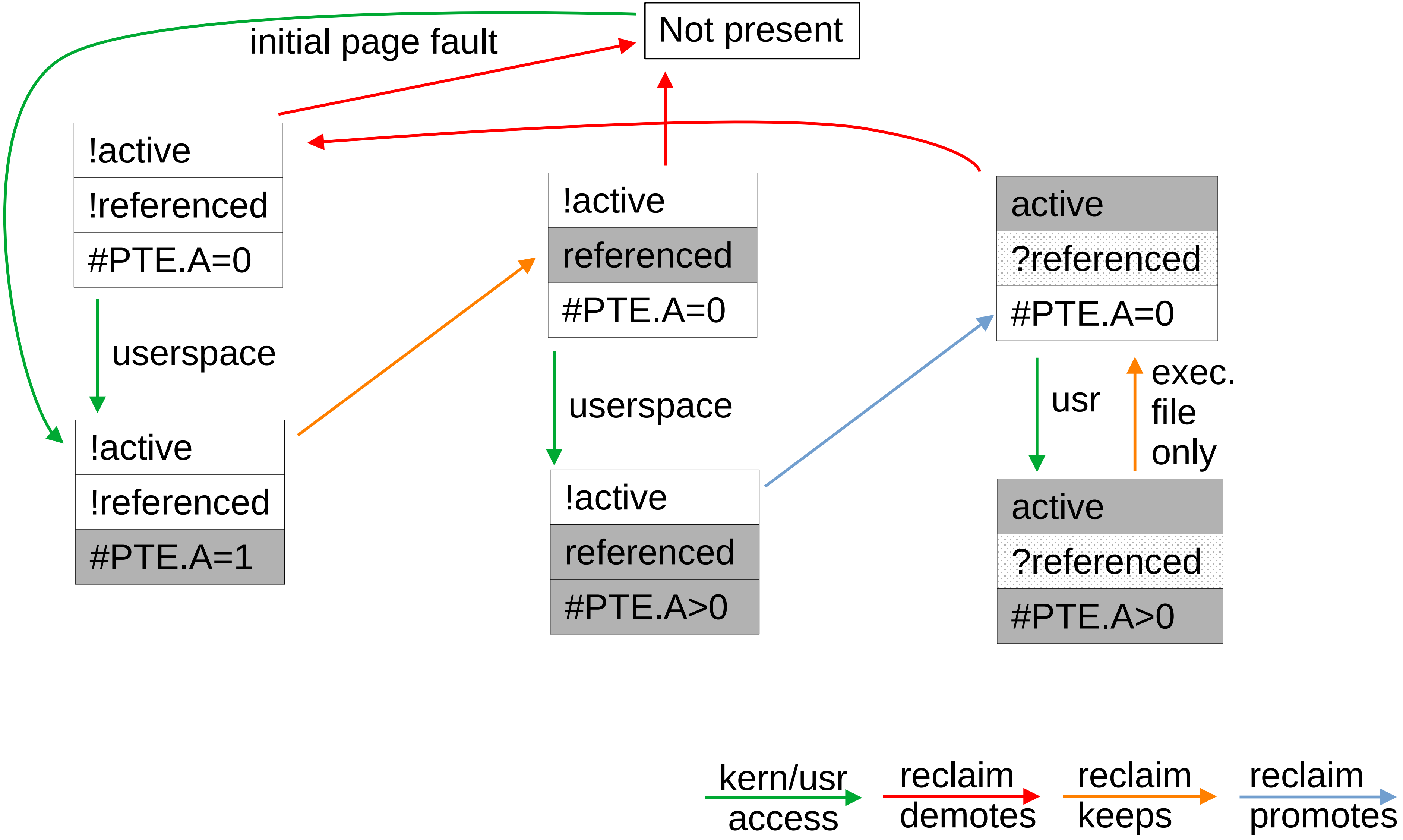
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
active
?referenced
#PTE.A=0
usr
active
?referenced
#PTE.A>0
kern/usr access
reclaim demotes
reclaim keeps
reclaim promotes



Not present
initial page fault
!active
!referenced
#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A=0
Executable file pages are kept on active list as long as they are accessed
referenced
#PTE.A>0
active
?referenced
#PTE.A=0
usr
exec. file only
active
?referenced
#PTE.A>0
kern/usr access
reclaim demotes
reclaim keeps
reclaim promotes


Not present
initial page fault
!active
!referenced
#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
active
?referenced
#PTE.A=0
usr
exec.
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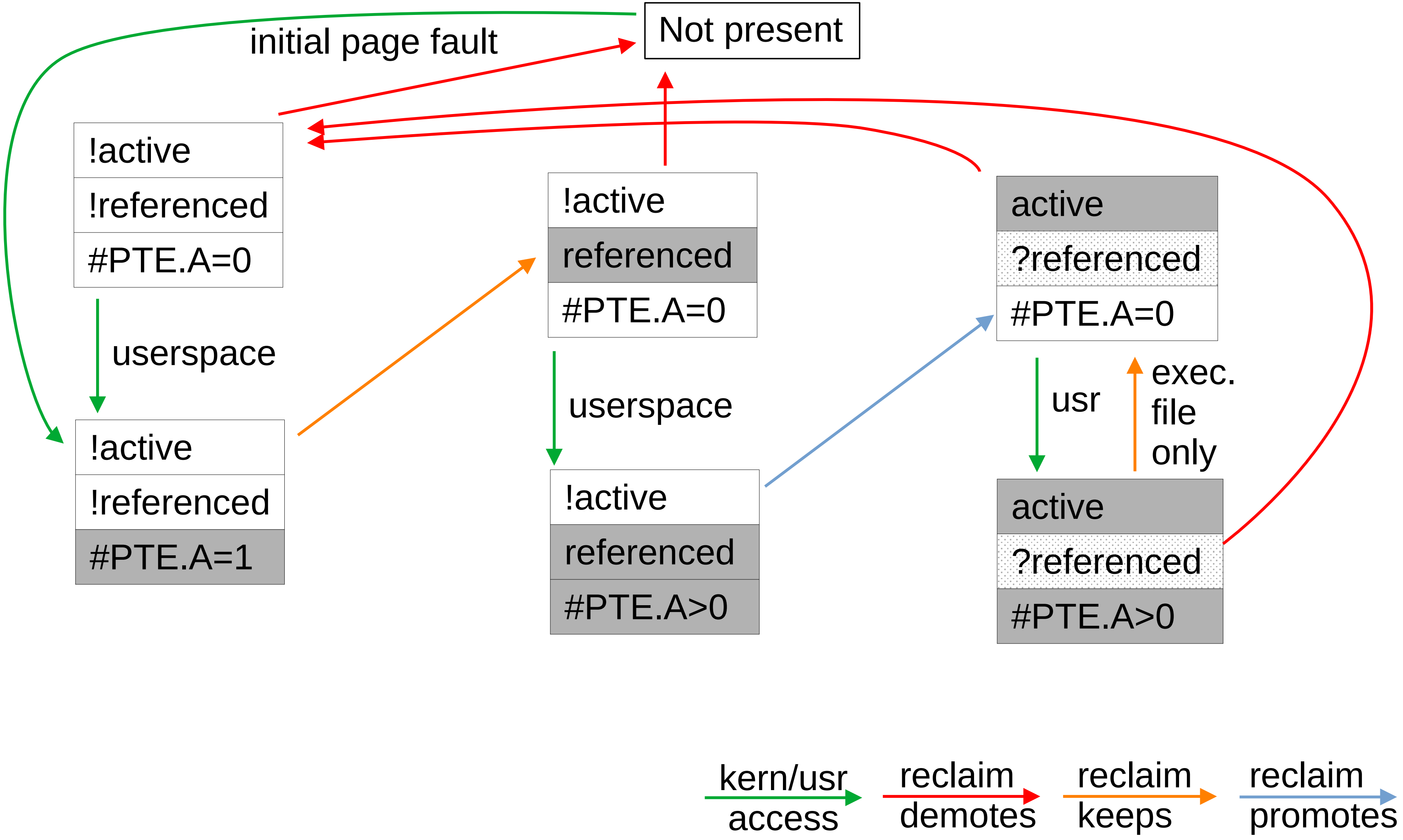
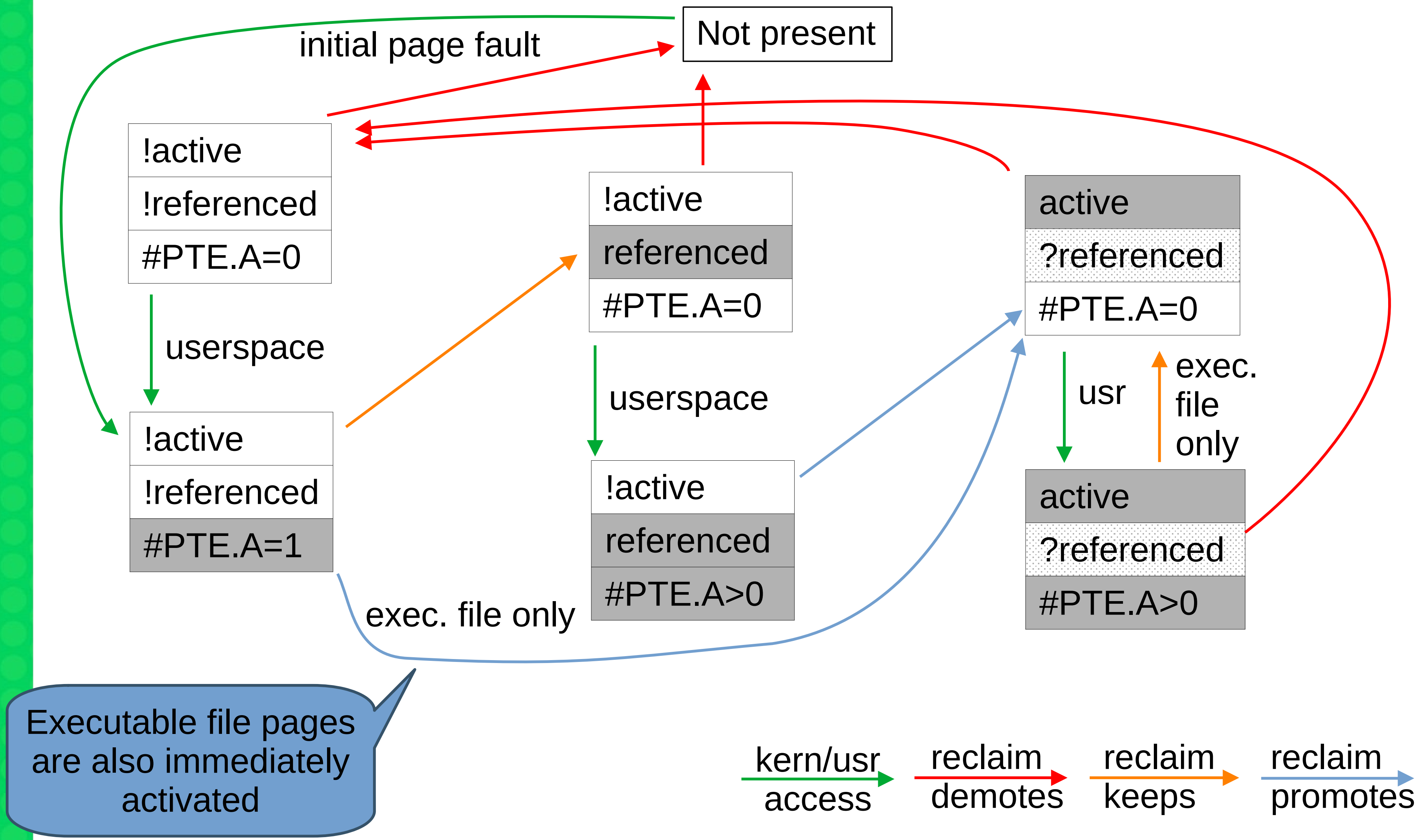
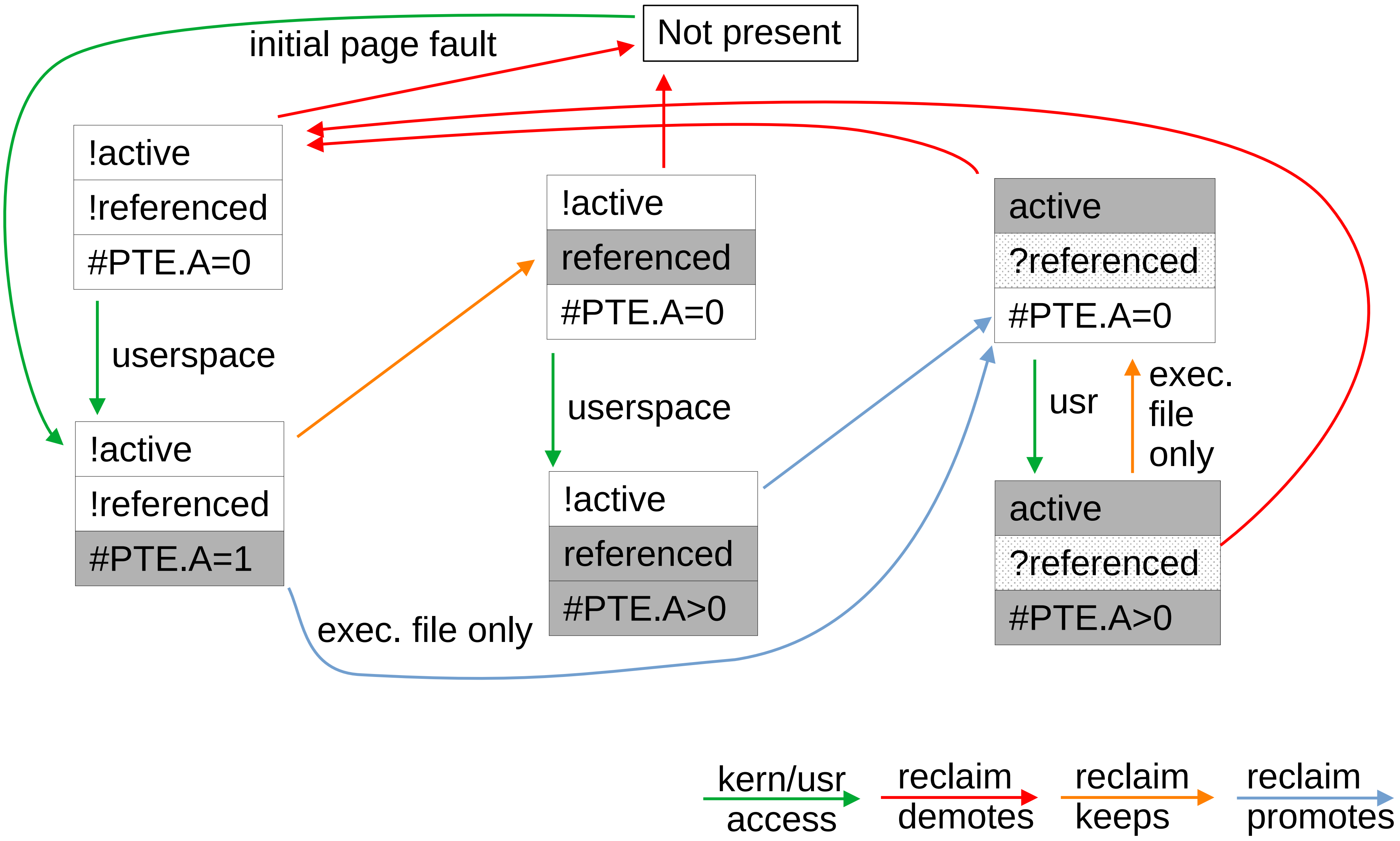
active
?referenced
#PTE.A>0
kern/usr
access
reclaim
demotes
reclaim
keeps
reclaim
promotes

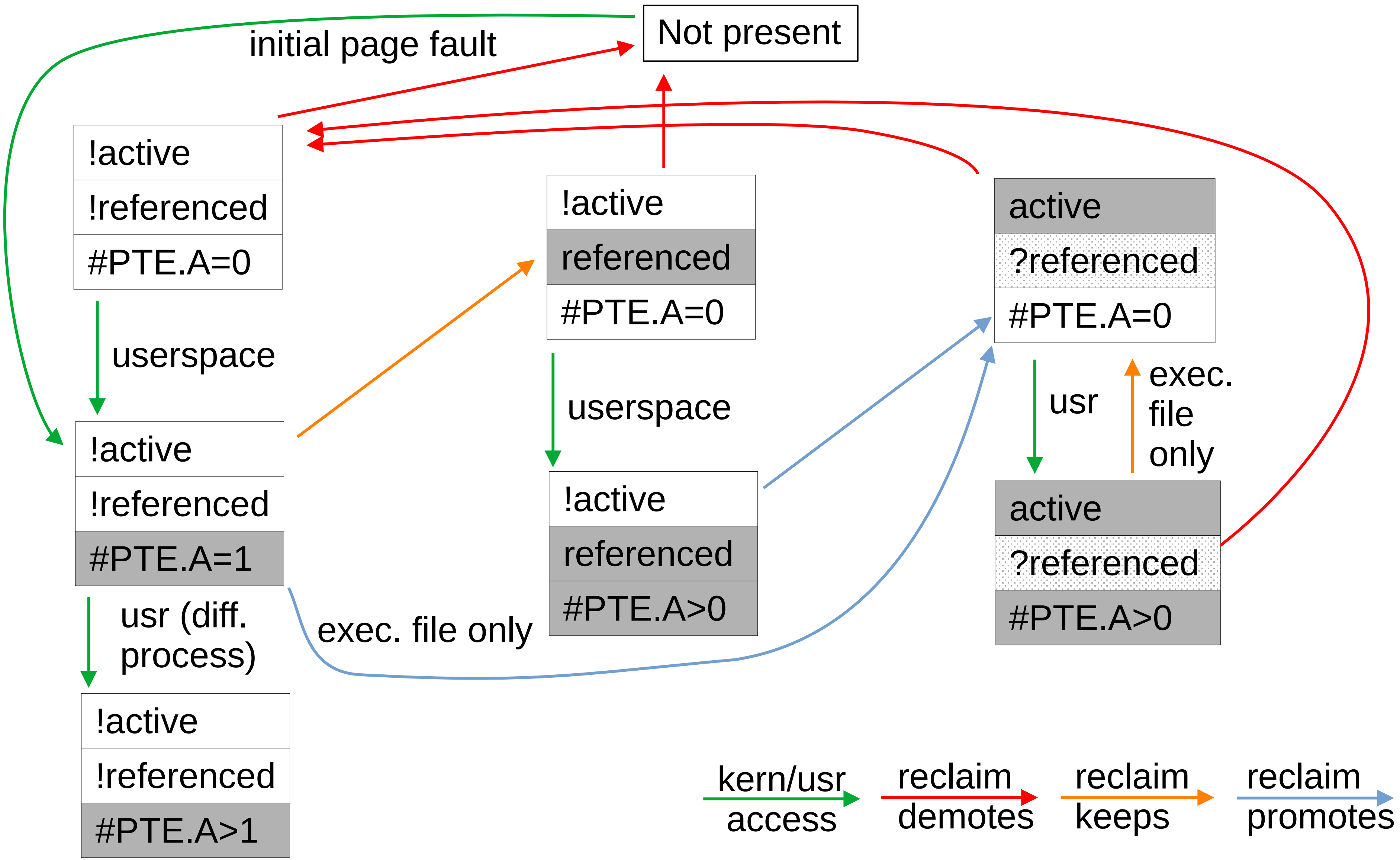

Not present
initial page fault
!active
!referenced
#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
active
?referenced
#PTE.A=0
usr
exec. file only
active
?referenced
#PTE.A>0
kern/usr access
reclaim demotes
reclaim keeps
reclaim promotes

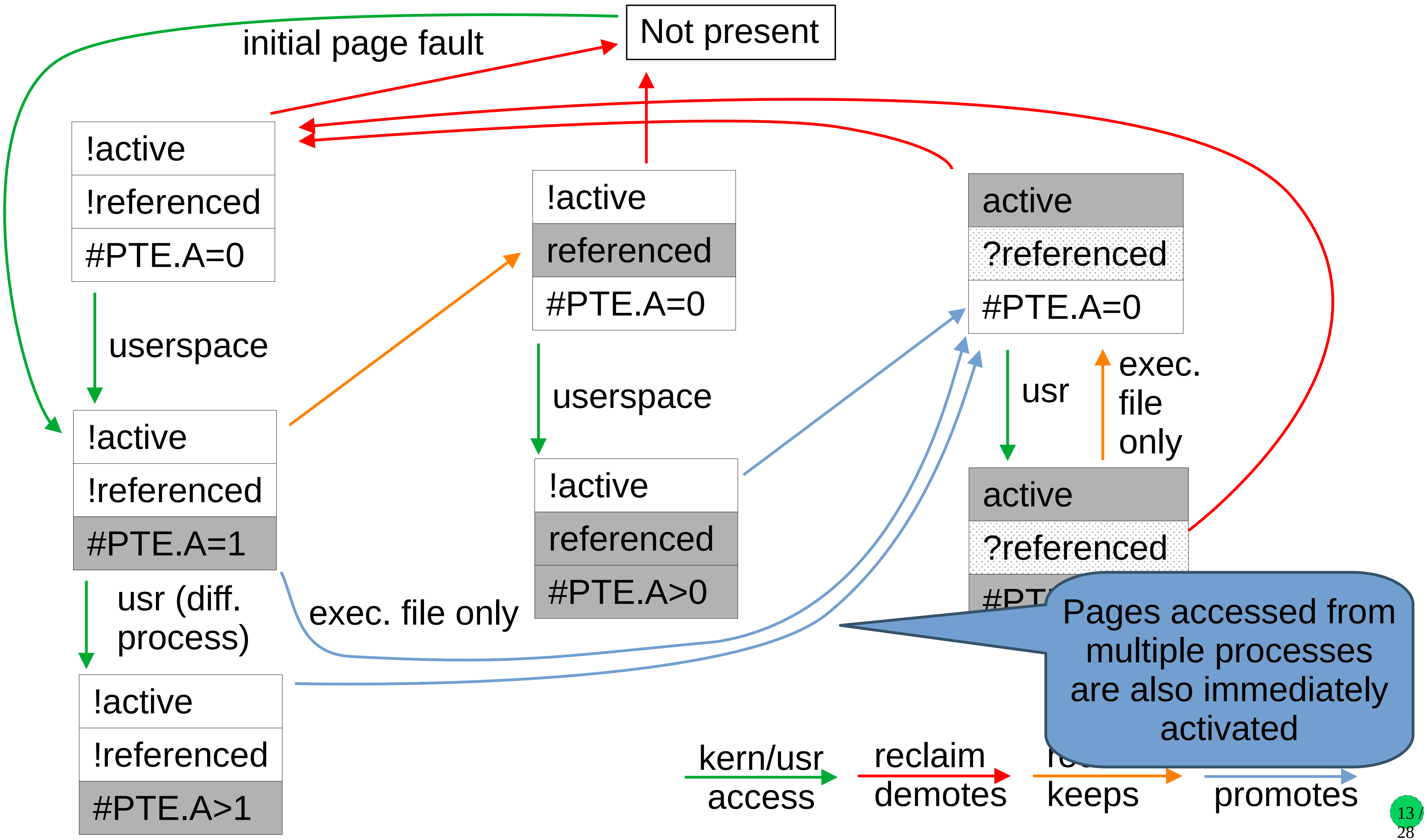


Not present
initial page fault
!active
!referenced
#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
active
?referenced
#PTE.A=0
usr
exec. file only
active
?referenced
#PTE.A>0
exec. file only
Executable file pages are also immediately activated
kern/usr access
reclaim demotes
reclaim keeps
reclaim promotes



Not present
initial page fault
!active
!referenced
#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
!active
referenced
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
exec. file only
active
?referenced
#PTE.A=0
usr
exec.
file
only
active
?referenced
#PTE.A>0
kern/usr
access
reclaim
demotes
reclaim
keeps
reclaim
promotes


Not present
initial page fault
!active
!referenced
#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
usr (diff. process)
!active
!referenced
#PTE.A>1
exec. file only
!active
referenced
#PTE.A=0
userspace
!active
referenced
#PTE.A>0
active
?referenced
#PTE.A=0
usr
exec. file only
active
?referenced
#PTE.A>0
kern/usr access
reclaim demotes
reclaim keeps
reclaim promotes


Not present
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referenced
#PTE.A>0
active
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active
?referenced
Pages accessed from multiple processes are also immediately activated
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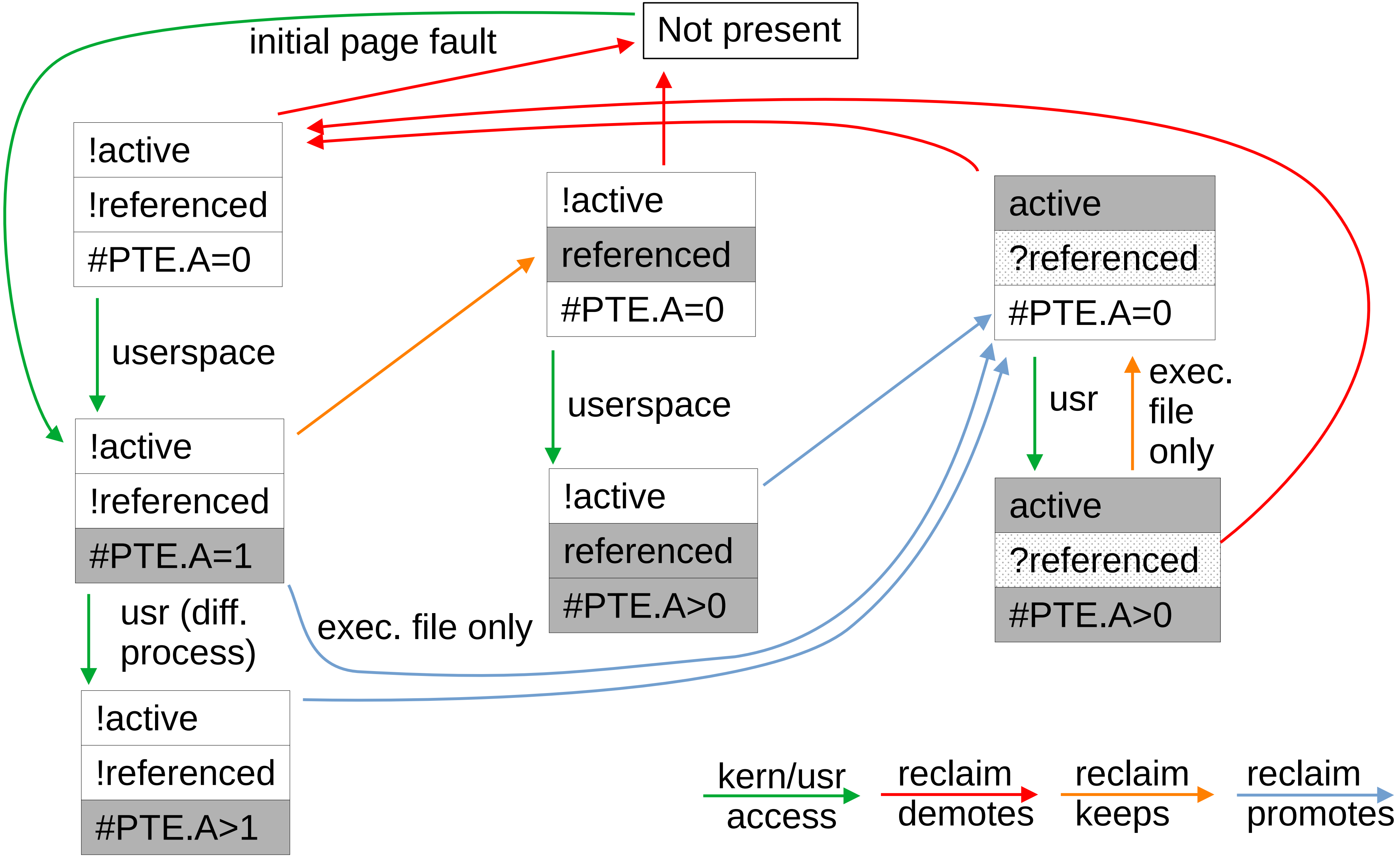
Not present
initial page fault
!active
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#PTE.A=0
userspace
!active
!referenced
#PTE.A=1
usr (diff. process)
!active
!referenced
#PTE.A>1
!active
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#PTE.A=0
userspace
!active
referenced
#PTE.A>0
exec. file only
active
?referenced
#PTE.A=0
usr
exec. file only
active
?referenced
#PTE.A>0
kern/usr access
reclaim demotes
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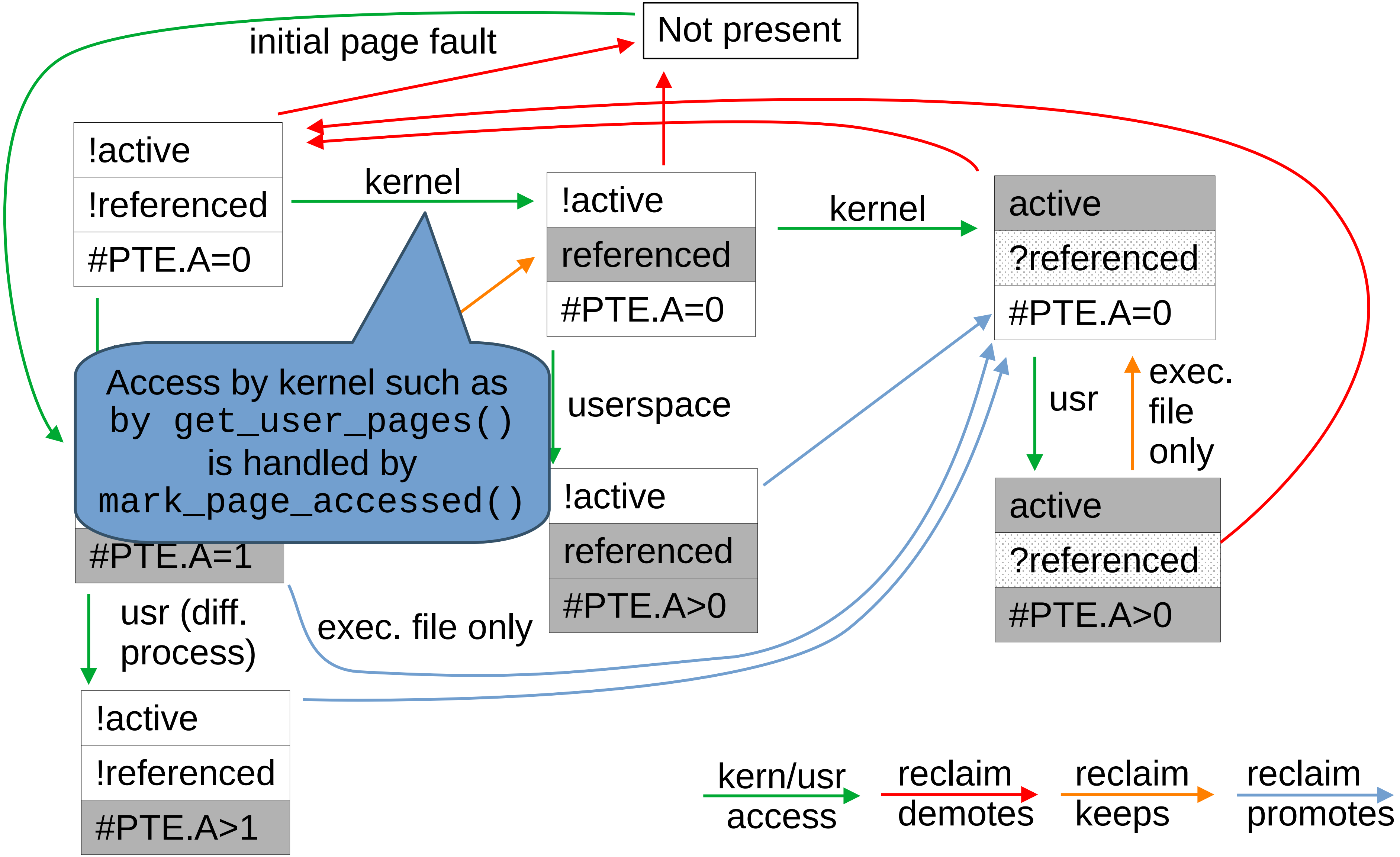
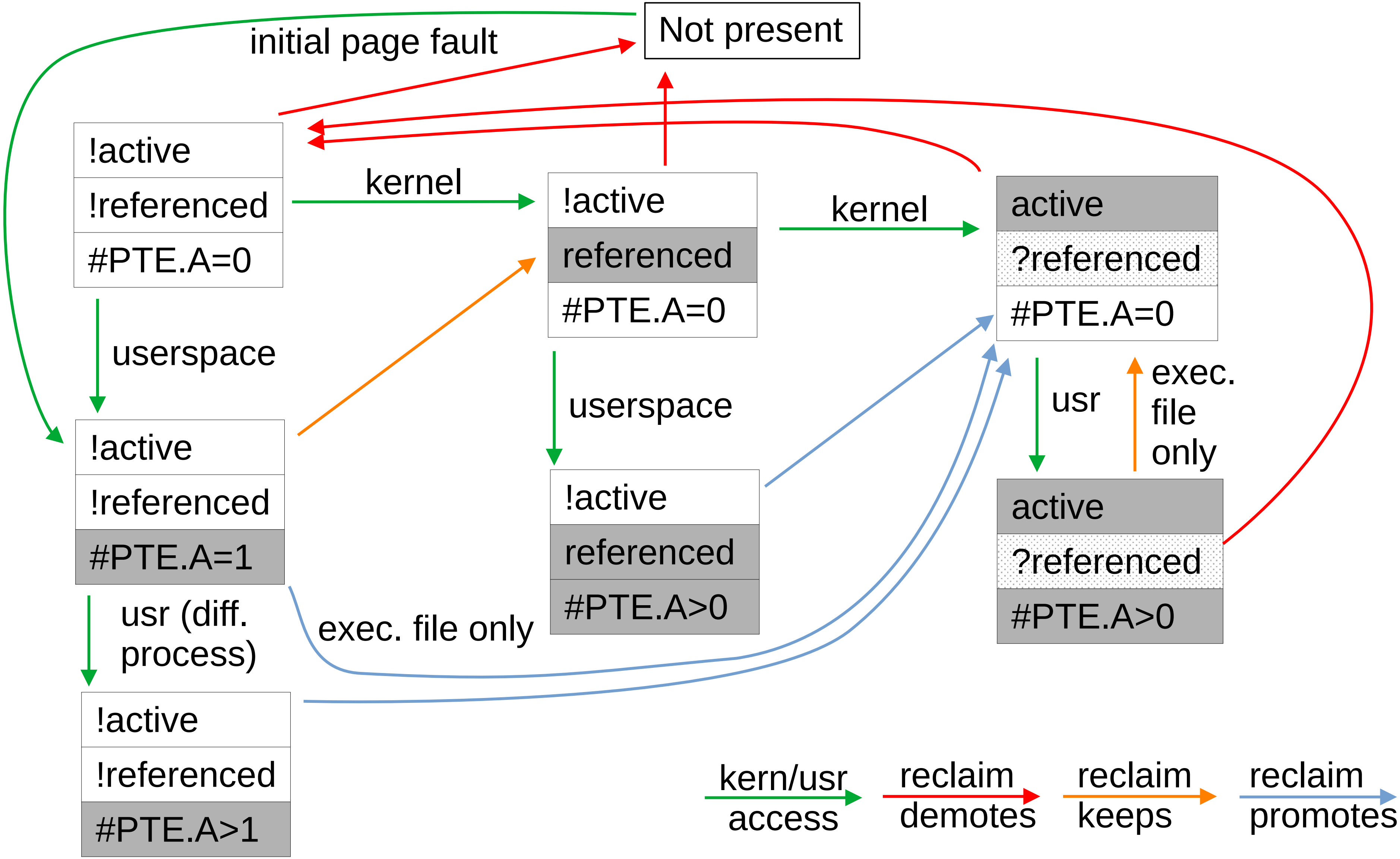

Not present
initial page fault
!active
!referenced
#PTE.A=0
kernel
!active
referenced
#PTE.A=0
kernel
active
?referenced
#PTE.A=0
Access by kernel such as by get_user_pages() is handled by mark_page_accessed()
userspace
usr
exec. file only
!active
referenced
#PTE.A>0
active
?referenced
#PTE.A>0
#PTE.A=1
usr (diff. process)
exec. file only
!active
!referenced
#PTE.A>1
kern/usr access
reclaim demotes
reclaim keeps
reclaim promotes


Not present
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#PTE.A=0
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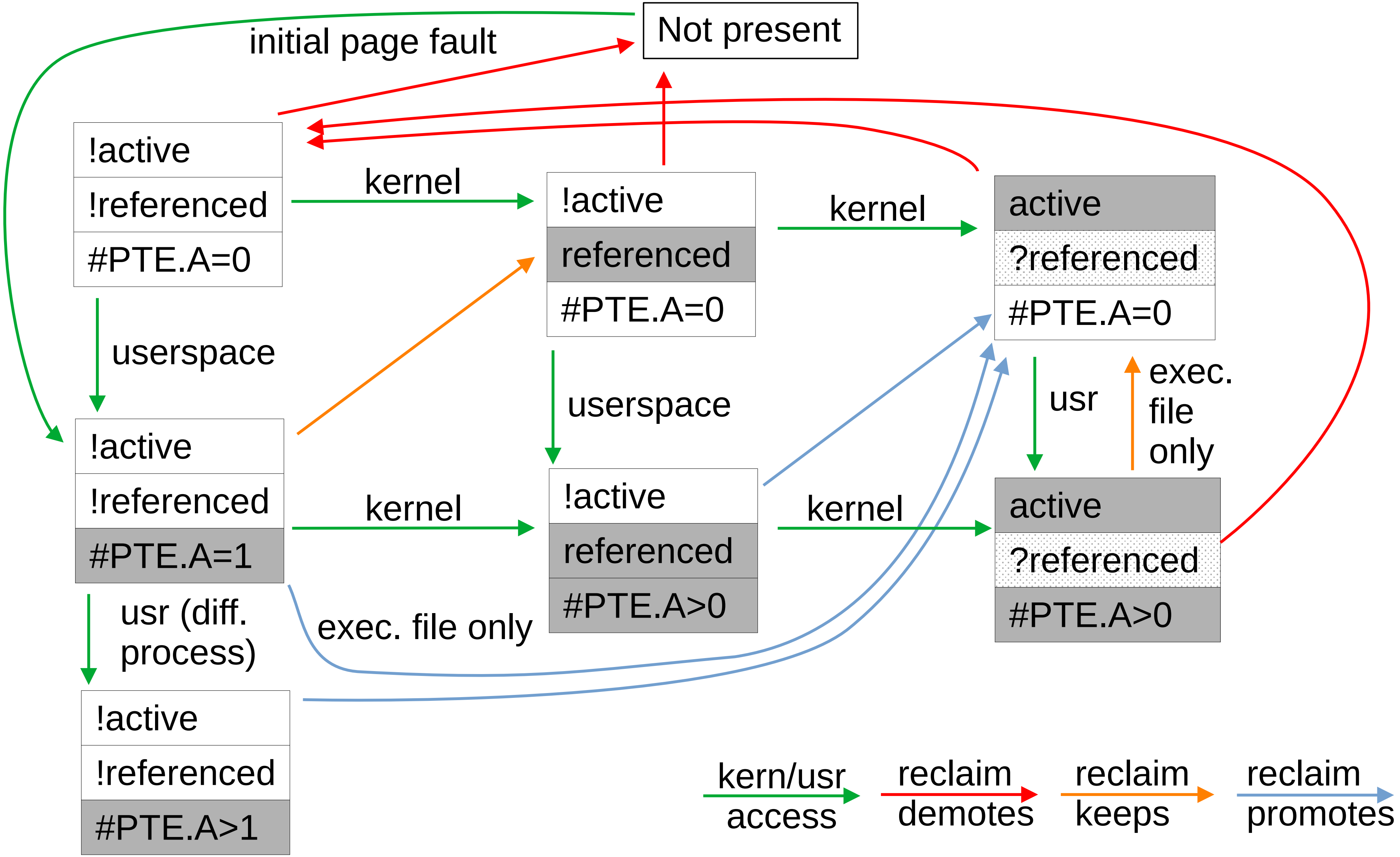

Not present
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kernel
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?referenced
#PTE.A>0
usr (diff. process)
exec. file only
!active
!referenced
#PTE.A>1
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reclaim keeps
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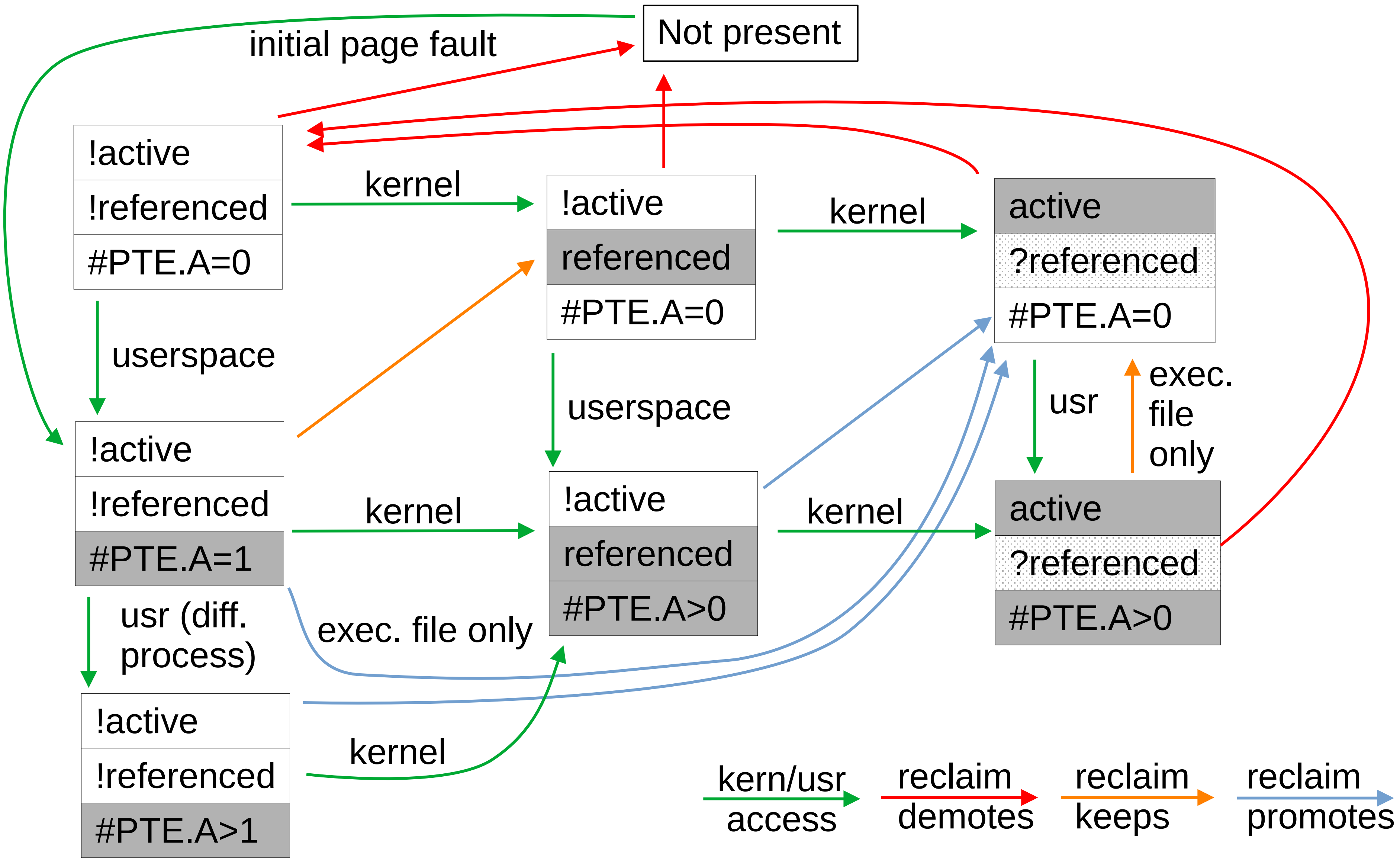

Not present
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active
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userspace
userspace
usr
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!active
!referenced
#PTE.A=1
kernel
!active
referenced
#PTE.A>0
kernel
active
?referenced
#PTE.A>0
usr (diff.
process)
exec. file only
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#PTE.A>1
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Workingset Detection

- Premise: transitioning workloads might be thrashing if pages are not accessed often enough while on inactive list to have chance to be promoted
  - Inactive list is intentionally small, the workload’s working set might be just larger
  - If a recently reclaimed page is faulted in again, we don’t know if it’s new or thrashing
  - Meanwhile the pages on active list might be idle, but we won’t know
- Example: Workload accesses pages 7 8 9 10 11 7 8 9 10 11 ...
  - The access distance is 5 (4 different pages between two accesses to the same page)
  - Inactive list only has 4 pages (NR_inactive = 4), thus each access is a fault
  - Pages 1 – 6 were active before but now may be actually idle
- Idea: determine this access distance, even for pages that have been evicted
  - Use *shadow entries* of radix tree/XArray for evicted pages to store information
  - Precise tracking again impossible, need to approximate

active						inactive				evicted
1	2	3	4	5	6	11	10	9	8	7

Approximating Access Distance (1)

- Observation: Access that causes page fault (7) places the page to inactive list head, pushes all other pages towards tail, evicts tail page (8)
- Observation: Access on inactive list (8) results in activation, also pushes all pages previously ahead of the page on the inactive list towards tail (now 9)
- Thus: sum of evictions and activations over some time period means at least N inactive page accesses happened during that period
- And: pushing an inactive page N slots towards tail needs at least N inactive/faulting page accesses

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active						inactive				evicted
1	2	3	4	5	6	11	10	9	8	7

1	2	3	4	5	6	7	11	10	9	8

Approximating Access Distance (1)

- Observation: Access that causes page fault (7) places the page to inactive list head, pushes all other pages towards tail, evicts tail page (8)
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active						inactive				evicted
1	2	3	4	5	6	11	10	9	8	7

↓

8	1	2	3	4	5	6	11	10	9	8

Approximating Access Distance (2)

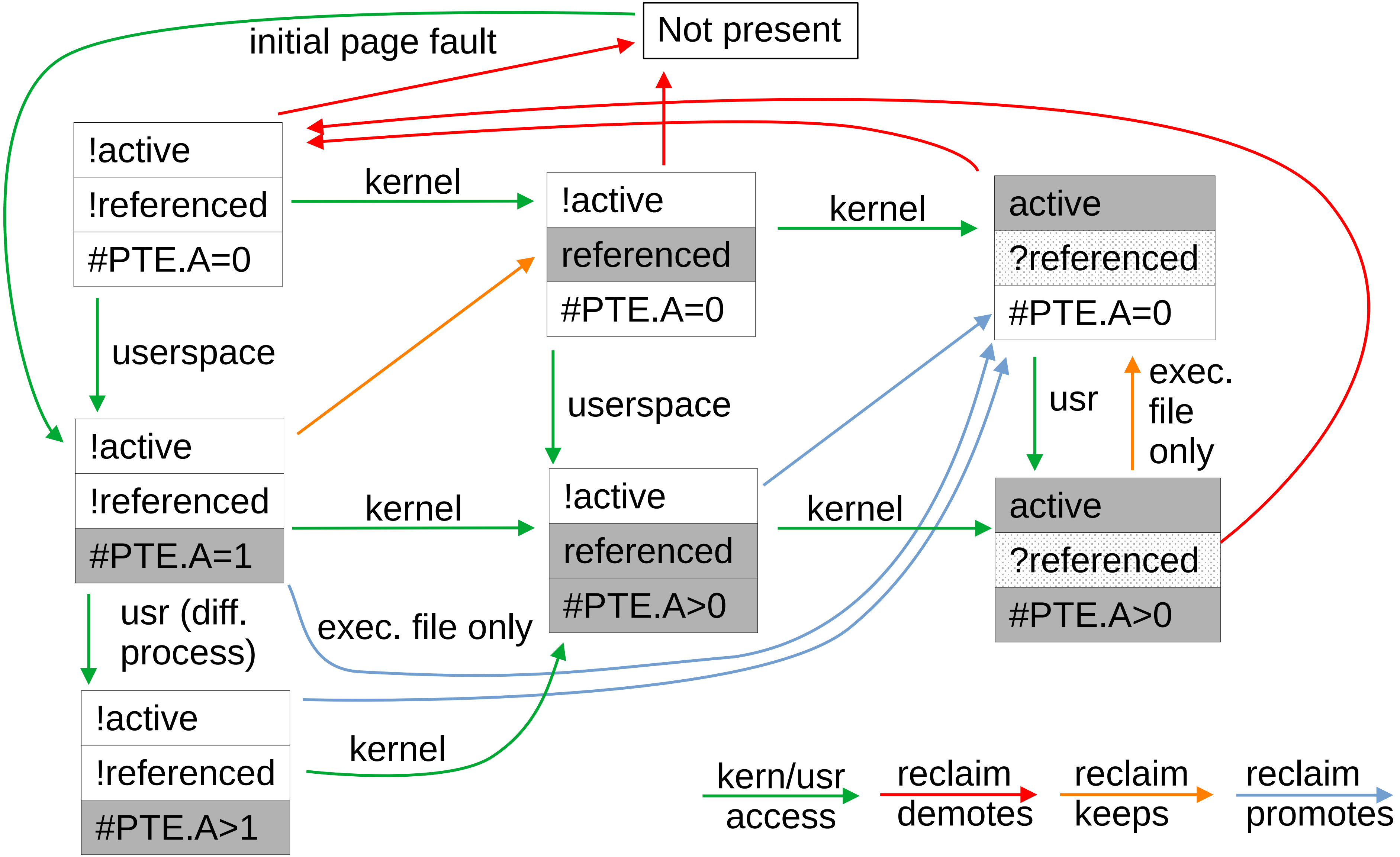
- Eviction of a page means at least **`NR_inactive`** pages were accessed while it was in memory
- If we note sum of evictions + activations at the moment of eviction (**`E`**), and at the moment of refault (**`R`**), the difference (**`R-E`**) approximates number of accesses while the page was evicted – called *refault distance*
- Combined minimum access distance: **`NR_inactive + (R–E)`**
- Page would possibly not have to be evicted if:

```
NR_inactive + (R–E) <= NR_active + NR_inactive
```

- Simplified:

```
(R–E) <= NR_active
```

- Thus when this inequality holds on refault, activate page immediately
- Full writeup: see `mm/workingset.c`


Not present
initial page fault
!active
!referenced
#PTE.A=0
kernel
!active
referenced
#PTE.A=0
kernel
active
?referenced
#PTE.A=0
userspace
userspace
usr
exec.
file
only
!active
!referenced
#PTE.A=1
kernel
!active
referenced
#PTE.A>0
kernel
active
?referenced
#PTE.A>0
usr (diff.
process)
exec. file only
!active
!referenced
#PTE.A>1
kernel
kern/usr
access
reclaim
demotes
reclaim
keeps
reclaim
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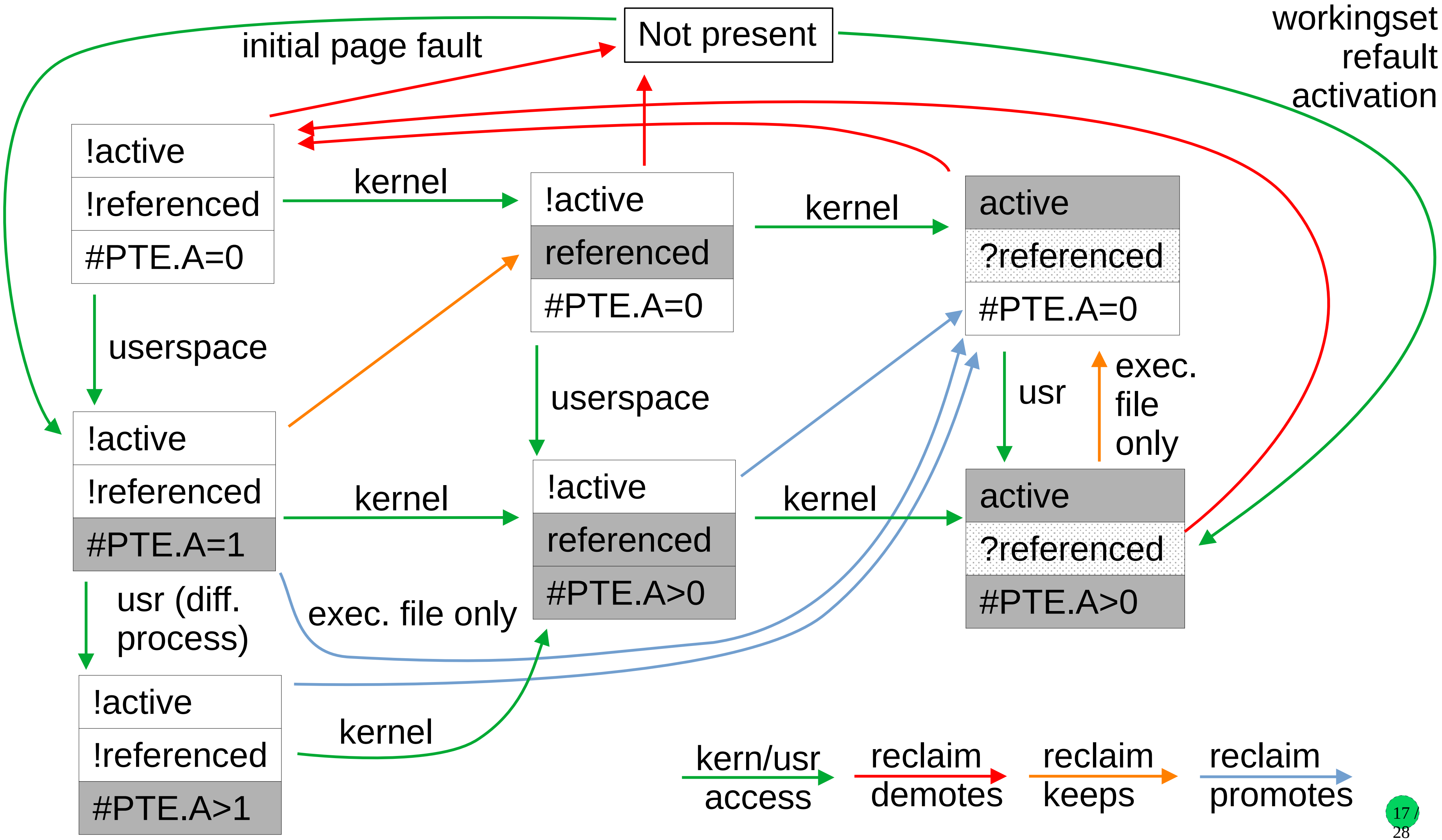
Not present
initial page fault
workingset
refault
activation
!active
!referenced
#PTE.A=0
kernel
!active
referenced
#PTE.A=0
kernel
active
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Workingset Detection Implementation

- Initially was implemented for file pages only, later also for anonymous pages
- Counter of evictions plus activations in `lruvec->nonresident_age`
  - Counters of workingset refaults in `lruvec->refaults[ANON_AND_FILE]`
- Refault distance (**`R-E`**) is compared to **workingset size**
  - Sum of all LRU sizes except the inactive list of the page's type
  - File page refault distance compared to `NR_active_file + NR_active_anon + NR_inactive_anon`
  - Anon page refault distance compared to `NR_active_anon + NR_active_file + NR_inactive_file`
  - But if swap is not available, anon list sizes are not included in the sums
- Additionally, when page is deactivated, its `Workingset` flag is set
  - The flag is recorded in a shadow entry, and set again upon refault, never cleared (i.e. only when stale shadow entries are reclaimed)
  - Refaults with `Workingset` flag restored play role in reclaim cost model

Global Reclaim Algorithm

- Per-node kswapd or direct reclaim when a node is below watermarks – both eventually call `shrink_node()`
- Decide if anon and/or file pages should be deactivated – active/inactive balancing
  - Goal: large active list with low amount of reclaim work, small inactive list as a busy “proving ground”, except when the workload’s working set is transitioning
  - Formula in `inactive_is_low()`, based on `sqrt` of the active+inactive list sizes
    - 1:1 up to 100MB worth of memory on the LRU lists
    - 3:1 (active:inactive) at 1GB memory – 25% pages should be on inactive list
    - 320:1 at 10TB memory
  - Deactivation allowed when inactive list size is below the target ratio
  - Or when workingset refaults are happening, based on a rather coarse check (the counter of file workingset refaults of anon/file changed since last reclaim)

Global Reclaim Algorithm #2

Anon/file balancing – decide how much to shrink from each type’s LRU

- Some corner case decisions first
  - “Many” (based on reclaim priority) inactive file pages and we do not deactivate file pages, prioritize file reclaim – “cache trim mode”
  - Too few file pages (active+inactive) with “many” inactive anon pages and we do not deactivate anon pages, prioritize anon reclaim – “file is tiny”
    - Tries to prevent runaway feedback loop where small file LRU means no chance to get pages promoted
- Iterate over all memcgs, calling `shrink_lruvec()`
- Determine how much to scan in each LRU list by `get_scan_count()`
  - Consider only file LRUs – swapping not possible or cache trim mode enabled
  - Consider only anon LRUs – “file is tiny”
  - Scan both equally – close to OOM (but `swappiness` is not 0) - no time for fine balancing
  - Balance anon and file LRUs according to Fractional Cost Model

Global Reclaim Algorithm #3

Anon/file fractional cost model – in `get_scan_count()`

- Idea: if reclaim causes more IO for file pages than anon pages, put more pressure on anon pages, and vice versa – pressure is inversely proportional to to cost
- We count workingset refaults that restore `Workingset` flag (which means a formerly active page was reclaimed), and dirty page write-outs, as the reclaim cost
  - To soften corner cases, soften the resulting pressure from interval [0, 1] to [1/3, 2/3]
- This is also weighted by `vm.swappiness` sysctl, with range from 0 to 200 (default 60)
  - `vm.swappiness=0` – anon reclaim has infinite cost, reclaim only file pages
  - `vm.swappiness=100` – anon and file pages have same IO cost
  - `vm.swappiness=200` – file reclaim has infinite cost, reclaim only anon pages
- The result is fraction between 0 and 1 for anon, and for file, both add up to 1
- Calculate how many pages to scan from each LRU list - *target*
  - `NR_pages >> reclaim_prio` (prio starts at 12 – 1/4096 of the list, prio decreased each round)
  - Apply calculated fraction, or set to 0 if we are not reclaiming the particular type

Global Reclaim Algorithm #4

- The LRU list shrinking itself
  - Call `shrink_list()` in a loop, scan up to 32 pages (`SWAP_CLUSTER_MAX`) in iteration
    - Skip active list if deactivation is not allowed
  - Isolate pages from tail of list, then deactivate, keep or reclaim according to their flags and page table entries with active bit set
  - Terminate when budget (initialized by `get_scan_count()` targets) is exhausted for all lists
  - After having reclaimed the target number of pages (`SWAP_CLUSTER_MAX` or high watermark), keep scanning to deplete the rest of the budget, but:
    - Stop scanning the file/anon type with lower remaining budget
    - For the other type, adjust the budget to keep the original anon/file ratio
    - Example: target was 64 file, 32 anon pages, after scanning and reclaiming 16 from each, scan additional 16 file pages (so the result is 32 file, 16 anon)
  - Finally, scan 32 pages from active anon list
    - If swap is available and inactive anon is low
    - Ignores prior decision whether to deactivate anon

Reclaiming a page - `shrink_inactive_list()`

- Remove (isolate) from the LRU list
- Unmap from processes mapping the page
- Clean page can be freed immediately
- Dirty page – has to be written back first
  - File pages – tricky due to potentially large stacks, deadlock concerns (GFP_NOFS)
    - Normally should be written back from flusher threads / in response to dirty throttling
    - From kswapd – may in some cases write back (`pageout()`) immediately
    - Otherwise only mark page with reclaim flag and rotate to active list
  - Anonymous page, allocate swap if needed, `pageout()`
  - In the process, page’s writeback and reclaim flags will be set, asynchronous write initiated, and page will rotate back to head of inactive list
  - When writeback is finished, folio_end_writeback() will notice the reclaim flag and rotate the page to the end of inactive list

`madvise(2)` - reclaim related flags

- `MADV_DONTNEED` – throw away private anonymous pages, unmap file pages
  - might be reclaimed later due to memory pressure, no explicit reclaim action
- `MADV_FREE` (since 4.5) – private anon only – clear page dirty, referenced flags, move it to inactive *file* list
  - pages will be discarded (destructive, no swap-out) soon in case of memory pressure
  - a write to the page before the discard will cancel the discard
  - cheaper than MADV_DONTNEED – no immediate page table zapping

Since 5.4, also two new always non-destructive modes:

- `MADV_COLD` – deactivate pages (move to inactive list, clear referenced flags)
  - swap-out or dirty page writeback will happen during reclaim
  - only pages not mapped by multiple processes
- `MADV_PAGEOUT` – immediately reclaim pages
  - including swap-out or dirty page writeback
  - only pages not mapped by multiple processes

Page reclaim - conclusion

- This was an overview, implementation has even more details and special cases
- Some topics omitted (almost) completely
  - Writeback, swapping, dirty throttling, memcg reclaim, slab reclaim (shrinkers), watermarks handling, kswapd vs direct reclaim, reclaim/compaction, OOM, PSI…
- Complex system, results of years of evolution, including big recent changes
  - No overall documentation
- Many moving parts, hard to predict behavior, hard to evaluate patches!
  - Elaborate cost models applied only to 1/3 of decision space
  - OTOH, major decisions made by looking if a number has changed since last time
  - Explicit corner case heuristics against undesired feedback loops
  - We’ve seen issues (in older kernel) e.g. with file pages thrashing and anon not reclaimed
  - Users expecting no swapping until page cache low, but now thanks to workingset estimation, cold anonymous pages can be swapped out during e.g. overnight virus scan

Multigenerational LRU Framework

- Patchset from Yu Zhao (Google) merged in v6.1 (Dec 2022)
- Multiple generations (at least 3) instead of active/inactive lists – separate lists (per file/anon and zone), generation number in page flags word
  - Faults go to youngest generation, buffered file accessed to oldest
  - Accessed bit (found during scan) moves page to youngest generation
- Generations also divided to tiers for more fine-grained `mark_page_accessed()` counting, tier also part of page flags, but not separate lists
  - Balancing tiers using workingset refault info, PID controller-like feedback loop
- Scanning for accessed bits through page table walks, not lru lists
  - Attempts to exploit spatial locality, avoid expensive rmap walks (fallback to lru on sparse mappings); actually similar to how old Linux versions used to work
  - Maintains lists of mm structs per memcgs, skipping of sleeping processes and inactive PMDs, no page level zigzag between vma's
- Eviction processes oldest generation, balances between file and anon by refaults

Multigenerational LRU Framework

- Optional. Has sysfs knobs for run-time enable, thrashing protection
- Pros:
  - Kswapd reduced rmap walk CPU usage, reduced direct reclaim latency
  - Tools for workload scheduling decisions (workingset estimation), proactive reclaim
  - Some success stories – reduced swap storms, improved throughputs…
- Cons:
  - Changed many things at once, kernel development prefers incremental improvements
    - Feedback not fully successful, “Linus likes this” helped merging anyway
  - Largely orthogonal to existing mechanism, not its replacement → maintenance burden
  - Adds user space knobs (at least not mandatory to use)

Thank you.