Dynamic memory

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Important stuff

- Memory is the new(?) bottleneck
- Management must be fast+space-efficient

Roadmap

- Memory management in Linux
- Memory for efficient I/O:
  - A slow way of doing it
  - A Linux way of doing it
  - A faster way of doing it: Fbufs & IO-Lite
  - A different way of doing it: Beltway Buffers & pipesfs

Linux kernel memory management

- MM in kernel is harder than in uspace
- x86 as running example
- Physical pages are basic units of MM
- Every page is represented by: struct page

• ulong	flags	← dirty, locked
• atomic_t	count	← how many refs to page
• struct list_head	list	
• struct AS	*mapping	← adress space associated to the page
• ulong	index	
• struct list_head	lru	
• (pte)		
• (private)		
• void *	virtual	← virtual address (could be null)

for every phys. page!

- page frame descriptor array is called mem_map

Zones

- zone DMA
  - pages capable of undergoing DMA
- zone normal
  - regularly mapped pages
- zone highmem
  - pages not permanently mapped in kernel's AS
  - (in)famous 896MB boundary

zone pools

- different pools for different zones
- if we need DMA-able memory, use zone DMA pool
- no hard requirement (e.g., normal page could also come from zone DMA or highmem)

say we have 2GB of memory

getting pages

- low-level mechanism to get pages:
  - struct page *alloc_pages (uint gfp_mask, uint order)

    or (if you are only interested in the logical address):
  - ulong __get_free_pages (uint gfp_mask, uint order)
    - allocates 2^{order} pages
    - GFP mask encapsulates a bunch of things
      - zone
      - behaviour of allocator (can it block? can it start disk or FS I/O? etc)
    - Examples: GFP_KERNEL, GFP_ATOMIC, GFP_DMA

higher level

- allloc_pages (and friends) are low-level
  - work on pages
  - are good when you need a set of physically contiguous pages
- for byte sized allocations
  - kmalloc (size, gfp_mask): physically contiguous
  - vmalloc (size, gfp_mask): virtually contiguous

hold on...

- this is actually quite complicated
- we must track free memory, handle external fragmentation, etc.
  - first fit? best fit? worst fit?
  - defragmentation?
- and it has to be fast
- so how does allocation really work?

buddy allocation

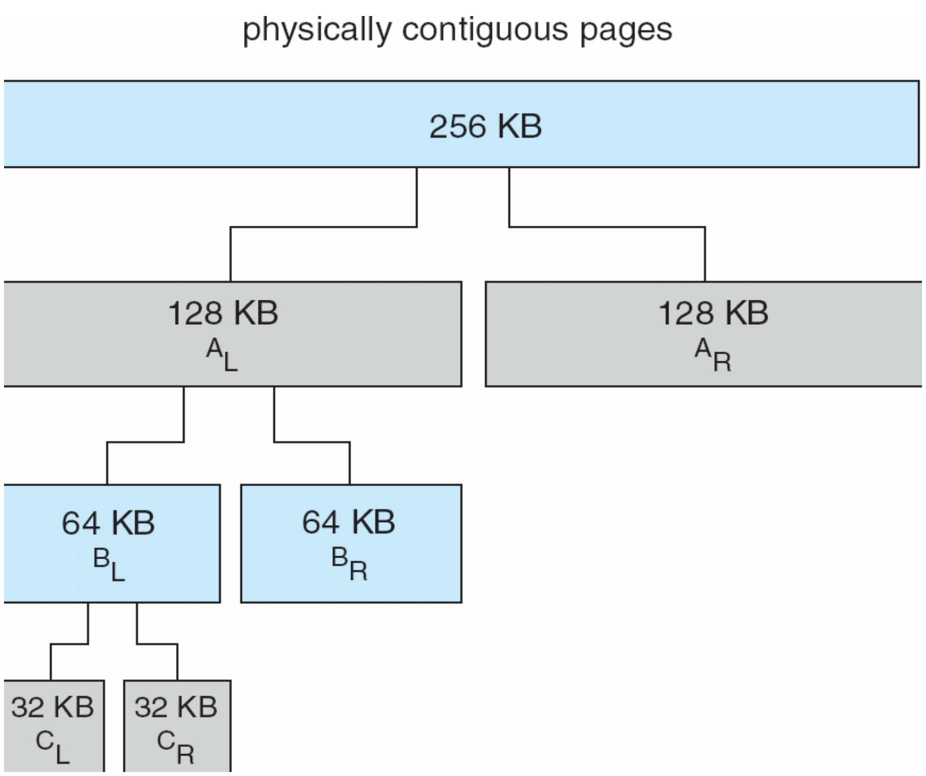
(Harry Markowitz in 1963)

buddy allocation

Fast, simple allocation for blocks of 2^n bytes

void *allocate (k bytes)

- raise allocation to nearest $s = 2^n$
- search free list for appropriate size
  - Represent free list with bitmap
  - Recursively divide larger free
  - blocks until find block of size s
  - "Buddy" block remains free
- mark corresponding bits as allocated



free(ptr)

- mark bits as free
- recursively coalesce block with buddy, if buddy is free
  - May coalesce lazily (later, in background) to avoid overhead

Buddy allocation

- Program A requests memory 34K..64K in size
- Program B requests memory 66K..128K in size
- Program C requests memory 35K..64K in size
- Program D requests memory 67K..128K in size

- Program C releases its memory
- Program A releases its memory
- Program B releases its memory
- Program D releases its memory

	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K	64K
$t = 0$	1024K															
$t = 1$	A-64K	64K	128K		256K				512K							
$t = 2$	A-64K	64K	B-128K		256K				512K							
$t = 3$	A-64K	C-64K	B-128K		256K				512K							
$t = 4$	A-64K	C-64K	B-128K		D-128K		128K		512K							
$t = 5$	A-64K	64K	B-128K		D-128K		128K		512K							
$t = 6$	128K		B-128K		D-128K		128K		512K							
$t = 7$	256K				D-128K		128K		512K							
$t = 8$	1024K															

Buddy allocation

- works really well
- but has a serious disadvantage...

Buddy allocation

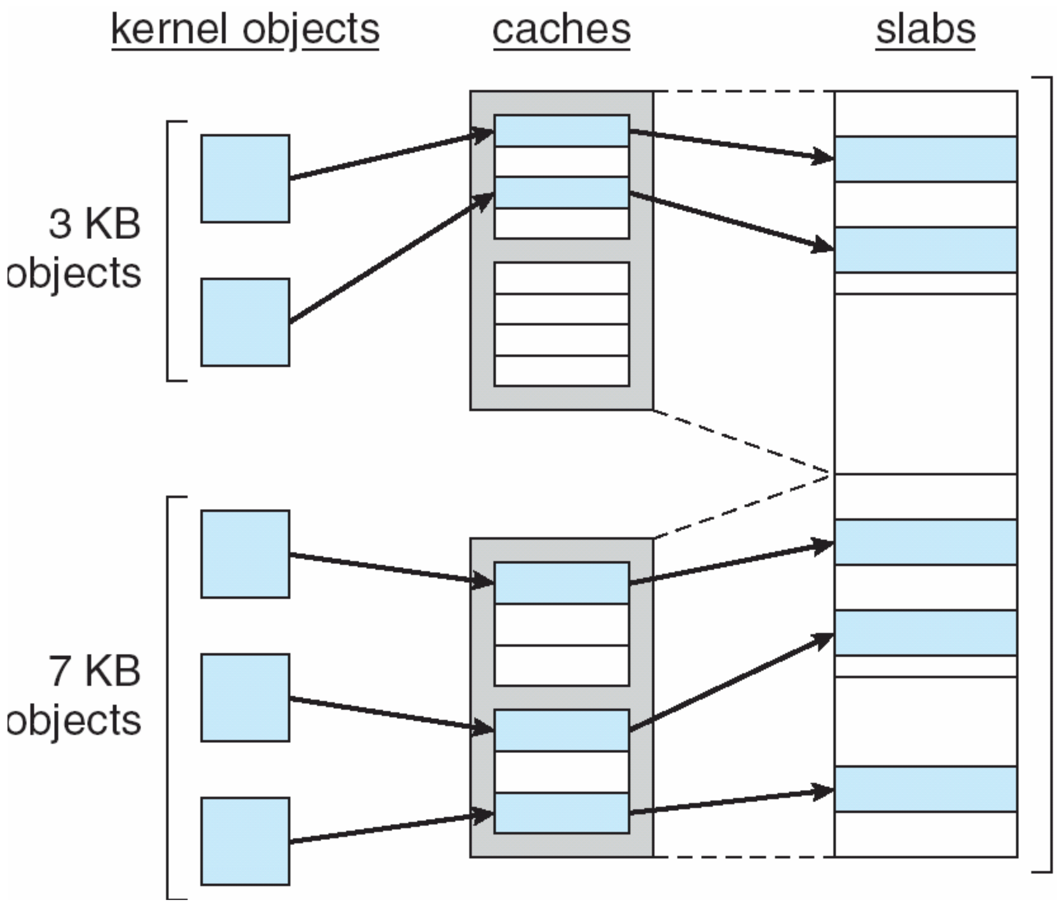
- suffers from internal fragmentation that can be quite significant
- also: consider frequent allocation and de-allocation of same-size chunk

slab allocator

- many allocations and de-allocations are for same-size objects
- we don't want the overhead
- so: cache the allocation

Slab Allocation

- Slab – One or more phys. contiguous pages
- Cache – One or more slabs
  - Single cache for each unique kernel data structure (process descriptor, inode, semaphore, ...)
- Object – instance of a kernel data structure

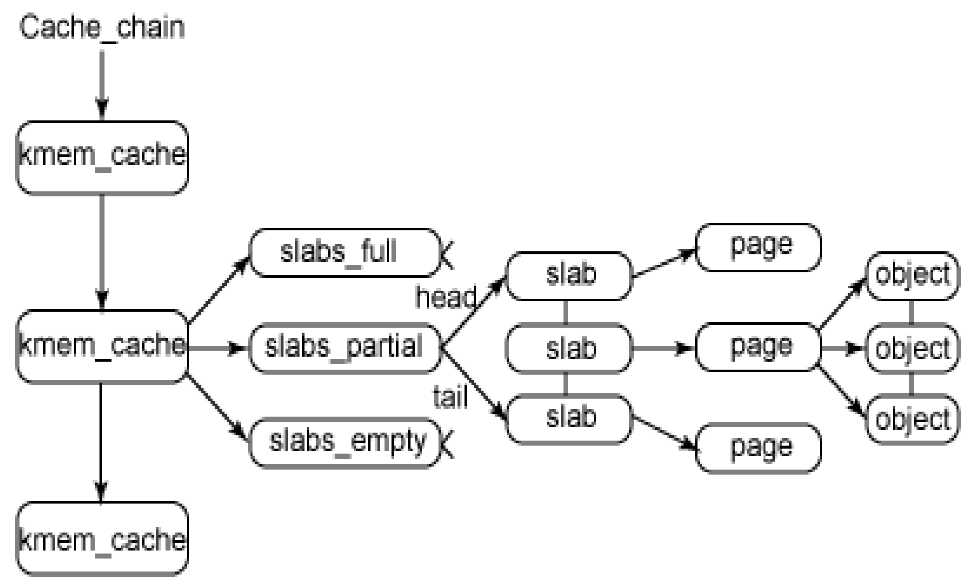


Slab allocation

- Set of objects pre-allocated
- Marked as free
- When needed assign a free one and mark as used
- No free ones available?
  - Allocate a new slab
  - Slab states: full, empty, partial
  - Fill partial slab first
- Advantage
  - No fragmentation
  - Memory requests are satisfied quickly

slab descriptors

- cache represented by kmem_cache_t struct
  - three lists:
    - slabs_full
    - slabs_empty
    - slabs_partial



- slab descriptor, struct slab, represents each slab

```
struct slab {

    struct list_head   list;        ← it is a list!
    ulong              colour;
    void               *s_mem;      ← first object in slab
    uint               in_use;      ← number of allocated objects
    kmem_bufctl_t      free;        ← first free object (if any)

};
```

slab descriptors

- slab descriptor are allocated
  - inside slab if total slab size small
  - outside slab in a general cache

```
struct slab {

        struct list_head    list;        ← it is a list!
        ulong               colour;
        void                *s_mem;      ← first object in slab
        uint                in_use;      ← number of allocated objects
        kmem_bufctl_t       free;        ← first free object (if any)

};
```

General and specific caches

- specific caches can be created to store objects of certain sizes
- general caches contain 13 geometrically distributed caches
  - from 32 to 131,072 bytes increased in power of 2
- kmalloc is built on top of slab layer using a family of general purpose caches

SLAB is great

- but are there any disadvantages?

SL*B

- SLAB
- SLOB
  - traditional UNIX with SLAB emulation
  - for embedded systems
  - slower
- SLUB
  - newer way of doing SLAB
  - removes some problems (e.g., alignment issues due to descriptors in slab)

when would you use

- slab?
- buddy?

the process address space

Linux process address space

- flat 32b or 64b address space
- memory areas: intervals of legal addresses
- processes can dynamically add and remove memory areas
- Memory regions have an initial logical address and a length, which is a multiple of 4K
- SEGV: process acesses invalid memory area

process address spaces

- Typical situations in which a process gets new memory regions
  - growing its stack
  - creating shared memory (shmat())
  - expanding its heap (malloc())
  - Creating a new process (fork())
  - loading an entirely new program (execve())
  - memory mapping a file (mmap())

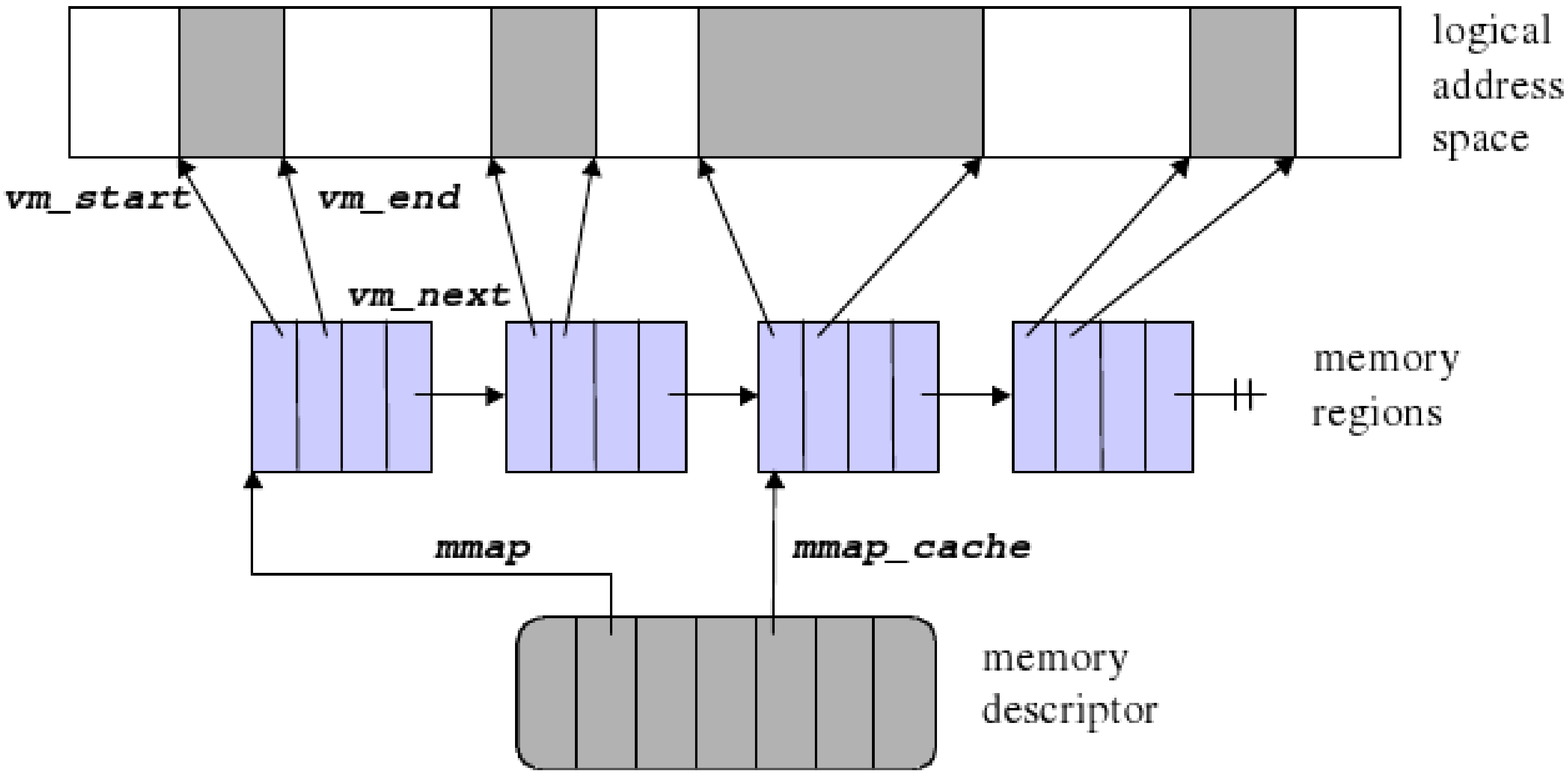
process memory descriptor

- all info related to the process address space is included in the memory descriptor (mm_struct) referenced by the mm field of the process descriptor
- Memory descriptors are allocated from the slab allocator cache using mm_alloc()
- Some examples of included information
  - A pointer to the top level of the page table, the Page Global Directory
  - Number of page frames allocated to the process
  - Process' address space size in pages
  - Number of locked pages
  - Number of processes sharing the same mm_struct, i.e., threads
  - list of memory areas (struct vm_area struct ***mmap**)

memory areas

- Linux represents a memory region with vm_area struct
  - Contains a reference to the memory descriptor that owns the region (vm_mm field),
  - the start (vm_start field) and end (vm_end field) of the interval
- Memory areas never overlap
- Kernel tries to merge contiguous regions (if access rights match)
- All regions are maintained on a simple list (vm_next field) in ascending order by address

global view



logical
address
space
vm_start
vm_end
vm_next
memory
regions
mmap
mmap_cache
memory
descriptor

Example:

cat /proc/`pidof bc`/maps

```
08048000-08058000 r-xp 00000000 08:01 15024544   /usr/bin/bc
08058000-08059000 rw-p 00010000 08:01 15024544   /usr/bin/bc
08059000-0807a000 rw-p 08059000 00:00 0          [heap]
b7cfd000-b7d3c000 r--p 00000000 08:01 15089747   /usr/lib/locale/en_AU.utf8/LC_CTYPE
b7d3c000-b7d3d000 rw-p b7d3c000 00:00 0
b7d3d000-b7d3f000 r-xp 00000000 08:01 15501619   /lib/tls/i686/cmov/libdl-2.7.so
b7d3f000-b7d41000 rw-p 00001000 08:01 15501619   /lib/tls/i686/cmov/libdl-2.7.so
b7d41000-b7e8a000 r-xp 00000000 08:01 15501532   /lib/tls/i686/cmov/libc-2.7.so
b7e8a000-b7e8b000 r--p 00149000 08:01 15501532   /lib/tls/i686/cmov/libc-2.7.so
b7e8b000-b7e8d000 rw-p 0014a000 08:01 15501532   /lib/tls/i686/cmov/libc-2.7.so
b7e8d000-b7e91000 rw-p b7e8d000 00:00 0
b7e91000-b7ebe000 r-xp 00000000 08:01 15466565   /lib/libncurses.so.5.6
b7ebe000-b7ec1000 rw-p 0002c000 08:01 15466565   /lib/libncurses.so.5.6
b7ec1000-b7eed000 r-xp 00000000 08:01 15466577   /lib/libreadline.so.5.2
b7eed000-b7ef1000 rw-p 0002c000 08:01 15466577   /lib/libreadline.so.5.2
b7ef1000-b7ef2000 rw-p b7ef1000 00:00 0
b7eff000-b7f06000 r--s 00000000 08:01 15042231   /usr/lib/gconv/gconv-modules.cache
b7f06000-b7f09000 rw-p b7f06000 00:00 0
b7f09000-b7f0a000 r-xp b7f09000 00:00 0          [vdso]
b7f0a000-b7f24000 r-xp 00000000 08:01 15466534   /lib/ld-2.7.so
b7f24000-b7f26000 rw-p 00019000 08:01 15466534   /lib/ld-2.7.so
bf99f000-bf9b4000 rw-p bffeb000 00:00 0          [stack]
```

creating an address interval

- mmap / do_mmap
  - creates 'new' address interval
  - except: if adjacent, it tries to merge with existing one (requires permissions to be the same)
  - do_mmap() used in kernel
  - exported to user space using mmap() syscall

- munmap() / do_munmap()

the page cache

page cache

- Linux has one primary disk cache: page cache
- It is (drum roll)... *a cache of pages*
- idea:
  - store in phys. memory data accessed from disk
  - next access will be from memory
  - use as many available pages as possible
- caches *any* page-based object (e.g., files and file mappings)
- single read-ahead to speed up seq. access

use as much as possible for PC

MemTotal:	3950112 kB
MemFree:	622560 kB
Buffers:	78048 kB
Cached:	**2901484 kB**
SwapCached:	0 kB
Active:	3108012 kB
Inactive:	55296 kB
HighTotal:	0 kB
HighFree:	0 kB
LowTotal:	3950112 kB
LowFree:	622560 kB
SwapTotal:	4198272 kB
SwapFree:	4198244 kB
Dirty:	416 kB
Writeback:	0 kB
Mapped:	999852 kB
Slab:	57104 kB
Committed_AS:	3340368 kB
PageTables:	6672 kB
VmallocTotal:	536870911 kB
VmallocUsed:	35300 kB
VmallocChunk:	536835611 kB
HugePages_Total:	0
HugePages_Free:	0
Hugepagesize:	2048 kB

/proc/meminfo for system with 4G of memory

looking up a page is fairly hard

- because multiple non-contiguous disk blocks may be in a page
- you cannot just index page cache with device name and block number

address_space

- struct address_space is used to identify pages

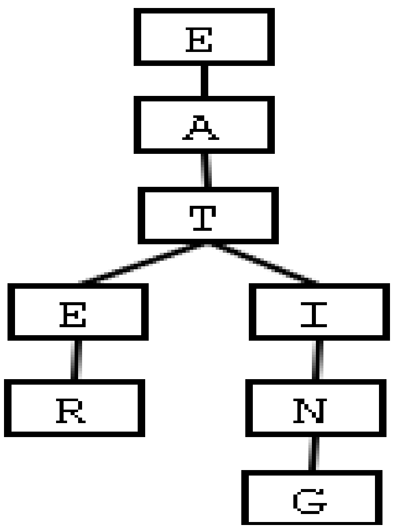
```
struct address_space {
        struct inode              *host;              /* owner: inode, block_device */
        struct radix_tree_root    page_tree;          /* radix tree of all pages */
        rwlock_t                  tree_lock;          /* and rwlock protecting it */
        unsigned int              i_mmap_writable;    /* count VM_SHARED mappings */
        struct prio_tree_root     i_mmap;             /* tree of private and shared mappings */
        struct list_head          i_mmap_nonlinear;   /*list VM_NONLINEAR mappings */
        spinlock_t                i_mmap_lock;        /* protect tree, count, list */
        unsigned int              truncate_count;     /* Cover race condition with truncate */
        unsigned long             nrpages;            /* number of total pages */
        pgoff_t                   writeback_index;    /* writeback starts here */
        const struct address_space_operations *a_ops;   /* methods */
        unsigned long             flags;              /* error bits/gfp mask */
        struct backing_dev_info   *backing_dev_info;  /* device readahead, etc */
        spinlock_t                private_lock;       /* for use by the address_space
        struct list_head          private_list;       /* ditto */
        struct address_space      *assoc_mapping;     /* ditto */
}
```

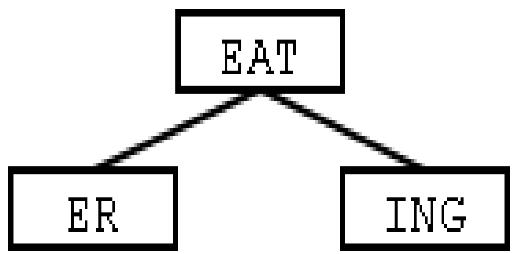
reading a page

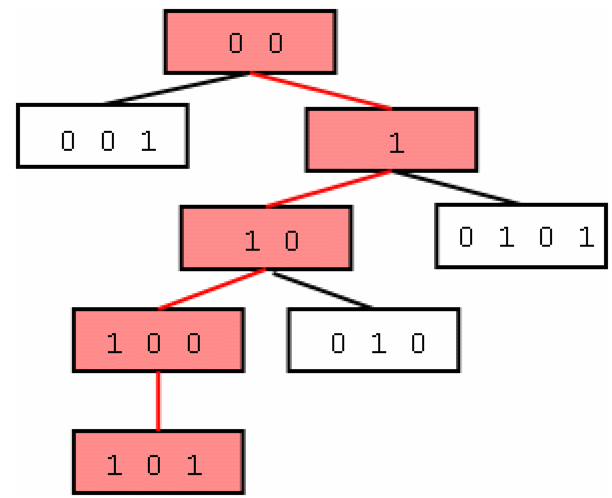
- lookup: given address_space plus offset pair

→ use the radix tree for efficient lookup

skip radix tree







Look-up of {00110100101 1100} in a PATRICIA Trie

radix tree in Linux

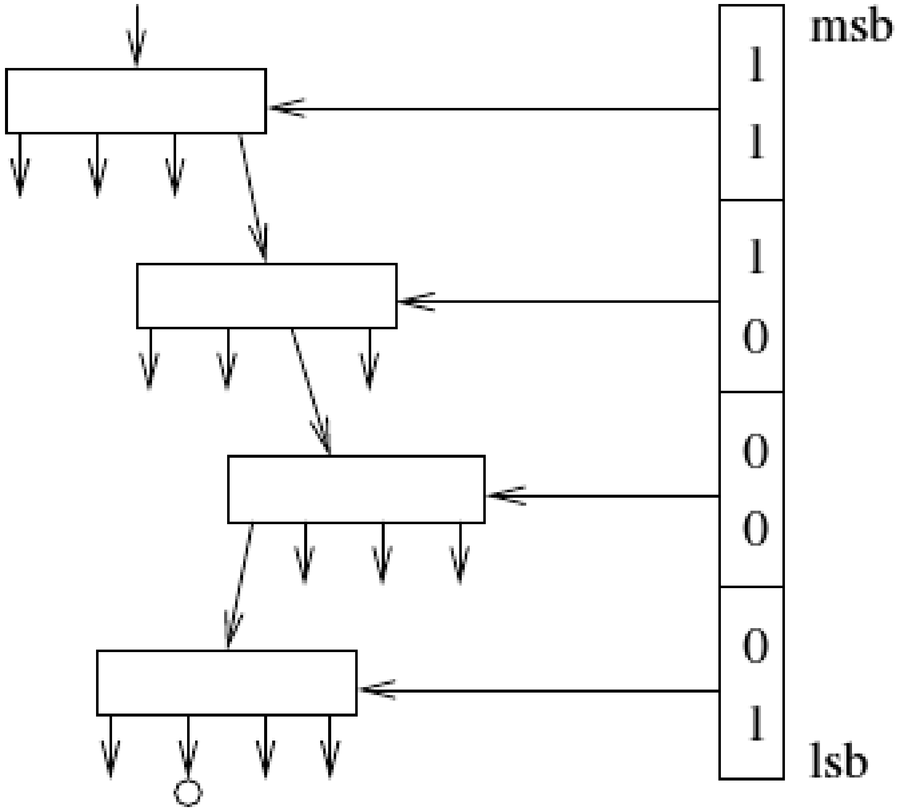


Figure 1: 8-bit radix tree

tagged radix tree in Linux

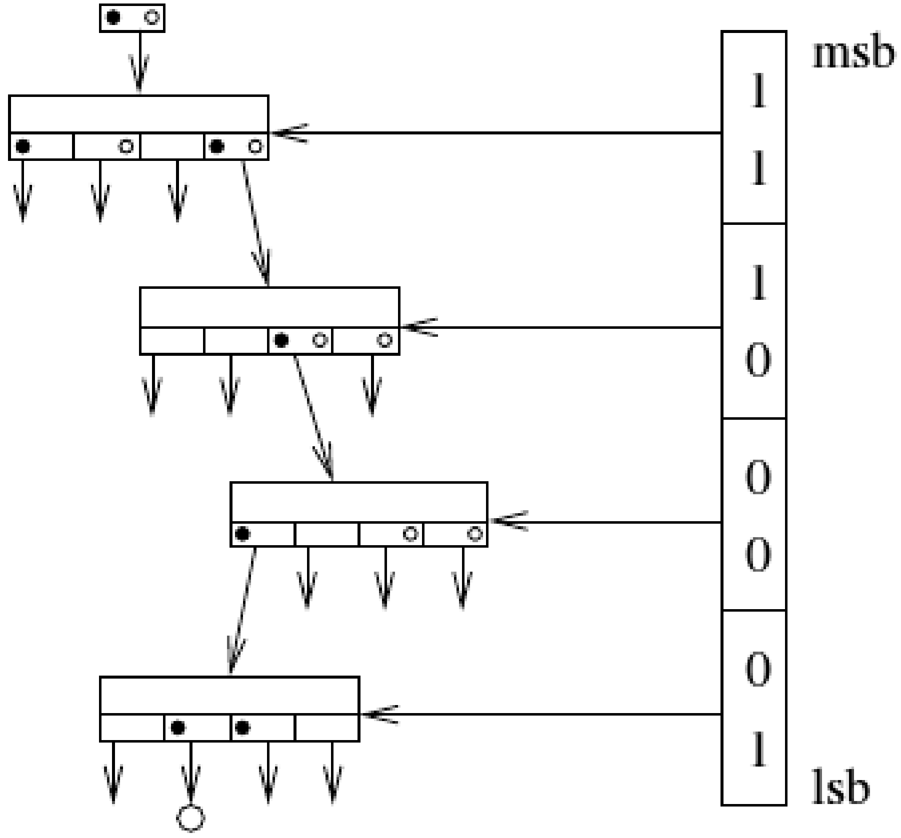
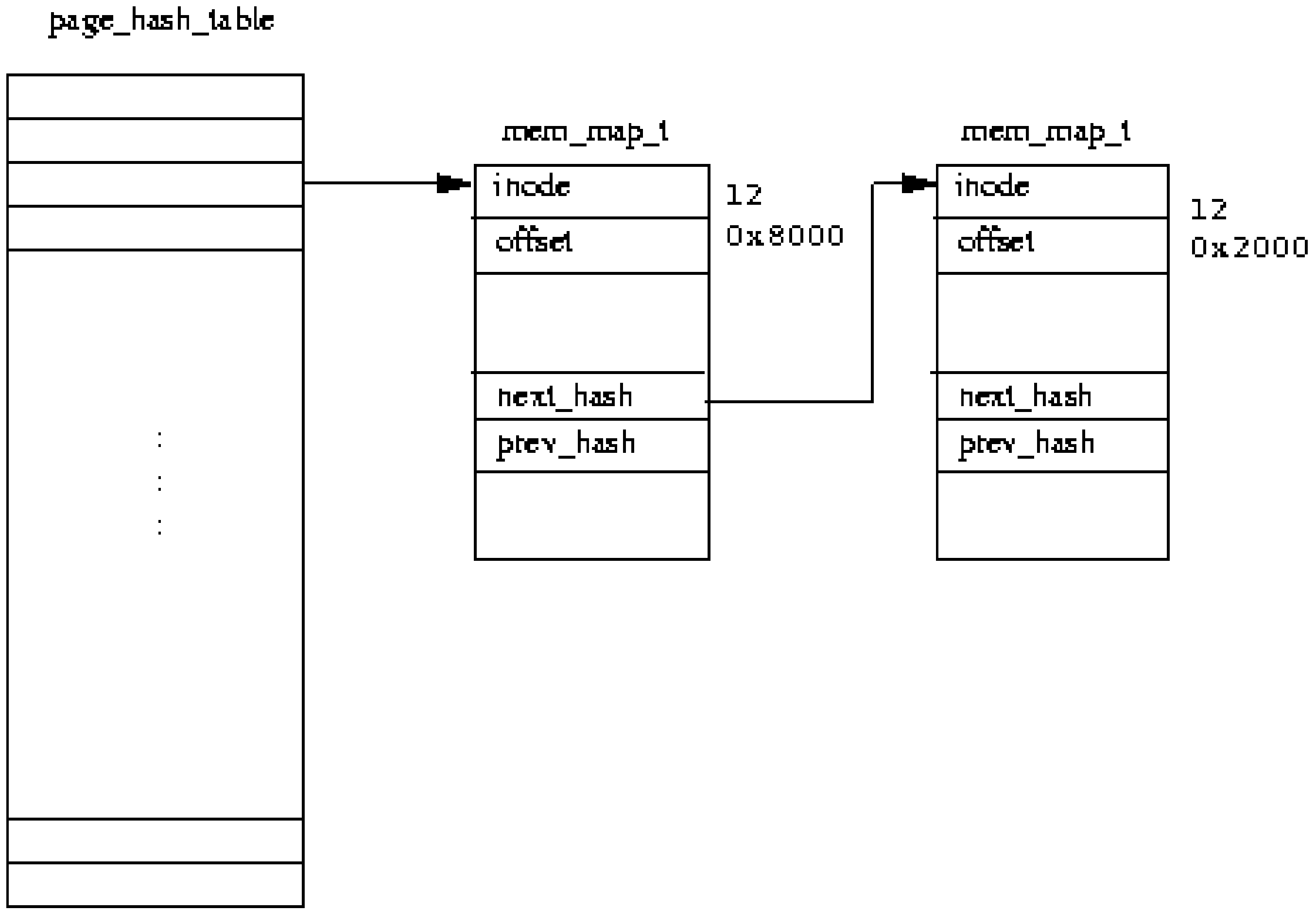


Figure 2: 8-bit radix tree with 2 bitmap indices

old way: the page hash table



dirty pages must be flushed

- pdflush daemon is responsible for this
- when to flush?
  - when free memory shrinks below threshold
  - when dirty data grows older than threshold
- >1 pdflush threads
  - why?

Summary part I

- dynamic memory
  - buddy
  - slab
- process address space
- page cache