



# Linux Kernel Analysis

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## OS Fundamentals

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## Lab References

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# Homework

## Weekly tech question

1. What was I trying to do?
2. How did I do it? (steps)
3. The expected output? The real output?
4. How did I try to solve it? (steps, books, web links)
5. How many hours did I struggle on it?

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🇬🇧 Preferably in English

📖 in [stackoverflow](#) style

OR simply show me the tech questions you asked on any website

# 1 Overview

## 1.1 Basic Operating System Concepts



# Basic Operating System Concepts

## Two main objectives of an OS:

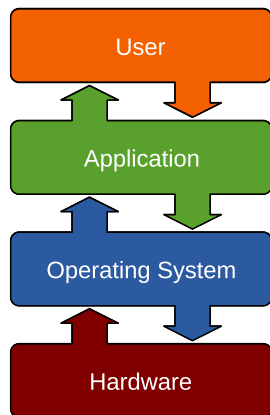
- ▶ Interact with the hardware components
- ▶ Provide an execution environment to the applications

## Different OS, different ways

**Unix** hides all low-level details from applications

*User mode vs. Kernel mode*

**MS-DOS** allows user programs to directly play with the hardware components



## Typical Components of a Kernel

**Interrupt handlers:** to service interrupt requests

**Scheduler:** to share processor time among multiple processes

**Memory management system:** to manage process address spaces

**System services:** Networking, IPC...

# Kernel And Processes

## Kernel space

- ▶ a protected memory space
- ▶ full access to the hardware

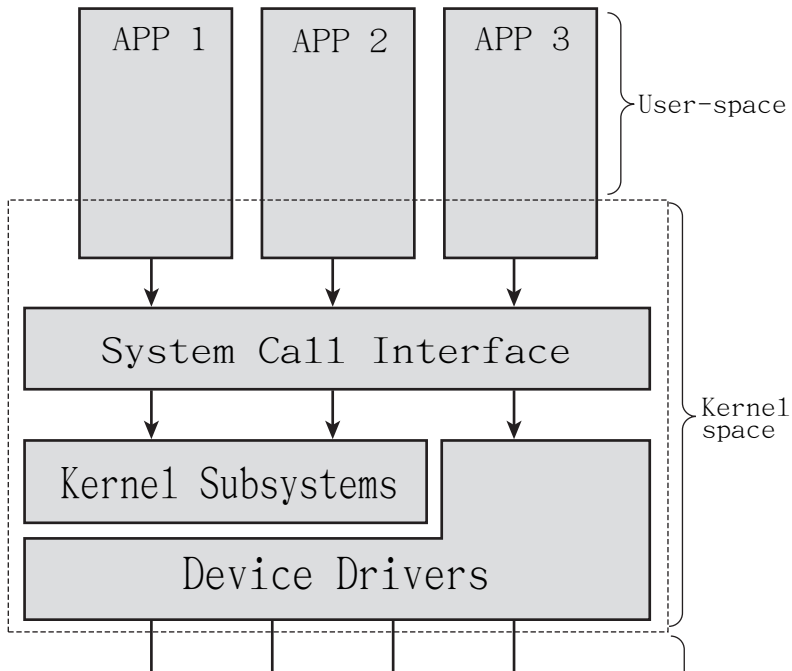
When executing the kernel, the system is in kernel-space executing in *kernel mode*.

## User Space

- ▶ Can only see a subset of available resources
- ▶ unable to perform certain system functions, nor directly access hardware

Normal user execution in user-space executing in *user mode*.

user mode  $\xrightarrow{\text{system calls}}$  kernel mode



# Kernel And Hardware

## Interrupts

Whenever hardware wants to communicate with the system, it issues an interrupt that asynchronously interrupts the kernel.

- ▶ Interrupt vector
- ▶ Interrupt handlers

# Kernel Architecture

## Monolithic kernels

Simplicity and performance

- ▶ exist on disk as single static binaries
- ▶ All kernel services run in the kernel address space
- ▶ Communication within the kernel is trivial

Most Unix systems are monolithic in design.

## Microkernels

- ▶ are not implemented as single large processes
- ▶ break the kernel into separate processes (*servers*).
  - ▶ in the microkernel
    - ▶ a few synchronization primitives
    - ▶ a simple scheduler
    - ▶ an IPC mechanism
  - ▶ top of the microkernel
    - ▶ memory allocators
    - ▶ device drivers
    - ▶ system call handlers

## Advantages of microkernel OS

- ▶ modularized design
- ▶ easily ported to other architectures
- ▶ make better use of RAM

## Performance Overhead

- ▶ Communication via *message passing*
- ▶ Context switch (kernel-space  $\Leftrightarrow$  user-space)
  - ▶ Windows NT and Mac OS X keep all servers in kernel-space. (defeating the primary purpose of microkernel designs)
- ▶ Microkernel OSes are generally slower than monolithic ones.
- ▶ Academic research on OS is oriented toward microkernels.



## 1.2 Linux Versus Other Unix-Like Kernels

Linux is a monolithic kernel with modular design

Modularized approach — makes it easy to develop new modules

Platform independence — if standards compliant

Frugal main memory usage — run time (un)loadable

No performance penalty — no explicit message passing is required



## Linux Versus Other Unix-Like Kernels

- ▶ share fundamental design ideas and features
- ▶ from 2.6, Linux kernels are POSIX-compliant
  - ▶ Unix programs can be compiled and executed on Linux
- ▶ Linux includes all the features of a modern Unix
  - ▶ VM, VFS, LWP, SVR4 IPC, signals, SMP support ...

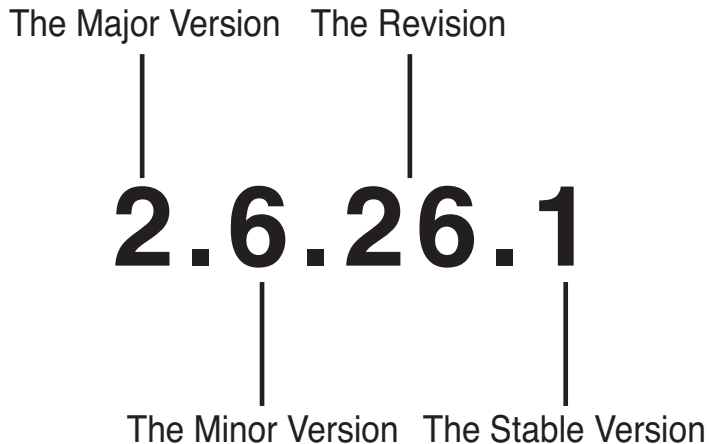
## Linux Kernel Features

- ▶ Monolithic kernel
- ▶ loadable modules support
- ▶ Kernel threading
- ▶ Multithreaded application support
- ▶ Preemptive kernel
- ▶ Multiprocessor support
- ▶ File systems

## Advantages Over Its Commercial Competitors

- ▶ cost-free
- ▶ fully customizable in all its components
- ▶ runs on low-end, inexpensive hardware platforms
- ▶ performance
- ▶ developers are excellent programmers
- ▶ kernel can be very small and compact
- ▶ highly compatible with many common operating systems
  - ▶ filesystems, network interfaces, wine ...
- ▶ well supported

# Linux Versions



## 1.3 An Overview of Unix Kernels



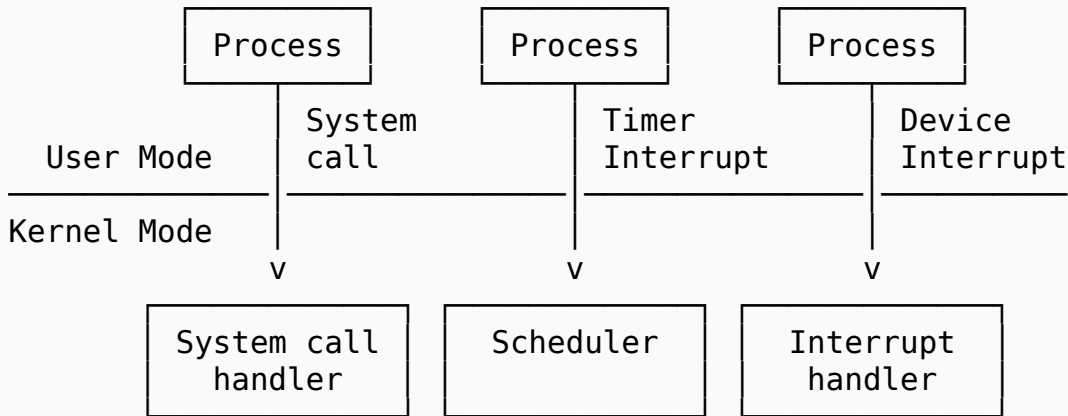
# The Unix Process/Kernel Model

## User Mode vs. Kernel Mode

- ▶ Processes can run in either user mode or kernel mode
- ▶ The kernel itself is not a process but a process manager

processes  $\xrightarrow{\text{system calls}}$  process manager

## Kernel routines can be activated in several ways



## Unix Kernel Threads

- ▶ run in Kernel Mode in the kernel address space
- ▶ no interact with users
- ▶ created during system startup and remain alive until the system is shut down

## Process Implementation

- ▶ Each process is represented by a *process descriptor (PCB)*
- ▶ Upon a process switch, the kernel
  - ▶ saves the current contents of several registers in the PCB
  - ▶ uses the proper PCB fields to load the CPU registers

## Registers

- ▶ The program counter (PC) and stack pointer (SP) registers
- ▶ The general purpose registers
- ▶ The floating point registers
- ▶ The processor control registers (Processor Status Word) containing information about the CPU state
- ▶ The memory management registers used to keep track of the RAM accessed by the process

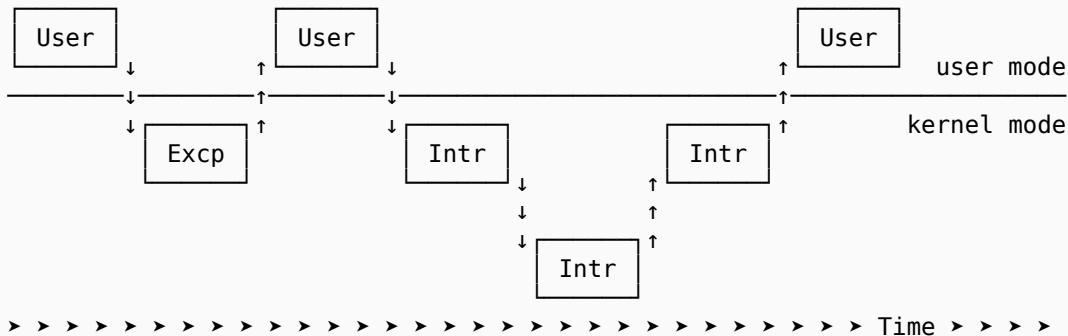
# Reentrant Kernels

**Reentrant Kernels** several processes may be executing in Kernel Mode at the same time

i.e. several processes can wait in kernel mode

**Kernel control path** denotes the sequence of instructions executed by the kernel to handle a system call, an exception, or an interrupt.

## Interleaving of kernel control paths



# Process Address Space

## Each process runs in its private address space

- ▶ User-mode private stack (user code, data...)
- ▶ Kernel-mode private stack (kernel code, data...)

## Sharing cases

- ▶ The same program is opened by several users
- ▶ Shared memory IPC
- ▶ `mmap()`

# Synchronization and Critical Regions

## Re-entrant kernel requires synchronization

If a kernel control path is suspended while acting on a kernel data structure, no other kernel control path should be allowed to act on the same data structure unless it has been reset to a consistent state.

## Race condition

When the outcome of a computation depends on how two or more processes are scheduled, the code is incorrect. We say that there is a *race condition*.

- ▶ Kernel preemption disabling
- ▶ Interrupt disabling
- ▶ Semaphores
- ▶ Spin locks
- ▶ Avoiding deadlocks

## Signals and IPC

Unix signals notifying processes of system events

```
$ man 7 signal
```

IPC semaphores , message queues , and shared memory

```
shmget(), shmat(), shmdt()
```

```
semget(), semctl(), semop()
```

```
msgget(), msgsnd(), msgrcv()
```

```
$ man 5 ipc
```



# Process Management

`fork()` to create a new process

`wait()` to wait until one of its children terminates

`_exit()` to terminate a process

`exec()` to load a new program

## Zombie processes

**Zombie** a *process state* representing terminated processes

- ▶ a process remains in that state until its parent process executes a `wait()` system call on it

Orphaned processes become children of *init*.

## Process groups

```
$ ls | sort | less
```

```
$ ls *.pdf | wc -l
```

SESSION

Group 1

`ls | sort | less`

Group 2

`ls *.pdf | wc -l`

- ▶ `bash` creates a new group for these 3 processes
- ▶ each PCB includes a field containing the *process group ID*
- ▶ each group of processes may have a *group leader*
- ▶ a newly created process is initially inserted into the process group of its parent

### login sessions

- ▶ All processes in a process group must be in the same login session
- ▶ A login session may have several process groups active simultaneously

# Memory Management

## Virtual memory

Application memory requests
Virtual memory
MMU

- ▶ Several processes can be executed concurrently
- ▶ Virtual memory can be larger than physical memory
- ▶ Processes can run without fully loaded into physical memory
- ▶ Processes can share a single memory image of a library or program
- ▶ Easy relocation

# RAM Usage

## Physical memory

- ▶ A few megabytes for storing the kernel image
- ▶ The rest of RAM are handled by the virtual memory system
  - ▶ dynamic kernel data structures, e.g. buffers, descriptors ...
  - ▶ to serve process requests
  - ▶ caches of buffered devices

## Problems faced:

- ▶ the available RAM is limited
- ▶ memory fragmentation
- ▶ ...

# Kernel Memory Allocation

## User mode process memory

- ▶ Memory pages are allocated from the list of free page frames
- ▶ The list is populated using a page-replacement algorithm
- ▶ free frames scattered throughout physical memory

## Kernel memory allocation

- ▶ Treated differently from user memory
  - ▶ allocated from a free-memory pool

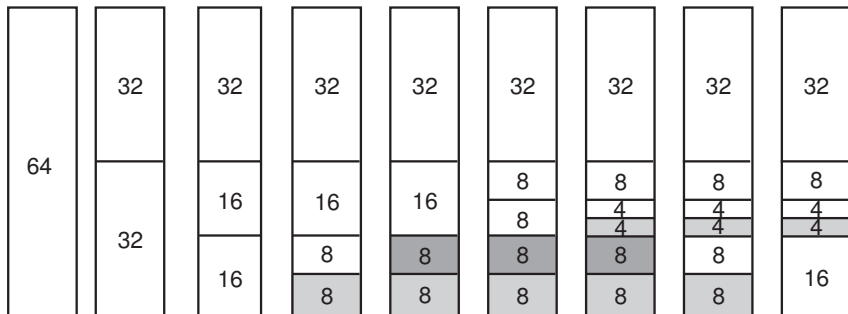
Because:

- ▶ must be fast, i.e. avoid searching
- ▶ minimize waste, i.e. avoid fragmentation
- ▶ maximize contiguousness

Linux's KMA uses a *Slab allocator* on top of a *buddy system*.

## Buddy system

- By splitting memory into halves to try to give a best-fit
- Adjacent units of allocatable memory are paired together





## Object creation and deletion

- ▶ are widely employed by the kernel
- ▶ more expensive than allocating memory to them

## Slab allocation

- ▶ memory chunks suitable to fit data objects of certain type or size are preallocated
  - ▶ avoid searching for suitable memory space
  - ▶ greatly alleviates memory fragmentation
- ▶ Destruction of the object does not free up the memory, but only opens a slot which is put in the list of free slots by the slab allocator

## Benefits

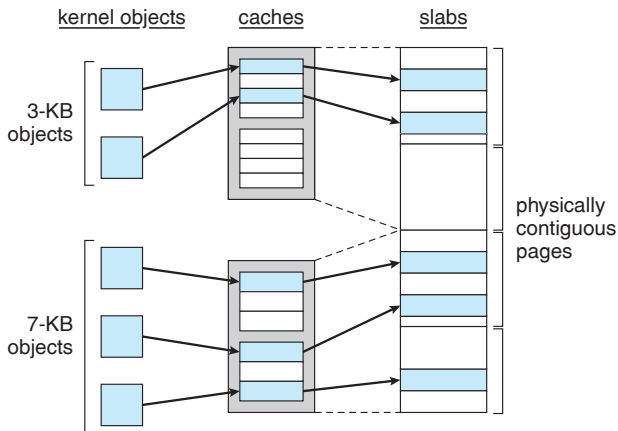
- ▶ No memory is wasted due to fragmentation
- ▶ Memory request can be satisfied quickly

## Slab allocation

**Slab** is made up of several physically contiguous pages

**Cache** consists of one or more slabs.

- A storage for a specific type of object such as semaphores, process descriptors, file objects etc.



## Process virtual address space handling

- ▶ demand paging
- ▶ copy on write

## Caching

- ▶ hard drives are very slow
- ▶ to defer writing to disk as long as possible
- ▶ When a process asks to access a disk, the kernel checks first whether the required data are in the cache
- ▶ `sync()`

# Device Drivers

The kernel interacts with I/O devices by means of device drivers

## The device files in `/dev`

- ▶ are the user-visible portion of the device driver interface
- ▶ each device file refers to a specific device driver

## 2 Before Diving Into The Kernel Source

## 2.1 Getting Started with the Kernel

# Obtaining The Kernel Source

Web: <http://www.kernel.org>

Git: Version control system

```
$ git clone git://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux-2.6.git
```



# Installing The Kernel Source

In /usr/src/ directory:

```
$ tar xvjf linux-x.y.z.tar.bz2
```

```
$ tar xvzf linux-x.y.z.tar.gz
```

```
$ xz -dc linux-x.y.z.tar.xz | tar xf -
```

```
$ ln -s linux-x.y.z linux
```

“sudo” if needed.

# The Kernel Source Tree

arch	Architecture-specific source
block	Block I/O layer
crypto	Crypto API
Documentation	Kernel source documentation
drivers	Device drivers
firmware	Device firmware needed to use certain drivers
fs	The VFS and the individual filesystems
include	Kernel headers
init	Kernel boot and initialization
ipc	Interprocess communication code
kernel	Core subsystems, such as the scheduler
lib	Helper routines
mm	Memory management subsystem and the VM
net	Networking subsystem
samples	Sample, demonstrative code
scripts	Scripts used to build the kernel
security	Linux Security Module
sound	Sound subsystem
usr	Early user-space code (called initramfs)
tools	Tools helpful for developing Linux
virt	Virtualization infrastructure

```
$ tree /usr/src/linux
```

# Building The Kernel

## Configuration

```
make config | make menuconfig | make gconfig
```

```
$ make defconfig # Defaults
```

```
$ make oldconfig # Using .config file
```

## Make

```
$ make -jN > /dev/null
```

**N:** number of jobs. Usually one or two jobs per processor.

## Installing The New Kernel

```
$ sudo make modules_install
```

```
$ sudo make install
```

grub2 config should be updated automatically. Check

- ▶ /etc/grub.d/

- ▶ /boot/grub/grub.cfg

“sudo reboot” to try your luck.

## 2.2 A Beast Of A Different Nature

# A Beast Of A Different Nature

- ▶ Neither the C library nor the standard C headers
- ▶ GNU C
- ▶ Lack of memory protection
- ▶ No floating-point operations
- ▶ Small per-process fixed-size stack
- ▶ Synchronization and concurrency
- ▶ Portability

## No libc or standard headers

- ▶ Chicken-and-the-egg situation
- ▶ Speed and size

Many of the usual libc functions are implemented inside the kernel. For example,

- ▶ String operation: `lib/string.c`, `linux/string.h`
- ▶ `printk()`

The kernel developers use both ISO C99 and GNU C extensions to the C language.

- ▶ Inline functions
- ▶ Inline assembly



## Inline functions

Inserted inline into each function call site

- 😊 eliminates the overhead of function invocation and return (register saving and restore)
- 😊 allows for potentially greater optimization
- 😞 code size increases

```
1 | static inline void wolf(unsigned long tail_size)
```

- ▶ Kernel developers use inline functions for small time-critical functions
- ▶ The function declaration must precede any usage

**Common practice:** place inline functions in header files

## Inline assembly

Embedding assembly instructions in normal C functions

- 😊 speed
- 😞 Architecture dependent (poor portability)

Example: Get the value from the timestamp(tsc) register

```
1 unsigned int low, high;  
2 asm volatile("rdtsc" : "=a" (low), "=b" (high));
```

## Branch prediction

The `likely()` and `unlikely()` macros allow the developer to tell the CPU, through the compiler, that certain sections of code are likely, and thus should be predicted, or unlikely, so they shouldn't be predicted.

```
1 #define likely(x) __builtin_expect(!!(x),1)  
2 #define unlikely(x) __builtin_expect(!!(x),0)
```

## Example: kernel/time.c

```
asmlinkage long sys_gettimeofday(struct timeval __user *tv, struct timezone __user *tz)  
{  
    if (likely(tv != NULL)) {  
        struct timeval ktv;  
        do_gettimeofday(&ktv);  
        if (copy_to_user(tv, &ktv, sizeof(ktv)))  
            return -EFAULT;  
    }  
    if (unlikely(tz != NULL)) {  
        if (copy_to_user(tz, &sys_tz, sizeof(sys_tz)))  
            return -EFAULT;  
    }  
    return 0;  
}
```

## No memory protection

- ▶ Memory violations in the kernel result in an *oops*
- ▶ Kernel memory is not pageable

## No (easy) use of floating point

- ▶ rarely needed
- ▶ expensive: saving the FPU registers and other FPU state takes time
- ▶ not every architecture has a FPU, e.g. those for embedded systems

## Small, fixed-size stack

- ▶ On x86, the stack size is configurable at compile time, 4K or 8K (1 or 2 pages)

## 2.3 Common Kernel Data-types

# Data Types in the Kernel

Three main classes:

1. Standard C types, e.g. `int`
2. Explicitly sized types, e.g. `u32`
3. Types used for special kernel objects, e.g. `pid_t`



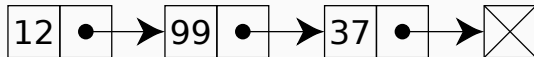
# Common Kernel Data-types

## Many objects and structures in the kernel

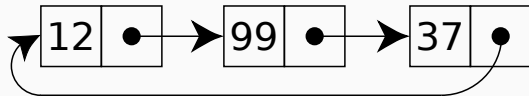
- ▶ memory pages
  - ▶ processes
  - ▶ interrupts
  - ▶ ...
1. linked-lists — to group them together
  2. binary search trees — to efficiently find a single element

# Linked Lists

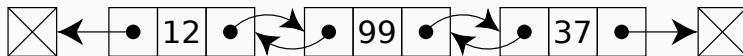
## Singly linked list



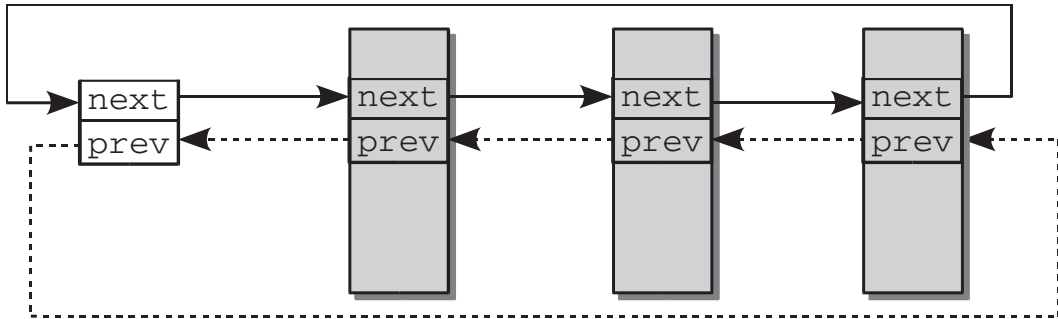
## Circularly linked list



## Doubly linked list



## Circular doubly linked-lists



## Things to note

1. List is *inside the data item* you want to link together.
2. You **can put** “struct list\_head” **anywhere** in your structure.
3. You **can name** “struct list\_head” **variable anything** you wish.
4. You **can have** multiple lists!

## Linked Lists

A linked list is initialized by using the `LIST_HEAD` and `INIT_LIST_HEAD` macros

```
include/linux/list.h

struct list_head {
    struct list_head *next, *prev;
};

#define LIST_HEAD_INIT(name) { &(name), &(name) }

#define LIST_HEAD(name) \
    struct list_head name = LIST_HEAD_INIT(name)

#define INIT_LIST_HEAD(ptr) do { \
    (ptr)->next = (ptr); (ptr)->prev = (ptr); \
} while (0)
```

**Q1:** Why both `LIST_HEAD_INIT` and `INIT_LIST_HEAD`?

**Q2:** Why `do-while`?

## Example

```
struct fox {  
    unsigned long tail_length;  
    unsigned long weight;  
    bool is_fantastic;  
    struct list_head list;  
};
```

The list needs to be initialized before in use

► Run-time initialization

```
struct fox *red_fox; /* just a pointer */  
red_fox = kmalloc(sizeof(*red_fox), GFP_KERNEL);  
red_fox->tail_length = 40;  
red_fox->weight = 6;  
red_fox->is_fantastic = false;  
INIT_LIST_HEAD(&red_fox->list);
```

► Compile-time initialization

```
struct fox red_fox = {  
    .tail_length = 40,
```

## The do while(0) trick

```
#define INIT_LIST_HEAD(ptr) do { \
    (ptr)->next = (ptr); (ptr)->prev = (ptr); \
} while (0)

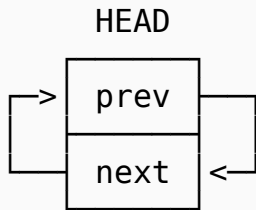
if (1)
    INIT_LIST_HEAD(x);
else
    error(x);

/* after "gcc -E macro.c" */
if (1)
    do { (x)->next = (x); (x)->prev = (x); } while (0);
else
    error(x);

/***** Wrong *****/
#define INIT_LIST_HEAD2(ptr) { \
    (ptr)->next = (ptr); (ptr)->prev = (ptr); \
}

if (1)
    INIT_LIST_HEAD2(x); /* the semicolon is wrong! */
else
    error(x);
```

## After INIT\_LIST\_HEAD macro is called



```
struct list_head {
    struct list_head *next, *prev;
};

#define LIST_HEAD_INIT(name) { &(amp;name), &(amp;name) }

#define LIST_HEAD(name) \
    struct list_head name = LIST_HEAD_INIT(name)

#define INIT_LIST_HEAD(ptr) do { \
    (ptr)->next = (ptr); (ptr)->prev = (ptr); \
} while (0)
```

Example: to start an empty fox list

```
1 | static LIST_HEAD(fox_list);
```



## Manipulating linked lists

- ▶ To add a new member into fox\_list:

```
list_add(&new->list,&fox_list);  
    ▶ fox_list->next->prev = new->list;  
    ▶ new->list->next = fox_list->next;  
    ▶ new->list->prev = fox_list;  
    ▶ fox_list->next = new->list;  
list_add_tail(&f->list,&fox_list);
```

- ▶ To remove an old node from list:

```
list_del(&old->list);  
    ▶ old->list->next->prev = old->list->prev;  
    ▶ old->list->prev->next = old->list->next;
```

- ▶ a lot more...

# List Traversing

```
1 struct list_head *p;  
2 list_for_each(p, fox_list){ ... }
```

## list\_for\_each

```
/**  
 * list_for_each - iterate over a list  
 * @pos: the &struct list_head to use as a loop counter.  
 * @head: the head for your list.  
 */  
#define list_for_each(pos, head) \  
    for (pos = (head)->next; prefetch(pos->next), pos != (head); \  
        pos = pos->next)
```

Not so useful. Usually we want the pointer to the container struct.

```

struct fox {
    unsigned long tail_length;
    unsigned long weight;
    bool is_fantastic;
    struct list_head list;
};

```

Q: Given a pointer to *list*, how to get a pointer to *fox*?

```
f = list_entry(p, struct fox, list);
```

```
list_entry(ptr, type, member)
```

```

/**
 * list_entry - get the struct for this entry
 * @ptr:        the &struct list_head pointer.
 * @type:       the type of the struct this is embedded in.
 * @member:     the name of the list_struct within the struct.
 */

```

```

#define list_entry(ptr, type, member) \
    container_of(ptr, type, member)

```

```

#define container_of(ptr, type, member) ({
    const typeof( ((type *)0)->member ) *mptr = (ptr);

```

```
list_for_each_entry(pos, head, member)
```

```
struct fox *f;
```

```
list_for_each_entry(f, &fox_list, list) {  
    /* on each iteration, 'f' points to the next fox structure ... */  
}
```

```
list_for_each_entry(pos, head, member)
```

```
/**  
 * list_for_each_entry - iterate over list of given type  
 * @pos: the type * to use as a loop counter.  
 * @head: the head for your list.  
 * @member: the name of the list_struct within the struct.  
 */  
#define list_for_each_entry(pos, head, member) \\\n    for (pos = list_entry((head)->next, typeof(*pos), member); \\\n        prefetch(pos->member.next), &pos->member != (head); \\\n        pos = list_entry(pos->member.next, typeof(*pos), member))
```

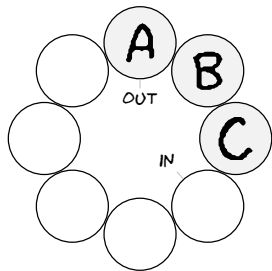
# Queue (FIFO)

## Circular buffer

Empty:  $in == out$

Full:  $(in + 1) \% BUFFER\_SIZE == out$

Can be lock-free.



# KFIFO

```
include/linux/kfifo.h

struct kfifo {
    unsigned char *buffer;    /* the buffer holding the data */
    unsigned int size;        /* the size of the allocated buffer */
    unsigned int in;          /* data is added at offset (in % size) */
    unsigned int out;         /* data is extracted from off. (out % size) */
    spinlock_t *lock;         /* protects concurrent modifications */
};
```

The *spinlock* is rarely needed.

Initialization:

```
int kfifo_alloc(struct kfifo *fifo,
               unsigned int size,
               gfp_t gfp_mask);

void kfifo_init(struct kfifo *fifo,
               void *buffer,
               unsigned int size);
```

Example: to have a PAGE\_SIZE-sized queue

```
struct kfifo fifo;
int ret;
ret = kfifo_alloc(&fifo, PAGE_SIZE, GFP_KERNEL);
if (ret)
    return ret;
```

## kfifo operations

```
/* Enqueue */
unsigned int kfifo_in(struct kfifo *fifo,
                     const void *from, unsigned int len);

/* Dequeue */
unsigned int kfifo_out(struct kfifo *fifo,
                      void *to, unsigned int len);

/* Peek */
unsigned int kfifo_out_peek(struct kfifo *fifo, void *to,
                           unsigned int len, unsigned offset);

/* Get size */
static inline unsigned int kfifo_size(struct kfifo *fifo);

/* Get queue length */
static inline unsigned int kfifo_len(struct kfifo *fifo);

/* Get available space */
static inline unsigned int kfifo_avail(struct kfifo *fifo);

/* Is it empty? */
static inline int kfifo_is_empty(struct kfifo *fifo);

/* Is it full? */
```



## Example

1. To enqueue 32 integers into *fifo*

```
    unsigned int i;
    for (i = 0; i < 32; i++)
        kfifo_in(fifo, &i; sizeof(i));
```

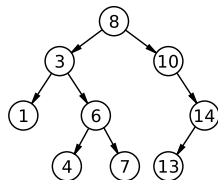
2. To dequeue and print all the items in the queue

```
    /* while there is data in the queue ... */
    while (kfifo_len(fifo)) {
        unsigned int val;
        int ret;
        /* ... read it, one integer at a time */
        ret = kfifo_out(fifo, &val, sizeof(val));
        if (ret != sizeof(val))
            return -EINVAL;
        printk(KERN_INFO "%u\n", val);
    }
```

# Trees

- ▶ Used in Linux memory management
  - ▶ fast store/retrieve a single piece of data among many
- ▶ generally implemented as *linked lists* or *arrays*
- ▶ the process of moving through a tree — *traversing*

# Binary Search Tree



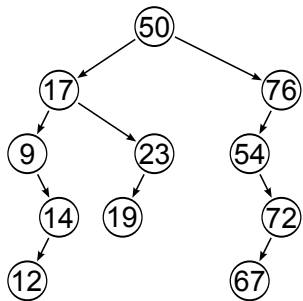
## Properties:

- ▶ The left subtree of a node contains only nodes with keys less than the node's key.
- ▶ The right subtree of a node contains only nodes with keys greater than the node's key.
- ▶ Both the left and right subtrees must also be binary search trees.

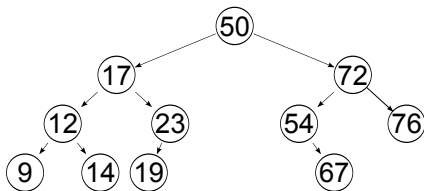
Efficient in:

1. searching for a given node
2. in-order traversal (e.g. Left-Root-Right)

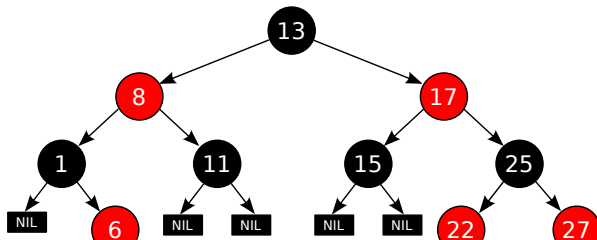
Unbalanced binary tree

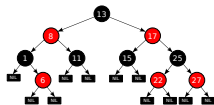


Balanced binary tree



Red-black tree





**Red-black tree** A type of *self-balancing BST* in which each node has a red or black color attribute.

Properties to make it *semi-balanced*:

1. All nodes are either red or black
2. Leaf nodes are black (root's color)
3. Leaf nodes do not contain data (NULL)
4. All non-leaf nodes have two children
5. If a node is red, both its children are black
6. When traversing from the root node to a leaf, each path contains the same number of black nodes

These properties ensure that *the deepest leaf has a depth of no more than double that of the shallowest leaf*.

## Advantages

- ▶ faster real-time bounded worst case performance for insertion and deletion
  - ▶ usually at most two rotations
- ▶ slightly slower (but still  $O(\log n)$ ) lookup time

## Many red-black trees in use in the kernel

- ▶ The deadline and CFQ I/O schedulers employ rbtrees to track requests;
- ▶ the packet CD/DVD driver does the same
- ▶ The high-resolution timer code uses an rbtree to organize outstanding timer requests
- ▶ The ext3 filesystem tracks directory entries in a red-black tree
- ▶ Virtual memory areas (VMAs) are tracked with red-black trees
- ▶ epoll file descriptors, cryptographic keys, and network packets in the “hierarchical token bucket” scheduler

```
<linux/rbtree.h>
```

```
struct rb_node
```

```
{
```

```
    struct rb_node *rb_parent;
```

```
    int rb_color;
```

```
#define RB_RED 0
```

```
#define RB_BLACK 1
```

```
    struct rb_node *rb_right;
```

```
    struct rb_node *rb_left;
```

```
};
```

```
struct rb_root
```

```
{
```

```
    struct rb_node *rb_node;
```

```
};
```

```
#define RB_ROOT (struct rb_root) { NULL, }
```

```
#define rb_entry(ptr, type, member) \
    container_of(ptr, type, member)
```

## Example

```
struct fox {  
    struct rb_node node;  
    unsigned long tail_length;  
    unsigned long weight;  
    bool is_fantastic;  
};
```

## Search

```
struct fox *fox_search(struct rb_root *root, unsigned long ideal_length)  
{  
    struct rb_node *node = root->rb_node;  
  
    while (node) {  
        struct fox *a_fox = container_of(node, struct fox, node);  
  
        int result;  
  
        result = tail_compare(ideal_length, a_fox->tail_length);  
  
        if (result < 0)  
            node = node->rb_left;  
        else if (result > 0)  
            node = node->rb_right;  
    }  
}
```



## Example

### Searching for a specific page in the page cache

```
struct page *rb_search_page_cache(struct inode *inode,
                                  unsigned long offset)
{
    struct rb_node *n = inode->i_rb_page_cache.rb_node;
    while (n) {
        struct page *page = rb_entry(n, struct page, rb_page_cache);
        if (offset < page->offset)
            n = n->rb_left;
        else if (offset > page->offset)
            n = n->rb_right;
        else
            return page;
    }
    return NULL;
}
```

## 2.4 Assembly

# x86 Assembly

## The Pentium class x86 architecture

- ▶ Data ordering is in Little Endian
- ▶ Memory access is in byte (8 bit), word (16 bit), double word (32 bit), and quad word (64 bit).
- ▶ the usual registers for code and data instructions can be broken down into three categories: *control*, *arithmetic*, and *data*.

## Byte ordering is architecture dependent

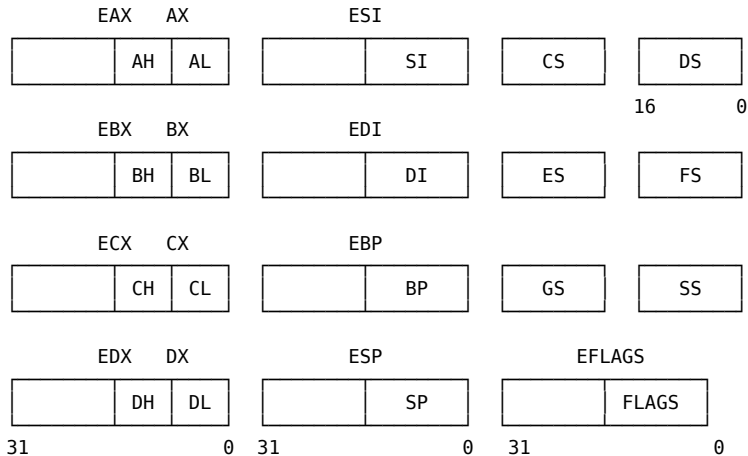
Storing an int (0x01234567) at address 0x100:

Big endian

	0x100	0x101	0x102	0x103	
...	01	23	45	67	...

Little endian

	0x100	0x101	0x102	0x103	
...	67	45	23	01	...



## Three kinds of registers

1. general purpose registers
2. segment registers
3. status/control registers

## General purpose registers

**EAX** Accumulator register

**EBX** Base register

**ECX** Counter for loop operations

**EDX** Data register

**ESI** Source Index

**EDI** Destination Index

**ESP** Stack Pointer

**EBP** Base Pointer pointing to the top of previous stack frame

## Segment registers

CS Code segment

SS Stack segment

DS,ES,FS,GS Data segment

## A memory address is an offset in a segment

ES:EDI references memory in the ES (extra segment) with an offset of the value in the EDI

DS:ESI

CS:EIP

SS:ESP

## State/Control registers

**EFLAGS** Status, control, and system flags

**EIP** The instruction pointer, contains an offset from CS (CS:EIP)

## FLAGS

15				11				7	6						0
-	-	-	-	O	D	I	T	S	Z	-	A	-	P	-	C

**CF** Carry flag

**ZF** Zero flag

**SF** Sign flag, Negative flag

**OF** Overflow flag



## Control Instructions (Intel syntax)

Instruction	Function	EFLAGS
je	Jump if equal	$ZF = 1$
jg	Jump if greater	$ZF = 0$ $SF = OF$
jge	Jump if greater or equal	$SF = OF$
jl	Jump if less	$SF \neq OF$
jle	Jump if less or equal	$ZF = 1$
jmp	Unconditional jump	unconditional

## Example (Intel syntax)

```
    pop    eax           ; Pop top of the stack into eax
loop2:
    pop    ebx
    cmp    eax, ebx      ; Compare the values in eax and ebx
    jge    loop2         ; Jump if eax >= ebx
```

Data can be moved

- ▶ between registers
- ▶ between registers and memory
- ▶ from a constant to a register or memory, but
- ▶ **NOT** from one memory location to another

## Data instructions (Intel syntax)

1. `mov eax, ebx`

Move 32 bits of data from ebx to eax

2. `mov eax, WORD PTR[data3]`

Move 32 bits of data from memory variable data3 to eax

3. `mov BYTE PTR[char1], al`

Move 8 bits of data from al to memory variable char1

4. `mov eax, 0xbeef`

Move the constant value 0xbeef to eax

5. `mov WORD PTR[my_data], 0xbeef`

Move the constant value 0xbeef to the memory variable my\_data

## Address operand syntax (AT&T syntax)

`ADDRESS_OR_OFFSET(%BASE_OR_OFFSET, %INDEX, MULTIPLIER)`

- ▶ up to 4 parameters
  - ▶ ADDRESS\_OR\_OFFSET and MULTIPLIER must be **constants**
  - ▶ %BASE\_OR\_OFFSET and %INDEX must be **registers**
- ▶ all of the fields are optional
  - ▶ if any of the pieces is left out, substituted it with zero
- ▶ final address =

$\text{ADDRESS\_OR\_OFFSET} + \%BASE\_OR\_OFFSET + \%INDEX * MULTIPLIER$

## Why so complicate?

To serve several *addressing modes*

direct addressing mode `movl ADDRESS, %eax`

- ▶ load data at ADDRESS into %eax

indexed addressing mode `movl START(,%ecx,1), %eax`

- START – starting address;      - %ecx – offset/index

indirect addressing mode `movl (%eax), %ebx`

- ▶ load data at address pointed by %eax into %ebx
- ▶ %eax contents an address pointer

base pointer addressing mode `movl 4(%eax), %ebx`

immediate mode `movl $12, %eax`

without \$ Direct addressing

## indexed addressing mode

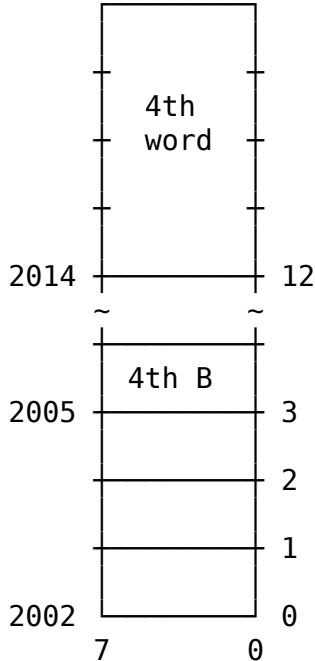
```
movl START(,%ecx,1), %eax
```

START starting address

%ecx offset/index

START(,INDEX,MULTIPLIER):

- ▶ to access the 4<sup>th</sup> byte from location 2002  
 $2002(, 3, 1) = 2002 + 3 \times 1 = 2005$
- ▶ to access the 4<sup>th</sup> word from location 2002  
 $2002(, 3, 4) = 2002 + 3 \times 4 = 2014$



## Example (AT&T syntax)

```
# get the pointer to top of stack
movl %esp, %eax

# get top of stack
movl (%esp), %eax

# get the value right below top of stack
movl 4(%esp), %eax
```

- ▶ each word is 4 bytes long
- ▶ stack grows downward
- ▶ `movl` — long, 32 bits
- ▶ `%eax` — extended, 32 bits

## Example (AT&T syntax)

# Full example:

# load  $*(ebp - 4 + (edx * 4))$  into `eax`

**movl** -4(%ebp, %edx, 4), %eax

# Typical example:

# load a stack variable into `eax`

**movl** -4(%ebp), %eax

# No offset:

# copy the target of a pointer into a register

**movl** (%ecx), %edx

# Arithmetic:

# multiply `eax` by 4 and add 8

**leal** 8(,%eax,4), %eax

# Arithmetic:

# multiply `eax` by 2 and add `eax` (i.e. multiply by 3)

**leal** (%eax,%eax,2), %eax

### Example — stack setup (AT&T syntax)

# Preserve current frame pointer

**pushl %ebp**

# Create new frame pointer pointing to current stack top

**movl %esp, %ebp**

# allocate 16 bytes for locals on stack

**subl \$16, %esp**



# Stack Setup

## Before executing a function, the program

- ▶ pushes all of the parameters for the function onto the stack. Then
- ▶ issues a *call* instruction indicating which function it wishes to start. The call instruction does two things
  1. pushes the address of the next instruction (return address) onto the stack.
  2. modifies the instruction pointer (`%eip`) to point to the start of the function.

## At the time the function starts...

The stack looks like this:

```
Parameter #N  
...  
Parameter 2  
Parameter 1  
Return Address <- (%esp)
```

## The function initializes the %ebp

```
pushl %ebp  
movl %esp, %ebp
```

Now the stack looks like this:

```
Parameter #N <- N*4+4(%ebp)  
...  
Parameter 2 <- 12(%ebp)  
Parameter 1 <- 8(%ebp)  
Return Address <- 4(%ebp)  
Old %ebp <- (%esp) and (%ebp)
```

each parameter can be accessed using base pointer addressing mode using the %ebp register

## The function reserves space for locals

```
subl $8, %esp
```

Our stack now looks like this:

```
Parameter #N <- N*4+4(%ebp)
...
Parameter 2 <- 12(%ebp)
Parameter 1 <- 8(%ebp)
Return Address <- 4(%ebp)
Old %ebp <- (%ebp)
Local Variable 1 <- -4(%ebp)
Local Variable 2 <- -8(%ebp) and (%esp)
```

When a function is done executing, it does three things:

1. stores its return value in %eax
2. resets the stack to what it was when it was called
3. `ret` — `popl %eip` #set eip to *return address*

```
1 | movl %ebp, %esp  
2 | popl %ebp  
3 | ret
```

## After ret

```
Parameter #N  
...  
Parameter 2  
Parameter 1 <- (%esp)
```

## How about the parameters?

- ▶ Under many calling conventions the items popped off the stack by the epilogue include the original argument values, in which case there usually are no further stack manipulations that need to be done by the caller.
- ▶ With some calling conventions, however, it is the caller's responsibility to remove the arguments from the stack after the return.

# Generating Assembly From C Code

simple.c

```
int main()  
{  
    return 0;  
}
```

```
$ gcc -S  
    simple.c
```

simple.s (AT&T syntax)

```
.file    "simple.c"  
.text  
.globl  main  
.type   main, @function  
  
main:  
.LFB0:  
    .cfi_startproc  
    pushl   %ebp  
    .cfi_def_cfa_offset 8  
    .cfi_offset 5, -8  
    movl    %esp, %ebp  
    .cfi_def_cfa_register 5  
    movl    $0, %eax  
    popl    %ebp  
    .cfi_def_cfa 4, 4  
    .cfi_restore 5  
    ret  
    .cfi_endproc  
  
.LFE0:  
    .size   main, .-main  
    .ident  "GCC: (Debian 4.6.3-1) 4.6.3"  
    .section .note.GNU-stack,"",@progbits
```

# Outline of an Assembly Language Program

## Assembler directives (Pseudo-Ops)

Anything starting with a '.'

`.section .data` starts the data section

`.section .text` starts the text section

`.globl SYMBOL`

`SYMBOL` is a *symbol* marking the location of a program

`.globl` makes the symbol visible to 'ld'

`LABEL:` a *label* defines a *symbol's* value (address)



# Generating Assembly From C Code

## simple.s (Oversimplified)

```
pushl    %ebp
movl     %esp, %ebp
movl     $0, %eax
popl     %ebp
ret
```

## Operation Prefixes

\$ constant numbers  
% register

## suffixes

b byte (8 bit)  
s short (16 bit integer) or single  
(32-bit floating point)  
w word (16 bit)  
l long (32 bit integer or 64-bit  
floating point)  
q quad (64 bit)  
t ten bytes (80-bit floating point)

# Generating Assembly From C Code

count.c

```
int main()
{
    int i, j=0;

    for(i=0; i<8; i++)
        j=j+i;

    return 0;
}
```

\$ gcc -S count.c

count.S (AT&T syntax)

```
.file    "count.c"
.text
.globl   main
.type    main, @function

main:
.LFB0:
.cfi_startproc
pushl    %ebp
.cfi_def_cfa_offset 8
.cfi_offset 5, -8
movl     %esp, %ebp
.cfi_def_cfa_register 5
subl     $16, %esp
movl     $0, -8(%ebp)
movl     $0, -4(%ebp)
jmp      .L2

.L3:
movl     -4(%ebp), %eax
addl     %eax, -8(%ebp)
addl     $1, -4(%ebp)

.L2:
cmpl     $7, -4(%ebp)
jle      .L3
movl     $0, %eax
leave
.cfi_restore 5
.cfi_def_cfa 4, 4
```

# Generating Assembly From C Code

count.s (oversimplified)

```
        pushl    %ebp
        movl     %esp, %ebp
        subl     $16, %esp
        movl     $0, -8(%ebp)
        movl     $0, -4(%ebp)
        jmp      .L2

.L3:
        movl     -4(%ebp), %eax
        addl     %eax, -8(%ebp)
        addl     $1, -4(%ebp)

.L2:
        cmpl     $7, -4(%ebp)
        jle      .L3
        movl     $0, %eax
        leave
        ret
```

```
1  leave:
2      movl %ebp, %esp
3      popl %ebp
4
5  enter:
6      pushl %ebp
7      movl %esp, %ebp
```

# Inline Assembly

## Construct

```
1 | asm (assembler instructions
2 |      : output operands      /* optional */
3 |      : input operands      /* optional */
4 |      : clobbered registers /* optional */
5 |      );
```

## Example

```
1 | asm ("movl %eax, %ebx");
2 | asm ("movl %eax, %ebx" :::);
```

Use `__asm__` if the keyword `asm` conflicts with something in our program:

```
1 | __asm__ ("movl %eax, %ebx");
2 | __asm__ ("movl %eax, %ebx" :::);
```

## Example: `exit(0)`

```
{  
    asm("movl  $1,%%eax;"      /* SYS_exit is 1 */  
        "xorl  %%ebx,%%ebx;"  /* Argument is in ebx, it is 0 */  
        "int   $0x80"         /* Enter kernel mode */  
    );  
}
```

## Example

```
int foo(void)
{
    int ee = 0x4000, ce = 0x8000, reg;
    __asm__ __volatile__
    (
        "movl %1, %%eax";
        "movl %2, %%ebx";
        "call setbits" ;
        "movl %%eax, %0"
        : "=r" (reg)           // reg [param %0] is output
        : "r" (ce), "r" (ee)   // ce [param %1], ee [param %2] are inputs
        : "%eax", "%ebx"      // %eax and % ebx got clobbered
    )
    printf("reg=%x", reg);
}
```

- ▶ ee, ce, reg are local variables that will be passed as parameters to the inline assembler
- ▶ “\_\_volatile\_\_” tells the compiler not to optimize the inline assembly routine
- ▶ “r” means *register*; It's a constraint.
- ▶ “=” denotes an output operand, and it's *write-only*

## 2.5 Quirky C Language Usage

# Quirky C Language Usage

## asmlinkage and fastcall

### asmlinkage

```
asmlinkage int sys_fork(struct pt_regs regs)
```

- ▶ tells the compiler to pass parameters on the local stack.

### fastcall

```
fastcall unsigned int do_IRQ(struct pt_regs *regs)
```

- ▶ tells the compiler to pass parameters in the general-purpose registers.

Macro definition:

- ▶ *#define asmlinkage CPP\_ASMLINKAGE \_\_attribute\_\_((regparm(0)))*
- ▶ *#define fastcall \_\_attribute\_\_((regparm(3)))*



# Quirky C Language Usage

## UL

UL tells the compiler to treat the value as a long value.

- ▶ This prevents certain architectures from overflowing the bounds of their datatypes.
- ▶ Using UL allows you to write architecturally independent code for large numbers or long bitmasks.

## Example

```
#define GOLDEN_RATIO_PRIME 0x9e370001UL  
  
#define ULONG_MAX (~0UL)  
  
#define SLAB_POISON 0x00000800UL /* Poison objects */
```

# Quirky C Language Usage

`static inline`

`inline` An `inline` function results in the compiler attempting to incorporate the function's code into all its callers.

`static` Functions that are visible only to other functions in the same file are known as *static functions*.

## Example

```
static inline void prefetch(const void *x)
```

# Quirky C Language Usage

`const`

## `const` — read-only

`const int *x`

- ▶ a pointer to a `const` integer
- ▶ the pointer can be changed but the integer cannot

`int const *x`

- ▶ a `const` pointer to an integer
- ▶ the integer can change but the pointer cannot

# Quirky C Language Usage

## volatile

### Without volatile

```
static int foo;

void bar(void) {
    foo = 0;
    while (foo != 255);
}

/* optimized by compiler */
void bar_optimized(void) {
    foo = 0;
    while (true);
}
```

However, `foo` might represent a location that can be changed by other elements of the computer system at any time, such as a hardware register of a device connected to the CPU.

To prevent the compiler from optimizing code, the `volatile` keyword is used:

```
static volatile int foo;
```

## 2.6 Miscellaneous Quirks

# Miscellaneous Quirks

`__init`

```
#define __init __attribute__((__section__(".init.text")))
```

- ▶ The `__init` macro tells the compiler that the associated function or variable is used only upon initialization.
- ▶ The compiler places all code marked with `__init` into a special memory section that is freed after the initialization phase ends

## Example

```
static int __init batch_entropy_init(int size, struct entropy_store *r)
```

Similarly,

```
__initdata, __exit, __exitdata
```

## 2.7 A Quick Tour of Kernel Exploration Tools

# Kernel Exploration Tools

**objdump** Display information about object files

```
$ objdump -S simple.o
```

```
$ objdump -Dslx simple.o
```

**readelf** Displays information about ELF files

```
$ readelf -h a.out
```

**hexdump** ASCII, decimal, hexadecimal, octal dump

```
$ hd a.out
```

**nm** List symbols from object files

```
$ nm a.out
```



## 2.8 Kernel Speaks: Listen to Kernel Messages

# Listen To Kernel Messages

`printk()` behaves almost identically to the C library `printf()` function

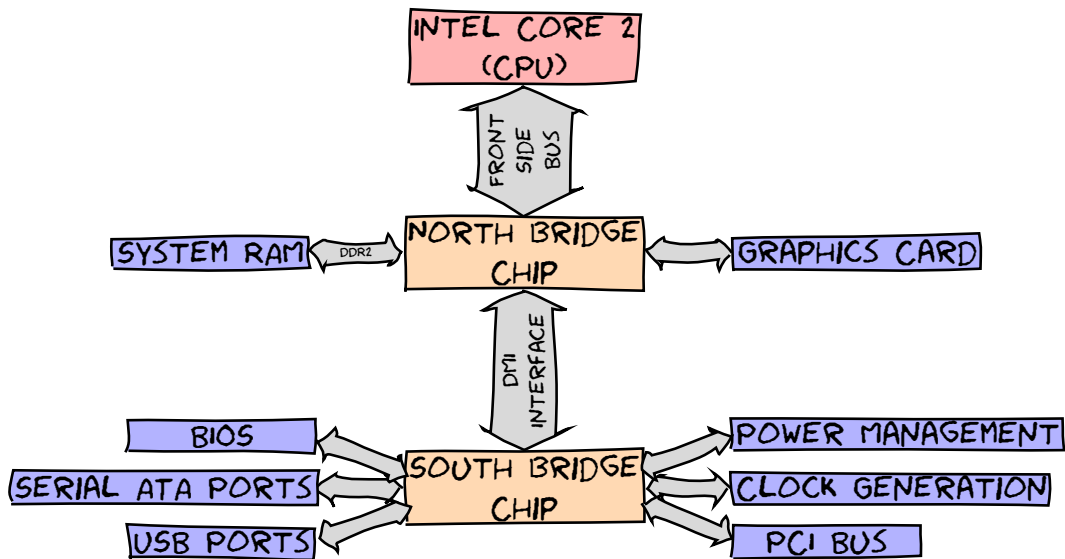
`dmesg` print or control the kernel ring buffer

`/var/log/messages` is where a majority of logged system messages reside

### 3 From Power Up To Bash Prompt

## 3.1 Motherboard Chipsets And The Memory Map

# Motherboard Chipsets And The Memory Map



## Facts

- ▶ The CPU doesn't know what it's connected to
  - CPU test bench? network router? toaster? brain implant?
- ▶ The CPU talks to the outside world through its pins
  - some pins to transmit the physical memory address
  - other pins to transmit the values
- ▶ The CPU's gateway to the world is the front-side bus

## Intel Core 2 QX6600

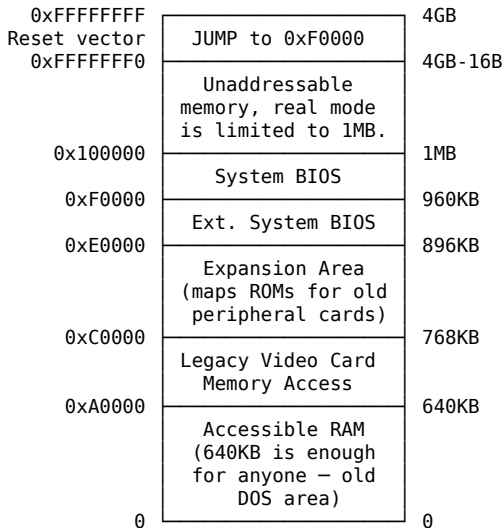
- ▶ 33 pins to transmit the physical memory address
  - so there are  $2^{33}$  choices of memory locations
- ▶ 64 pins to send or receive data
  - so data path is 64-bit wide, or 8-byte chunks

This allows the CPU to physically address 64GB of memory ( $2^{33} \times 8B$ )

## Some physical memory addresses are mapped away!

- ▶ only the addresses, not the spaces
- ▶ Memory holes
  - 640KB ~ 1MB
  - /proc/iomem
- ▶ Memory-mapped I/O
  - ▶ BIOS ROM
  - ▶ video cards
  - ▶ PCI cards
  - ▶ ...

This is why 32-bit OSes have problems using 4G of RAM.



What if you don't have 4G RAM?

## the northbridge

1. receives a physical memory request
2. decides where to route it
  - to RAM? to video card? to ...?
  - decision made via the *memory address map*
    - ▶ `/proc/iomem`
    - ▶ it is built in `setup()`



## The CPU modes

**real mode:** CPU can only address 1MB RAM

- ▶ 20-bit address, 1-byte data unit

**32-bit protected mode:** can address 4GB RAM

- ▶ 32-bit address, 1-byte data unit

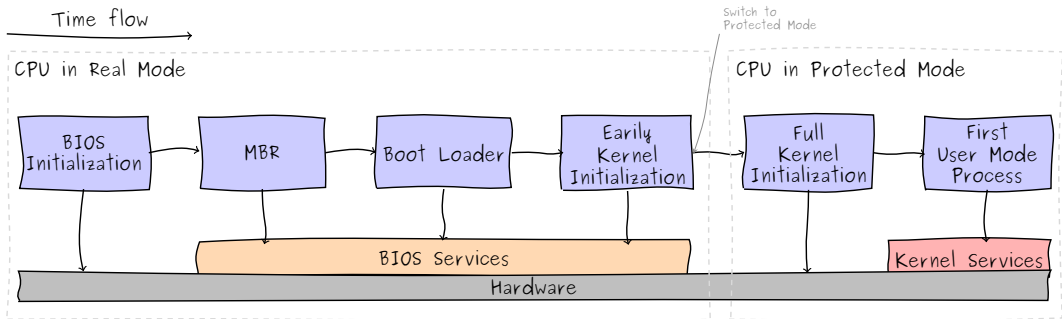
**64-bit protected mode:** can address 64GB RAM (Intel Core 2 QX6600)

- ▶ 33 address pins, 8-byte data unit

```
$ grep 'address sizes' /proc/cpuinfo
```

## 3.2 How Computers Boot Up

# Bootstrapping



1. bringing at least a portion of the OS into main memory, and
2. having the processor execute it
3. the initialization of kernel data structures
4. the creation of some user processes, and
5. the transfer of control to one of them

\$ man 7 boot

## Motherboard power up

1. initializes motherboard firmwares (chipset, etc.)
2. gets CPU running

# Real mode

CPU acts as a 1978 Intel 8086

- ▶ any code can write to any place in memory
- ▶ only 1MB of memory can be addressed
- ▶ registers are initialized
  - EIP has 0xFFFFFFF0, the **reset vector**
  - at the reset vector, there is a jump instruction, jumping to the *BIOS entry point* (0xF0000).

0xFFFFFFFF		4GB
Reset vector	JUMP to 0xF0000	
0xFFFFFFF0		4GB-16B
	Unaddressable memory, real mode is limited to 1MB.	
0x100000		1MB
	System BIOS	
0xF0000		960KB
	Ext. System BIOS	
0xE0000		896KB
	Expansion Area (maps ROMs for old peripheral cards)	
0xC0000		768KB
	Legacy Video Card Memory Access	
0xA0000		640KB
	Accessible RAM (640KB is enough for anyone – old DOS area)	

# BIOS

## BIOS uses Real Mode addresses

- ▶ No GDT, LDT, or paging table is needed
  - ▶ the code that initializes the GDT, LDT, and paging tables must run in Real Mode
- ▶ Real mode address translation:

$$\text{segmentnumber} \times 2^4 + \text{offset}$$

e.g. to translate <FFFF:0001> into physical address:

$$FFFF \times 16 + 0001 = FFFF0 + 0001 = FFFF1$$

if:  $\text{offset} > 0xF$  (overflow)

then:  $\text{address} \% 2^{20}$  (wrap around)

- ▶ only 80286 and later x86 CPUs can address up to:

$$FFFF0 + FFFF = 10FFEF$$

# CPU starts executing BIOS code

## 1. POST

- ▶ an ACPI-compliant BIOS builds several tables that describe the hardware devices present in the system

## 2. initializes hardwares

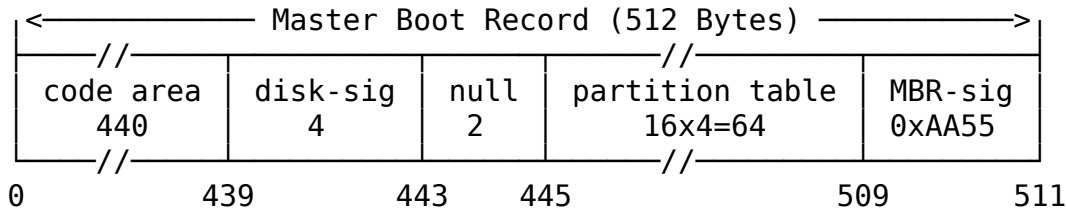
- ▶ at the end of this phase, a table of installed PCI devices is displayed

## 3. find a boot device

## 4. load MBR into 0x7c00

## 5. Jump to 0x7c00

## 6. MBR moves itself away from 0x7c00



# GRUB

1. GRUB stage 1 (in MBR) loads GRUB stage 2
2. stage 2 reads GRUB configuration file, and presents boot menu
3. loads the kernel image file into memory
  - ▶ can't be done in real mode, since it's bigger than 640KB
    - ▶ BIOS supports *unreal mode*
  - ▶ 1<sup>st</sup> 512 bytes — INITSEG, 0x00090000
  - ▶ setup() — SETUPSEG, 0x00090200
  - ▶ load low — SYSSEG, 0x00010000
  - ▶ load high — 0x00100000
4. jumps to the kernel entry point (`jmp trampoline`)
  - ▶ line 80 in 2.6.11/arch/i386/boot/setup.S



# Memory At Bootup Time

## The kernel image

- ▶ `/boot/vmlinuz-x.x.x-x-x`
- ▶ has been loaded into memory by the boot loader using the BIOS disk I/O services
- ▶ The image is split into two pieces:
  - ▶ a small part containing the real-mode kernel code is loaded below the 640K barrier
  - ▶ the bulk of the kernel, which runs in protected mode, is loaded after the first megabyte of memory

	~	load high	~	
0x00100000		reserved		1M
0x000A0000				640K
0x00098000		real mode stack		
		2nd part of GRUB		
0x00096C00		new location of MBR (512B)		
0x00096A00				
0x00090400		setup sector (512B)		577K
0x00090200		1st 512 bytes of kernel image		576.5K
0x00090000				576K
0x00010000		load low		64K
0x00007C00		MBR (512B)		31K
		compressed		145/303

### 3.3 The Kernel Boot process

## The setup() Function

boots and loads the executable image to  $(0x9000 \ll 4)$  and jumps to  $(0x9020 \ll 4)$

```
/*  
 *      setup.S      Copyright (C) 1991, 1992 Linus Torvalds  
 *  
 *  setup.s is responsible for getting the system data from the BIOS,  
 *  and putting them into the appropriate places in system memory.  
 *  both setup.s and system has been loaded by the bootblock.  
 *  
 *  This code asks the bios for memory/disk/other parameters, and  
 *  puts them in a "safe" place: 0x90000-0x901FF, ie where the  
 *  boot-block used to be. It is then up to the protected mode  
 *  system to read them from there before the area is overwritten  
 *  for buffer-blocks.
```

- ▶ 2.6.11/arch/i386/boot/setup.S
- ▶ Re-initialize all the hardware devices
- ▶ Sets the A20 pin (turn off *wrapping around*)
- ▶ Sets up a provisional IDT and a provisional GDT
- ▶ PE=1, PG=0 in cr0
- ▶ jump to startup\_32()

`setup() -> startup_32()`

### `startup_32()` for compressed kernel

- ▶ in `arch/i386/boot/compressed/head.S`
  - ▶ physically at
    - `0x00100000` — load high, or
    - `0x00001000` — load low
  - ▶ does some basic register initialization
  - ▶ `decompress_kernel()`
- ▶ the uncompressed kernel image has overwritten the compressed one starting at 1MB
- ▶ jump to the protected-mode kernel entry point at 1MB of RAM (`0x10000 << 4`)
  - ▶ `startup_32()` for real kernel

## startup\_32() for real kernel

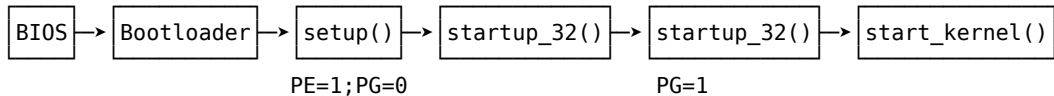
### startup\_32() in arch/i386/kernel/head.S

- ▶ Zeroes the kernel BSS for protected mode
- ▶ sets up the final GDT
- ▶ builds provisional kernel page tables so that paging can be turned on
- ▶ enables paging (cr3->PGDir; PG=1 in cr0)
- ▶ initializes a stack
- ▶ setup\_idt() — creates the final interrupt descriptor table
- ▶ gdtr->GDT; idtr->IDT
- ▶ start\_kernel()

`start_kernel()` — a long list of calls to initialize various kernel subsystems and data structures

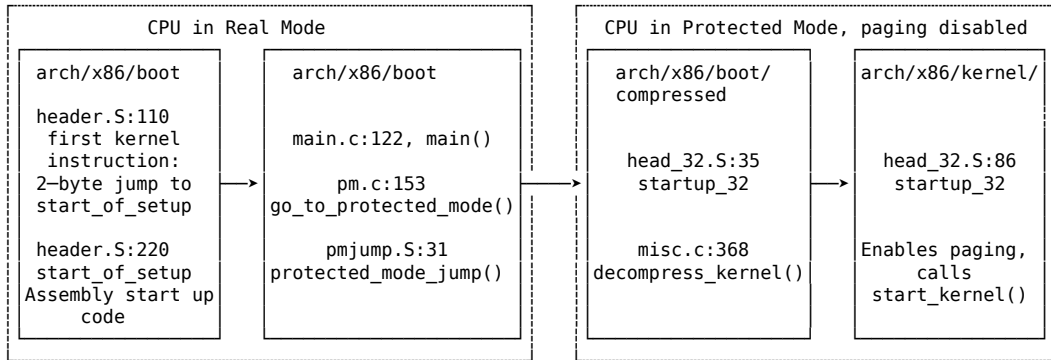
- ▶ `sched_init()` — scheduler
- ▶ `build_all_zonelists()` — memory zones
- ▶ `page_alloc_init()`, `mem_init()` — buddy system
- ▶ `trap_init()`, `init_IRQ()` — IDT
- ▶ `time_init()` — time keeping
- ▶ `kmem_cache_init()` — slab allocator
- ▶ `calibrate_delay()` — CPU clock
- ▶ `kernel_thread()` — The kernel thread for process 1
- ▶ login prompt

# The Kernel Boot Process

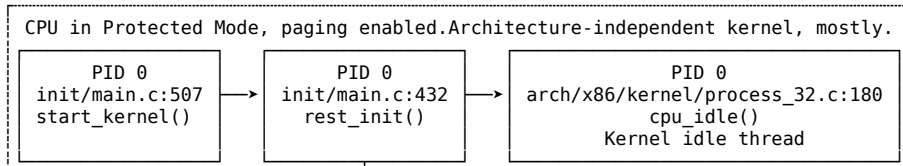


# The Kernel Boot Process

— Time Flow —>



— Time Flow —>

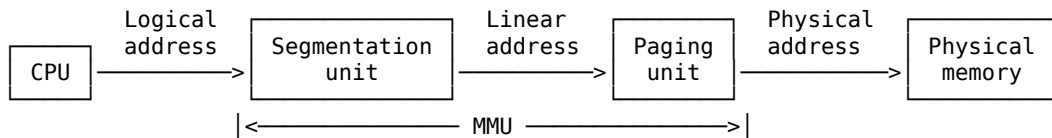


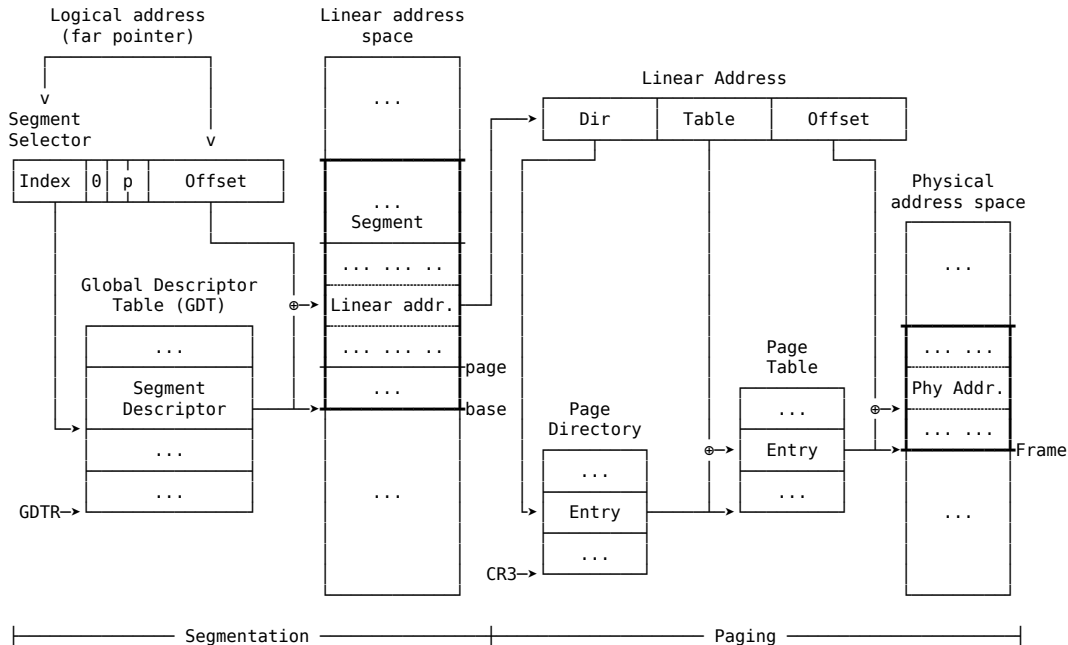


## 4 Memory Addressing

## 4.1 Memory Addresses

# Three Kinds Of Addresses





# All CPUs Share The Same Memory

## Memory Arbiter

if: the chip is free

then: grants access to a CPU

if: the chip is busy servicing a request by another processor

then: delay it

Even uniprocessor systems use memory arbiters because of *DMA*.

## 4.2 Segmentation in Hardware

# Real Mode Address Translation

- ▶ Backward compatibility of the processors
- ▶ BIOS uses real mode addressing
- ▶ Use 2 16-bit registers to get a 20-bit address

## Logical address format

`<segment:offset>`

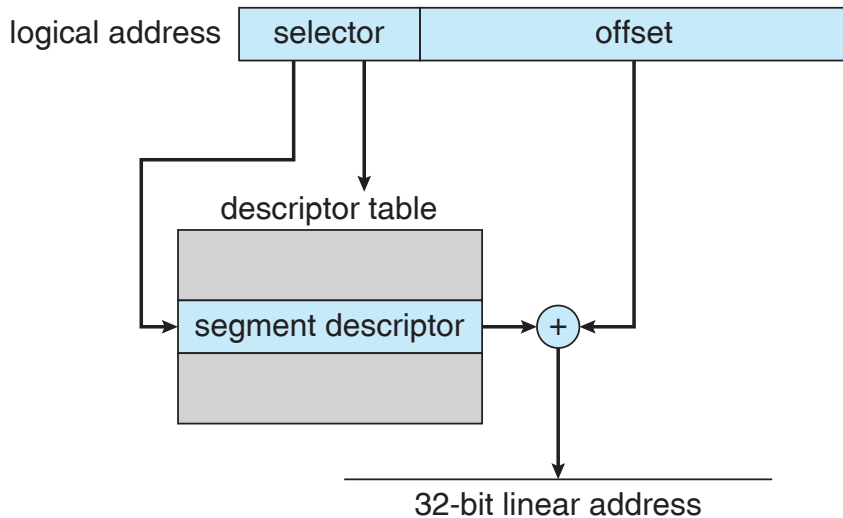
## Real mode address translation

$$\text{segment number} \times 2^4 + \text{offset}$$

e.g. to translate `<FFFF:0001>` into linear address:

$$\text{FFFF} \times 16 + 0001 = \text{FFFF0} + 0001 = \text{FFFF1}$$

## Protected Mode Address Translation



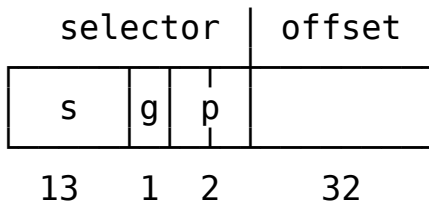


# Segment Selectors

A logical address consists of two parts:

segment selector	:	offset
16 bits		32 bits

Segment selector is an index into GDT/LDT



s – segment number  
g – 0 (global)  
1 (local)  
p – protection use

# Segmentation Registers

## Segment registers hold segment selectors

**cs** code segment register

**CPL** 2-bit, specifies the Current Privilege Level of the CPU

**00** - Kernel mode

**11** - User mode

**ss** stack segment register

**ds** data segment register

**es/fs/gs** general purpose registers, may refer to arbitrary data segments

# Segment Descriptors

All the segments are organized in 2 tables:

**GDT** *Global Descriptor Table*

- ▶ shared by all processes
- ▶ GDTR stores address and size of the GDT

**LDT** *Local Descriptor Table*

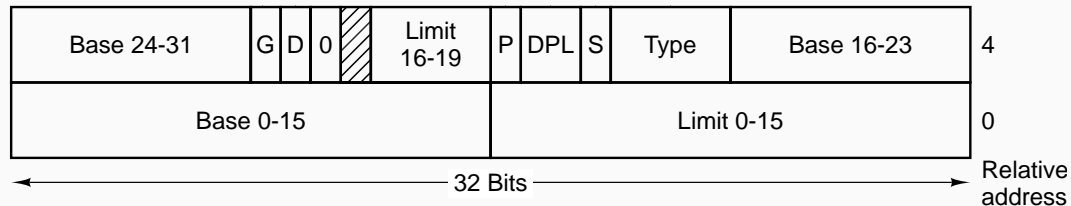
- ▶ one process each
- ▶ LDTR stores address and size of the LDT

**Segment descriptors** are entries in either GDT or LDT, 8-byte long

## Analogy

Process	↔	Process Descriptor(PCB)
File	↔	Inode
Segment	↔	Segment Descriptor

## Example: A LDT entry for code segment



**Base:** Where the segment starts

**Limit:** 20 bit,  $\Rightarrow 2^{20}$  in size

**G:** Granularity flag

0 - segment size in bytes

1 - in 4096 bytes

**S:** System flag

0 - system segment, e.g. LDT

**D/B:** 0 - 16-bit offset

1 - 32-bit offset

**Type:** segment type (cs/ds/tss)

**TSS:** Task status, i.e. it's executing or not

**DPL:** Descriptor Privilege Level. 0/3

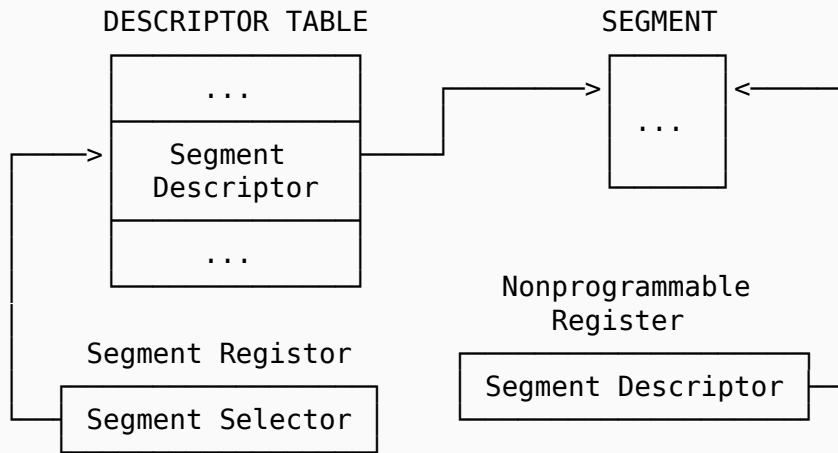
**P:** Segment-Present flag

0 - not in memory

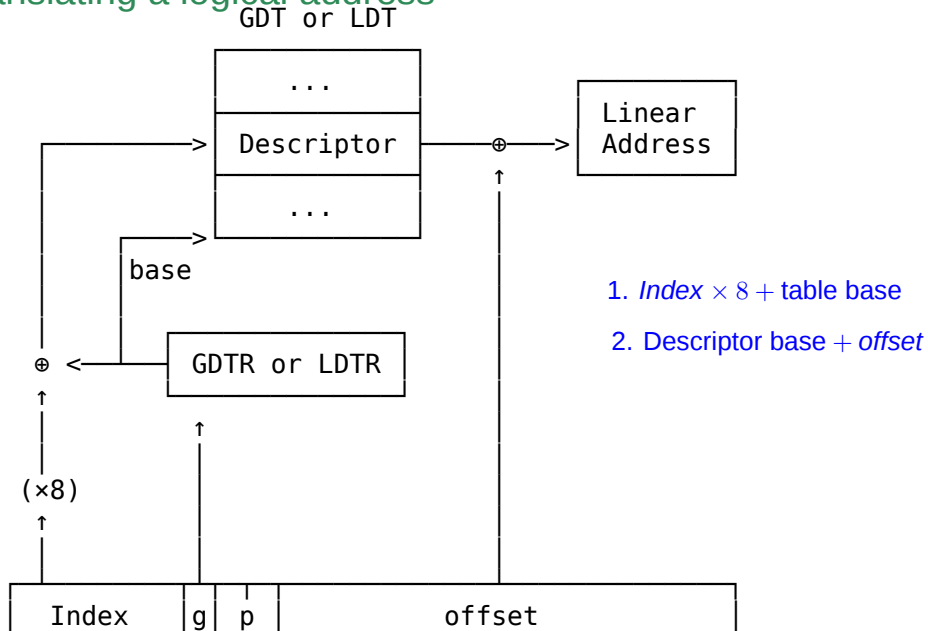
1 - in memory

# Fast Access to Segment Descriptors

a non-programmable cache register for each segment register



## Translating a logical address



## 4.3 Segmentation in Linux

# Linux prefers paging to segmentation

## Because

- ▶ Segmentation and paging are somewhat redundant
- ▶ Memory management is simpler when all processes share the same set of linear addresses
- ▶ Maximum portability. RISC architectures in particular have limited support for segmentation

The Linux 2.6 uses segmentation only when required by the 80x86 architecture.



# The Linux GDT Layout

Each GDT includes 18 segment descriptors and 14 null, unused, or reserved entries

```
include/asm-i386/segment.h
```

0	null	11	reserved	22	PNPBIOS support
1	reserved	12	kernel code segment	23	APM BIOS support
2	reserved	13	kernel data segment	24	APM BIOS support
3	reserved	14	default user CS	25	APM BIOS support
4	unused	15	default user DS	26	ESPFIX small SS
5	unused	16	TSS	27	per-cpu
6	TLS segment #1	17	LDT	28	stack_canary-20
7	TLS segment #2	18	PNPBIOS support	29	unused
8	TLS segment #3	19	PNPBIOS support	30	unused
9	reserved	20	PNPBIOS support	31	TSS for double fault handler
10	reserved	21	PNPBIOS support		

# The Four Main Linux Segments

Every process in Linux has these 4 segments

Segment	Base	G	Limit	S	Type	DPL	D/B	P
user code	0x00000000	1	0xffffffff	1	10	3	1	1
user data	0x00000000	1	0xffffffff	1	2	3	1	1
kernel code	0x00000000	1	0xffffffff	1	10	0	1	1
kernel data	0x00000000	1	0xffffffff	1	2	0	1	1

All linear addresses start at 0, end at 4G-1

- ▶ All processes share the same set of linear addresses
- ▶ Logical addresses coincide with linear addresses

# Segment Selectors

```
include/asm-i386/segment.h
```

```
#define GDT_ENTRY_DEFAULT_USER_CS      14
#define __USER_CS (GDT_ENTRY_DEFAULT_USER_CS * 8 + 3)

#define GDT_ENTRY_DEFAULT_USER_DS      15
#define __USER_DS (GDT_ENTRY_DEFAULT_USER_DS * 8 + 3)

#define GDT_ENTRY_KERNEL_BASE      12

#define GDT_ENTRY_KERNEL_CS          (GDT_ENTRY_KERNEL_BASE + 0)
#define __KERNEL_CS (GDT_ENTRY_KERNEL_CS * 8)

#define GDT_ENTRY_KERNEL_DS          (GDT_ENTRY_KERNEL_BASE + 1)
#define __KERNEL_DS (GDT_ENTRY_KERNEL_DS * 8)
```

*Selector = Index  $\ll$  3 + G + RPL*

__USER_CS	$14 \ll 3 + 3 = 115$	0000 0000 0111 0011
__USER_DS	$15 \ll 3 + 3 = 123$	0000 0000 0111 1011
__KERNEL_CS	$12 \ll 3 + 0 = 96$	0000 0000 0110 0000

### Example:

To address the kernel code segment, the kernel just loads the value yielded by the `__KERNEL_CS` macro into the `cs` segmentation register.

### Note that

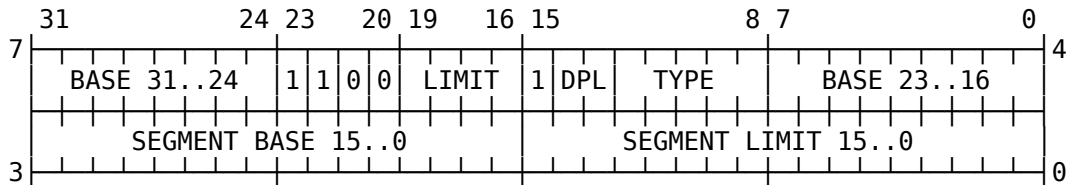
1. `base = 0`
2. `limit = 0xffffffff`

This means that

- ▶ all processes, either in User Mode or in Kernel Mode, may use the same logical addresses
- ▶ logical addresses (Offset fields) coincide with linear addresses

# The Linux GDT

## 8 byte segment descriptor



arch/i386/kernel/head.S

ENTRY(cpu\_gdt\_table)

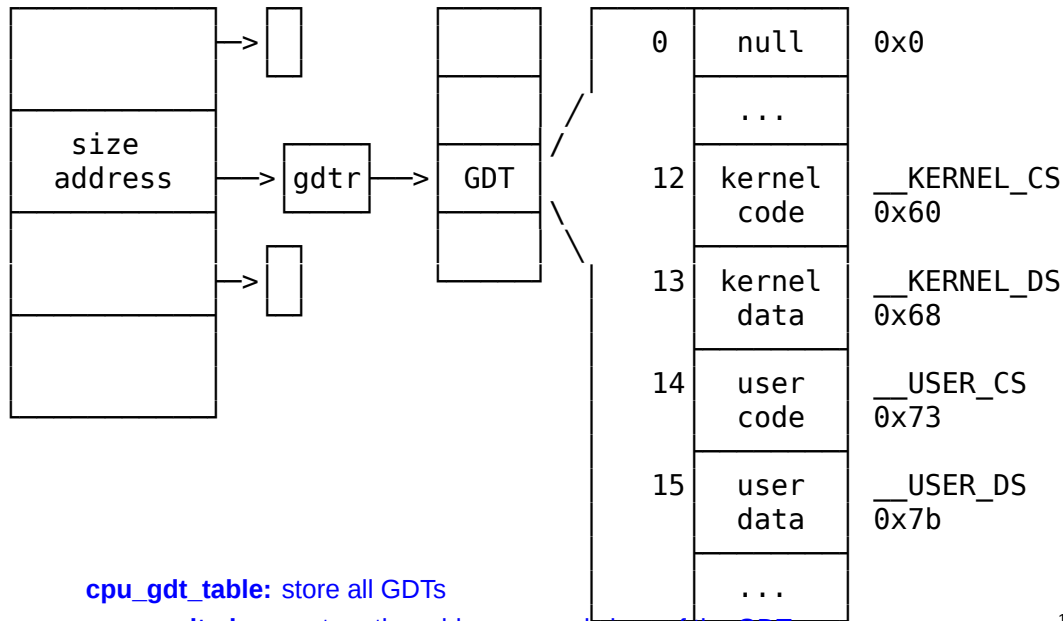
```
.quad 0x00cf9a0000000fff /* 0x60 kernel 4GB code at 0x00000000 */
.quad 0x00cf920000000fff /* 0x68 kernel 4GB data at 0x00000000 */
.quad 0x00cffa0000000fff /* 0x73 user 4GB code at 0x00000000 */
.quad 0x00cff20000000fff /* 0x7b user 4GB data at 0x00000000 */
```

cpu\_gdt\_descr

cpu\_gdt\_table

GDT

Selector



## 4.4 Paging in Hardware

# Paging in Hardware

Starting with the 80386, all 80x86 processors support paging

## A page is

- ▶ a set of linear addresses
- ▶ a block of data

## A page frame is

- ▶ a constituent of main memory
- ▶ a storage area

## A page table

- ▶ is a data structure
- ▶ maps linear to physical addresses
- ▶ stored in main memory



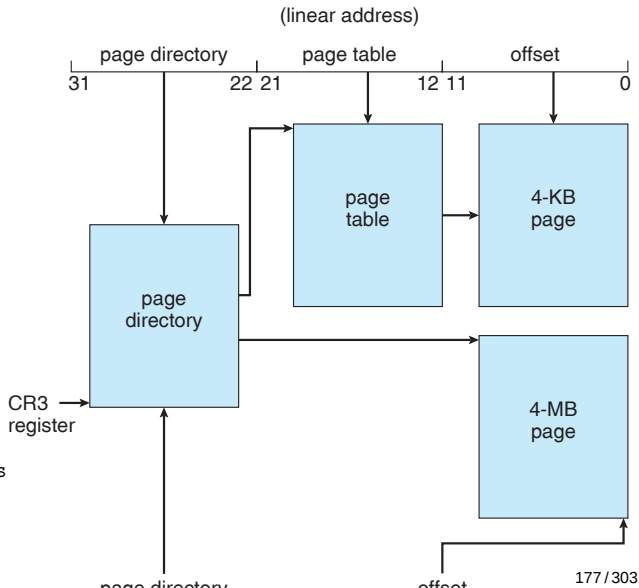
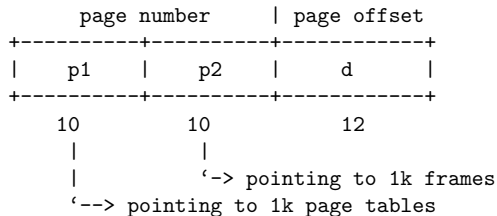
# Pentium Paging

Linear Address  $\Rightarrow$  Physical Address

Two page size in Pentium:

4K: 2-level paging

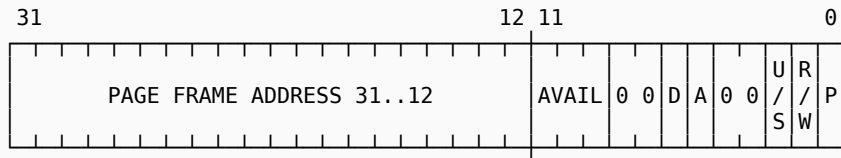
4M: 1-level paging



## Same structure for Page Dirs and Page Tables

- ▶ 4 bytes (32 bits) long
- ▶ Page size is usually 4k ( $2^{12}$  bytes). OS dependent
  - \$ `getconf PAGESIZE`
- ▶ Could have  $2^{32-12} = 2^{20} = 1M$  pages
  - Could addressing  $1M \times 4KB = 4GB$  memory

## Intel i386 page table entry



P – PRESENT

R/W – READ/WRITE

U/S – USER/SUPERVISOR

A – ACCESSED

D – DIRTY

AVAIL – AVAILABLE FOR SYSTEMS PROGRAMMER USE

NOTE: 0 INDICATES INTEL RESERVED. DO NOT DEFINE

# Physical Address Extension (PAE)

32-bit linear  $\Rightarrow$  36-bit physical

## Need a new paging mechanism

	Linear Address	Physical Address	Max RAM	Page Size	PTE Size	Paging Level
No PAE	32 bits	32 bits	$2^{32} = 4GB$	4K, 4M	32 bits	1, 2
PAE	32 bits	36 bits	$2^{36} = 64GB$	4K, 2M	64 bits	2, 3

### 3-level paging for 4K-pages

PD PT	Page DIR	Page Table	Offset
2	9	9	12

### 2-level paging for 2M-pages

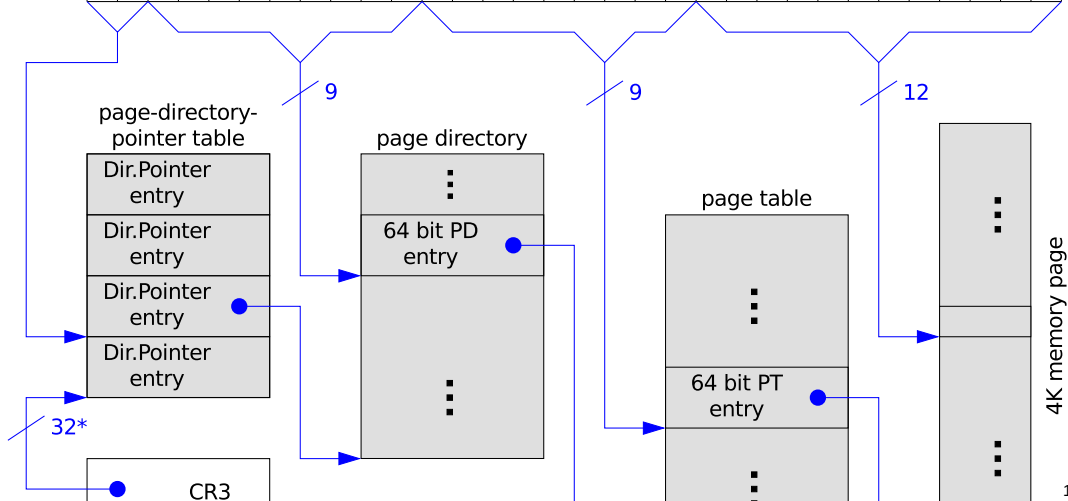
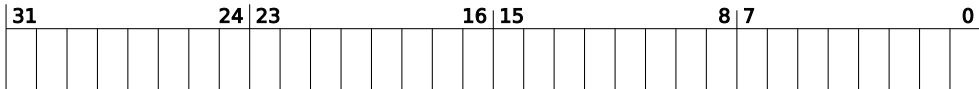
PD PT	Page DIR	Offset
2	9	21

**PDPT** Page Directory Pointer Table, is a new level of Page Table

64-bit entry  $\times 4$

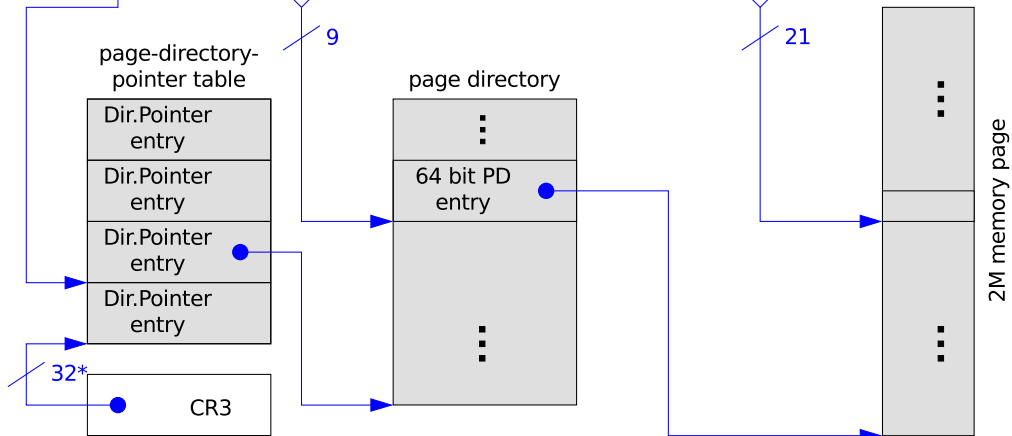
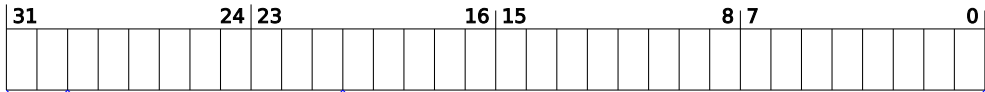
# PAE with 4K pages

Linear address:



# PAE with 2M pages

Linear address:



# Physical Address Extension (PAE)

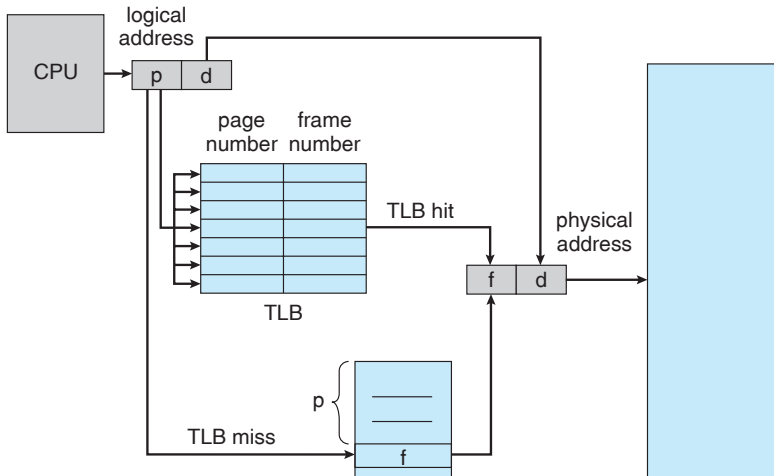
## The linear address are still 32 bits

- ▶ A process cannot use more than 4G RAM
- ▶ The kernel programmers have to reuse the same linear addresses to map 64GB RAM
- ▶ The number of processes is increased

# Translation Lookaside Buffers (TLB)

## Fact: 80-20 rule

- Only a small fraction of the PTEs are heavily read; the rest are barely used at all

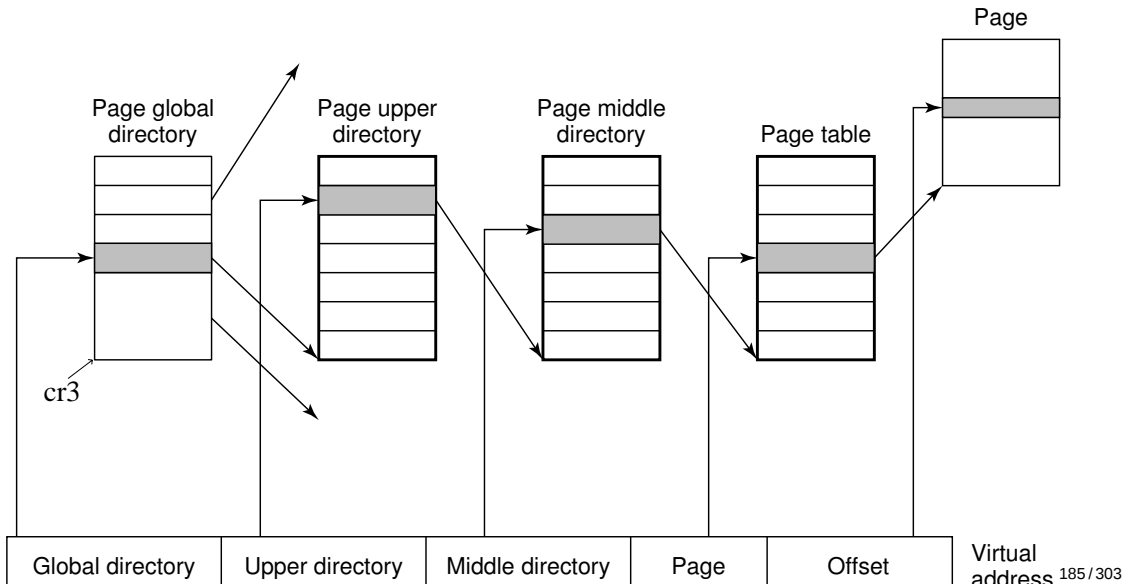


## 4.5 Paging in Linux



# Paging In Linux

4-level paging for both 32-bit and 64-bit



## 4-level paging for both 32-bit and 64-bit

### ► 64-bit: four-level paging

1. Page Global Directory
2. Page Upper Directory
3. Page Middle Directory
4. Page Table

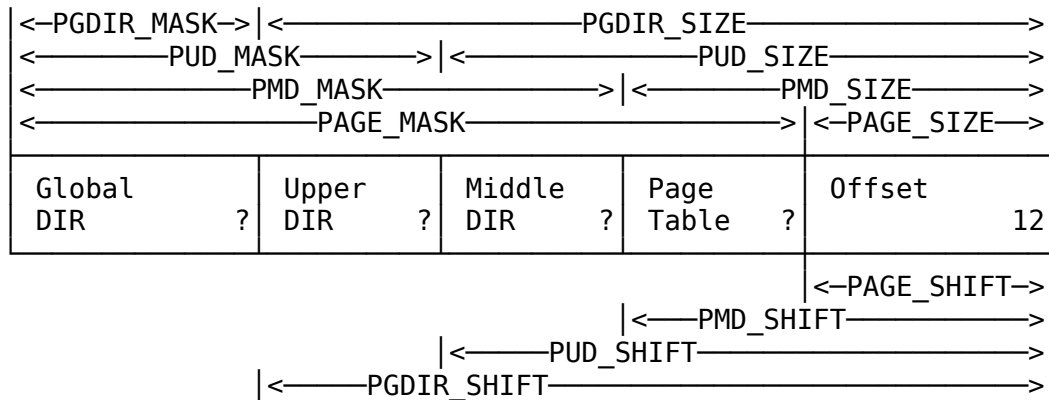
### ► 32-bit: two-level paging

1. Page Global Directory
2. Page Upper Directory — 0 bits; 1 entry
3. Page Middle Directory — 0 bits; 1 entry
4. Page Table

The same code can work on 32-bit and 64-bit architectures

Arch	Page size	Address bits	Paging levels	Address splitting
x86	4KB(12bits)	32	2	10 + 0 + 0 + 10 + 12
x86-PAE	4KB(12bits)	32	3	2 + 0 + 9 + 9 + 12
x86-64	4KB(12bits)	48	4	9 + 9 + 9 + 9 + 12

## The Linear Address Fields



\*\_SHIFT to specify the number of bits being mapped

\*\_MASK to mask out all the upper bits

\*\_SIZE how many bytes are addressed by each entry

\*\_MASK and \*\_SIZE values are calculated based on \*\_SHIFT

```
include/asm-i386/page.h
```

```
/* PAGE_SHIFT determines the page size */  
#define PAGE_SHIFT          12  
#define PAGE_SIZE           (1UL << PAGE_SHIFT)  
#define PAGE_MASK           (~ (PAGE_SIZE-1))  
  
#define LARGE_PAGE_MASK    (~ (LARGE_PAGE_SIZE-1))  
#define LARGE_PAGE_SIZE    (1UL << PMD_SHIFT)
```

PAGE\_SIZE:  $2^{12} = 4k$

PAGE\_MASK: 0xfffff000

LARGE\_PAGE\_SIZE: depends

PAE:  $2^{21} = 2M$

no PAE:  $2^{22} = 4M$

# Compile Time Dual-mode

```
include/asm-i386/pgtable.h
```

```
/*  
 * The Linux x86 paging architecture is 'compile-time dual-mode', it  
 * implements both the traditional 2-level x86 page tables and the  
 * newer 3-level PAE-mode page tables.  
 */  
#ifdef CONFIG_X86_PAE  
# include <asm/pgtable-3level_types.h>  
# define PMD_SIZE      (1UL << PMD_SHIFT)  
# define PMD_MASK      (~ (PMD_SIZE - 1))  
#else  
# include <asm/pgtable-2level_types.h>  
#endif  
  
#define PGDIR_SIZE      (1UL << PGDIR_SHIFT)  
#define PGDIR_MASK      (~ (PGDIR_SIZE - 1))
```

	PMD_SHIFT	PUD_SHIFT	PGDIR_SHIFT
2-level	22	22	22
3-level	21	21	30

```
include/asm-i386/pgtable-2level-defs.h #define PGDIR_SHIFT
```

## 2-level — no PAE, 4K-page

PMD and PUD are folded

Global dir    10	Upper dir    0	Mdl dir    0	Page tbl    10	Offset 12
---------------------	-------------------	-----------------	-------------------	--------------

```
include/asm-generic/pgtable-nopud.h
```

```
#define PUD_SHIFT      PGDIR_SHIFT
#define PTRS_PER_PUD   1
#define PUD_SIZE       (1UL << PUD_SHIFT)
#define PUD_MASK       (~ (PUD_SIZE-1))
```

```
include/asm-generic/pgtable-nopmd.h
```

```
#define PMD_SHIFT      PUD_SHIFT
#define PTRS_PER_PMD   1
#define PMD_SIZE       (1UL << PMD_SHIFT)
#define PMD_MASK       (~ (PMD_SIZE-1))
```

## 3-level — PAE enabled

3-level paging for 4K-pages

PD PT	Page DIR	Page Table	Offset
2	9	9	12

```
include/asm-i386/pgtable-3level-defs.h
```

```
1  #define PGDIR_SHIFT 30
2  #define PTRS_PER_PGD 4
3  #define PMD_SHIFT 21
4  #define PTRS_PER_PMD 512
```

PUD is eliminated

## 4-level — x86\_64

### 48 address bits

Global DIR	9	Upper DIR	9	Middle DIR	9	Page Table	9	Offset	12
---------------	---	--------------	---	---------------	---	---------------	---	--------	----

`include/asm-x86_64/pgtable.h`

```
1 #define PGDIR_SHIFT 39
2 #define PTRS_PER_PGD 512
3
4 #define PUD_SHIFT 30
5 #define PTRS_PER_PUD 512
6
7 #define PMD_SHIFT 21
8 #define PTRS_PER_PMD 512
```



# Page Table Handling

## — Data formats

### include/asm-i386/page.h

```
#ifdef CONFIG_X86_PAE
extern unsigned long long __supported_pte_mask;
typedef struct { unsigned long pte_low, pte_high; } pte_t;
typedef struct { unsigned long long pmd; } pmd_t;
typedef struct { unsigned long long pgd; } pgd_t;
typedef struct { unsigned long long pgprot; } pgprot_t;
#define pmd_val(x) ((x).pmd)
#define pte_val(x) ((x).pte_low | ((unsigned long long)(x).pte_high << 32))
#define __pmd(x) ((pmd_t) { (x) })
#define HPAGE_SHIFT 21
#else
typedef struct { unsigned long pte_low; } pte_t;
typedef struct { unsigned long pgd; } pgd_t;
typedef struct { unsigned long pgprot; } pgprot_t;
#define boot_pte_t pte_t /* or would you rather have a typedef */
#define pte_val(x) ((x).pte_low)
#define HPAGE_SHIFT 22
#endif
```

# Page Table Handling

Read or modify page table entries

## Macros and functions

<code>pte_none</code>	<code>pte_clear</code>	<code>set_pte</code>	<code>pte_same(a,b)</code>
<code>pte_present</code>	<code>pte_user()</code>	<code>pte_read()</code>	<code>pte_write()</code>
<code>pte_exec()</code>	<code>pte_dirty()</code>	<code>pte_young()</code>	<code>pte_file()</code>
<code>mk_pte_huge()</code>	<code>pte_wrprotect()</code>	<code>pte_rdprotect()</code>	<code>pte_exprotect()</code>
<code>pte_mkdirty()</code>	<code>pte_mkread()</code>	<code>pte_mkexec()</code>	<code>pte_mkclean()</code>
<code>pte_mkdirty()</code>	<code>pte_mkold()</code>	<code>pte_mkyoung()</code>	<code>pte_modify(p,v)</code>
<code>mk_pte(p,prot)</code>	<code>pte_index(addr)</code>	<code>pte_page(x)</code>	<code>pte_to_pgoff(pte)</code>

a lot more for pmd, pud, pgd ...

## Example — To find a page table entry

mm/memory.c

```
pgd_t *pgd;  
pud_t *pud;  
pmd_t *pmd;  
pte_t *ptep, pte;  
  
pgd = pgd_offset(mm, address);  
if (pgd_none(*pgd) || unlikely(pgd_bad(*pgd)))  
    goto out;  
  
pud = pud_offset(pgd, address);  
if (pud_none(*pud) || unlikely(pud_bad(*pud)))  
    goto out;  
  
pmd = pmd_offset(pud, address);  
if (pmd_none(*pmd) || unlikely(pmd_bad(*pmd)))  
    goto out;  
  
ptep = pte_offset_map(pmd, address);
```

# Physical Memory Layout

0x00100000 — The kernel starting point

## Reserved page frames

- ▶ unavailable to users
- ▶ kernel code and data structures
- ▶ no dynamic assignment, no swap out

The kernel is loaded starting from the second megabyte (0x00100000) in RAM

- ▶ Page frame 0 — BIOS
- ▶ 640K ~ 1M — the well-know hole
- ▶ /proc/iomem

0xFFFFFFFF	JUMP to 0xF0000	4GB
Reset vector		
0xFFFFFFFF0	Unaddressable memory, real mode is limited to 1MB.	4GB-16B
0x100000		
	System BIOS	1MB
0xF0000		
	Ext. System BIOS	960KB
0xE0000		
	Expansion Area (maps ROMs for old peripheral cards)	896KB
0xC0000		
	Legacy Video Card Memory Access	768KB
0xA0000		
	Accessible RAM (640KB is enough for anyone – old DOS area)	640KB
0		0

## While booting

1. The kernel queries the BIOS for available physical address ranges
2. `machine_specific_memory_setup()` — builds the physical addresses map
3. `setup_memory()` — initializes a few variables that describe the kernel's physical memory layout
  - ▶ `min_low_pfn`, `max_low_pfn`, `highstart_pfn`, `highend_pfn`, `max_pfn`

# BIOS-Provided Physical Addresses Map

## Example — a typical computer with 128MB RAM

Start	End	Type
0x00000000	0x0009ffff (640K)	Usable
0x000f0000 (960K)	0x000ffffff (1M-1)	Reserved
0x00100000 (1M)	0x07feffff	Usable
0x07ff0000	0x07ff2fff	ACPI data
0x07ff3000	0x07ffffff (128M)	ACPI NVS
0xffff0000	0xffffffff	Reserved

## Variables describing the physical memory layout

Variable name	Description
<code>num_physpages</code>	Page frame number of the highest usable page frame
<code>totalram_pages</code>	Total number of usable page frames
<code>min_low_pfn</code>	Page frame number of the first usable page frame after the kernel image in RAM
<code>max_pfn</code>	Page frame number of the last usable page frame
<code>max_low_pfn</code>	Page frame number of the last page frame directly mapped by the kernel (low memory)
<code>totalhigh_pages</code>	Total number of page frames not directly mapped by the kernel (high memory)
<code>highstart_pfn</code>	Page frame number of the first page frame not directly mapped by the kernel
<code>highend_pfn</code>	Page frame number of the last page frame not directly mapped by the kernel

## The first 768 page frames (3 MB) in Linux 2.6

page			160			256			768
frame:	0	1	0xa0			0x100			0x300
		avail	resvd	avail	kernel code	Initialized data	BSS data	avail	.. ..
	0	4K	640K	<code>_text</code>		<code>_etext</code>	<code>_edata</code>	<code>_end</code>	3M

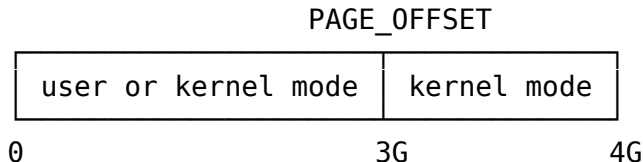


# Process Page Tables

0xC0000000  $\Leftrightarrow$  PAGE OFFSET

```
include/asm-i386/page.h
```

```
#define __PAGE_OFFSET (0xC0000000)
#define PAGE_OFFSET ((unsigned long)__PAGE_OFFSET)
```



## Why?

- ▶ easy to switch to kernel mode
- ▶ easy physical addressing due to direct mapping

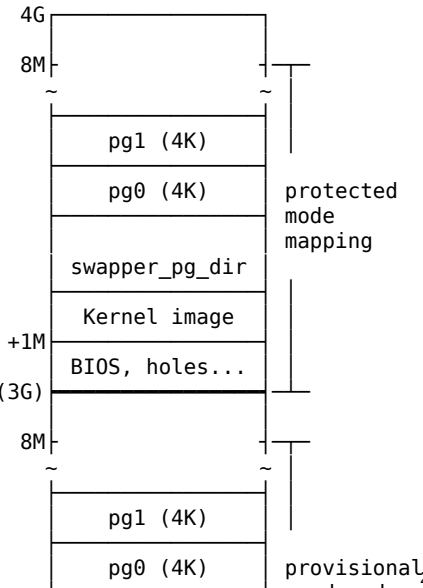
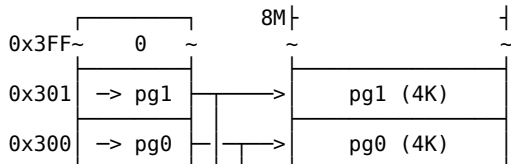
$$Physical = Virtual - \text{PAGE OFFSET}$$

# Kernel Page Tables

## Master Kernel Page Global Directory

swapper\_pg\_dir:

- ▶ has 1K entries pointing to 1K page tables;
- ▶ only 4 entries (0,1,0x300,0x301) are used in initialization phase;
- ▶ after initialization, it's used as a reference model for all processes.



# In The Beginning, There Is No Paging

Before tuning on paging, the page tables must be ready

Two phases:

1. **Bootstrapping:** sets up page tables for just 8MB so the paging unit can be enabled
  - 8MB? 2 page tables (pg0, pg1), enough to handle the kernel's code and data segments, and 128 KB for some dynamic data structures (page frame bitmap)
2. **Finalising:** initializes the rest of the page tables

# Provisional Page Global Directory

- ▶ A provisional PGDir is initialized statically during kernel compilation

```
.section ".bss.page_aligned", "w"  
ENTRY(swapper_pg_dir)  
.fill 1024, 4, 0
```

- ▶ The provisional PTs are initialized by `startup_32()` in `arch/i386/kernel/head.S`
- ▶ `swapper_pg_dir` — A 4KB area for holding provisional PGDir
- ▶ provisional PGDir has only 4 useful entries: 0, 1, 0x300, 0x301

## What's it for?

Linear		Physical
0 ~ 8MB	⇒	0 ~ 8MB
PAGE_OFFSET ~ (PAGE_OFFSET + 8MB)	↗	

So that the kernel image (< 8MB) in physical memory can be addressed in both real mode and protected mode.

# Provisional Page Table Initialization

arch/i386/kernel/head.S

```
page_pde_offset = (__PAGE_OFFSET >> 20);
```

```
    movl $(pg0 - __PAGE_OFFSET), %edi
    movl $(swapper_pg_dir - __PAGE_OFFSET), %edx
    movl $0x007, %eax          # 0x007 = PRESENT+RW+USER
```

10:

```
    leal 0x007(%edi), %ecx      # Create PDE entry
    movl %ecx, (%edx)          # Store identity PDE entry
    movl %ecx, page_pde_offset(%edx) # Store kernel PDE entry
    addl $4, %edx
    movl $1024, %ecx
```

11:

```
    stosl    # movl %eax, (%edi)
             # addl $4, %edi
    addl $0x1000, %eax
    loop 11b
    # End condition: we must map up to and including INIT_MAP_BEYOND_END
    # bytes beyond the end of our own page tables; the +0x007 is the
    # attribute bits
    leal (INIT_MAP_BEYOND_END + 0x007)(%edi), %ebp
    cmpl %ebp, %eax
    jb 10b
    movl %edi, (init_pg_tables_end - __PAGE_OFFSET)
```

## Equivalent pseudo C code

```
/*
 * Provisional PGDir and page tables setup
 *
 * for mapping two linear address ranges to the same physical address range
 *
 * + Linear address ranges:
 *     - User mode:  $i \times 4M \sim (i+1) \times 4M - 1$ 
 *     - Kernel mode:  $3G + i \times 4M \sim 3G + (i+1) \times 4M - 1$ 
 * + Physical address range:  $i \times 4M \sim (i+1) \times 4M - 1$ 
 */
typedef unsigned int PTE;
PTE *pg = pg0;      /* physical address of pg0 */
PTE pte = 0x007;     /* 0x007 = PRESENT+RW+USER */
for(i=0;;i++){
    swapper_pg_dir[i] = pg + 0x007;          /* store identity PDE entry */
    swapper_pg_dir[i+page_pde_offset] = pg + 0x007; /* kernel PDE entry */
    for(j=0;j<1024;j++){                    /* populating one page table */
        pg[i*1024 + j] = pte;               /* fill up one page table entry */
        pte += 0x1000;                      /* next 4k */
    }
    if(pte >= ((char*)pg + i*1024 + j)*4 + 0x007 + INIT_MAP_BEYOND_END)
    {
        init_pg_tables_end = pg + i*0x1000 + j;
        break;
    }
}
```

## Enable paging

startup\_32() in arch/i386/kernel/head.S

```
# Enable paging
movl $swapper_pg_dir - __PAGE_OFFSET, %eax
movl %eax, %cr3  # set the page table pointer..
movl %cr0, %eax
    orl $0x80000000, %eax
movl %eax, %cr0  # ..and set paging (PG) bit
```

# Final Kernel Page Table Setup

- ▶ master kernel PGDir is still in `swapper_pg_dir`
- ▶ initialized by `paging_init()`

## Situations

1. RAM size < 896M
  - ▶ every RAM cell is mapped
2. 896M < RAM size < 4G
  - ▶ 896M are mapped
3. RAM size > 4G
  - ▶ PAE enabled



## When RAM size is less than 896 MB

### `paging_init()` without PAE

```
void __init paging_init(void)
{
#ifdef CONFIG_X86_PAE
    /* ... */
#endif

    pagetable_init();
    load_cr3(swapper_pg_dir);

#ifdef CONFIG_X86_PAE
    /* ... */
#endif

    __flush_tlb_all();
    kmap_init();
    zone_sizes_init();
}
```

2 level paging: PUD and PMD are folded

Global dir    10	Upper dir    0	Mdl dir    0	Page tbl    10	Offset 12
---------------------	-------------------	-----------------	-------------------	--------------

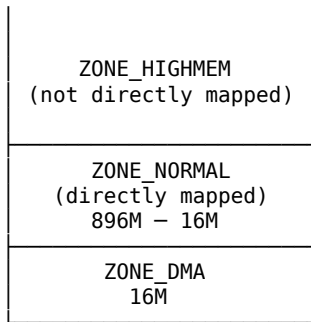
`pagetable_init()` — re-initializes the PGDir at `swapper_pg_dir`

Equivalent code:

```
pgd = swapper_pg_dir + pgd_index(PAGE_OFFSET); /* 768 */
phys_addr = 0x00000000;
while (phys_addr < (max_low_pfn * PAGE_SIZE))
{
    pmd = one_md_table_init(pgd); /* returns pgd itself */
    set_pmd(pmd, __pmd(phys_addr | pgprot_val(__pgprot(0x1e3))));
    /* 0x1e3 == Present, Accessed, Dirty, Read/Write, Page Size, Global */
    phys_addr += PTRS_PER_PTE * PAGE_SIZE; /* 0x400000, 4M */
    ++pgd;
}
```

# When RAM Size Is Between 896MB ~ 4096MB

Physical memory zones:

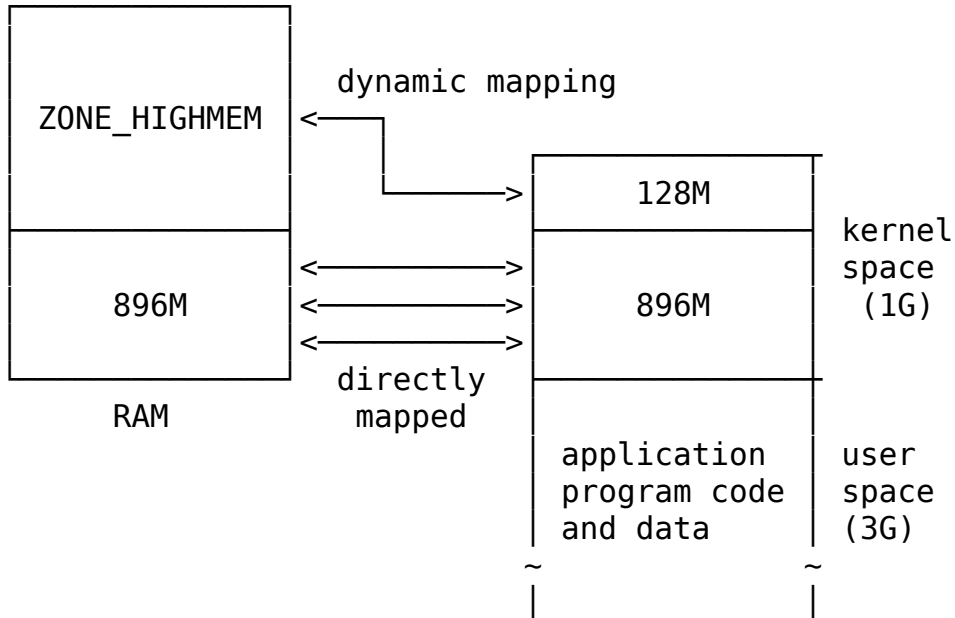


Physical RAM

Direct mapping for ZONE\_NORMAL:

```
#define __pa(x) ((unsigned long) (x) - PAGE_OFFSET)
#define __va(x) ((void *) ((unsigned long) (x) + PAGE_OFFSET))
```

## High Memory



## When RAM Size Is More Than 4096MB (PAE)

A 3-level paging model is used

3-level paging for 4K-pages

PD PT	Page DIR	Page Table	Offset
2	9	9	12

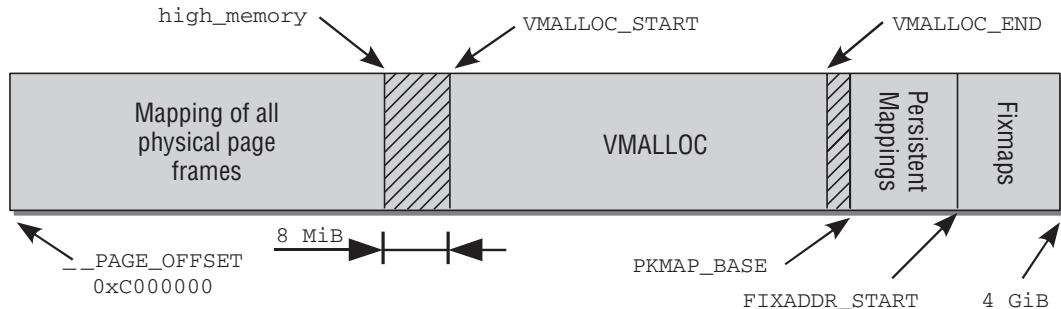
PGDir	PUD	PMD	PT	OFFSET
2	0	9	9	12

## The PGDir is initialized by a cycle equivalent to the following:

```
pgd_idx = pgd_index(PAGE_OFFSET); /* 3 */
for (i=0; i<pgd_idx; i++)
    set_pgd(swapper_pg_dir + i, __pgd(__pa(empty_zero_page) + 0x001));
    /* 0x001 == Present */
pgd = swapper_pg_dir + pgd_idx;
phys_addr = 0x00000000;
for (; i<PTRS_PER_PGD; ++i, ++pgd) {
    pmd = (pmd_t *) alloc_bootmem_low_pages(PAGE_SIZE);
    set_pgd(pgd, __pgd(__pa(pmd) | 0x001)); /* 0x001 == Present */
    if (phys_addr < max_low_pfn * PAGE_SIZE)
        for (j=0; j < PTRS_PER_PMD /* 512 */
            && phys_addr < max_low_pfn*PAGE_SIZE; ++j) {
            set_pmd(pmd, __pmd(phys_addr | pgprot_val(__pgprot(0x1e3))));
            /* 0x1e3 == Present, Accessed, Dirty, Read/Write,
               Page Size, Global */
            phys_addr += PTRS_PER_PTE * PAGE_SIZE; /* 0x200000 */
        }
    }
swapper_pg_dir[0] = swapper_pg_dir[pgd_idx];
```

# Division Of The Kernel Address Space

On IA-32 Systems



- ▶ Virtually contiguous memory areas that are *not* contiguous in physical memory can be reserved in the vmalloc area.
- ▶ *Persistent mappings* are used for persistent kernel mapping of highmem page frames.
- ▶ *Fixmaps* are virtual address space entries associated with a fixed but freely selectable page in physical address space.

## 5 Processes



## 5.1 Processes, Lightweight Processes, and Threads

# Processes

A process is

- ▶ an instance of a program in execution
- ▶ a dynamic entity (has lifetime)
- ▶ a collection of data structures describing the execution progress
- ▶ the unit of system resources allocation

The Linux kernel internally refers to processes as *tasks*.

# When A Process Is created

## The child

- ▶ is almost identical to the parent
  - ▶ has a logical copy of the parent's address space
  - ▶ executes the same code
- ▶ has its own data (stack and heap)

# Multithreaded Applications

## Threads

- ▶ are execution flows of a process
- ▶ share a large portion of the application data structures

## Lightweight processes (LWP) — Linux way of multithreaded applications

- ▶ each LWP is scheduled individually by the kernel
  - ▶ no nonblocking syscall is needed
- ▶ LWPs may share some resources, like the address space, the open files, and so on.

## 5.2 Process Descriptor

# Process Descriptor

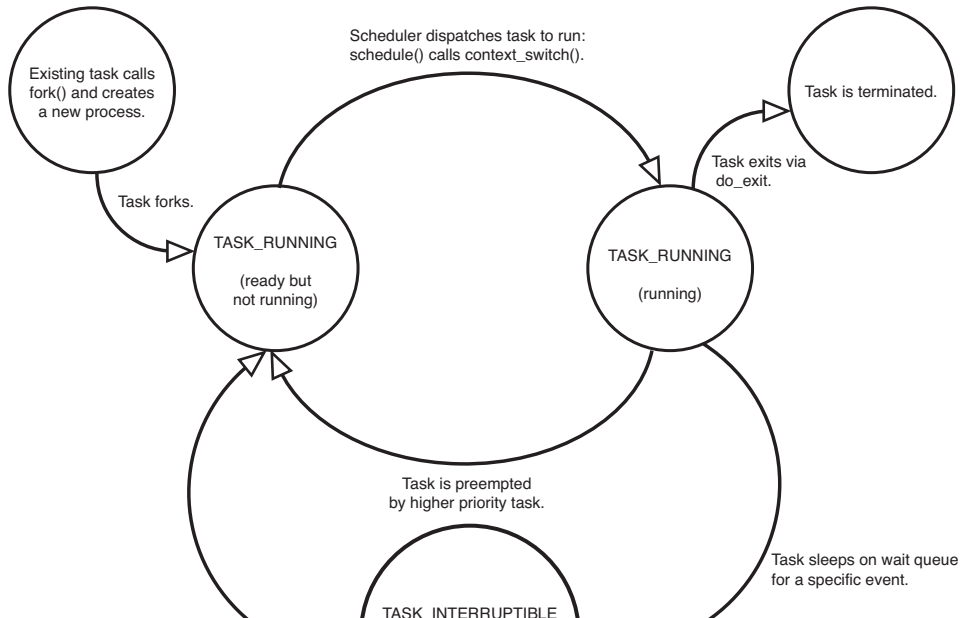
To manage processes, the kernel must have a clear picture of what each process is doing.

- ▶ the process's priority
- ▶ running or blocked
- ▶ its address space
- ▶ files it opened
- ▶ ...

**Process descriptor:** a `task_struct` type structure containing all the information related to a single process.

```
struct task_struct {  
    /* 160 lines of code in 2.6.11 */  
};
```

# Process State



## PID AND TGID

- ▶ kernel finds a process by its *process descriptor pointer* pointing to a `task_struct`
- ▶ users find a process by its **PID**
- ▶ all the threads of a multithreaded application share the same identifier  
**tgid**: the PID of the thread group leader

```
struct task_struct {  
    ...  
    pid_t pid;  
    pid_t tgid;  
    ...  
};
```

```
$ ps -eo pgid,ppid,pid,tgid,tid,nlwp,comm --sort pid
```



## How many PIDs can there be?

- ▶ *#define PID\_MAX\_DEFAULT 0x8000*
- ▶ Max PID number =  $PID\_MAX\_DEFAULT - 1 = 32767$
- \$ cat /proc/sys/kernel/pid\_max

## Which are the free PIDs?

```
1 static pidmap_t pidmap_array[PIDMAP_ENTRIES] =  
2 {  
3     [ 0 ... PIDMAP_ENTRIES-1 ] =  
4     { ATOMIC_INIT(BITS_PER_PAGE), NULL }  
5 };
```

pidmap\_array consumes a single page.

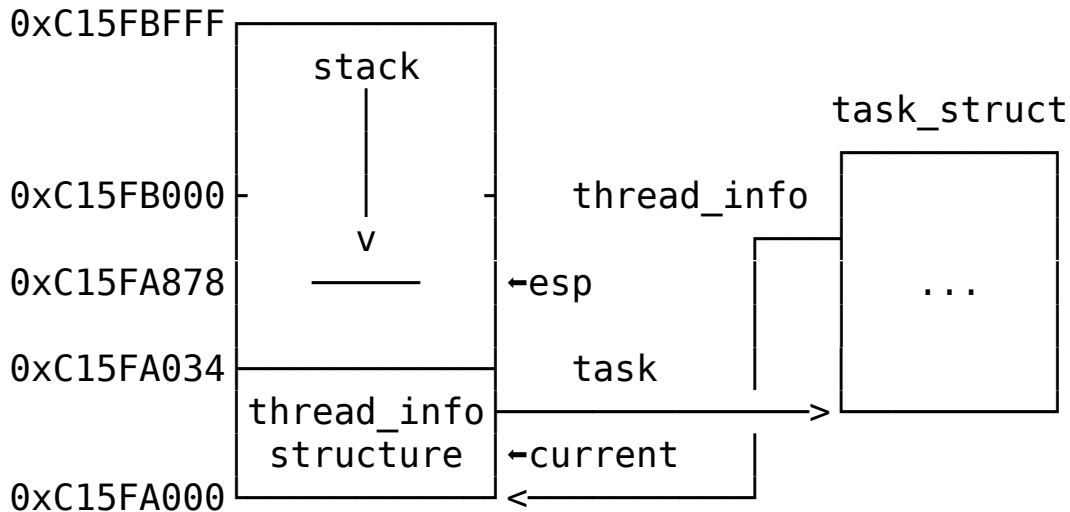
# Process Descriptor Handling

`thread_union`: 2 consecutive page frames (8K) containing

- ▶ a process kernel stack
- ▶ a `thread_info` structure

```
1 union thread_union {  
2     struct thread_info thread_info;  
3     unsigned long stack[2048]; /* 1024 for 4KB stacks */  
4 };
```

## Kernel Stack



```

struct thread_info {
    struct task_struct    *task;           /* main task structure */
    struct exec_domain    *exec_domain;    /* execution domain */
    unsigned long         flags;           /* low level flags */
    unsigned long         status;          /* thread-synchronous flags */
    __u32                 cpu;             /* current CPU */
    __s32                 preempt_count;   /* 0 => preemptable, <0 => BUG */

    mm_segment_t          addr_limit;      /* thread address space:
                                           0-0xBFFFFFFF for user-thread
                                           0-0xFFFFFFFF for kernel-thread
                                           */
    struct restart_block   restart_block;

    unsigned long          previous_esp;    /* ESP of the previous stack in case
                                           of nested (IRQ) stacks
                                           */
    __u8                   supervisor_stack[0];
};

```

## Why both task\_struct and thread\_info?

- ▶ There wasn't a thread\_info in pre-2.6 kernel
- ▶ Size matters

thread\_info and task\_struct are mutually linked

```
struct thread_info {  
    struct task_struct *task; /* main task structure */  
    ...  
};  
  
struct task_struct {  
    ...  
    struct thread_info *thread_info;  
    ...  
};
```

# Identifying The Current Process

Efficiency benefit from `thread_union`

- Easy get the base address of `thread_info` from `esp` register by masking out the 13 least significant bits of `esp`

`current_thread_info()`

```
/* how to get the thread information struct from C */  
static inline struct thread_info *current_thread_info(void)  
{  
    struct thread_info *ti;  
    __asm__ ("andl %%esp, %0;" : "=r" (ti) : "0" (~(THREAD_SIZE - 1)));  
    return ti;  
}
```

Can be seen as:

```
movl $0xffffe000, %ecx /* or 0xfffff000 for 4KB stacks */  
andl %esp, %ecx  
movl %ecx, p
```

## To get the process descriptor pointer

`current_thread_info()->task`

```
movl $0xffffe000,%ecx /* or 0xffffffff000 for 4KB stacks */
andl %esp,%ecx
movl (%ecx),p
```

Because the `task` field is at offset 0 in `thread_info`, after executing these 3 instructions `p` contains the process descriptor pointer.

## `current` — a macro pointing to the current running task

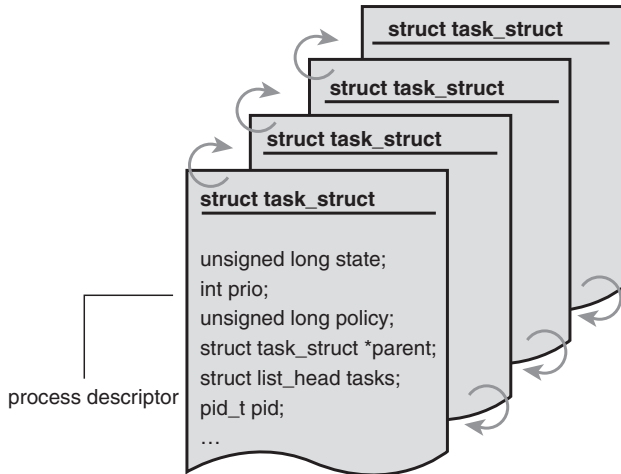
```
static inline struct task_struct * get_current(void)
{
    return current_thread_info()->task;
}

#define current get_current()
```

## Task List

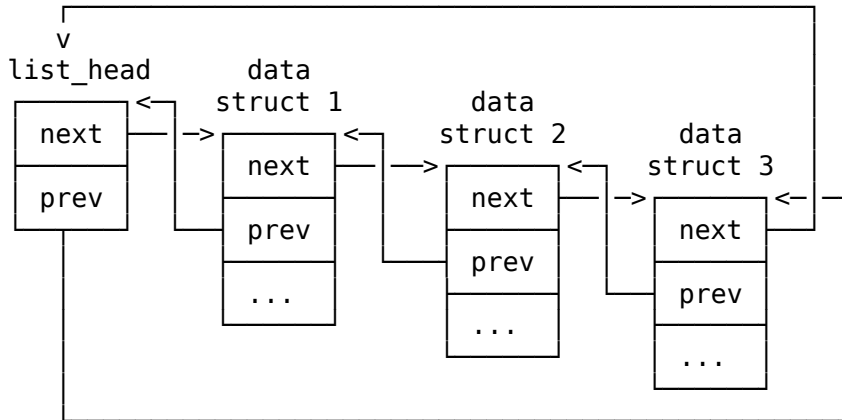
The kernel stores the list of processes in a **circular doubly linked list** called the **task list**.

**Swapper** The head of this list, `init_task`, process 0.





# Doubly Linked List



```
1 struct list_head {  
2     struct list_head *next, *prev;  
3 };
```

```
1 struct task_struct {  
2     ...  
3     struct list_head tasks;  
4     ...  
5 };
```

## List operations

SET\_LINKS insert into the list

REMOVE\_LINKS remove from the list

for\_each\_process scan the whole process list

```
#define for_each_process(p) \
    for (p = &init_task ; (p = next_task(p)) != &init_task ; )
```

list\_for\_each iterate over a list

```
#define list_for_each(pos, head) \
    for (pos = (head)->next; prefetch(pos->next), pos != (head); \
         pos = pos->next)
```

## Example: Iterate over a process' children

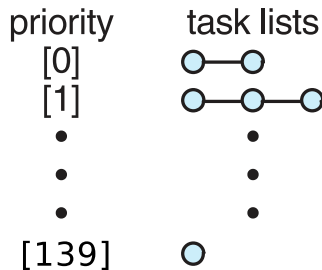
```
struct task_struct *task;
struct list_head *list;
list_for_each(list, &current->children) {
    task = list_entry(list, struct task_struct, sibling);
    /* task now points to one of current's children */
}
```

## A task can be in multiple lists

```
struct task_struct {  
    struct list_head run_list;  
    struct list_head tasks;  
    struct list_head ptrace_children;  
    struct list_head ptrace_list;  
    struct list_head children; /* list of my children */  
    struct list_head sibling; /* linkage in my parent's children list */  
}
```

# The List Of TASK\_RUNNING Processes

- ▶ Each CPU has its own runqueue
- ▶ Each runqueue has 140 lists
- ▶ One list per process priority
- ▶ Each list has zero to many tasks



```
1 struct task_struct {  
2     ...  
3     int prio, static_prio;  
4     struct list_head run_list;  
5     prio_array_t *array;  
6     ...  
7 };
```

## Each Runqueue Has A prio\_array\_t Struct

```
1 typedef struct prio_array prio_array_t;
2
3 struct prio_array {
4     unsigned int nr_active;
5     unsigned long bitmap[BITMAP_SIZE];
6     struct list_head queue[MAX_PRIO];
7 };
```

**nr\_active:** The number of process descriptors linked into the lists (the whole runqueue)

**bitmap:** A priority bitmap. Each flag is set if the priority list is not empty

**queue:** The 140 heads of the priority lists

## To Insert A Task Into A Runqueue List

```
1 static void enqueue_task(struct task_struct *p, prio_array_t *array)
2 {
3     ...
4     list_add_tail(&p->run_list, &array->queue[p->prio]);
5     __set_bit(p->prio, array->bitmap);
6     array->nr_active++;
7     p->array = array;
8 }
```

**prio:** priority of this process

**array:** a pointer pointing to the `prio_array_t` of this runqueue

- To remove a process descriptor from a runqueue list, use `dequeue_task(p,array)` function.

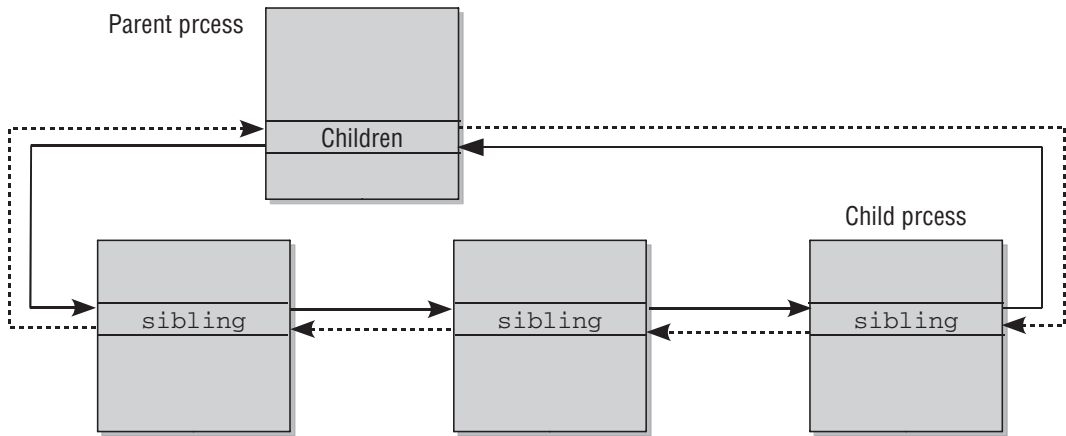
# Relationships Among Processes

## Family relationship

```
1 struct task_struct {  
2     ...  
3     struct list_head children; /* list of my children */  
4     struct list_head sibling; /* linkage in my parent's children list */  
5     ...  
6 };
```

**children:** is the list head for the list of all child elements of the process

**sibling:** is used to link siblings with each other





## Other Relationships

A process can be:

- ▶ a leader of a process group or of a login session
- ▶ a leader of a thread group
- ▶ tracing the execution of other processes

```
1 struct task_struct {  
2     ...  
3     pid_t tgid;  
4     ...  
5     struct task_struct *group_leader; /* threadgroup leader */  
6     ...  
7     struct list_head ptrace_children;  
8     struct list_head ptrace_list;  
9     ...  
10 };
```

# The Pid Hash Table And Chained Lists

PID  $\Rightarrow$  process descriptor pointer?

- ▶ Scanning the process list? — too slow
- ▶ Use hash tables

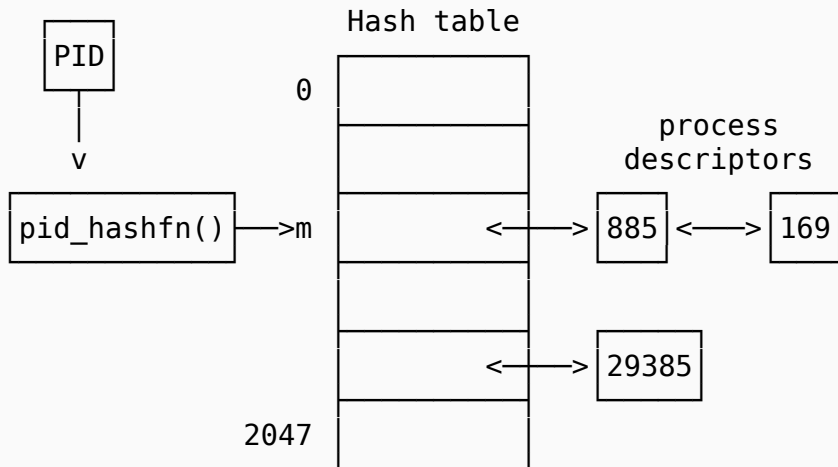
Four hash tables have been introduced

Why 4? For 4 types of PID

PID	} $\Rightarrow$ task_struct
TGID	
PGID	
SID	

## Collision

Multiple PIDs can be hashed into one table index



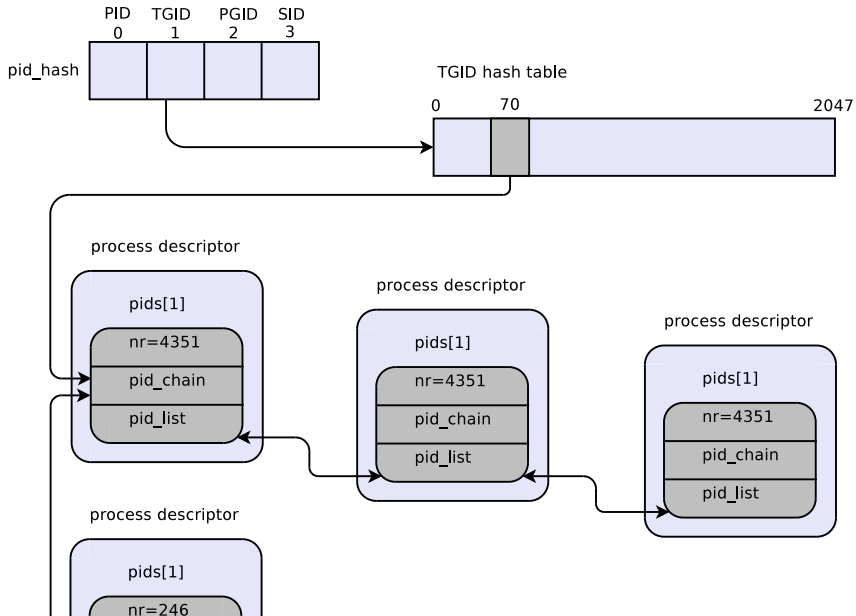
- ▶ Chaining is used to handle colliding PIDs
- ▶ No collision if the table is 32768 in size! But...

## The pid data structure

```
struct pid
{
    int nr;
    struct hlist_node pid_chain;
    struct list_head pid_list;
};
```

```
struct task_struct{
    ...
    struct pid pids[PIDTYPE_MAX];
    ...
}
```

# PID Hash Tables



## kernel/pid.c — Operations

- ▶ `do_each_task_pid(nr, type, task)`
- ▶ `while_each_task_pid(nr, type, task)`
- ▶ `find_task_by_pid_type(type, nr)`
- ▶ `find_task_by_pid(nr)`
- ▶ `attach_pid(task, type, nr)`
- ▶ `detach_pid(task, type)`
- ▶ `next_thread(task)`

# Wait Queues

- ▶ A wait queue represents a set of sleeping processes, which are woken up by the kernel when some condition becomes true.
- ▶ Wait queues are implemented as doubly linked lists whose elements include pointers to process descriptors.

Each wait queue is identified by a `__wait_queue_head`

```
struct __wait_queue_head {  
    spinlock_t lock;  
    struct list_head task_list;  
};  
typedef struct __wait_queue_head wait_queue_head_t;
```

`lock`: avoid concurrent accesses.

Elements of a wait queue list are of type `wait_queue_t`:

```
struct __wait_queue {
    unsigned int flags;
    struct task_struct * task;
    wait_queue_func_t func;
    struct list_head task_list;
};
typedef struct __wait_queue wait_queue_t;
```

`task`: address of this sleeping process

`task_list`: which wait queue are you in?

`flags`: 1 – exclusive; 0 – nonexclusive;

`func`: how it should be woken up?



# Process Resource Limits

## Limiting the resource use of a process

- ▶ The amount of system resources a process can use are stored in the `current->signal->rlim` field.
- ▶ `rlim` is an array of elements of type `struct rlimit`, one for each resource limit.

```
struct rlimit {  
    unsigned long    rlim_cur;  
    unsigned long    rlim_max;  
};
```

`rlim_cur`: the current resource limit for the resource

e.g. `current->signal->rlim[RLIMIT_CPU].rlim_cur` — the current limit on the CPU time of the running process.

`rlim_max`: the maximum allowed value for the resource limit

# Resource Limits

<code>RLIMIT_AS</code>	The maximum size of process address space
<code>RLIMIT_CORE</code>	The maximum core dump file size
<code>RLIMIT_CPU</code>	The maximum CPU time for the process
<code>RLIMIT_DATA</code>	The maximum heap size
<code>RLIMIT_FSIZE</code>	The maximum file size allowed
<code>RLIMIT_LOCKS</code>	Maximum number of file locks
<code>RLIMIT_MEMLOCK</code>	The maximum size of nonswappable memory
<code>RLIMIT_MSGQUEUE</code>	Maximum number of bytes in POSIX message queues
<code>RLIMIT_NOFILE</code>	The maximum number of open file descriptors
<code>RLIMIT_NPROC</code>	The maximum number of processes of the user
<code>RLIMIT_RSS</code>	The maximum number of page frames owned by the process
<code>RLIMIT_SIGPENDING</code>	The maximum number of pending signals for the process
<code>RLIMIT_STACK</code>	The maximum stack size

## 5.3 Process Switch

# Process Switch

**Process execution context:** all information needed for the process execution

**Hardware context:** the set of registers used by a process

Where is the hardware context stored?

- ▶ partly in the process descriptor (PCB)
- ▶ partly in the Kernel Mode stack

Process switch

- ▶ saving the hardware context of `prev`
- ▶ replacing it with the hardware context of `next`

Process switching occurs only in Kernel Mode.

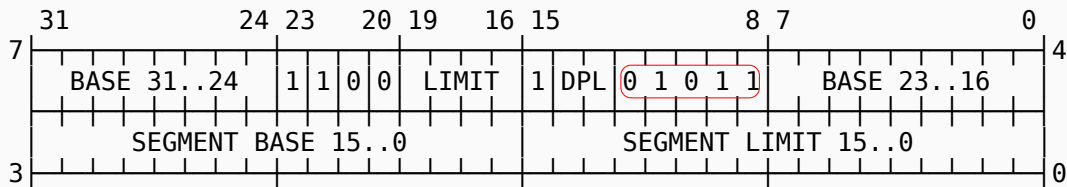
## Task State Segment (TSS)

- ▶ For storing hardware contexts
- ▶ One TSS for each process (Intel's design)
- ▶ Hardware context switching
  - ▶ `far jmp` to the TSS of `next`

## Linux doesn't use hardware context switch

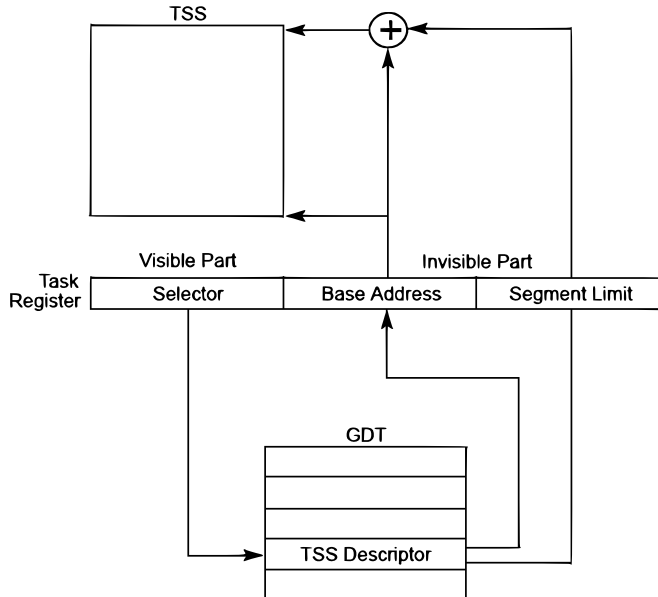
- ▶ One TSS for each CPU
  - ▶ The address of the kernel mode stack
  - ▶ I/O permission bitmap

## Task State Segment Descriptor (TSSD)



- S bit set to 0;
- Type bits set to 9/11;
- Busy bit set to 1.

# The Task Register (tr)



## Where to save the hardware context?

```
struct task_struct {  
    ...  
    struct thread_struct thread;  
    ...  
}
```

- ▶ `thread_struct` includes fields for most of the CPU registers, except the general-purpose registers such as `eax`, `ebx`, etc., which are stored in the Kernel Mode stack.



# Performing The Process Switch

`schedule()`

## Two steps:

1. Switching the Page Global Directory
2. Switching the Kernel Mode stack and the hardware context

`switch_to(prev,next,last)`

- ▶ in any process switch three processes are involved, not just two

## 5.4 Creating Processes

# Creating Processes

## The clone() system call

```
int clone(int (*fn) (void *), void *child_stack,  
         int flags, void *arg, ...  
         /* pid_t *ptid, struct user_desc *tls, pid_t *ctid */ );
```

## The traditional fork() system call

```
clone(func, child_stack, SIGCHLD, NULL);
```

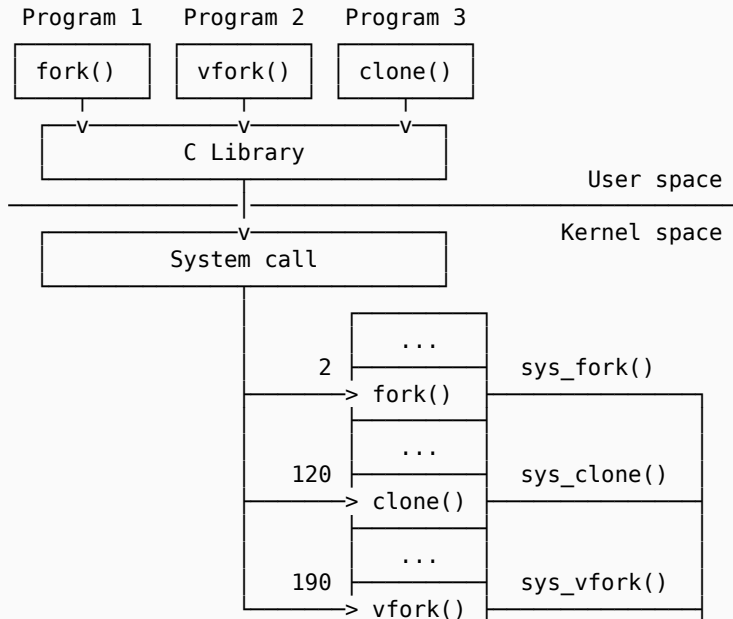
- ▶ child\_stack: parent stack pointer (copy-on-write)

## vfork()

```
clone(func, child_stack, CLONE_VM|CLONE_VFORK|SIGCHLD, NULL);
```

- ▶ child\_stack: parent stack pointer (copy-on-write)

## The `do_fork()` function does the real work



do\_fork() calls copy\_process() to make a copy of process descriptor

```
long do_fork(unsigned long clone_flags,
             unsigned long stack_start,
             struct pt_regs *regs,
             unsigned long stack_size,
             int __user *parent_tidptr,
             int __user *child_tidptr)
{
    struct task_struct *p;
    ...
    long pid = alloc_pidmap();
    ...
    p = copy_process(clone_flags, stack_start, regs,
                    stack_size, parent_tidptr,
                    child_tidptr, pid);
    ...
    return pid;
}
```

## `copy_process()`

1. `dup_task_struct()`: creates
  - ▶ a new kernel mode stack
  - ▶ `thread_info`
  - ▶ `task_struct`

Values are identical to the parent

2. is `current->signal->rlim[RLIMIT_NPROC].rlim_cur` confirmed?
3. Update child's `task_struct`
4. Set child's state to `TASK_UNINTERRUPTABLE`
5. `copy_flags()`: update flags in `task_struct`
6. `get_pid()` (check `pidmap_array` bitmap)
7. Duplicate or share resources (opened files, FS info, signal, ...)
8. `return p;`

# Creating A Kernel Thread

kernel\_thread() is similar to clone()

```
int kernel_thread(int (*fn)(void *), void * arg, unsigned long flags)
{
    ...
    return do_fork(flags | CLONE_VM | CLONE_UNTRACED, 0, &regs, 0, NULL, NULL);
}
```

# Process 0

Process 0 is a kernel thread created from scratch during the initialization phase.

- ▶ Also called *idle process*, or *swapper process*
- ▶ Its data structures are *statically* allocated

```
start_kernel()
```

- ▶ Initializes all the data structures
- ▶ Enables interrupts
- ▶ Creates another kernel thread — *process 1, the `init` process*



## Call graph

```
start_kernel()  
└─> rest_init()  
    └─> kernel_thread(init, NULL, CLONE_FS | CLONE_SIGHAND)  
        └─> cpu_idle()
```

- ▶ After having created the *init* process, *process 0* executes the `cpu_idle()` function.
- ▶ Process 0 is selected by the scheduler only when there are no other processes in the `TASK_RUNNING` state.
- ▶ In multiprocessor systems there is a process 0 for each CPU.

# Process 1

- ▶ Created via `kernel_thread(init, NULL, CLONE_FS|CLONE_SIGHAND);`
- ▶ PID is 1
- ▶ shares all per-process kernel data structures with process 0
- ▶ starts executing the `init()` function
  - ▶ completes the initialization of the kernel
- ▶ `init()` invokes the `execve()` system call to load the executable program `init`
  - ▶ As a result, the *init kernel thread* becomes a regular process having its own per-process kernel data structure
- ▶ The `init` process stays alive until the system is shut down

## 5.5 Destroying Processes

# Process Termination

- ▶ Usual way: call `exit()`
  - ▶ The C compiler places a call to `exit()` at the end of `main()`.
- ▶ Unusual way: Ctrl-C ...

## All process terminations are handled by `do_exit()`

- ▶ `tsk->flags |= PF_EXITING;` to indicate that the process is being eliminated
- ▶ `del_timer_sync(&tsk->real_timer);` to remove any kernel timers
- ▶ `exit_mm()`, `exit_sem()`, `__exit_files()`, `__exit_fs()`, `exit_namespace()`, `exit_thread()`: free pointers to the kernel data structures
- ▶ `tsk->exit_code = code;`
- ▶ `exit_notify()` to send signals to the task's parent
  - ▶ re-parents its children
  - ▶ sets the task's state to `TASK_ZOMBIE`
- ▶ `schedule()` to switch to a new process

# Process Removal

Cleaning up after a process and removing its process descriptor are separate.

## Clean up

- ▶ done in `do_exit()`
- ▶ leaves a zombie
  - ▶ To provide information to its parent
  - ▶ The only memory it occupies is its kernel stack, the `thread_info` structure, and the `task_struct` structure.

## Removal

- ▶ `release_task()` is invoked by
  - either `do_exit()` if the parent didn't wait
  - or `wait4()/waitpid()`
- ▶ `free_uid()`
- ▶ `unhash_process`: to remove the process from the `pidhash` and from the task list
- ▶ `put_task_struct()`
  - ▶ free the pages containing the process's kernel stack and `thread_info` structure
  - ▶ de-allocate the slab cache containing the `task_struct`

## 6 Process Scheduling



## 6.1 Multitasking

# Multitasking

1. Cooperative multitasking

**Yielding** a process voluntarily suspends itself

2. Preemptive multitasking

**Preemption** involuntarily suspending a running process

**Timeslice** the time a process runs before it's preempted

- ▶ usually dynamically calculated
- ▶ used as a configurable system policy

But Linux's scheduler is different

## 6.2 Linux's Process Scheduler

# Linux's Process Scheduler

up to 2.4: simple, scaled poorly

- ▶  $O(n)$
- ▶ non-preemptive
- ▶ single run queue (cache? SMP?)

from 2.5 on:  $O(1)$  scheduler

- ▶ 140 priority lists — scaled well
- ▶ one run queue per CPU — true SMP support
- ▶ preemptive
- ▶ ideal for large server workloads
- ▶ showed latency on desktop systems

from 2.6.23 on: Completely Fair Scheduler (CFS)

- ▶ improved interactive performance

## 6.3 Scheduling Policy

# Scheduling Policy

Must attempt to satisfy two conflicting goals:

1. fast process response time (low latency)
2. maximal system utilization (high throughput)

Linux tries

1. favoring I/O-bound processes over CPU-bound processes
2. doesn't neglect CPU-bound processes

# Process Priority

Usually,

- ▶ processes with a higher priority run before those with a lower priority
- ▶ processes with the same priority are scheduled *round-robin*
- ▶ processes with a higher priority receive a longer time-slice

Linux implements two priority ranges:

1. **Nice value:**  $-20 \sim +19$  (default 0)

- ▶ large value  $\Rightarrow$  lower priority
- ▶ lower value  $\Rightarrow$  higher priority  $\Rightarrow$  get larger proportion of a CPU

```
$ ps -el
```

The *nice value* can be used as

- ▶ a control over the *absolute* time-slice (e.g. MAC OS X), or
- ▶ a control over the *proportion* of time-slice (Linux)

2. **Real-time:**  $0 \sim 99$

- ▶ higher value  $\Rightarrow$  greater priority

```
$ ps -eo state,uid,pid,rtprio,time,comm
```



# Time-slice

too long: poor interactive performance

too short: context switch overhead

I/O-bound processes: don't need longer time-slices (prefer short queuing time)

CPU-bound processes: prefer longer time-slices (to keep their caches hot)

Apparently, any long time-slice would result in poor interactive performance.

# Problems With Nice Value

if two processes A and B

A:  $NI = 0, t = 100ms$

B:  $NI = 20, t = 5ms$

then, the CPU share

A: gets  $\frac{100}{105} = 95\%$

B: gets  $\frac{5}{105} = 5\%$

What if two  $B_{ni=20}$  running?

Good news: Each gets 50%

Bad news: This '50%' is  $\frac{5}{10}$ , NOT  $\frac{52.5}{105}$

Context switch twice every 10ms!

Comparing

$P_{ni=0}$  gets 100ms

$P_{ni=1}$  gets 95ms

With

$P_{ni=19}$  gets 10ms

$P_{ni=20}$  gets 5ms

This behavior means that “nicing down a process by one” has wildly different effects depending on the starting nice value.

# Completely Fair Scheduler (CFS)

For a perfect (unreal) multitasking CPU

- ▶  $n$  runnable processes can run at the same time
- ▶ each process should receive  $\frac{1}{n}$  of CPU power

For a real world CPU

- ▶ can run only a single task at once — unfair
  - 😊 while one task is running
  - 😞😞 the others have to wait
- ▶ `p->wait_runtime` is the amount of time the task should now run on the CPU for it becomes completely fair and balanced.
  - 😊 on ideal CPU, the `p->wait_runtime` value would always be zero
- ▶ CFS always tries to run the task with the largest `p->wait_runtime` value

# CFS

In practice it works like this:

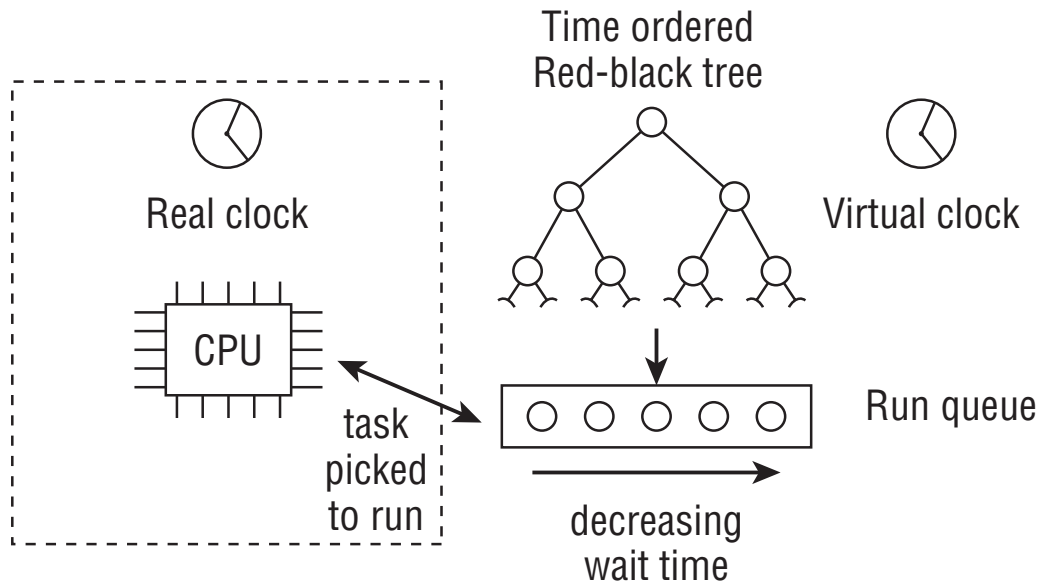
- ▶ While a task is using the CPU, its `wait_runtime` decreases

`wait_runtime = wait_runtime - time_running`

if: its `wait_runtime`  $\neq$   $\text{MIN}_{\text{wait\_runtime}}$  (among all processes)

then: it gets preempted

- ▶ Newly woken tasks (`wait_runtime = 0`) are put into the tree more and more to the right
- ▶ slowly but surely giving a chance for every task to become the 'leftmost task' and thus get on the CPU within a deterministic amount of time



- the run queue is sorted by waiting time with a red-black tree

# The virtual clock

Time passes slower on this clock than in real time  
more processes waiting  $\Rightarrow$  more slower

## Example

if: 4 processes in run queue  
then: the virtual clock speed is  $\frac{1}{4}$  of the real clock  
if: a process sitting in the queue for 20s in real time  
then: resulting to 5s in virtual time  
if: the 4 processes executing for 5s each  
then: the CPU will be busy for 20s in real time

## To sort tasks on the red-black tree

`fair_clock - wait_runtime`

`fair_clock` The virtual time, e.g. 5s in the previous example

`wait_runtime` Fairness imbalance measure

## To move a node rightward in the red-black tree

`wait_runtime = wait_runtime - time_running`

`time_running` When a task is allowed to run, the interval during which it has been running



# CFS

## Example:

Assuming *targeted latency* is 20ms. If we have

2 processes: each gets 10ms

4 processes: each gets 5ms

20 processes: each gets 1ms

$\infty$  processes: each gets 1ms (to avoid unacceptable context switching costs)

## Example

A system with two processes running:

1. a text editor, say, Emacs (I/O-bound)
2. gcc is compiling the kernel source (CPU-bound)

if: they both have the same nice value

then: the proportion they get would be 50%-50%

Consequence:

- ▶ Emacs uses far less than 50% of CPU
- ▶ gcc can enjoy more than 50% of CPU freely

When Emacs wakes up

1. CFS notes that it has 50% of CPU, but uses very little of it (far less than gcc)
2. CFS preempts gcc and enables Emacs to run immediately

Thus, better interactive performance.

## 6.4 Linux Scheduling Algorithm

# Scheduler Classes

Different, pluggable algorithms coexist

- ▶ Each algorithm schedules its own type of processes
- ▶ Each scheduler class has a priority

SCHED\_FIFO

SCHED\_RR

SCHED\_NORMAL

## Example: nice value difference

Assume:

1. nice value 5 pts up results in a  $\frac{1}{3}$  penalty
2. targeted latency is again 20ms
3. 2 processes in the system

Then:

- ▶  $P_{ni=0}$  gets 15ms;  $P_{ni=5}$  gets 5ms
- ▶  $P_{ni=10}$  gets 15ms;  $P_{ni=15}$  gets 5ms
- ▶ Absolute nice values no longer affect scheduling decision
- ▶ Relative nice values does

## 6.5 The Linux Scheduling Implementation

# Base Time Quantum

## $O(1)$ scheduler

$$\text{base time quantum (ms)} = \begin{cases} (140 - \text{static priority}) \times 20 & \text{if static priority} < 120, \\ (140 - \text{static priority}) \times 5 & \text{if static priority} \geq 120. \end{cases}$$

# Major Components of CFS

- ▶ Time Accounting
- ▶ Process Selection
- ▶ The Scheduler Entry Point
- ▶ Sleeping and Waking Up



# Time accounting

`sched_entity` keeps track of process accounting (`task_struct -> se`)

```
struct sched_entity {
    struct load_weight      load;           /* for load-balancing */
    struct rb_node          run_node;
    struct list_head        group_node;
    unsigned int            on_rq;

    u64                     exec_start;
    u64                     sum_exec_runtime;
    u64                     vruntime;
    u64                     prev_sum_exec_runtime;

    u64                     last_wakeup;
    u64                     avg_overlap;

    u64                     nr_migrations;

    u64                     start_runtime;
    u64                     avg_wakeup;

    /* many state variables elided, enabled only if CONFIG_SCHEDSTATS is set */
};
```

## The Virtual Runtime

`vruntime` stores the *virtual runtime* of a process. On an ideal processor, all tasks' `vruntime` would be identical.

Accounting is done in `update_curr()` and `__update_curr()`

# Process Selection

The core of CFS algorithm Pick the process with the smallest vruntime

- run the process represented by the leftmost node in the rbtrees

```
static struct sched_entity *__pick_next_entity(struct cfs_rq *cfs_rq)
{
    struct rb_node *left = cfs_rq->rb_leftmost;
    if (!left)
        return NULL;
    return rb_entry(left, struct sched_entity, run_node);
}
```

# Adding Processes to the Tree

- ▶ Happens when a process wakes up or is created
- ▶ `enqueue_entity()` and `__enqueue_entity()`

# Removing Processes from the Tree

- ▶ Happens when a process blocks or terminates
- ▶ `dequeue_entity()` and `__dequeue_entity()`

# The Scheduler Entry Point

# Sleeping and Waking Up