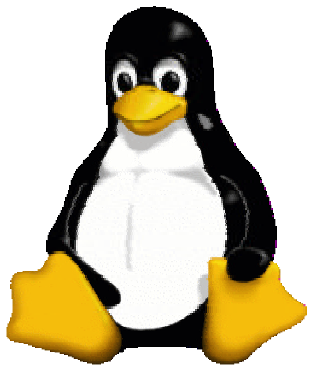
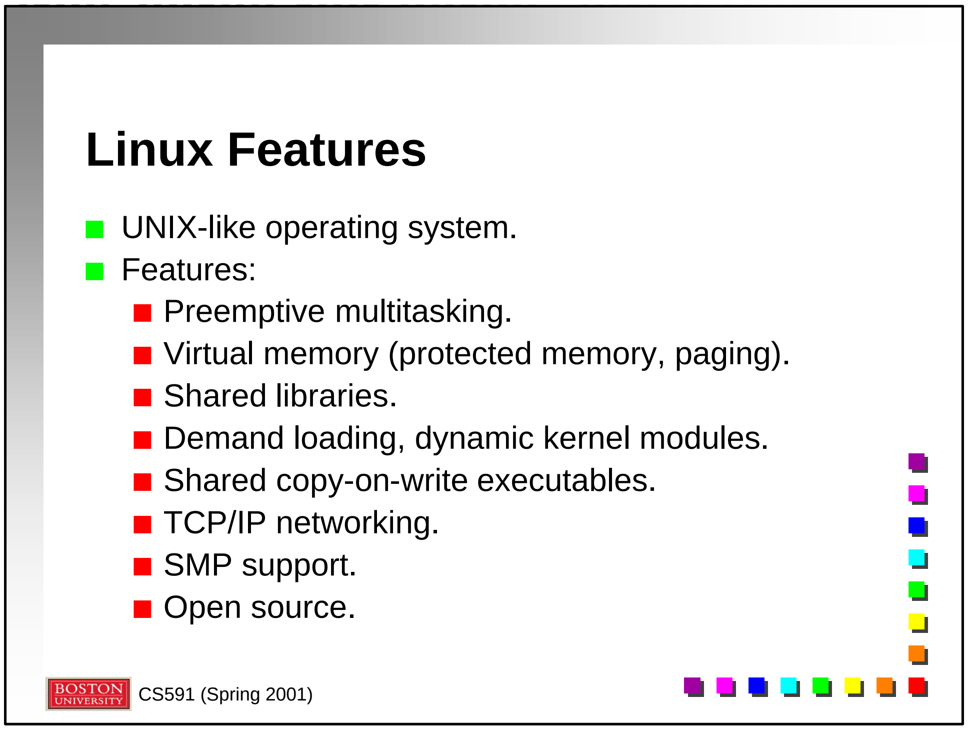
The Linux Kernel: Introduction



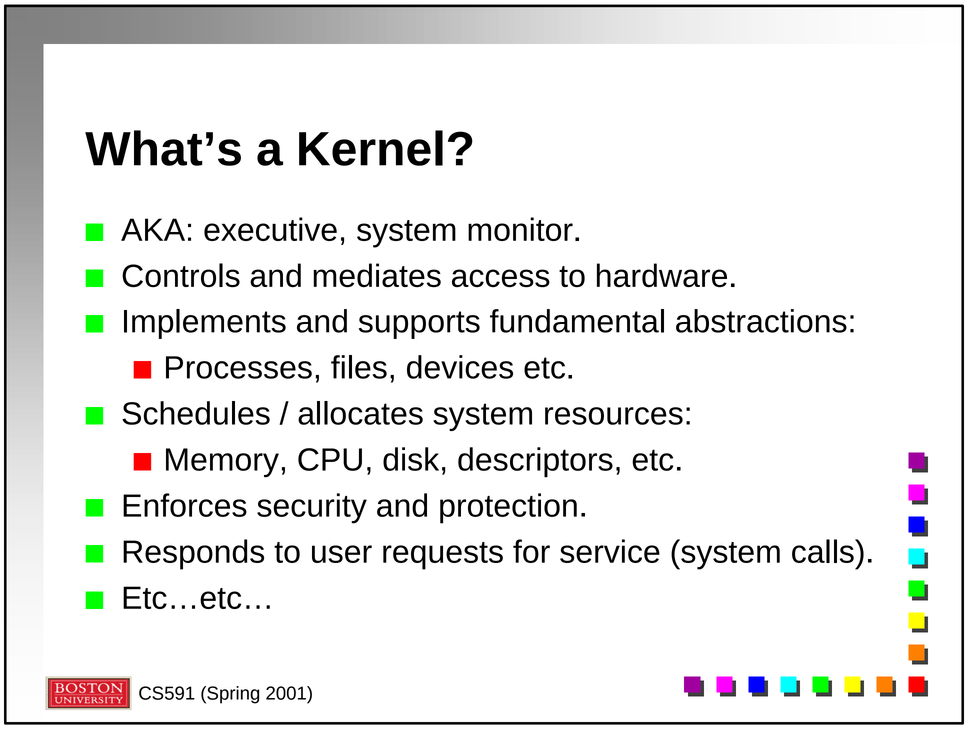
History

- UNIX: 1969 Thompson & Ritchie AT&T Bell Labs.
- BSD: 1978 Berkeley Software Distribution.
- Commercial Vendors: Sun, HP, IBM, SGI, DEC.
- GNU: 1984 Richard Stallman, FSF.
- POSIX: 1986 IEEE Portable Operating System unIX.
- Minix: 1987 Andy Tannenbaum.
- SVR4: 1989 AT&T and Sun.
- Linux: 1991 Linus Torvalds Intel 386 (i386).
- Open Source: GPL.



Linux Features

- UNIX-like operating system.
- Features:
  - Preemptive multitasking.
  - Virtual memory (protected memory, paging).
  - Shared libraries.
  - Demand loading, dynamic kernel modules.
  - Shared copy-on-write executables.
  - TCP/IP networking.
  - SMP support.
  - Open source.



What's a Kernel?

- AKA: executive, system monitor.
- Controls and mediates access to hardware.
- Implements and supports fundamental abstractions:
  - Processes, files, devices etc.
- Schedules / allocates system resources:
  - Memory, CPU, disk, descriptors, etc.
- Enforces security and protection.
- Responds to user requests for service (system calls).
- Etc…etc…

Kernel Design Goals

- Performance: efficiency, speed.
  - Utilize resources to capacity with low overhead.
- Stability: robustness, resilience.
  - Uptime, graceful degradation.
- Capability: features, flexibility, compatibility.
- Security, protection.
  - Protect users from each other & system from bad users.
- Portability.
- Extensibility.

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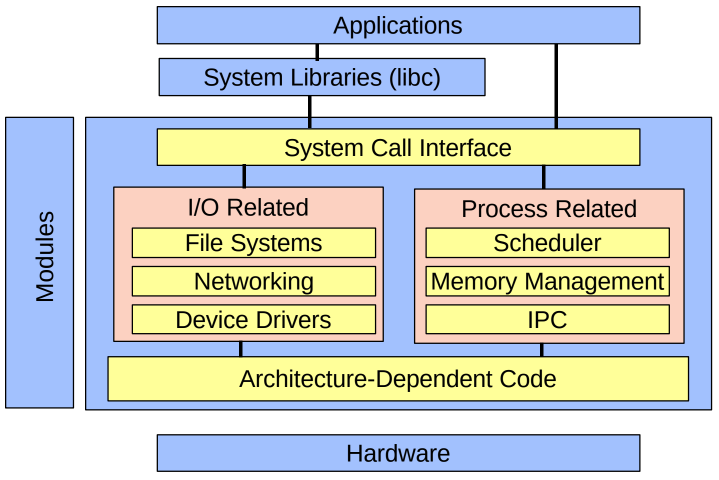
Example "Core" Kernel



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Architectual Approaches

- Monolithic.
- Layered.
- Modularized.
- Micro-kernel.
- Virtual machine.

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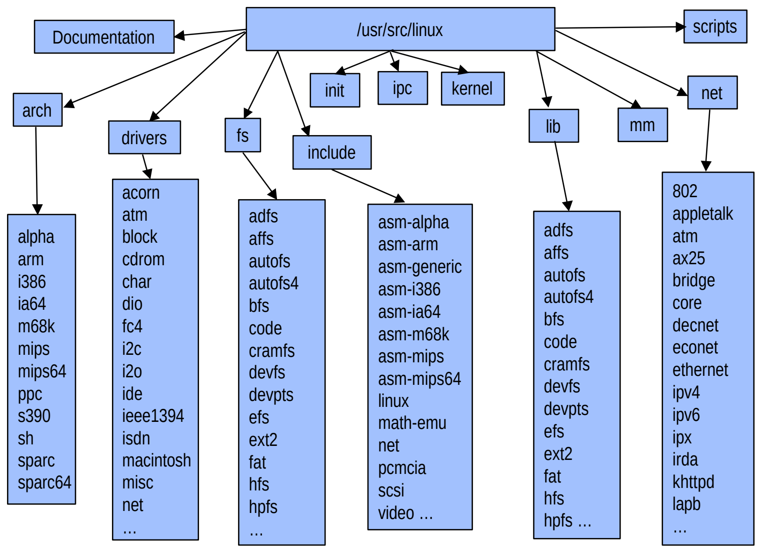
Linux Source Tree Layout



/usr/src/linux
Documentation
scripts
arch
drivers
fs
include
init
ipc
kernel
lib
mm
net
alpha arm i386 ia64 m68k mips mips64 ppc s390 sh sparc sparc64
acorn atm block cdrom char dio fc4 i2c i2o ide ieee1394 isdn macintosh misc net …
adfs affs autofs autofs4 bfs code cramfs devfs devpts efs ext2 fat hfs hpfs …
asm-alpha asm-arm asm-generic asm-i386 asm-ia64 asm-m68k asm-mips asm-mips64 linux math-emu net pcmcia scsi video …
adfs affs autofs autofs4 bfs code cramfs devfs devpts efs ext2 fat hfs hpfs …
802 appletalk atm ax25 bridge core decnet econet ethernet ipv4 ipv6 ipx irda khttpd lapb …

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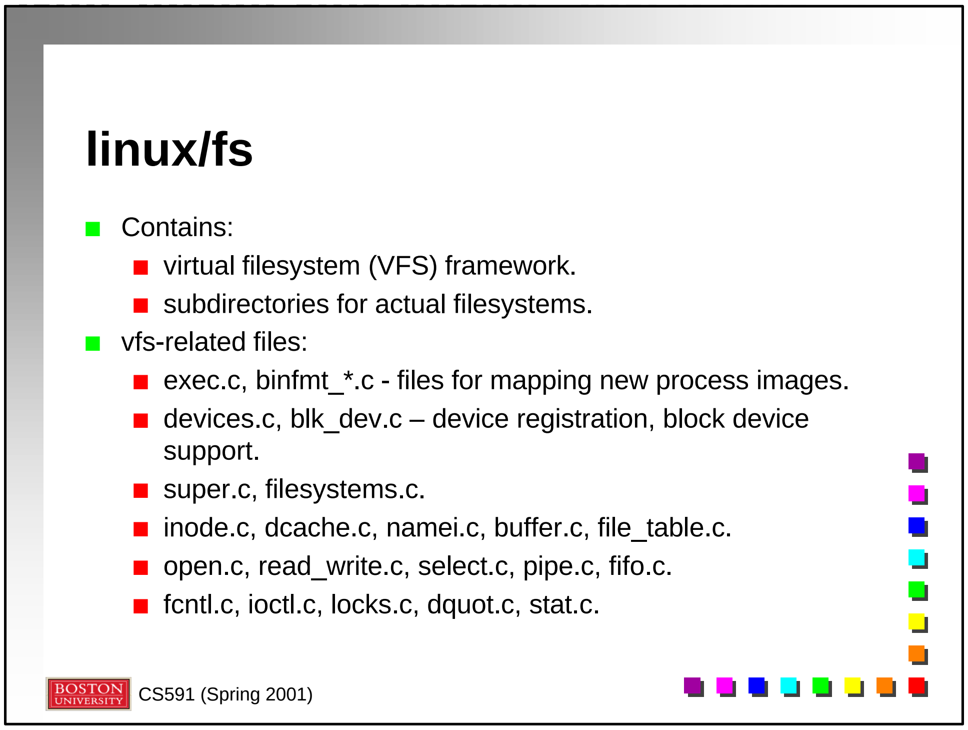
linux/arch

- Subdirectories for each current port.
- Each contains **kernel**, **lib**, **mm**, **boot** and other directories whose contents override code stubs in architecture independent code.
- **lib** contains highly-optimized common utility routines such as memcpy, checksums, etc.
- **arch** as of 2.4:
  - alpha, arm, i386, ia64, m68k, mips, mips64.
  - ppc, s390, sh, sparc, sparc64.

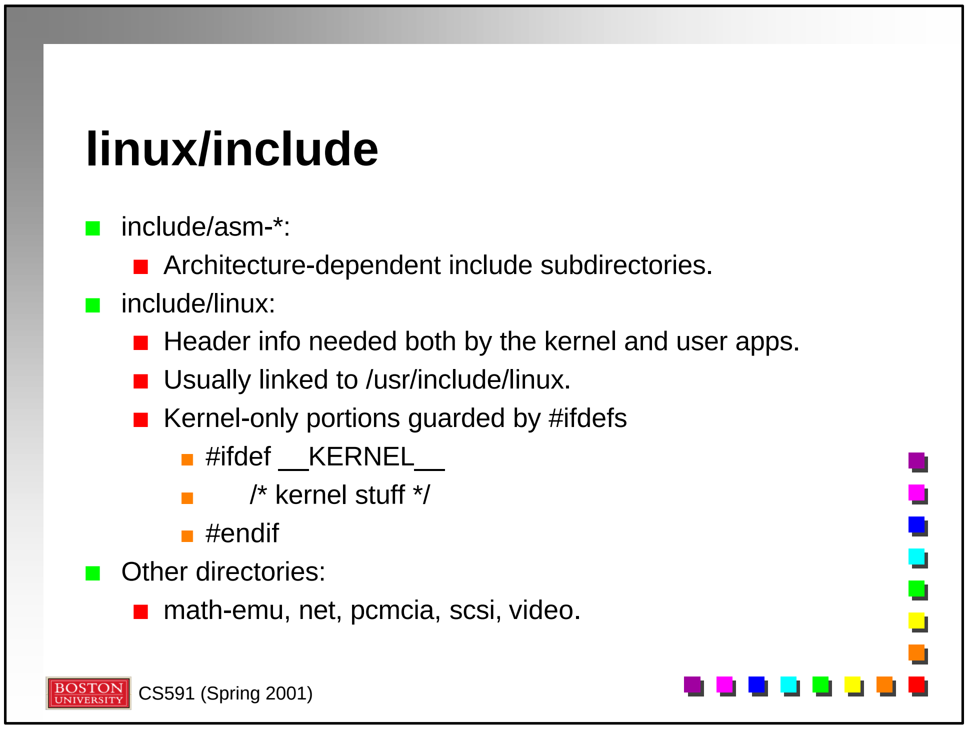
linux/drivers

- Largest amount of code in the kernel tree (~1.5M).
- device, bus, platform and general directories.
- drivers/char – n_tty.c is the default line discipline.
- drivers/block – elevator.c, genhd.c, linear.c, ll_rw_blk.c, raidN.c.
- drivers/net –specific drivers and general routines Space.c and net_init.c.
- drivers/scsi – scsi_*.c files are generic; sd.c (disk), sr.c (CD-ROM), st.c (tape), sg.c (generic).
- General:
  - cdrom, ide, isdn, parport, pcmcia, pnp, sound, telephony, video.
- Buses – fc4, i2c, nubus, pci, sbus, tc, usb.
- Platforms – acorn, macintosh, s390, sgi.



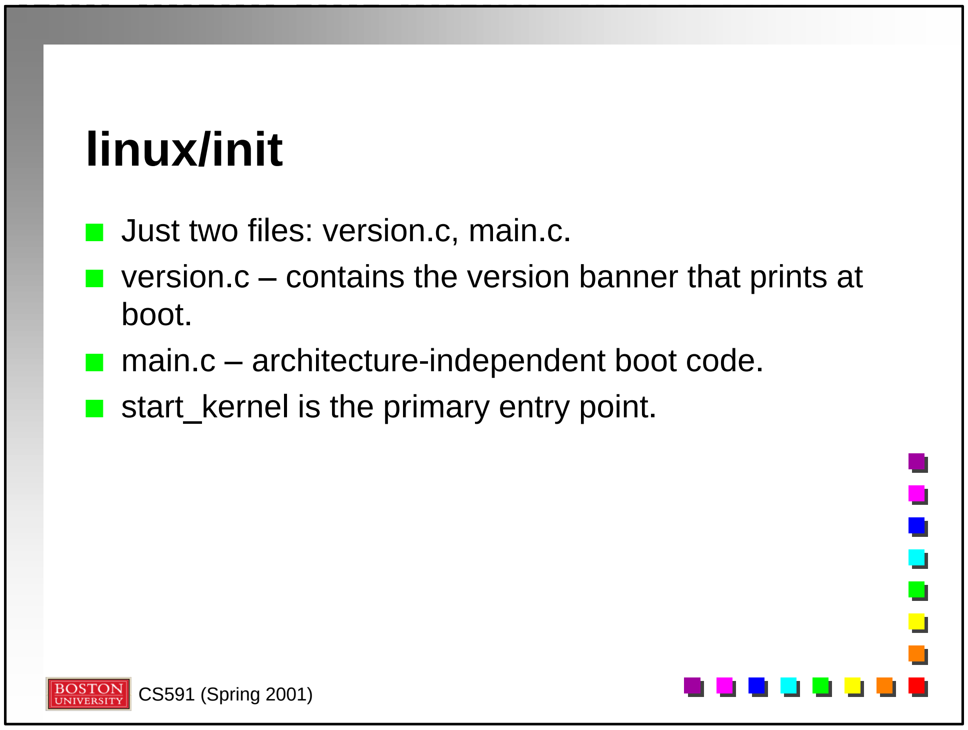
linux/fs

- Contains:
  - virtual filesystem (VFS) framework.
  - subdirectories for actual filesystems.
- vfs-related files:
  - exec.c, binfmt_*.c - files for mapping new process images.
  - devices.c, blk_dev.c – device registration, block device support.
  - super.c, filesystems.c.
  - inode.c, dcache.c, namei.c, buffer.c, file_table.c.
  - open.c, read_write.c, select.c, pipe.c, fifo.c.
  - fcntl.c, ioctl.c, locks.c, dquot.c, stat.c.



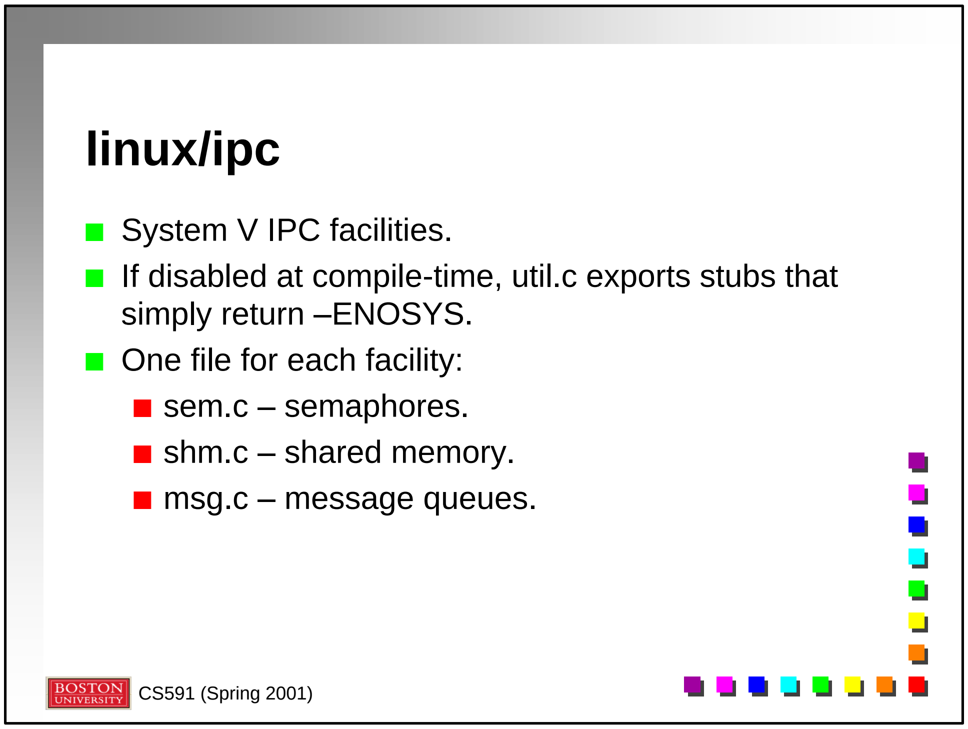
linux/include

- include/asm-*:
  - Architecture-dependent include subdirectories.
- include/linux:
  - Header info needed both by the kernel and user apps.
  - Usually linked to /usr/include/linux.
  - Kernel-only portions guarded by #ifdefs
    - #ifdef __KERNEL__
    -       /* kernel stuff */
    - #endif
- Other directories:
  - math-emu, net, pcmcia, scsi, video.



linux/init

- Just two files: version.c, main.c.
- version.c – contains the version banner that prints at boot.
- main.c – architecture-independent boot code.
- start_kernel is the primary entry point.



linux/ipc

- System V IPC facilities.
- If disabled at compile-time, util.c exports stubs that simply return –ENOSYS.
- One file for each facility:
  - sem.c – semaphores.
  - shm.c – shared memory.
  - msg.c – message queues.

linux/kernel

- The core kernel code.
- sched.c – "the main kernel file":
  - scheduler, wait queues, timers, alarms, task queues.
- Process control:
  - fork.c, exec.c, signal.c, exit.c etc…
- Kernel module support:
  - kmod.c, ksyms.c, module.c.
- Other operations:
  - time.c, resource.c, dma.c, softirq.c, itimer.c.
  - printk.c, info.c, panic.c, sysctl.c, sys.c.

linux/lib

- kernel code cannot call standard C library routines.
- Files:
  - brlock.c – "Big Reader" spinlocks.
  - cmdline.c – kernel command line parsing routines.
  - errno.c – global definition of errno.
  - inflate.c – "gunzip" part of gzip.c used during boot.
  - string.c – portable string code.
    - Usually replaced by optimized, architecture-dependent routines.
  - vsprintf.c – libc replacement.

linux/mm

- Paging and swapping:
  - swap.c, swapfile.c (paging devices), swap_state.c (cache).
  - vmscan.c – paging policies, kswapd.
  - page_io.c – low-level page transfer.
- Allocation and deallocation:
  - slab.c – slab allocator.
  - page_alloc.c – page-based allocator.
  - vmalloc.c – kernel virtual-memory allocator.
- Memory mapping:
  - memory.c – paging, fault-handling, page table code.
  - filemap.c – file mapping.
  - mmap.c, mremap.c, mlock.c, mprotect.c.

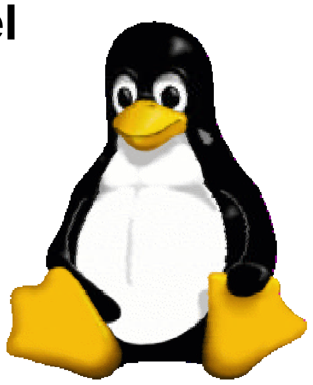
linux/scripts

- Scripts for:
  - Menu-based kernel configuration.
  - Kernel patching.
  - Generating kernel documentation.

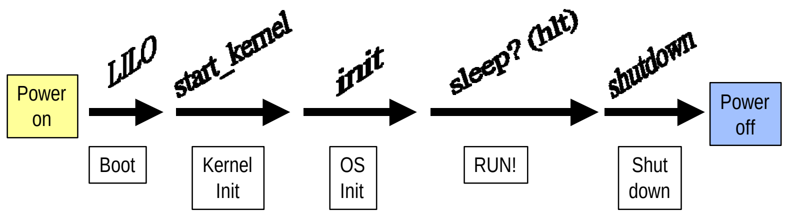
Summary

- Linux is a modular, UNIX-like monolithic kernel.
- Kernel is the heart of the OS that executes with special hardware permission (kernel mode).
- “Core kernel” provides framework, data structures, support for drivers, modules, subsystems.
- Architecture dependent source sub-trees live in /arch.

Booting and Kernel Initialization



System Lifecycle: Ups & Downs



Boot Terminology

- Loader:
  - Program that moves bits from disk (usually) to memory and then transfers CPU control to the newly “loaded” bits (executable).
- Bootloader / Bootstrap:
  - Program that loads the “first program” (the kernel).
- Boot PROM / PROM Monitor / BIOS:
  - Persistent code that is “already loaded” on power-up.
- Boot Manager:
  - Program that lets you choose the “first program” to load.

LILO: LInux LOader

- A versatile boot manager that supports:
  - Choice of Linux kernels.
  - Boot time kernel parameters.
  - Booting non-Linux kernels.
  - A variety of configurations.
- Characteristics:
  - Lives in MBR or partition boot sector.
  - Has no knowledge of filesystem structure so…
  - Builds a sector “map file” (block map) to find kernel.
- /sbin/lilo – “map installer”.
  - /etc/lilo.conf is lilo configuration file.

Example lilo.conf File

```
boot=/dev/hda
map=/boot/map
install=/boot/boot.b
prompt
timeout=50
default=linux

image=/boot/vmlinuz-2.2.12-20
        label=linux
        initrd=/boot/initrd-2.2.12-20.img
        read-only
        root=/dev/hda1
```

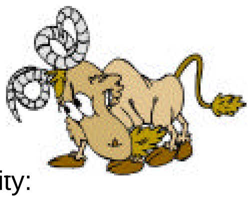
/sbin/init

- Ancestor of all processes (except idle/swapper process).
- Controls transitions between "runlevels":
  - 0: shutdown
  - 1: single-user
  - 2: multi-user (no NFS)
  - 3: full multi-user
  - 5: X11
  - 6: reboot
- Executes startup/shutdown scripts for each runlevel.

Shutdown

- Use /bin/shutdown to avoid data loss and filesystem corruption.
- Shutdown inhibits login, asks init to send SIGTERM to all processes, then SIGKILL.
- Low-level commands: halt, reboot, poweroff.
  - Use -h, -r or -p options to shutdown instead.
- Ctrl-Alt-Delete "Vulcan neck pinch":
  - defined by a line in /etc/inittab.
  - ca::ctrlaltdel:/sbin/shutdown -t3 -r now.

Advanced Boot Concepts

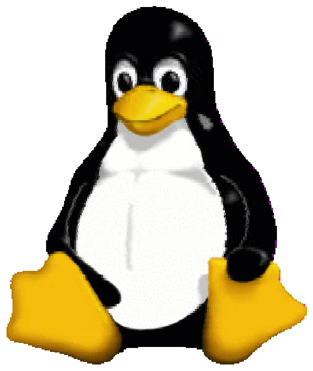


- Initial ramdisk (initrd) – two-stage boot for flexibility:
  - First mount “initial” ramdisk as root.
  - Execute linuxrc to perform additional setup, configuration.
  - Finally mount “real” root and continue.
  - See Documentation/initrd.txt for details.
  - Also see “man initrd”.
- Net booting:
  - Remote root (Diskless-root-HOWTO).
  - Diskless boot (Diskless-HOWTO).

Summary

- Bootstrapping a system is a complex, device-dependent process that involves transition from hardware, to firmware, to software.
- Booting within the constraints of the Intel architecture is especially complex and usually involves firmware support (BIOS) and a boot manager (LILO).
- /sbin/lilo is a “map installer” that reads configuration information and writes a boot sector and block map files used during boot.
- start_kernel is Linux “main” and sets up process context before spawning process 0 (idle) and process 1 (init).
- The init() function performs high-level initialization before exec’ing the user-level init process.

System Calls



System Calls

- Interface between user-level processes and hardware devices.
  - CPU, memory, disks etc.
- Make programming easier:
  - Let kernel take care of hardware-specific issues.
- Increase system security:
  - Let kernel check requested service via syscall.
- Provide portability:
  - Maintain interface but change functional implementation.

POSIX APIs

- API = Application Programmer Interface.
  - Function defn specifying how to obtain service.
  - By contrast, a system call is an explicit request to kernel made via a software interrupt.
- Standard C library (**libc**) contains wrapper routines that make system calls.
  - e.g., malloc, free are libc routines that use the brk system call.
- POSIX-compliant = having a standard set of APIs.
- Non-UNIX systems can be POSIX-compliant if they offer the required set of APIs.

Linux System Calls (1)

Invoked by executing **`int $0x80`**.

- Programmed exception vector number 128.
- CPU switches to kernel mode & executes a kernel function.

- Calling process passes **`syscall number`** identifying system call in **`eax`** register (on Intel processors).
- Syscall handler responsible for:
  - Saving registers on kernel mode stack.
  - Invoking syscall service routine.
  - Exiting by calling **`ret_from_sys_call()`**.

Linux System Calls (2)

- System call dispatch table:
  - Associates syscall number with corresponding service routine.
  - Stored in **`sys_call_table`** array having up to **`NR_syscall`** entries (usually 256 maximum).
  - nth entry contains service routine address of syscall n.

Initializing System Calls

- **`trap_init()`** called during kernel initialization sets up the IDT (interrupt descriptor table) entry corresponding to vector 128:
  - **`set_system_gate(0x80, &system_call);`**
- A system gate descriptor is placed in the IDT, identifying address of **`system_call`** routine.
  - Does not disable maskable interrupts.
  - Sets the descriptor privilege level (DPL) to 3:
    - Allows User Mode processes to invoke exception handlers (i.e. syscall routines).

The system_call() Function

- Saves syscall number & CPU registers used by exception handler on the stack, except those automatically saved by control unit.
- Checks for valid system call.
- Invokes specific service routine associated with syscall number (contained in **`eax`**):
  - **`call *sys_call_table(0, %eax, 4)`**
- Return code of system call is stored in **`eax`**.

Parameter Passing

- On the 32-bit Intel 80x86:
  - 6 registers are used to store syscall parameters.
    - **`eax`** (syscall number).
    - **`ebx`**, **`ecx`**, **`edx`**, **`esi`**, **`edi`** store parameters to syscall service routine, identified by syscall number.

Wrapper Routines

- Kernel code (e.g., kernel threads) cannot use library routines.
- **`_syscall0 … _syscall5`** macros define wrapper routines for system calls with up to 5 parameters.
- e.g., **`_syscall3(int,write,int,fd,`**
  `const char *,buf,unsigned int,count)`

Example: “Hello, world!”

```
.data                                   # section declaration

msg:
        .string "Hello, world!\n"       # our dear string
        len = . - msg                   # length of our dear string

.text                                   # section declaration

                        # we must export the entry point to the ELF linker or
    .global _start      # loader. They conventionally recognize _start as their
                        # entry point. Use ld -e foo to override the default.

_start:

# write our string to stdout

        movl    $len,%edx       # third argument: message length
        movl    $msg,%ecx       # second argument: pointer to message to write
        movl    $1,%ebx         # first argument: file handle (stdout)
        movl    $4,%eax         # system call number (sys_write)
        int     $0x80           # call kernel

# and exit

        movl    $0,%ebx         # first argument: exit code
        movl    $1,%eax         # system call number (sys_exit)
        int     $0x80           # call kernel
```

Linux Files Relating to Syscalls

- Main files:
  - arch/i386/kernel/entry.S
    - System call and low-level fault handling routines.
  - include/asm-i386/unistd.h
    - System call numbers and macros.
  - kernel/sys.c
    - System call service routines.

arch/i386/kernel/entry.S

```
.data
ENTRY(sys_call_table)
.long SYMBOL_NAME(sys_ni_syscall) /* 0  -  old "setup()" system
                                  call*/
    .long SYMBOL_NAME(sys_exit)
    .long SYMBOL_NAME(sys_fork)
    .long SYMBOL_NAME(sys_read)
    .long SYMBOL_NAME(sys_write)
```

- Add system calls by appending entry to sys_call_table:

```
.long SYMBOL_NAME(sys_my_system_call)
```

include/asm-i386/unistd.h

- Each system call needs a number in the system call table:
  - e.g., **`#define __NR_write 4`**
  - **`#define __NR_my_system_call nnn`**, where **`nnn`** is next free entry in system call table.

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kernel/sys.c

- Service routine bodies are defined here:
- e.g., **`asmlinkage retval`**

```
    sys_my_system_call (parameters) {
          body of service routine;
          return retval;
    }
```

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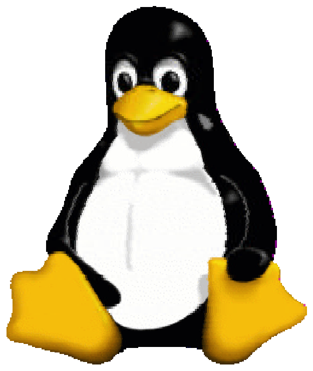
Kernel Modules



Kernel Modules

- See A. Rubini, “Device Drivers”, Chapter 2.
- Modules can be compiled and dynamically linked into kernel address space.
  - Useful for device drivers that need not always be resident until needed.
    - Keeps core kernel “footprint” small.
  - Can be used to “extend” functionality of kernel too!

Example: “Hello, world!”

```
#define MODULE
#include <linux/module.h>
int init_module(void) {
  printk(“<1>Hello, world!\n”);
  return 0;
}
void cleanup_module(void) {
  printk(“<1>Goodbye cruel world  \n”);
}
```

Using Modules

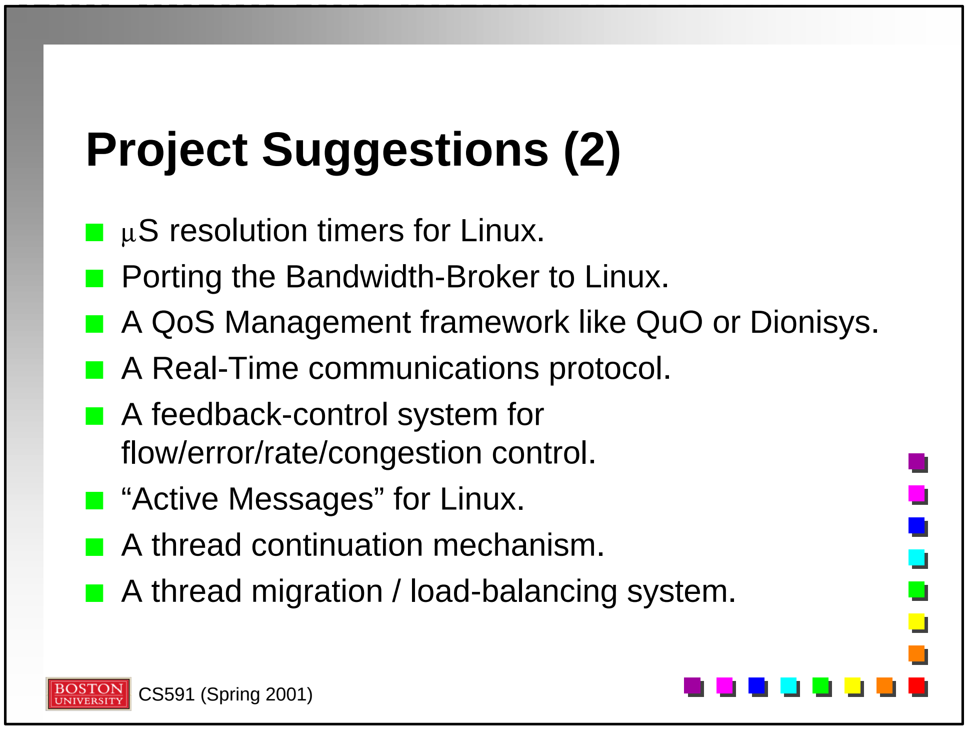
- Module object file is installed in running kernel using **`insmod module_name`**.
  - Loads module into kernel address space and links unresolved symbols in module to symbol table of running kernel.

The Kernel Symbol Table

- Symbols accessible to kernel-loadable modules appear in **`/proc/ksyms`**.
  - **`register_symtab`** registers a symbol table in the kernel’s main table.
  - Real hackers export symbols from the kernel by modifying **`kernel/ksyms.c`**

Project Suggestions (1)

- Real-Time thread library.
- Scheduler activations in Linux.
- A Linux “upcall” mechanism.
- Real-Time memory allocator / garbage collector.
- A distributed shared memory system.
- A QoS-based socket library.
- An event-based mechanism for implementing adaptive systems.
- DWCS packet scheduling.
- A heap-based priority scheduler for Linux.



Project Suggestions (2)

- μS resolution timers for Linux.
- Porting the Bandwidth-Broker to Linux.
- A QoS Management framework like QuO or Dionisys.
- A Real-Time communications protocol.
- A feedback-control system for flow/error/rate/congestion control.
- “Active Messages” for Linux.
- A thread continuation mechanism.
- A thread migration / load-balancing system.

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