27 Linux

Linux

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Winter Term 2008/09

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Recommended Reading[1]

- Bacon, J.: Operating Systems (24)
- Silberschatz, A.: Operating System Concepts (22)
- Tanenbaum, A.: Modern Operating Systems (10)
- Linux Textbooks
  - none of these has been rated excellent by *all reviewers*
- My personal recommendation:
  Bovet, D.P., Cesati, M.: "Understanding the LINUX Kernel, O'Reilly, 2. Edition, November 2005

Some slides of this lecture are taken from Silberschatz, others are taken from Athanasios E. Papathanasiou Computer Science Department, University of Rochester

[1] For details see slides of previous Proseminars: “Linux Internals”

Linux Textbooks & Online Info (2)

- C. Benvenuti: Understanding Linux Network Internals, December 2005
- J. Corbet: Linux Device Drivers, 3. Edition
- C. Hallinan: Embedded Linux Primer
- G. Kroah-Hartman: Linux Kernel in a Nutshell, dec. 2006
- R. Love: Linux System Programming
- C. Newham et al.: Bash Cookbook: Solution and Examples for Bash Users
- http://jungla.dit.upm.es/~jmseyas/linux/kernel/hackers-docs.html
- http://bravo.ce.uniroma2.it/kernelhacking2006/schedule.html
- http://www.spinics.net/linux/

Roadmap for Today

- Introduction
- Evaluation of Lecture
- Linux History
- Design Principles
- Kernel Modules
- Process Management
- Scheduling
- Memory Management
- File Systems
- Input and Output
- IPC
- Network Structure
- Security

Objectives of this Lecture

- Overview on history of UNIX and Linux
- Some principles Linux is designed upon
- Focus on Unix/Solaris/Linux process model, e.g.
  - How does Unix/Solaris/Linux schedule processes/threads
  - What inter-process communication (IPC) is offered
- Basics of memory management
- Design and implementation of
  - (Virtual) File systems and
  - I/O device management

What is Linux?

- Open source Unix alike OS kernel
- *What is Unix?*

"Unix is simple and coherent, but it takes a genius (or at any rate a programmer) to understand and appreciate its simplicity."

---Dennis Ritchie

What is Linux?

- Free does not mean bad !
  - ∃ exceptions to the line: "Quality has a price“
- It is a free OS, started by Linus Torvalds, together with some "volunteers" spread all over the "Internet". Most of the programmers that have contributed to Linux are working for free.
- There is a small **fixed team** working full time on it, and millions of users contribute to its development, even simply by sending
  - suggestions
  - detected errors
  - ...
- Because Linux is used (and then tested!) all over the world, on different machines with different configurations, some claim:

“Linux had an harder beta-test than any other commercial OS”

Linux History

History of ...nix Systems

- UNIX: 1969 Ken Thomson and Dennis Ritchie at AT&T Bell Labs
- BSD: 1978 Berkeley Software Distribution
- Commercial Vendors: Sun, HP, IBM, SGI, DEC
- GNU: 1984 Richard Stallmann, FSF = Free Software Foundation
- POSIX: 1986 IEEE Portable Operating System unIX
- Minix: 1987 Andy Tanenbaum
- SVR4: 1989 AT&T and Sun
- Linux: 1991 Linus Thorvalds on Intel 386
- OpenSource: GPL

What do People think of Linux?

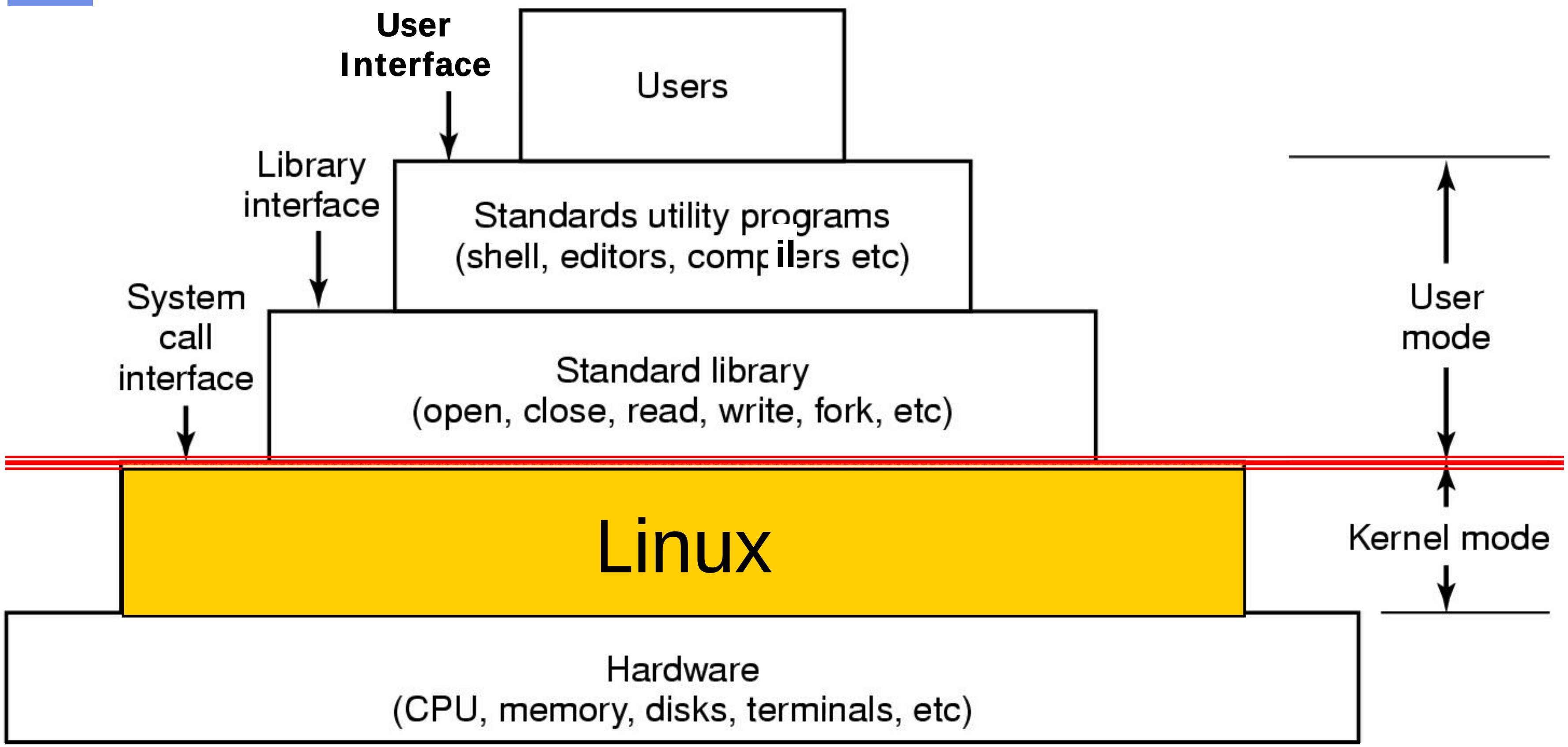
- "Well"-organized code*
- Linux = aesthetic system architecture*

?

- Others blame ...
  - its cryptic commands and system calls
  - its huge macro kernel (old fashioned SA style)
- Well defined generic interfaces
  - (e.g. VFS for all supported FSs)
  - ...

*Mauerer's opinion

Unix Architecture



Modern Unix Kernel

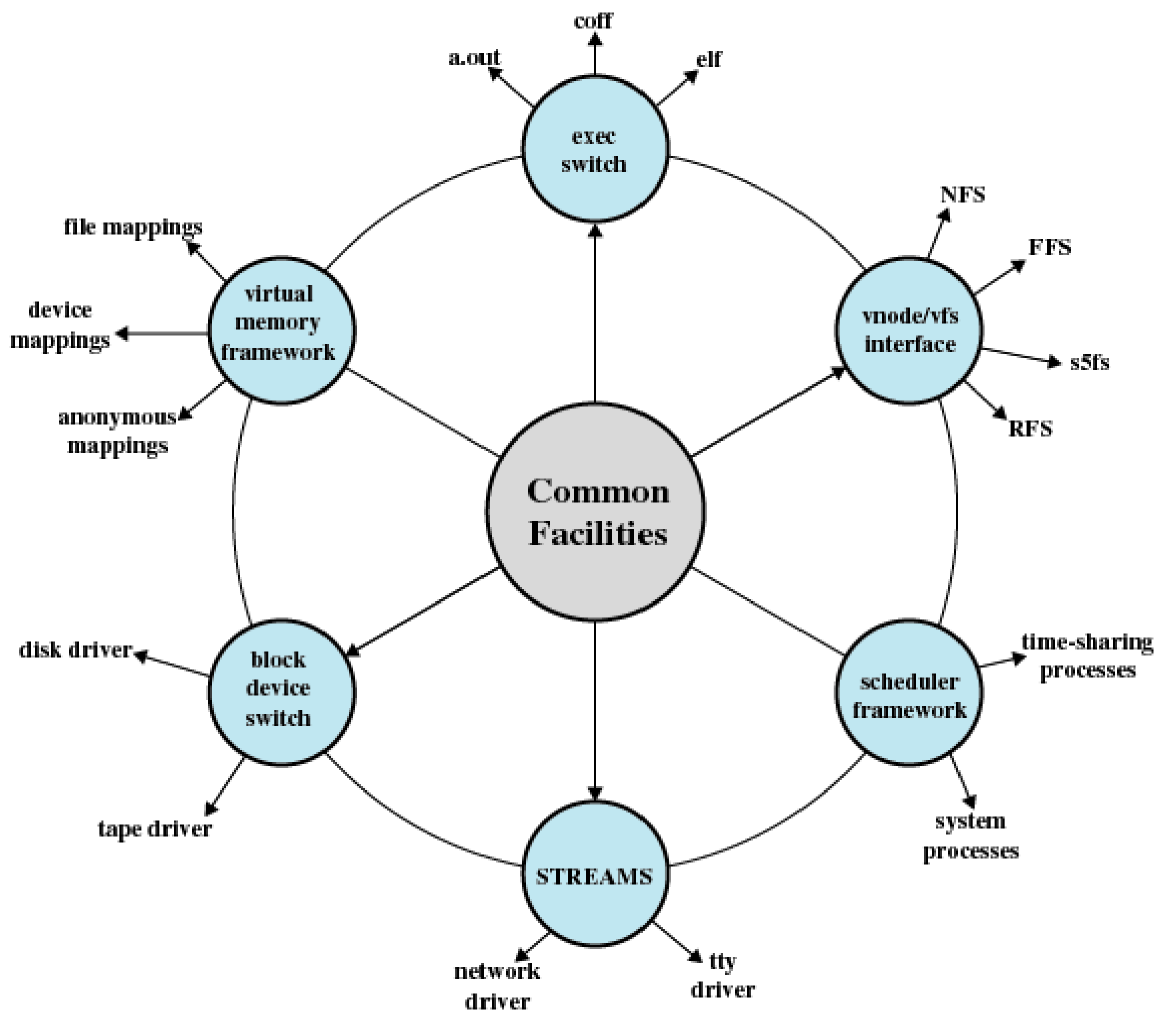


Figure 2.16 Modern UNIX Kernel [VAHA96]

Linux History

- A “modernized”, free* OS based on UNIX standards
- Small kernel in 1991 by Linus Torvalds, with the major design goal: UNIX compatibility
- Designed to run efficiently and reliably on common PC-HW, but also on some other platforms, e.g. high-end computers
- Core of Linux kernel entirely original, but it can run much existing free UNIX software, $\Rightarrow$

entire UNIX-compatible OS free from proprietary code

*In contrast to Tanenbaum’s Minix

Linux Kernel

- Version 0.01 (May 1991)
  - no networking
  - only on 80386-compatible Intel processors and on PC hardware
  - extremely limited device-driver support
  - only Tanenbaum's Minix file system

Linux Kernel

- Linux 1.0 (March 1994) included:
  - UNIX's standard TCP/IP networking protocols
  - BSD-compatible socket interface for networking
  - Device-driver support for running IP over an Ethernet
  - Enhanced file system
  - Support for a range of SCSI controllers for high-performance disk access
  - Extra hardware support
- Version 1.2 (March 1995) the final PC-only Linux kernel.

Linux 2.0

- Released (June 1996) 2 major new functionalities:
  - Support for multiple architectures (64-bit native Dec Alpha)
  - Support for multiprocessor architectures (SMPs)
- Other new features included:
  - Improved memory-management code
  - Improved TCP/IP performance
  - Support for internal kernel threads, ..., and for automatic loading of kernel modules on demand.
  - Standardized configuration interface
- Available for:
  - Motorola 68000-series ,
  - Sun Sparc systems, and
  - PC and PowerMac systems

Linux 2.4 + 2.6

- 2.4 and 2.6
  - increased SMP support
  - added journaling file system
  - preemptive kernel
  - 64-bit memory support

The Linux System

- Linux uses many tools developed as part of Berkeley’s BSD OS, MIT’s X Window System, and the Free Software Foundation's GNU project
- The min system libraries were started by the GNU project, with improvements provided by the Linux community
- Linux networking-administration tools were derived from 4.3BSD code; recent BSD derivatives such as Free BSD have borrowed code from Linux in return

Linux Distributions

- Standard, precompiled sets of packages, or distributions, include the basic Linux system, system installation and management utilities, and ready-to-install packages of common UNIX tools
- The first distributions managed these packages by simply providing a means of unpacking all the files into the appropriate places; modern distributions include advanced package management
- Early distributions included SLS and Slackware
  - Red Hat and Debian are popular distributions from commercial and noncommercial sources, respectively
- The RPM Package file format permits compatibility among the various Linux distributions

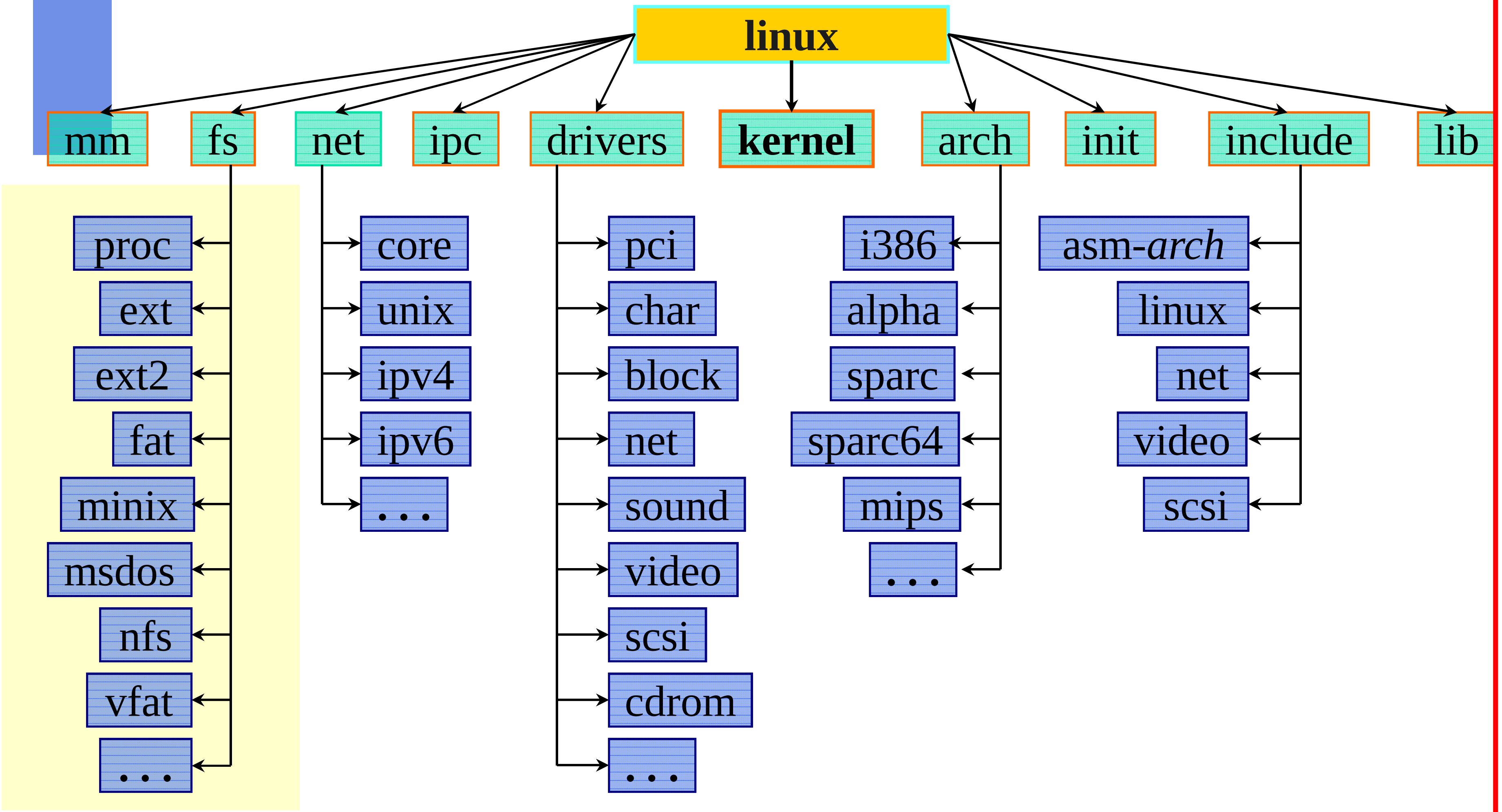
Linux Licensing

- The Linux kernel is distributed under the GNU General Public License (GPL), the terms of which are set out by the Free Software Foundation
- Anyone using Linux, or creating their own derivative of Linux, may not make the derived product proprietary; software released under the GPL may not be redistributed as a binary-only product

Design Principles

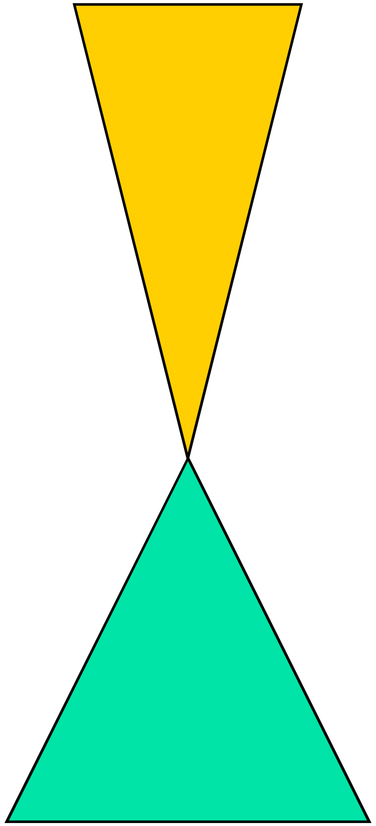
From Athanasios E. Papathanasiou

src Directory Structure



First View onto Linux

- Principles and Policies
- Mechanisms
- Algorithms
- Data Structures
- No Details
- Notions
- System Architecture
- Association of Ideas



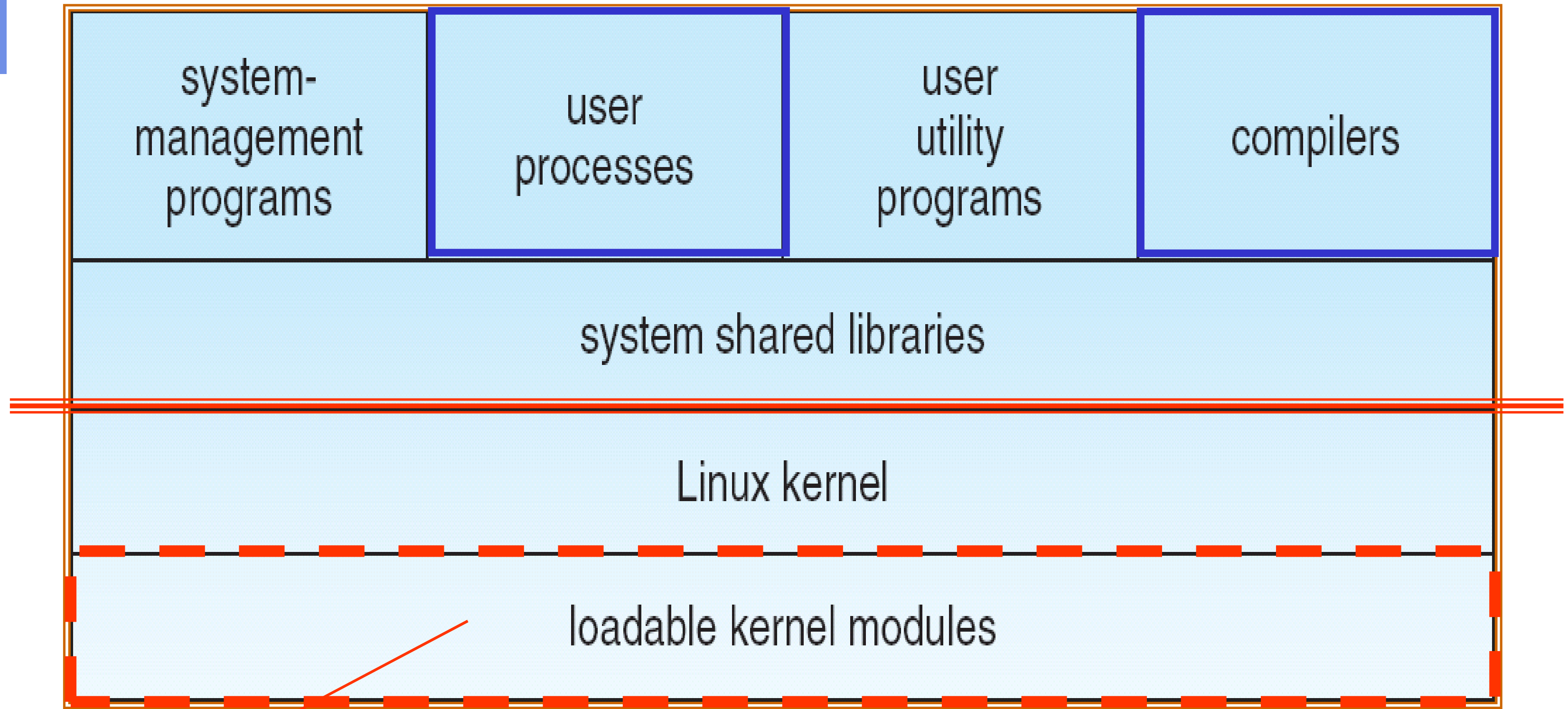
Design Principles 1

- Linux is a
  - Multi-User system
  - Multi-Tasking system with
  - A full set of UNIX-compatible tools
- Its FS adheres to traditional UNIX semantics, and it implements the standard UNIX networking model
- Main design goals have been:
  - Speed
  - Efficiency
  - Standardization

Design Principles 2

- Linux is compliant with the POSIX standards; two Linux distributions have achieved the official POSIX certification
- Linux programming interface adheres to SVR4 UNIX semantics, rather than to BSD behavior

Components of a Linux System

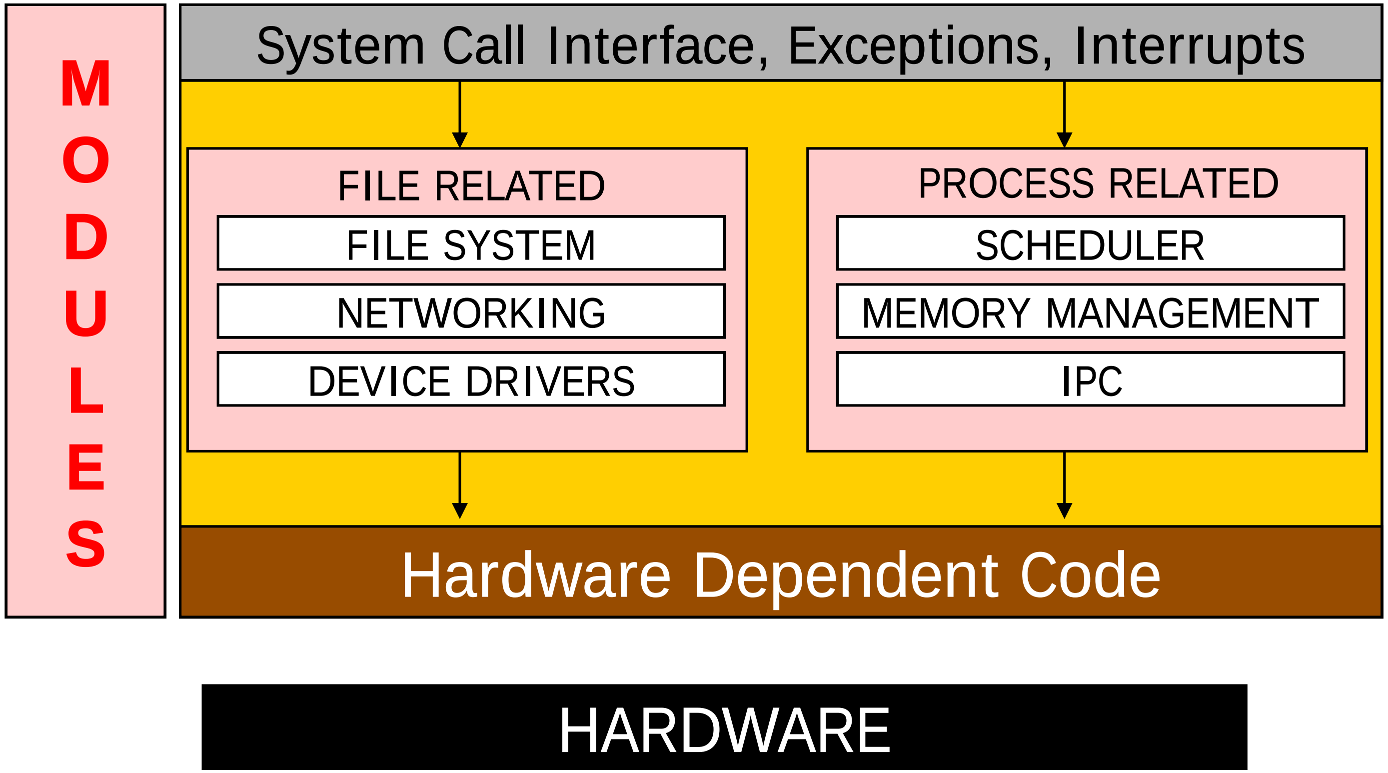


When loaded, then into the kernel AS

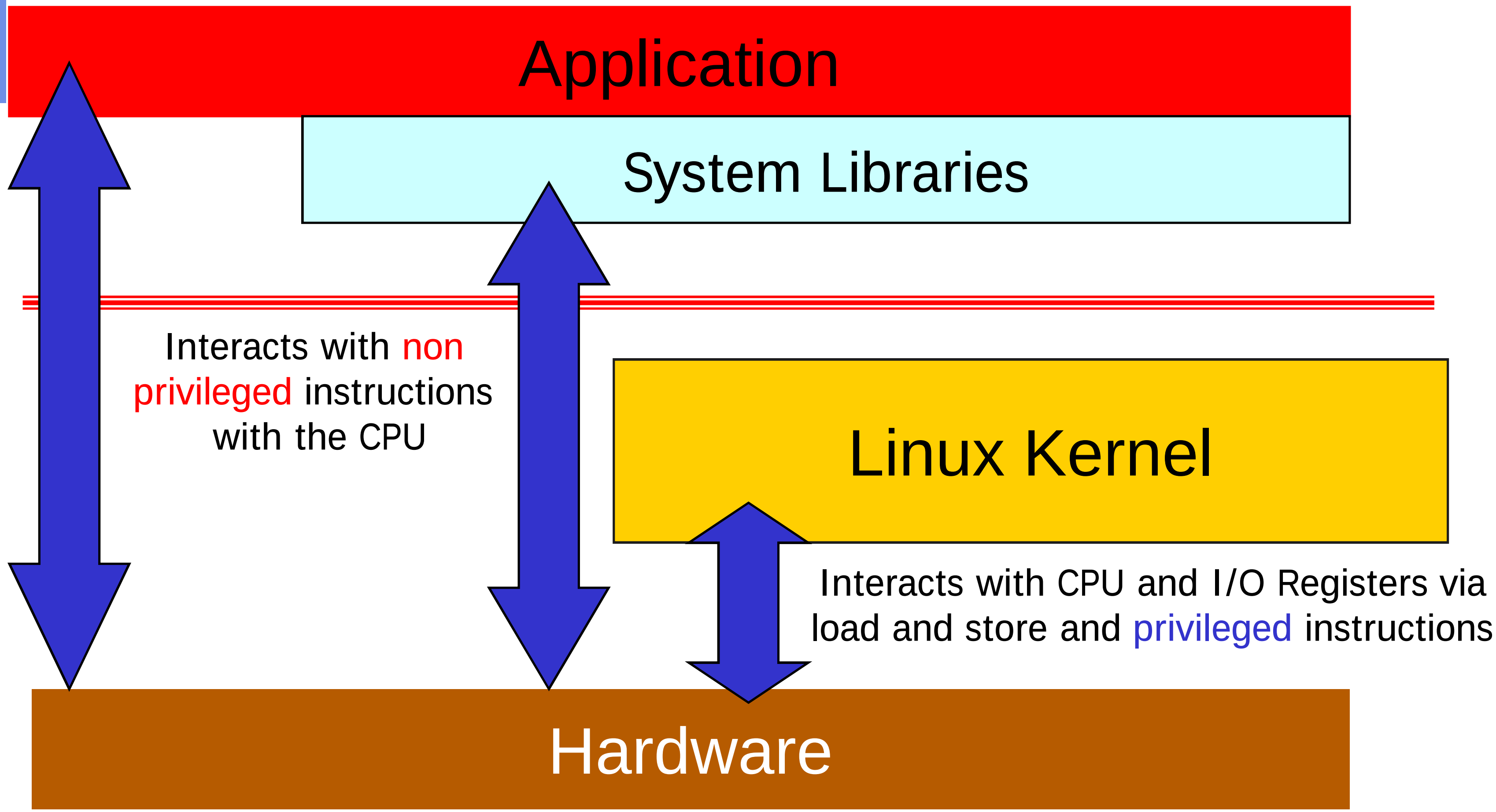
Linux Components

- Kernel (see next slides)
- System libraries = standard set of functions
  1. applications use to interact with the kernel
  2. Implementing some system services without interacting with the kernel
- System utilities perform individual specialized management tasks

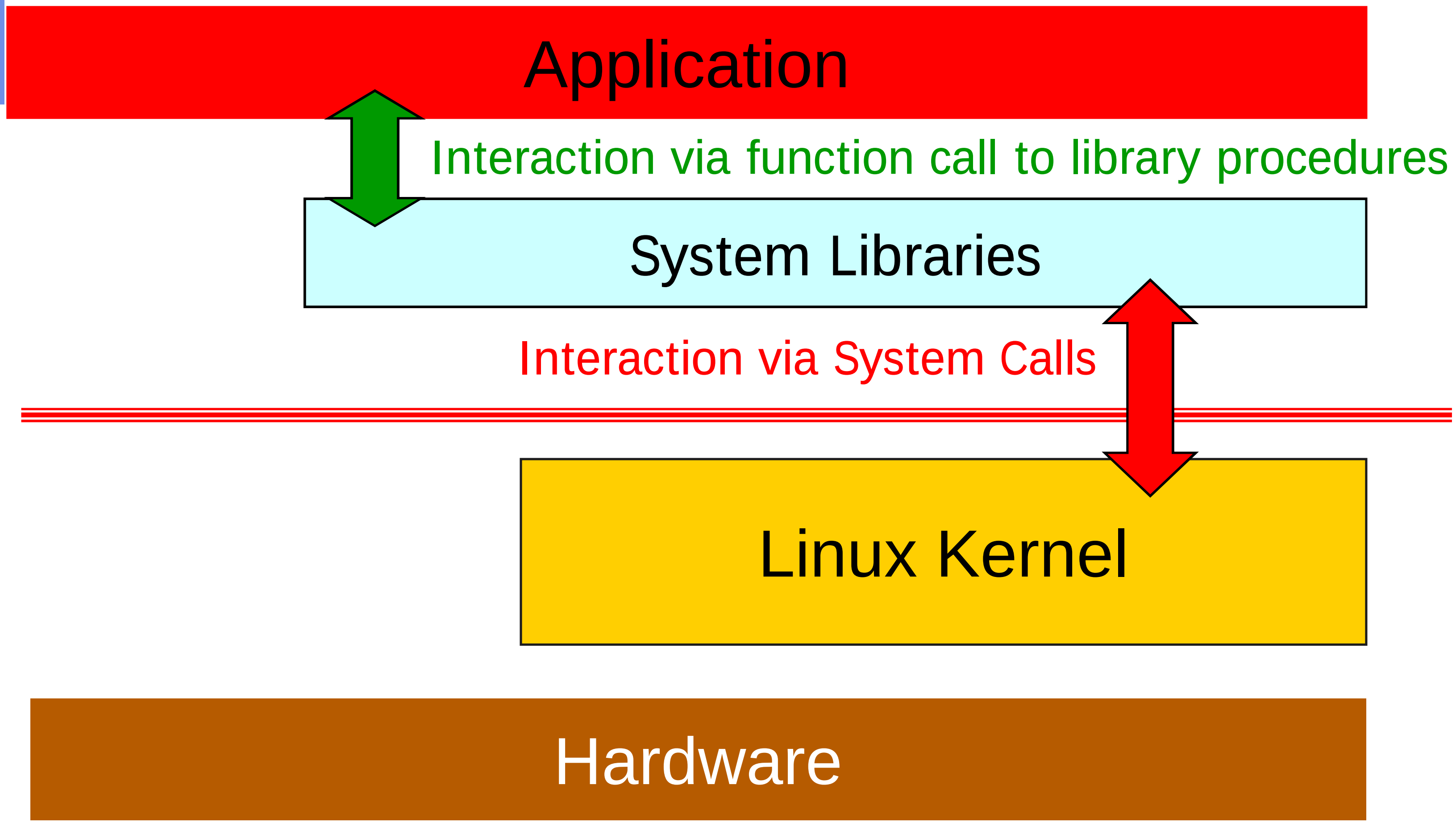
Core Kernel


MODULES
System Call Interface, Exceptions, Interrupts
FILE RELATED
FILE SYSTEM
NETWORKING
DEVICE DRIVERS
PROCESS RELATED
SCHEDULER
MEMORY MANAGEMENT
IPC
Hardware Dependent Code
HARDWARE

Interaction of System Components



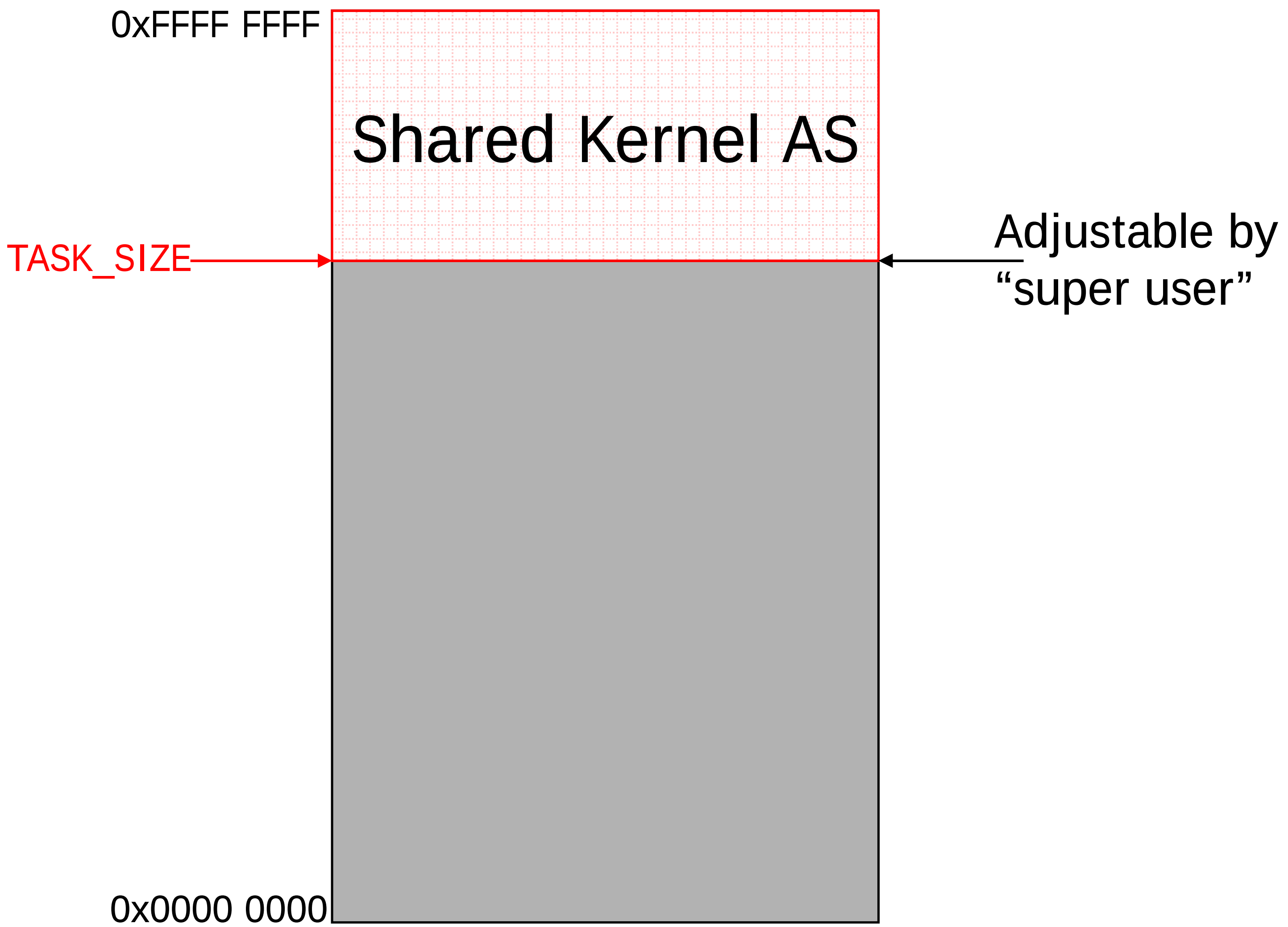
Interactions of System Components



Linux Kernel

- Two main abstractions of the system
  - Process (task)
  - File
- Only kernel executes in kernel mode with
  - full access to all physical resources and
  - allowed to execute all CPU instructions
- Kernel code & kernel data structures are kept in one single kernel address space KAS

User & Kernel Address Space



Kernel Modules

- Sections of kernel code that can be compiled, loaded, and unloaded independent of the rest of the kernel
- A kernel module typically implements
  - device driver
  - file system
  - networking protocol
  - ...
- Module interface allows third parties to write and distribute, on their own terms, e.g.
  - device drivers or
  - file systems

  that could not be distributed under the GPL

Kernel Modules (2)

- Kernel modules allow a Linux system to be set up with a standard, "minimal" kernel, without any extra device drivers built in

- Three components to Linux module support:
  - module management
  - driver registration
  - conflict resolution

Module Management

- Supports loading modules into memory and letting them interact with the rest of the kernel
- Module loading is split into two separate sections:
  - Managing sections of module code in kernel memory
  - Handling symbols that modules are allowed to reference
- The module requestor manages the loading of requested, but currently unloaded, modules
- It also regularly queries the kernel to see whether a dynamically loaded module is still in use, and will unload it when it is no longer actively needed

Driver Registration

- Allows modules to tell the rest of the kernel that a new driver has become available
- Kernel maintains dynamic tables of all known drivers, and provides a set of routines to allow drivers to be added to or removed from these tables at any time
- Registration tables include the following items:
  - Device drivers
  - File systems
  - Network protocols
  - Binary format

Conflict Resolution

- A mechanism that allows different device drivers to reserve hardware resources and to protect those resources from accidental use by another driver
- The conflict resolution module aims to:
  - Prevent modules from clashing over access to hardware resources
  - Prevent autoprobes from interfering with existing device drivers
  - Resolve conflicts with multiple drivers trying to access the same hardware

Summary on Kernel Modules

- Many kernel modules are written in C/C++ $\Rightarrow$ huge risk for the safety of the kernel
  - All modules share one and only one KAS
  - It's common to produce severe software bugs within these kernel modules, i.e.
  - System crashes are pre-programmed
- Added value of extensibility is lost due to the risk of increased insecurity
- If you are interested in a critical comment on extensible kernels, read the paper of P. Druschel

UNIX/Linux Process Management

- The UNIX process management separates the creation of processes and the running of a new program into two distinct system cals
  - The **`fork`** system call creates a new process
  - The new program is run after the system call **`execve`**
- Under UNIX, a process encompasses all the information that the OS must maintain to track the context of a single execution of a single program
- Under Linux, process properties fall into three groups:
  - Process identity
  - Process environment
  - Process context

Process Identity

- Process ID (PID): The unique identifier for the process; used to specify processes to the operating system when an application makes a system call to signal, modify, or wait for another process

- Credentials: Each process must have an associated user ID and one or more group IDs that determine the process's rights to access system resources and files

- Personality: Not traditionally found on UNIX systems, but under Linux each process has an associated personality identifier that can slightly modify the semantics of certain system calls
  - Used primarily by emulation libraries to request that system calls be compatible with certain specific flavors of UNIX

Process Environment

- Process's environment is inherited from its parent, and is composed of two null-terminated vectors:
  - Argument vector lists command-line arguments used to invoke the running program (starts with the name of the program itself)
  - Environment vector is a list of "NAME=VALUE" pairs that associates named environment variables with arbitrary textual values
- Passing environment variables among processes and inheriting variables by a process's children are flexible means of passing information to components of the user-mode system software
- The environment-variable mechanism provides a customization of the OS that can be set on a per-process basis, rather than being configured for the system as a whole

At least some flexibility

Process Context

- Context is the internal state of a running program at any point in time
- Scheduling context is the relevant part of the PCB the scheduler needs to suspend and restart the process
- Kernel maintains accounting information about the resources currently being consumed by each process, and the total resources consumed by the process in its lifetime so far
- The file table is an array of “pointers” (~capabilities) to kernel file structures
  - When making file I/O system calls, processes refer to files by their index into this table

Process Context (Cont.)

- Whereas the file table lists the existing open files, the file-system context applies to requests to open new files
  - The current root and default directories to be used for new file searches are stored here
- Signal-handler table defines the routine in the process's AS to be called when specific signals arrive
- Virtual-memory context of a process describes the full contents of the its private address space

Processes and Threads

- Linux uses same internal representation for threads and processes; a thread is simply a new process that happens to share the same AS as its parent
- A distinction is only made when a new thread is created by the **`clone()`** system call
  - **`fork()`** creates a new process with its own entirely new process context
  - **`clone()`** creates a "new process" with its own identity, but that is allowed to share the data structures of its parent
- **`clone()`** gives an application fine-grained control over exactly what is shared between caller and callee

Traditionaal Unix versus Solaris

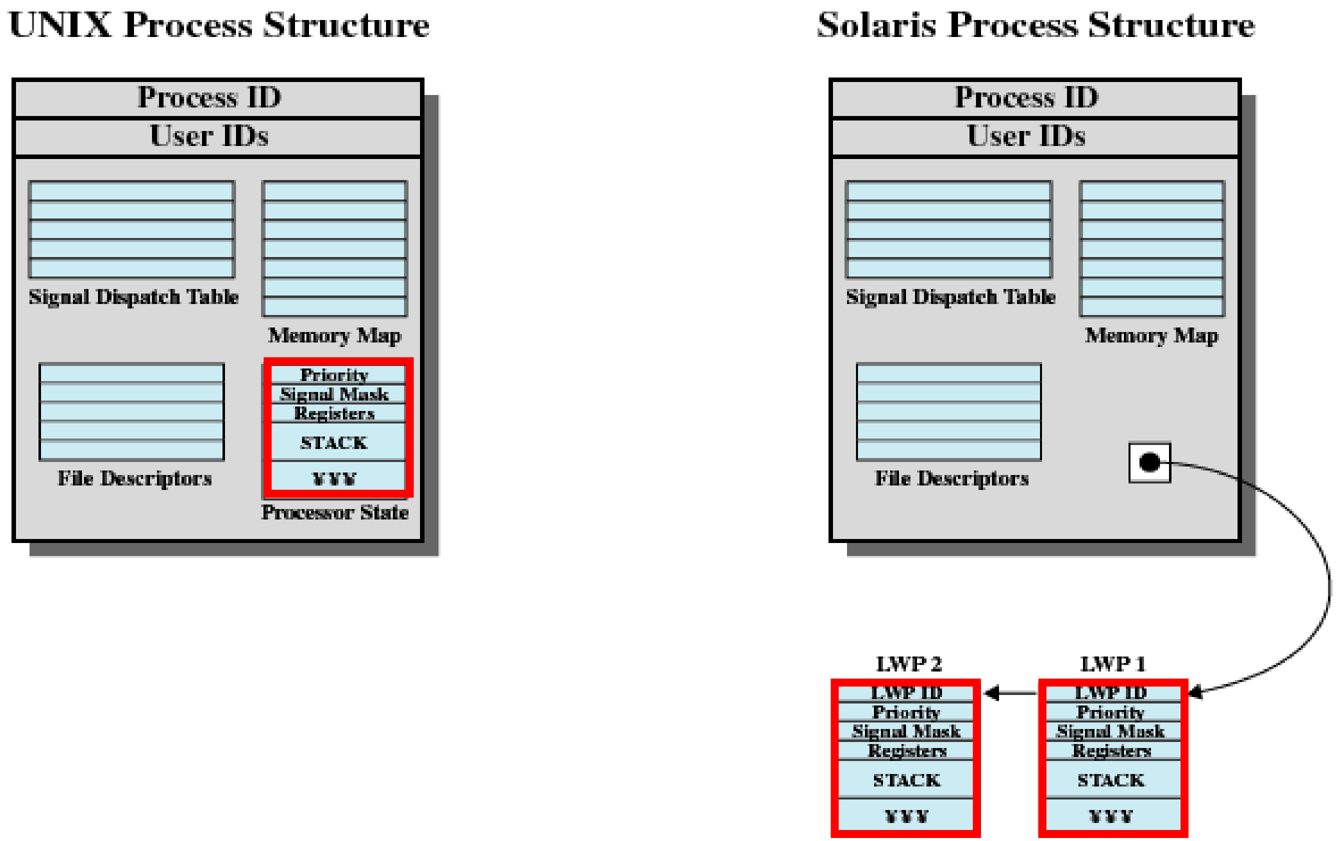


Figure 4.16 Process Structure in Traditional UNIX and Solaris [LEWI96]

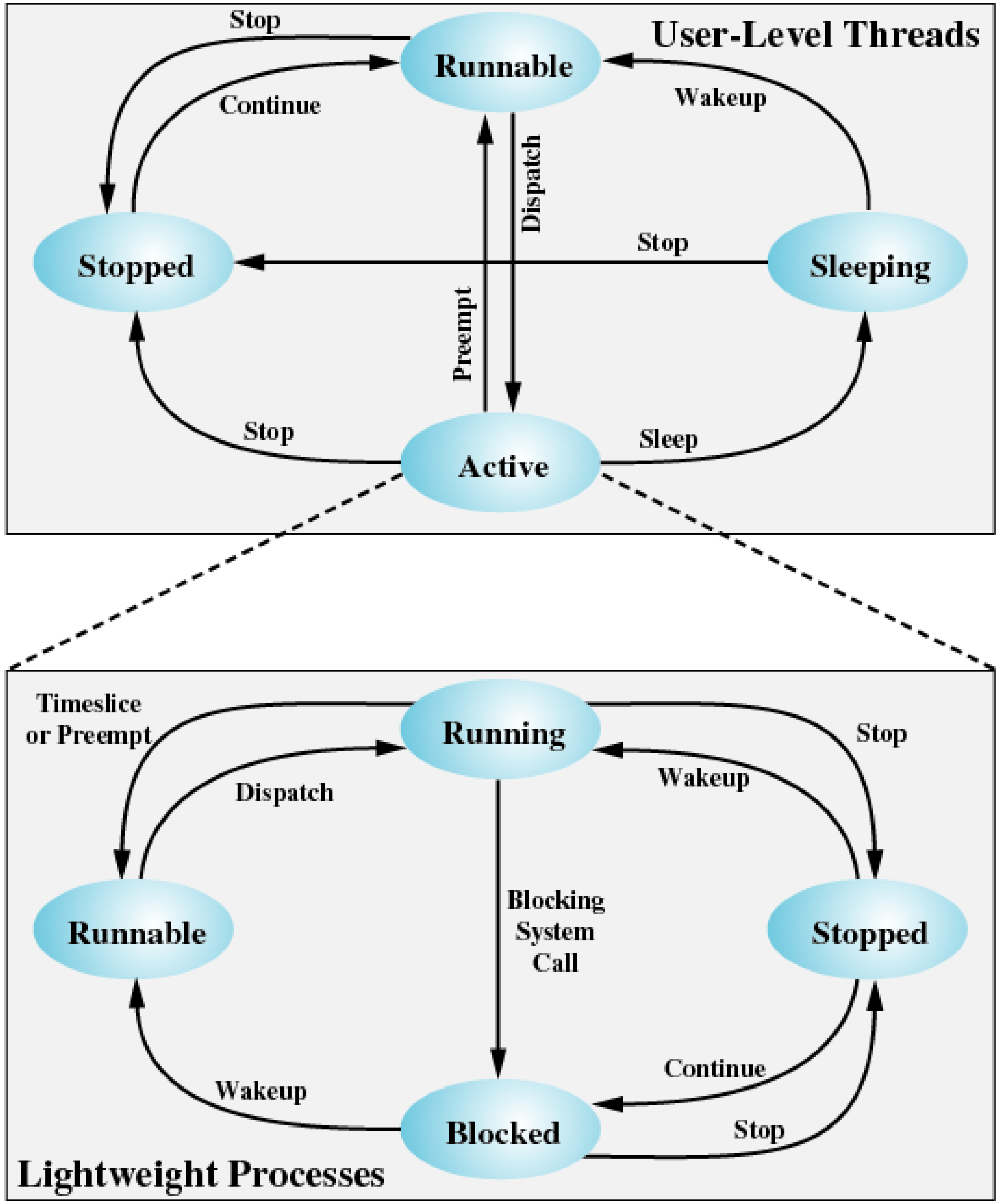


Figure 4.17 Solaris User-Level Thread and LWP States

Linux Process/Thread States

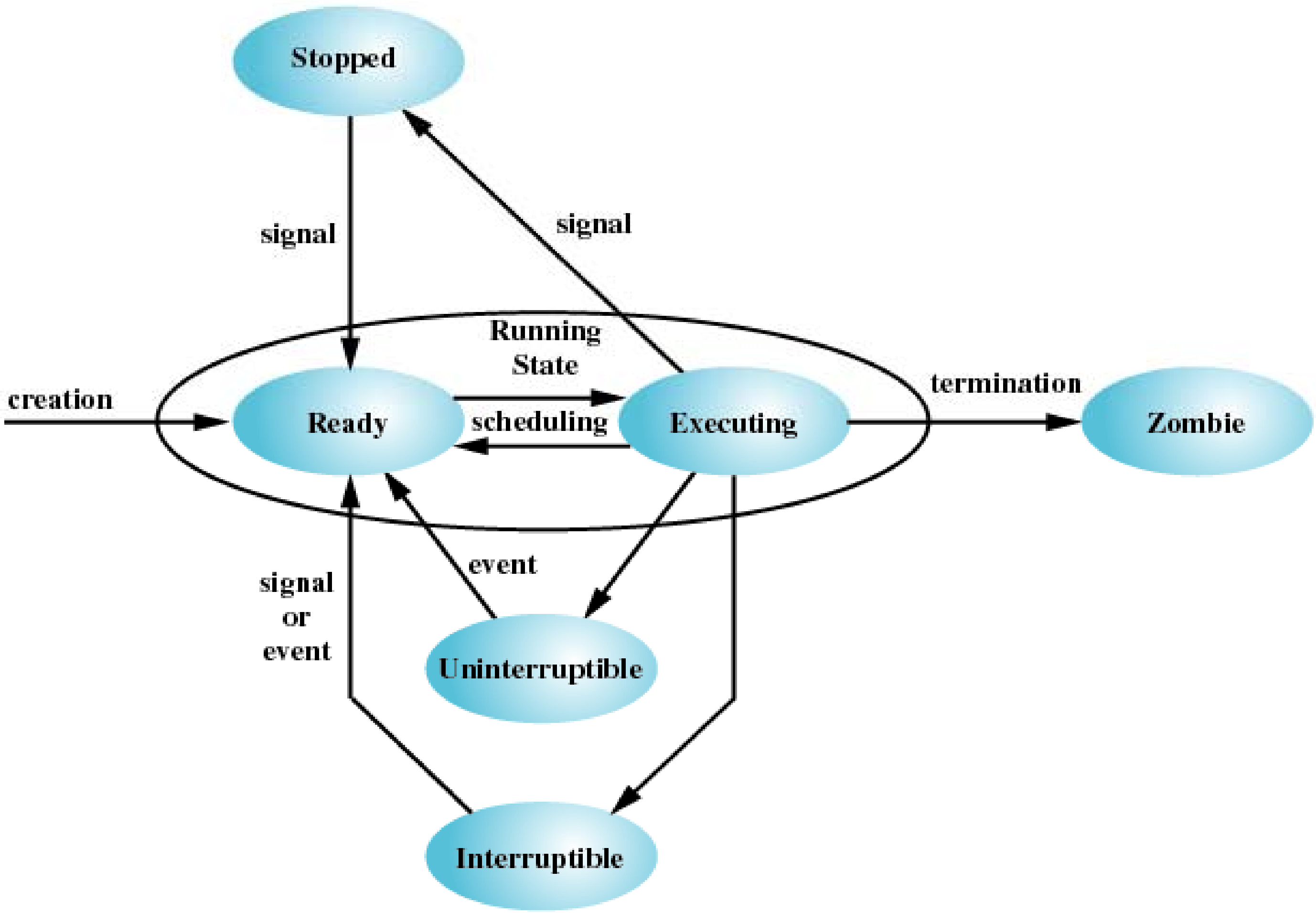
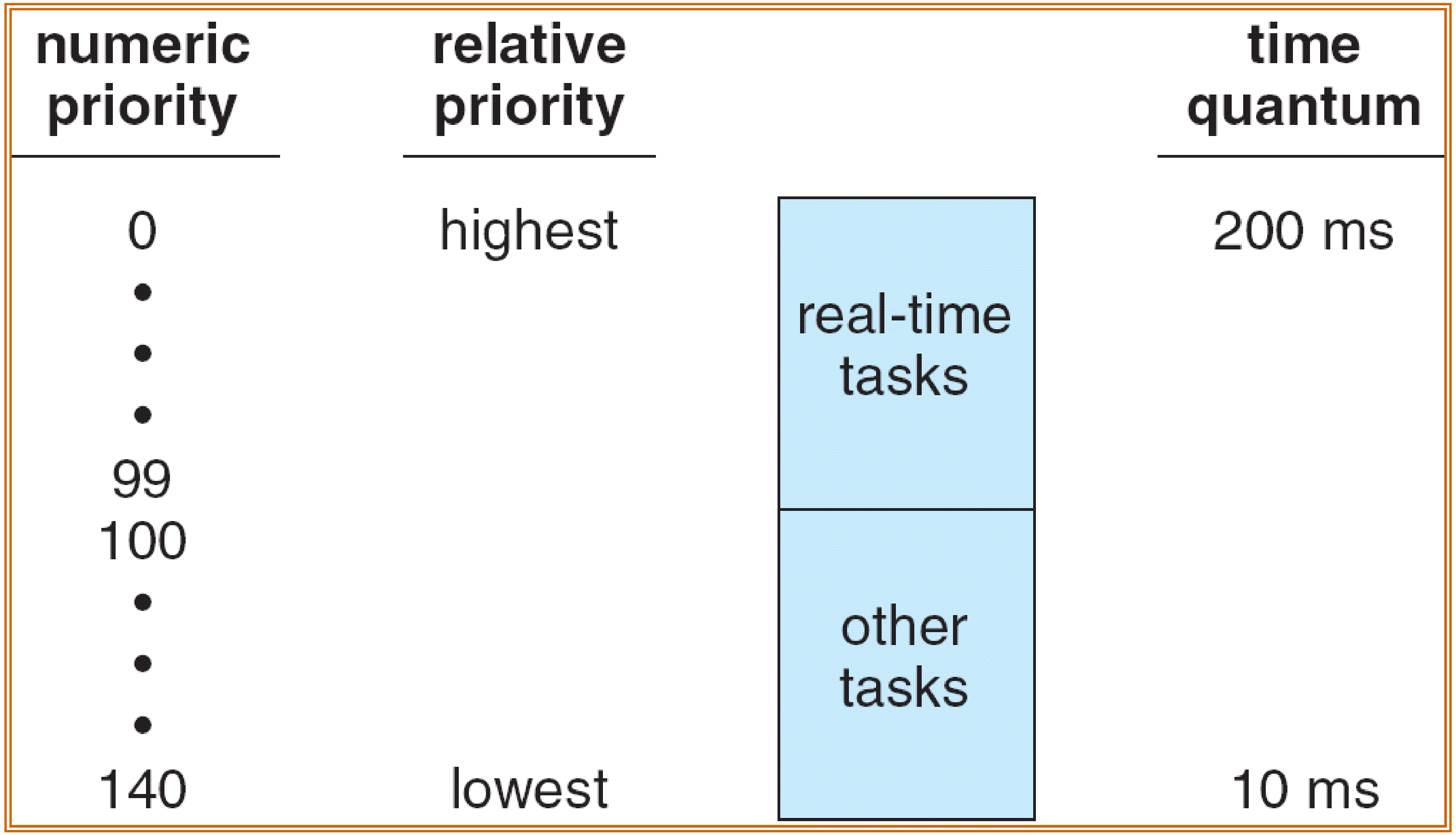


Figure 4.18 Linux Process/Thread Model

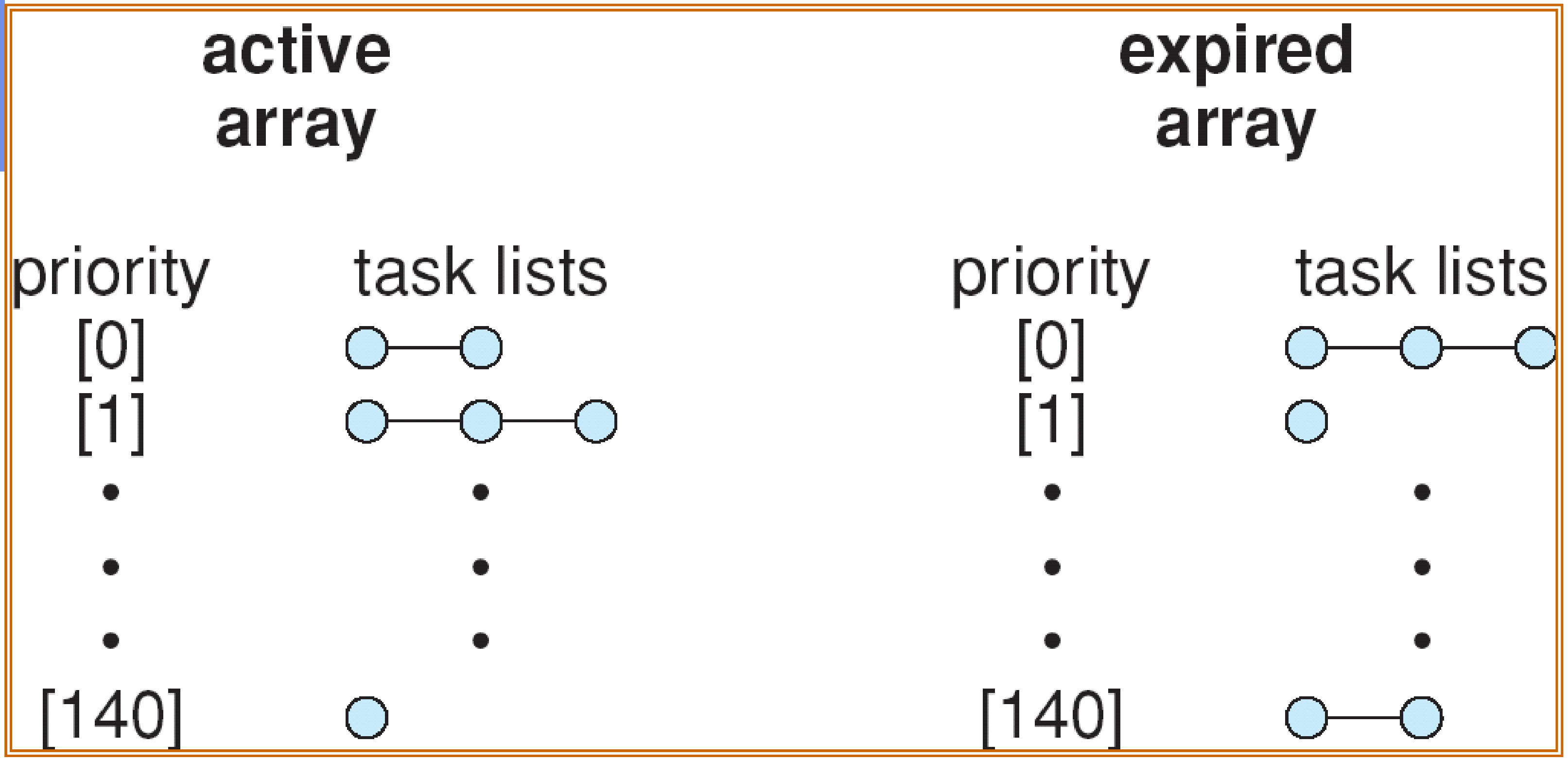
Scheduling

- While scheduling is normally thought of as the running and interrupting of application processes, in Linux, scheduling also includes the running of the various kernel activities
- Running kernel activities encompasses both tasks that are requested by a running process and tasks that execute internally on behalf of a device driver
- As of 2.5, new scheduling algorithm – preemptive, priority-based
  - real-time range
  - nice value

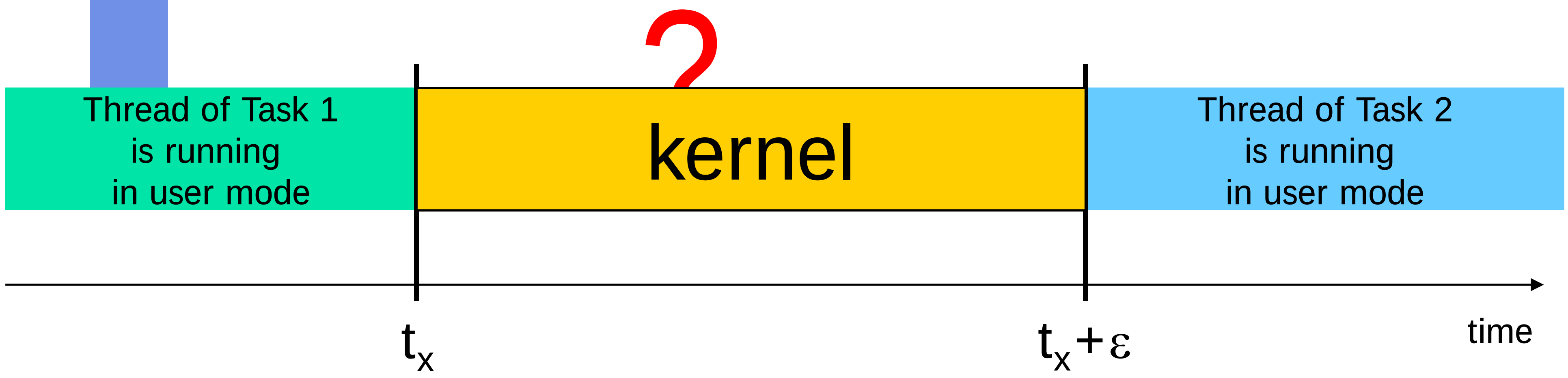
Relationship between Priority and TS-Length



List of Tasks Indexed by Priority



Process/Task Switch



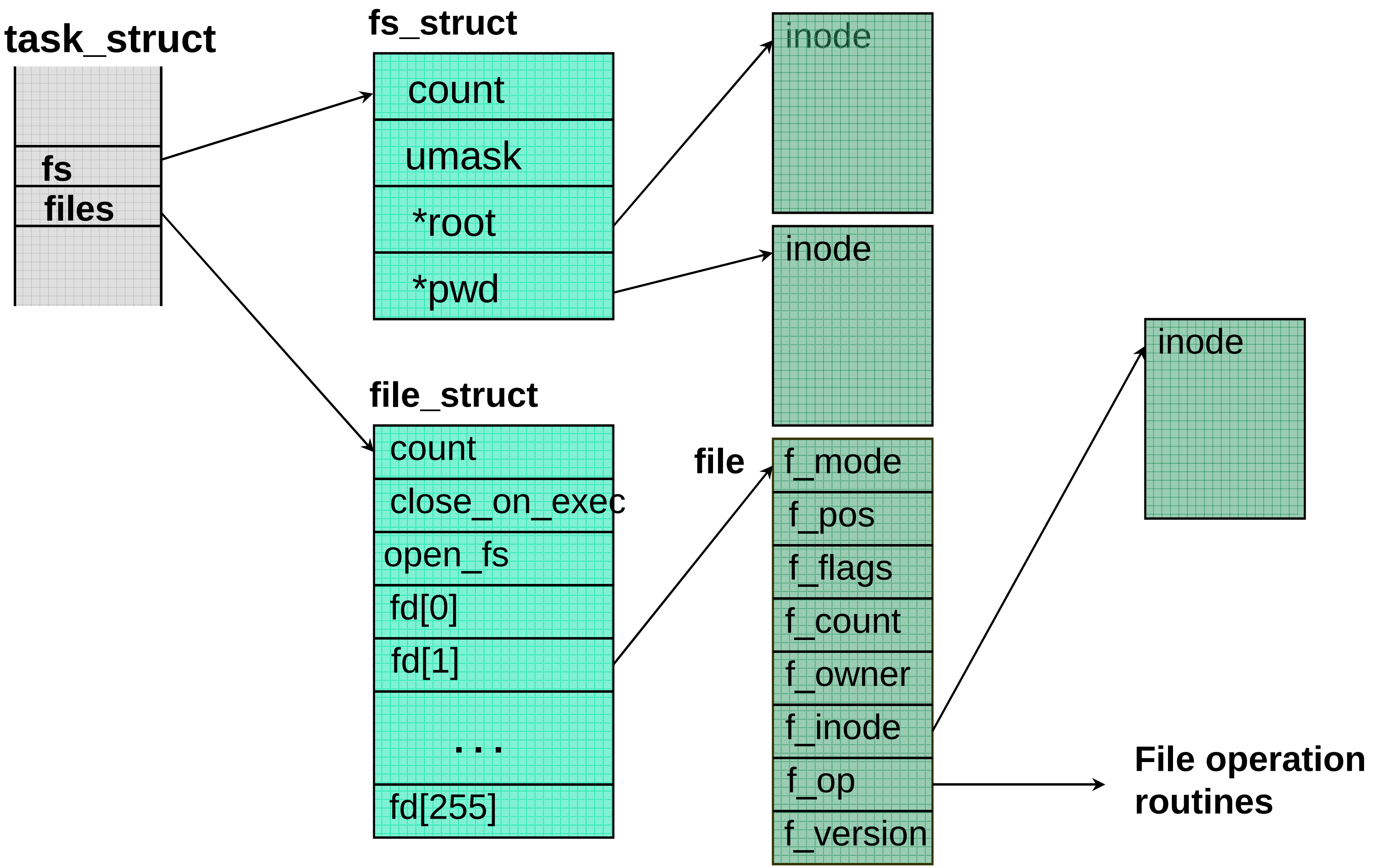
1. *What events trigger t_x?*
2. *Who switches system from user mode to kernel mode?*
3. *Who is selecting a thread of task 2?*
4. *How long does it take to switch from task 1 to task 2?*
5. *Where to continue or begin within task 2?*

Main Data Structures

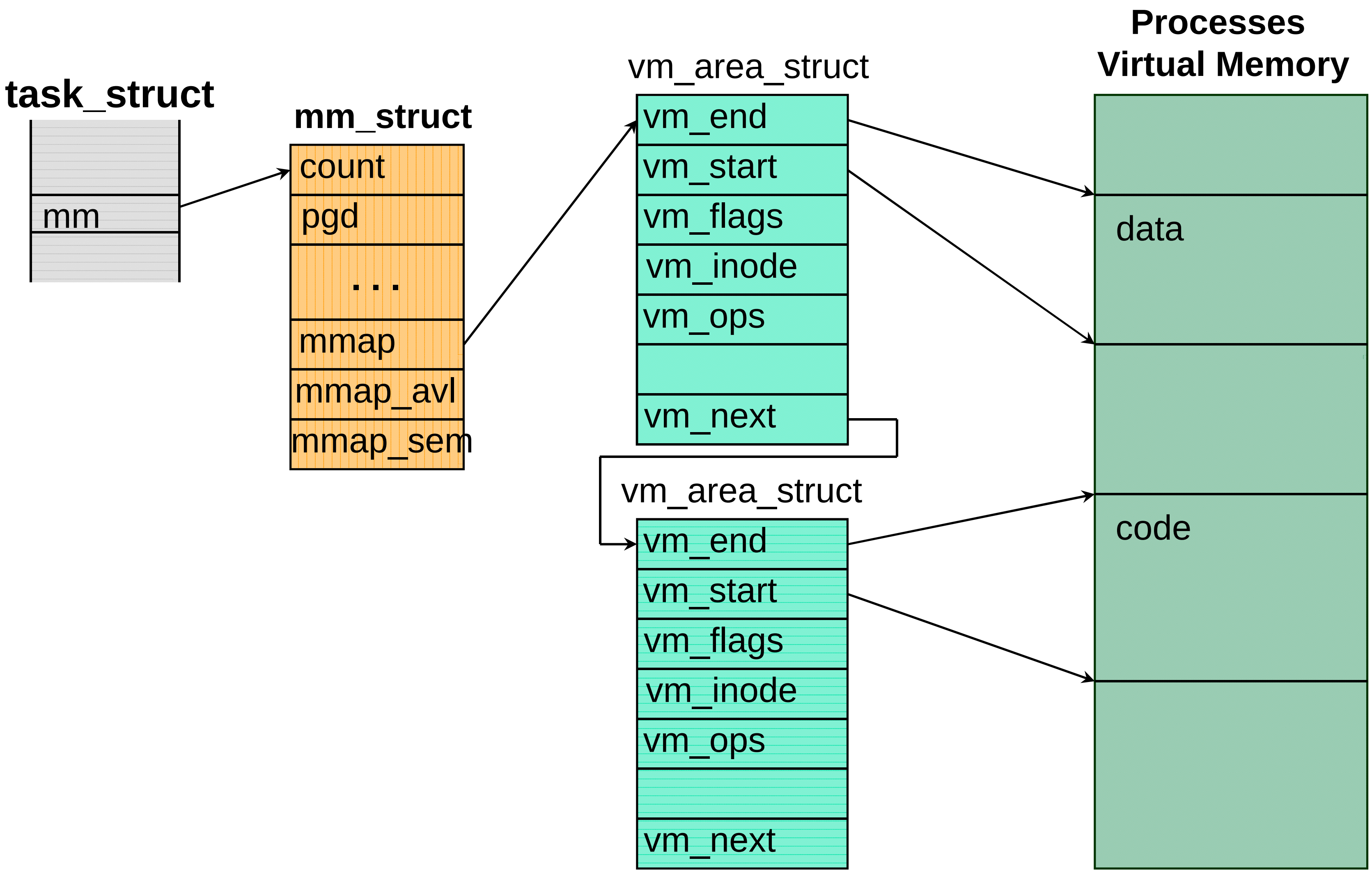
- The task structure (.../linux/sched.h)

```
struct task_struct {
     volatile long state; . . .
     long counter;
     long priority; . . .
     /* smp */
     int has_cpu (?); int processor; int last_processor
     struct task_struct *next_struct, *prev_struct;
     /* relationships */
     struct task_struct
     *p_opptr, *p_pptr, *p_cptr, *p_ysptr, *p_osptr; . . .
     /* memory */
     struct mm_struct *mm; . . .
     /* VFS - umask */
     struct fs_struct *fs;
     /* files */
     struct files_struct *files;
     };
```

Task Data Structure and Files



Task Data Structure: Memory



Kernel Synchronization

- Request for kernel-mode execution can occur in two ways:
  - A running program may request an OS service,
    - either explicitly via a system call
    - or implicitly, for example, when a page fault occurs
  - A device can deliver a hardware interrupt that causes the CPU to start executing a kernel-defined interrupt handler

- Kernel synchronization requires a framework that will allow the kernel's critical sections to run without interruption by another critical section

Kernel Synchronization (Cont.)

- Linux uses two techniques to protect critical sections:

  1. Normal kernel code is non preemptible (until 2.4)
     – when a time interrupt is received while a process is executing a kernel system service routine, the kernel's **need_resched** flag is set so that the scheduler will run once the system call has completed and control is about to be returned to user mode

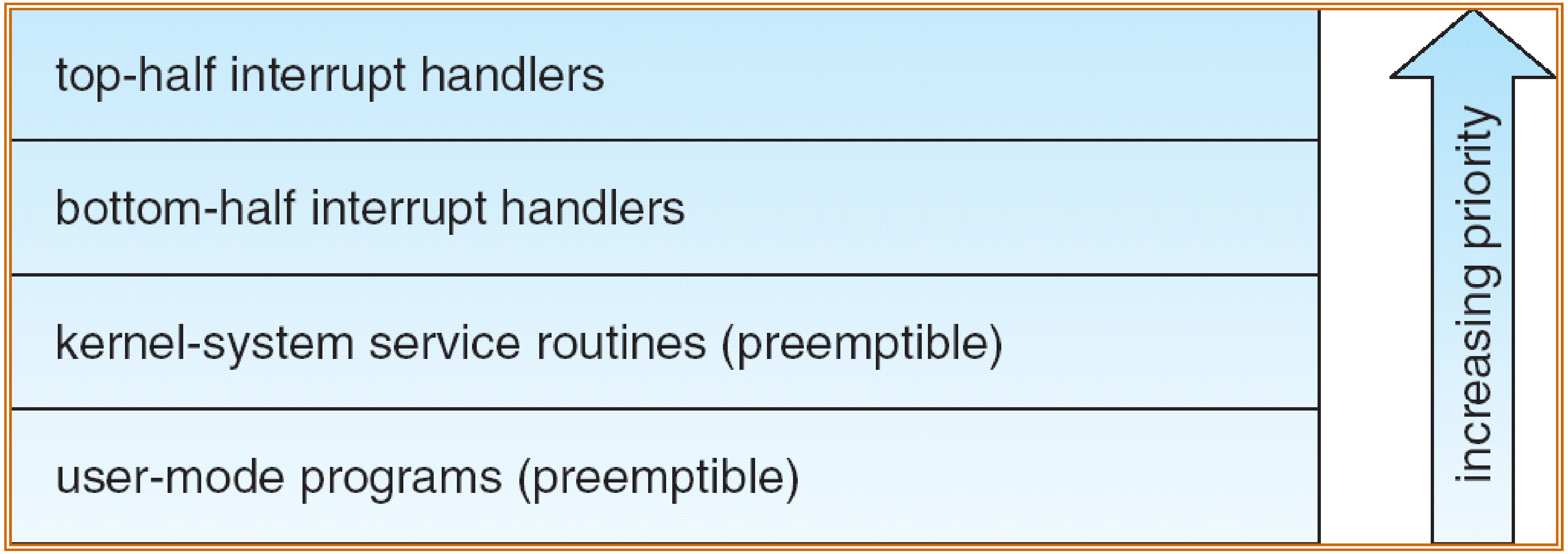
  2. The second technique applies to critical sections that occur in an interrupt service routines
     – By using the processor's interrupt control hardware to disable interrupts during a critical section, the kernel guarantees that it can proceed without the risk of concurrent access of shared data structures

Kernel Synchronization (Cont.)

- To avoid performance penalties, Linux's kernel uses a synchronization architecture that allows long critical sections to run without having interrupts disabled for the critical section's entire duration

- Interrupt service routines are separated into a top half and a bottom half.
  - The top half is a normal interrupt service routine, and runs with recursive interrupts disabled
  - The bottom half is run, with all interrupts enabled, by a miniature scheduler that ensures that bottom halves never interrupt themselves
  - This architecture is completed by a mechanism for disabling selected bottom halves while executing normal, foreground kernel code

Interrupt Protection Levels



- Each level may be interrupted by code running at a higher level, but will never be interrupted by code running at the same or a lower level
- User processes can always be preempted by another process when a time-sharing scheduling interrupt occurs

Process Scheduling

- Linux uses two separate scheduling algorithms:
  - A time-sharing algorithm for fair preemptive scheduling between multiple processes
  - A real-time algorithm for tasks where absolute priorities are more important than fairness
- A process's scheduling class defines which algorithm to apply
- For time-sharing processes, Linux uses a prioritized, credit based algorithm
  - The crediting rule
  - $$\text{credits} := \frac{\text{credits}}{2} + \text{priority}$$

    factors in both the process's history and its priority
  - This crediting system automatically prioritizes interactive or I/O-bound processes

Process Scheduling (Cont.)

- Linux implements the FIFO and round-robin real-time scheduling classes; in both cases, each process has a priority in addition to its scheduling class
  - The scheduler runs the process with the highest priority; for equal-priority processes, it runs the process waiting the longest
  - FIFO processes continue to run until they either exit or block
  - A round-robin process will be preempted after a while and moved to the end of the scheduling queue, so that round-robin processes of equal priority automatically time-share between themselves

Symmetric Multiprocessing

- Linux 2.0 was the first Linux kernel to support SMP hardware; separate processes or threads can execute in parallel on separate processors

- To preserve the kernel's non preemptible synchronization requirements, SMP imposes the restriction, via a single kernel spinlock, that only one processor at a time may execute kernel-mode code

- Newer versions allow preemptible kernels

Memory Management

- Linux’s physical memory-management system deals with allocating and freeing pages, groups of pages, and small blocks of memory

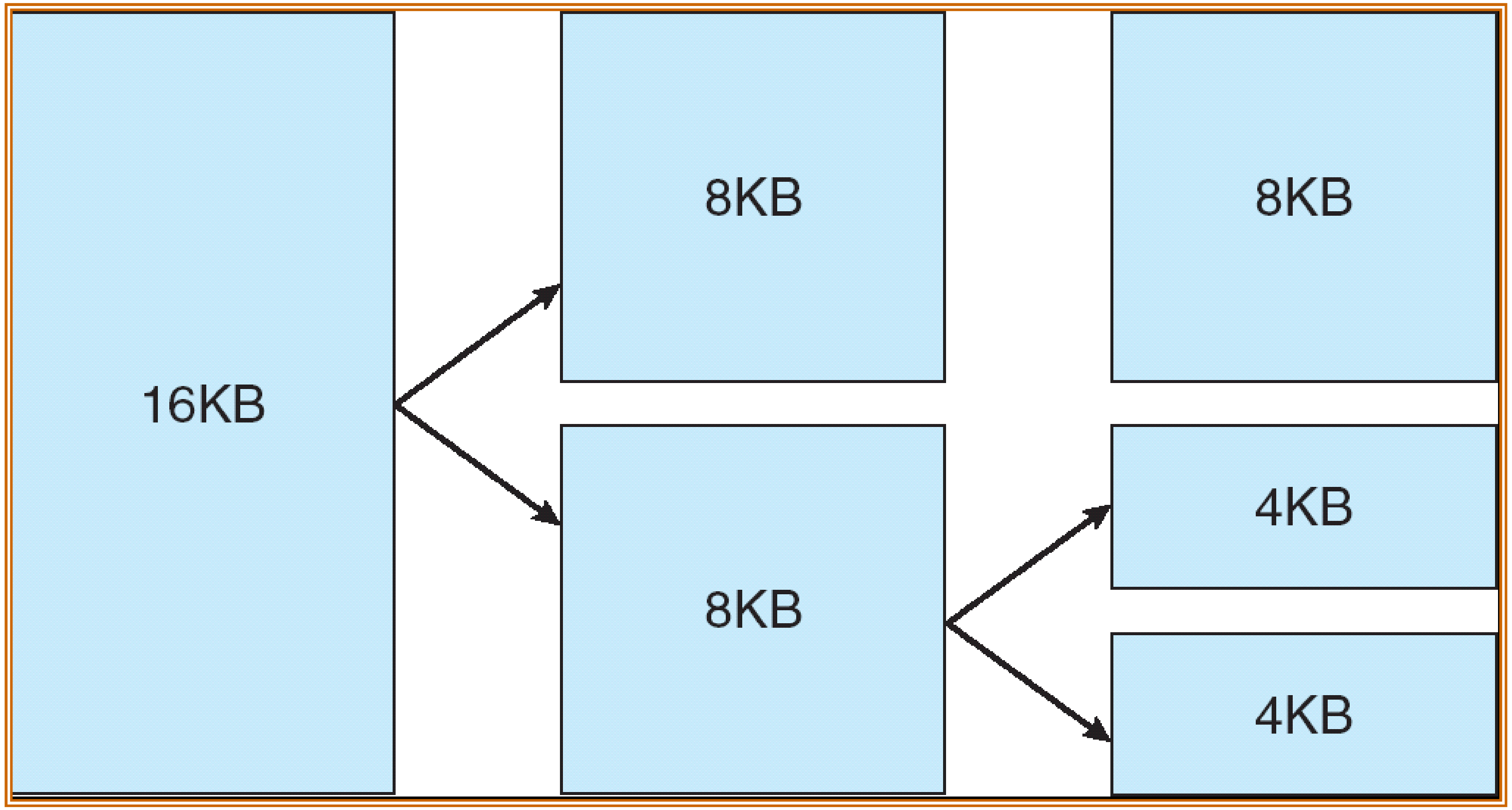
- It has additional mechanisms for handling virtual memory, memory mapped files into the address space of running processes

- Splits memory into three different zones due to hardware characteristics

Relationship of Zones and Physical Addresses on 80x86

zone	physical memory
ZONE_DMA	< 16 MB
ZONE_NORMAL	16 .. 896 MB
ZONE_HIGHMEM	> 896 MB

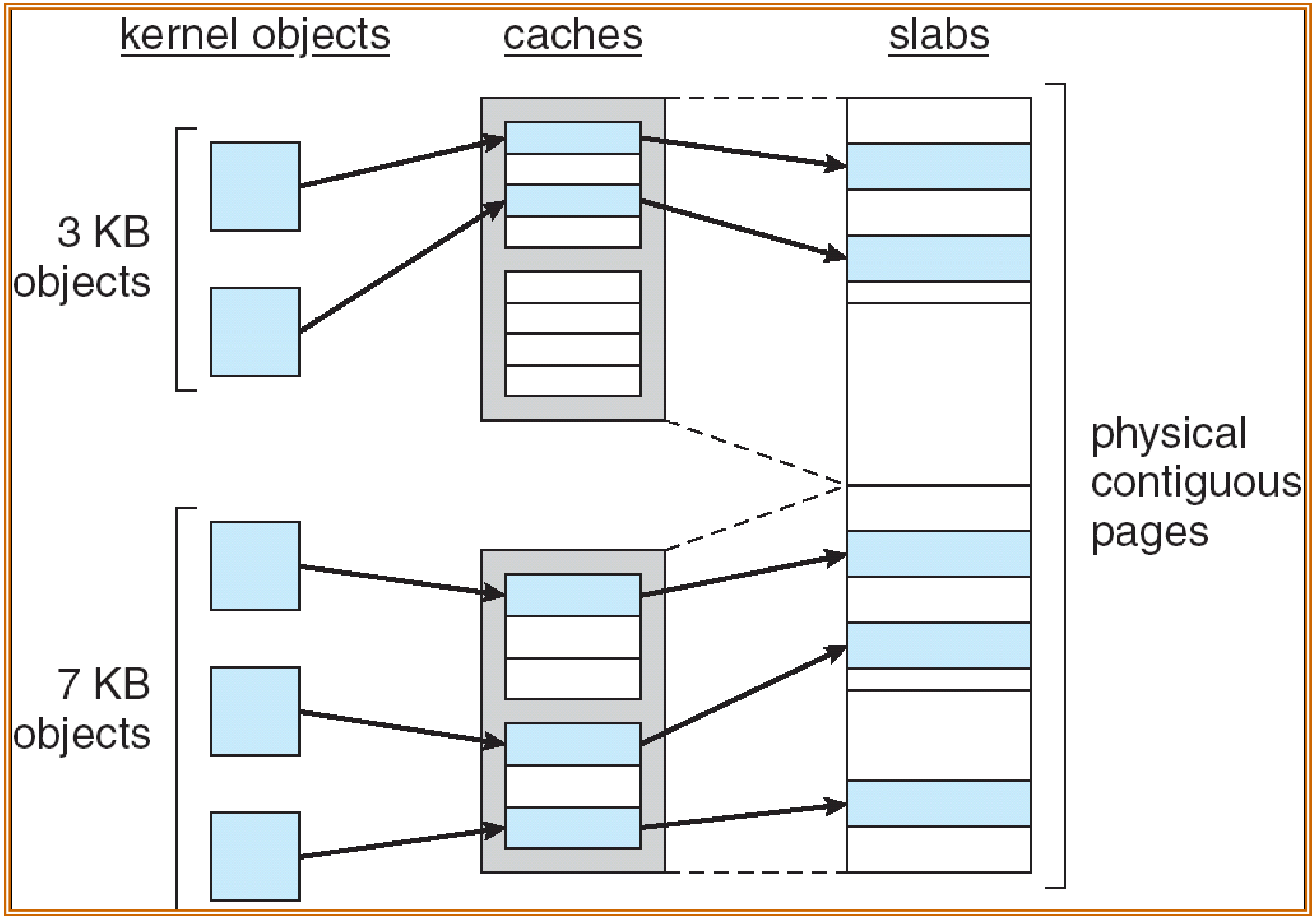
Splitting of Memory in a Buddy Heap



Managing Physical Memory

- The page allocator allocates and frees all physical pages; it can allocate ranges of physically-contiguous pages on request
- The allocator uses a buddy-heap algorithm to keep track of available physical pages
  - Each allocatable memory region is paired with an adjacent partner
  - Whenever two allocated partner regions are both freed up they are combined to form a larger region
  - If a small memory request cannot be satisfied by allocating an existing small free region, then a larger free region will be subdivided into two partners to satisfy the request
- Memory allocations in the Linux kernel occur either statically (drivers reserve a contiguous area of memory during system boot time) or dynamically (via the page allocator)
- Also uses slab allocator for kernel memory

21.07


kernel objects
caches
slabs
3 KB objects
7 KB objects
physical contiguous pages

Virtual Memory

- VM system maintains the AS visible to each process: it creates pages of virtual memory on demand, and manages the loading of those pages from disk or their swapping back out to disk as required

- VM manager maintains two separate views of a process's address space:
  - A logical view describing instructions concerning the layout of the address space
    - AS consists of a set of non overlapping regions, each one represents a continuous, page-aligned subset of the AS
  - A physical view of each AS which is stored in the hardware page tables for the process

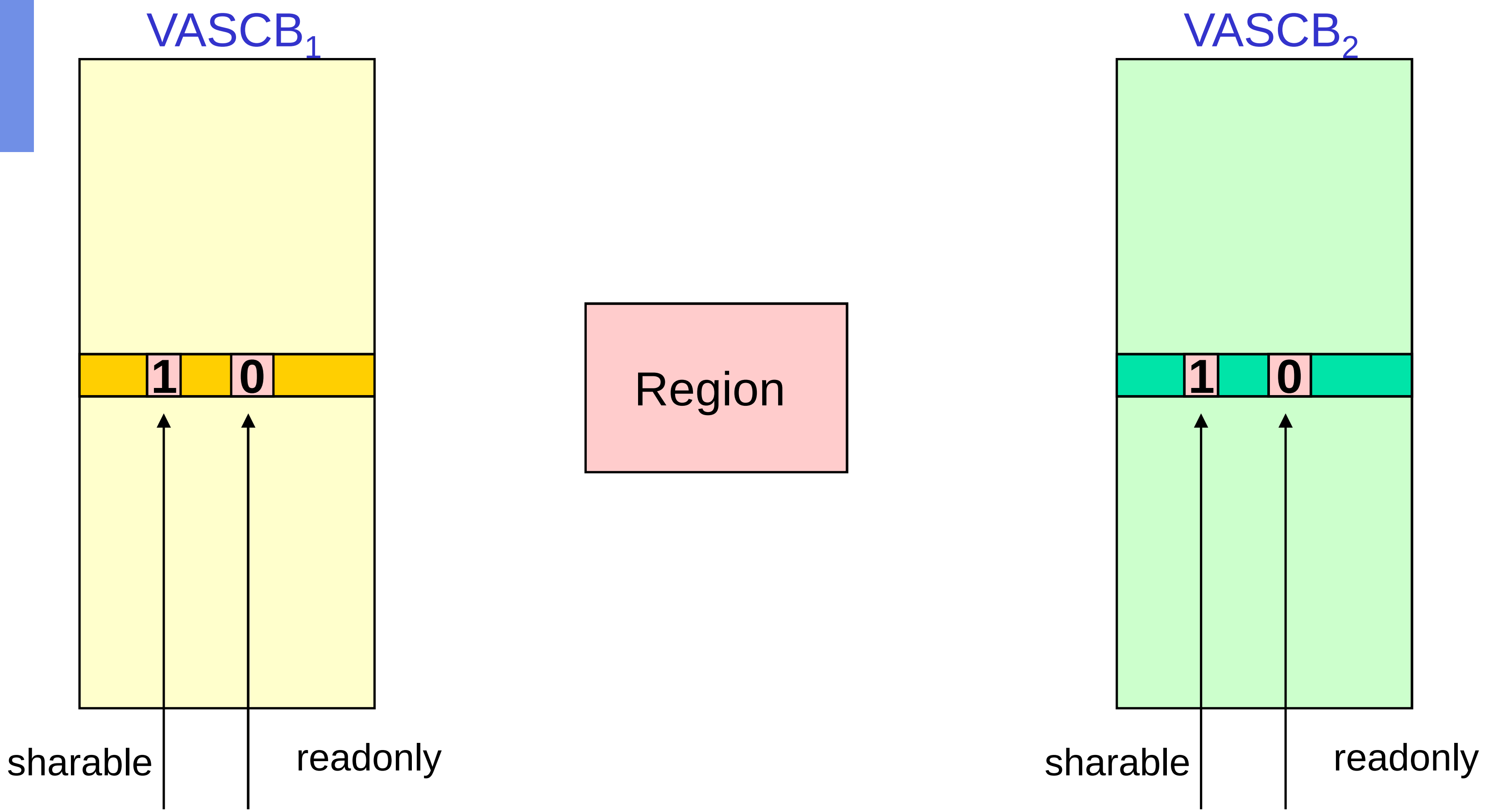
Virtual Memory (Cont.)

- Virtual memory regions are characterized by:
  - Backing store, which describes from where the pages for a region come
  - regions are usually backed by a file or by nothing (demand-zero memory)
  - The region's reaction to writes (explicit page sharing or copy-on-write)
- The kernel creates a new virtual AS
  1. When a process runs a new program via **`exec`**
  2. Upon creation of a new process by the **`fork`**

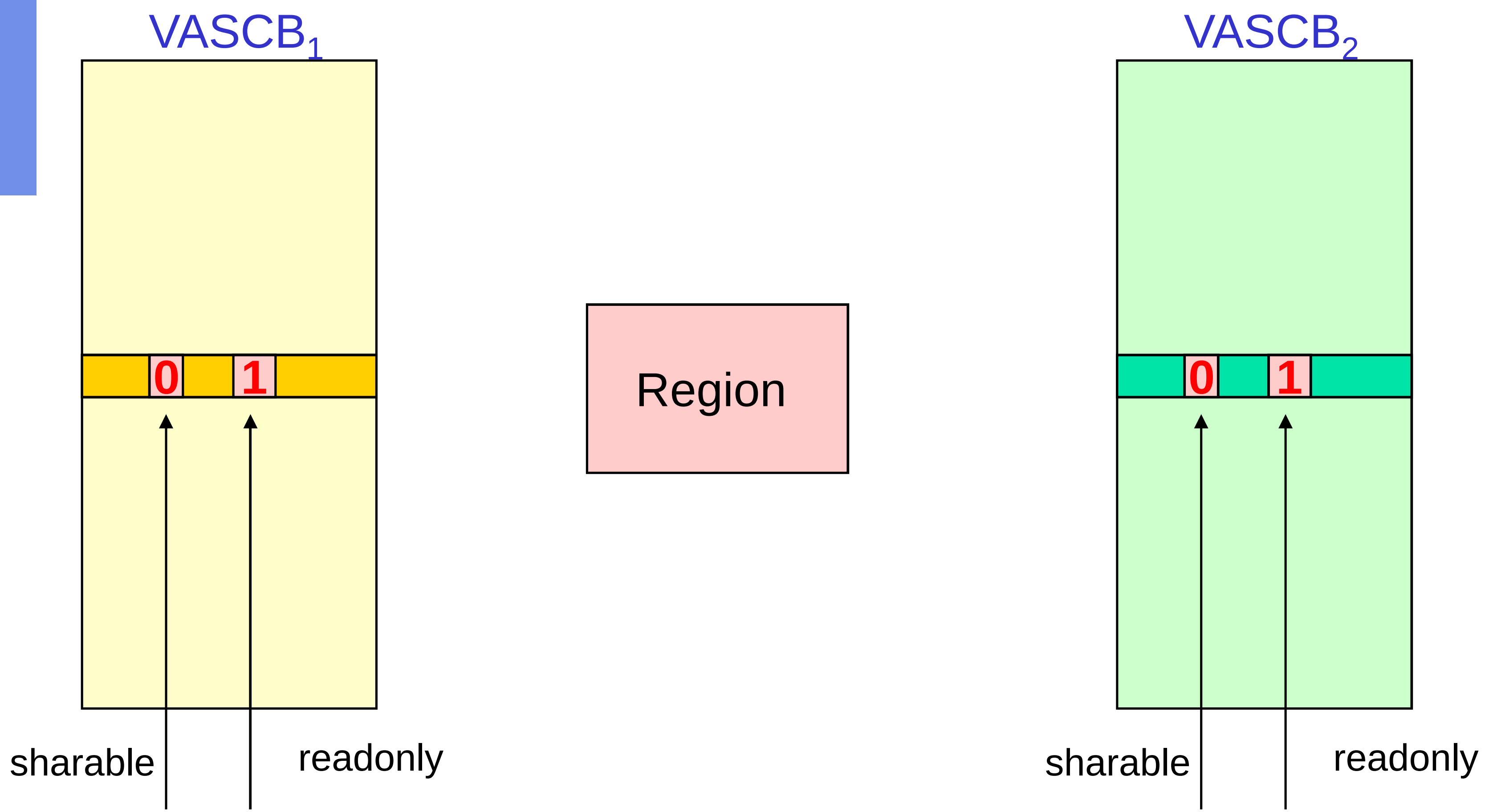
Virtual Memory (Cont.)

- On executing a new program, process is given a new, completely empty virtual AS; the program-loading routines populate the AS with virtual-memory regions
- Creating a new process with **`fork`** involves creating a "complete copy" of the existing process's virtual AS
  - kernel copies the parent process's VMA region descriptors, then creates a new set of page tables for the child
  - The parent's page tables are copied directly into the child with a incremented reference count of each page
  - After the fork, the parent and child share the same physical pages of memory in their address spaces
- How to avoid mutual overwriting? COPY ON WRITE

Shared Read-Write Region



Copy On Write Region



Writing to the region raises an exception ⇒ we need another control bit to distinguish between private read only and copy on write regions (pages)

Virtual Memory (Cont.)

- The VM paging system relocates pages of memory from physical memory out to disk when the memory is needed for something else

- The VM paging system can be divided into two sections:
  - Pageout-policy algorithm decides which pages to write out to disk, and when
  - Paging mechanism actually carries out the transfer, and pages data back into physical memory as needed

Virtual Memory (Cont.)

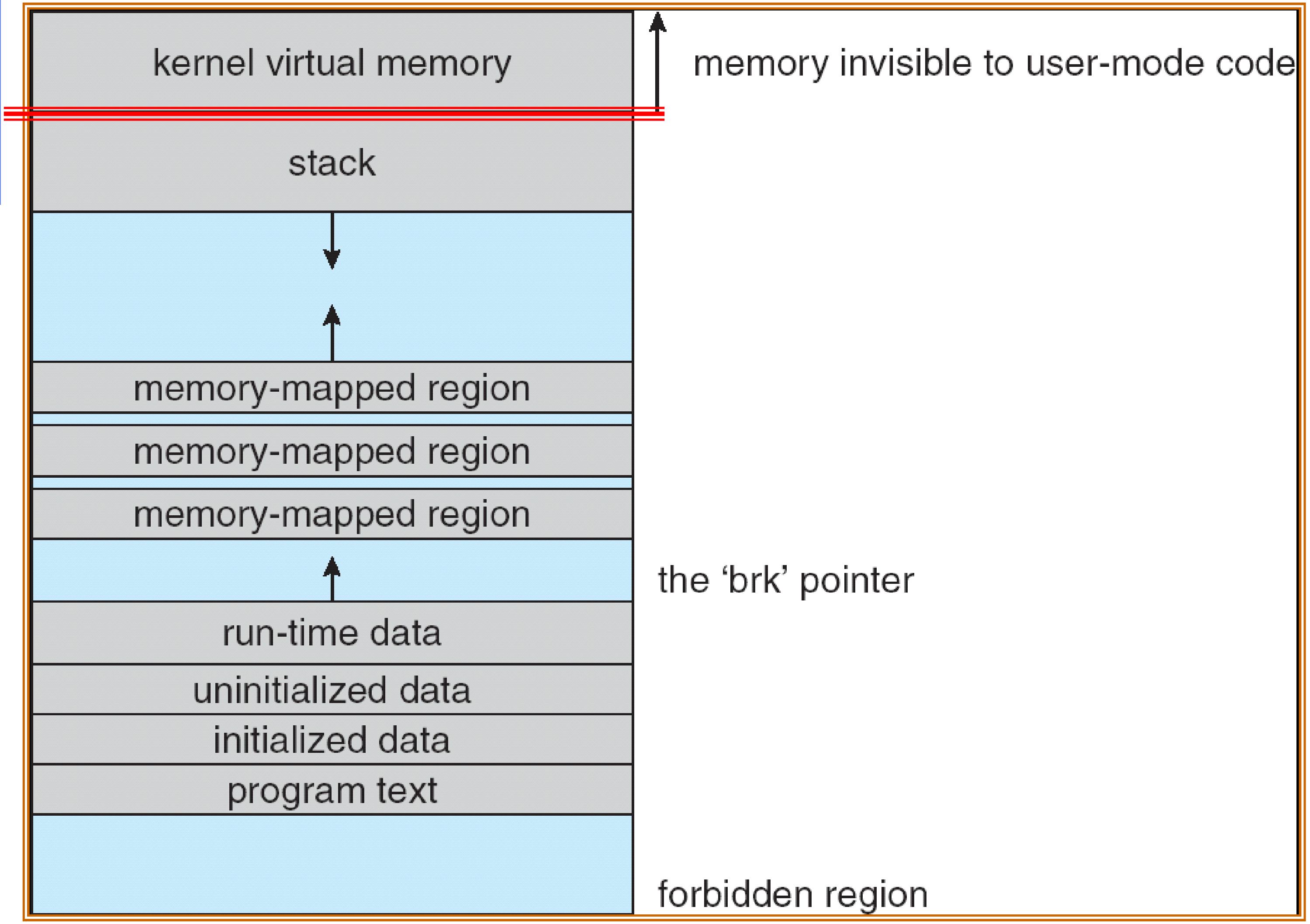
- Linux kernel reserves a constant, architecture-dependent region of the virtual AS of every process for its own internal use

- This kernel virtual-memory area contains two regions:
  - A static area that contains page table references to every available physical page of memory in the system, so that there is a simple translation from physical to virtual addresses when running kernel code
  - The reminder of the reserved section is not reserved for any specific purpose; its page-table entries can be modified to point to any other areas of memory

Executing and Loading User Programs

- Linux maintains a table of functions for loading programs; it gives each function the opportunity to try loading the given file when an exec system call is made
- The registration of multiple loader routines allows Linux to support both the ELF and **a.out** binary formats
- Initially, binary-file pages are mapped into virtual memory
  - Only when a program tries to access a given page will a page fault result in that page being loaded into physical memory
- An ELF-format binary file consists of a header followed by several page-aligned sections
  - The ELF loader works by reading the header and mapping the sections of the file into separate regions of virtual memory

Memory Layout for ELF Programs



Static and Dynamic Linking

- A program whose necessary library functions are embedded directly in the program's executable binary file is statically linked to its libraries

- The main disadvantage of static linkage is that every program generated must contain copies of exactly the same common system library functions

- Dynamic linking is more efficient in terms of both physical memory and disk-space usage because it loads the system libraries into memory only once

File Systems

- To the user, Linux's file system appears as a hierarchical directory tree obeying UNIX semantics
- Internally, kernel hides implementation details and manages the multiple different file systems via an abstraction layer, that is, the virtual file system (VFS)
- The Linux VFS is designed around object-oriented principles and is composed of two components:
  - A set of definitions that define what a file object is allowed to look like
    - The inode-object and the file-object structures represent individual files
    - the file system object represents an entire file system
  - A layer of software to manipulate those objects

Linux VFS

- Uniform FS interface to user processes
- Represents any conceivable file system's general feature and behavior
- Assumes files are objects that share basic properties regardless of the target file system

VFS

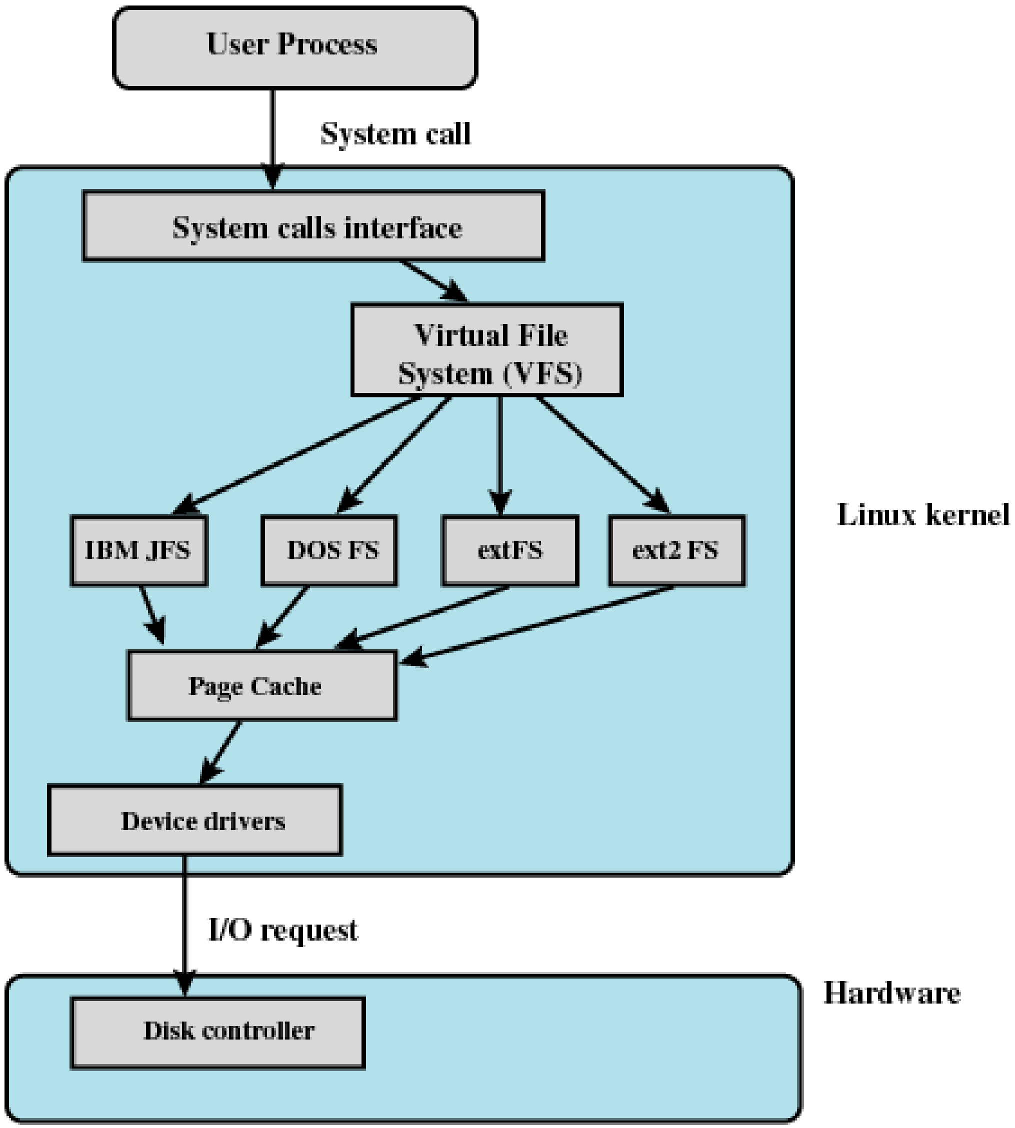


Figure 12.15 Linux Virtual File System Context

VFS

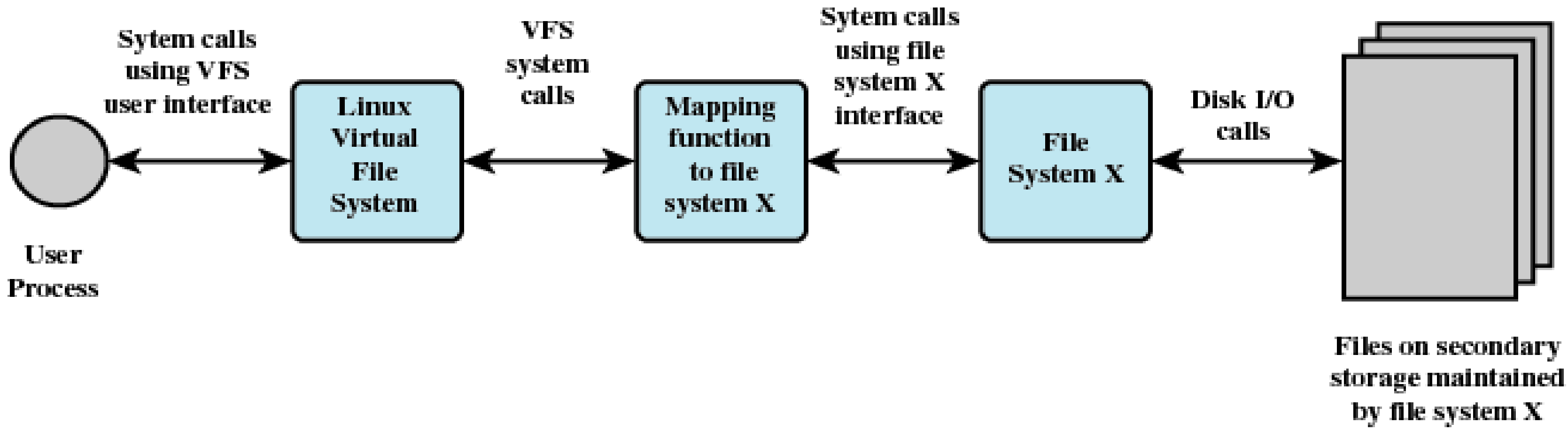
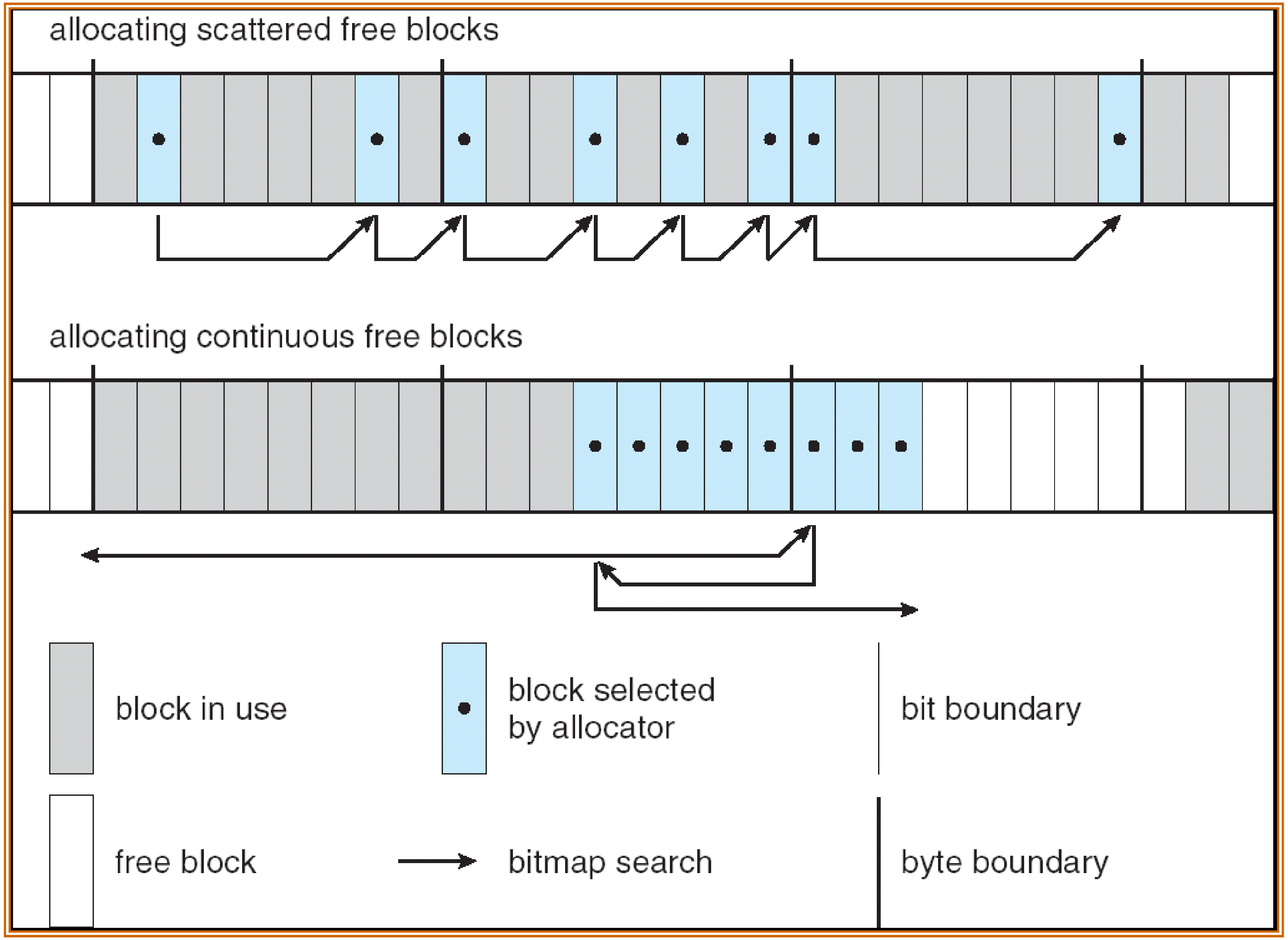


Figure 12.16 Linux Virtual File System Concept

The Linux Ext2fs File System

- Ext2fs uses a mechanism similar to that of BSD Fast File System (ffs) for locating data blocks belonging to a specific file
- The main differences between ext2fs and ffs concern their disk allocation policies
  - In ffs, the disk is allocated to files in blocks of 8Kb, with blocks being subdivided into fragments of 1Kb to store small files or partially filled blocks at the end of a file
  - Ext2fs does not use fragments; it performs its allocations in smaller units
    - The default block size on ext2fs is 1Kb, although 2Kb and 4Kb blocks are also supported
  - Ext2fs uses allocation policies designed to place logically adjacent blocks of a file into physically adjacent blocks on disk, so that it can submit an I/O request for several disk blocks as a single operation

Ext2fs Block-Allocation Policies



The Linux Proc File System

- The **proc** file system does not store data, rather, its contents are computed on demand according to user file I/O requests

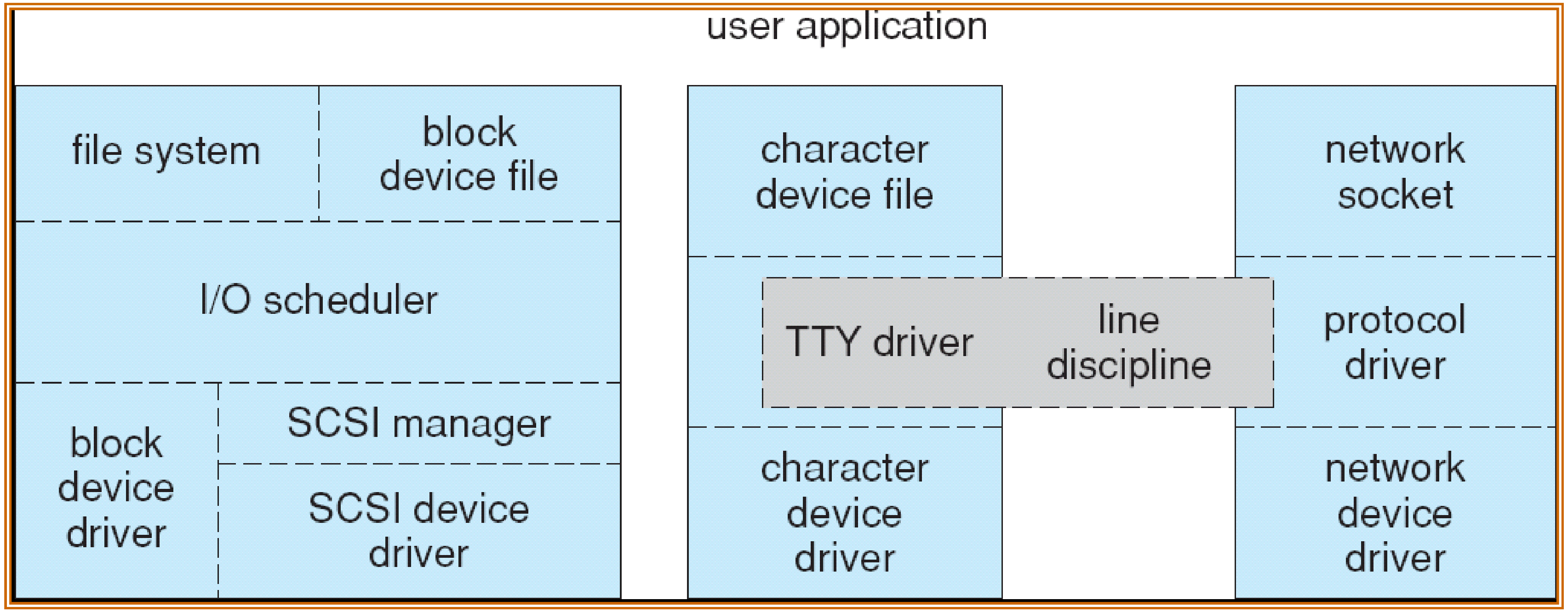
- **proc** must implement a directory structure, and the file contents within; it must then define a unique and persistent inode number for each directory and files it contains
  - It uses this inode number to identify just what operation is required when a user tries to read from a particular file inode or perform a lookup in a particular directory inode
  - When data is read from one of these files, **proc** collects the appropriate information, formats it into text form and places it into the requesting process's read buffer

Input and Output

- The Linux device-oriented file system accesses disk storage through two caches:
  - Data is cached in the page cache, which is unified with the virtual memory system
  - Metadata is cached in the buffer cache, a separate cache indexed by the physical disk block

- Linux splits all devices into three classes:
  - block devices allow random access to completely independent, fixed size blocks of data
  - character devices include most other devices; they don't need to support the functionality of regular files
  - network devices are interfaced via the kernel's networking subsystem

Device-Driver Block Structure



Block Devices

- Provide the main interface to all disk devices in a system
- Block buffer cache serves two main purposes:
  - it acts as a pool of buffers for active I/O
  - it serves as a cache for completed I/O
- Request manager manages the reading and writing of buffer contents to and from a block device driver

Character Devices

- A device driver which does not offer random access to fixed blocks of data
- A character device driver must register a set of functions which implement the driver's various file I/O operations
- The kernel performs almost no preprocessing of a file read or write request to a character device, but simply passes on the the request to the device
- The main exception to this rule is the special subset of character device drivers which implement terminal devices, for which the kernel maintains a standard interface

Interprocess Communication

- Like UNIX, Linux informs processes that an event has occurred via signals
- There is a limited number of signals, and they cannot carry information: Only the fact that a signal occurred is available to a process
- The Linux kernel does not use signals to communicate with processes with are running in kernel mode, rather, communication within the kernel is accomplished via scheduling states and wait.queue structures

Passing Data Between Processes

- Classic pipe mechanism allows a child to inherit a communication channel to its parent, data written to one end of the pipe can be read a the other
- Shared memory offers an extremely fast way of communicating; any data written by one process to a shared memory region can be read immediately by any other process that has mapped that region into its address space
- To obtain synchronization, however, shared memory must be used in conjunction with another Inter-process-communication mechanism

Shared Memory Object

- The shared-memory object acts as a backing store for shared-memory regions in the same way as a file can act as backing store for a memory-mapped memory region
- Shared-memory mappings direct page faults to map in pages from a persistent shared-memory object
- Shared-memory objects remember their contents even if no processes are currently mapping them into virtual memory

Network Structure

- Networking is a key area of functionality for Linux.
  - It supports the standard Internet protocols for UNIX to UNIX communications
  - It also implements protocols native to non UNIX operating systems, in particular, protocols used on PC networks, such as Appletalk and IPX
- Internally, networking in the Linux kernel is implemented by three layers of software:
  - The socket interface
  - Protocol drivers
  - Network device drivers

Network Structure (Cont.)

- The most important set of protocols in the Linux networking system is the internet protocol suite
  - It implements routing between different hosts anywhere on the network
  - On top of the routing protocol are built the UDP, TCP and ICMP protocols

Security

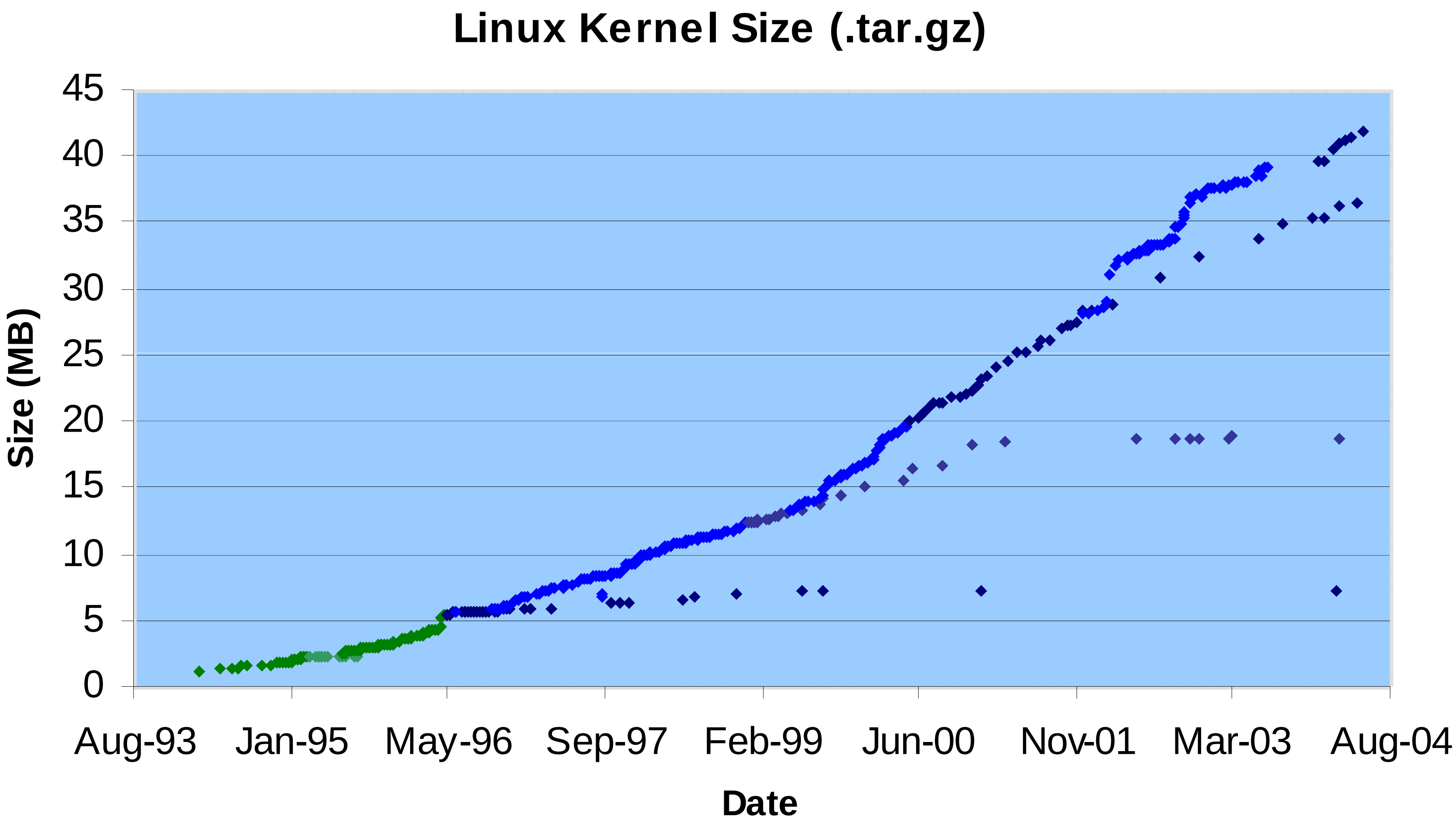
- The *pluggable authentication modules (PAM)* system is available under Linux
- PAM is based on a shared library that can be used by any system component that needs to authenticate users
- Access control under UNIX systems, including Linux, is performed through the use of unique numeric identifiers (**uid** and **gid**)
- Access control is performed by assigning objects a *protections mask*, which specifies which access modes:
  - read, write, or execute

  are to be granted to processes with owner, group, or world access

Security (Cont.)

- Linux augments the standard UNIX **setuid** mechanism in two ways:
  - It implements the POSIX specification's saved *user-id* mechanism, which allows a process to repeatedly drop and reacquire its effective uid
  - It has added a process characteristic that grants just a subset of the rights of the effective uid
- Linux provides another mechanism that allows a client to selectively pass access to a single file to some server process without granting it any other privileges

Linux Evolution



Problem: Complexity of OS ⇒ *worse maintainability*